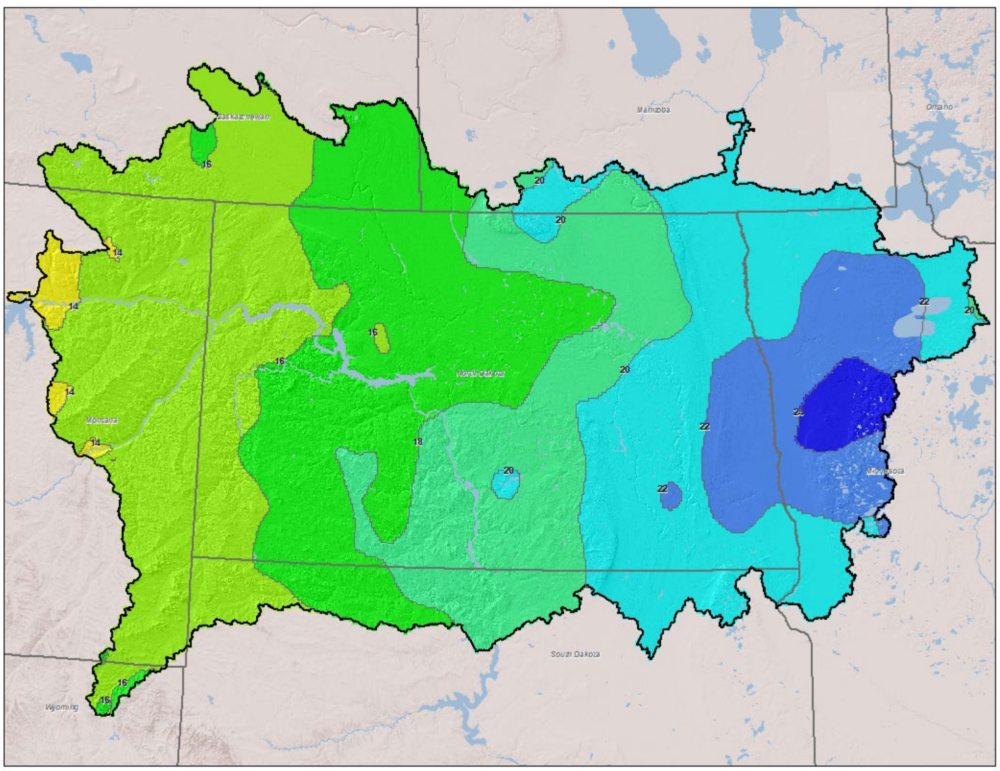
Probable Maximum Precipitation Study For North Dakota
Final Report

Prepared for:

North Dakota State Water Commission

NORTH Dakota | Water Commission
Be Legendary.™



Prepared by:

Applied Weather Associates, LLC
PO Box 175, Monument, CO 80132
(719) 488-4311
www.appliedweatherassociates.com

June 2021

NOTICE

This report was prepared by Applied Weather Associates, LLC (AWA). The results and conclusions in this report are based upon best professional judgment using currently available data. Therefore, neither AWA nor any person acting on behalf of AWA can: (a) make any warranty, expressed or implied, regarding future use of any information or method in this report, or (b) assume any future liability regarding use of any information or method contained in this report.

DISCLAIMER

This report is an instrument of service of Applied Weather Associates, LLC (AWA). The report has been prepared for the exclusive use of the North Dakota State Water Commission (Client) for the specific application to provide PMP depths and associated meteorological data for any location within the overall PMP domain evaluated in this study, and it may not be relied upon by any other party without AWA's written consent.

AWA has prepared this report in a manner consistent with the level of care, skill, and diligence ordinarily provided by members of the same profession for projects of similar scope at the time and place the services were rendered. AWA makes no warranty, express or implied.

Use of or reliance upon this instrument of service by the Client is subject to the following conditions:

1. The report is to be read in full, with section or parts of the report relied upon in the context of the whole report.
2. The Executive Summary is a selection of key elements of the report. It does not include details needed for proper application of the findings and recommendation in the report.
3. The report is based on information provided to AWA by the Client or by other parties on behalf of the Client. AWA has not verified the correctness or accuracy of such information and makes no representations regarding its correctness or accuracy. AWA shall not be responsible to the Client for the consequences of any error or omission contained in Client-supplied information.
4. AWA or the North Dakota State Water Commission should be consulted regarding the interpretation or application of the findings and recommendations in the report.

Bill Kappel, President/Chief Meteorologist, Applied Weather Associates

Credits and Acknowledgements

Applied Weather Associates would like to express sincere appreciation and thanks for the hard work and dedication of all involved in the study, including the members of the state dam safety office and state water commission and the entire staff of Applied Weather Associates.

Applied Weather Associates would also like to acknowledge with much appreciation the review and feedback of the study's Steering Committee and other study observers and participants. Furthermore, Applied Weather Associates would like to express gratitude and thanks to staff members from the Federal Energy Regulatory Commission for their support, discussion, insight, and suggestions.

A study of this magnitude and complexity would not have been possible without the involvement and contribution of all involved.

The following staff of Applied Weather Associates participated in this PMP development:

Bill Kappel	Project Manager/Chief Meteorologist
Doug Hultstrand, PhD	Senior Hydrometeorologist
Jake Rodel	GIS Analyst
Geoff Muhlestein	Senior GIS Analyst
Kristi Steinhilber	Staff Meteorologist

We gratefully acknowledge the assistance of the following individuals for providing project review and information:

Damon Grabow	North Dakota State Water Commission
Michael Hall	North Dakota State Water Commission
Karen Goff	North Dakota State Water Commission
Aaron Carranza	North Dakota State Water Commission
John Paul Martin	Steering Committee Bismarck National Weather Service
Greg Gust	Steering Committee Grand Forks National Weather Service
Charles McWilliams	Steering Committee US Army Corps of Engineers
Matt Masek	Steering Committee US Army Corps of Engineers
Adnan Akyuz	Steering Committee North Dakota State University
Jonathan Petersen	Steering Committee Natural Resources Conservation Service
Nathan Zoch	Federal Energy Regulatory Commission
Kevin Griebenow	Federal Energy Regulatory Commission
Scott Airato	Federal Energy Regulatory Commission
Zach Hermann	Houston Engineering
Paul LeClaire	Houston Engineering
Dennis Reep	HDR Engineering
Joel Toso	BARR Engineering
Alexis Faber	BARR Engineering
Tom MacDougall	RJH Associates

Table of Contents

Table of Figures

Table of Tables

Appendices

Executive Summary

This study produced gridded PMP depths for the project domain which included the state of North Dakota and hydrologically important regions that immediately surround the state extending from southern Canada, eastern Montana, northeastern Wyoming, northern South Dakota, and western Minnesota. PMP depths were developed at a spatial resolution of 90 arc-seconds, or approximately 2-square miles. Variations in topography, climate and storm types across the region were explicitly considered. A large set of storm data were analyzed for use in developing the PMP depths. This included PMP for both all-season (June through September) and cool-season (March-May). PMP depths calculated during this study replace those provided in Hydrometeorological Reports (HMRs) 48, 51, 52, and 55A. Detailed evaluations of the snow water equivalent (SWE) and associated temperature times series were developed for application with the cool-season PMP depths. These data sets were developed on a daily basis covering the entire domain and are utilized with the cool-season PMP depths to produce a total runoff that is a combination of rainfall and snowmelt.

Results of this analysis reflect the current standard of practice 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 for storm maximization, development of SWE and temperature time series climatologies, and improved understanding of the weather and climate related to extreme rainfall and rain-on-snow 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 PMP development utilizes the storm-based approach. This is the same general procedure 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 when adequate data are available. The storm-based approach identified extreme rainfall events that have occurred in regions considered transpositionable to any location within the overall region. These are storms that had meteorological and topographical characteristics similar to extreme storms that could occur over any location within the project domain and were deemed to be PMP-type storm events. These were separated by storm type; Local and General, as well as season. Detailed storm analyses were completed for the largest of these rainfall events and used for final PMP calculations.

Data, assumptions, and analysis techniques used in this study have been reviewed and accepted by the Steering Committee (which included representative from the NWS, Academia, NRCS, and USACE) and the North Dakota State Water Commission with significant input provided by other study participants including the Federal Energy Regulatory Commission and various private consultants.

Although this study produced deterministic values, it must be recognized that there is some uncertainty 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, application of storm transposition limits, and combinations associated with snowmelt and rain-on-snow timing. 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.

Forty-four all-season and eight cool-season PMP-type rainfall events were identified across the storm search area as having similar characteristics to rainfall that could potentially control PMP depths at various locations and durations within the study region. These include 16 General storms, 22 local storm rainfall centers, and an additional six storm centers which exhibited characteristics of both storm types, termed Hybrid storms. These were evaluated as General and Local storms in the PMP determination process. All eight of the cool-season storms were considered General storms.

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). Improved 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 PMP Manual. Updated precipitation frequency analyses data available from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 were used for this study. In addition, updated precipitation frequency climatologies were developed for the regions not covered by NOAA Atlas 14 (Canada and eastern Montana). This updated precipitation frequency climatology was developed following the same processes and data analysis as utilized in NOAA Atlas 14. This allowed for consistency between the data sets and allowed the frequency climatologies to be combined for PMP calculations and analysis.

Precipitation frequency depths were used to calculate the Geographic Transposition Factors (GTFs) for each storm. The GTF procedure, through its correlation process comparing the 100-year precipitation frequency depth, provided quantifiable and reproducible analyses of the effects of terrain and all precipitation processes on rainfall 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, the results of which were used to define the PMP depths.

Maximization factors were computed for each of the storm events used for PMP development utilizing updated dew point climatologies. These were calculated by defining the storm representative dew point for each storm, then comparing that to the maximum moisture that could have been available based on the 100-year recurrence interval dew point climatologies. The dew point climatology included the maximum average 3-, 6-, 12-, and 24-hour 100-year return frequency values. The most appropriate duration consistent with the duration of the observed storm rainfall was used. HYSPLIT model output were utilized to represent model reanalysis fields of air flow in the atmosphere to help identify moisture source regions and timing of moisture inflow into individual storms. For storm events prior to 1948 when HYSPLIT output become available, NWS synoptic weather maps and previous storm analysis data were used as guidance in identifying the storm representative moisture source regions.

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 depths 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, from 1/3rd-square mile through the entire domain.

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 in southeastern North Dakota into southwestern Minnesota and lowest in the far western study region. These spatial variations in PMP depth match the general weather patterns of the region related to moisture availability, topography, and storm dynamics.

Many watersheds regulated by the North Dakota State Water Commission and the NRCS in the region are relatively small in area size, less than 100-square miles. Therefore, 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. The larger basins in the region are often affected by snowmelt and combined rain-on-snow runoff. These include the Souris River basin and the Red River of the North. To ensure the worst-case, yet physically possible runoff scenario was met for these large basins, emphasis was placed on general storms that could produce significant rainfall in the spring snowmelt period that would be most important for these types of basins. Providing PMP depths down to area sizes as small as 1/3rd-square mile by storm type and season, along with North Dakota specific temporal accumulation patterns were significant improvements for dam safety evaluations over what was previously available in the HMRs

In general, the largest reductions were over western North Dakota, with smaller reductions and in some locations small increases, especially over the southwestern portions of North Dakota and western portions of Minnesota. 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 transposition zone and represent the largest of all storm types.

Mean 10 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 6hr	PMP 6hr	% Change 6hr	HMR 51 12hr	PMP 12hr	% Change 12hr	HMR 51 24hr	PMP 24hr	% Change 24hr
1	21.7	19.9	-8.5%	25.9	24.1	-6.8%	27.6	24.2	-12.3%
2	20.8	16.7	-19.8%	24.7	20.3	-17.7%	26.5	20.3	-23.2%
3	20.8	15.9	-23.2%	24.6	19.4	-21.2%	26.5	19.4	-26.6%

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

Mean 200 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 6hr	PMP 6hr	% Change 6hr	HMR 51 12hr	PMP 12hr	% Change 12hr	HMR 51 24hr	PMP 24hr	% Change 24hr
1	16.1	14.8	-8.0%	19.3	15.7	-18.6%	20.9	18.0	-14.0%
2	15.2	13.3	-12.6%	18.2	14.1	-22.5%	20.0	15.5	-22.6%
3	15.0	12.9	-13.7%	17.6	13.7	-22.6%	19.6	15.2	-22.8%

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

Mean 1,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	16.0	14.0	-12.3%	18.2	16.4	-10.1%	19.7	16.6	-15.3%
2	15.4	13.2	-14.4%	17.4	14.8	-15.2%	18.6	14.9	-20.1%
3	15.1	13.2	-13.0%	17.1	14.7	-14.2%	18.3	14.8	-19.1%

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

Mean 5,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	10.9	10.7	-1.1%	13.1	14.0	6.9%	14.6	14.2	-2.9%
2	10.4	10.0	-4.5%	12.4	11.8	-5.1%	13.6	11.9	-12.8%
3	10.3	9.9	-4.1%	12.2	11.5	-5.9%	13.3	11.5	-13.0%

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

Mean 10,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	8.9	9.4	5.7%	11.0	12.6	13.9%	12.5	12.7	1.7%
2	8.5	8.7	1.7%	10.2	10.4	2.1%	11.5	10.6	-8.2%
3	8.4	8.6	2.2%	10.0	10.1	0.5%	11.2	10.2	-8.6%

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

Mean 20,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	6.8	7.9	15.8%	9.1	10.6	17.4%	10.5	10.8	3.6%
2	6.4	7.4	15.1%	8.3	9.0	9.0%	9.5	9.2	-3.1%
3	6.3	7.4	16.5%	8.0	8.9	10.2%	9.1	9.0	-0.8%

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.

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

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

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

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

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 curve: Rainfall accumulation at a given area size through time.

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.

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

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.

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: 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.

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.

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

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

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: 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.

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

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.

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

SAF: Spatial Adjustment Factor

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 calculated Probable Maximum Precipitation (PMP) depths within the state of North Dakota, including areas immediately adjacent to the state that also provide runoff into drainage basins important for North Dakota dam safety (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 the Missouri River basin above Fort Peck Dam, MT. PMP depths provided in this study supersede the current HMR PMP depths from Hydrometeorological Reports (HMRs) 48 (Riedel, 1973), 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 over a given area size. 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 depths 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 and General storms. Hundreds of storms were considered and included both all-season storms (June-October) and cool-season storms (March-May). In total 44 all-season storm events were used for final PMP estimation, and eight cool-season storm events were used for cool-season PMP estimation. The large number of storm events provided an adequate database from which to derive the PMP depths within an acceptable amount of uncertainty for both the all-season and cool-season PMP scenarios. 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 meteorological factors in a physically possible manner. Finally, the cool-season PMP depths were combined with a 100-year snow water equivalent (SWE) daily climatology. The SWE depths were melted utilizing the daily temperature times series developed specifically for this study. The temperature time series and SWE were developed over the same grid as the PMP depths, so that a total runoff which combined the cool-season PMP depths with the daily SWE melt could be evaluated for basins where this scenario would present the worst-case PMF.

During this calculation process, air masses that provide moisture to both the historic observed storm and the hypothetical PMP storm were assumed to be saturated through the entire depth of the atmosphere and contain the maximum moisture possible represented by surface dew point observation converted to an amount of precipitable water. This saturation process used moist pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm.

The storm-based method assumed that the period of record available covering a large region included enough extreme rainfall events so that at least a few storms attained the maximum storm efficiency possible for converting atmospheric moisture to rainfall. PMP development processes assume that if surplus atmospheric moisture had been available, an individual extreme storm would have maintained the same efficiency for converting atmospheric moisture to rainfall and therefore produce more rainfall. The ratio of the maximized rainfall amounts to the actual rainfall amounts is represented by the ratio of the precipitable water in the observed storm versus the climatological maximum precipitable water 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, data is evaluated from the entire period of record (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, the assumption is that at least one storm with dynamics (storm efficiency) that approached the maximum efficiency for rainfall production used in the PMP development has been included. In essence, the process is trading time for space to capture PMP processes.

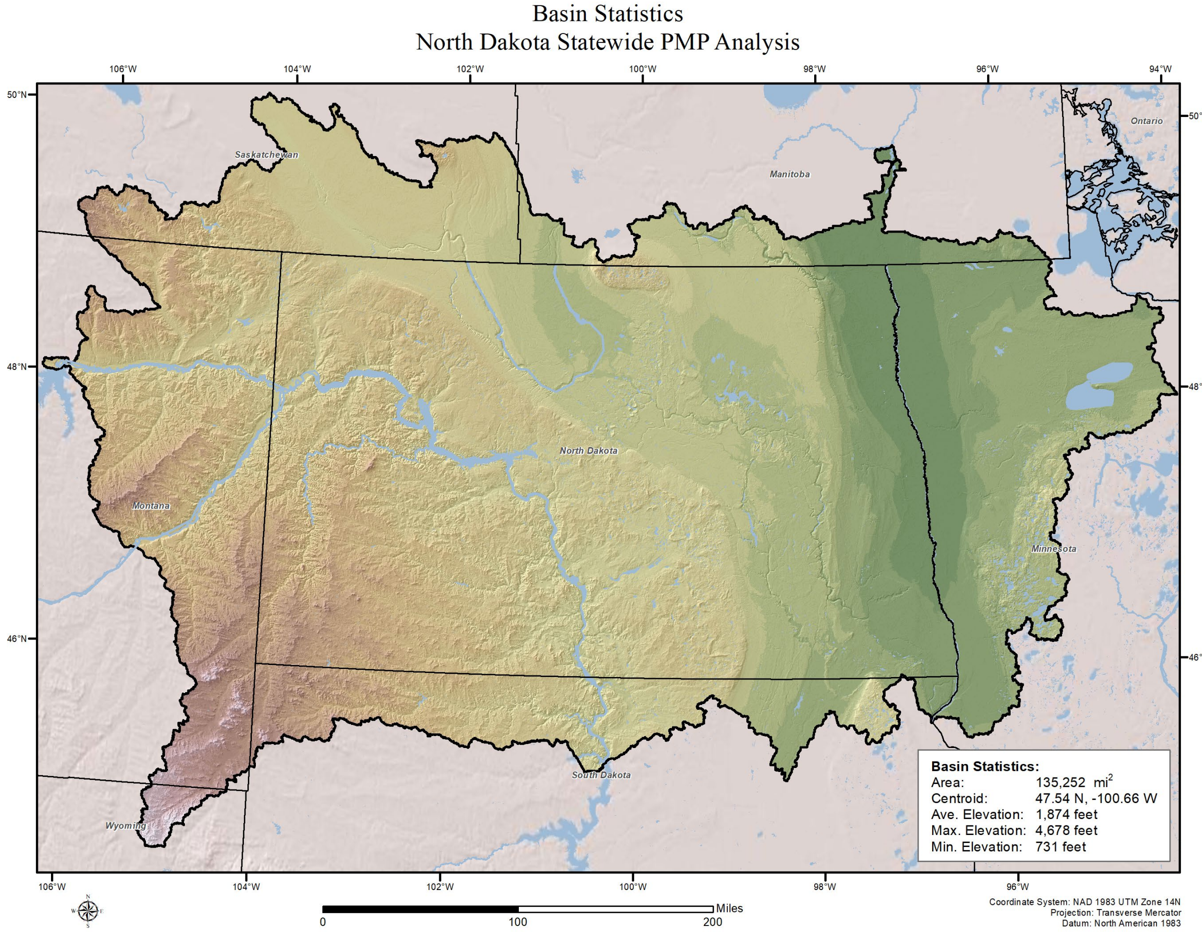


Figure 1.1: Probable Maximum Precipitation study domain

1.1 Previous PMP and Storm Analysis 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 depths presented in their reports are used to calculate the PMF, which in turn, is often used for the design of high hazard hydraulic structures. It is important to remember that the methods used to derive PMP and the hydrological procedures that use the PMP depths 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 depths or for the hydrologic applications of those depths.

The generalized PMP studies currently in use in the contiguous United States are shown in 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, 2004-2018) are available for use in determining precipitation return periods. Several site-specific, statewide, and regional studies (e.g., Tomlinson et al., 2002-2013; Kappel et al., 2012-2021) 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 2021. PMP results from this study provide values that replace those derived from HMRs 48, 51, and 52.

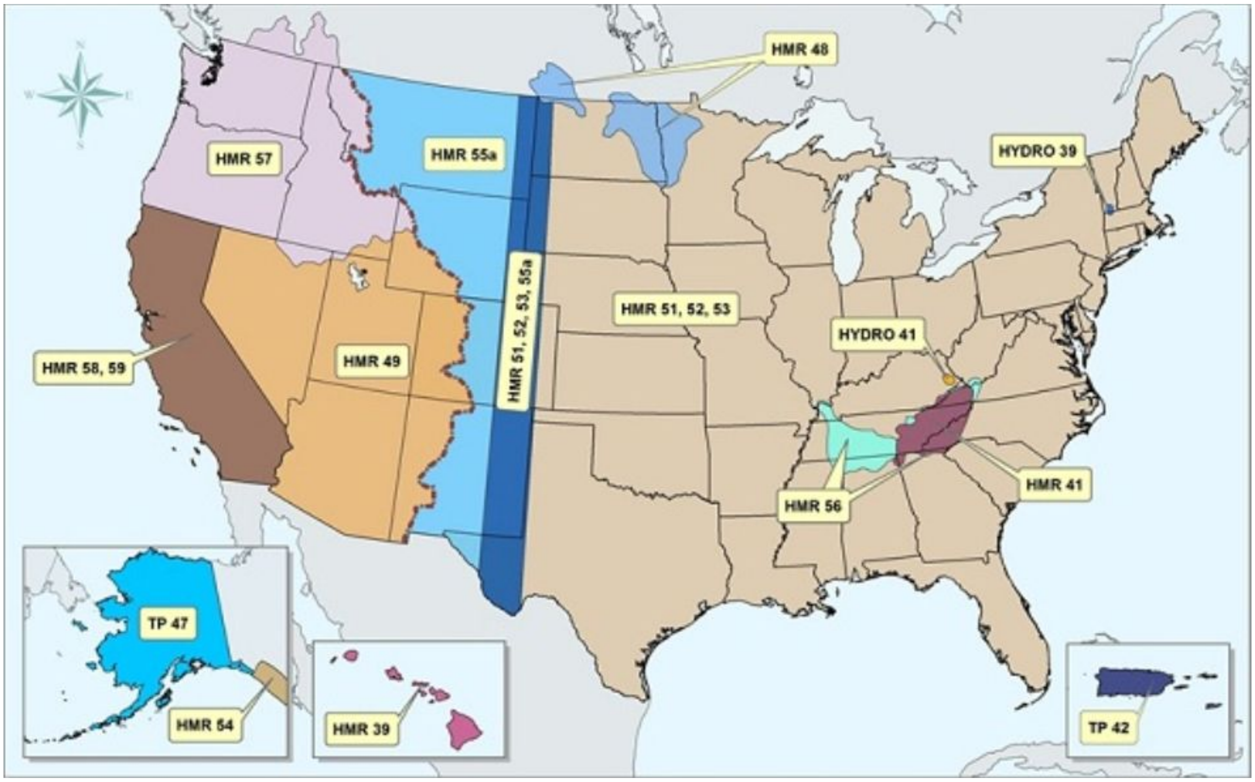


Figure 1.2: Hydrometeorological Report coverages across the United States

The region analyzed is included within the domain covered by HMR 48, 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), while HMR 48 was specifically developed to determine the cool-season PMF and snowmelt combinations for the Red River of the North and Souris River basins. 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 in Montana and Wyoming. 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.

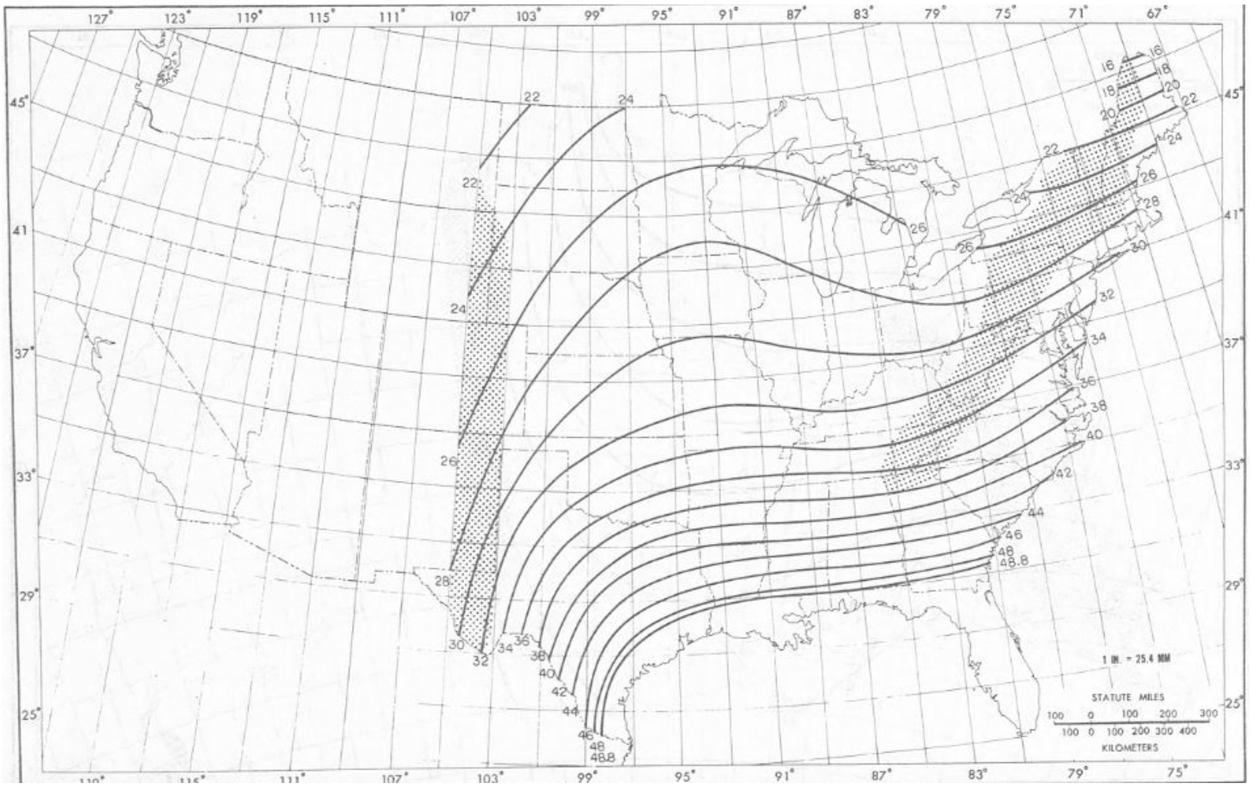


Figure 1.3: Example of HMR 51 72-hour 200-square mile PMP map (from Schreiner and Riedel, 1978).

The region analyzed in this study included climatic variations that extend from direct effects of the western High Plains low-level jet (LLJ) interactions to area effected by slow-moving large-scale frontal systems to spring rain-on-snow flooding situations (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 study 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.

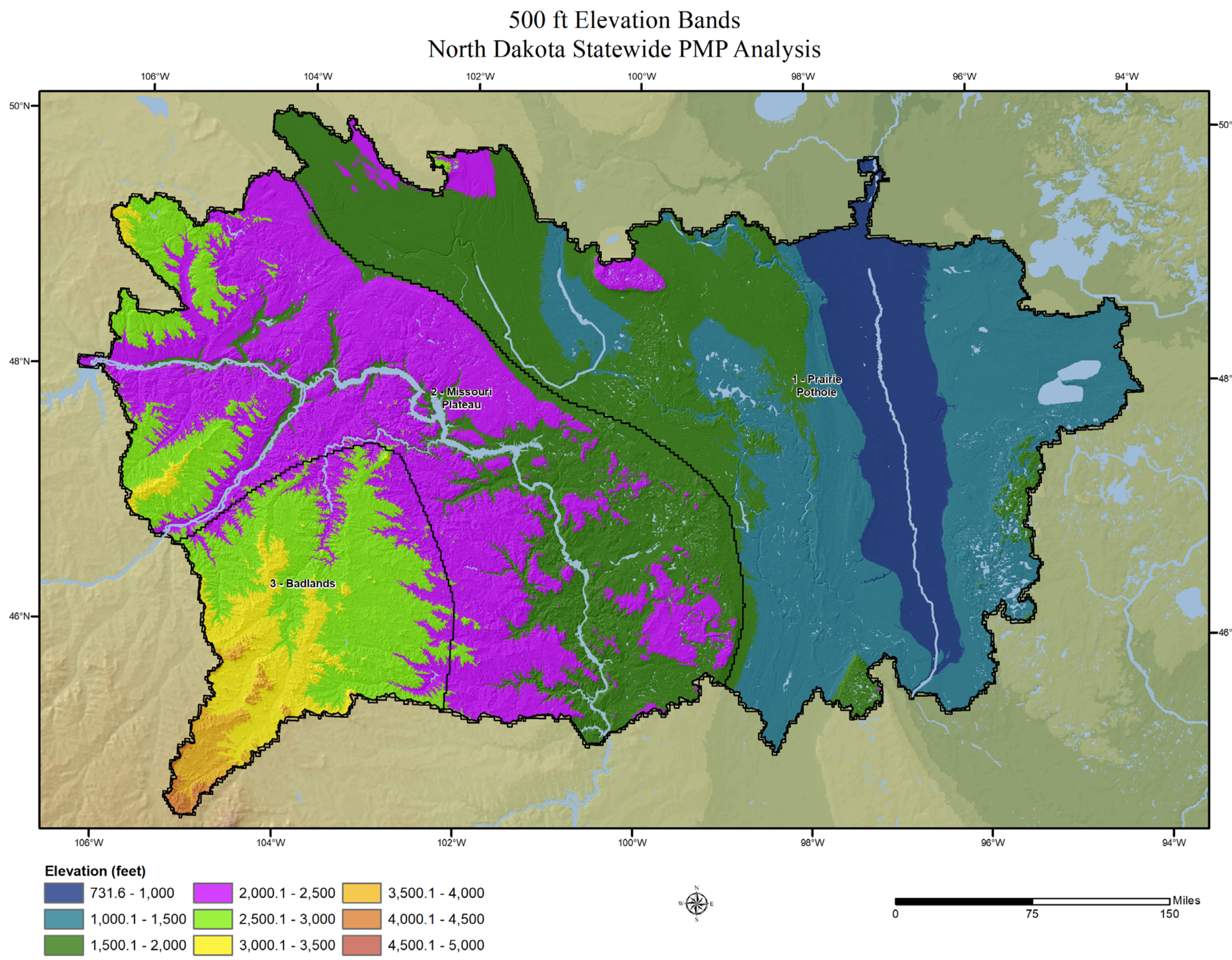


Figure 1.4: Elevations contours over the study Region at 500-foot intervals with transposition zones shown

Previous site-specific, statewide, and regional PMP projects completed by AWA provide examples of PMP studies that explicitly consider the unique climatology, seasonality, and 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 data, 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 high hazards dams and other relevant infrastructure. 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 regions directly relevant to this study (Figure 1.5). Each of these studies provided PMP depths which updated those from the relevant HMR. 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 in similar regions to this study were utilized. 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), US Army Corps of Engineers (USACE), the US Bureau of Reclamation (USBR), the 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 depths. These procedures, together with the Storm Precipitation Analysis System (SPAS) rainfall analyses (Hultstrand and Kappel, 2017), were used to compute PMP depths following standard procedures specific to all locations within the study Region.

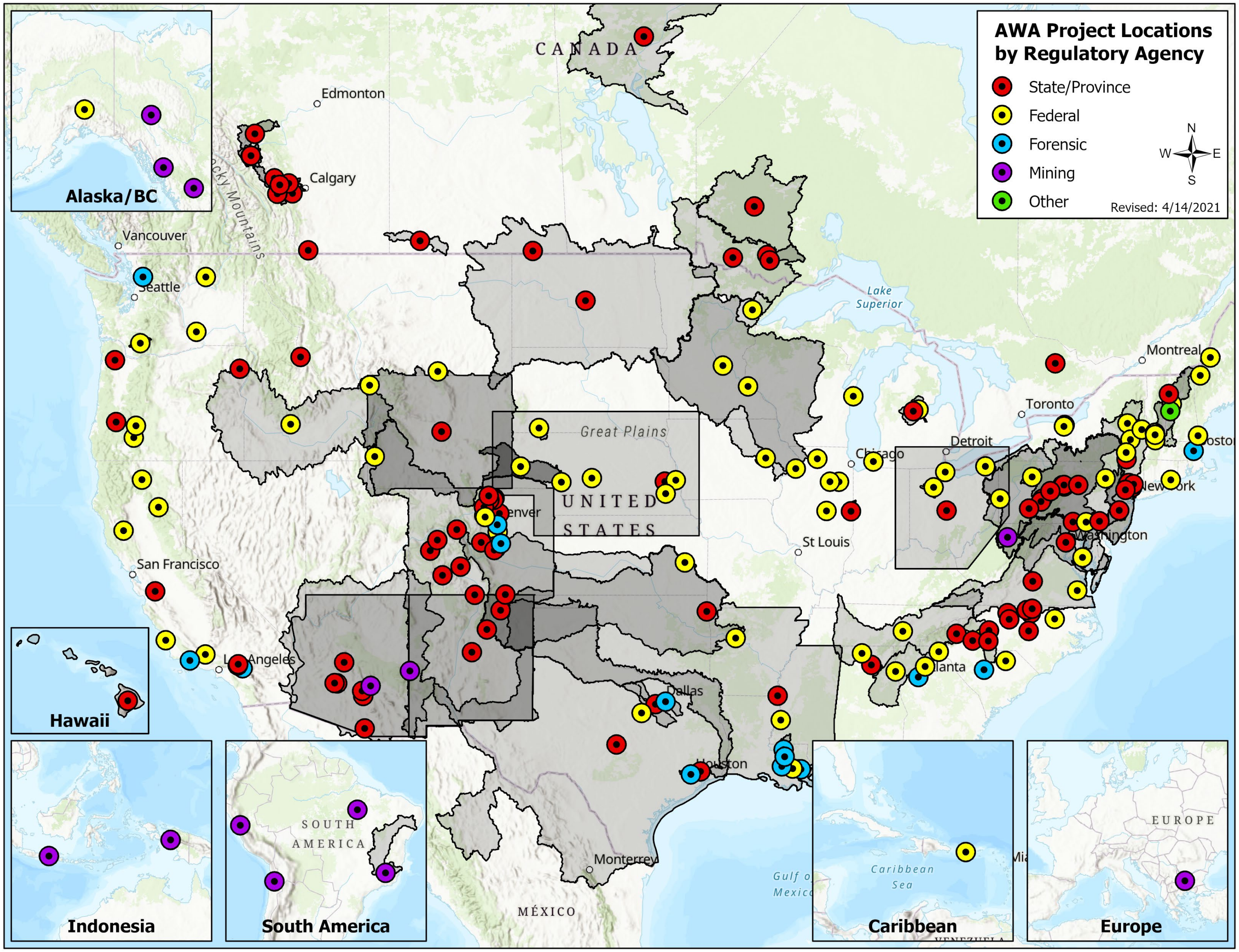


Figure 1.5: Locations of AWA PMP studies as of April 2021

1.2 Objective

This study determines reproducible estimates of PMP depths for use in computing the PMF for various watersheds within the overall project domain. This includes explicit development of both the all-season (June-October) PMP depths and the cool-season (March-May) PMP depths to be combined with snowmelt based on the SWE and temperature time series developed specifically as part of this study. 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 boundary for which the North Dakota State Water Commission 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 the North Dakota State Water Commission, FERC, NRCS, Steering Committee 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 68,277 grid cells with centroids within the domain. Each grid cell represents an approximate area of 2-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 45.0° N and 105.0° W with the adjacent grid point to the west at 45.0° N and 105.025° W. As an example, the PMP analysis grid over the Turtle River basin is shown in Figure 1.6.

0.025 x 0.025 Decimal Degree PMP Grid Network - Turtle River Drainage Basin
North Dakota Statewide PMP Analysis

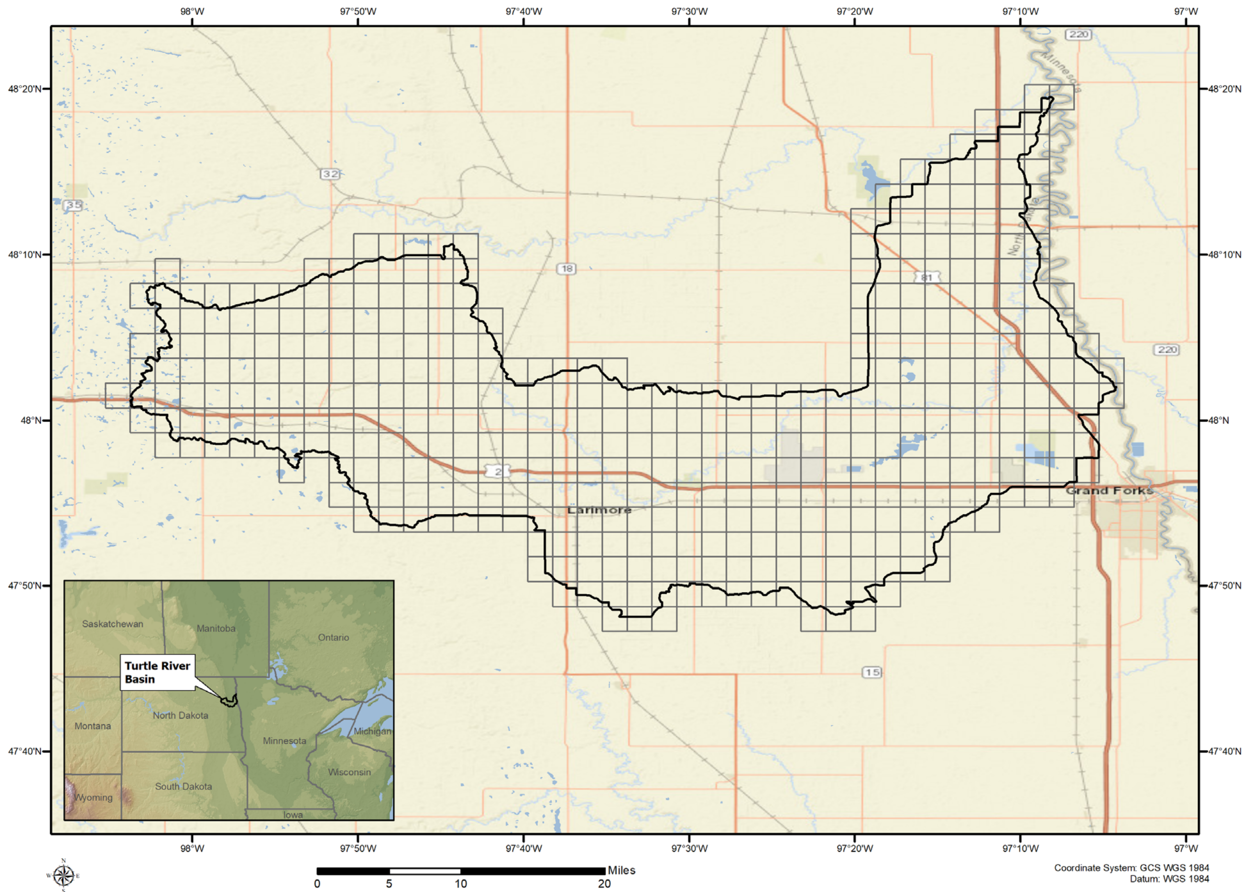


Figure 1.6: PMP analysis grid placement over the Turtle River basin

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 defined areas where those storms were considered transpositionable. Each of the PMP storm types capable of producing PMP-level rainfall for both the all-season and cool-season were identified and investigated. The PMP storm types included Local and General 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.

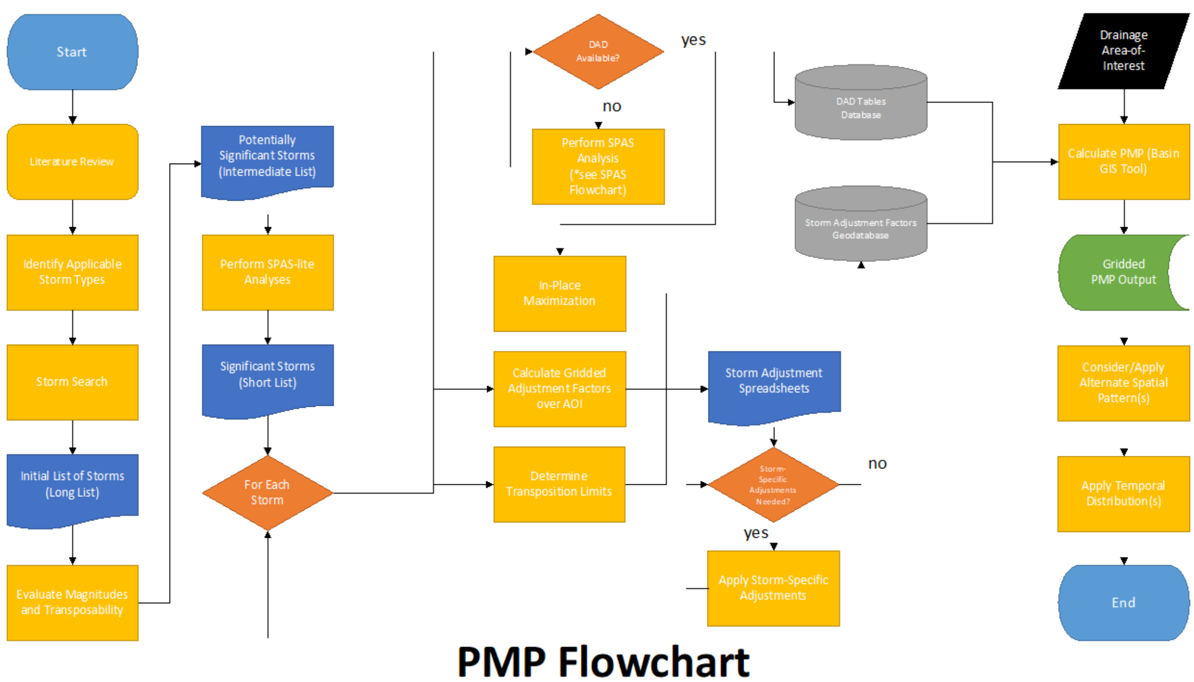


Figure 2.1: Probable Maximum Precipitation calculation steps

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 Steering Committee/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.

SPAS is utilized to analyze the rainfall associated with each storm used for PMP development. SPAS has been used to analyze more than 800 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 (Hultstrand and Kappel, 2017). Several peer reviewed journal articles have utilized SPAS output and processes for various scientific investigations (e.g., Keim et al., 2018 and Brown et al., 2020). 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, the Moisture Transposition Factor (MTF) was calculated for sensitivity purposes and to help with storm transposition evaluations. However as has been the practice in AWA PMP studies since 2018, it has been demonstrated that 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 the TAF applied for PMP calculations.

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 all processes that effect rainfall, including terrain, location, moisture, 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. PMP output depths are then provided for durations required for PMF analysis at a given location by storm type and provided as a basin average. These data have various spatial and temporal patterns associated with them for hydrologic modeling implementation. The spatial patterns are based on climatological patterns and observed storm patterns while the temporal patterns represent a synthesis of historic storm accumulation from storms used in this study. Various combinations of alternative spatial and temporal patterns are also possible at a given location. The user should consult with North Dakota State Water Commission regulations for guidance regarding the use of alternative spatial and/or temporal patterns provided in the PMP tool developed during this study.

Some specific limitations are suggested based on the storm data and application process developed during this study. The following is a summary of limitations resulting from this work:

- Local storm PMP depths should be limited to 100-square miles or less
- Local storm PMP should be evaluated separately from General storm PMP, and the results should not be combineds
- Alternative spatial patterns are only required for basins larger than 100-square miles
- Cool-season PMP is not required for basins less than 100-square miles
- Critically stacked temporal patterns will produce the worst-case PMF outcome, therefore alternative temporal patterns can be investigated in place of the critically stacked pattern if needed
- Cool-season SWE and temperature time series should be investigated using an iterative process to find the ideal start and end dates to maximize the volume of snowmelt in combination with cool-season PMP

3. Weather and Climate of the Region

The region is influenced by several factors that can potentially contribute to extreme rainfall and has a relatively active and varied weather pattern throughout the year. Consequently, rainfall events at both short and long durations are common. The region is open to intrusions of warm, moist air from the south, originating from the Gulf of Mexico, most often from spring through fall. This allows high amounts of moisture to move directly into the region although it will have been modified by the time it reaches the North Dakota domain. The lift required to convert these high levels of moisture into rainfall on the ground is provided in several ways.

Numerous large-scale weather systems, areas of low pressure, with their associated fronts traverse the region, especially from spring through fall. 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 widespread flooding.

Areas of low pressure are often associated with frontal activity. These most often form in the lee of the Rocky Mountains from Alberta through Colorado, then generally move from southwest to northeast or northwest to southeast across the region. These enhance the atmospheric lift by causing rising motions as air converges into the center of the low pressure and the general airflow around the low helps to draw in additional moisture from the south and east ahead of the advancing low pressure system.

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 or updrafts in the atmosphere. 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 and/or be enhanced by a shortwave or troughs moving through the region. These shortwaves and troughs can cause additional lift and instability. 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.

3.1. Regional Climatological Characteristics Affecting PMP Storm Types

Weather patterns in the region are characterized by two main storm types:

1. Areas of low pressure and their associated frontal systems moving through the region from the northwest-west-southwest to the southeast-east-northeast (General storms);
    a. PMP-type General storms have a distinct seasonality with all-season events in the summer and fall and cool-season events on the spring.
2. Isolated thunderstorms/Mesoscale Convective Systems (Local storms)

a. This storm type only produces PMP level rainfall in the late spring through late summer

3.2. Storm Types

The PMP storm types investigated during the study were isolated thunderstorms and Mesoscale Convective Systems (MCS) where the main rainfall occurs over short durations and small area sizes (Local storms) and General storms where main rainfall occurs over large areas sizes and longer durations. Spatial and temporal patterns associated with each of these storms types was explicitly investigated and utilized in this study. The development of these patterns and application for this study are described in Section 13.

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 Steering Committee 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; Kappel et al., 2019; and Kappel et al., 2021) resulting in 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 when compared to General storms
- Occurred during the appropriate season, May through September

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

It should be noted that some of the storms exhibit characteristics of both storm types and therefore have been included for PMP development as both a Local storm and General storm. These are classified as hybrid storms.

3.2.1. Local Storms

Localized thunderstorms and MCSs can produce 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.
MCCs are a mesoscale convective system that satisfies all of the following criteria (from Penn State's e-education institute):

- 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 40,000 square miles, 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 20,000 square miles;
- 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 (-26 degrees Fahrenheit) 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 nocturnal low-level jet (LLJ) 3,000-5,000 feet above the ground. This feed of moisture is very common over the southern and central Great Plains, but it is much less common over the North Dakota study region. However, on rare occasions when extremely high levels of instability occurs over the region and is continually replenished by the LLJ, extreme rainfall accumulations can occur.

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.

Because this storm type is associated with an isolated environment conducive to convective development, these storms go through a distinct life cycle and general do not last more than an hour or two. However, within this short timeframe, extremely heavy, but localized rainfall can accumulate.

3.2.2. General Storms

General storms occur in association with frontal systems, boundaries between contrasting air masses. Precipitation associated with frontal systems is enhanced when the movement of weather pattern slows 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 high levels of moisture, PMP-level precipitation can occur.

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 spring through fall. In addition, during spring, these types of events can produce significant rainfall that is less than summer and fall season total amounts, however, they can occur with antecedent snowfall on the ground or when river systems are in flood from previously melting snow. In these situations, the total amount of runoff may be greater than rainfall only runoff during the summer and fall seasons and produce a more critical PMF. Note that strong frontal systems do affect many parts of the region in winter, however, these produce snowfall and no direct runoff.

4. Topographic Effects on Precipitation

Differences in elevation, even seemly slow rises across large region such as North Dakota, can play a significant role in precipitation development and accumulation patterns and magnitude. 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) and whether the terrain limits moisture availability to a given location. In the North Dakota study region, these two factors are constantly working against each other. This occurs as air and moisture are forced to rise as they move inland and encounter higher terrain moving east to west through the region. However, the higher terrain in the study region is generally further from the moisture source to the north and west. In these locations, the effect of rising elevations is too gradual to overcome the loss of atmospheric moisture. In general, the highest annual rainfall and PMP depths are located in regions closest to the main moisture source, the Gulf of Mexico, in southern and eastern portions of the study domain.

To account for the effect of terrain on precipitation and how this relates to PMP development, explicit evaluations were performed using precipitation frequency climatologies, investigations into past storm spatial patterns, and individual storm accumulation patterns across the region. NOAA Atlas 14 precipitation frequency climatologies (NOAA Atlas 14 Volume 2 Bonnin et al., 2006 and NOAA Atlas 14 Volume 8 Perica et al., 2013), were used in this analysis. In addition, an updated precipitation frequency climatology was developed to cover the regions not included in NOAA Atlas 14. These were southern Canada and eastern Montana (northeastern Wyoming was already updated by AWA as part of the Wyoming statewide PMP study in 2013). Details on the precipitation frequency updates are provided in Section 14.

These climatologies were used to derive the GTF and develop 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, with the exception of the far southwestern portion of the study domain approaching the northern portion of the Black Hills region (Figure 4.1). Elevations vary from around 800 feet along the Red River of the North to over 4,000 feet along the upper reaches of the Little Missouri River in northeastern Wyoming. 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 to precipitation. These interactions must be taken into account in the PMP determination procedure, and quantiied in the storm adjustment process.

Quantification of terrain effects are inherently captured in the GTF process by evaluating rainfall depths at the 100-year recurrence interval using the 6-hour duration for Local storms and the 24-hour duration for General storms at both the source (storm center) and target (grid point) location. This comparison produces 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.

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 durations representative of each storm type, it is assumed the storms being compared using the precipitation frequency data are of similar moisture availability and other precipitation-producing factors.

Use of the GTF calculation to represent differences in all precipitation processes between two locations was explicitly evaluated and determined during the course of this study through various sensitivities and discussions with the Steering Committee, North Dakota State Water Commission, FERC, and others involved in this study. Recent AWA PMP studies have included similar 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).

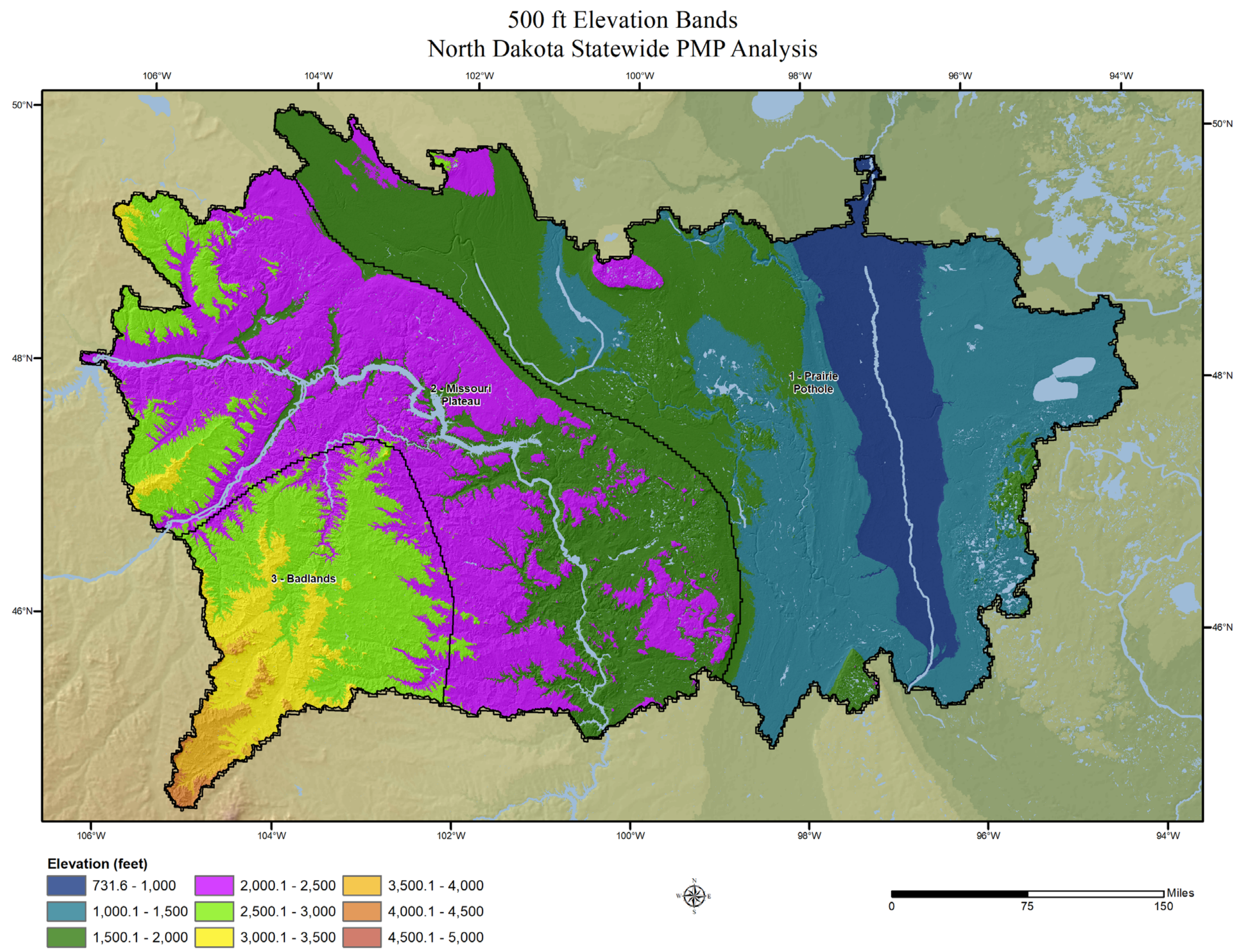


Figure 4.1: Topography variation in 500-foot contours across the domain analyzed

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, Wyoming, Colorado, Oklahoma, Arkansas and several site-specific studies within the region including Canada). The updated storm search completed was used to augment those previous storm lists and utilized data from the sources below:

1. Discussions with the Steering Committee and other study participants
2. Hydrometeorological Reports, each of which can be downloaded from the Hydrometeorological Design Studies Center website at http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html
3. Cooperative Summary of the Day / TD3200 through 2020. 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.
4. 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.
5. NCEI Recovery Disk. These are stored on AWA's database server and can be obtained directly from the NCEI.
6. U.S. Corps of Engineers Storm Studies (USACE, 1973)
7. United States Geological Society (USGS) Flood Reports
8. Environment Canada storm studies
9. Other data published by NWS offices. These can be accessed from the National Weather Service homepage at http://www.weather.gov/.
10. Data from supplemental sources, such as Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), Weather Underground, Forecast Systems Laboratories, RAWS, and various Google searches
11. Previous and ongoing PMP and storm analysis work (Tomlinson, 1993; Tomlinson et al., 2008-2013; Kappel et al., 2013-2020; Dillon 1991; Acres International 2000; IBI Group 2006; KGS Group 2018; and Wood 2018)
12. Peer reviewed journals

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 periodically updated by AWA, most recently in 2018. Storm precipitation amounts were maximized using the ratio of precipitable water calculated from 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). This table is reproduced and included in each of the TAF spreadsheets for each storm used in this study.

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 mechanisms that represent the upper limit of physically possible rainfall amounts. 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. Importantly, 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 from which to develop the climatologies out to the 100-year recurrence interval with confidence. These data were not available in sufficient quantity and period of record during the development of HMR 51 and specifically the dew point climatologies used to maximize storms in the and previous HMRs.

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) updated dew point climatologies covering those storms were developed. HMR 55A contained updated maximum dew point values for a portion of United States from the Continental Divide eastward into the Central Plains, but again utilized the persisting dew point process. 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 (Tomlinson 1993). 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 Michigan and Wisconsin PMP study (Section 2-1 and 7, Tomlinson, 1993). That study included original authors of HMR 51 on the review board.

The Michigan and Wisconsin PMP study was conducted using an at-site method of analysis with L-moment statistics. The Review Board 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 and additional data were available. 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).

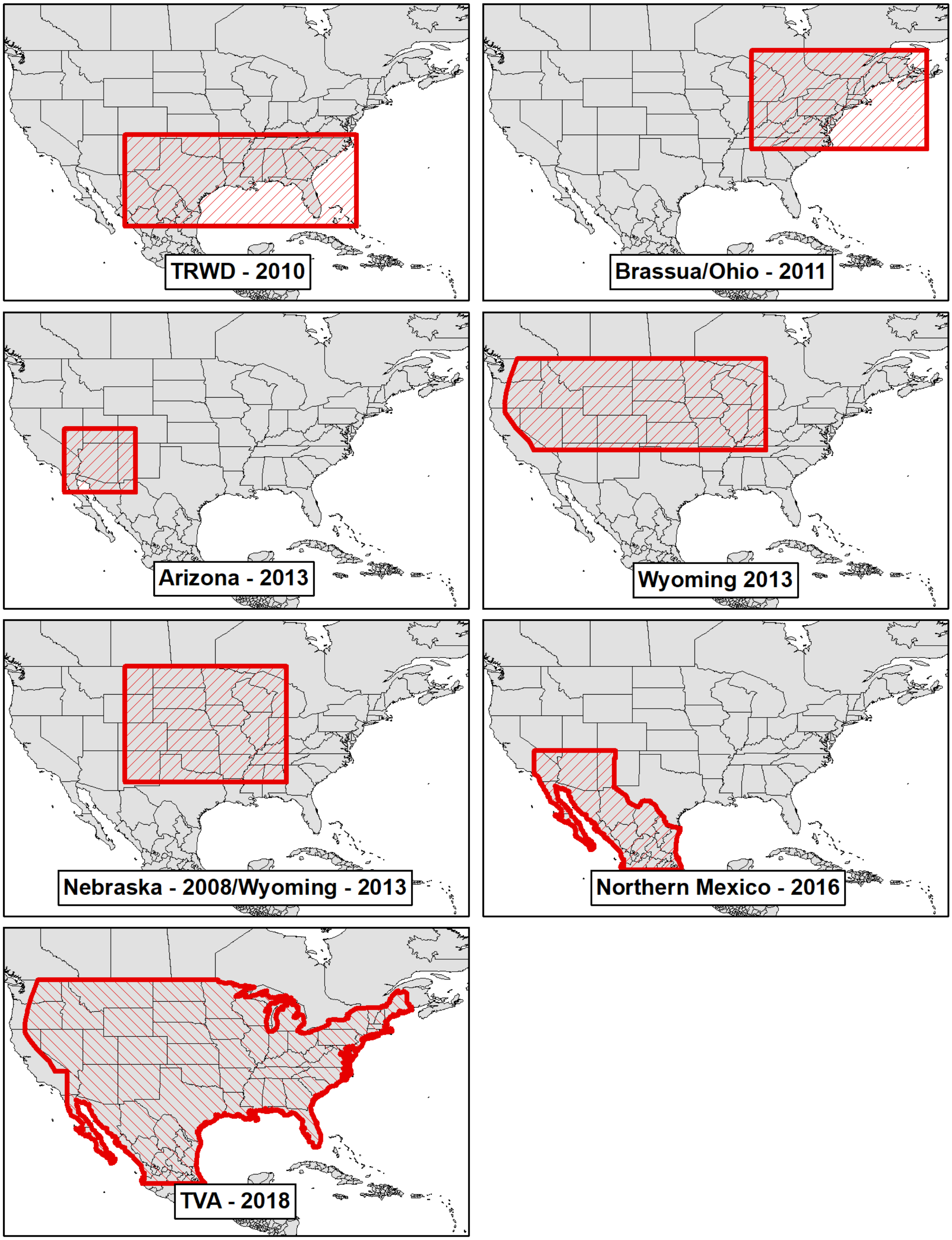


Figure 5.1: Maximum dew point climatology development regions and dates

6. Data Quality Control and Quality Assurance

During the development of the deterministic PMP depths, quality control (QC) and quality assurance (QA) measures were in-place to ensure data used were free from errors and processes followed acceptable scientific procedures. AWA QC/QA procedures were in-place internally while the Steering Committee, North Dakota State Water Commission, FERC, and other study participants provided detailed additional review.

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 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 confirm proper spatial continuity of PMP depths. Updates were applied to develop 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 Steering Committee 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 adjustment values for each storm were reviewed, and the PMP depths across the region reviewed and discussed. Extensive testing of the PMP tool and specifically the cool-season PMP and rain-on-snow components were completed. The results of these tests were crucial in setting limitations and guidelines for appropriate application. In addition, the Steering Committee 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 numerous site-specific, statewide, and regional 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, Environment Canada storm studies, and NWS information.

The direct interaction with the NWS that were part of the Steering Committee provided valuable information during the storm search process. These discussions helped identify dates with large rainfall amounts for locations within the storm search domain and specifically within North Dakota. Several storms were identified for further investigation, with full SPAS analyses completed as part of this study (Table 7.1). This was beneficial in note only providing important in situ data but also provided two storms events that were important for setting PMP depths. This included the Leonard, ND June 1975 (SPAS 1725) and Turtle River, ND June 2000 (SPAS 1726). This helped improve the reliability of the study results and demonstrated the importance of the Steering Committee process.

Storms from each of these sources were evaluated to see if they occurred within the overall region considered to be transpositionable to any location 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 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 or General) and whether they were appropriate for all-season or cool-season based on their accumulating characteristics and seasonality as discussed in Section 2. Storm types were discussed with the Steering Committee to ensure concurrence and cross-referenced with previous storm typing for consistency. 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 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 Steering Committee 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 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.

Each storm on the final short storm list 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 Steering Committee and other study participants. These included evaluations and comparisons of the meteorological characteristics of each storm, 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 various area sizes, and comparison of precipitation values after applying a 50% maximum increase to the observed values.

7.2 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 to develop an all-season storm list and a cool-season storm list. Each storm on the final short storm lists exhibited characteristics that were determined to be possible over some portion of the overall study domain. Storms that made it through these final evaluations were placed on the short storm list (Tables 7.2 and 7.3). Figures 7.2-7.4 provide the all-season short list storms and Figure 7.5 provides the cool-season short list storms. The callouts also provide the storm name and date that can be cross-referenced with the information provided in Tables 7.2 and 7.3. Each of these storms were fully analyzed in previous PMP studies or as part of this study using the SPAS process (Appendix E). Table 7.1 lists the storms that were newly analyzed for this study. Ultimately, only a subset of the storms on the short list control PMP depths at a given location for a given duration, with most providing support for the PMP depths.

The short storm list contains 44 all-season and eight cool-season storms, 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 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 TAR value for the smaller rainfall event that is greater than the larger rainfall event after all adjustments are applied.

Table 7.1: New storms analyzed in this study and used for PMP development

SPAS_ID	Storm Name	State	Lat	Lon	Year	Month	Day	Maximum Rainfall
SPAS_1725_1	LEONARD	ND	46.5958	-97.3375	1975	6	29	20.66
SPAS_1726_1	TURTLE RIVER	ND	47.9550	-97.7550	2000	6	13	20.00
SPAS_1727_1	DRUMMOND	WI	46.3150	-91.4150	2018	6	14	17.33
SPAS_1728_1	CROSS PLAINS	WI	43.1450	-89.6150	2018	8	21	16.24
SPAS_1729_1	FOUNTAIN	MI	44.0350	-86.1850	2019	7	20	15.77
SPAS_1734_1	THIEF RIVER FALLS	MN	48.1625	-96.2625	1949	5	27	9.96
SPAS_1735_1	COLDWATER	MI	41.9625	-85.0042	1989	5	30	9.2
SPAS_1736_1	STANTON	NE	41.8208	-97.0292	1944	6	10	17.49
SPAS_1738_1	HARLAN	IA	41.7208	-95.2125	1972	9	10	15.81
SPAS_1744_1	EAST TROUT LAKE	SK	54.4375	-104.7542	1974	7	10	12.32
SPAS_1732_1	MADISON	SD	44.0350	-97.2250	2012	4	29	8.43
SPAS_1733_1	GROTON	SD	45.3750	-98.1150	2007	5	2	11.02
SPAS_1737_1	CHAN GURNEY	SD	42.9150	-97.3850	2019	3	13	4.52
SPAS_1739_1	IRON RIVER	MI	46.0875	-88.6208	1903	4	29	9.27
SPAS_1740_1	CROSWELL	MI	43.3208	-82.5792	1929	4	4	5.15
SPAS_1743_1	BELCOURT	ND	48.7950	-99.7250	1999	5	3	8.36

Storm Search Domain
North Dakota Statewide PMP Analysis

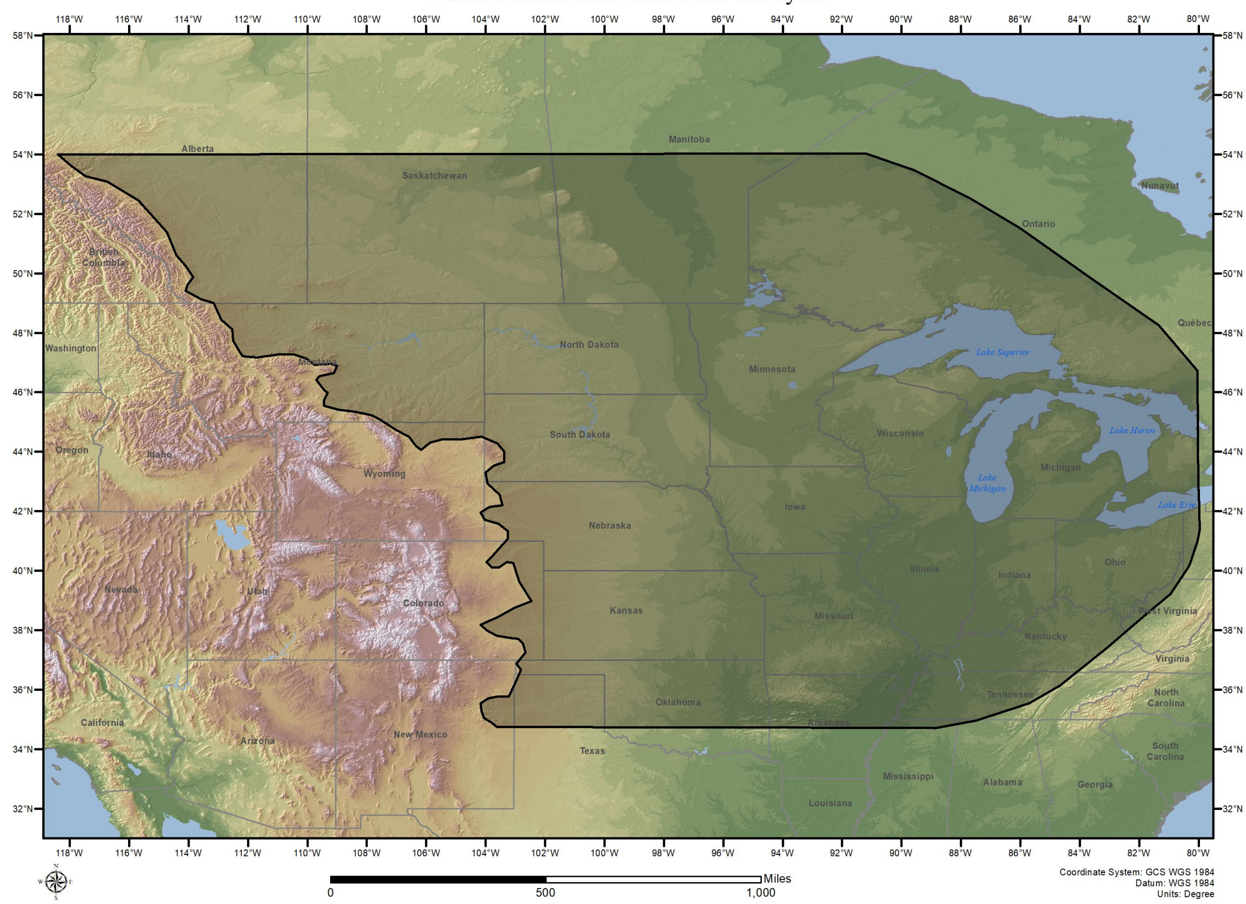


Figure 7.1: Overall storm search domain used to identify potential storm events

Table 7.2: All-season short storm list

SPAS_ID	Storm Name	State	Lat	Lon	Year	Month	Day	Maximum Point Rainfall	Elevation	Storm Rep Analysis Duration	Storm Rep Dew Point	In Place Max Dew Point	In Place Max Factor	Temporal Transposition Date	Storm Rep Lat	Storm Rep Lon	Moisture Inflow Vector	PMP_TYPE
SPAS_1335_1	WARRICK	MT	48.0791	-109.7041	1906	6	5	13.69	4123	24	66.00	75.50	1.50	20-Jun	45.92	-102.20	ESE @ 380	General
SPAS_1697_1	IRONWOOD	MI	46.4542	-90.2064	1909	7	21	13.41	1443	24	72.00	80.50	1.50	15-Jul	42.75	-92.25	SSW @ 275	General
SPAS_1426_1	COOPER	MI	42.3764	-85.6103	1914	8	31	13.39	875	6	75.00	82.00	1.41	15-Aug	40.25	-89.50	SW @ 250	Local
SPAS_1336_1	SPRINGBROOK	MT	47.3642	-105.7778	1921	6	17	15.20	2687	24	74.00	78.00	1.22	5-Jul	45.30	-98.55	ESE @ 370	General
SPAS_1325_1	SAVAGETON	WY	43.8458	-105.8042	1923	9	27	17.56	5056	24	71.50	74.50	1.19	15-Sep	38.90	-100.08	SE @ 450	General
SPAS_1521_2	BASSANO	AB	50.7792	-112.5708	1923	5	29	7.72	2690	6	59.00	73.50	1.50	15-Jun	48.50	-107.00	ESE @ 295	Local
SPAS_1427_1	BOYDEN	IA	43.1958	-95.9958	1926	9	17	24.22	1438	12	77.00	79.00	1.10	3-Sep	40.85	-94.75	SSE @ 175	Local
SPAS_1699_1	HAYWARD	WI	45.9958	-91.0958	1941	8	28	15.35	1377	24	73.00	80.00	1.40	15-Aug	42.99	-89.78	SSE @ 225	Hybrid (G/L)
SPAS_1736_1	STANTON	NE	41.8208	-97.0292	1944	6	10	17.49	1571	6	75.00	80.50	1.30	24-Jun	35.00	-100.00	SSW @ 500	Local
SPAS_1433_1	COLLINSVILLE	IL	38.6708	-90.0042	1946	8	12	19.07	563	24	76.00	80.00	1.21	1-Aug	35.71	-91.60	SSW @ 225	General
SPAS_1434_1	HOLT	MO	39.4542	-94.3292	1947	6	18	17.62	949	6	79.00	81.50	1.13	5-Jul	36.18	-95.25	SSW @ 230	Local
SPAS_1734_1	THIEF RIVER FALLS	MN	48.1625	-96.2625	1949	5	27	9.96	1146	6	69.00	77.00	1.49	11-Jun	46.18	-98.56	SW @ 175	Local
SPAS_1583_1	COUNCIL GROVE	KS	38.6458	-96.6208	1951	7	9	18.56	1430	24	75.00	80.50	1.30	15-Jul	36.05	-93.32	SE @ 250	General
SPAS_1630_1	BOLTON	ONT	43.8375	-79.9792	1954	10	14	11.23	1250	24	68.00	71.50	1.19	1-Oct	41.16	-81.35	SSW @ 200	General
SPAS_1334_1	BUFFALO GAP	SK	49.1146	-105.2896	1961	5	30	10.50	2,600	6	67.50	76.00	1.50	15-Jun	41.50	-104.00	SSE @ 530	Local
SPAS_1527_1	IDA GROVE	IA	42.3625	-95.4958	1962	8	30	12.67	1329	24	71.00	80.00	1.50	15-Aug	38.60	-96.65	SSW @ 265	General
SPAS_1030_1	DAVID CITY	NE	41.2132	-97.0710	1963	6	24	15.98	1627	6	73.50	82.00	1.50	9-Jul	39.41	-94.83	SE @ 175	Local
SPAS_1183_1	EDGERTON	MO	40.4125	-95.5125	1965	7	18	20.76	915	24	76.00	80.50	1.24	15-Jul	39.22	-96.58	SW @ 100	Hybrid (G/L)
SPAS_1324_1	GLEN ULLIN	ND	47.3041	-101.3875	1966	6	24	12.87	1724	6	72.00	80.00	1.49	8-Jul	42.00	-102.00	S @ 370	Local
SPAS_1209_1	WOOSTER	OH	40.9146	-81.9729	1969	7	4	14.95	1164	24	76.00	79.00	1.16	15-Jul	39.43	-83.80	SW @ 140	Local
SPAS_1504_1	PELICAN MOUNTAIN	AB	55.5542	-113.6625	1970	6	26	11.25	2733	24	67.50	76.00	1.50	15-Jul	51.14	-103.08	ESE @ 530	General

Table 7.2: All-season short storm list (continued)

SPAS_ID	Storm Name	State	Lat	Lon	Year	Month	Day	Maximum Point Rainfall	Elevation	Storm Rep Analysis Duration	Storm Rep Dew Point	In Place Max Dew Point	In Place Max Factor	Temporal Transposition Date	Storm Rep Lat	Storm Rep Lon	Moisture Inflow Vector	PMP_TYPE
SPAS_1738_1	HARLAN	IA	41.7208	-95.2125	1972	9	10	15.81	1368	24	74.50	78.00	1.19	27-Aug	39.21	-98.23	SW @ 235	General
SPAS_1502_1	VETERAN	AB	51.8625	-110.4292	1973	6	13	9.56	2185	24	69.00	75.00	1.36	1-Jul	49.07	-103.00	ESE @ 380	General
SPAS_1744_1	EAST TROUT LAKE	SK	54.4375	-104.7542	1974	7	10	12.32	1650	6	72.50	76.00	1.19	15-Jul	51.00	-105.00	S @ 240	Local
SPAS_1725_1	LEONARD	ND	46.5958	-97.3375	1975	6	29	20.66	1061	24	76.50	80.00	1.18	15-Jul	44.12	-93.53	SE @ 250	Hybrid (G/L)
SPAS_1035_1	FOREST CITY	MN	45.2394	-94.5404	1983	6	20	17.00	1082	12	72.00	81.00	1.50	6-Jul	44.02	-92.94	SE @ 115	Local
SPAS_1337_1	PARKMAN	SK	49.7020	-101.8958	1985	8	3	15.75	2080	24	75.50	78.50	1.16	21-Jul	39.60	-102.75	S @ 700	General
SPAS_1206_1	BIG RAPIDS	MI	43.6125	-85.3125	1986	9	9	13.18	987	24	70.50	78.50	1.48	25-Aug	41.36	-88.68	SW @ 230	General
SPAS_1210_1	MINNEAPOLIS	MN	44.8895	-93.4021	1987	7	23	11.55	940	6	78.00	82.50	1.24	15-Jul	44.54	-95.16	WSW @ 90	Local
SPAS_1673_1	HARROW	ONT	42.0042	-82.9375	1989	7	19	17.74	600	12	71.00	78.50	1.43	15-Jul	42.04	-82.18	E @ 40	Local
SPAS_1735_1	COLDWATER	MI	41.9625	-85.0042	1989	5	30	9.2	960	24	72.00	78.50	1.38	14-Jun	31.19	-89.36	SW @ 300	General
SPAS_1286_1	AURORA COLLEGE	IL	41.4575	-88.0699	1996	7	16	18.13	636	24	74.00	80.50	1.36	15-Jul	38.63	-92.24	SW @300	Hybrid (G/L)
SPAS_1036_1	PAWNEE CREEK	CO	40.7752	-103.6253	1997	7	29	13.58	4497	6	75.50	81.50	1.38	15-Jul	39.20	-100.15	SE @ 215	Local
SPAS_1177_1	VANGUARD	SK	49.9218	-107.2100	2000	7	3	15.29	2487	6	76.50	79.00	1.13	15-Jul	46.00	-104.00	SSE @ 310	Local
SPAS_1726_1	TURTLE RIVER	ND	47.9550	-97.7550	2000	6	13	20.00	1224	6	74.50	79.00	1.24	26-Jun	47.97	-97.40	E @ 16	Local
SPAS_1033_1	OGALLALA	NE	41.1247	-101.7166	2002	7	6	14.92	3213	6	74.50	81.00	1.39	15-Jul	39.34	-101.97	S @ 125	Local
SPAS_1297_1	WARROAD	MN	48.8750	-95.0850	2002	6	9	14.62	1099	24	72.00	77.50	1.32	25-Jun	43.55	-99.55	SSW @ 425	General
SPAS_1048_1	HOKAH	MN	43.8125	-91.3625	2007	8	18	18.26	1092	24	74.00	80.50	1.36	3-Aug	38.91	-93.85	SSW @ 360	General
SPAS_1228_1	FALL RIVER	KS	37.6300	-96.0500	2007	6	30	25.50	889	24	76.50	81.00	1.24	15-Jul	31.00	-95.50	S @ 460	Hybrid (G/L)
SPAS_1220_1	DUBUQUE	IA	42.4400	-90.7500	2011	7	27	15.14	902	12	79.00	82.00	1.16	15-Jul	40.95	-90.27	SSE @ 105	Local
SPAS_1296_1	DULUTH	MN	47.0150	-91.6650	2012	6	19	10.73	611	12	76.00	81.50	1.30	5-Jul	42.87	-94.78	SW @ 325	Hybrid (G/L)
SPAS_1727_1	DRUMMOND	WI	46.3150	-91.4150	2018	6	14	17.33	1303	6	77.00	80.50	1.18	30-Jun	44.50	-92.50	SSW @ 135	Local
SPAS_1728_1	CROSS PLAINS	WI	43.1450	-89.6150	2018	8	21	16.24	1006	6	75.00	81.50	1.37	6-Aug	38.47	-88.70	S @ 325	Local
SPAS_1729_1	FOUNTAIN	MI	44.0350	-86.1850	2019	7	20	15.77	697	12	79.50	82.50	1.15	15-Jul	41.00	-91.00	SW @ 320	Local

Table 7.3: Cool-season short storm list

SPAS_ID	Storm Name	State	Lat	Lon	Year	Month	Day	Maximum Point Rainfall	Elevation	Storm Rep Analysis Duration	Storm Rep Dew Point	In Place Max Dew Point	In Place Max Dew Point	In Place Max Factor	Temporal Transposition Date	Storm Rep Lat	Storm Rep Lon	Moisture Inflow Vector
SPAS_1245_1	ASHLAND	WI	46.5542	-90.9100	2001	4	20	8.62	822	24	66.00	72.00	71.89	1.34	5-May	39.00	-94.90	SSW @ 560
SPAS_1698_1	BELLEFONTAINE	OH	40.3670	-83.7670	1913	3	23	11.20	1224	24	69.00	70.50	70.46	1.09	5-Apr	33.36	-87.22	SSW @ 520
SPAS_1732_1	MADISON	SD	44.0350	-97.2250	2012	4	29	8.43	1806	12	70.50	74.50	74.35	1.22	15-May	40.00	-91.50	SE @ 405
SPAS_1733_1	GROTON	SD	45.3750	-98.1150	2007	5	2	11.02	1303	12	73.00	78.00	77.82	1.27	19-May	33.33	-96.92	S @ 835
SPAS_1737_1	CHAN GURNEY	SD	42.9150	-97.3850	2019	3	13	4.52	1297	12	63.00	69.50	69.69	1.40	27-Mar	34.76	-98.18	S @ 565
SPAS_1739_1	IRON RIVER	MI	46.0875	-88.6208	1903	4	29	9.27	1586	24	56.00	69.50	69.28	1.50	13-May	44.47	-90.79	SW @ 155
SPAS_1740_1	CROSWELL	MI	43.3208	-82.5792	1929	4	4	5.15	763	6	65.00	68.50	68.54	1.19	18-Apr	41.59	-93.62	W @ 575
SPAS_1743_1	BELCOURT	ND	48.7950	-99.7250	1999	5	3	8.36	1831	24	68.00	75.00	74.92	1.42	15-May	35.85	-97.36	S @ 900

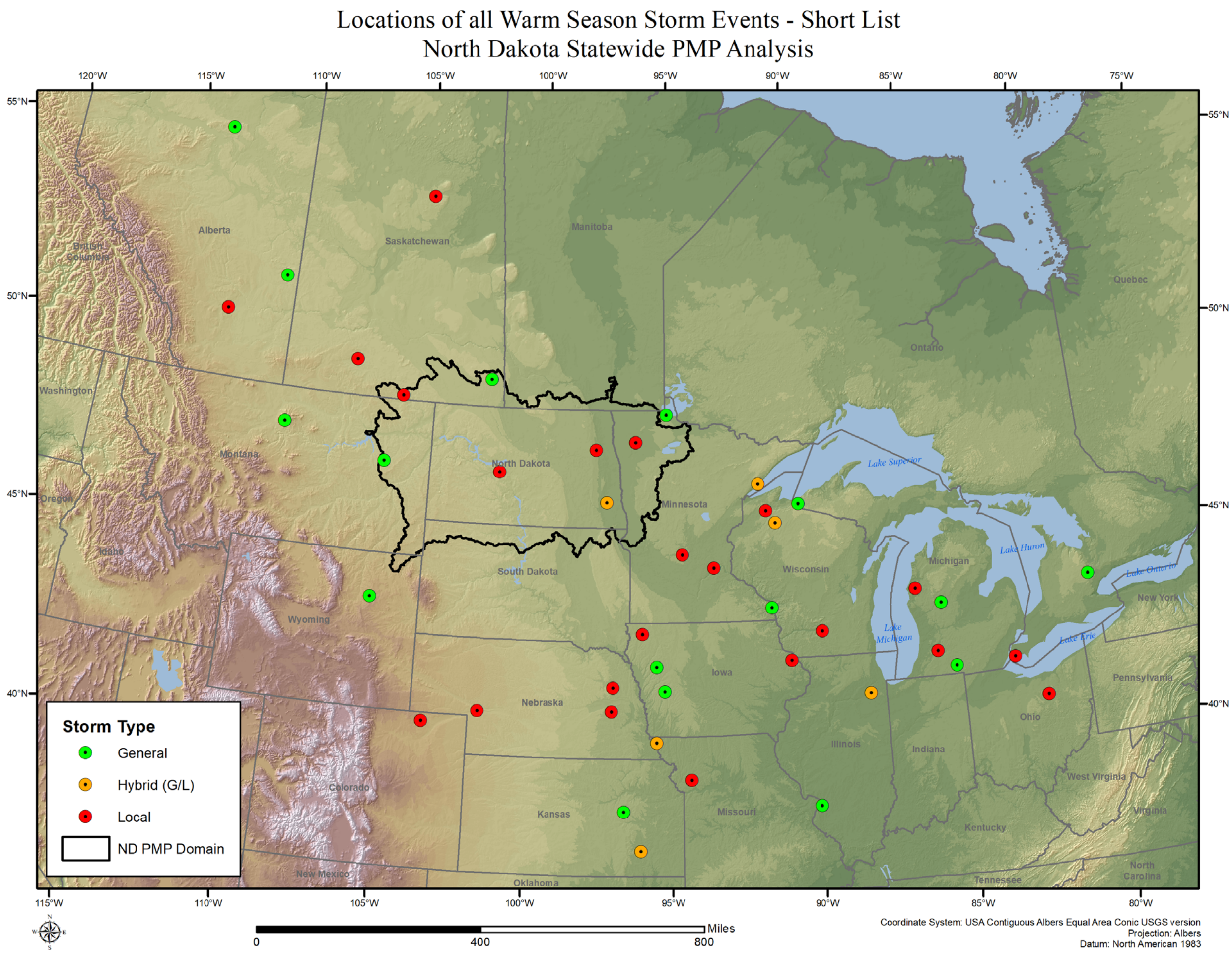


Figure 7.2: All-season short storm list locations, all storms

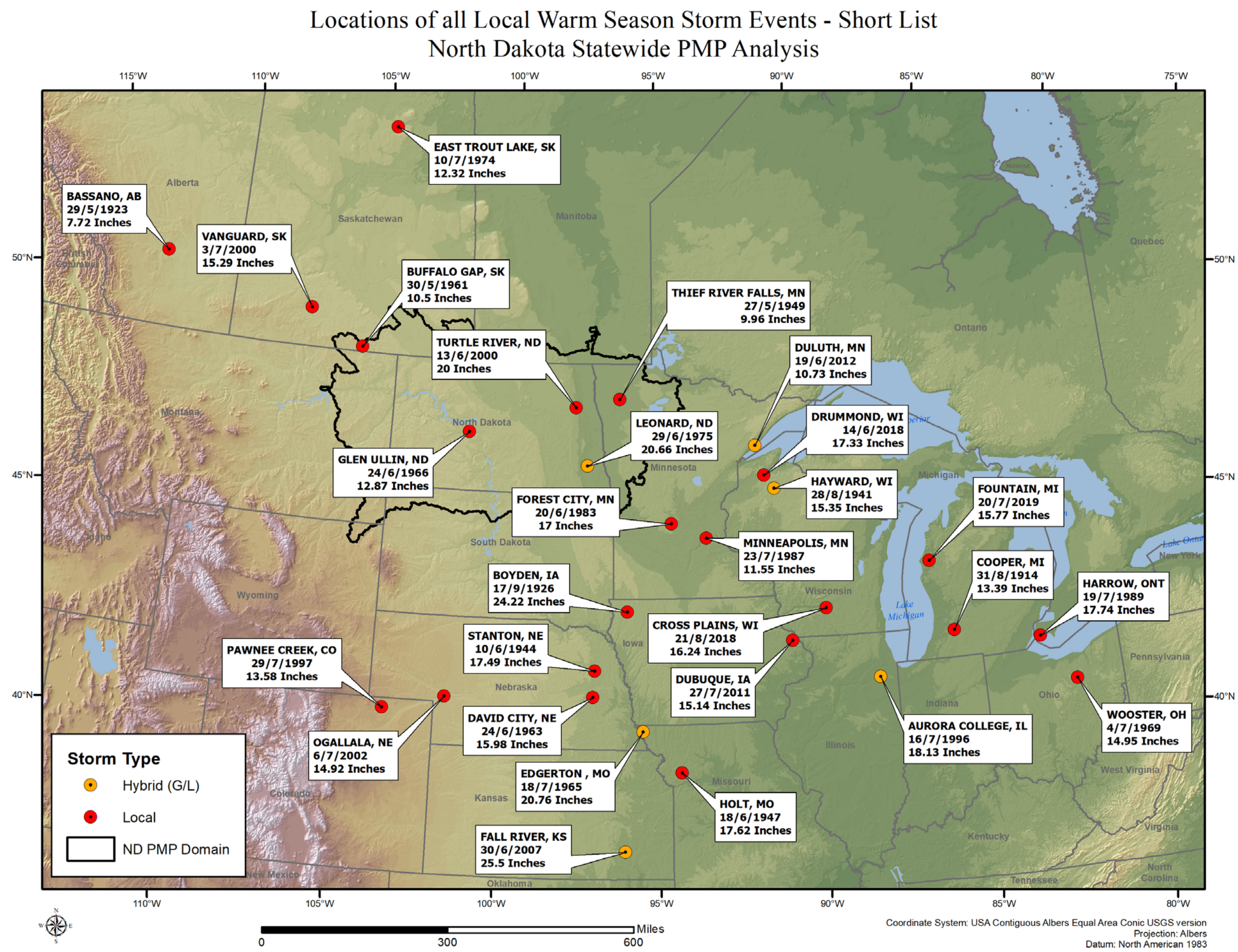


Figure 7.3: Location of all-season Local storms on the short list

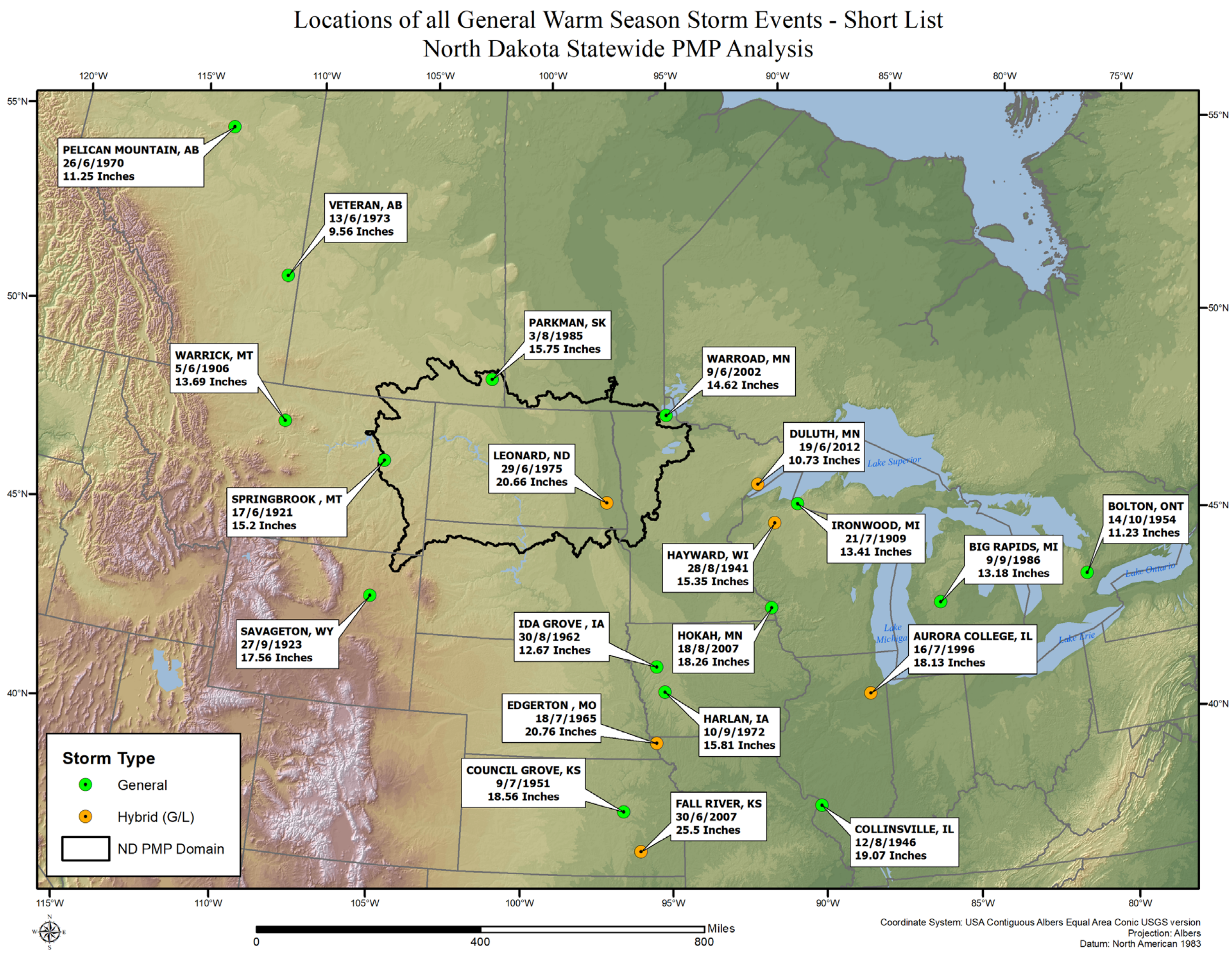


Figure 7.4: Location of all-season General storms on the short list

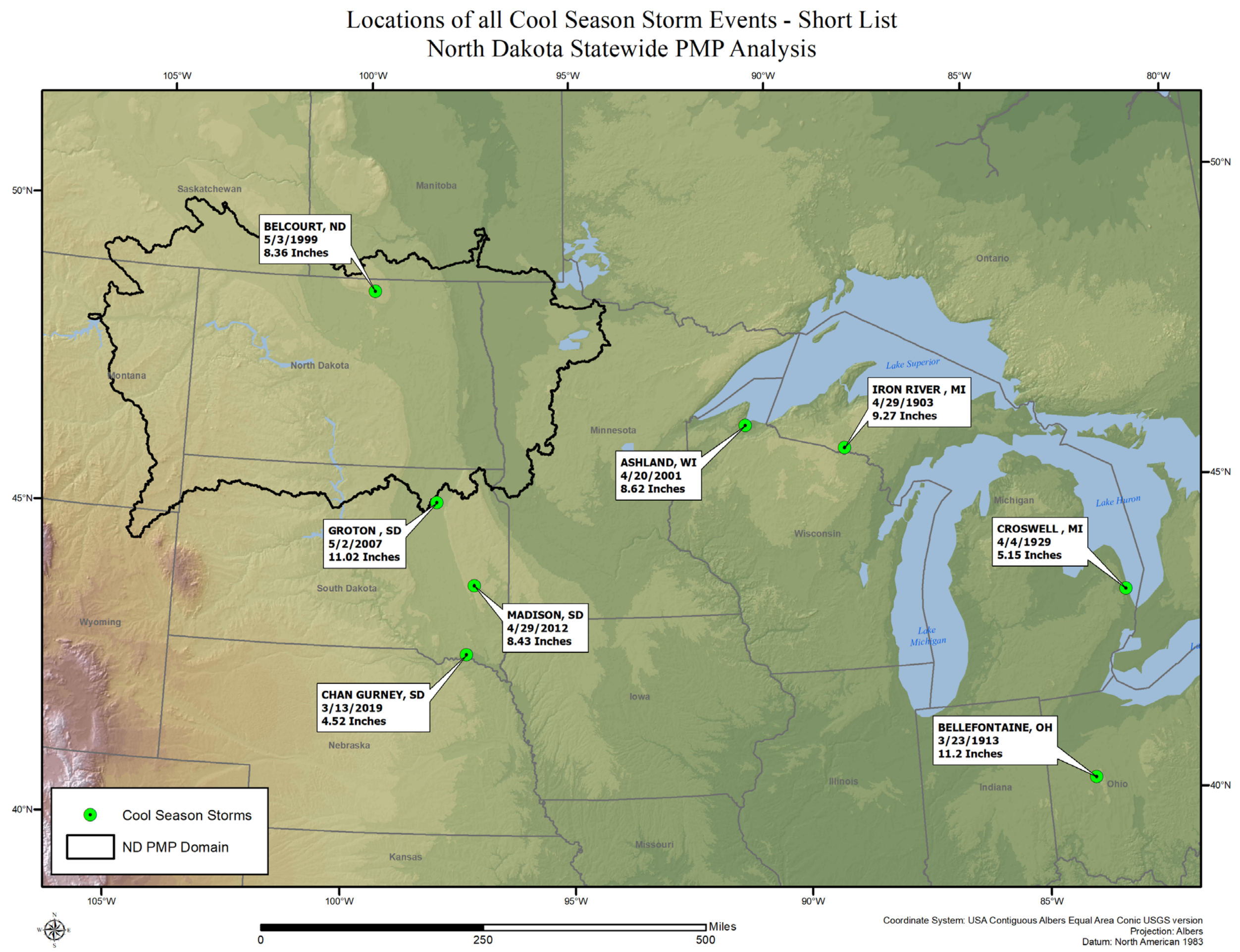


Figure 7.5: Cool-season short storm list locations

8. SPAS Analysis Results

For all storms identified as part of this study, Depth-Area-Duration (DAD) data were utilized. 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 and hourly gridded rainfall data for all the storms. Results of all SPAS analyses used in the study are provided in Appendix F. This 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 highly 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 between rain gage locations 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. If the hourly data are sufficient to capture all 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.

8.3. Hourly and Sub-Hourly Precipitation Maps

At this point, SPAS can either operate in its standard basemap 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

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 using their network of Doppler radars (NEXRAD) located across the United States. A standard default Z-R algorithm of Z = 300R1.4 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, NEXRAD rainfall depths 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. In addition, 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 (Hultstrand and Kappel, 2017). 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. 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 discovered during the updated data mining process were incorporated into SPAS that were not utilized in the original analysis. SPAS utilizes sophisticated algorithms to distribute rainfall temporally and spatially. 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 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 occurred. This procedure assumes that the storm could have occurred with the same storm dynamics two weeks towards the time in the year when higher maximum dew points (and hence more moisture) could 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 to determine each storm representative dew point and storm adjustment investigations including the HYSPLIT model output, the surface dew point observations, the storm center location, the storm representative location, and the IMPF for each storm.

Each storm used for PMP development has been thoroughly reviewed either in previous PMP studies or was evaluated by the Steering Committee 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
- 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 were reasonable for PMP development.

For storm maximization, average dew point 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 is then maximized using the appropriate climatological value representing the 100-year recurrence interval at the same location moved two weeks towards the season of higher climatological maximum values.

HYSPLIT model output (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, the moisture source region for candidate storms is determined. This procedure is similar to the approach used in the HMRs. However, by utilizing the HYSPLIT model, much of the subjectivity 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 comparison of the storm representative dew point against the climatological maximum dew point 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 to produce a hypothetical storm event that represents the upper limit of rainfall that a given storm could have produced with the ideal 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.

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., 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., 6-hour, 12-hour, or 24-hour.

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 (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 since 2006. During these analyses, the model trajectory results were verified, and the utility explicitly evaluated (e.g., Tomlinson et al., 2006-2012; Kappel et al., 2013-2021).

In determining the moisture inflow trajectories, 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 most 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., 2012-2021) 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 values at all stations with dew point data in a large region along the HYSPLIT inflow vectors. Values representing the average 6-, 12-, and 24-hour dew points 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. This evaluation includes an analysis of the timing of the observed dew point 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 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 using HYSPLIT and updated maximum dew point 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 Glen Ullin, ND June 1966 (SPAS 1324) storm. HYSPLIT trajectories showed a general inflow from the Gulf of Mexico flowing north, then northwest into the storm and a boundary that provided the focusing area and extra lift. The turning of the moisture into the storm environment shows the convergence of the high levels of moisture along the boundary and at the northern edge of the high pressure covering much of the central and eastern US. This is a common scenario for heavy rains over the region in the summer, 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. In this case, surface dew point values were analyzed for a region starting at the storm center and extending southward through the Central Plains. All the

HYSPLIT inflow vectors showed the moisture feed from the Gulf of Mexico along with a significant LLJ drawing in moisture from the surface through the mid-levels of the atmosphere.

The air mass source region supplying the atmospheric moisture for this storm was located over eastern Nebraska and South Dakota 24 hours prior to the rainfall occurring over central North Dakota. 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 6-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

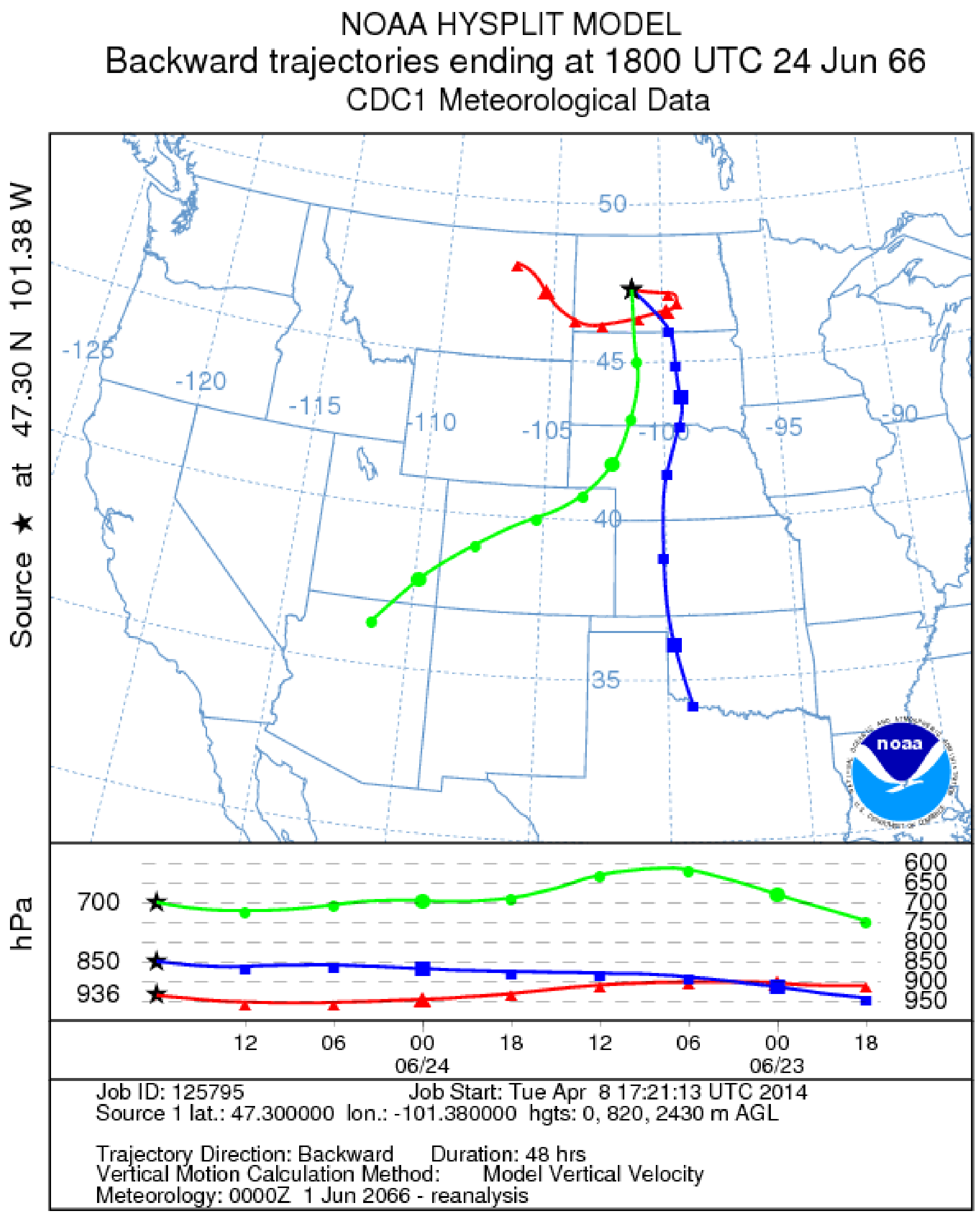


Figure 9.1: HYSPLIT trajectory model results for the Glen Ullin, ND June 1966 (SPAS 1324) storm

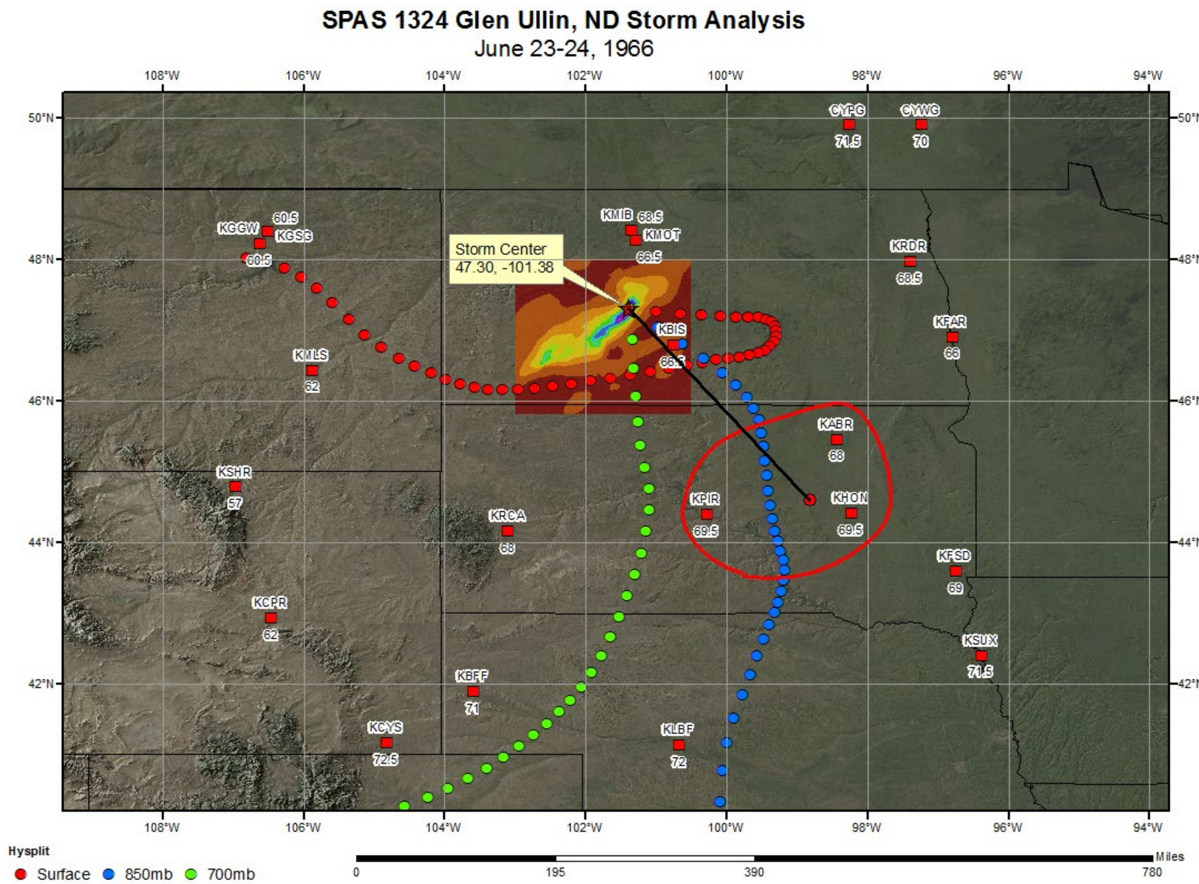


Figure 9.2: Surface stations, 6-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Glen Ullin, ND June 1966 (SPAS 1324) storm

All storms have maximization factors that are greater than 1.00, with an average of around 1.32 in this study (Table 7.2). Similar, the average IPMF for the cool-season storms is 1.30 (Table 7.3). Lower IPMF generally results when sufficient observational data have captured the moisture source region and when a storm is as close to PMP as can reasonably be expected. In these cases, the values reflect observed dew point 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.

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 storm 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 GTF.

The regional transposition zones developed for this study were largely based on the variable meteorological and topographical characteristics across the domain along with considerations of moisture source region climatologies. NCEI (formally the National Climatic Data Center) climate regions, USGS physiographic regions, NOAA Atlas 14 precipitation frequency climatologies, discussions with the Steering Committee and study participants helped to determine the transposition zones that were developed.

Figure 9.3 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.

Transposition Zones
North Dakota Statewide PMP Analysis

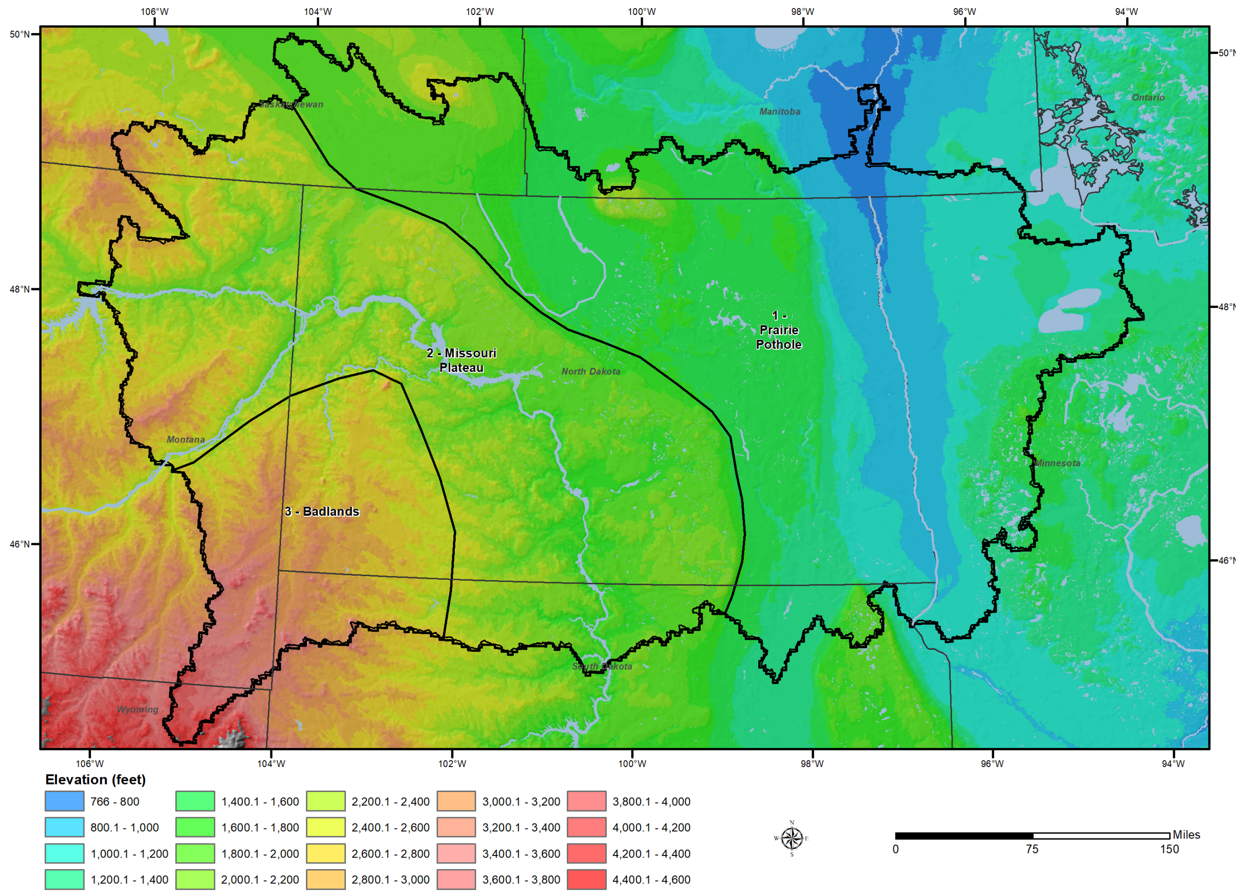


Figure 9.3: Transposition zones utilized for PMP development

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 Steering Committee and others involved in the study

An important aspect of this study was the involvement of the Steering Committee 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 9.3. 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 realistic 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. It is important to note that site-specific studies may utilize more refined transposition limits when only the specific basin characteristics are conserved versus the overall study domain utilized in the analysis.

A significant amount of time was spent on the storms which were most important for controlling PMP depths. The ultimate transposition limits applied to each of these storms was more conservative than was applied by the NWS and in previous AWA studies. However, the goal was to produce smooth PMP gradient across the study region. These included the following storms

- Warrick, MT June 1906 (SPAS 1335)
- Springbrook, MT June 1921 (SPAS 1336)
- Savageton, WY September 1923 (SPAS 1325)
- Hayward, WI August 1941 (SPAS 1699)
- Veteran, Alberta June 1973 (SPAS 1502)
- East Trout Lake, Saskatchewan July 1974 (SPAS 1744)
- Big Rapids, MI September 1986 (SPAS 1206)
- Aurora College, IL July 1996 (SPAS 1286)
- Vanguard, Saskatchewan July 2000 (SPAS 1177)

Although somewhat subjective, decisions to adjust the transposition limits for a storm were based on the understanding of the meteorology which produced 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. GTF values greater than 1.50 indicate that transposition limits have most likely have 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 or less than 0.50.

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 without knowing whether the precipitation frequency climatologies already quantify this difference. Numerous discussions have occurred during previous studies and again during this study with the Steering Committee to try and quantify moisture differences. Recent analyses as part of AWA PMP studies have 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.

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.

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,

$W_{p,trans(30,000')}$ = 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 produce the rainfall amount resulting 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.

GTF values were calculated utilizing precipitation frequency data at the 100-year recurrence interval. These data sets were used to produce consistency in the climatological datasets and to provide required coverage for all storm locations within the overall storm search domain. As noted, the storms used in the development NOAA Atlas 14 and the additional precipitation frequency climatologies 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 precipitation frequency climatologies were 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. 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.

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

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 precipitation processes and interactions related to terrain that are not well understood or quantified. Therefore, observed data (precipitation accumulations represented in the precipitation frequency data) are used as a proxy. 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 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:

- Precipitation frequency climatologies represent all precipitation producing factors that have occurred at a location. This is because 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 precipitation frequency climatologies are 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 storm. Precipitation frequency data were taken from NOAA Atlas 14 volume 2 (Bonnin et al., 2006), NOAA Atlas 14 volume 8 (Perica et al., 2013), and the updated Precipitation Frequency climatologies developed for this study.

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 values 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 basin for each applicable duration and storm type. The gridded PMP is averaged over the basin of interest to derive a basin average and the accumulated PMP depths are temporally and spatially 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 provides depths at an area-average for a given basin area size. This area can be overwritten with a specific user-defined area-size within the tool dialogue. 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/Cool-Season Storm PMP Durations:
1-, 6-, 12-, 24-, 48-, and 72-hour

10.1.1. Spatial Application Considerations

It is important to remember that the initial gridded PMP depths are spatially distributed closely following the precipitation frequency patterns. This represents one possible spatial scenario and is generally considered a conservative application. However, alternative spatial patterns are possible and may result in a more severe flood response. For smaller basins, less than 50-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 the basins covered in the study is almost unlimited, it is not feasible to test all possible spatial patterns as part of the GIS tool output. Instead, a representative sample of spatial patterns covering various patterns were investigated from the short list storm database. These were separated by storm type to provide different possible spatial scenarios. It is recommended that other spatial patterns be tested for larger basins where the location of the storm center and associated accumulation patterns could produce an outcome that is significantly different than the default spatial pattern. 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.

A Spatial Distribution Tool was developed and included with the North Dakota PMP GIS tools. The tool accepts PMP grid point feature classes produced by the PMP tool as input and spatially redistributes the PMP based on total storm rainfall accumulation patterns from the various historical events included in the PMP storm database. Total storm isohyetal patterns from all storms used for PMP development were investigated to determine standard patterns by storm type and location. Based on the results of these analyses, the following representative spatial patterns identified and included as additional spatial patterns:

Local Storm:

- LS - Wooster, OH, Jul. 1969 (SPAS_1209_1) – SE↔NW elongated orientation
- LS - Boyden, IA, Sep. 1926 (SPAS_1427_1) - NE↔SW orientation
- LS - Hayward, WI, Aug. 1941 (SPAS_1699_1) - E↔W orientation

General Storm:

- GS - Ida Grove, IA, Aug. 1962 (SPAS_1527_1) - NE↔SW orientation
- GS - Council Grove, KS, Jul. 1951 (SPAS_1583_1) - E↔W orientation

Cool-Season Storm:

- CS - Bellefontaine, OH, Mar. 1913 (SPAS_1698_1) - NE↔SW orientation
- CS - Groton, SD, May. 2007 (SPAS_1733_1) - N↔S orientation

Additionally, the user has the option to apply any of the storm patterns from the PMP database for investigative purposes. The tool allows the spatial pattern to be centered at the basin centroid by default, or the user can input coordinates for any point location within the area of concern to center the patterns. Additional information on the Spatial Distribution Tool usage and output is included in Appendix G.

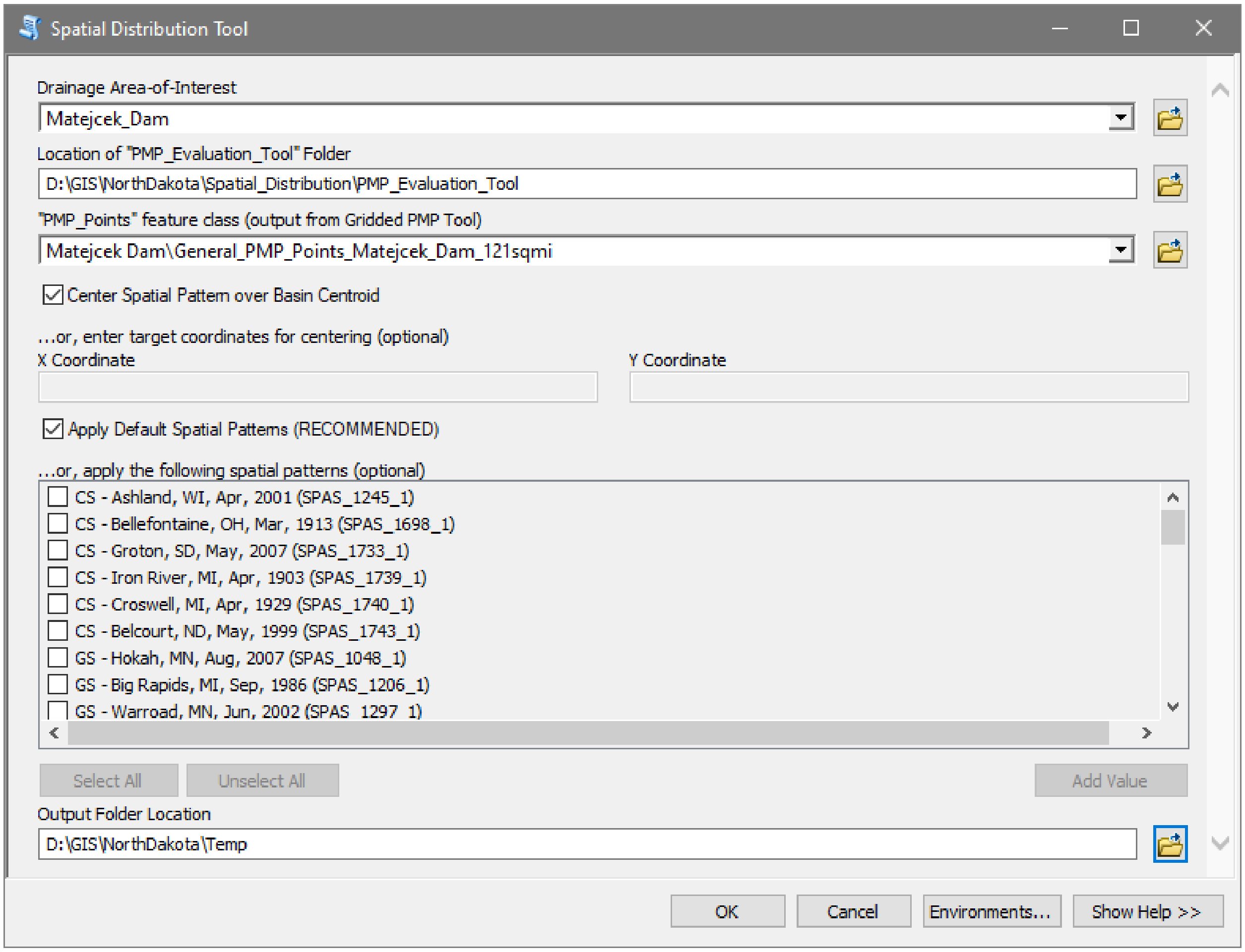


Figure 10.1: Spatial Distribution GIS tool input dialog window

The following steps describe the method for applying each storm's spatial distribution pattern within the ArcGIS environment:

1. Shift the total storm rainfall raster from its in-place location to the basin. The shift is determined by taking the difference between the basin centroid coordinates (or user-supplied center location coordinates) and the storm center coordinates (i.e., location with largest total storm rainfall)
2. Extract the total storm rainfall depths to each PMP grid point location over the basin. The total storm rainfall depths are scaled down to produce a reasonable spatial variation in depths across the basin domain. Adjusted total storm rainfall depths (P_s) for each grid point over the basin were calculated from the original shifted total storm rainfall depths (P_o) using the following equation:

$$P_s = P_o^{\frac{1}{x}}$$

Where:

P_s = Adjusted "scaled" rainfall
P_o = Original total storm rainfall
x = adjustment factor

An adjustment factor (x) of 5 was applied to provide appropriate scaling for this project, as determined by conducting sensitivities with a range of factors.

3. Calculate the Spatial Adjustment Factor (SAF) for each grid point by dividing the adjusted total storm rainfall (P_s) by the basin average adjusted total storm rainfall (P_s). The average adjusted total storm rainfall (P_{ave}) is the average of all adjusted total storm rainfall values extracted to each grid point.

$$SAF = \frac{P_s}{P_{ave}}$$

4. Multiply the basin average PMP by the SAF to determine the spatially adjusted rainfall at each grid point for each duration.
5. Convert the spatially adjusted rainfall points to gridded raster output for each duration.

10.2. Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Aurora College, IL of July 1996 (SPAS 1286) general storm event when transposed to 45.750°N, 97.450°W (grid point ID #5,000). The target location is about 555 miles northwest of the storm location at an elevation of 1,854 feet in far northeastern South Dakota (Figure 10.2). 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 - Aurora College, IL Adjustment Factors for Sample Target Location

ID	STORM	LON	LAT	ZONE	ELEV	IPMF	MTF	GTF	TAF	TRANS
5000	1286_1	-97.450	45.750	1	1,854	1.36	1.00	0.75	1.01	1

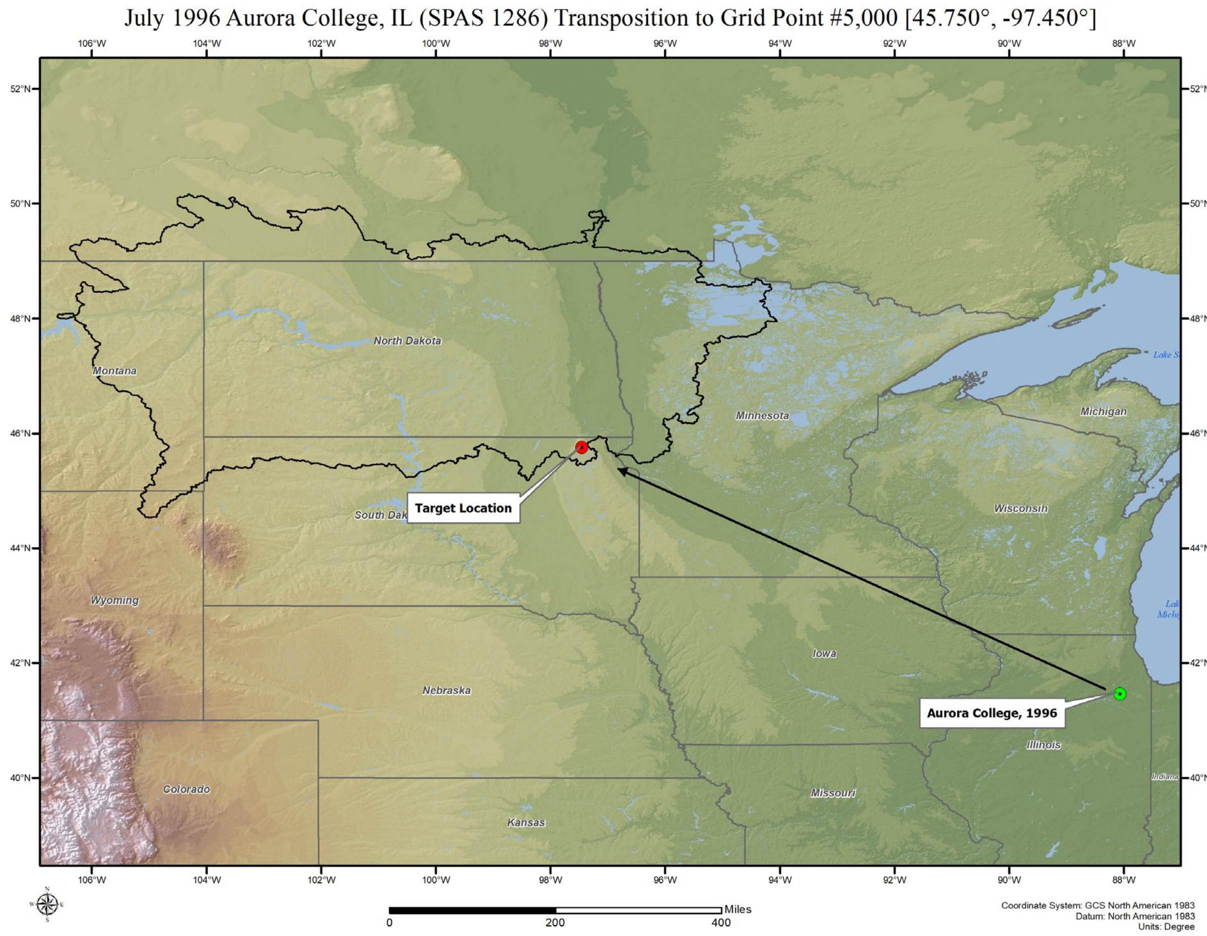


Figure 10.2: Sample transposition of Aurora College, IL, 1996 (SPAS 1286) to grid point #5,000

10.2.1. 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 74.0°F at the storm representative dew point location 300 miles southwest of the storm center (see Appendix F for the detailed storm maximization and analysis information). The storm center elevation is approximated at 600 feet at the storm center location of 41.4575°N, 88.0699°W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 4:

$$W_{p,rep} = W(@74.0°)_{p,30,000'} - W(@74.0°)_{p,600'}$$

or,

$$W_{p,rep} = 2.73" - 0.15"$$

$$W_{p,rep} = 2.58"$$

The mid-July storm occurred very close to the highest moisture date, so no temporal transposition was necessary. The July climatological 100-year maximum 24-hour average dew point at the storm representative dew point location is 80.61°F. This is then rounded to the nearest ½ degree to a climatological maximum dew point temperature of 80.5°F. The in-place climatological maximum available moisture ($W_{p,\ max}$) is calculated.

$$W_{p,max} = W(@80.5°)_{p,30,000'} - W(@80.5°)_{p,600'}$$

$$W_{p,max} = 3.68" - 0.18"$$

$$W_{p,max} = 3.50"$$

10.2.2. 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:

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

$$IPMF = \frac{3.50"}{2.58"}$$

$$IPMF = 1.36$$

10.2.3. Sample GTF Calculation

The ratio of the 100-year 24-hour climatological precipitation depth at the target grid point #5,000 location to the Aurora College, IL 1996 storm center was evaluated to determine the storm's GTF at the target location. The 24-hour rainfall depth (R_t) of 5.80" was extracted at the grid point #5,000 location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_t = 5.80"$$

Similarly, the 24-hour rainfall depth (R_s) of 7.76" was extracted at the storm center location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_s = 7.76"$$

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

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

$$GTF = \frac{5.80"}{7.76"}$$

$$GTF = 0.75"$$

The GTF at grid #5,000 is 0.75, or a 25% rainfall decrease from the storm center location due to differences 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.

10.2.4. Sample TAF Calculation

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

$$TAF = 1.36 \times 0.75$$

$$TAF = 1.01$$

The TAF for Aurora College, IL 1996 when moved to the grid point at 45.750°N, 97.475°W, representing storm maximization and transposition, is 1.01. This is an overall increase of 1% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the storm's rainfall depth taken from the SPAS DAD 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, 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 12. 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.

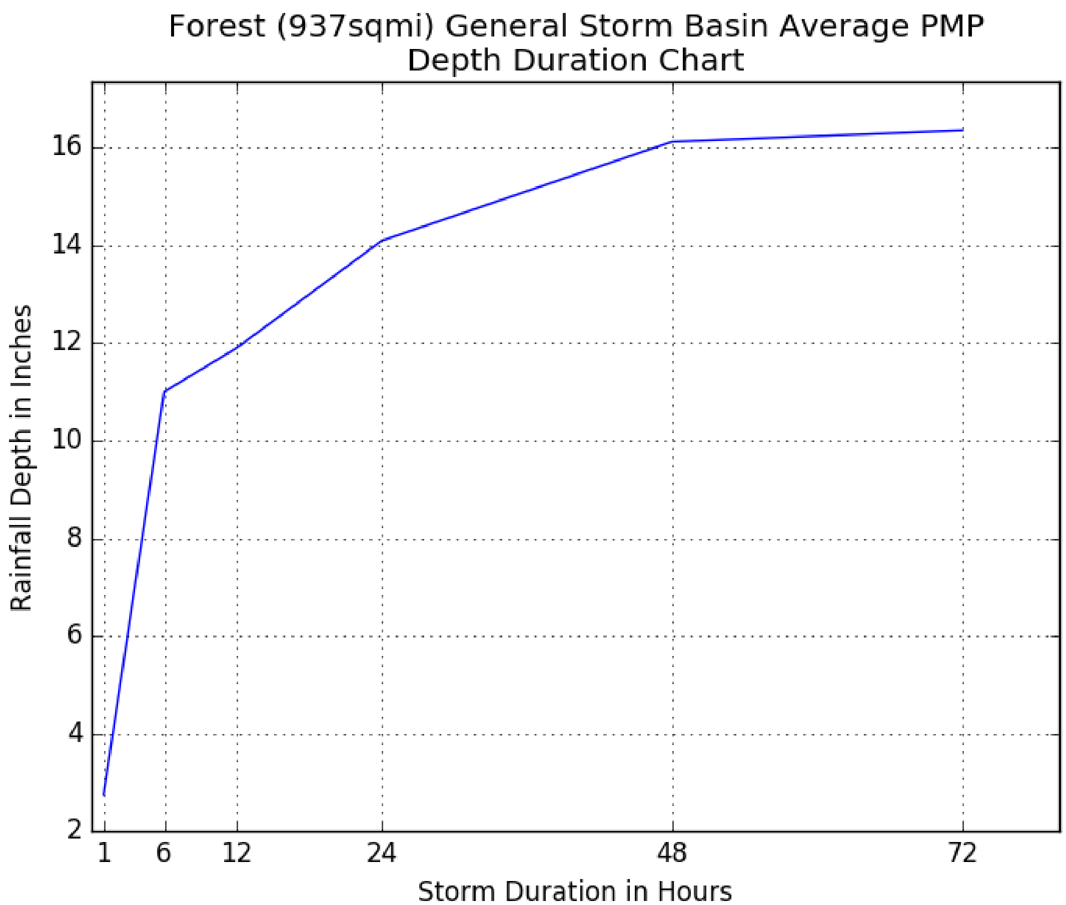


Figure 11.1: Sample PMP depth-area chart image provided in output folder

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 100-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 cool season storm PMP at 6-, 12-, 24-, and 72-hour durations.

12. Snowmelt

Climatological daily temperature and snow water equivalent (SWE) gridded timeseries were developed for this study to be used to estimate snowmelt during cool-season PMP events. In addition, a Snowmelt Tool was developed to produce gridded snowmelt timeseries for user-supplied drainage basins. The resulting basin melt information can be utilized in conjunction with cool-season PMP to produce a total runoff that includes rainfall and snowmelt.

Gridded 100-year snowpack in conjunction with an average daily temperature timeseries were developed specific for the overall study domain. The information was developed to cover a timeframe representing a complete picture of snow accumulation, ripening of the snowpack, and snowmelt patterns throughout the study domain. It is important to note that the meteorological conditions associated with the full Probable Maximum Precipitation (PMP) rainfall event are valid from June through September over the North Dakota region. No direct snowmelt is expected to occur during the all-season PMP rainfall event.

Snowmelt data were needed to account for rain-on-snow situations that may generate large volumes of water and total runoff versus the all-season PMP (June-September). The cool-season PMP and associated snowmelt conditions are valid from March through May. The development of the SWE at the 100-year recurrence interval along with the temperature times series and associated snowmelt coefficients at a daily times steps allows unique snowmelt amounts to be calculated for any days or series of days during the cool-season PMP timeframe (March through May). This is a very important aspect of this study and provides the required data needed to determine the worst-case runoff scenarios for many larger basins within the study domain. Development of this data set and the gridded process from which to dervie daily snowmelt is a significant improvement over previous data sets and process, including HMR 48. This information allows for an explicit calculation of total runoff from cool-season PMP and snowmelt to be derived on a grided basis for any day during the cool-season period. The database and calculation procedures allow for detailed investigation regarding snowmelt parameters and combinations that were not available previously and provide the opportunity to efferently determine the worst-case combination of factors. In addition, the format of the database in Excel and GIS allows for updates and additional information to be applied going forward.

Note, that the cool-season PMP and snowmelt calculations are not required for basins less than 100-square miles in area size. Complete details on the development and implementation on the gridded snowmelt calculations are described in Appendix J.

13. Development of Temporal Distribution for Use in Runoff Modeling

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), the Pennsylvania PMP temporal study (Kappel et al., 2019), and the Oklahoma-Arkansas-Louisiana-Mississippi Regional PMP 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, and hybrid.

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. Some storms exhibit characteristics of both the local and general storms 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 13.2) 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.

Finally, the actual accumulation patterns associated with the various controlling storms were utilized as additional temporal patterns. This, along with the Synthetic and Huff Curves, are included as options in the PMP Tool. Included in the PMP Tool temporal output is a check function that notes whether a given temporal pattern passes or fail. A “fail” results when a temporal pattern produces a PMP depth at an interim duration that is larger than the actual PMP depth for that particular location.

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 13.5 addresses local storm incremental accumulation but again provides very limited data and analysis background.

13.1. 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.

13.1.1. 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.

13.1.2. 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 $R_n = 0.5$

13.1.3. 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 Hybrid (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 additional temporal patterns should be tested and the user should consult with dam safety regulations for further guidance on temporal applications beyond what is provided in the GIS PMP tool.

13.1.4. 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, 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.

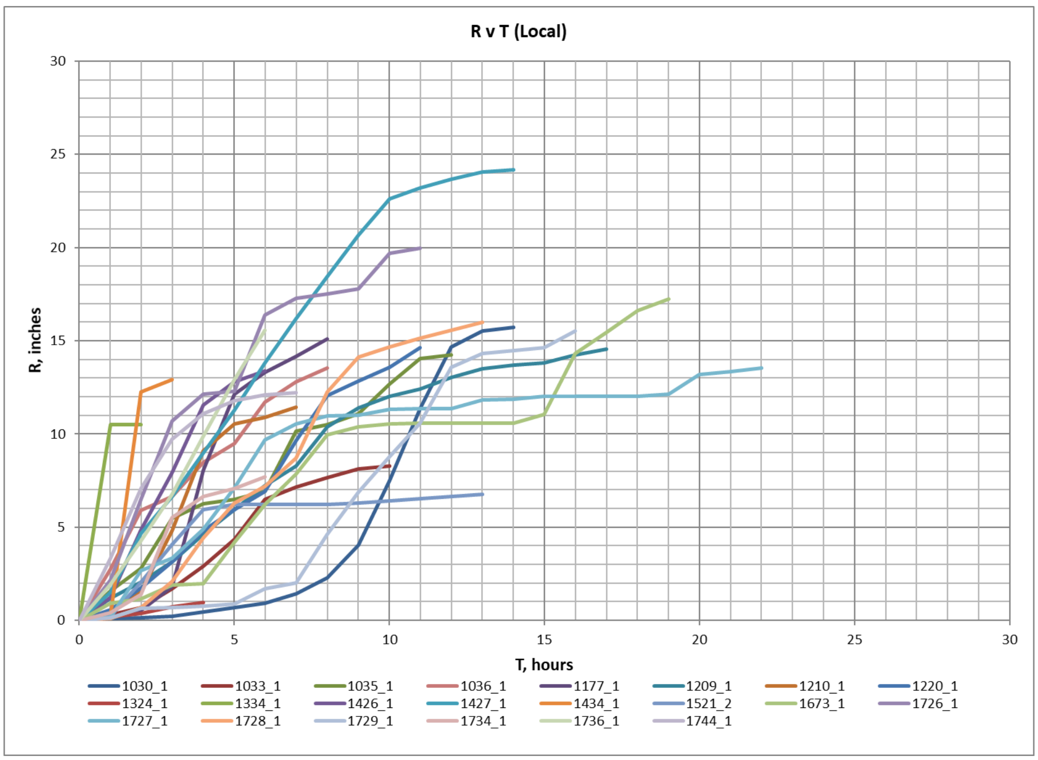


Figure 13.1: SPAS Rainfall (R) versus time (T) for Local Type Storm

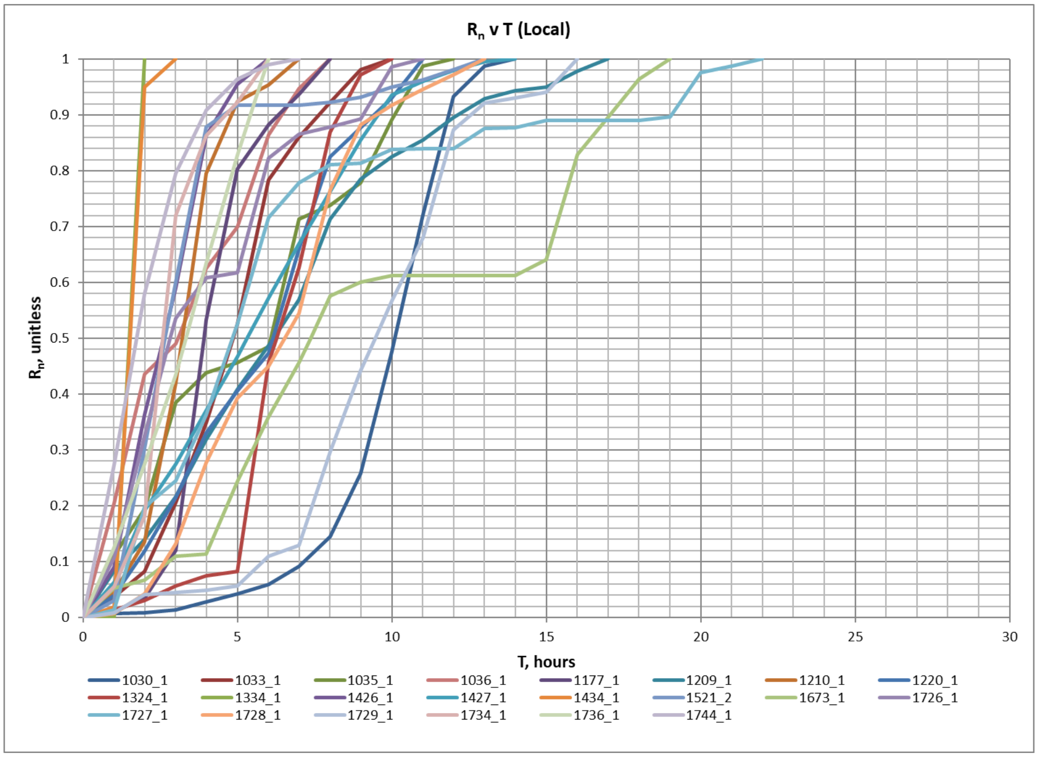


Figure 13.2: Normalized R (Rn) versus time (T) for Local Type Storm

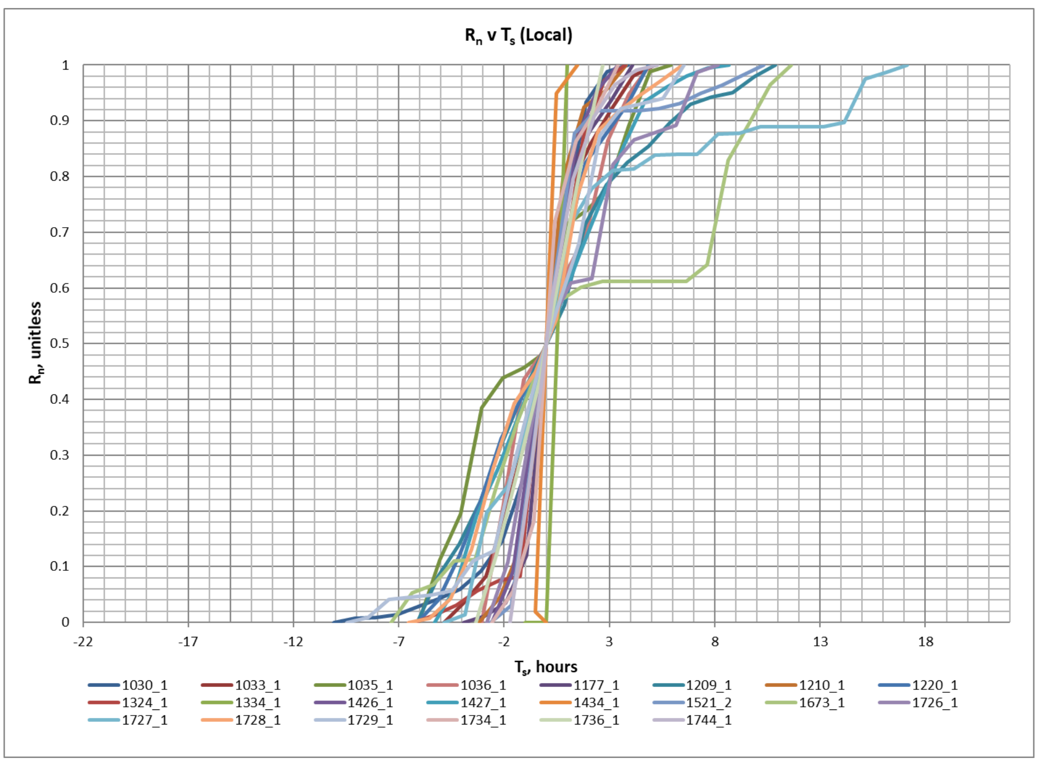


Figure 13.3: Normalized R (Rn) versus shifted time (Ts) for Local Type Storm

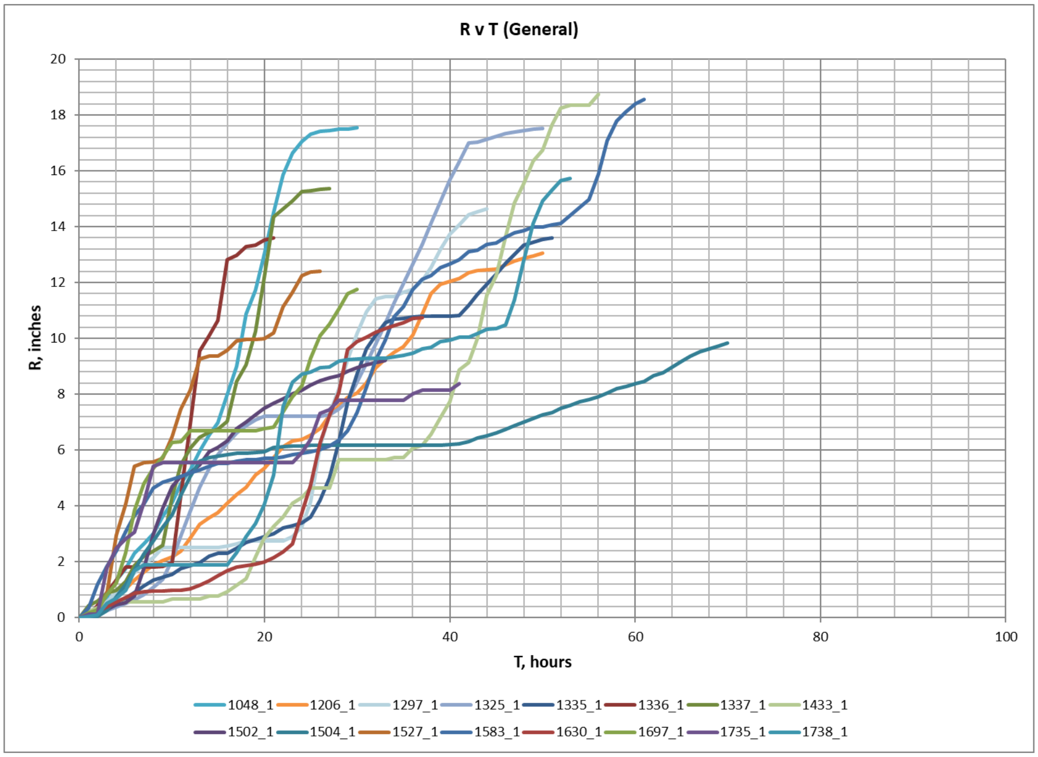


Figure 13.4: SPAS Rainfall (R) versus time (T) for General Type Storm

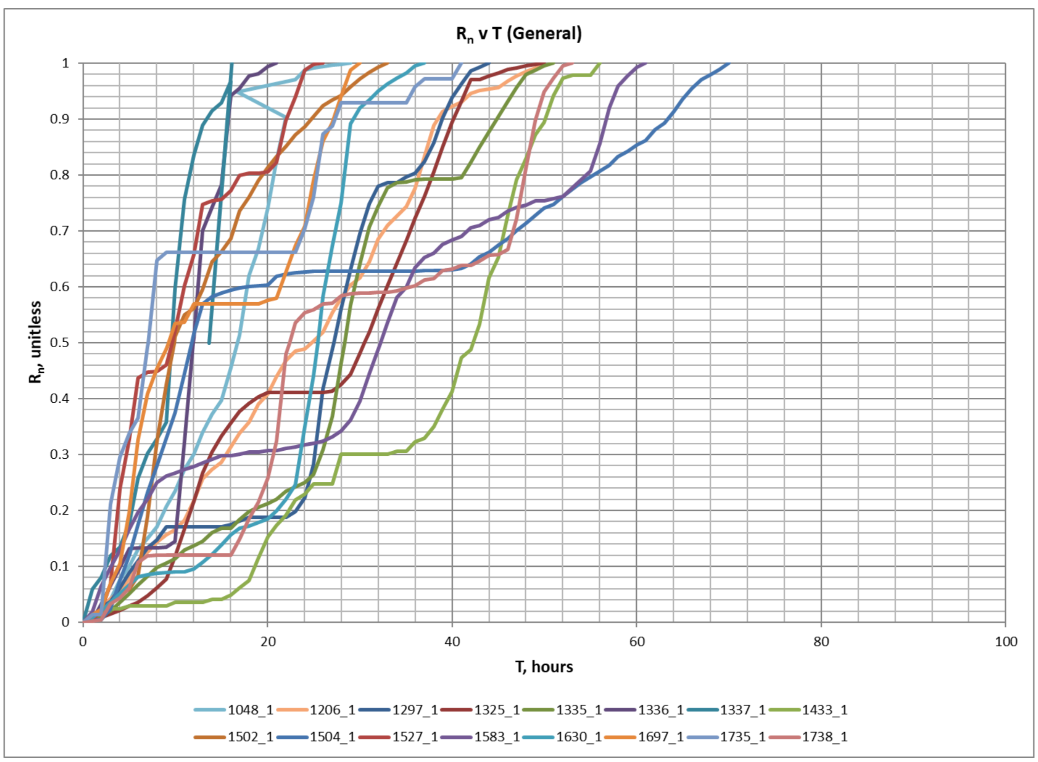


Figure 13.5: Normalized R (Rn) versus time (T) for General Type Storm

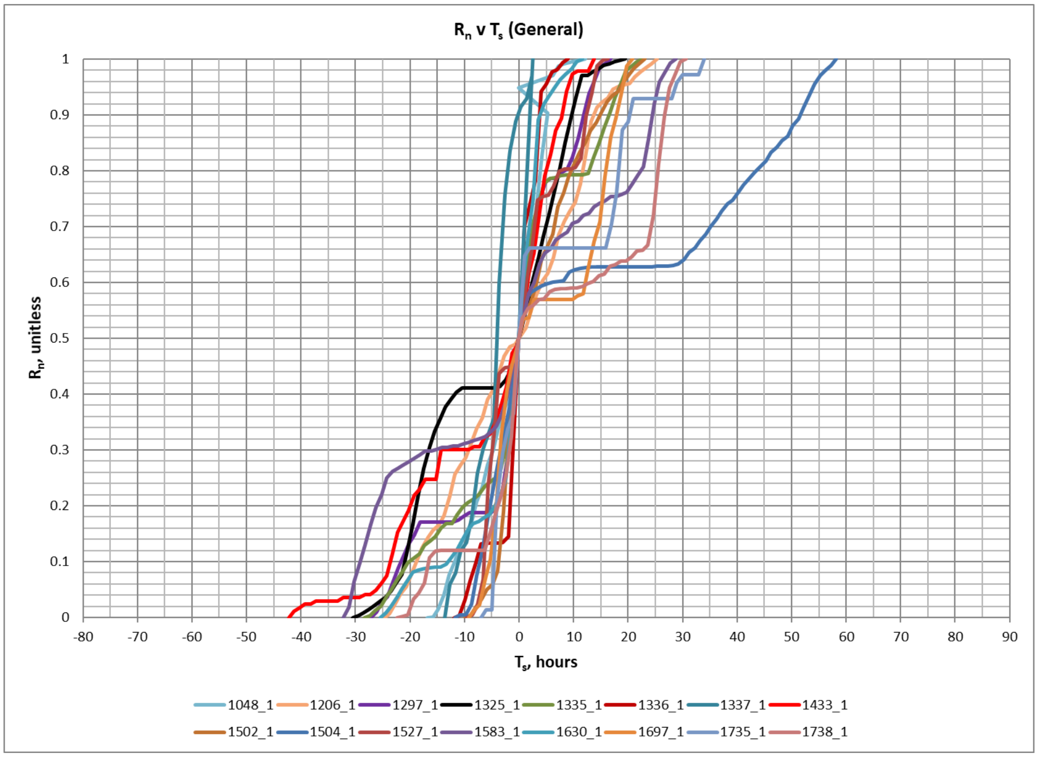


Figure 13.6: Normalized R (Rn) versus shifted time (Ts) for General Type Storm

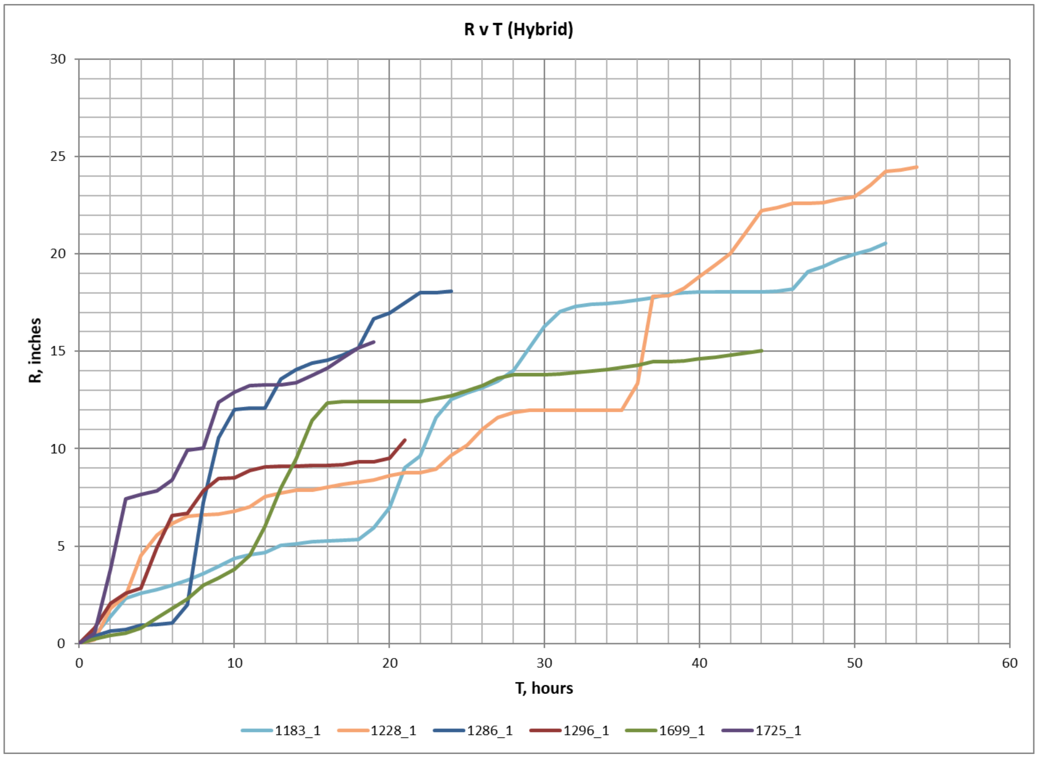


Figure 13.7: SPAS Rainfall (R) versus time (T) for Hybrid Type Storm

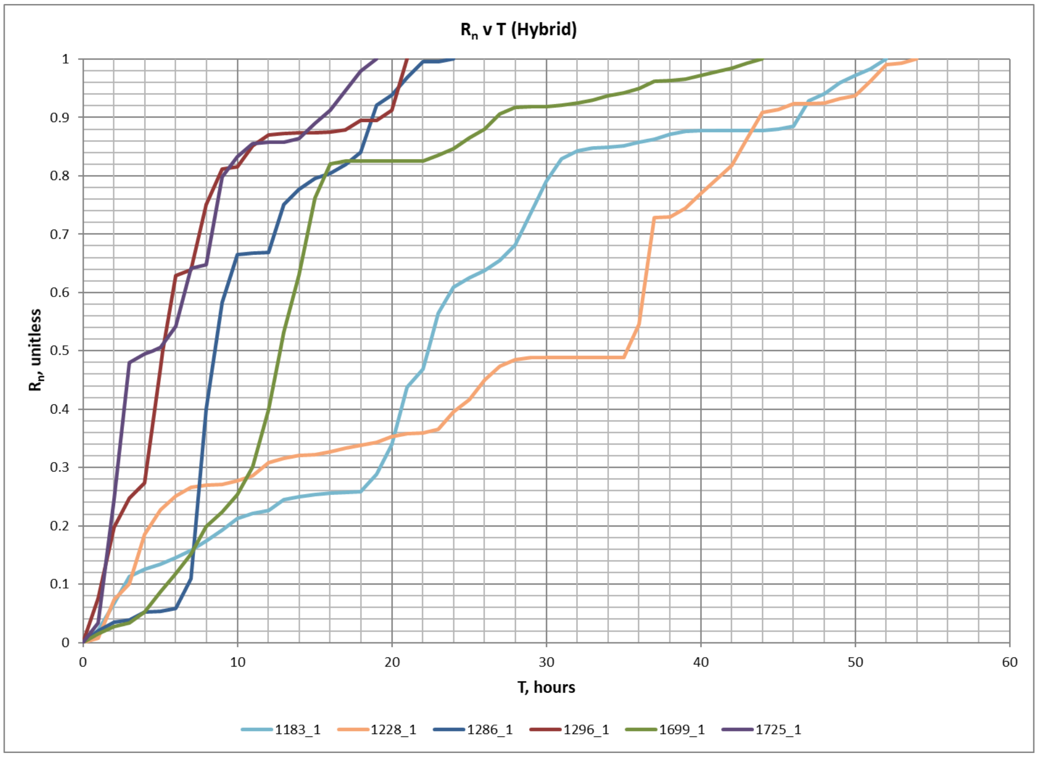


Figure 13.8: Normalized R (Rn) versus time (T) for Hybrid Type Storm

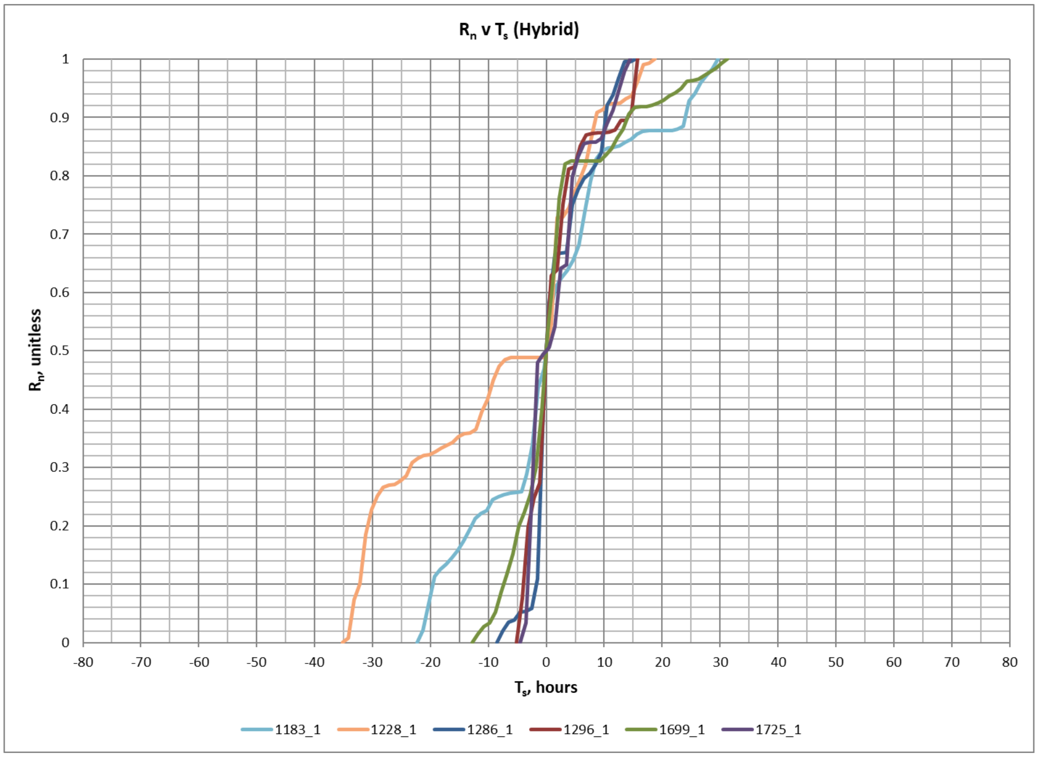


Figure 13.9: Normalized R (Rn) versus shifted time (Ts) for Hybrid Type Storm

13.2. 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 was 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 and by storm type: local, general, 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 (90th and 10th) 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:

- 90th curve - the 90th curve indicates that 10% of the corresponding SPAS storms had distributions that fell above and to the left of the 90th curve (front-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 13.10-13.12), 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 13.7 for additional description (NRCS, 2005). The Type II curve is added to figures in its native state for comparison (Type II).

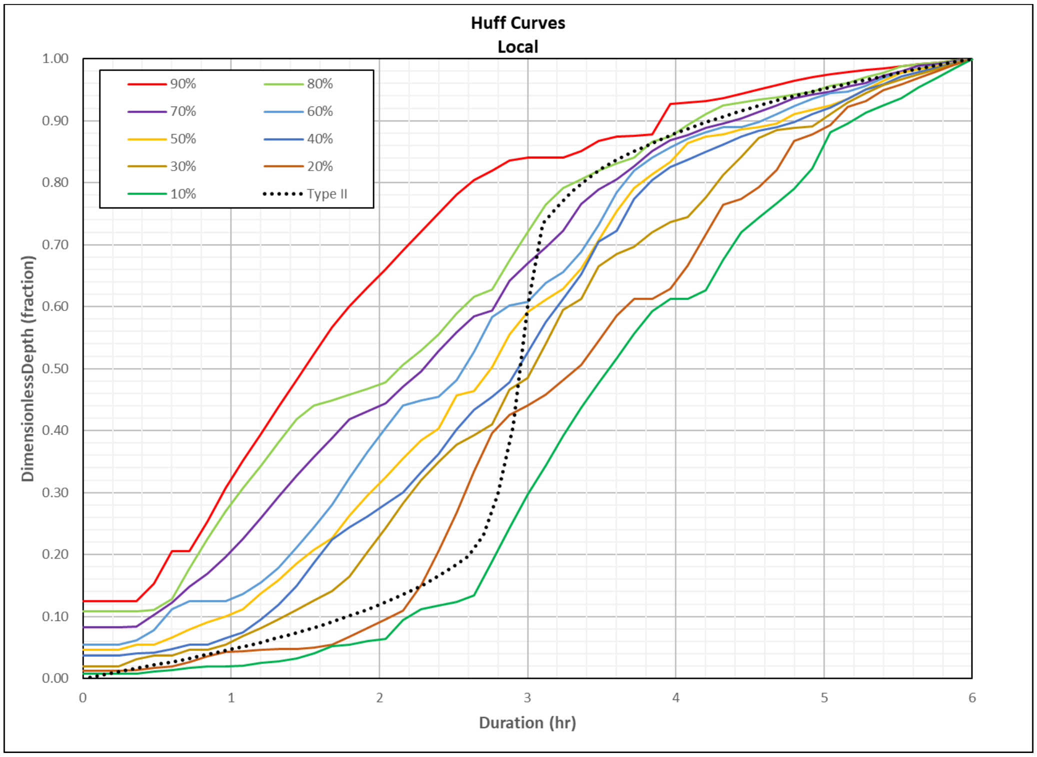


Figure 13.10: Raw Huff temporal curves for 6-hour Local storms

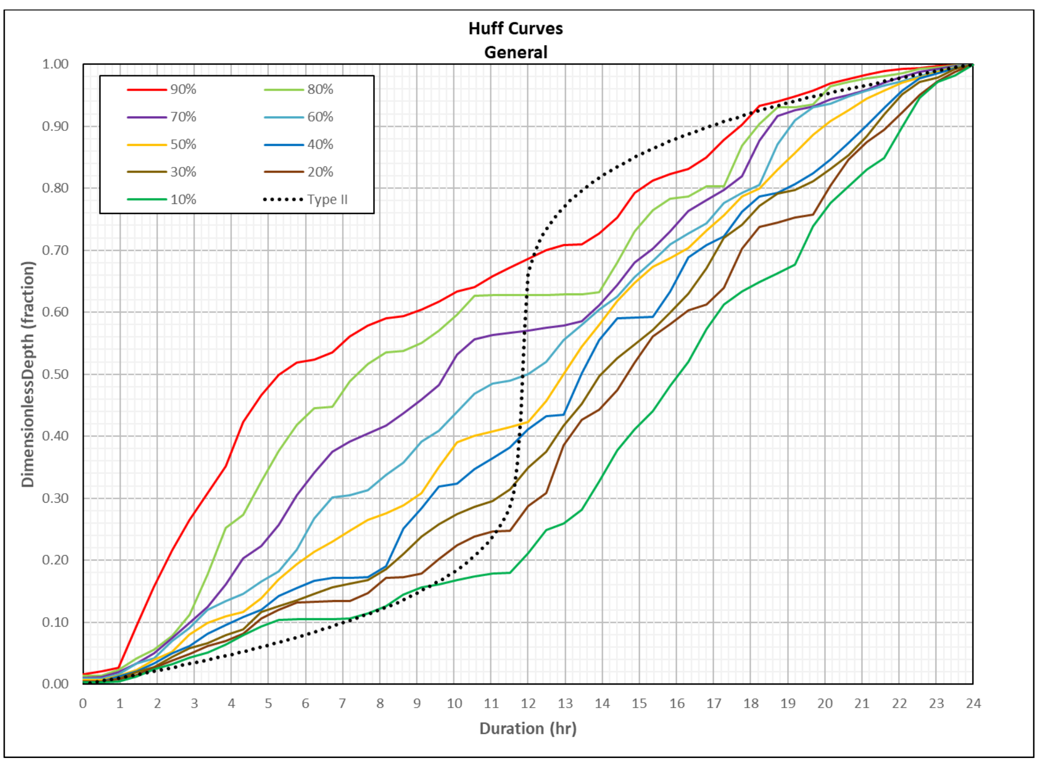


Figure 13.11: Raw Huff temporal curves for 24-hour General storms

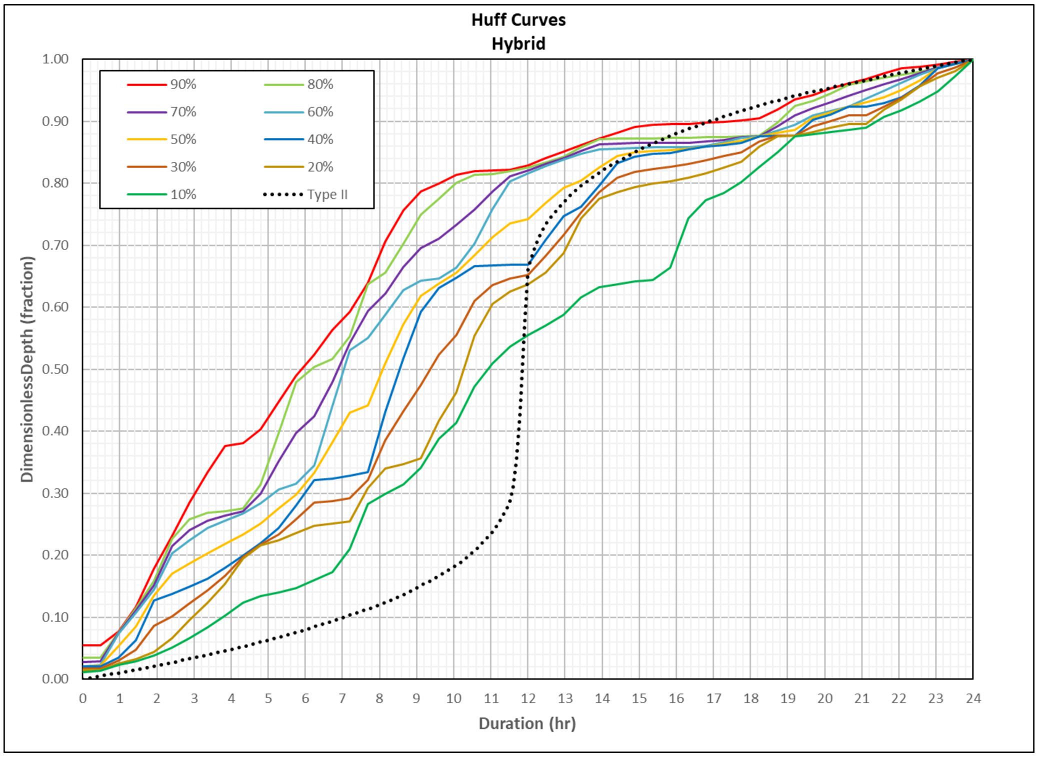


Figure 13.12: Raw Huff temporal curves for 24-hour Hybrid storms

13.3. 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 13.13 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.

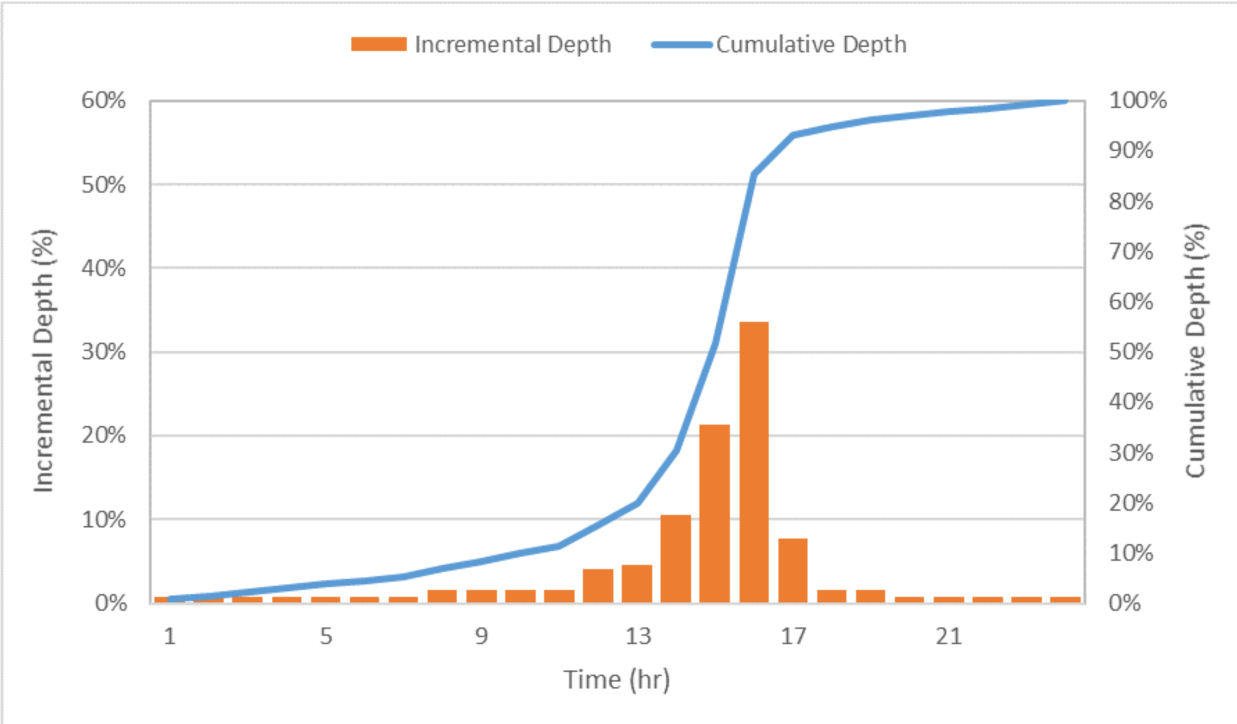


Figure 13.13: Graphical representation of the critically stacked temporal pattern

13.4. Sub-hourly Timing and 2-hour Local Storm Timing

AWA evaluated the 5-minute incremental rainfall accumulations patterns for 36 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 18 of the 36 storms events allowed a specific evaluation of the sub-hourly rainfall patterns to be considered for the North Dakota 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 13.1 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, Colorado-New Mexico, and OK-AR-LA-MS statewide PMP analyses are provided in Table 13.1

for comparison with the North Dakota 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 13.14.

Table 13.1: Sub-hourly ratio data from HMR 55A and the OK-AR-LA-MS study

Duration (hr)	Duration (min)	HMR 55a	ND	AR-LA-MS- OK	PA	CO/NM	AZ
0.083	5	-	18%	15%	16%	15%	-
0.167	10	-	31%	26%	28%	28%	-
0.25	15	68%	42%	36%	38%	39%	34%
0.50	30	86%	66%	61%	64%	65%	61%
0.75	45	94%	84%	80%	83%	84%	82%
1.00	60	100%	100%	100%	100%	100%	100%

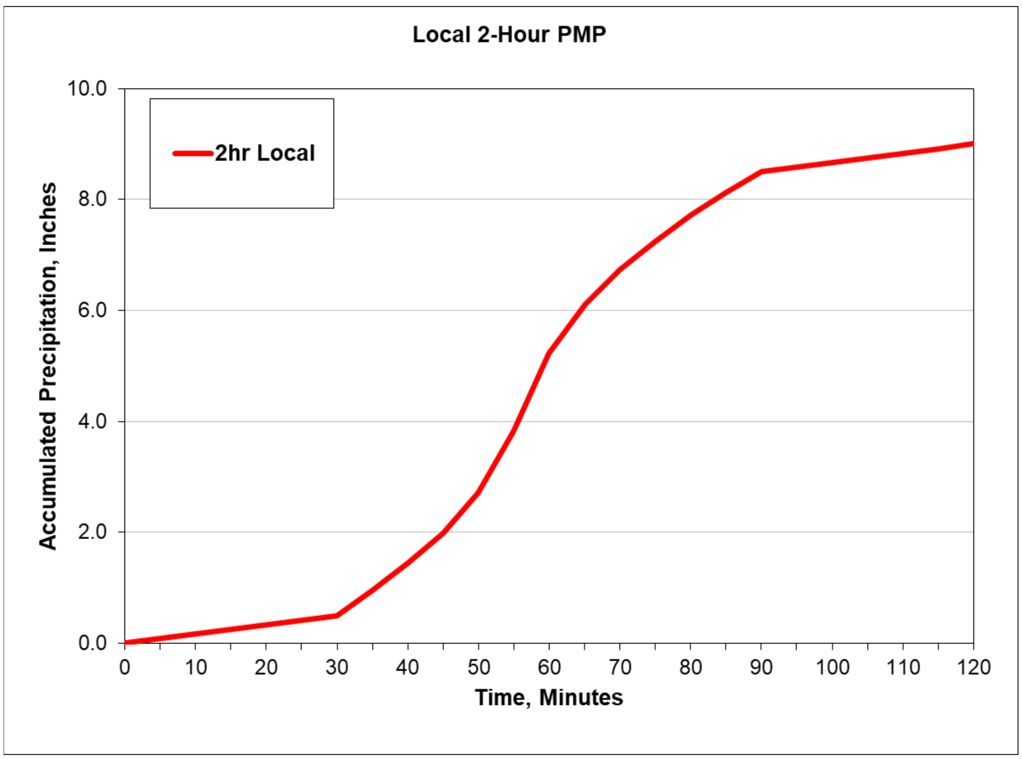


Figure 13.14: Hypothetical 2-hour local storm distribution

13.5. 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.

13.6. NRCS Type II Distribution Discussion

Each of the temporal patterns analyzed for all sites were significantly different than the NRCS Type II curve. Figure 13.15 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).

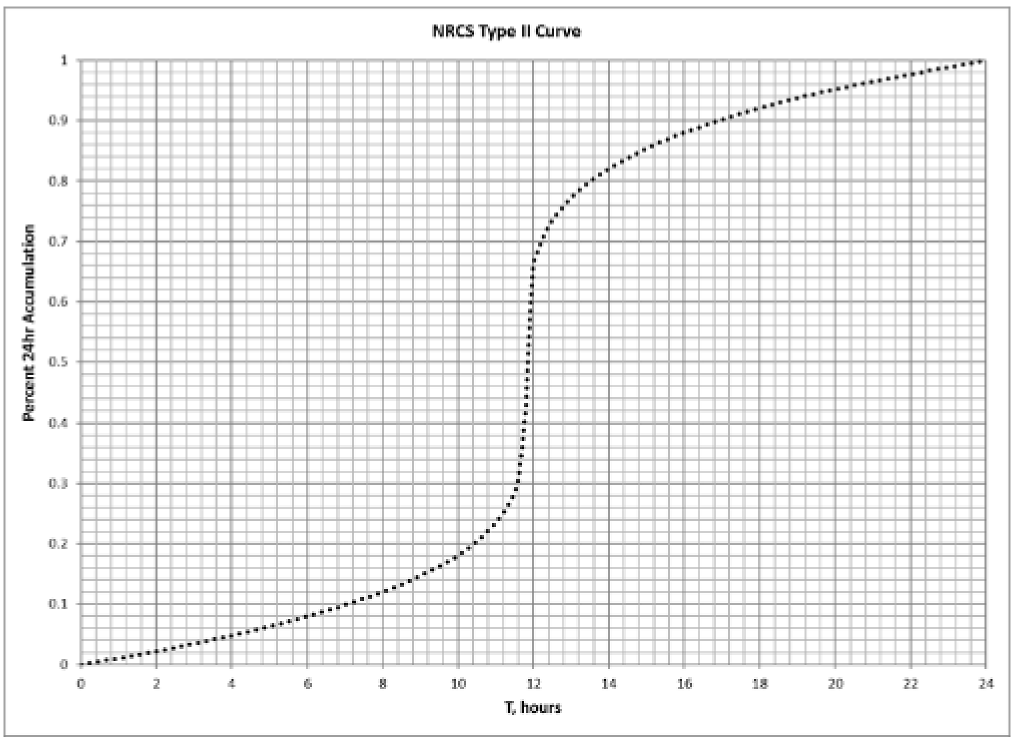


Figure 13.15: Natural Resource Conservation Service (NRCS) Type II curve

13.7. 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 final 10 storm patterns recommended and included in the PMP Tool are shown in six Figures 13.16-13.19 as hypothetical PMP. The final local storm, general, and Hybrid storm patterns are compared to NRCS Type II temporal pattern (Figures 13.20 – 13.22). 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.

The total duration for potential use in runoff modeling for the general storm and hybrid 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 10 curves described above and illustrated below. 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.

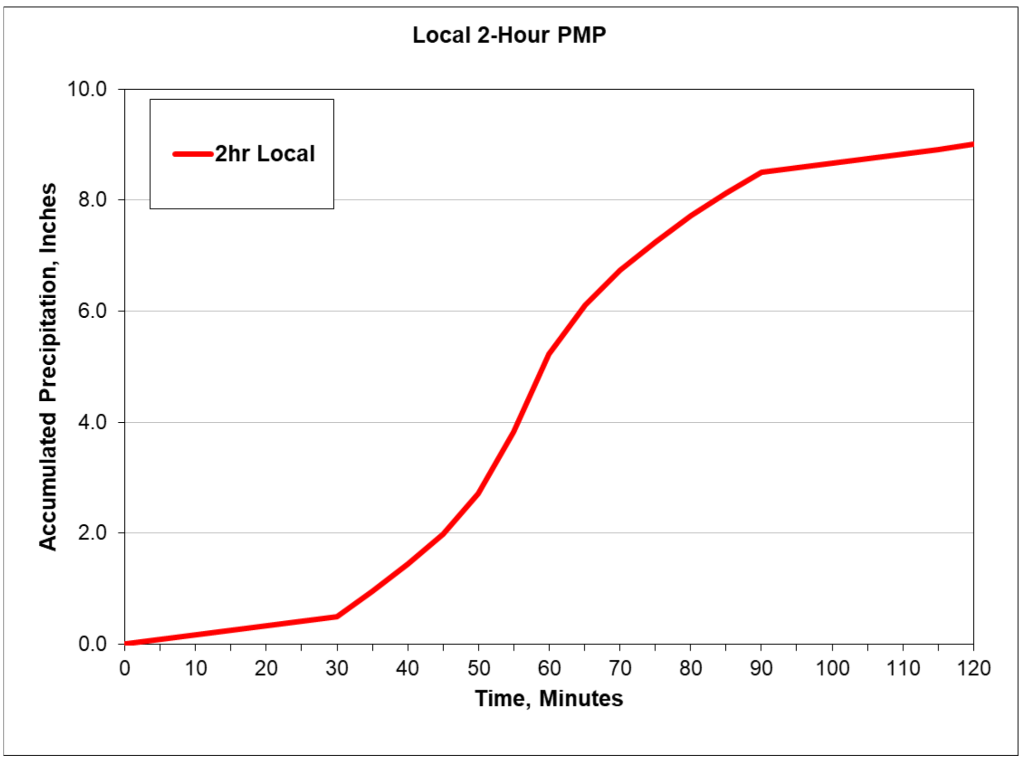


Figure 13.16: Hypothetical 2-hour local storm pattern at 5-minute time step

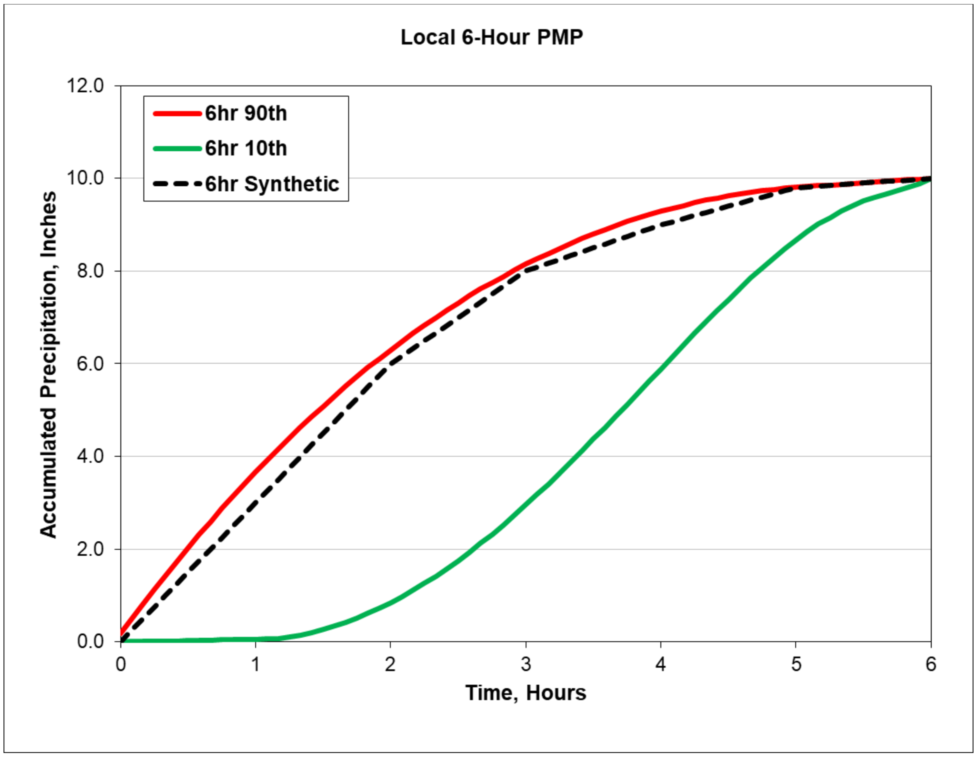


Figure 13.17: Hypothetical 6-hour local storm pattern at 5-minute time step. Red line is the 90th percentile curve, green line is the 10th percentile curve, and the black dashed line is the synthetic curve.

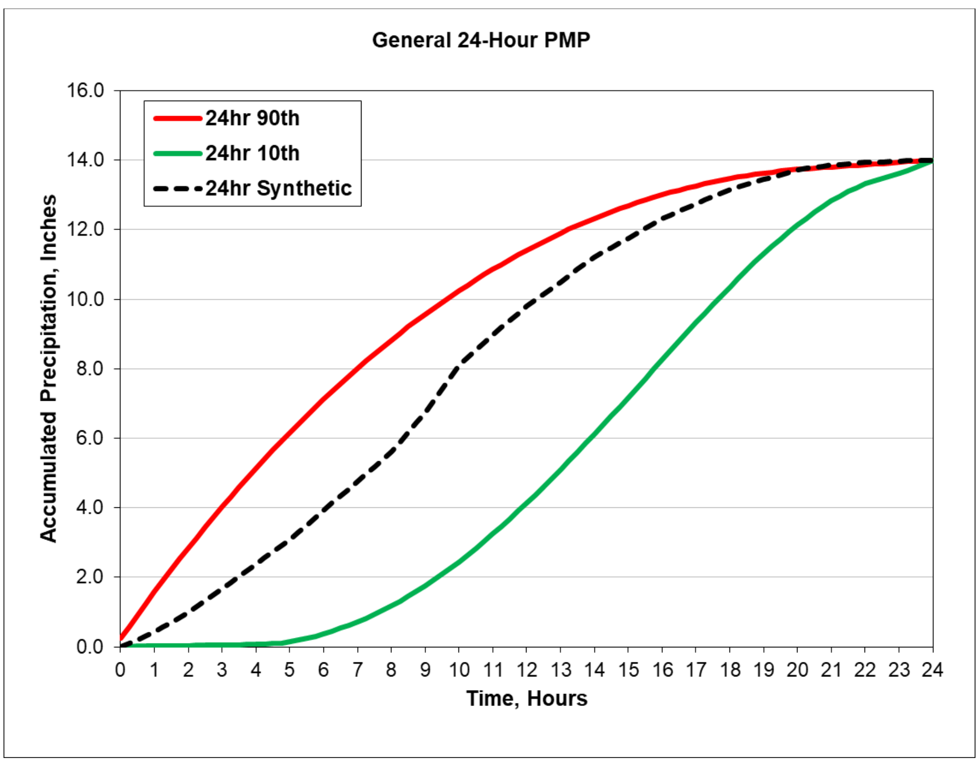


Figure 13.18: Hypothetical 24-hour general storm pattern at 15-minute time step. Red line is the 90th percentile curve, green line is the 10th percentile curve, and black dashed line is the synthetic curve.

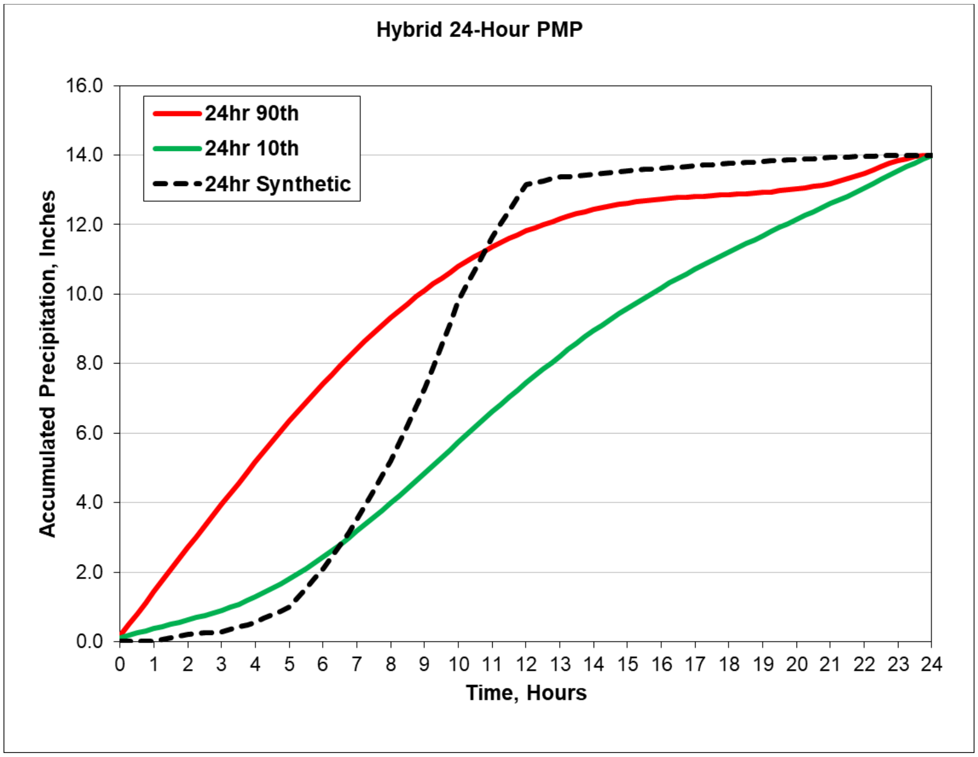


Figure 13.19: Hypothetical 24-hour Hybrid storm pattern at 15-minute time step. Red line is the 90th percentile curve, green line is the 10th percentile curve, and black dashed line is the synthetic curve.

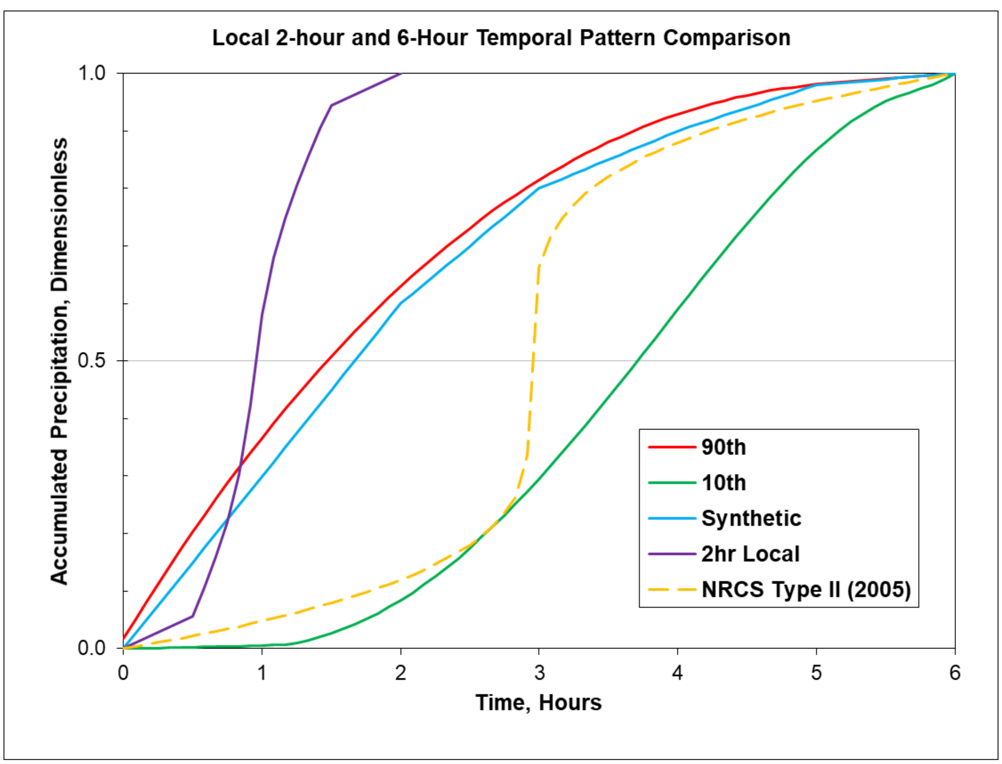


Figure 13.20: Comparison of final Local storm patterns to NRCS Type II temporal pattern

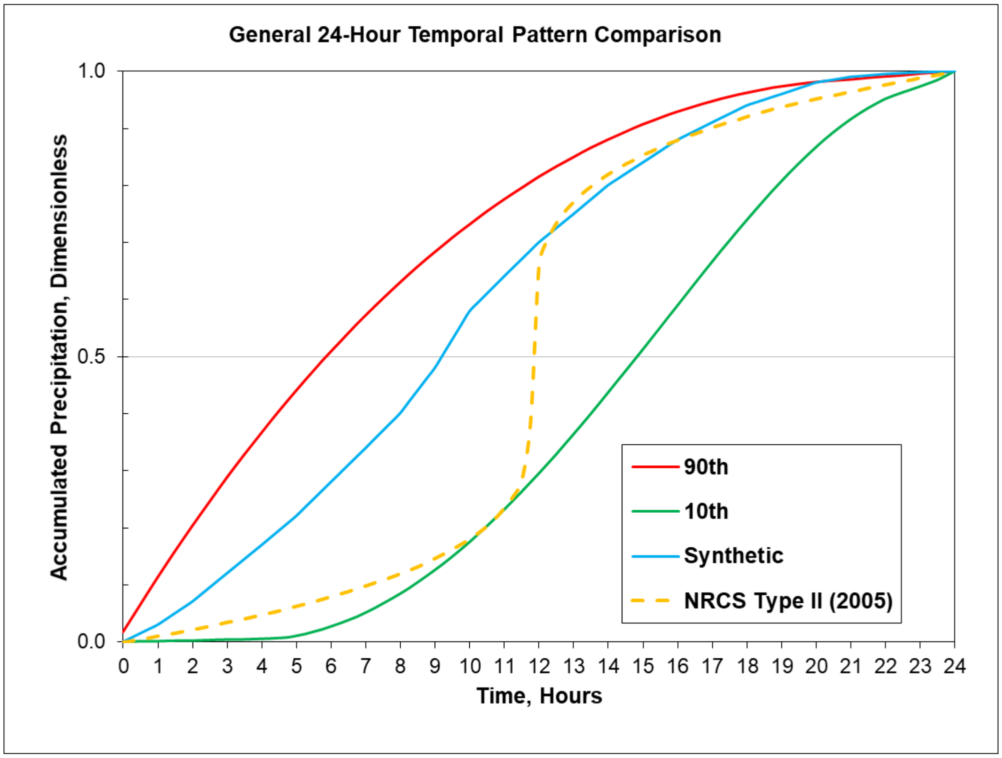


Figure 13.21: Comparison of final General storm patterns to NRCS Type II temporal pattern

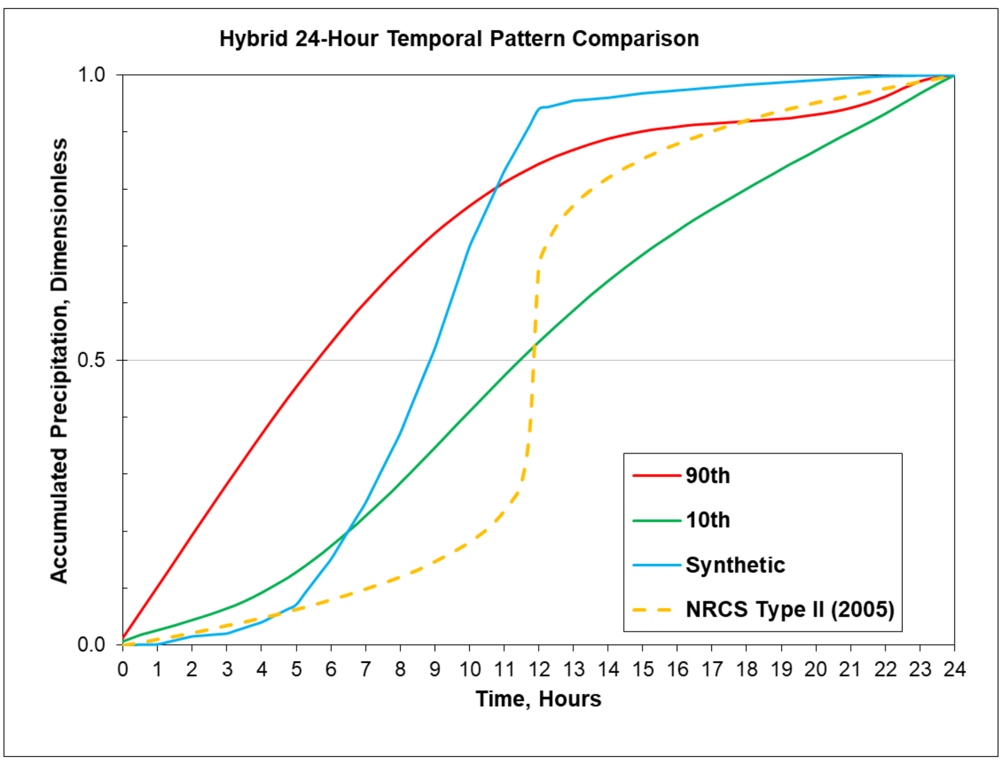


Figure 13.22: Comparison of final Hybrid storm patterns to NRCS Type II temporal pattern

14. Sensitivities and Comparisons

In the process of deriving PMP depths, 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.

14.1. 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 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
- Updated and expanded precipitation frequency climatology to cover region not included in NOAA Atlas 14
- Updated dew point climatologies used for storm maximizations
- Explicitly applied storm transposition limits

Unfortunately, working papers and notes from the HMRs are not available in most cases. Therefore, PMP comparisons between the HMRs and the depths 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. PMP depths in this study resulted in a wide range of both reductions and some 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 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 14.1-14.6 provide the average percent difference (negative is a reduction) from HMR 51 across each of the transposition regions analyzed. The differences between these updated PMP depths and HMR PMP depths across the study domain is shown for several standard area sizes and duration in Figures 14.1-14.11.

Table 14.1: Percent difference from HMR 51 PMP at 10-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 10 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 6hr	PMP 6hr	% Change 6hr	HMR 51 12hr	PMP 12hr	% Change 12hr	HMR 51 24hr	PMP 24hr	% Change 24hr
1	21.7	19.9	-8.5%	25.9	24.1	-6.8%	27.6	24.2	-12.3%
2	20.8	16.7	-19.8%	24.7	20.3	-17.7%	26.5	20.3	-23.2%
3	20.8	15.9	-23.2%	24.6	19.4	-21.2%	26.5	19.4	-26.6%

Table 14.2 Percent difference from HMR 51 PMP at 200-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 200 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 6hr	PMP 6hr	% Change 6hr	HMR 51 12hr	PMP 12hr	% Change 12hr	HMR 51 24hr	PMP 24hr	% Change 24hr
1	16.1	14.8	-8.0%	19.3	15.7	-18.6%	20.9	18.0	-14.0%
2	15.2	13.3	-12.6%	18.2	14.1	-22.5%	20.0	15.5	-22.6%
3	15.0	12.9	-13.7%	17.6	13.7	-22.6%	19.6	15.2	-22.8%

Table 14.3 Percent difference from HMR 51 PMP at 1,000-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 1,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	16.0	14.0	-12.3%	18.2	16.4	-10.1%	19.7	16.6	-15.3%
2	15.4	13.2	-14.4%	17.4	14.8	-15.2%	18.6	14.9	-20.1%
3	15.1	13.2	-13.0%	17.1	14.7	-14.2%	18.3	14.8	-19.1%

Table 14.4 Percent difference from HMR 51 PMP at 5,000-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 5,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	10.9	10.7	-1.1%	13.1	14.0	6.9%	14.6	14.2	-2.9%
2	10.4	10.0	-4.5%	12.4	11.8	-5.1%	13.6	11.9	-12.8%
3	10.3	9.9	-4.1%	12.2	11.5	-5.9%	13.3	11.5	-13.0%

Table 14.5 Percent difference from HMR 51 PMP at 10,000-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 10,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	8.9	9.4	5.7%	11.0	12.6	13.9%	12.5	12.7	1.7%
2	8.5	8.7	1.7%	10.2	10.4	2.1%	11.5	10.6	-8.2%
3	8.4	8.6	2.2%	10.0	10.1	0.5%	11.2	10.2	-8.6%

Table 14.6 Percent difference from HMR 51 PMP at 20,000-square miles. PMP depths are averaged over each transposition zone and represent the largest of all storm types

Mean 20,000 mi² PMP (max of all types) Percent Change from HMR 51 by Transposition Zone									
Transposition Zone	HMR 51 24hr	PMP 24hr	% Change 24hr	HMR 51 48hr	PMP 48hr	% Change 48hr	HMR 51 72hr	PMP 72hr	% Change 72hr
1	6.8	7.9	15.8%	9.1	10.6	17.4%	10.5	10.8	3.6%
2	6.4	7.4	15.1%	8.3	9.0	9.0%	9.5	9.2	-3.1%
3	6.3	7.4	16.5%	8.0	8.9	10.2%	9.1	9.0	-0.8%

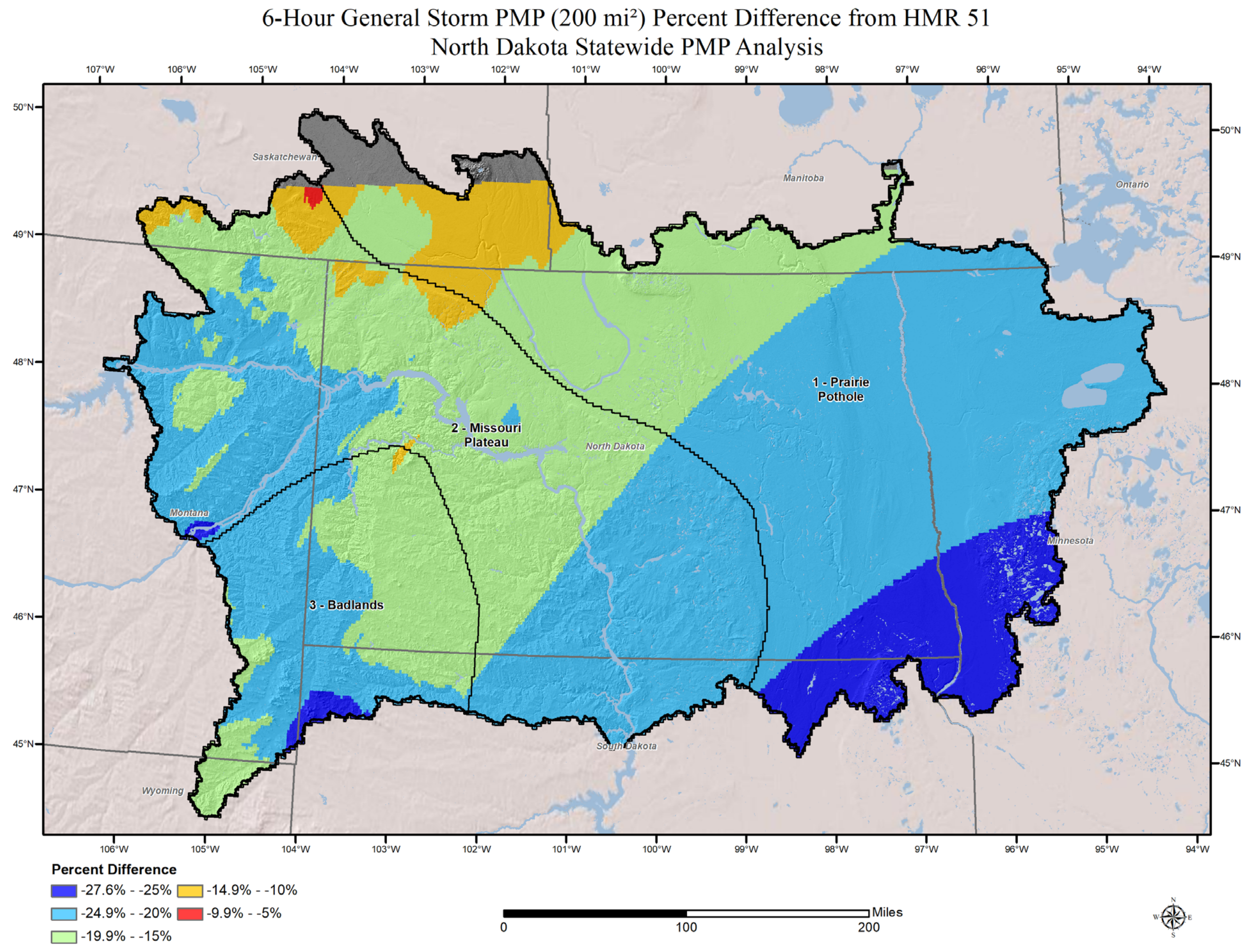


Figure 14.1: General Storm 200 mi² Percent Difference from HMR 51 – 6 hour

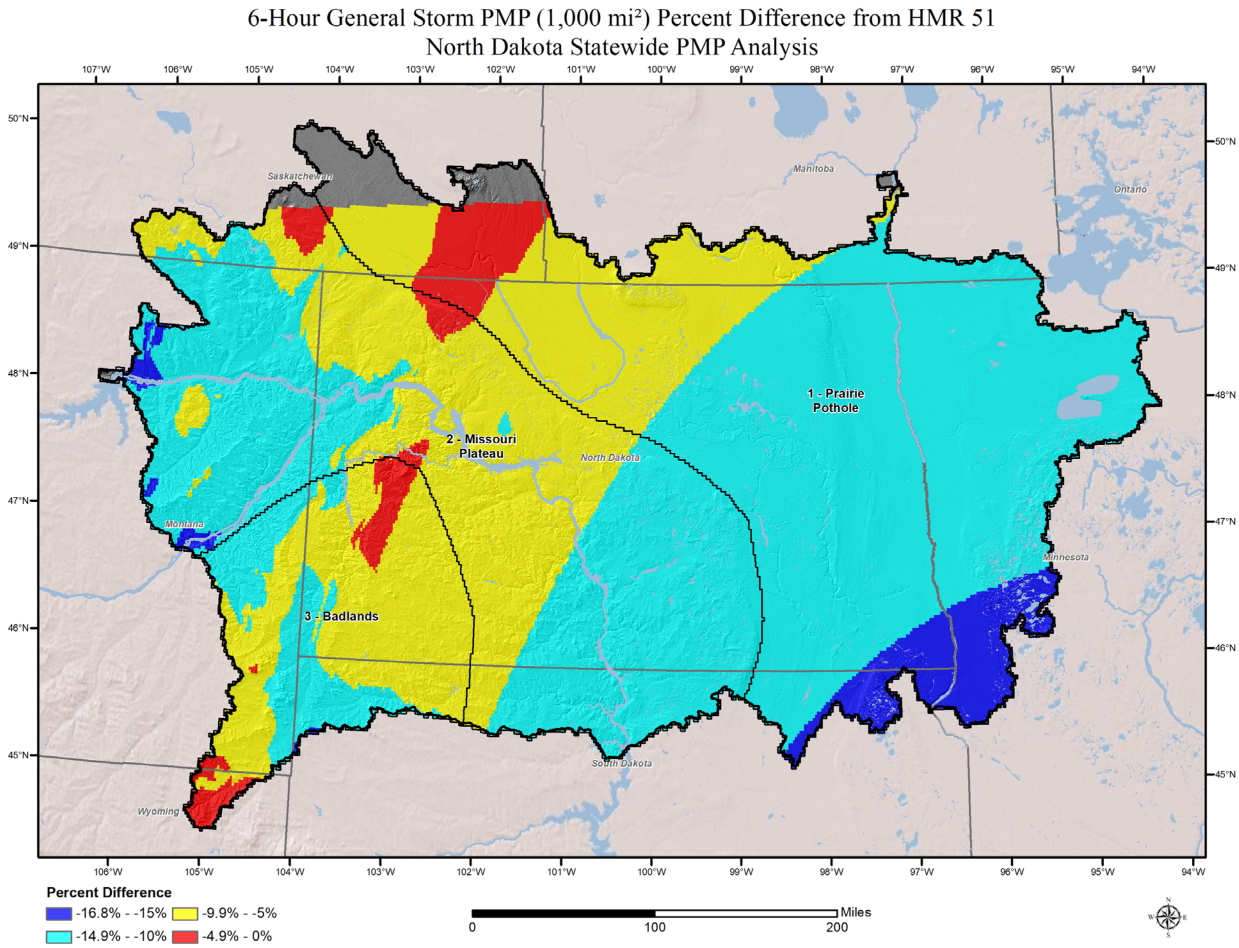


Figure 14.2: General Storm 1,000 mi^2 Percent Difference from HMR 51 – 6 hour

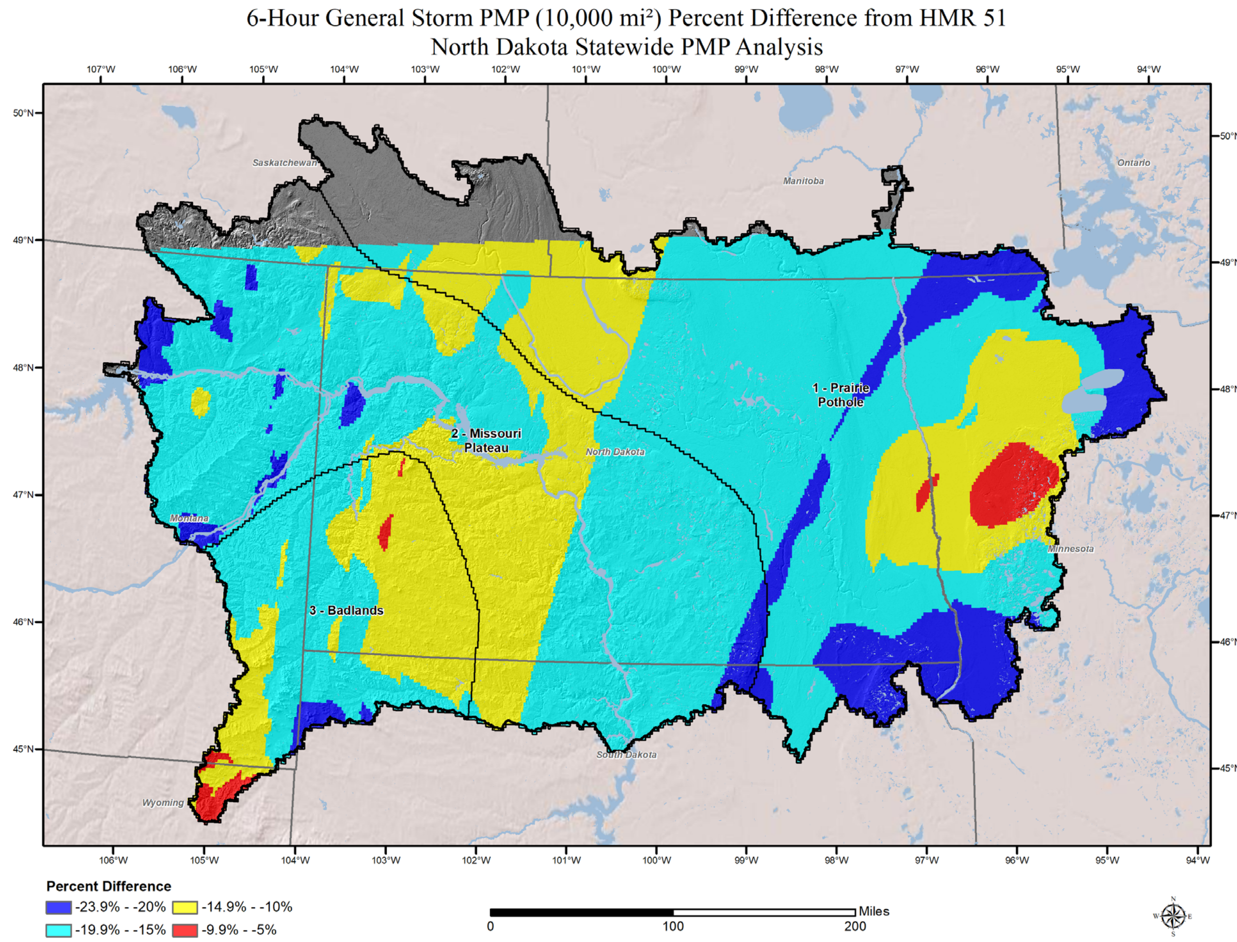


Figure 14.3: General Storm 10,000 mi² Percent Difference from HMR 51 – 6 hour

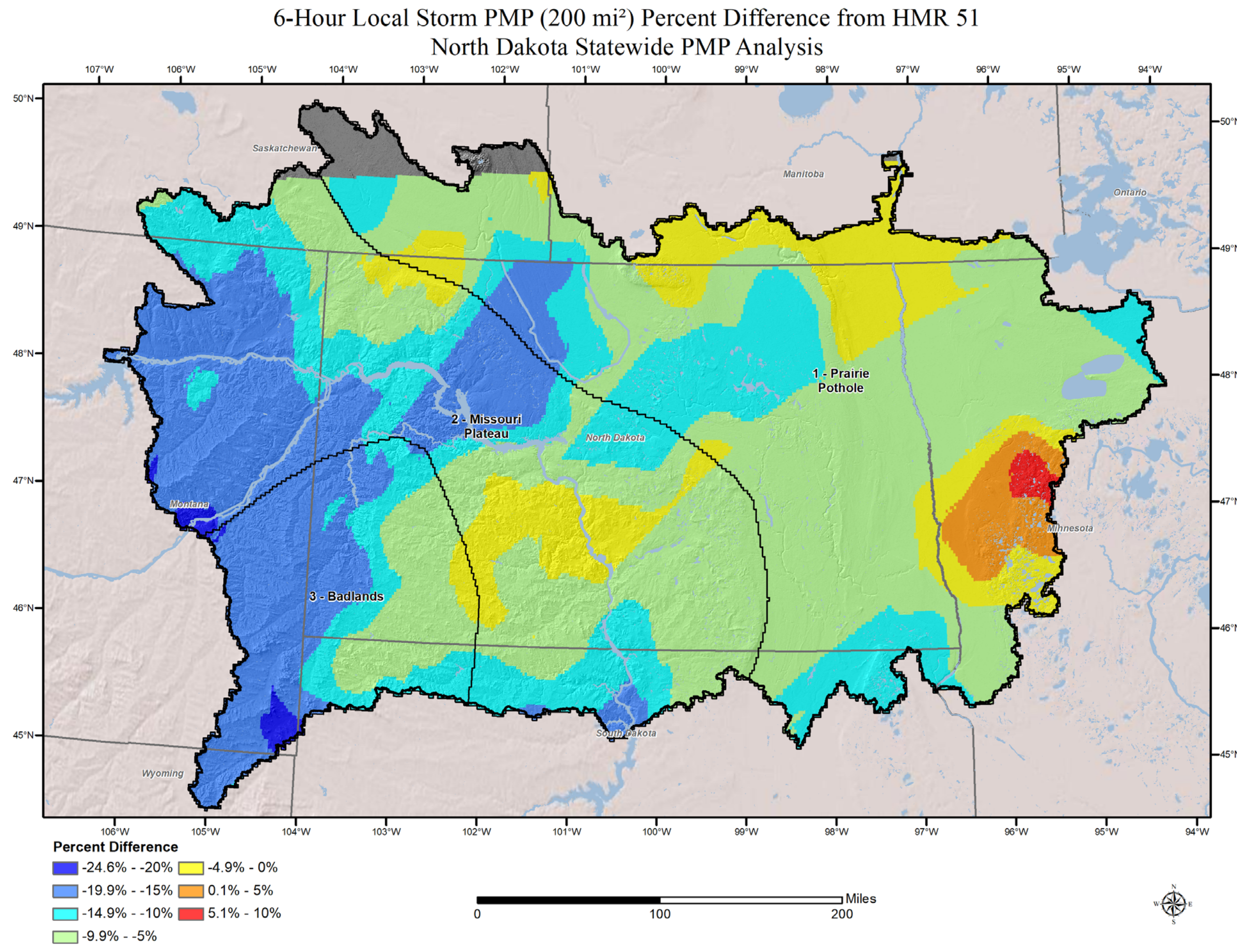


Figure 14.4: Local Storm 200 mi² Percent Difference from HMR 51 – 6 hour

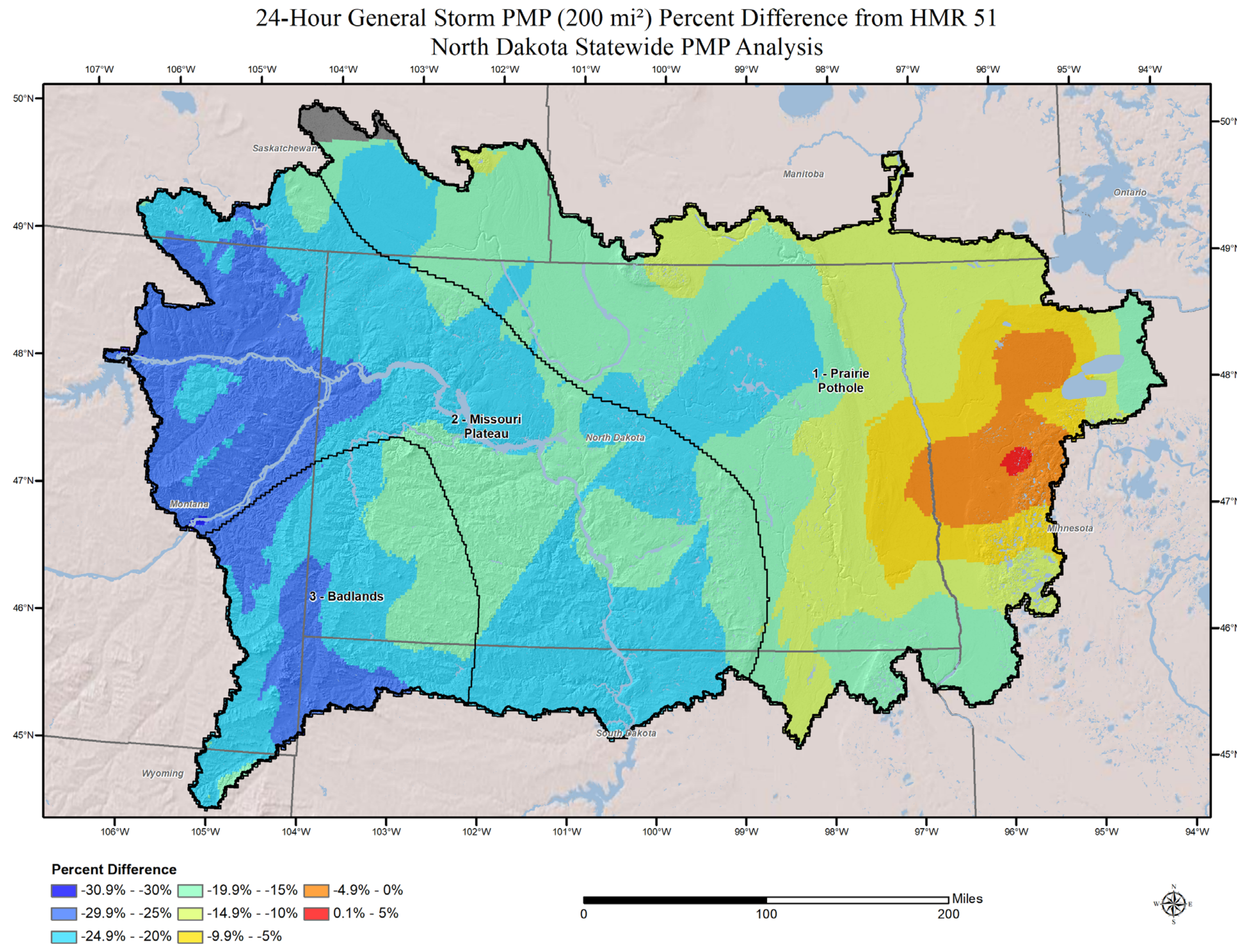


Figure 14.5: General Storm 200 mi² Percent Difference from HMR 51 – 24 hour

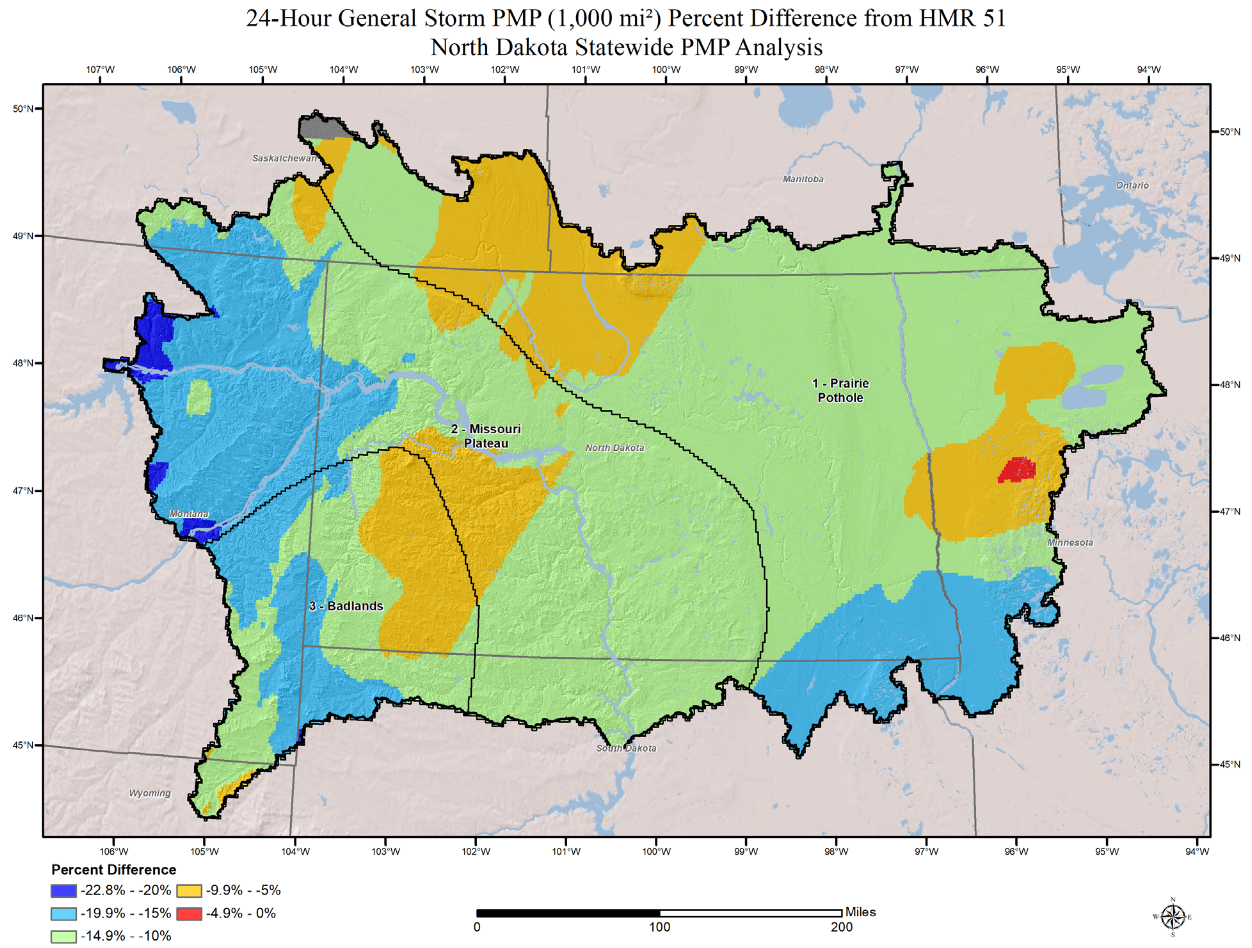


Figure 14.6: General Storm 1,000 mi² Percent Difference from HMR 51 – 24 hour

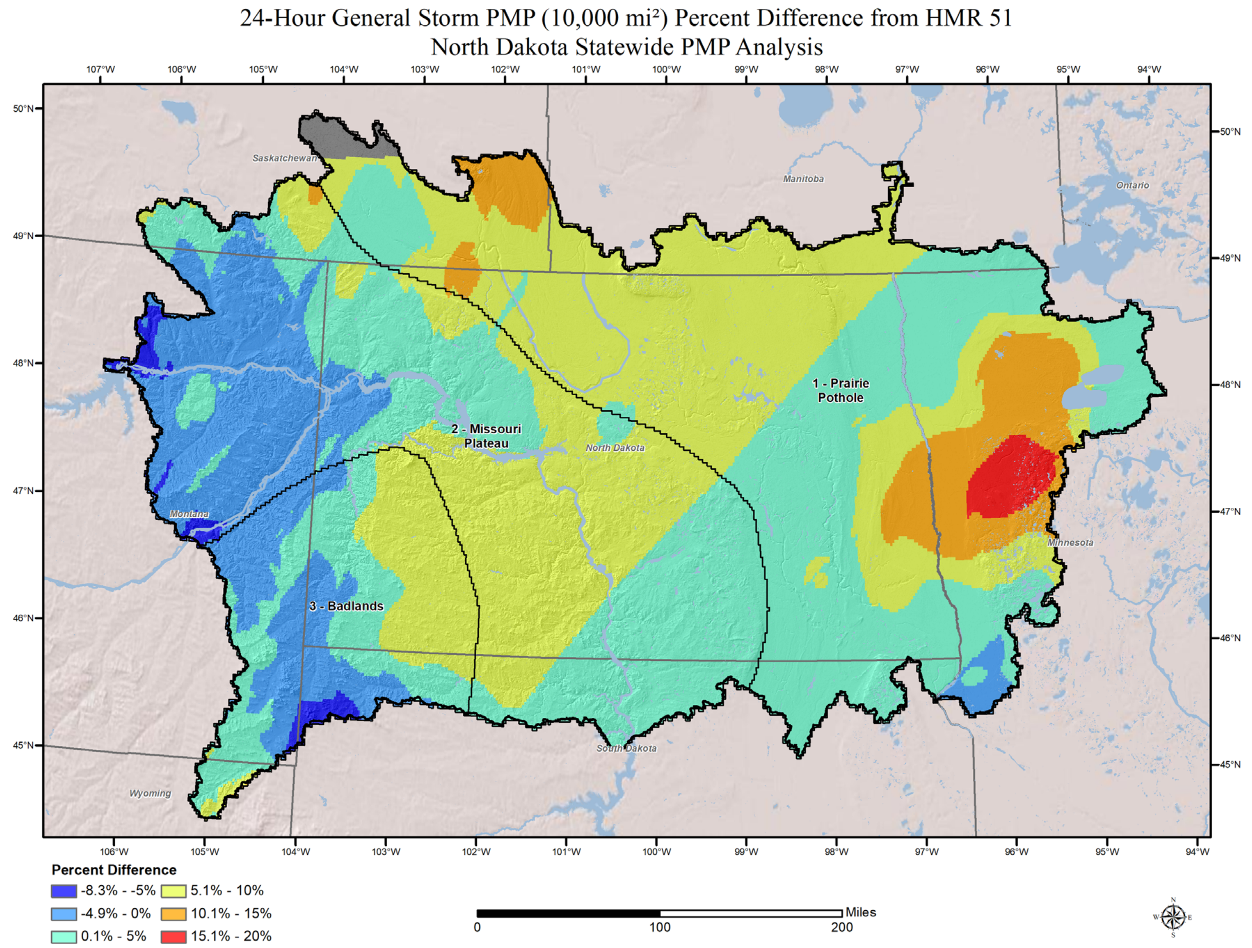


Figure 14.7: General Storm 10,000 mi² Percent Difference from HMR 51 – 24 hour

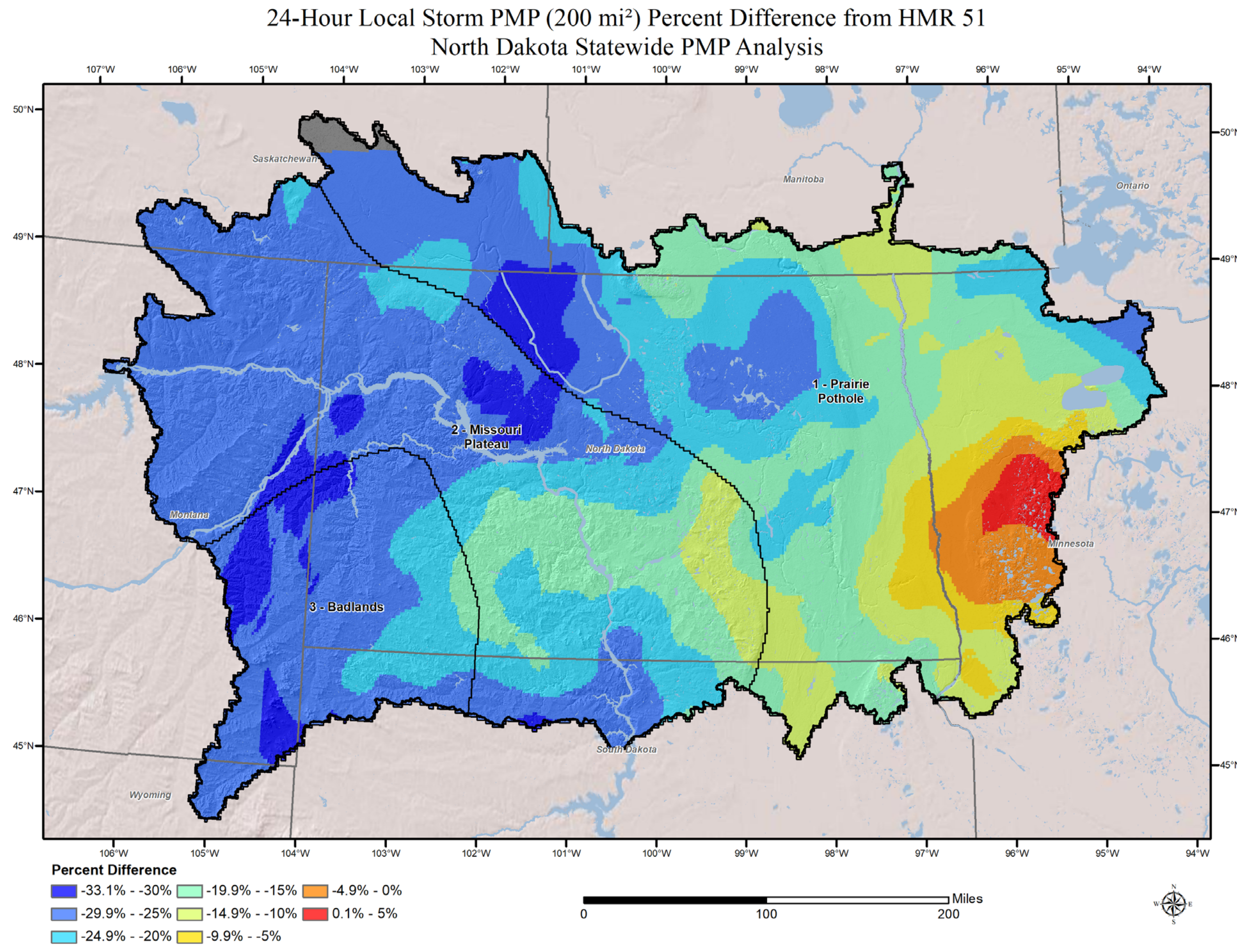


Figure 14.8: Local Storm 200 mi² Percent Difference from HMR 51 – 24 hour

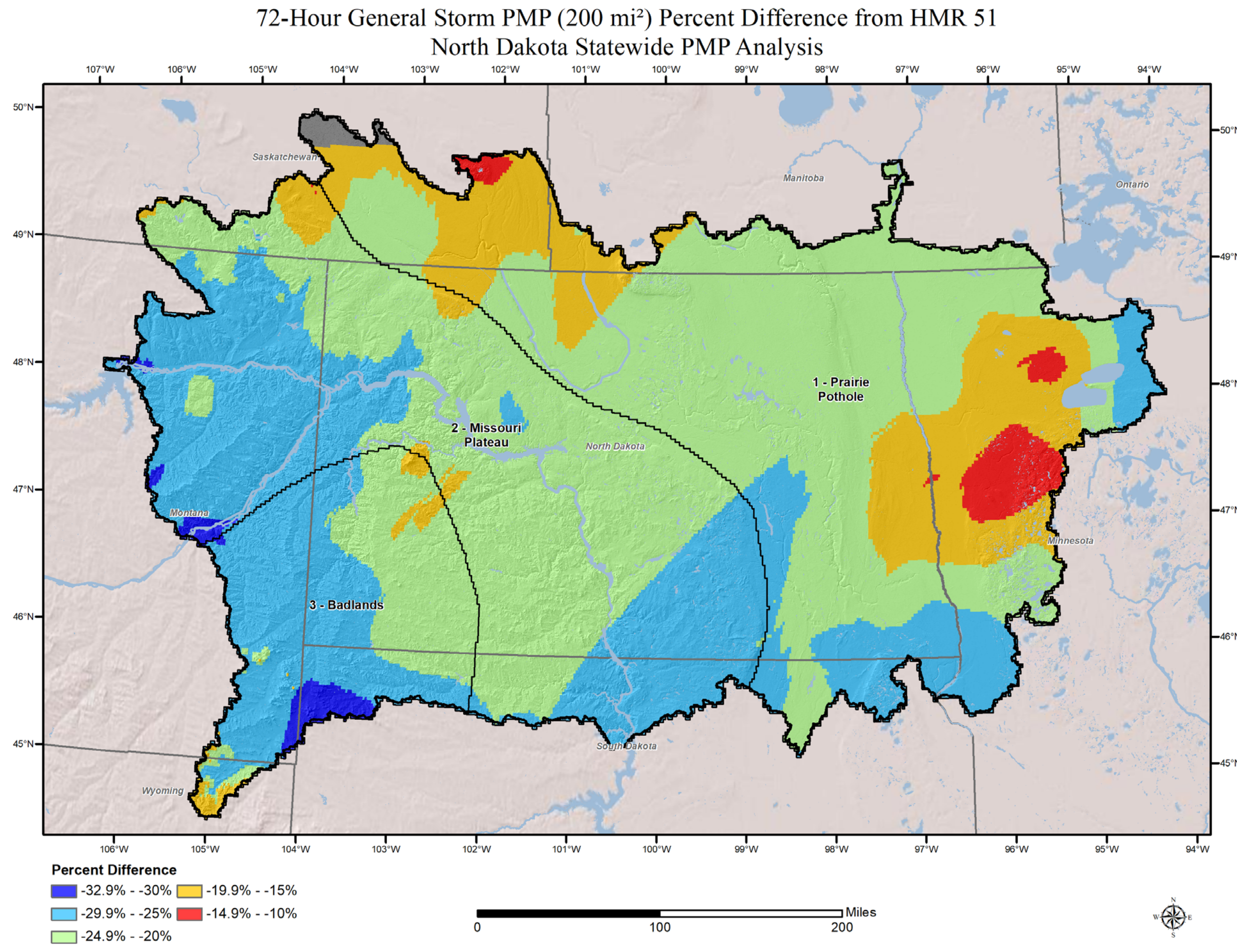


Figure 14.9: General Storm 200 mi² Percent Difference from HMR 51 – 72 hour

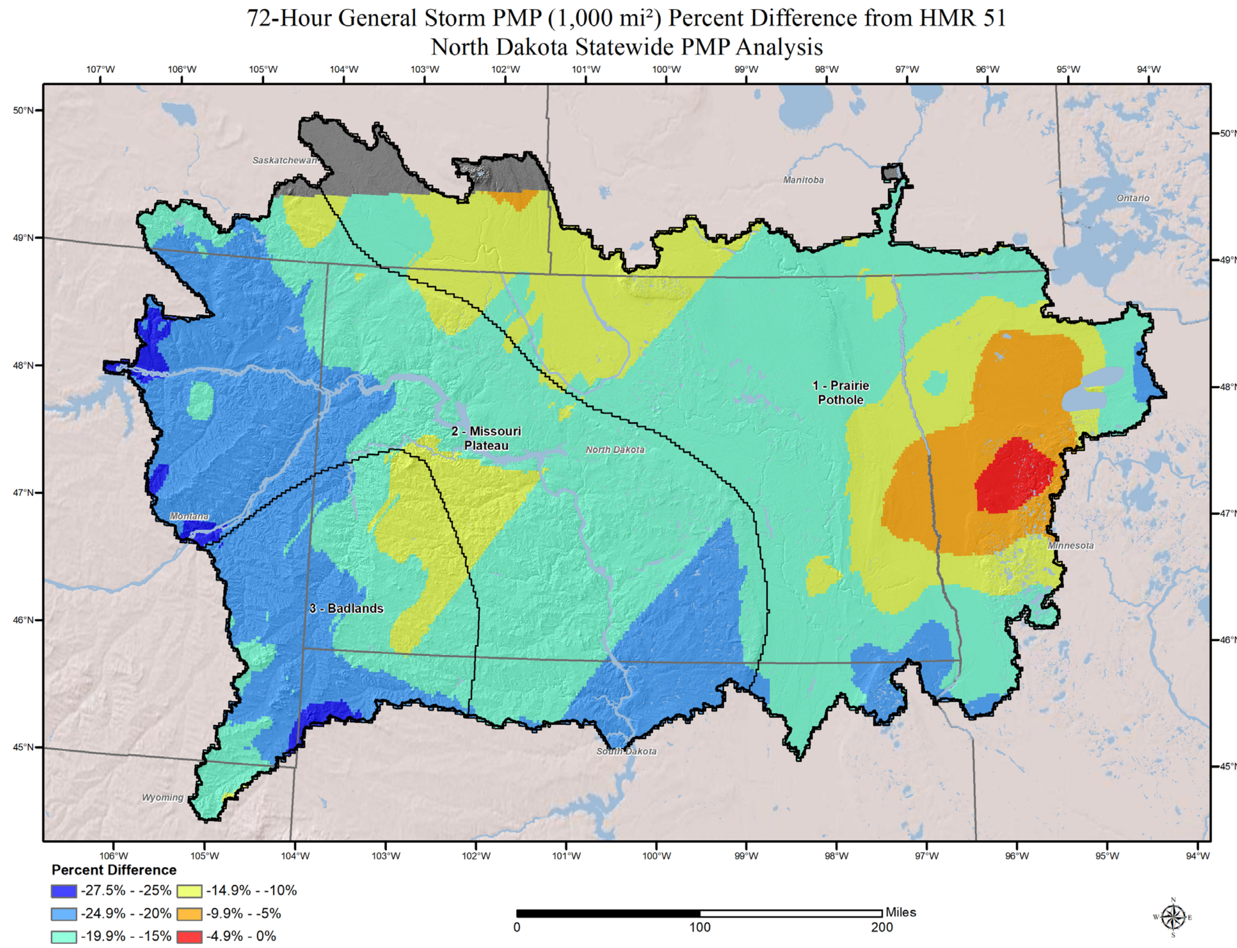


Figure 14.10: General Storm 1,000 mi² Percent Difference from HMR 51 – 72 hour

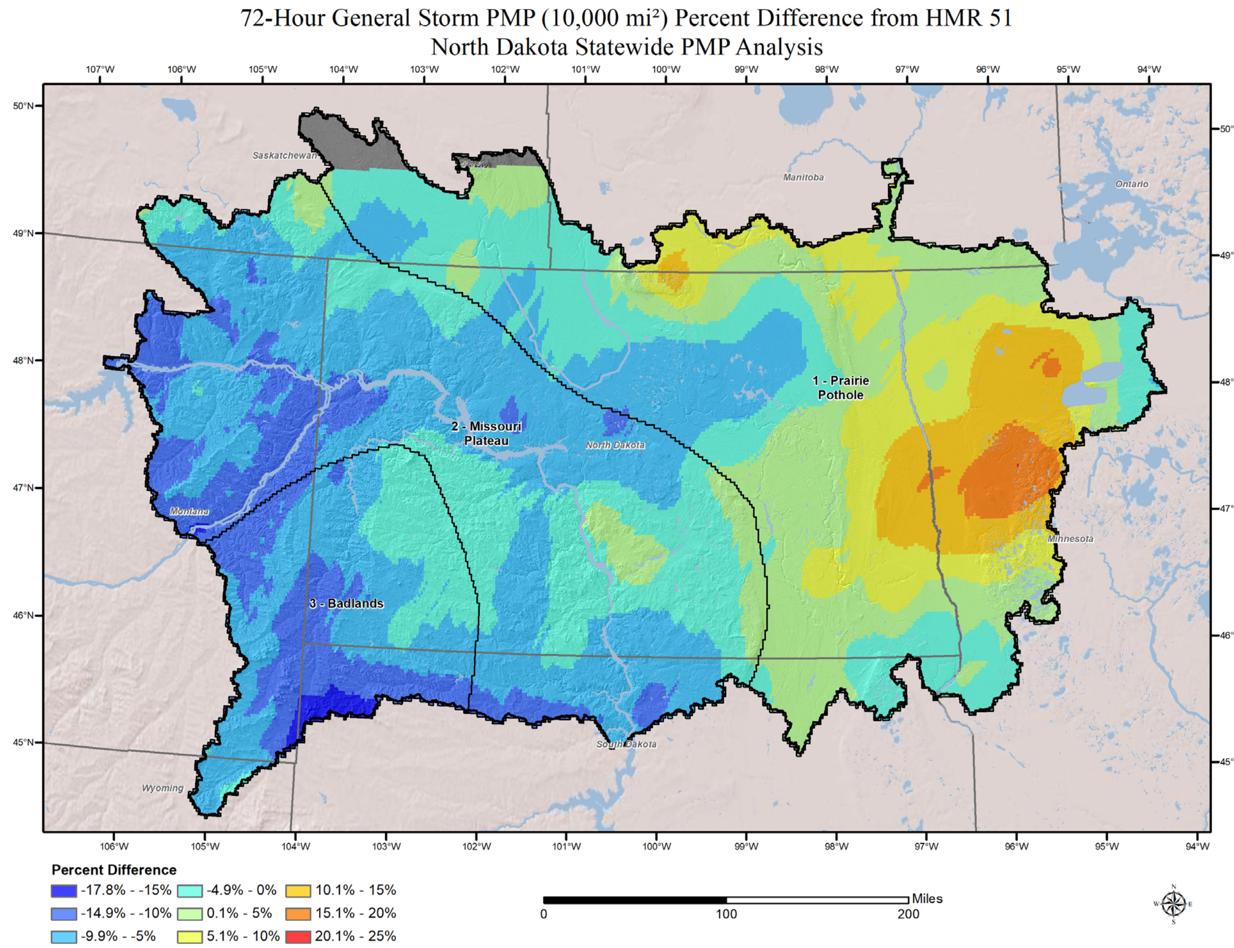


Figure 14.11: General Storm 10,000 mi² Percent Difference from HMR 51 – 72 hour

14.2. 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 precipitation frequency 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 14.1-14.2 illustrate the PMP to 100-year rainfall ratios for 6-hour Local storm PMP, 24-hour General storm PMP respectively. The PMP to 100-year return period precipitation ratios vary from 3.4 to 4.8, after combining storm types. The values are in reasonable proportion expected for the study area and demonstrate the PMP depths are at appropriately rare levels.

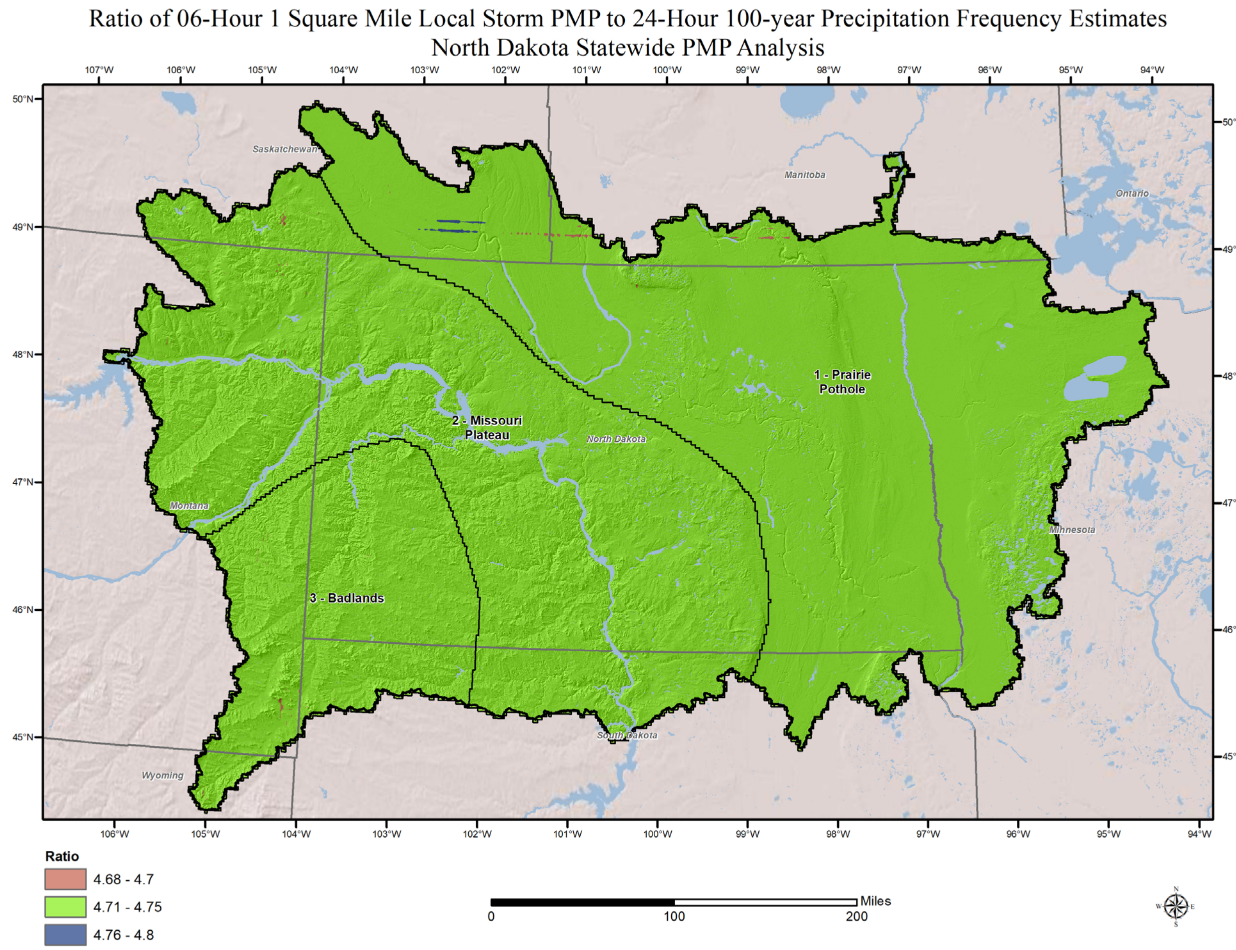


Figure 14.12: Ratio of 6-hour 1-square mile Local storm PMP to 100-year precipitation

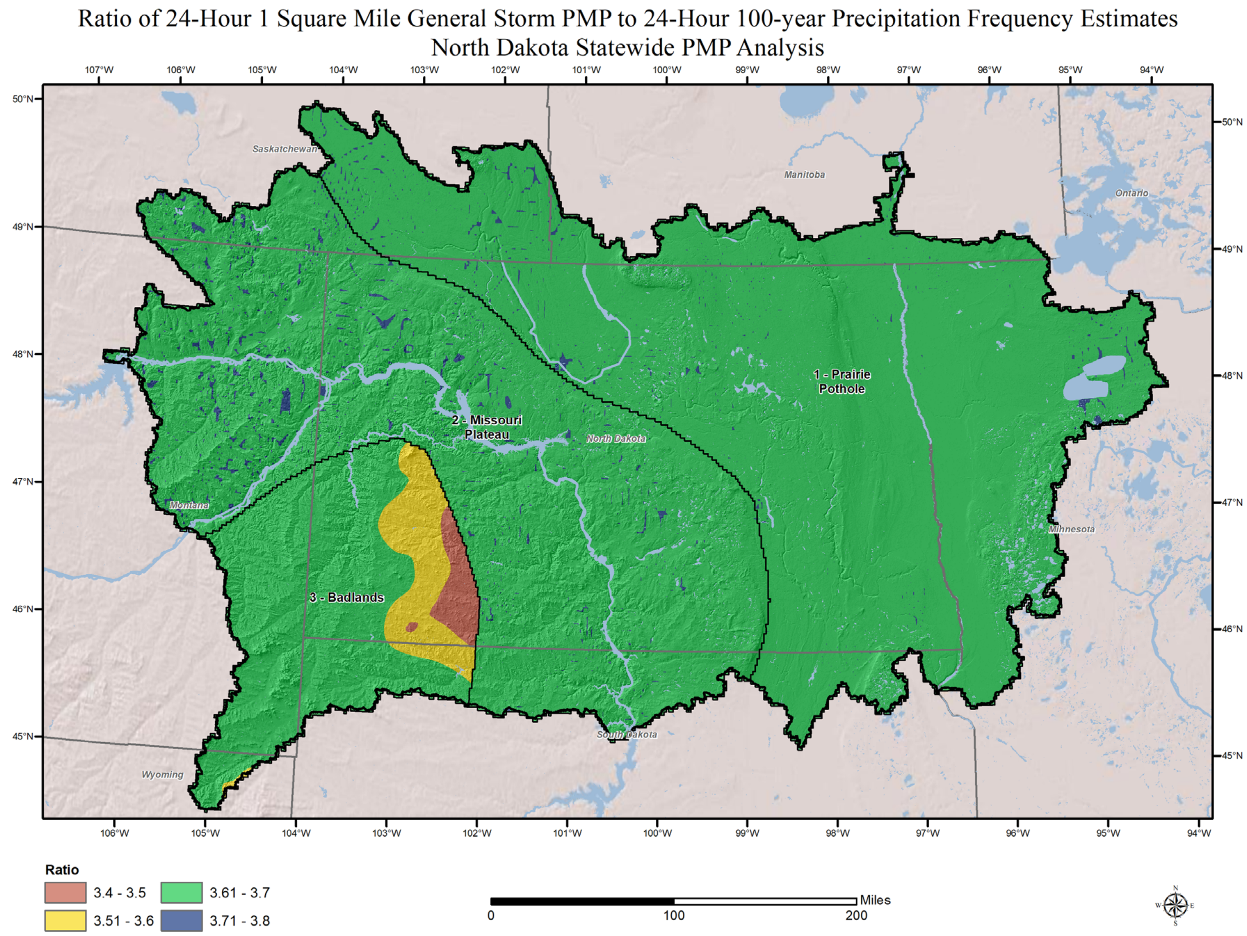


Figure 14.13: Ratio of 24-hour 1-square mile General storm PMP to 100-year precipitation

15. Uncertainty and Limitations

15.1. Sensitivity of Parameters

In the process of deriving PMP depths, 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 depths to assumptions that were made and to the variability of parameter values.

15.2. 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 70ºF 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 76ºF 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 76ºF 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.

15.3. 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.

15.4. 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.

15.5. 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 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 Steering Committee 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.

15.6. Limitation of Applying the PMP Depths

This study focused on the development of PMP depths from 1-hour through 72-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 Missouri River basin above Fort Peck Dam, MT.

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”.

15.6.1. Specific Limitations for PMP Development

Several aspects of PMP implementation require additional limitation specific to the PMP development for North Dakota and to produce efficiency in running the tool. These limitations are also noted in the PMP tool dialogue.

- Local storm PMP should be limited to 100-square miles or less at any given time
- Cool-Season PMP is only required for basins larger than 100-square miles
- General storm PMP is only required for basins larger than 20-square miles
- Additional spatial patterns are only required for basins larger than 50-square miles

15.7. 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). AWA has completed several detailed analyses of climate change projections on PMP (Kappel et al., 2020). These results are inconclusive and often show no significant change is likely, even under the most aggressive future emission scenarios.

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).

16. References

Alaya, Ben M.A., F. Zwiers, and X. Zhang, 2018: Probable Maximum Precipitation: Its Estimation and Uncertainty Quantification Using Bivariate Extreme Value Analysis. *J. Hydrometeor.,* **19**, 679–694.

Alexander et al., 2015: The High-Resolution Rapid Refresh (HRRR): The operational implementation, in 95th Annual meeting of the American Meteorological Society.

Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2006: NOAA Atlas 14 Volume 2, Precipitation-Frequency Atlas of the United States, Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia. NOAA, National Weather Service, Silver Spring, MD

Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2011: NOAA Atlas 14 Volume 1 Version 5.0, Precipitation-Frequency Atlas of the United States, Semiarid Southwest. NOAA, National Weather Service, Silver Spring, MD.

Bontà, V., 2003: Estimation of parameters characterizing frequency distributions of times between storms. Transactions of the ASAE. 46.

Carroll, T., D. Cline, G. Fall, A. Nilsson, L. Li, and A. Rost. 2001. NOHRSC Operations and the Simulation of Snow Cover Properties for the Conterminous U.S. Proceedings of the 69th Annual Meeting of the Western Snow Conference, pp. 1-14.

Chen, L.-C., and A. A. Bradley (2006), Adequacy of using surface humidity to estimate atmospheric moisture availability for probable maximum precipitation, Water Resour. Res., 42, W09410

Corps of Engineers, U.S. Army, 1945-1973: Storm Rainfall in the United States, Depth-Area-Duration Data. Office of Chief of Engineers, Washington, D.C.

Corrigan, P., D.D. Fenn, D.R. Kluck, and J.L. Vogel, 1999: Probable Maximum Precipitation for California, Hydrometeorological Report Number 59, National Weather Service, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, Silver Spring, MD, 392 pp.

Cudworth, A.G., 1989: Flood Hydrology Manual, Water Resources Technical Publication, United States Dept, of the Interior, United States Bureau of Reclamation, Denver office, 243pp.

Daly, C., R.P. Neilson, and D.L. Phillips, 1994: A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. J. Appl. Meteor., 33, 140–158.

Daly, C., Taylor, G., and W. Gibson, 1997: The PRISM Approach to Mapping Precipitation and Temperature, 10th Conf. on Applied Climatology, Reno, NV, Amer. Meteor. Soc., 10-12.

Dickens, J., 2003: On the Retrieval of Drop Size Distribution by Vertically Pointing Radar. American Meteorological Society 32nd Radar Meteorology Conference, Albuquerque, NM, October 2005

Dirmeyer, P. A., and J. L. Kinter III, 2009: The "Maya Express": Floods in the U.S. Midwest. *Eos, Trans. Amer. Geophys. Union*, **90**, 101–102.

Draxler, R.R. and Rolph, G.D., 2013: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) NOAA Air Resources Laboratory, Silver Spring, MD. Model access via NOAA ARL READY Website, http://ready.arl.noaa.gov/HYSPLIT.php

Dwight, B.W., 1822; An Account of a Remarkable storm which occurred at Catskill, July 26, 1819, *in* The American Journal of Science and Arts, Vol. IV, Articl XII.

Eisenlohr, W.S., and J. E. Stewart, 1952: Notable local floods of 1942-43, Floods of July 18, 1942 in north-central Pennsylvania, with a section on Descriptive details of the storm and floods

EM 1110-2-1411, "Standard Project Flood Determinations." (Civil Works Engineer Bulletin No. 52-8, March 1952, revised March 1965.

Environmental Data Service, 1968: Maximum Persisting 12-Hour, 1000mb Dew Points (°F) Monthly and of Record. *Climate Atlas of the United States*, Env. Sci. Srv. Adm., U.S. Dept of Commerce, Washington, D.C., pp 59-60.

Environmental Systems Research Institute (ESRI), ArcGIS Version 10.1 Computer Software, 2012.

Fernández-Cabán, P.L., A.A. Alford, M.J. Bell, M.I. Biggerstaff, G.D. Carrie, B. Hirth, K. Kosiba, B.M. Phillips, J.L. Schroeder, S.M. Waugh, E. Williford, J. Wurman, and F.J. Masters, 2019: Observing Hurricane Harvey's Eyewall at Landfall. *Bull. Amer. Meteor. Soc.,* **100**, 759–775.

Gelber, Ben, 1992: *Pocono Weather*, Uriel Publishing, Stroudsburg, Pennsylvania, 291 pp.

Goodyear, H.V., and J.T., Riedel, 1965: Probable Maximum Precipitation, Susquehanna River Drainage Above Harrisburg, PA *Hydrometeorological Report Number 40*, Hydrometeorological Branch, Office of Hydrology, U.S. Weather Bureau, Washington, D.C., 78 pp.

GRASS (Geographic Resources Analysis Support System) GIS is an open source, free software GIS with raster, topological vector, image processing, and graphics production functionality that operates on various platforms. http://grass.itc.it/.

Hansen, E.M, F.K. Schwarz, and J.T Reidel, 1977: Probable Maximum Precipitation Estimates. Colorado River and Great Basin Drainages. Hydrometeorological Report No. 49, NWS, NOAA, U.S. Department of Commerce, Silver Spring, MD, 161 pp.

Hansen, E.M, and F.K. Schwartz, 1981: Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages. Hydrometeorological Report No. 50, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 167 pp.

Hansen, E.M., L.C. Schreiner and J.F. Miller, 1982: Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian. Hydrometeorological Report No. 52, U.S. Department of Commerce, Washington, D.C., 168 pp.

Hansen, E.M, Fenn, D.D., Schreiner, L.C., Stodt, R.W., and J.F., Miller, 1988: Probable Maximum Precipitation Estimates, United States between the Continental Divide and the 103rd Meridian, Hydrometeorological Report Number 55A, National weather Service, National Oceanic and Atmospheric Association, U.S. Dept. of Commerce, Silver Spring, MD, 242 pp.

Hansen, E.M, Schwarz, F.K., and J.T. Riedel, 1994: Probable Maximum Precipitation- Pacific Northwest States, Columbia River (Including portion of Canada), Snake River, and Pacific Drainages. Hydrometeorological Report No. 57, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 353 pp.

Herath, S.M., Sarukkalige, R., and V.T., Van Nguyen, 2018: Evaluation of empirical relationships between extreme rainfall and daily maximum temperature in Australia, Journal of Hydrology, Volume 556, Pages 1171-1181.

Hershfield, D.M., 1961: *Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years*. Weather Bureau Technical Paper No. 40, U.S. Weather Bureau, Washington, D.C., 115 pp.

Hicks, N. S., J. A. Smith, A. J. Miller, *and* P. A. Nelson (2005), Catastrophic flooding from an orographic thunderstorm in the central Appalachians, Water Resour. Res., 41, *W12428*

Hosking, J.R.M. and J.R. Wallis, 1997. Regional Frequency Analysis an Approach Based on L-Moments, Cambridge University Press, 224 pp.

Huff, F.A., 1967: Time Distribution of Rainfall in Heavy Storms, Water Resources Research.

Hultstrand, D.M., and Kappel, W.D. 2017. The Storm Precipitation Analysis System (SPAS) Report. *Nuclear Regulatory Commission (NRC)* Inspection Report No 99901474/2016-201, Enercon Services, Inc., 95pp.

Hultstrand, D.M., and Fassnacht, S.R. 2020 (*in review*). The Best Precipitation Estimates for a Hydrologic Model by Combining Gauge and Radar Data. *Geographical Research Letters*.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., E.M. Tomlinson, and T. Parzybok. July 2013: Probable Maximum Precipitation Study for Arizona. Prepared for the Arizona Dept. of Water Resources, Dam Safety Division.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., and D. McGlone, July 2014: Site-Specific Probable Maximum Precipitation (PMP) Study for the College Lake Basin, Colorado, prepared for Colorado State University.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., Parzybok, T.W, and E.M. Tomlinson, December 2014: Statewide Probable Maximum Precipitation (PMP) Study for Wyoming.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., and McGlone, D., December 2015: Application of Temporal Patterns of PMP for Dam Design in Wyoming. Prepared for the Wyoming State Engineer's Office.

Kappel, W.D., Hultstrand, D.M., Rodel, J.T., Muhlestein, G.A., Steinhilber, K., McGlone, D., Rodel, J., and B. Lawrence, November 2015: Statewide Probable Maximum Precipitation or Virginia. Prepared for the Virginia Department of Conservation and Recreation.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., and McGlone, D, February 2016: Site-Specific Probable Maximum Precipitation for Hebgen Dam, MT.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., Rodel, J.T., McGlone, D., Parzybok, T.W., and B. Lawrence, September 2016: Statewide Probable Maximum Precipitation for Texas. Prepared for the Texas Commission of Environmental Quality.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Rodel, J.T., Steinhilber, K., McGlone, D., and Lawrence, B., May 2017: Site-Specific Probable Maximum Precipitation and Annual Exceedance Probability Assessment for the Gross Reservoir Basin, Colorado. Prepared for Denver Water.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Rodel, J.T., Steinhilber, K., and Lawrence, B., May 2018: Site-Specific Probable Maximum Precipitation and Annual Exceedance Probability Assessment for the Painted Rocks and East Fork Basins, Montana. Prepared for AECOM and Montana Dept. of Natural Resources.

Kappel, W.D., Rodel, J.T., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., and McGlone, D, June 2018: Site-Specific Probable Maximum Precipitation and Annual Exceedance Probability Assessment for the Catawba Wateree Basin. Prepared for Duke Energy.

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., and B. Lawrence, August 2018: Regional Probable Maximum Precipitation for the States of Colorado and New Mexico. Prepared for the Colorado Division of Water Resources and the New Mexico State Engineers Office.

Keim, B.D., R.A. Muller, and G.W. Stone, 2007: Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricane Strikes from Texas to Maine. *J. Climate*, **20**, 3498–3509.

Kent, E.C, Woodruff, S. D., and D. I. Berry, 2007: Metadata from WMO Publication No. 47 and an Assessment of Voluntary Observing Ship Observation Heights in ICOADS. *J. Atmos and Ocean Tech.*, **24(2)**, 214-234.

Konrad, C.E., 2001: The Most Extreme Precipitation Events over the Eastern United States from 1950 to 1996: Considerations of Scale. *J. Hydrometeor.*, **2**, 309–325.

Letkewicz, C.E., M.D. Parker, 2010: Forecasting the Maintenance of Mesoscale Convective Systems Crossing the Appalachian Mountains. *Wea. Forecasting*, **25**, 1179–1195.

Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.,* 61**,** 1374-1387.

Mahoney, Kelly, 2016: Examining terrain elevation assumptions used in current extreme precipitation estimation practices: A modeling study of the 2013 Colorado Front Range floods. Amer. Meteor. Soc. 30th Conf. on Hydrology, January 2016, New Orleans, LA.

Martner, B.E, and V. Dubovskiy, 2005: Z-R Relations from Raindrop Disdrometers: Sensitivity to Regression Methods And DSD Data Refinements. 32nd Radar Meteorology Conference, Albuquerque, NM.

Miller, J.F., R.H. Frederick and R.S. Tracey, 1973: NOAA Atlas 2, Precipitation: Frequency Atlas of the Western United States. U.S. Dept. of Commerce, NOAA, National Weather Service, Washington DC.

Minty, L.J., Meighen, J. and Kennedy, M.R. (1996) Development of the Generalized Southeast Australia Method for Estimating Probable Maximum Precipitation, HRS Report No. 4, Hydrology Report Series, Bureau of Meteorology, Melbourne, Australia, August 1996.

Moore, B.J., Neiman, P.J., Ralph, F.M., and F.E. Barthold, 2011: Physical Processes Associated with Heavy Flooding Rainfall in the Nashville, TN and Vicinity during 1-2 May 2010: The Role of an Atmospheric River and Mesoscale Convective System. *Mon. Wea. Rev.*, **140**, 358–378.

National Climatic Data Center (NCDC). NCDC TD-3200 and TD-3206 datasets - Cooperative Summary of the Day

National Climatic Data Center (NCDC) Heavy Precipitation Page http://www.ncdc.noaa.gov/oa/climate/severeweather/rainfall.html#maps

National Oceanic and Atmospheric Association, Forecast Systems Laboratory FSL Hourly/Daily Rain Data, http://precip.fsl.noaa.gov/hourly_precip.html

National Operational Hydrologic Remote Sensing Center. 2004. Snow Data Assimilation System (SNODAS) Data Products at NSIDC, Version 1. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5TB14TC. [Date Accessed]

Natural Resources Conservation Service (NRCS), Conservation Engineering Division. (2005, July). Earth Dams and Reservoirs, TR-60.

Parzybok, T. W., and E. M. Tomlinson, 2006: A New System for Analyzing Precipitation from Storms, *Hydro Review*, Vol. XXV, No. 3, 58-65

Perica, S. Martin, D., S. Pavlovic, I. Roy, C., Laurent, M.S., Trypaluk, D. Unruh, M. Yekta, and G. Bonnin, 2013: *NOAA Atlas 14 Volume 8 version 2, Precipitation-Frequency Atlas of the United States, Midwestern States* NOAA, National Weather Service, Silver Spring, MD.

Perica, S. Martin, D., S. Pavlovic, I. Roy, C., Laurent, M.S., Trypaluk, D. Unruh, M. Yekta, and G. Bonnin, 2013: *NOAA Atlas 14 Volume 9 version 2, Precipitation-Frequency Atlas of the United States, Southeastern States* NOAA, National Weather Service, Silver Spring, MD.

Perica, S., Pavlovic, S., Laurent, M.S., Trypaluk, D. Unruh, Martin, D., and O. Wilhite, 2015: *NOAA Atlas 14 Volume 10 version 2, Precipitation-Frequency Atlas of the United States, Northeastern States,* NOAA, National Weather Service, Silver Spring, MD.

Perica, S., S. Pavlovic, M. St. Laurent, C. Trypaluk, D. Unruh, O. Wilhite, 2018: *NOAA Atlas 14 Volume 11, Precipitation-Frequency Atlas of the United States, Texas*. NOAA, National Weather Service, Silver Spring, MD.

Pomeroy, J.W., D.M. Gray, 1995. Snowcover: accumulation, relocation, and management. Saskatoon, Sask., Canada: National Hydrology Research Institute (NHRI).

Pontrelli, M.D., Bryan, G., and J.M. Fritsch, 1999: The Madison County, Virginia, Flash Flood of 27 June 1995, *Weather and Forecasting.*, **14**, 384-404.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004

Reynolds, R.W., T.M. Smith, C. Liu, D.B. Chelton, K.S. Casey, and M.G. Schlax, 2007: Daily High-resolution Blended Analysis for Sea Surface Temperature. *J. Climate.*, **20**, 5473-5496.

Riedel, J.T., and L.C. Schreiner, 1980: Comparison of Generalized Estimates of Probable Maximum Precipitation with Greatest Observed Rainfalls, *NOAA Technical Report NWS 25*, US Department of Commerce, NOAA, Silver Spring, Md, 46 pp.

Robinson, D.A., I. Miyares, M. Pavlovskaya, G.A. Pope, 2001: Hurricane Floyd rainfall in New Jersey from the Hudson to the Hamptons: Snapshots of the New York Metropolitan Area.

Rolph, G., Stein, A., and Stunder, B., 2017: Real-time Environmental Applications and Display sYstem: READY. Environmental Modeling & Software, 95, 210-228.

Schaake, J., Henkel, A., Cong, S. 2004. Application of PRISM Climatologies for Hydrologic Modeling and Forecasting in the Western U.S. In: *18th Conference on Hydrology*, American Meteorological Society, Seattle, WA.

Schreiner, L.C., and J.T. Riedel, 1978: Probable Maximum Precipitation Estimates, United States East of the 105th Meridian. Hydrometeorological Report No. 51, U.S. Department of Commerce, Silver Spring, Md, 242 pp.

Schulzweida, Uwe. (2019, October 31). CDO User Guide (Version 1.9.8). http://doi.org/10.5281/zenodo.3539275

Smith, J.A., M.L. Baeck, M. Steiner, and A.J. Miller, 1996: Catastrophic Rainfall from an Upslope Thunderstorm in the Central Appalachians: The Rapidan Storm of June 27, 1995. *Water Res. Research*, **32**, 3099-3113.

Smith, J. A., M. L. Baeck, G. Villarini, and W. F. Krajewski, 2010: The Hydrology and Hydrometeorology of Flooding in the Delaware River Basin. J. Hydrometeor, **11**, 841-859.

Smith, J A., Gabriele Villarini, and Mary Lynn Baeck, 2011: Mixture Distributions and the Hydroclimatology of Extreme Rainfall and Flooding in the Eastern United States. *J. Hydrometeor*, **12**, 294–309.

Smith, J A., M. L. Baeck, A.A., Ntelekos, G. Villarini, and M. Syeiner, 2011: Extreme Rainfall and Flooding from Orographic Thunderstorms in the Central Appalachians. *Water Res. Research*, **47**, W04514, 24pp.

Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, and F. Ngan, 2015: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. Bull. Amer. Meteor. Soc., 96, 2059–2077.

Storm Studies – Pertinent Data Sheets, and Isohyetal Map, U.S. Department of Interior, Bureau of Reclamation, Denver, CO.

Thaler, J.S., 1996: *Catskill Weather*, Purple Mountain Press, Ltd., Fleischmanns, New York, 167 pp.

Thornton, P.E., M.M. Thornton, B.W. Mayer, Y. Wei, R. Devarakonda, R.S. Vose, and R.B. Cook. 2016. Daymet: Daily Surface Weather Data on a 1-km Grid for North America, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1328

Tomlinson, E.M., 1993: Probable Maximum Precipitation Study for Michigan and Wisconsin, Electric Power Research Institute, Palo Alto, CA, TR-101554, V1.

Tomlinson, E.M., Kappel W.D., and Parzybok, T.W., February 2008: Site-Specific Probable Maximum Precipitation (PMP) Study for the Magma FRS Drainage Basin, Prepared for AMEC, Tucson, Arizona.

Tomlinson, E.M., Kappel W.D., Parzybok, T.W., Hultstrand, D., Muhlestein, G., and P. Sutter, December 2008: Statewide Probable Maximum Precipitation (PMP) Study for the state of Nebraska, Prepared for Nebraska Dam Safety, Omaha, Nebraska.

Tomlinson, E.M., Kappel, W.D., and Parzybok, T.W., February 2011: Site-Specific Probable Maximum Precipitation (PMP) Study for the Magma FRS Drainage Basin, Arizona.

Tomlinson, E.M., Kappel, W.D., and Parzybok, T.W., March 2011: Site-Specific Probable Maximum Precipitation (PMP) Study for the Tarrant Regional Water District, Texas.

Tomlinson, E.M., Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., S. Lovisone, and Parzybok, T.W., March 2013: Statewide Probable Maximum Precipitation (PMP) Study for Ohio.

U.S. Army Corps of Engineers, 1998. Engineer Manual 1110-2-1406 - Runoff from Snowmelt. Washington DC.

U.S. Navy Marine Climate Atlas of the World (NAVAIR50-1C-65), 1981: Volume IX, Naval Oceanographic Command Detachment, Asheville, NC.

U.S. Weather Bureau, 1946: Manual for Depth-Area-Duration analysis of storm precipitation. *Cooperative Studies Technical Paper No. 1*, U.S. Department of Commerce, Weather Bureau, Washington, D.C., 73pp.

U.S. Weather Bureau, 1951: Tables of Precipitable Water and Other Factors for a Saturated Pseudo-Adiabatic Atmosphere. *Technical Paper No. 14*, U.S. Department of Commerce, Weather Bureau, Washington, D.C., 27 pp.

U.S. Weather Bureau, 1952. *Maximum 24-Hour Precipitation in the United States*. Technical Paper No. 16, U.S. Department of Commerce, Hydro-meteorological Section.

Weather Bureau, 1940: Maximum Possible Precipitation Over The Ompompasoosuc Basin Above Union Village, Vermont, A Study of Meteorological Causes of Record Storms and

Quantitative Estimates of Critical Precipitation Rates, Hydrometeorological Report 1, pp205.
Weather Underground, http://www.wunderground.com/stationmaps/
World Meteorological Organization, 1986: Manual for Estimation of Probable Maximum Precipitation, Operational Hydrology Report No 1, 2nd Edition, WMO, Geneva, 269 pp.
World Meteorological Organization, 2009: Manual for Estimation of Probable Maximum Precipitation, Operational Hydrology Report No 1045, WMO, Geneva, 259 pp.
Worley, S.J., S.D. Woodruff, R.W. Reynolds, S.J. Lubker, and N. Lott, 2005: ICOADS Release 2.1 data and products. *Int. J. Climatol. (CLIMAR-II Special Issue)*, **25**, 823-842.
Zehr, R.M. and V.A. Myers, 1984: NOAA Technical Memorandum NWS Hydro 40, *Depth-Area Ratios in the Semi-Arid Southwest United States*, Silver Spring, MD 55pp.
Zurndorfer, E.A., F.K. Schwarz, E.M. Hansen, D.D. Fenn, and J.F. Miller, 1986: Probable Maximum and TVA Precipitation Estimates, With Areal Distribution for Tennessee River Drainages Less Than 3,000 Mi^2 in Area. *Hydrometeorological Report No. 56*, National Weather Service, National Oceanic and Atmospheric Association, U.S. Dept of Commerce, Silver Spring, MD, 238pp.