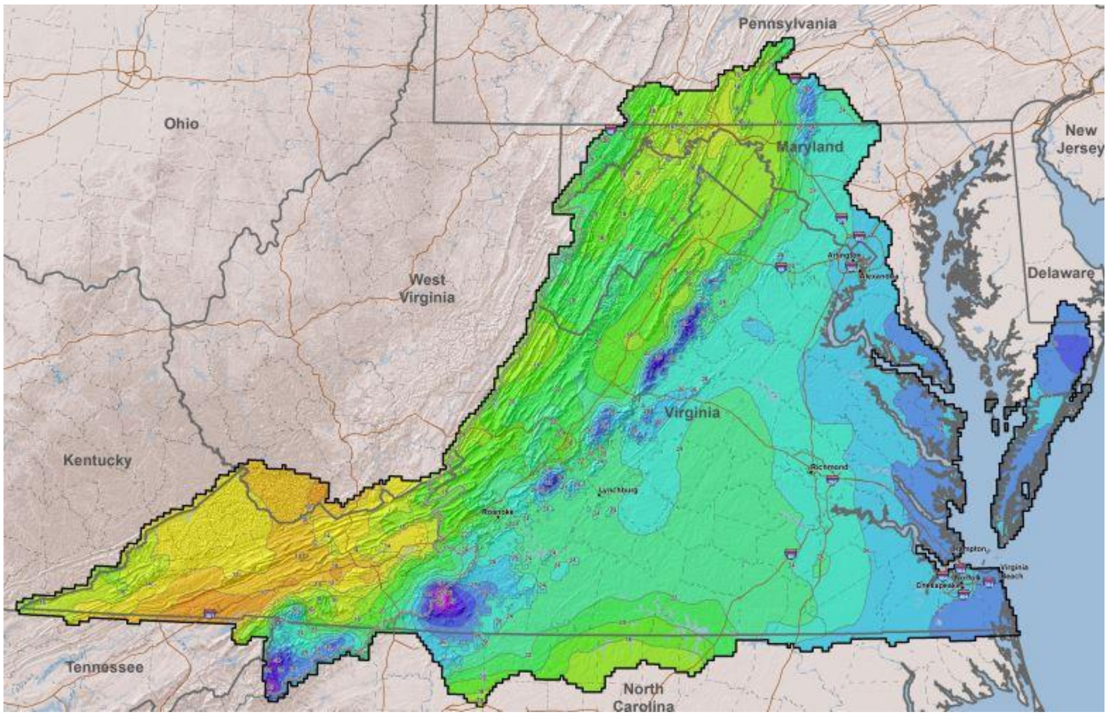
Probable Maximum Precipitation Study for Virginia



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November 2015

Notice

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Acknowledgements

The Virginia Department of Conservation and Recreation (Department) and the Virginia Soil and Water Conservation Board (Board) would like to express sincere appreciation and thanks for the hard work and dedication of the entire staff of Applied Weather Associates, LLC.

The Department and the Board would also like to acknowledge with much appreciation the review and feedback of the study's independent Technical Review Panel comprised of John Harrison, PE, Schnabel Engineering, Inc., Mathew Lyons, PE, USDA Natural Resources Conservation Service, Dr. Arthur Miller, AECOM, and Stephen Rich, CCM, Southeast Weather Consulting.

Furthermore, the Department and the Board would like to express gratitude and thanks to staff members from the Federal Energy Regulatory Commission, Ken Fearon, Elise Dombeck, and Kevin Griebenow.

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Executive Summary

During the 2014 Virginia General Assembly Session, the legislature passed (House Bill 1006 and Senate Bill 582) and the Governor approved on April 1, 2014 (Chapters 475 and 489 of the 2014 Virginia Acts of Assembly), legislation that authorized a new Virginia Probable Maximum Precipitation Study to be completed by December 1, 2015. The legislation directed "*[t]hat the Department of Conservation and Recreation, on behalf of the Virginia Soil and Water Conservation Board, shall utilize a storm-based approach in order to derive the Probable Maximum Precipitation (PMP) for locations within or affecting the Commonwealth. The PMP revisions shall be based on accepted storm evaluation techniques and take into account such factors as basin characteristics that affect the occurrence and location of storms and precipitation, regional and basin terrain influences, available atmospheric moisture, and seasonality of storm types. The results shall be considered by the Virginia Soil and Water Conservation Board in its decision to authorize the use of the updated PMP values in Probable Maximum Flood calculations, thus replacing the current PMP values.*"

In accordance with this legislative direction, Applied Weather Associates (AWA), on behalf of the Virginia Soil and Water Conservation Board, completed a statewide Probable Maximum Precipitation (PMP) study for Virginia. A Technical Review Board of experts, with additional ad-hoc participation by cooperating state and federal agencies, was established by the Department to provide advice and expertise throughout the development of the study. The Technical Review Board met to review and discuss study progress and results in July and November of 2014 and April and October of 2015 and accepted AWA's estimates for probable maximum precipitation (PMP) for Virginia.

This study produced gridded PMP values for the project domain at a spatial resolution of approximately 2.5-square miles. Variations in topography, climate and storm types across the state were explicitly taken into account. A large set of storm data were analyzed for use in developing the PMP values. These values replace those provided in Hydrometeorological Reports (HMRs) 40, 51, 52, and 56 (1965, 1978, 1982, and 1986 respectively). The full PMP values for regions east of the Appalachian crest are valid from June through October. For areas west of the Appalachian crest, the seasonality is similar, except that 100% of PMP from the general storm type can occur from September 15 through May 15 and the local storm can occur as early as April 15. Results of this analysis reflects the most current practices used for defining PMP, including comprehensive storm analyses procedures, extensive use of geographical information systems (GIS), explicit quantification of orographic effects, updated maximum dew point climatologies for storm maximization and transposition, and an updated understanding of the weather and climate throughout the state.

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 in the last fifteen years. This was the storm-based approach and it follows the same general procedures used by the National Weather Service (NWS) in the development of the HMRs. The World Meteorological Organization (WMO) Manual on Estimation of PMP recommends this same approach. The storm based approach identified extreme rainfall events that have occurred in regions considered transpositionable to locations in Virginia. These are storms that had meteorological and topographical characteristics similar to extreme rainfall storms that could occur over any location within the project domain. Detailed storm analyses were completed for the largest of these rainfall events.

The data, assumptions, and analysis techniques used in this study have been reviewed and accepted by the Technical Review Board and the Virginia Department of Conservation and Recreation. Although this study produced deterministic values, it must be recognized that there is some subjectivity associated with the PMP development procedures. Examples of decisions where scientific judgment was involved include the determination of storm maximization factors and storm transposition limits. For areas where uncertainties in data analysis results were recognized, conservative assumptions were applied unless sufficient data existed to make a more informed decision. All data and information supporting decisions in the PMP development process have been documented so that results can be reproduced and verified.

Sixty-six rainfall events were identified as having similar characteristics to rainfall that could potentially control PMP values at various locations within the state. Several storm events had multiple Depth-Area-Duration (DAD) zones (also referred to as SPAS DAD zones) that were used in the PMP determination process. A total of 78 storm DAD centers were used in the development of PMP for the state. This includes 31 tropical storm rainfall centers, 25 general storm rainfall centers, and 23 local storm rainfall centers. Note, the storm centered near Big Meadows, VA during October 1942 exhibited characteristics of both local and general storm types and was therefore evaluated as part of both the general and local storm PMP determination process.

Seventy-eight individual storm centers were 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 (NWS) 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 and moisture transposition adjustments (e.g. HMR 51 Section 2.3 and Section 2.4). New techniques and new datasets were used in other procedures to increase accuracy and reliability when justified by utilizing advancements in technology and meteorological understanding, while adhering to the basic approach used in the HMRs and in the WMO Manual. Updated precipitation frequency analyses data available from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 were used for this study. These were used to calculate the Orographic Transposition Factors (OTFs) for each storm. The OTF procedure provided explicit evaluations of the effects of terrain on rainfall and corrected for the lack of analysis in the "stippled' region of HMR 51. The OTF procedure, through its correlation process, provided quantifiable and reproducible analyses of the effects of terrain on rainfall. Results of these three factors (in-place maximization, moisture transposition, and orographic transposition) were applied for each storm at each of the grid points for each of the area sizes and durations used in this study to define the PMP values.

Maximization factors were computed for each of the analyzed storm events using updated dew point and sea surface temperature climatologies representing the maximum moisture equivalent to the 100-year recurrence interval for dew points or +2 sigma for sea surface temperatures that could have been associated with each rainfall event. The dew point climatology included the maximum average 6-, 12-, and 24-hour 100-year return frequency values, while the SST climatology provided the +2 sigma values. The most appropriate duration consistent with the duration of the storm rainfall was used. HYSPLIT model trajectories and NWS weather maps were used as guidance in identifying the storm representative moisture source region.

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

This represents the kind of summary information I believe would be valuable. Would like to see the results of Chapter 10/ Tables 10.8 and 10.9 captured in the summary.

When compared to previous PMP values provided in HMRs 40, 51, 52, and 56, the updated values from this study resulted in a wide range of reductions at most area sizes and durations, with some region resulting in minor increases. PMP values are highest near the coast and along the Blue Ridge. These regions have exhibited past extreme rainfall accumulations that are the result of both moisture availability and topographic enhancement. Regions along and near the coast are also affected by coastal convergence processes which act to enhance lift and provide an additional mechanism for enhanced rainfall production versus other locations in the study domain. Minimum values are seen in the most protected interior valleys and in the transition region of the Piedmont between the coast to the Blue Ridge. This is expected because of the lack decrease in moisture and reduced or negative orographic effects relative to other regions.

Commonwealth-wide it was found that on average, PMP values for local storms showed an 16% reduction at 6-hour 10-square miles and a 21% reduction at 12-hour 10-square miles. For the longer durations, larger area sizes, Commonwealth-wide reductions were 30% at 24-hour 200-square miles and 1000-square miles, and 25% at 72-hours 200-square miles and 1000-square miles. Tables E.1-E.3 provides the average percent difference (negative is a reduction) from HMR 51 across each of the transposition region analyzed. Upon adoption by the Virginia Soil and Water Conservation Board, impounding structure owners will have the opportunity to utilize this new data to review their spillway design capacity needs and determine rehabilitation requirements for their structures.

Table E.1 Local storm PMP percent difference from HMR 51 PMP at 6-hour and 12-hour 10-square miles. Grayed out rows represent regions where either tropical or general storm PMP values were controlling.

Local Storm 10 Sq Mi Average PMP						
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr
1 - Interior Valley	27.6	19.7	-28.7%	32.2	21.2	-34.3%
2 - Cumberland Plateau	28.7	19.2	-33.2%	33.8	21.5	-36.6%
3 - Great Valley	28.9	17.1	-40.7%	34.1	19.2	-43.9%
4 - Blue Ridge West	28.9	19.7	-31.8%	34.1	22.1	-35.5%
5 - Blue Ridge East	27.8	19.8	-28.8%	32.5	21.3	-34.5%
6 - Piedmont	28.5	26.1	-8.5%	33.7	29.0	-13.9%
7 - Coastal Plain	28.6	29.6	3.7%	33.8	33.1	-2.1%
Statewide Domain	**28.4**	**23.8**	**-16.2%**	**33.4**	**26.3**	**-21.4%**

Table E.2 Tropical storm PMP percent difference from HMR 51 PMP at 24-hour and 72-hour 200- and 1000-square miles. Grayed out rows represent regions where either tropical or general storm PMP values were controlling.

Tropical Storm 200 Sq Mi Average PMP						
Transposition Zone	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	26.5	16.7	-37.1%	31.5	19.3	-38.8%
2 - Cumberland Plateau	27.4	12.3	-54.9%	33.1	16.0	-51.7%
3 - Great Valley	27.8	10.8	-61.1%	33.6	14.0	-58.4%
4 - Blue Ridge West	28.1	19.2	-31.9%	33.8	21.0	-38.2%
5 - Blue Ridge East	26.7	20.0	-25.0%	31.7	22.1	-30.4%
6 - Piedmont	28.4	20.3	-28.5%	33.8	25.9	-23.3%
7 - Coastal Plain	29.3	22.9	-21.6%	34.7	29.1	-16.1%
Statewide Domain	**28.0**	**19.5**	**-30.3%**	**33.3**	**23.8**	**-28.7%**

Tropical Storm 1000 Sq Mi Average PMP						
Transposition Zone	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	21.2	12.0	-43.5%	25.0	14.8	-41.1%
2 - Cumberland Plateau	22.2	10.8	-51.2%	26.5	14.3	-46.0%
3 - Great Valley	22.8	9.5	-58.1%	27.1	12.5	-53.8%
4 - Blue Ridge West	23.1	13.9	-40.1%	27.3	18.0	-34.4%
5 - Blue Ridge East	21.3	14.5	-32.2%	25.2	18.3	-27.8%
6 - Piedmont	23.4	17.5	-24.7%	27.5	23.1	-15.5%
7 - Coastal Plain	24.3	19.7	-18.6%	28.6	26.1	-8.6%
Statewide Domain	**22.9**	**15.9**	**-30.5%**	**27.0**	**20.8**	**-23.3%**

Table E.3 General storm PMP percent difference from HMR 51 PMP at 24-hour and 72-hour 200- and 1000-square miles. Grayed out rows represent regions where either tropical or general storm PMP values were controlling.

General Storm 200 Sq Mi Average PMP						
Transposition Zone	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	26.5	14.3	-46.1%	31.5	14.9	-52.6%
2 - Cumberland Plateau	27.4	16.0	-41.5%	33.1	17.9	-46.0%
3 - Great Valley	27.8	13.7	-50.6%	33.6	16.1	-52.2%
4 - Blue Ridge West	28.1	16.2	-42.4%	33.8	18.9	-44.3%
5 - Blue Ridge East	26.7	14.9	-44.0%	31.7	15.8	-50.2%
6 - Piedmont	28.4	17.9	-37.0%	33.8	19.3	-42.8%
7 - Coastal Plain	29.3	17.6	-39.9%	34.7	21.3	-38.7%
Statewide Domain	**28.0**	**16.6**	**-40.9%**	**33.3**	**18.4**	**-44.9%**

General Storm 1000 Sq Mi Average PMP						
Transposition Zone	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	21.2	12.5	-41.1%	25.0	14.2	-43.2%
2 - Cumberland Plateau	22.2	13.3	-40.0%	26.5	14.9	-44.0%
3 - Great Valley	22.8	11.4	-50.0%	27.1	14.3	-47.1%
4 - Blue Ridge West	23.1	13.7	-40.9%	27.3	17.4	-36.8%
5 - Blue Ridge East	21.3	13.1	-38.9%	25.2	14.9	-41.0%
6 - Piedmont	23.4	15.6	-32.9%	27.5	17.8	-35.1%
7 - Coastal Plain	24.3	15.7	-35.3%	28.6	18.3	-35.9%
Statewide Domain	**22.9**	**14.4**	**-36.9%**	**27.0**	**16.7**	**-38.2%**

Glossary

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

Adiabatic: Referring to the process described by adiabat.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 kilometer 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 (LLJ): 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 (MCC): 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 (MCS): 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.

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

Orographic Effect: When air is lifted as it moves over topography. As the air rises and cools, orographic clouds form and serve as the source enhanced precipitation, generally on the upwind side of the topography. The opposite effect occurs as the air descends on the leeward side, resulting in drying of the air and less precipitation.

Orographic Transposition Factor (OTF): A factor representing the comparison of precipitation frequency relationships between two locations that quantifies how rainfall is affected by topography. It is assumed the precipitation frequency data are a combination of what rainfall would have accumulated with any topographic affect and what accumulated because of the topography at the location and upwind of the location.

Polar front: A semi-permanent, semi-continuous front that separates tropical air masses from polar air masses.

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 (PMF): 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 (PMP): 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.

Rain shadow: The region, on the lee side of a mountain or mountain range, where the precipitation is noticeably less than on the windward side.

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

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

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

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

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

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

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.

Acronyms and Abbreviations used in the report

AMS: Annual maximum series

AWA: Applied Weather Associates

DAD: Depth-Area-Duration

DCR: Virginia Department of Conservation and Recreation

dd: decimal degrees

EPRI: *Electric Power Research Institute*

F: *Fahrenheit*

GCS: Geographical coordinate system

GIS: Geographic Information System

GRASS: Geographic Resource Analysis Support System

HMR: Hydrometeorological Report

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory Model

IPMF: In-place Maximization Factor

LLJ: Low-level jet

mb: millibar

MCS: Mesoscale Convective System

MTF: Moisture Transposition Factor

NCDC: National Climatic Data Center

NCEP: National Centers for Environmental Prediction

NEXRAD: Next Generation Radar

NOAA: National Oceanic and Atmospheric Administration

NWS: National Weather Service

NRCS: Natural Resources Conservation Service

OTF: Orographic Transposition Factor

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

PRISM: Parameter-elevation Relationships on Independent Slopes

PW: Precipitable Water

SPAS: Storm Precipitation and Analysis System

SST: Sea surface temperature

TAF: Total Adjustment Factor

USACE: US Army Corps of Engineers

USBR: Bureau of Reclamation

USGS: United States Geological Survey

WMO: World Meteorological Organization

1. Introduction

This study provides Probable Maximum Precipitation (PMP) values for any drainage basin within Virginia, including regions adjacent to the state that also provide runoff into drainage basins within Virginia. The full PMP values for regions east of the Appalachian crest are valid from June through October. For areas west of the Appalachian crest, the seasonality is similar, except that 100% of PMP from the general storm type can occur from September 15 through May 15 and the local storm can occur as early as April 15. The PMP values are used in the computation of the Probable Maximum Flood (PMF). PMP values provided in this study supersede PMP values from Hydrometeorological Reports (HMRs) 40 (Goodyear and Riedel, 1965), HMR 51 (Schreiner and Riedel, 1978), HMR 52 (Hansen et al., 1982), and HMR 56 (Zurndorfer et al., 1986).

PMP is a deterministic estimate of the theoretical maximum depth of precipitation that can occur over a specified area. Parameters to estimate PMP were developed using the storm based, deterministic approach as presented in the HMRs and subsequently refined in the numerous site-specific, statewide, and regional PMP studies completed since its publication in 1978.

Methods used to derive PMP values for this study included consideration of an adequate number of extreme rainfall events that have been appropriately adjusted to each grid point. This large number of storm events provided enough data from which to derive the PMP. The process of combining maximized storm events into one PMP design storm resulted in a reliable PMP estimation. During this calculation process, air masses that provide moisture to both the historic storm and the possible PMP storm were assumed to be saturated through the entire depth of the atmosphere and contain the maximum moisture possible based on the surface dew point or sea surface temperatures (SST). This saturation process used moist pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm. The method assumed that a sufficient period of record was available for rainfall observations and that at least a few storms which have been observed, attained or came close to attaining the maximum storm efficiency possible for converting atmospheric moisture to rainfall for regions with similar climates and topography. In addition, if surplus atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. Therefore, the ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water in the atmosphere associated with each storm.

Current understanding of meteorology does not support an explicit evaluation of storm efficiency for use in PMP evaluation. To compensate for this, the period of record was extended to include the entire historic record of rainfall data (nearly 200 years for this study), along with an extended geographic region from which to choose storms. Using the long period of record and the large geographic region, there should have been at least one storm with dynamics that approached the maximum efficiency for rainfall production used in the PMP development.

1.1 Background

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

The generalized PMP studies currently in use in the conterminous United States include HMRs 49 (1977) and 50 (1981) for the Colorado River and Great Basin drainage; HMRs 51 (1978), 52 (1982) and 53 (1980) for the U.S. east of the 105th meridian; HMR 55A (1988) for the area between the Continental Divide and the 103rd meridian; HMR 57 (1994) for the Columbia River Drainage; and HMRs 58 (1998) and 59 (1999) for California (Figure 1.1). In addition to these HMRs, numerous Technical Papers and Reports deal with specific subjects concerning precipitation (e.g. Technical Paper 1, 1946; Technical Paper 16, 1952; NOAA Tech. Report NWS 25, 1980; and NOAA Tech. Memorandum NWS HYDRO 40, 1984). Topics in these papers include maximum observed rainfall amounts for various return periods and specific storm studies. Climatological atlases (e.g. Technical Paper No. 40, 1961; NOAA Atlas 2, 1973; and NOAA Atlas 14, 2004-2015) are available for use in determining precipitation return periods. A number of site-specific, statewide, and regional studies (e.g. Tomlinson et al., 2002; Tomlinson et al., 2003; Tomlinson et al., 2008; Tomlinson et al., 2009; Tomlinson et al., 2010; Tomlinson et al., 2011; Kappel et al., 2012; Kappel et al., 2013; Tomlinson et al., 2013, Kappel et al., 2014, Kappel et al., 2015) 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 values 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 August of 2015. PMP results from this study provide values that replace those derived from HMRs 40, 51, 52, and 56.

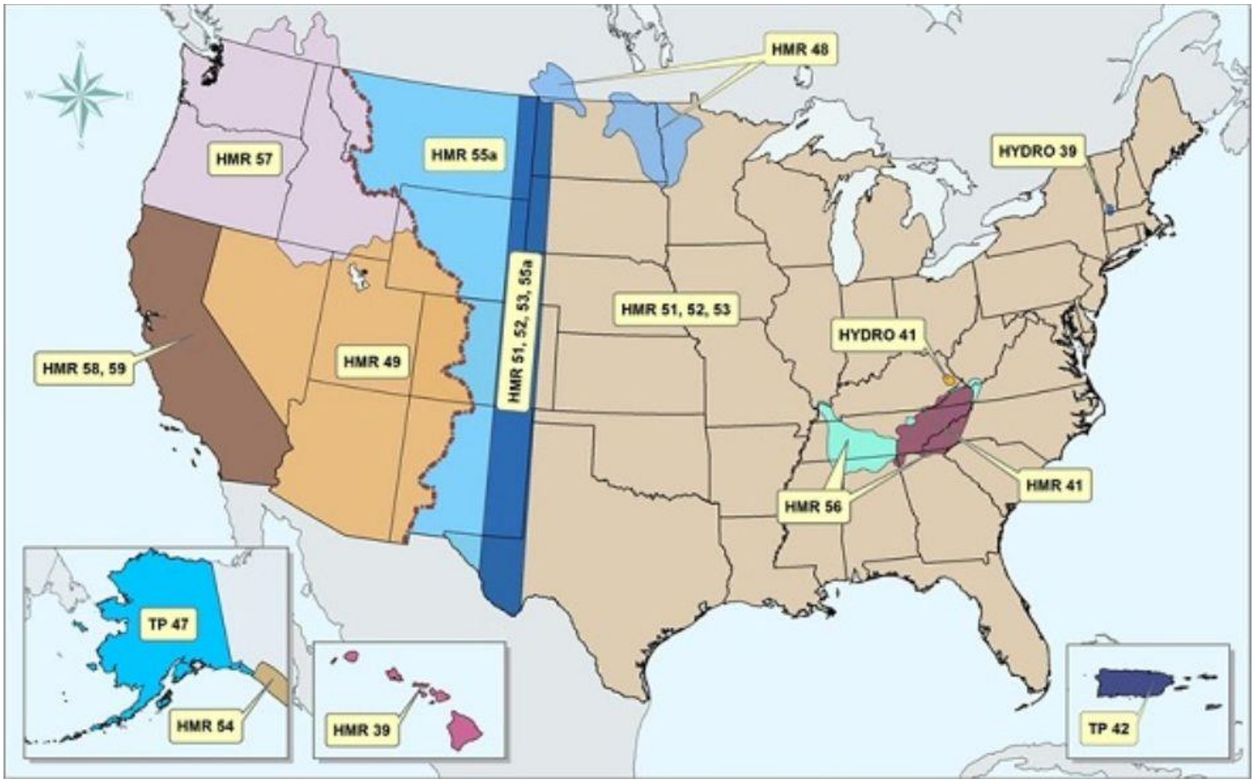

Figure 1.1 Hydrometeorological Report coverages across the United States

Virginia is included within the domain covered by HMR 40, HMR 51, HMR 52, and HMR 56. HMR 51 is the most relevant HMR for this study, covering the entire region. HMR 40 was explicitly developed for the Susquehanna River basin and provided storm information that was used in this analysis. HMR 52 provided background information on much of the storm data used for HMR 51, while HMR 56 was explicitly developed for the Tennessee Valley Authority (TVA) and overlaps the far southwestern region of Virginia. 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. This is especially true for basins that are located within the stippled regions (Figure 1.2). HMR 51 includes the statement "…we suggest that major projects within the stippled regions be considered on a case-by-case basis as the need arises." (HMR 51, p.3). 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.

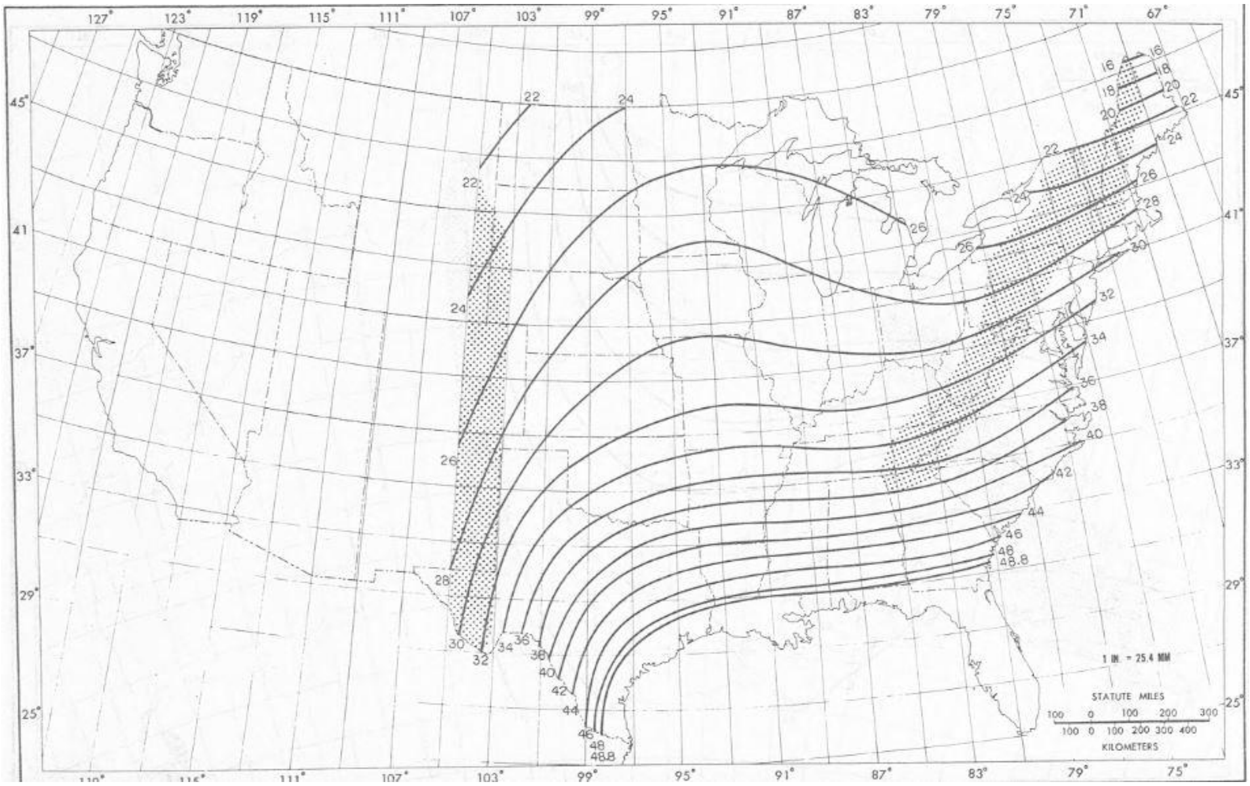

Figure 1.2 Example of HMR 51 72-hour 200-square mile PMP map showing the stippled regions (from Schreiner and Riedel, 1978).

Virginia contains many diverse regions as well (Figure 1.3). In Virginia, climate and terrain vary greatly, sometimes over short distances. Because of the distinctive climate regions and significant topography, the development of PMP values must account for the complexity of the meteorology and terrain throughout the state. Although the HMRs provided accurate 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 east of the Appalachian crest and mid 1980's west of the Appalachian crest, no process used to address orographic effects, inconsistent data and procedures used among the HMRs, 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.

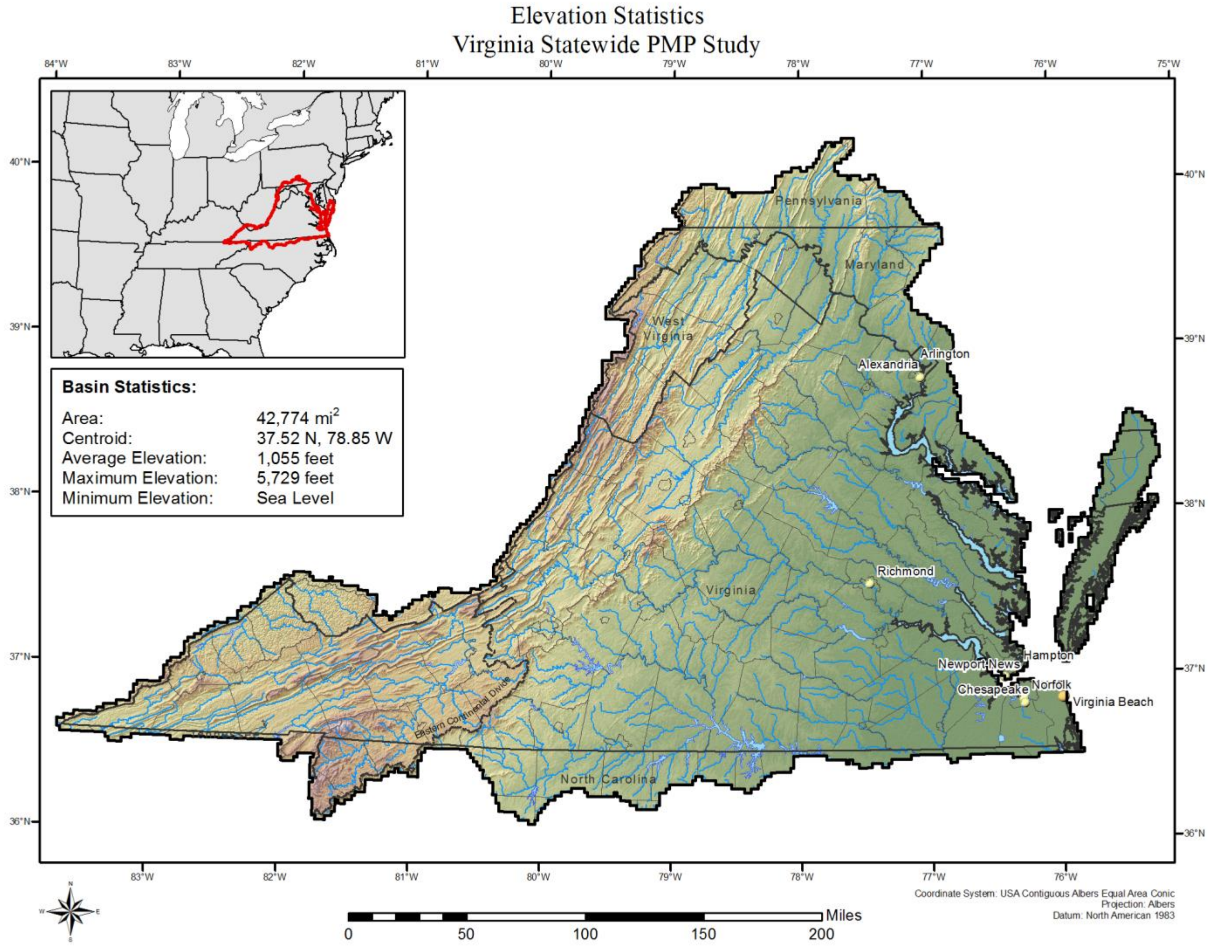

Figure 1.3 Virginia PMP project domain. The overall project domain extends beyond the state boundaries in some areas to ensure all drainage areas are included in the analysis.

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

Several PMP studies have been completed by AWA within the region covered by HMRs 51 and 56, which are directly relevant to Virginia (Figure 1.4). Each of these studies provided PMP values which updated those from HMR 51 and 56. These are examples of PMP studies that explicitly consider the meteorology and topography of the study location along with characteristics of historic extreme storms over climatically similar regions. Information, experience, and data from these PMP studies were utilized in this study. These included use of previously analyzed storm events using the SPAS program, previously derived storm lists, previously derived in-place storm maximization factors, climatologies, and explicit understanding of the meteorology of the region. In addition, comparisons to these previous studies provided sensitivity and context with results of this study. These regional and site-specific PMP studies received extensive review and were accepted by the appropriate regulatory agencies, including the Federal Energy Regulatory Commission (FERC), state dam safety regulators, and the Natural Resources Conservation Service (NRCS). Results have been used in computing the PMF for individual watersheds. This study followed the same procedures used in those studies to determine PMP values. These procedures, together with the Storm Precipitation Analysis System (SPAS) rainfall analyses (Parzybok and Tomlinson, 2006), were used to compute PMP values following standard procedures outlined in HMR 51.

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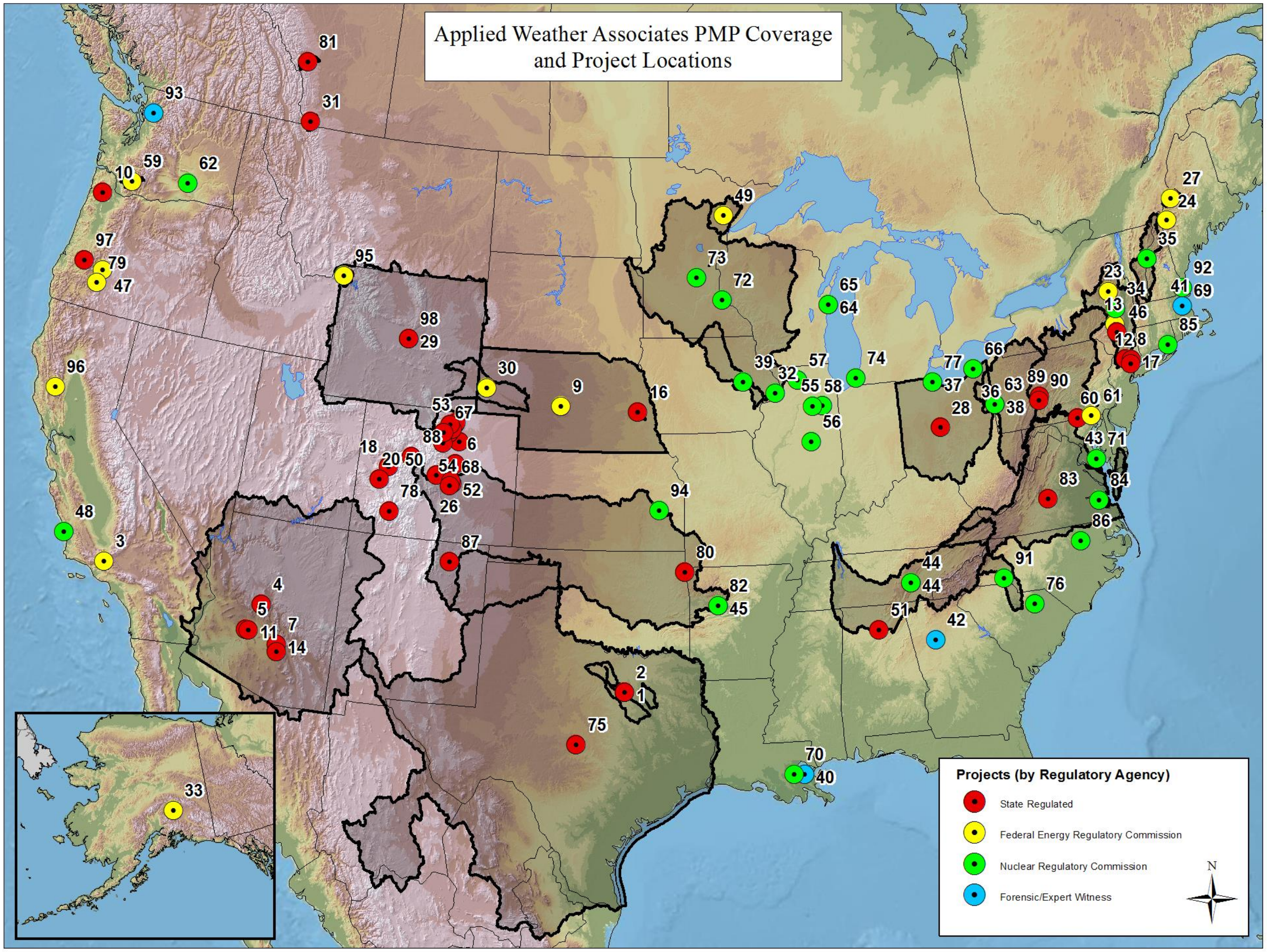

Figure 1.4 Locations of AWA PMP studies as of November 2015

1.2 Objective

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

1.3 Approach

The approach used in this study followed the procedures used in the development of the HMRs, with updated procedures used where appropriate. This includes updates AWA implemented in several recently completed PMP projects as well as updates developed during this study. These updated procedures were applied with a consideration for meteorology and terrain, and their interactions within Virginia. The weather and climate of the region are discussed in Section 2. Section 3 discusses the effects of topography on rainfall and PMP within Virginia. Sections 4 describes the development of the updated dew point and sea surface temperature (SST) climatologies. The initial step of identifying extreme storms and the development of the final list of storms used to derive PMP are in Section 5. Adjustments for storm maximization, storm transposition, and calculation of final PMP values are provided in Sections 6, 7, and 8 respectively. The process for extracting PMP for a drainage basin is discussed in Section 9. Discussions on sensitivities are provided in Section 10 and 11, and recommendations for application are presented in Section 12.

A goal of this study was to maintain as much consistency as possible with the general methods used in recent HMRs, the WMO manual for PMP (2009), and the previous PMP studies completed by AWA. Deviations were incorporated when justified by developments in meteorological analyses and available data. The approach identified major storms that occurred within the region. Each of the main storm types which produce extreme rainfall were identified and investigated. The main storm types include local storms, tropical storms, and general storms. The moisture content of each of these storms was maximized to provide worst-case rainfall estimation for each storm at the location where it occurred. Storms were then transpositioned to each grid point with similar topography and meteorological conditions. Adjustments were applied to each storm as it was transpositioned to each grid point to represent what the amount of rainfall that storm would have produced at the new location, 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 a product of the in-place maximization factor (IPMF), the moisture transposition factor (MTF), and the orographic transposition factor (OTF). Section 8 provides a more detailed discussion on this process and application.

$$\text{Total Adjustment Factor} = \text{IPMF} * \text{MTF} * \text{OTF} \qquad \text{Equation 1.1}$$

Advanced computer-based technologies, Weather Service Radar WSR-88D NEXt generation RADar (NEXRAD), and SPAS were used in the storm analyses along with new meteorological data sources. New technology such as HYSPLIT model trajectories and data were incorporated into the study when they provided improved reliability, while maintaining as much consistency as possible with previous studies.

For some applications such as storm maximization, storm transpositioning, defining PMP by storm type, and combining storms to create a PMP design storm, this study applied standard methods presented in previous publications (e.g. WMO Operational Hydrology Reports, 1986, 2009), while for other applications, new procedures were developed. Moisture analyses have historically used monthly maximum 12-hour persisting dew point values. For this project, an updated maximum average dew point climatology developed in previous studies for the 6-, 12-, and 24-hour duration periods was used to better represent the atmospheric moisture for rainfall durations associated with the different storm types that affect Virginia. This updated dew point climatology provided 100-year recurrence interval return frequency values for 3-, 6-, 12-, and 24-hour duration periods. These recurrence interval durations better represent available atmospheric moisture used to maximize individual storms versus the persisting dew point process employed in the HMRs. The updated dew point climatology values replaced the 12-hour maximum persisting dew point values used in the HMRs. The resulting storm representative dew point values better represent the available atmospheric moisture that actually contributed to each storm's rainfall production. The maximum dew point climatologies used the most up-to-date periods of record, adding over 40 years of data to the datasets used in previous climatologies.

In addition to the updated dew point climatologies, SST climatologies were used to maximize storms whose moisture source region originated from the Atlantic Ocean. This provides a significant improvement from HMR 51 which did not have a process to quantify this moisture source in the in-place maximization process. The SST climatology developed replaced the Marine Climate Atlas of the World (U.S. Navy, 1981) that was used in the HMRs. This updated climatology dataset included monthly mean and 2-sigma maps for the entire Gulf of Mexico and the western Atlantic Ocean basin (Kent et al., 2007; Reynolds et al., 2007; and Worley et al., 2005). In conjunction with the climatology maps, daily SST maps based on ship and buoy reports as well as satellite data (after 1979) were produced and used in deriving the storm representative SST values for each storm event where the moisture source originated over water. The use of SST climatology as a surrogate to maximize storms was employed consistently starting with HMR 57 (Section 4.3, Hansen et al., 1994).

A reanalysis of transposition limits was completed that explicitly evaluated the effects of coastal convergence, topographical effects on storm structure, and moisture availability to explicitly evaluate which storms were transpositionable to any location within the domain. Extensive discussions with the study participants defined which storms would ultimately be used for PMP development. This re-analysis of the transposition limits provided precise guidance and constraints on the regions of influence for individual storms on a site-specific basis.

Environmental Systems Research Institute's ESRI ArcGIS Desktop GIS software was extensively used to evaluate topography and climatological datasets; analyze spatial relationships; store, organize, and process the large amounts of spatial data; design, implement, and execute the PMP database; and to provide visualization and mapping support throughout the process. SPAS used gridded storm analysis techniques to provide both spatial and temporal analyses for extreme rainfall storm events (see Appendix G for a complete description of SPAS).

1.4 PMP Analysis Domain

The project domain was defined to cover the entire State of Virginia as well as watersheds that extended beyond state boundaries. This study allows for gridded PMP values to be determined for each grid cell within the project domain. The full PMP analysis domain is shown in Figure 1.5. Discussions with the Virginia Department of Conservation and Recreation (DCR), the Federal Energy Regulatory Commission (FERC), Natural Resources Conservation Service (NRCS), and Review Board members were conducted to refine the analysis region beyond state boundaries to fully incorporate all potential sites that may affect Virginia.

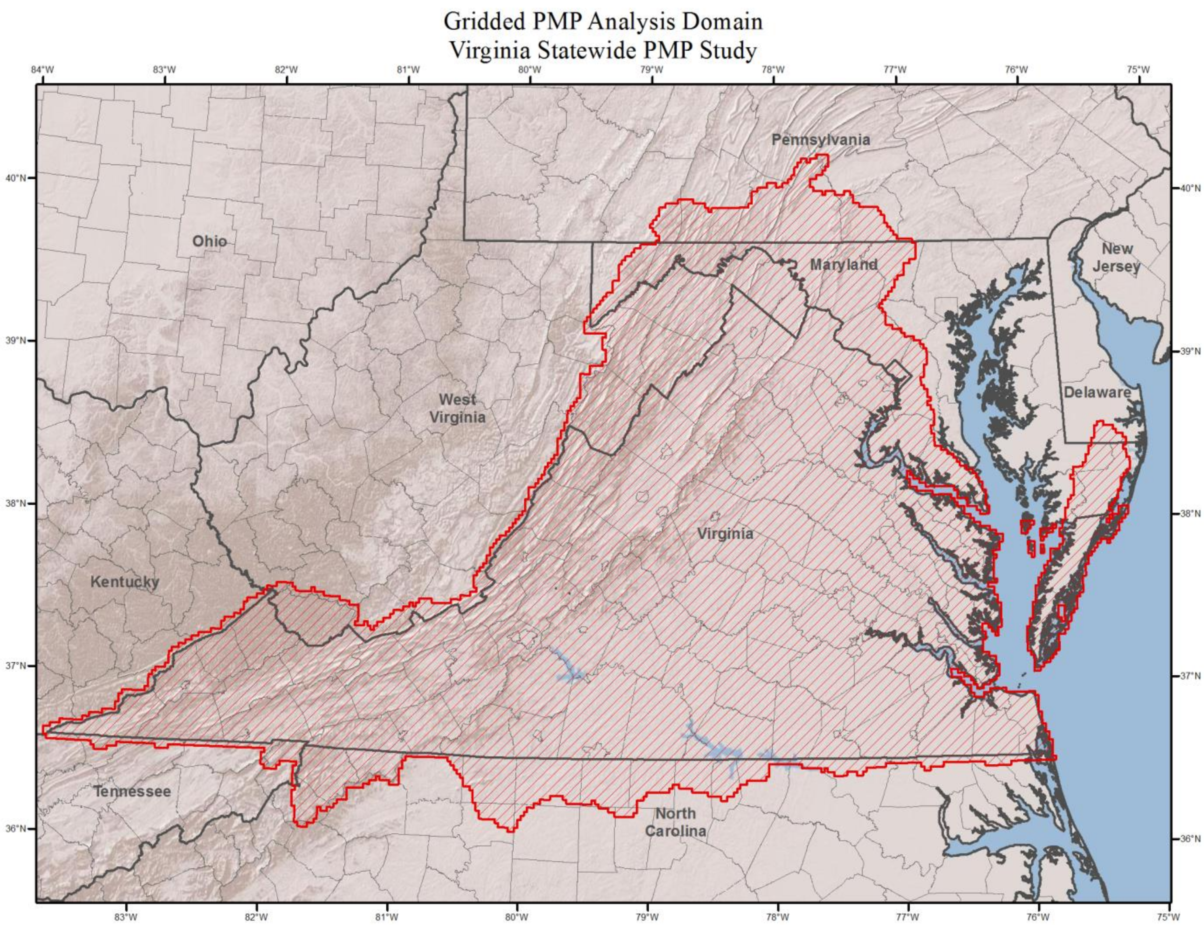

Figure 1.5 PMP analysis project domain

1.5 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 24,372 grid cells with centroids within the domain shown in Figure 1.5. Each grid cell has an approximate area of 2.2-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 38° N and 78° W with the adjacent grid point to the west at 38° N and 78.025° W. As an example, the PMP analysis grid over the North Anna drainage basin is shown in Figure 1.6.

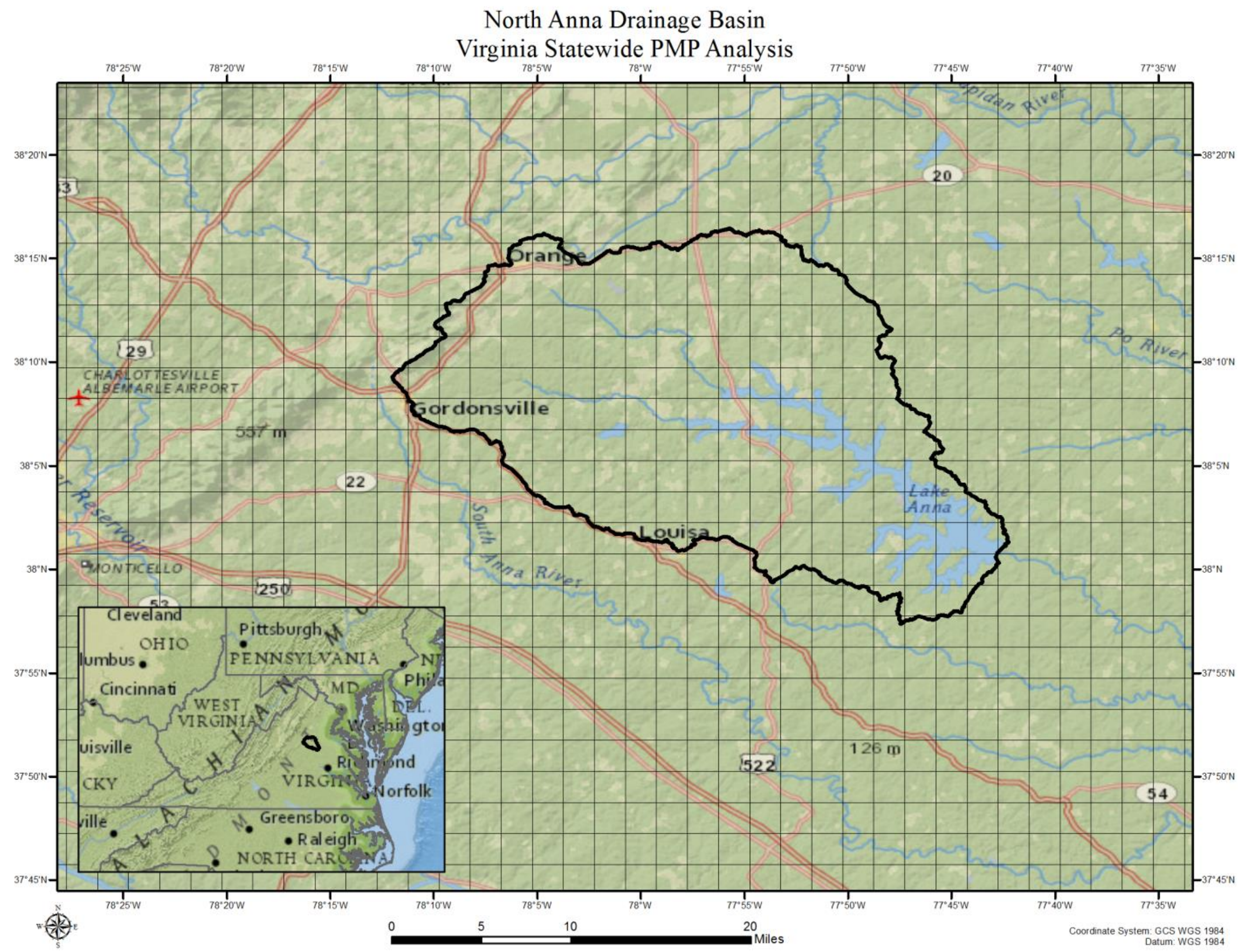

Figure 1.6 PMP analysis grid placement over the North Anna basin

2. Weather and Climate of the Region

Mountain topography and ocean currents create unique weather patterns and climate zones across much of the eastern United States (Figure 2.1). The change in terrain elevation helps to create a wide variety of climate patterns. The interaction between the Appalachian Mountains and the intervening lowlands has an effect on the final amounts of moisture available for precipitation production over the region as well as the spatial rainfall pattern of individual storms. The elevated mountainous areas act to enhance/decrease rainfall production because of the effects of the underlying topography, referred to as orographic effects. Rain accumulates with higher intensity and with higher frequency on upwind elevated upslope regions than on surrounding lower elevations or rain shadowed regions (Gelber, 1992; Thaler, 1996).

The relatively high elevations of the upper portion of the basin together with its access to moisture from the Atlantic Ocean combined with a location within the general storm track contribute to an active weather pattern over the basin. The latitude extent of the region analyzed, between 36° and 40°, frequently places the region in the path of the polar jet stream boundary, allowing fronts and areas of low pressure to traverse the region frequently. Storms originating in the Great Plains, Gulf of Mexico, and Atlantic Ocean can produce significant rainfall over different parts of the overall domain.

The region affecting areas west of the Appalachian crest is influenced by several factors that can potentially contribute to extreme rainfall. First is the proximity of the region to the Gulf of Mexico and the fact that no intervening mountain barriers prevent moisture from moving north out of the Gulf of Mexico into the majority of the domain (Figure 2.2). This allows high amounts of moisture to move directly into the region. The limiting factor is the duration that these high levels of atmospheric moisture are able to feed into storms in the region. More atmospheric moisture is available over the more southern and western regions compared with the northern and eastern portions of the basin. Because of the movement and strength of the upper level winds in the region, storm patterns generally do not stay fixed over any location for long periods. Therefore, the synoptic situations which produce high levels of atmospheric moisture moving into the region, most often from the Gulf of Mexico, are generally transient and limit the magnitude of rainfall. However, PMP-type rainfall occurs during situations where the storm movement is blocked or slow and allowed to concentrate heavy rainfall for extended durations over the same region. In addition, topography plays a significant role in the spatial distribution of rainfall, as well as the magnitude of rainfall. Higher elevations generally act to enhance rainfall production and therefore exhibit higher rainfall values. Conversely, sheltered valleys and regions in general downwind locations (eastern and northern sides of major barriers) exhibit lower rainfall values.

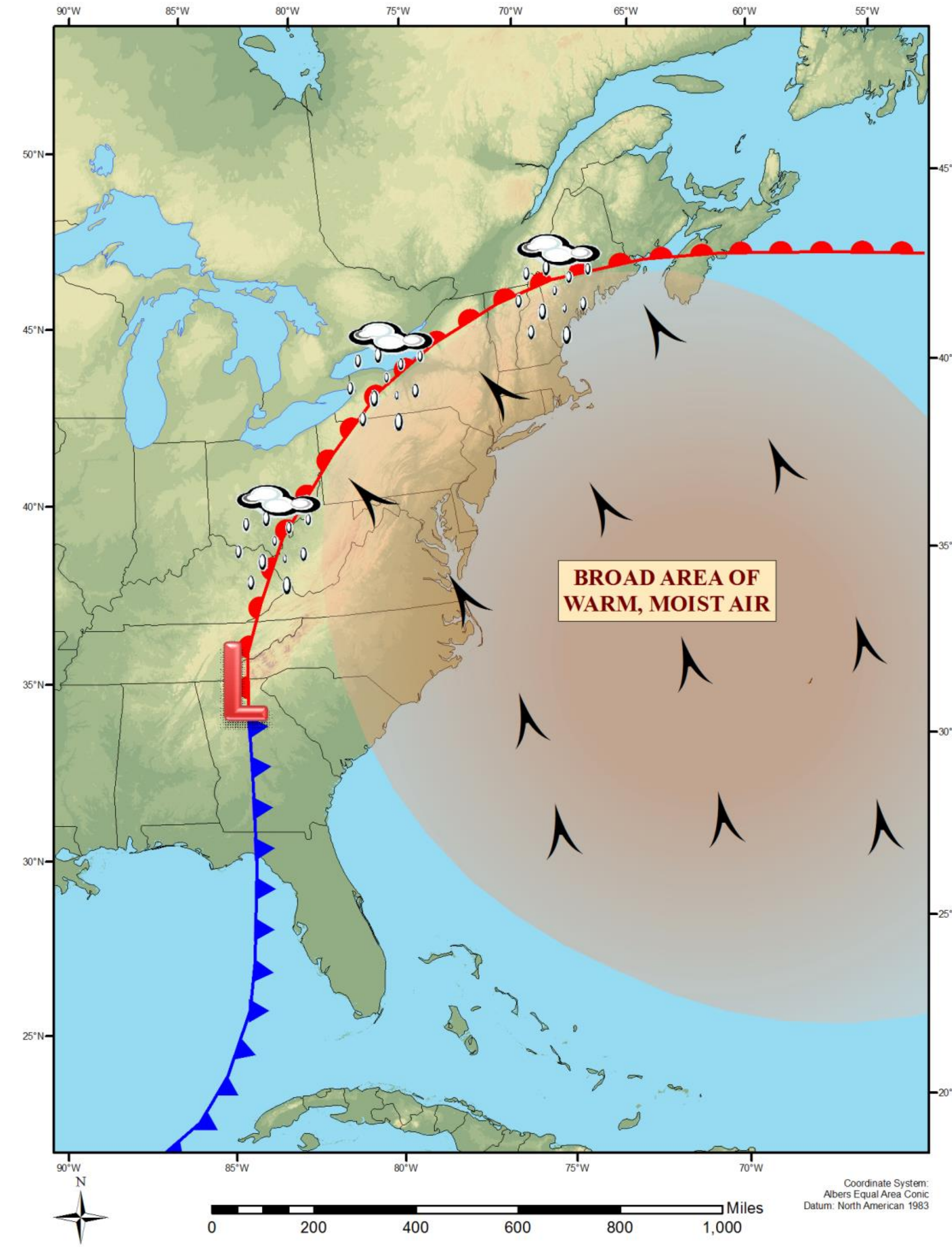

Figure 2.1 Synoptic weather features associated with moisture from the Atlantic Ocean

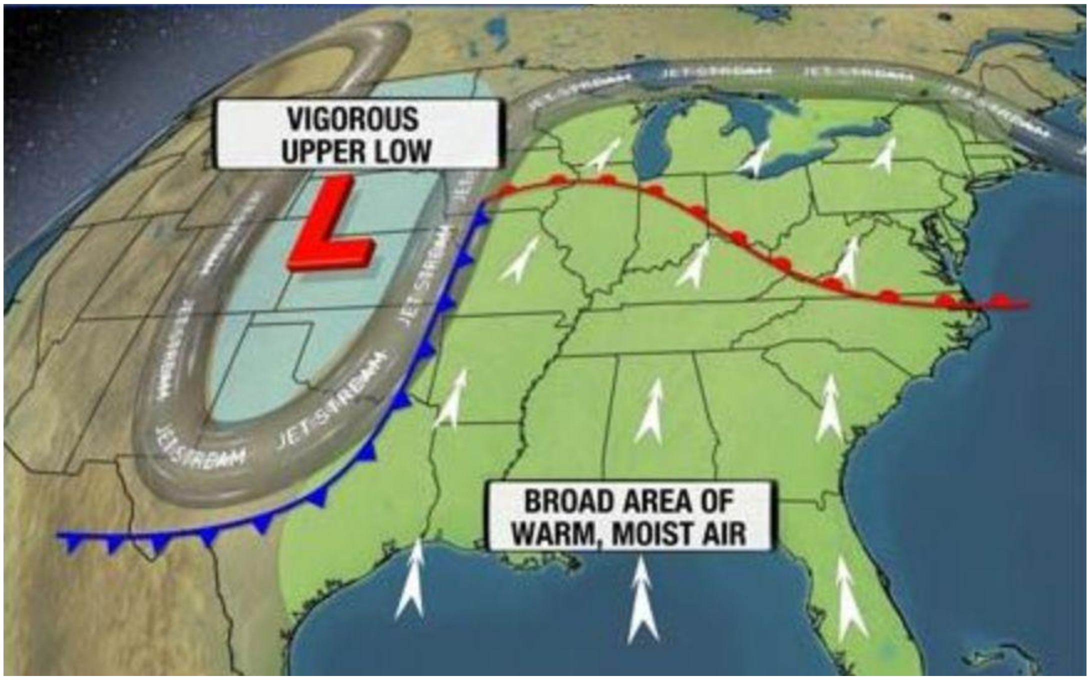

Figure 2.2 Locations of surface features associated with moisture advection from the Gulf of Mexico into Virginia and surrounding regions

The lift required to convert atmospheric moisture into rainfall on the ground is provided in several ways in and around the region. Synoptic storm dynamics are very effective in converting atmospheric moisture into rainfall. These are most often associated with fronts (boundaries between two different air masses) which affect the region. Fronts can be a focusing mechanism providing upward motion in the atmosphere resulting in heavy rainfall production. In some instances the pattern can become blocked causing these fronts to stall or move very slowly across the region. This pattern allows heavy rainfall to continue for several days in the same general area, causing extreme and/or widespread flooding.

Another mechanism which creates lift in the region is heating of the lower atmosphere by solar radiation, conduction, and convection. This creates warmer air below colder air resulting in atmospheric instability and leads to rising motions called convection. In unique circumstances, the instability and moisture levels in the atmosphere can reach very high and unstable levels, and can potentially stay over the same region for an extended period of time. This can lead to intense thunderstorms and very heavy rainfall.

A final mechanism for heavy rainfall is associated with remnant tropical systems which affect portions of the domain from summer to early fall. The lift associated with such storms is a combination of convective process and topographic lift.

Each of these scenarios can be enhanced or reduced by the effects of topography. More details on the PMP storm types which produce PMP level rainfalls in and around the region are given in Section 2.2.

2.1 Air Mass Source Regions

The main air mass types that affect the weather and climate of the region leading to heavy rainfall events are maritime tropical (mT) and maritime polar (mP), although other air mass types affect different parts of the domain throughout different times of the year (Figure 2.3). Often, both the mT and mP air masses affect the region at the same time, providing a large contrast in temperatures and moisture content and setting the stage for extreme precipitation. The situation is often exacerbated when the front between the two air masses stalls over the region for an extended period and/or is augmented by tropical moisture originating from the Gulf of Mexico and/or Atlantic Ocean. The mP air mass originates in the Gulf of St. Lawrence and Labrador Sea. This air mass is accompanied by strong winds from the east and northeast and has high levels of atmospheric moisture, especially in the lower levels of the atmosphere. Fog, low clouds, and steady rainfall along with cooler temperatures are signature features of this air mass. Heavy rainfall can result when this air mass interacts with an approaching low pressure system from the west/northwest. Along frontal boundaries, strong thunderstorms and heavy rain can develop, and are often enhanced by topographic features in the region. The mT air mass common to the region originates from the Gulf of Mexico and Gulf Stream regions of the Atlantic Ocean and contains copious amounts of atmospheric moisture in a conditionally unstable atmosphere. These air masses are most directly responsible for producing heavy rainfall in the region, especially when this air mass interacts with a frontal boundary in the area and/or is lifted by underlying terrain.

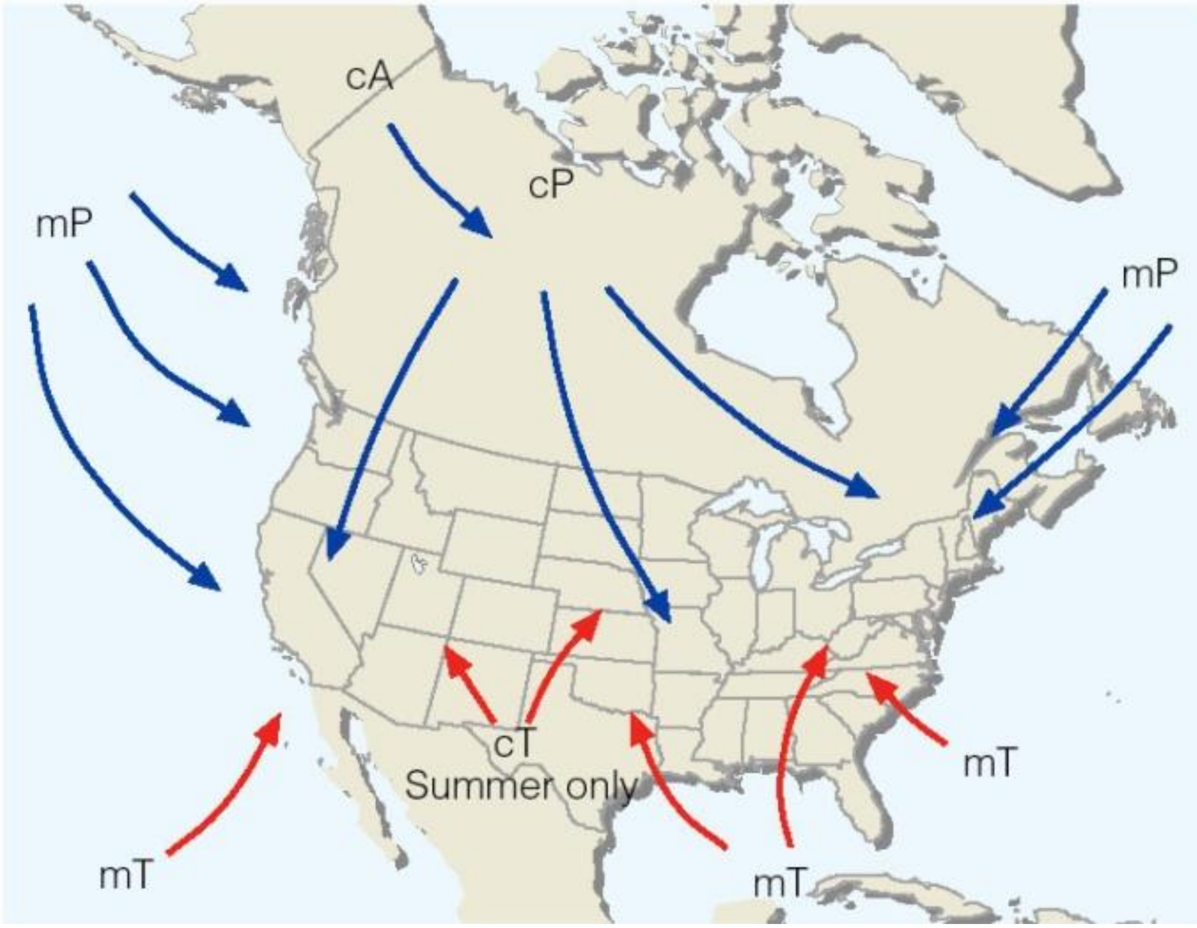

Figure 2.3 Air mass source regions affecting the Virginia basin (Ahrens, 2007)

2.2 PMP Storm Types

The region surrounding and including Virginia has an active and varied weather regime throughout the year. Consequently, light to moderate rainfall events of both short and long durations are common. The largest amount of low-level moisture available for precipitation over the region comes from the Atlantic Ocean east of the Appalachian crest and from the Gulf of Mexico west of the Appalachian crest. The major types of extreme precipitation events in the region are produced by thunderstorms (short durations and small area sizes), synoptic events/fronts (large area sizes and longer durations), and/or remnant tropical systems.

2.2.1 General Storms

The polar front, which separates cool, dry Canadian air to the north from warm, moist air to the south, is often a preferred location of heavy rainfall over large areas and for long durations in the region. These fronts provide energetic storm dynamics to the atmosphere as fronts move through the region. Frontal systems are strongest and most active over the region from late fall through the middle of spring.

A common type of storm occurrence with the polar front in the region is an overrunning event. Frontal overrunning occurs when warm, humid air, carried northward around the western edge of the Bermuda High circulation in the Atlantic Ocean, encounters the frontal zone and is forced to rise over the cooler, drier air mass at the surface. This forced ascent condenses moisture in the air mass creating clouds and precipitation, while releasing latent heat. Widespread rainfall for long durations is often produced, but can also enhance convection. Air that arrives at the frontal boundary is conditionally unstable, where the lower layers are much warmer and more humid than the air above. When this conditionally unstable air mass is forced to rise at the frontal boundary, the air mass begins to release energy creating more instability that results in further uplift. This forced ascent over the polar front initiates the lifting of the warm air mass and release of its energy.

A stationary polar front located in the region will often provide the mechanism necessary for this warm, humid air mass to release its convective potential. When this occurs, rainfall is produced, sometimes associated with pockets of convection and extremely heavy rainfall. Pockets of heavy rain are usually associated with a minor wave riding along the frontal boundary, called a shortwave. These are not strong enough to move the overall large-scale pattern, but enhance storm dynamics and energy available for producing greater precipitation. These storm environments can be enhanced when interacting with upslope topography and depleted when interacting with downsloping/protected valleys.

This type of storm environment (synoptic frontal) will usually not produce the highest rainfall rates over short durations, but instead leads to flooding situations as moderate to heavy rain continues over the same regions for an extended period of time. This storm type is most important for PMP depths in regions west of the Appalachian crest.

2.2.2 Tropical Storms

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

These types of storms require warm water and proper atmospheric conditions to be prevalent over the Gulf of Mexico and Atlantic Ocean, and therefore generally form from late June through early November, with August through October being the most common period. This storm type is most important for PMP depths in all regions east of the Appalachian crest for durations greater than 6 hours and area sizes larger than 100-square miles.

2.2.3 Hybrid Storms

It is not unusual for the largest rainfalls that affect the region to incorporate characteristics of both the synoptic and remnant tropical storm types. A common scenario includes a frontal boundary stalled over the region that becomes a focusing mechanism as tropical moisture moves north or northwest into the region from the Gulf of Mexico and/or Atlantic Ocean. The energy associated with the high levels of moisture and latent heat release is then focused along the front and the rainfall production mechanisms are enhanced during the transition phase from a pure tropical system to an extra-tropical (synoptic) system. This can cause widespread heavy rainfall or local bursts of intense convection (e.g. Tyro, VA August, 1969). If this scenario is positioned over the same region for an extended period, very high rainfall amounts can result. Occasionally, a tropical storm that is a considerable distance offshore over the Gulf Stream in the Atlantic Ocean will transport large amounts of atmospheric moisture northward into a mid-latitude cyclonic storm system, enabling it to produce extreme rainfall amounts over this region (e.g. Big Meadows, VA October, 1942).

2.2.4 Local Storms (Thunderstorms and Mesoscale Convective Systems)

Local storms and Mesoscale Convective Systems (MCSs) are capable of producing extreme amounts of precipitation for short durations and over small area sizes, generally 12 hours or less over area sizes of 500-square miles or less. The current understanding of MCS type storms has progressed tremendously with the advent of satellite technology in the 1970s and early 1980s. The name MCS was first applied in the late 1970s to these type of "flood producing," strong thunderstorm complexes (Maddox, 1980). Mesoscale convective systems are so named because the rainfall pattern they produce are small in areal extent (10s to 100s of square miles), whereas synoptic storm events are 100s to 1000s of square miles.

Mesoscale convective systems are included in the more general definition of Mesoscale Convective Complexes (MCCs), which include a wider variety of mesoscale sized storm systems such as squall lines, tropical cyclones, and MCSs that do not fit the strict definition of size, duration, and/or appearance on satellite imagery. Climatologically, MCSs primarily form during the warm season months of April through October, but have been known to occur in any month of the year.

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 MCCs or MCSs. However, this nomenclature had not yet been introduced into the scientific literature, nor were the events fully understood.

For regions west of the Appalachian crest, a typical MCS 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 storms begins to form a mesoscale high pressure area. This mesoscale high moves along with the area of thunderstorms. During nighttime hours, the MCS undergoes rapid development as it encounters increasingly warm and humid air from the Gulf of Mexico, usually associated with the low-level jet (LLJ) 3,000-5,000 feet above the ground. 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 MCS 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.

For regions east of the Appalachian crest, this storm type is not a strict MCS, but instead a MCC which includes interaction with a front or remnant tropical moisture (Letkewitcz and Parker, 2010). Examples of this situation would be Hurricane Irene remnants during August 2011. These are very important storms for determining PMP values for small area sizes and short durations.

3. Topographic Effects on PMP Rainfall

The terrain within the state of Virginia and the domain analyzed varies significantly, often over relatively short distances (Figure 3.1), particularly in Blue Ridge and Appalachian Mountain regions (Figure 3.2). Elevations vary from sea level along the Atlantic coastline to over 5,500 feet along the highest peaks of the Appalachian Mountains. When elevated terrain features are upwind of a drainage basin, depletion of low level atmospheric moisture available to storms over the basin can occur. Conversely, when incoming air is forced to rise as it encounters elevated terrain, release of conditional instability can occur more effectively and enhance the conversion of moisture in the air to precipitation. These interactions must be taken into account in the PMP determination procedure, explicitly in the storm adjustment process.

To account for the enhancements and reductions of precipitation by terrain features (called orographic effects), explicit evaluations were performed using precipitation frequency climatologies. These included NOAA Atlas 14, Volume 2 (Bonnin et al., 2004), NOAA Atlas 14, Volume 8 (Perica et al., 2013), NOAA Atlas 14, Volume 9 (Perica et al., 2013), NOAA Atlas 14, Volume 10 (Perica et al., 2015), and the Texas precipitation frequency climatologies developed as part of the ongoing Texas statewide PMP study. These climatologies were used to derive the Orographic Transposition Factors (OTFs). This approach is similar to that used in HMRs 55A, 57 and 59 that used the Storm Separation Method (SSM) to quantify orographic effects in topographically significant regions. The assumption and use of precipitation frequency climatologies to quantify the effects of terrain between two locations also follows the guidance provided in the WMO PMP manuals (e.g. Section 3.1.4, WMO, 2009). However, in contrast to the SSM methodology, the OTF procedure is significantly more objective and reproducible. In Appendix I, a detailed example of the subjectivity and issues associated with the SSM is provided. In Appendix I, AWA tried to replicate the SSM process and data using information provided in HMRs 55A, 57, and 59. The results of that analysis explicitly showed that the SSM method is not reproducible and highly subjective.

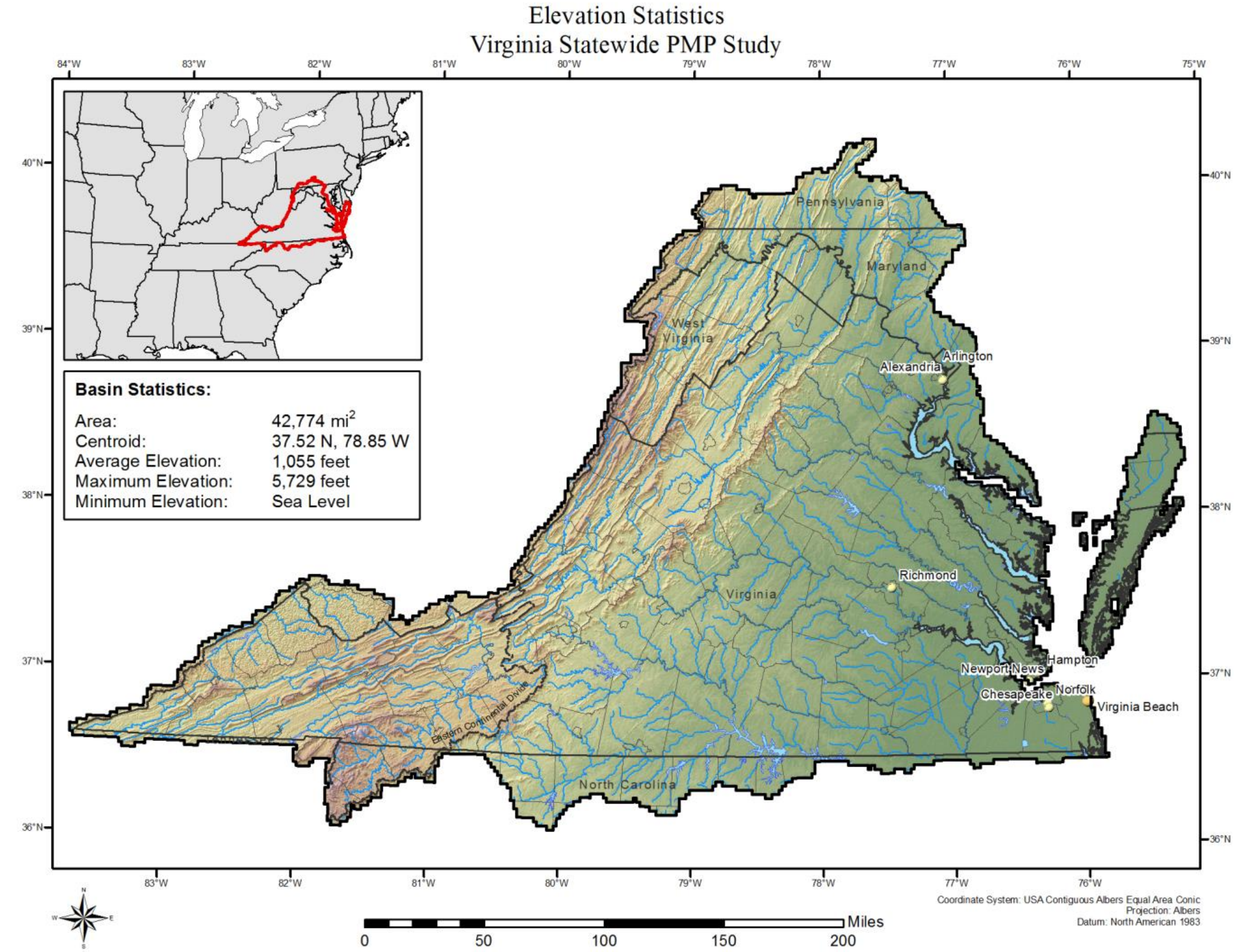

Figure 3.1 Topography across the analysis domain

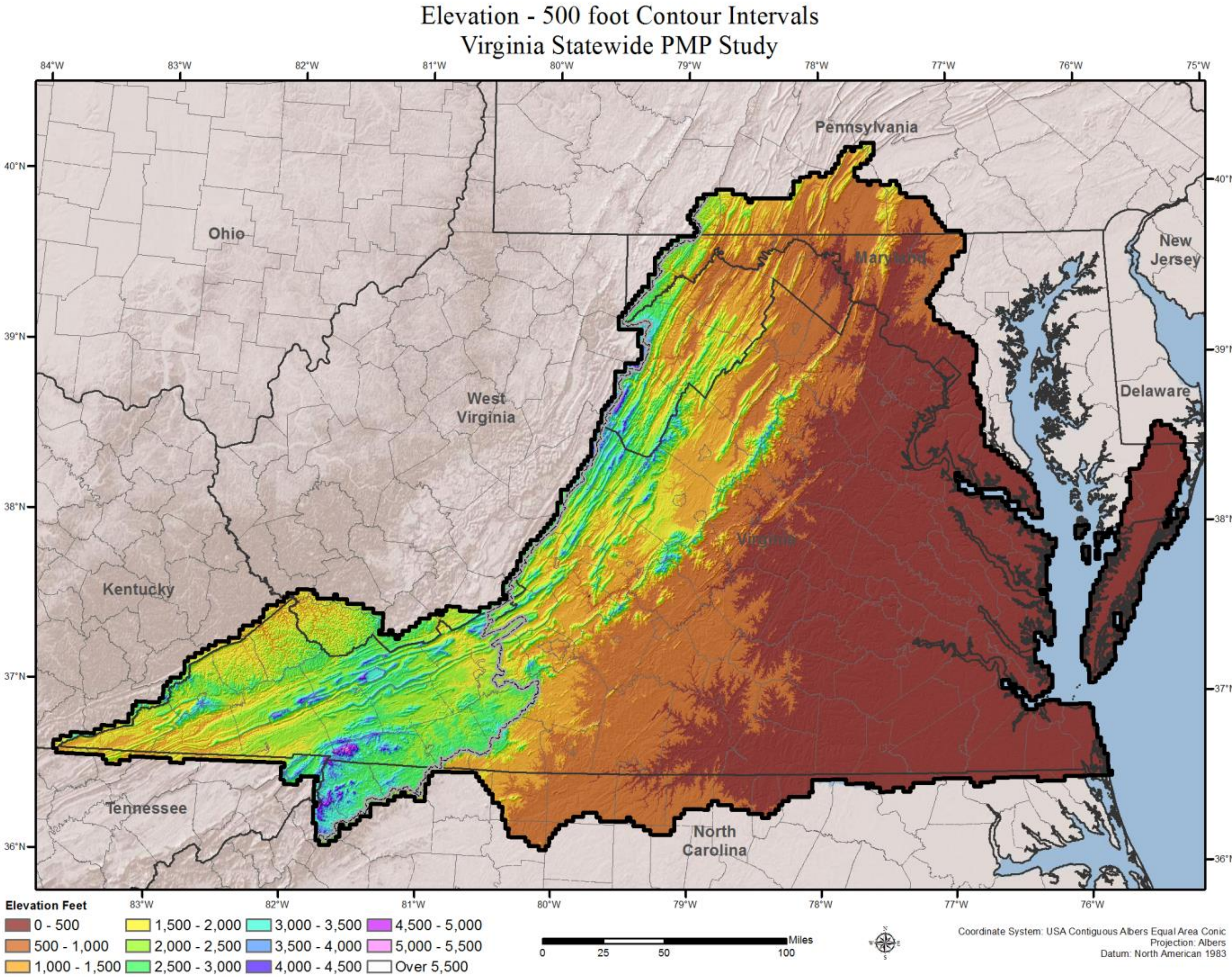

Figure 3.2 Elevation contours at 500 foot intervals over the state of Virginia

3.1 Orographic Effects

Orographic effects on rainfall are explicitly captured in climatological analyses that use precipitation data from historical record (WMO, 2009). These historical rainfall amounts include precipitation that would have accumulated without topography, together with the amount of precipitation that accumulated because of the effects of topography, both at and surrounding a given observation site. Orographic effects produce both enhanced rainfall (on elevated windward terrain) and decreased rainfall (on lower leeward terrain and in protected valleys). Although the orographic effects at a particular location may vary from storm to storm, the overall effect of the topographic influence 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.

For Virginia, extreme storm events (PMP-type storms) include local storms (both individual thunderstorms and MCCs), general storms, and tropical storms. Thunderstorms/MCCs are the primary controlling storm type of the precipitation frequency climatology at durations of 6 hours or less, while the general and tropical storms are responsible for the precipitation frequency climatology values for durations of 24 hours and greater. Hence, climatological analyses of the rainfall data associated with these storm types adequately reflects the differences in topographic influences at different locations when evaluated by storm type and duration.

The procedure used in this study to account for orographic effects determines the differences between the climatological information at the in-place storm location and the individual grid point. This is a departure from the SSM used in HMRs 55A, 57, and 59. The SSM used in the HMRs is highly subjective and is not reproducible.

The OTF process used in this study reduces the amount of subjectivity involved and provides information which is reproducible. By evaluating rainfall values for a range of recurrence intervals at both locations, a relationship between the two locations was established. For this study, gridded precipitation frequency climatologies from NOAA Atlas 14 were used to develop the precipitation frequency relationships and quantify orographic effects. The OTF method was developed originally for orographic regions as a way to replace the HMR SSM method, but because the calculations are relying on relationships between precipitation frequency climatologies between two locations considered transpositionable, the process can be applied in non-orographic regions. The validity of the OTF process for use in calculating PMP in both orographic and non-orographic regions and for each storm type analyzed (local, general, and tropical) has been extensively reviewed during previous AWA PMP studies (e.g. Tomlinson et al., 2011; Tomlinson et al, 2013, Kappel et al., 2014; Kappel et al., 2015) and again during this study. Each of the independent review boards agreed that it was a reasonable process to use in all meteorological scenarios.

It is still important to ensure that non-orographic storms are not transpositioned into orographic regions and vice versa because the precipitation frequency relationships and resulting OTF values would no longer be representative of the same storm types. This was recognized by the WMO 2009 Section 3.1.4 as well, where they state "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 transpostion limits, we are ensuring the storms being compared using the precipitation frequency data are of similar moisture availability and other precipitation-producing factors.

The precipitation frequency estimates utilize information from the mean annual maximum grids developed using the Oregon State University Climate Group's PRISM (Parameter-elevation Relationships on Independent Slopes Model) system to help spatially distribute the values between observational data locations (Perica et al., 2013). PRISM is a peer-reviewed modeling system that combines statistical and geospatial concepts to evaluate gridded rainfall with particular effectiveness in orographic areas (Daly et al., 1994, 1997). The precipitation frequency estimates used in this study implicitly express orographic controls through the adoption of the PRISM system (Perica et al., 2013). A major component of the OTF process is the assumption that the relationship between precipitation frequency values in areas of similar meteorology and topography (transpositionable regions) are a reflection of the difference in orographic effect between the two locations being compared (WMO, 2009). It is also assumed that the influence of terrain is the primary contributing factor to the variability in the relationship between precipitation climatology values at two distinct point locations of interest.

The orographically adjusted rainfall for a storm at a target (grid point) location may be calculated by determining the relationship between the precipitation frequency data series at the source storm location (i.e. the location where the historic storm occurred) and the corresponding data series at the target location. For the transposition of a single grid point at a given duration, the orographic relationship is defined as the linear relationship of the precipitation frequency values, at that duration, over a range of recurrence intervals between the source and target locations. This study evaluated the trend of precipitation frequency estimates through the 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-year average recurrence intervals. The relationship between the target and the source can be expressed as a linear function with P_i as the independent variable and P_o as the dependent variable as shown in Equation 3.1.

$$P_o = mP_i + b \qquad \text{Equation 3.1}$$

where,

P_o	=	target orographically adjusted rainfall (inches)
P_i	=	SPAS-analyzed in-place rainfall (inches)
m	=	slope of least square lines
b	=	origin offset (inches)

Equation 3.1 provides the orographically transpositioned rainfall depth, as a function of the in-place rainfall depth. The in-place rainfall depth used to calculate the orographically transpositioned rainfall corresponds, in duration, to the precipitation frequency datasets used

(i.e., 6-hour for local storms and 24-hour for general and tropical storms). To express the orographic effect as a ratio, or OTF, the orographically adjusted rainfall (P_o) is divided by the original source in-place rainfall depth (P_i). It is assumed the orographic effect for a given transposition scenario is the same for all durations analyzed once it is determined. Therefore, the 6-hour OTF determined for local storms, or the 24-hour OTF determined for general and tropical storms, is applied for all other analyzed durations for the given storm type. Use of the 6-hour precipitation frequency climatology helps to ensure that the precipitation frequency climatology data being used to quantify the OTF for local storms represents that storm type. This is because local storms are the storm type that would produce high enough magnitudes of rainfall accumulation at the 6-hour duration to result in the annual maximum series data that is used to calculate the precipitation frequency estimates. Conversely, the annual maximum series used to derive 24-hour precipitation frequency estimates would result from either general or tropical storm types, and not local storms. Thereby, potential issues of using mixed populations of storm types in the OTF calculations are addressed.

The orographic relationship can be visualized by plotting the average precipitation frequency depths for the grid point at the source location on the *x*-axis and the depths for the grid point at the target location on the *y*-axis and drawing a best-fit linear line among the return frequency depth points. The linear line shows the general relationship between the precipitation frequency values at the grid point location and the values at the in-place storm grid point location. At the 10- to 1,000-year return frequencies, the coefficient of determination (*R-squared*) for the best-fit trendline is consistently very close to 1.00 indicating the goodness-of-fit of the statistical model (see Figure 8.5). As an alternative to producing the best-fit linear trendline graphically, linear regression can be used to determine the relationship mathematically. An example of the determination of the orographic relationship and development of the OTF is given in Section 8.4.

4. Dew Point and SST Climatology Background

This study incorporated updated procedures and data analysis methods used in other PMP studies completed by AWA but were not in the development of the HMRs. This section describes the development of the updated dew point climatologies. The maximum average dew point climatology was developed and used in the storm maximization process.

4.1 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 storm. Prior to the mid-1980s, maps of maximum 12-hour persisting dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. This study used the 100-year return frequency dew point climatology, which is continuously updated by AWA. Storm precipitation amounts were maximized using the ratio of precipitable water for the maximum dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere through 30,000 feet. The precipitable water values associated with each storm representative value were taken from the WMO Manual for PMP Annex 1 (1986). Discussion and calculation examples of this procedure are provided in Appendices C and D.

The use of the 100-year recurrence interval dew point climatology in the maximization process is appropriate because it provides a sufficiently rare occurrence of moisture level when combined with the maximum storm efficiency to produce a combination of rainfall producing mechanism that could physically occur. 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 represent a local extreme moisture value that is often the result of local evapotransporation and other factors not associated with a storm environment and saturated atmosphere. Also, the data available has changed significantly since the publication of the maximum dew point climatologies used in HMR 51. Hourly dew point observations became standard at all first order NWS weather stations starting in 1948. This has allowed for a sufficient period of record of hourly data to exist from which to develop the climatologies out to the 100-year recurrence interval. These data were not available in sufficient quantity and period of record during the development of HMR 51.

This choice to use a recurrence interval and average duration was first determined to be most appropriate during the EPRI Michigan/Wisconsin region PMP study (Section 2-1 and 7, Tomlinson, 1993). That study included original authors of HMR 51 on the review board.

Maximum dew point climatologies are used to determine the maximum atmospheric moisture that could have been available. Prior to the mid-1980s, maps of maximum dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. For the region covered by HMR 49, HMR 50 (Hansen and Schwartz, 1981) provided updated dew point climatologies. HMR 55A contained updated maximum dew point values for a portion of United States from the Continental Divide eastward into the Central Plains. HMR 57 updated the 12-hour persisting dew points values and added a 3-hour persisting dew point climatology. The regional PMP study for Michigan and Wisconsin produced dew point frequency maps representing the 50-year recurrence interval. This study was conducted using an at-site method of analysis with L-moment statistics. The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year recurrence interval values were appropriate for use in PMP calculations. For the Nebraska state-wide study, the Review Committee and FERC Board of Consultants agreed that the 100-year recurrence interval dew point climatology maps were appropriate because their use added a layer of conservatism over the 50-year return period. This has subsequently been employed 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 2013 (Figure 4.1).

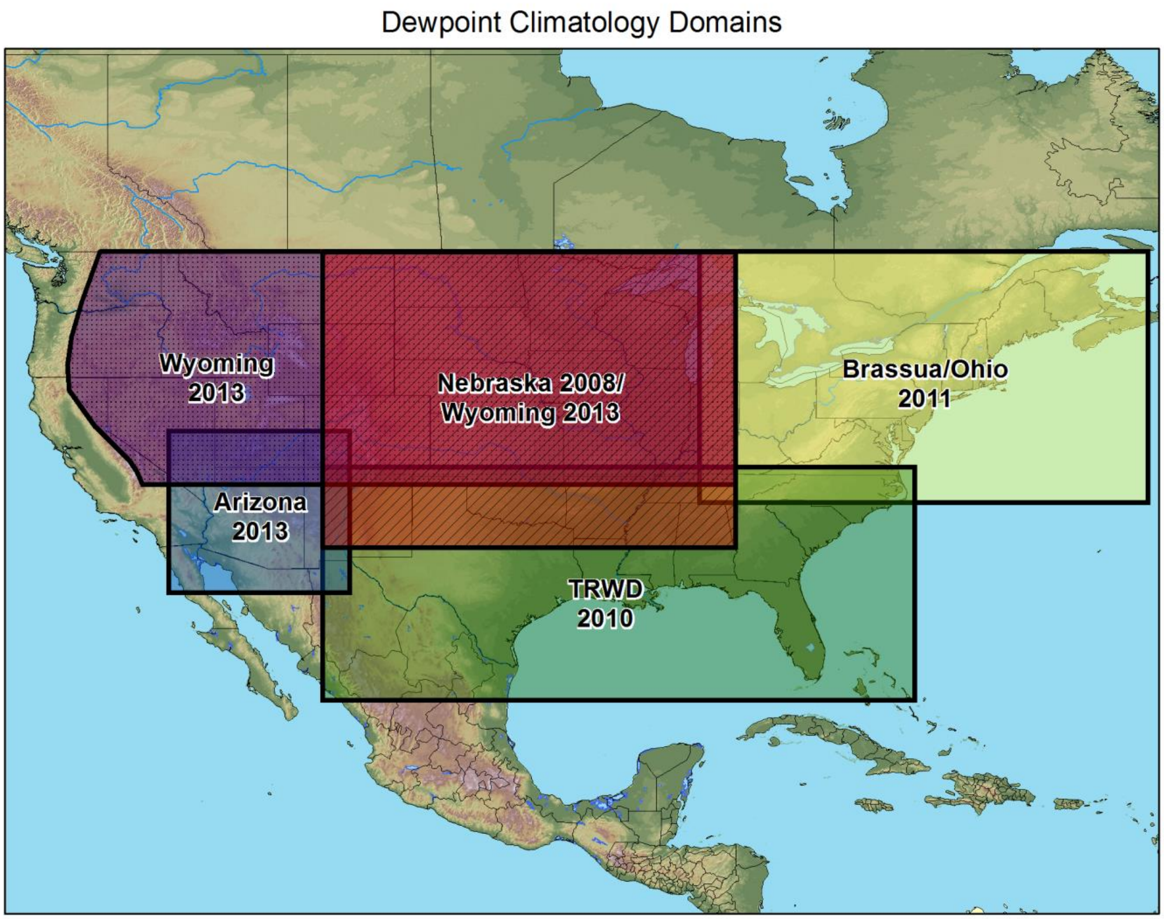

Figure 4.1 Maximum dew point climatology development regions and dates

4.2 Use of Sea Surface Temperatures

Dew point observations are not generally available over ocean regions. When the source region of atmospheric moisture feeding an extreme rainfall event originates from over the ocean, a substitute for dew points observations is required. The NWS adopted a procedure for using SSTs as surrogates for dew point data. The value used as the maximum SST in the PMP calculations is determined using the SSTs two standard deviations warmer (+2-sigma) than the mean SST. This provides a value for the maximum SST that has a probability of occurrence of about 0.025 (i.e. about the 40-year recurrence interval value).

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

Timing is not as critical for inflow wind vectors extending over the oceans since SSTs change very slowly with time compared to dew point values over land. What is important is the changing wind direction, especially for situations where there is curvature in the wind fields. Any changes in wind curvature and variations in timing are inherently captured in the HYSPLIT model re-analysis fields, thereby eliminating another subjective parameter. Timing of rainfall is determined using the rainfall mass curves from the region of maximum rainfall associated with a given storm event. The location of the storm representative SST was determined by identifying the location where the SSTs are generally changing less than 1°F in an approximate 1° x 1° latitude and/or longitude distance following the inflow vector upwind. This is used to identify the homogeneous (or near homogeneous) region of SSTs associated with the atmospheric moisture source for the storm being analyzed. The value from the SST daily analysis for that location is used for the storm representative SST. The storm representative SST becomes a surrogate for the storm representative dew point in the maximization procedure.
The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for several storms where the inflow vector originated over the Atlantic Ocean. The storm spreadsheets presented in Appendix F list the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations. For storm maximization, the value for the maximum SST is determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology values in the maximization and transpositioning procedure. Storm representative SSTs and the mean +2 sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology in the maximization and transpositioning procedure.

5. Extreme Storm Identification

5.1 Storm Search Area

A comprehensive storm search was conducted for this study to identify all of the extreme rainfall storms that have occurred in meteorological and topographically similar regions surrounding the basin. This search included evaluation of storms identified in previous PMP work completed in the region by AWA (Tomlinson, 1993; Tomlinson et al., 2002; Tomlinson et al., 2003; Tomlinson et al., 2008; Tomlinson et al., 2011; Kappel et al., 2012; Kappel et al., 2013; Kappel et al., 2014; Kappel et al., 2015), ongoing AWA PMP studies (e.g. Texas statewide PMP study), and those storms utilized in HMR 40 and HMR 51. In addition, an updated search was completed for this study to include storms important for the region as identified by study participants. The search included events for the entire calendar year. The primary search area included all geographic locations where extreme rain storms similar to those that could occur over any location within the overall domain have been observed.

For locations east of the Appalachian crest, the search area extended from northern New England, west to the crest of the Appalachians, east to the Atlantic coastline, and south to 30°N. For areas west of the Appalachian crest, the search area extended from Canada to the north, within 50 miles of the Gulf of Mexico and west to the 2,000 foot elevation contour line (Figure 5.1). This large search domain insured a large enough area was included to capture all significant storms that could potentially influence PMP values for any location with the study domain. Storms identified within this large region were further investigated and discussed to refine specific transposition limits of each storm by type and season.

5.2 Data Sources

The storm search was conducted using separate databases. The database used in the storm search contained rainfall data from several sources. The primary data sources are listed below:

1. Cooperative Summary of the Day / TD3200 through 2000. These data are published by the National Climatic Data Center (NCDC). These are stored on AWA's database server and can be obtained directly from the NCDC.
2. Hourly Weather Observations published by NCDC, 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 NCDC.
3. NCDC Recovery Disk. These are stored on AWA's database server and can be obtained directly from the NCDC.
4. National Weather Service Hydrometeorological Reports publication series. Each of which can be downloaded from the Hydrometeorological Design Studies Center website at http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html.
5. Army Corps of Engineers Storm Studies (USACE, 1973)

6. Environment Canada storm studies. The are stored on AWA's database server and can be obtained from Environment Canada.
7. Other data published by National Weather Service regional climate offices, state climate offices, and local National Weather Service offices. These can be accessed from the National Weather Service homepage at http://www.weather.gov/.
8. American Meteorological Society journals (e.g. Smith et al., 1996; Pontrelli et al., 1999; Konrad, 2001; Robinson et al., 2001; Hicks et al., 2005; Smith et al., 2010, Smith et al., 2011).
9. Storm lists from previous studies in the region (e.g. Blenheim Gilboa, Tomlinson et al., 2008; Brassua Dam, Tomlinson et al., 2011; and Conowingo Dam, Kappel et al., 2015).
10. United States Geological Society (USGS) Flood Reports (e.g. Eisenlohr, 1952)
11. Data from supplemental sources, such as Community Collaborative Rain, Snow, and Hail Network (CoCoRaHS), Weather Underground, Forecast Systems Laboratories, RAWS, and various Google searches.
12. Flood and precipitation reports from members involved in the study (Steven Snell, personal communication, December 2014; Matt Lyons, personal communication, November 2014).

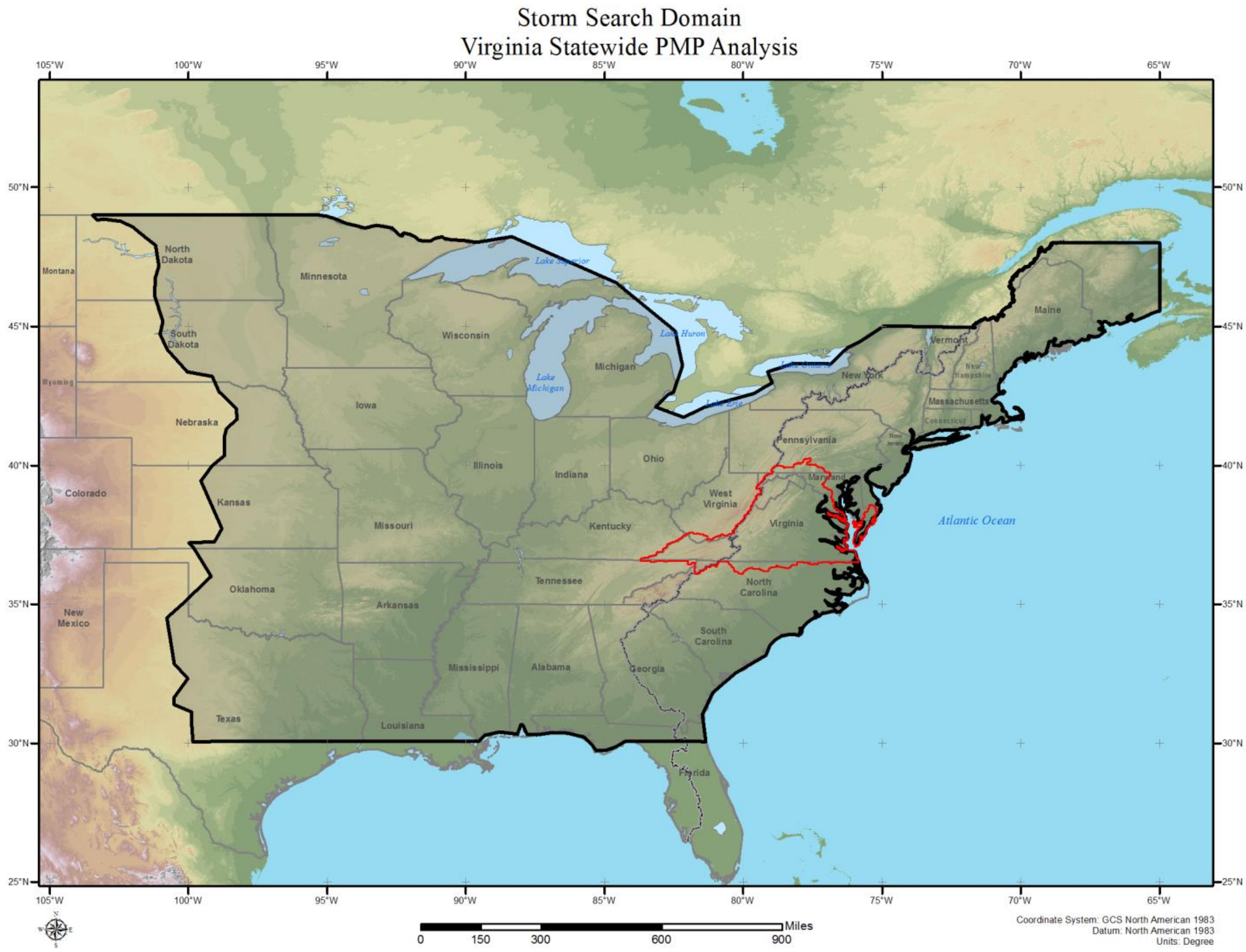

Figure 5.1 Virginia storm search domain

5.3 Storm Search Method

The initial search began with identifying all storms within the storm search domains described previously which were used in preceding PMP studies. These storms were evaluated to identify the largest precipitation totals for various durations associated with the each storm type; local storms, tropical storms, and general storms. Other reference sources such as members involved in the study, journal articles, HMRs, USGS reports, NWS reports, and climate center reports were reviewed to identify dates with large rainfall amounts for locations within the storm search domain. The initial threshold for storms to make the initial list of significant storms (referred to as the long storm list) were rainfall values that exceeded the 100-year return frequency value for specified durations at the station location.

The resulting long storm list was extensively quality controlled to ensure that only the highest storm rainfall values for each event were selected. Storms were then grouped by storm type, storm location, and duration for further analysis. Table 5.1 lists the storms identified east of the Appalachian and Table 5.2 lists the storms identified west of the Appalachians.

These storms were plotted in a GIS to better evaluate the spatial coverage of the events throughout the region. From this initial long storm list, the potential storms to analyze list was derived. This list was developed after extensive discussion and review with the Review Board, representatives from DCR, FERC, and NRCS. Each storm was investigated for references in both published and unpublished (NWS offices, USGS reports, other local Flood Reports, HMRs, AMS journals, etc.) to determine its significance in the storm and flood history of Virginia and surrounding regions.

Table 5.1 Virginia long storm list-east of the Appalachians, listed chronologically.

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
CATSKILL	NY	1819	7	27	15.00	SPAS 1547
PATERSON	NJ	1882	9	20	17.90	NA 1-3
UNION POINT	GA	1887	7	27	16.50	SA 3-1
WELLSBORO	PA	1889	5	30	10.11	SPAS 1339
MANNING	SC	1893	8	26	13.20	SA 2-1
JEWELL	MD	1897	7	26	15.80	NA 1-7B
EUTAW	AL	1900	4	15	13.90	LMV 2-5
PATERSON	NJ	1903	10	8	15.51	GL 4-9
CARLTON BRIDGE	GA	1908	8	24	13.70	Metstat
MONROE 4 SE	NC	1908	8	24	18.00	SA 2-6
ST. GEORGE	GA	1911	8	28	19.10	SA 3-11
ALTA PASS	NC	1916	7	13	24.90	SPAS 1299 Zone 2
KINGSTREE	NC	1916	7	13	16.79	SPAS 1299 Zone 1
CALLAVILLE	VA	1919	7	16	15.60	SA 5-25
ORANGE	VA	1923	7	27	12.10	SA 1-15
BEAUFORT	NC	1924	9	13	14.80	SA 3-16
KINSMAN NOTCH	NH	1927	11	2	14.00	NA 1-17
THOMASVILLE	AL	1928	6	1	15.20	LMV 2-18
CHELTENHAM	MD	1928	8	10	13.30	NA 1-18
DARLINGTON	SC	1928	9	16	12.60	SA 2-15
ELBA	AL	1929	3	12	29.73	SPAS 1305
GLENVILLE	GA	1929	9	23	20.00	SA 3-20
MONCURE	NC	1929	9	29	11.55	SPAS 1517 zone 2
SETTLE	NC	1929	9	29	9.97	SPAS 1517 zone 3
SALUDA	SC	1929	10	1	10.51	SA 3-23
FAIRFIELD	TX	1932	9	2	19.58	SPAS 1428
WESTERLY	RI	1932	9	16	12.20	NA 1-20A
ROCKY MOUNT	VA	1932	10	15	9.30	SA 5-11A
YORK	PA	1933	8	22	14.00	NA 1-24B
PEEKAMOOSE	NY	1933	8	22	16.00	NA 1-24A
MILLRY	AL	1934	11	19	13.00	LMV 1-18
HECTOR	NY	1935	7	6	14.20	NA 1-27
EASTON	MD	1935	9	4	16.70	SA 1-26
PINKHAM NOTCH	NH	1936	3	9	9.70	SPAS 1194
PINKHAM NOTCH	NH	1936	3	16	11.30	SPAS 1195 Zone 1
PADDY MOUNTAIN	WV	1936	3	16	8.31	SPAS 1195 Zone 2
BIG MEADOWS	VA	1937	4	24	11.60	SA 5-13
LOCK NO2	AL	1938	4	5	13.60	GM 2-25
BUCK	CT	1938	9	17	18.06	SPAS 1341

Table 5.1 Virginia long storm list-east of the Appalachians, listed chronologically (continued).

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
BELHAVEN	NC	1938	9	16	14.10	SA 5-16
TUCKERTON	NJ	1939	8	19	18.00	NA 2-2
EWAN	NJ	1940	9	1	24.00	SPAS 1023
KEYSVILLE	VA	1940	8	11	17.50	SA 5-19A
BUCK CREEK	NC	1940	8	11	16.40	SA 5-19B
SWANSBORO	NC	1940	8	11	19.60	SA 5-19C
BIG MEADOWS	VA	1942	10	12	19.77	SPAS 1340
HATTERAS	NC	1942	10	12	16.00	SA 1-28B
GREENWOOD	VA	1944	9	19	15.10	SPAS lite 5766
ROCKINGHAM	NC	1945	9	13	14.80	SA 5-27
TRAY MOUNTAIN	GA	1946	1	5	11.27	TVA FLOOD REPORT
WATERLOO	AL	1948	2	11	10.38	TVA FLOOD REPORT
PITTSFIELD	MA	1948	12	28	11.00	SPAS 1255
LITTLE RIVER	VA	1949	6	17	15.13	SPAS 1546
GREENVILLE	ME	1950	11	30	7.40	M-28-NB-11-50
FLAT TOP	GA	1954	1	14	8.38	TVA FLOOD REPORT
MT MITCHELL	NC	1954	1	20	8.90	TVA FLOOD REPORT
SKYTOP	PA	1955	8	10	21.32	SPAS lite 5767 zone 1
BIG MEADOWS	VA	1955	8	10	21.49	SPAS lite 5767 zone 2
JAMES CITY	NC	1955	8	10	20.35	SPAS lite 5767 zone 3
SLIDE MOUNTAIN	NY	1955	8	11	14.70	SPAS 1003
WESTFIELD	MA	1955	8	17	19.90	SPAS 1001/1243
WEST SHOKAN	NY	1955	10	14	18.50	SPAS 1006
COVE CREEK	NC	1956	6	30	12.00	HMR 45 Table 2.1
SPARTA	NC	1959	9	30	10.00	METSTAT
DAHLONEGA	GA	1960	7	26	12.50	HMR 45 Table 2.1
BIRMINGHAM	AL	1961	2	19	13.58	HYDRO 13
CATALOOCHEE	NC	1963	3	5	6.45	TVA FLOOD REPORT
VALLEY HEAD	AL	1963	4	29	8.14	METSTAT
EDGEFIELD	SC	1964	8	29	8.59	METSTAT
FRANKFORT	AL	1968	9	16	11.10	NCDC
TYRO	VA	1969	8	19	27.00	NA 2-23
KERR SCOTT RESERVOIR	NC	1970	8	9	10.37	METSTAT
ZERBE	PA	1972	6	18	18.79	SPAS 1276
WILKESBORO	NC	1972	6	20	9.00	METSTAT
LAURENS	SC	1976	10	8	9.04	METSTAT
LENOIR	NC	1977	11	6	9.73	Metstat
PINKHAM NOTCH	NH	1984	5	27	12.98	SPAS 1403
ELK POND MOUNTAIN	VA	1985	11	1	22.52	SPAS lite 5770
MONTEBELLO	VA	1985	11	1	22.52	SPAS 1533

Table 5.1 Virginia long storm list-east of the Appalachians, listed chronologically (continued).

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
LOFT MOUNTAIN	VA	1987	9	5	17.63	SPAS lite 5768
LOCKHART	SC	1990	10	12	9.03	METSTAT
BELLE MINA	AL	1990	12	22	12.04	METSTAT
HARTWELL	GA	1994	8	16	9.15	METSTAT
RAPIDAN	VA	1995	6	27	28.39	SPAS 1406
ANTREVILLE	SC	1995	8	26	18.50	SPAS 1373
CEDARTOWN	GA	1995	10	4	9.43	METSTAT
PINNACLE	VA	1996	9	6	19.52	SPAS lite 5769
GORHAM	ME	1996	10	19	22.40	SPAS 1025
WILLIAMSBURG	VA	1999	9	14	16.98	SPAS 1012-zone 2
PINKHAM NOTCH	NH	1999	9	15	10.55	SPAS 1198 Zone 1
MT MANSFIELD	VT	1999	9	15	11.35	SPAS 1198 Zone 2
NEWARK	NJ	1999	9	15	14.45	SPAS 1002
SPARTA	NJ	2000	8	11	16.70	SPAS 1017
UPPER SHERANDO	VA	2003	9	17	20.20	SPAS 1535 Zone 2
TABERNACLE	NJ	2004	7	13	15.63	SPAS 1040
RICHMOND	VA	2004	8	30	14.38	SPAS 1551
HALIFAX	VT	2005	10	7	15.40	SPAS 1201
RALEIGH	VA	2006	6	10	10.53	SPAS lite 5764
TAMAQUA	PA	2006	6	26	12.26	SPAS 1047
WRIGHTSVILLE BEACH	NC	2006	9	1	14.61	NWS report
DELAWARE COUNTY	NY	2007	6	19	11.69	SPAS 1049
NEW BERN	VA	2010	9	27	23.44	SPAS 1350
MAPLECREST	NY	2011	8	27	22.91	SPAS 1224
HARRISBURG	PA	2011	9	4	18.32	SPAS 1298
ONEONTA	AL	2011	9	5	11.49	METSTAT
PENSACOLA	FL	2012	6	8	27.72	COCORAHS
ISLIP	NY	2014	8	13	14.23	SPAS 1415
SAUL'S RUN	WV	2003	8	11	5.90	Smith et al. 2010

Table 5.2 Virginia long storm list-west of the Appalachians, listed chronologically.

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
BOWLING GREEN	KY	1883	2	2	11.40	OR 5-11
ROCKPORT	WV	1889	7	18	19.01	World Record Rainfall Table
LARRABEE	IA	1891	9	10	13.00	MR 4-2
PHILLIPSBURG	MO	1895	12	16	12.20	MR 1-1
GREELEY	NE	1896	6	4	12.30	MR 4-3
LAMBERT	MN	1897	7	18	8.00	UMV 1-2
CANTON	MS	1899	1	4	9.20	LMV 3-7
RIPLEY	MS	1902	3	25	11.80	LMV 2-7
WOODBURN	IA	1903	8	24	15.50	MR 1-10
WILLOW SPRINGS	MO	1904	3	24	7.50	UMV 2-4
MEDFORD	WI	1905	6	4	11.20	GL 2-12
BONAPARTE	IA	1905	6	10	12.10	UMV 2-5
AUSTIN	MS	1906	11	17	19.40	LMV 1-4
MALVERN	AR	1907	1	1	9.20	LMV 1-5
MEEKER	OK	1908	10	19	16.23	SW 1-11
GOLCONDA	IL	1910	10	3	15.40	OR 4-8
BEE BRANCH	AR	1913	1	10	7.50	LMV 1-9
BELLEFONTAINE	OH	1913	3	23	11.20	OR 1-15
COOPER	MI	1914	8	31	13.39	SPAS 1426
IRONTON	MO	1916	1	26	9.40	MR 2-13
BELOIT	WI	1916	3	31	5.60	GL 4-14
HENDERSON	TN	1919	3	15	10.60	LMV 1-12
ROCK ISLAND	TN	1919	3	21	10.30	OR 7-15
GRANT CITY	MO	1922	7	9	13.90	MR 2-29
JOHNSON CITY	TN	1924	6	13	16.14	SPAS 1343
BOYDEN	IA	1926	9	17	24.22	SPAS 1427
NEOSHO FALLS	KS	1926	9	12	14.00	SW 2-1
JEFFERSON PLAQ	LA	1927	4	12	20.40	LMV 4-8
LOLA	KS	1928	11	15	11.20	MR 3-20
ELBA	AL	1929	3	12	29.73	SPAS 1305
ROCK ISLAND	TN	1929	3	21	10.30	OR 7-15
GLENVILLE	GA	1929	9	23	21.20	SPAS 1516
GLENVILLE	GA	1929	9	23	20.88	SPAS 1516 Zone 2
ARKADELPHIA	AR	1930	1	6	10.90	LMV 2-22
FAIRFIELD	TX	1932	9	2	19.58	SPAS 1428
HERNANDO	MS	1935	1	18	13.85	LMV 1-19
MELVILLE	LA	1935	5	2	13.40	LMV 4-20
SIMMESPORT	LA	1935	5	16	14.10	LMV 4-21
GREENVILLE	KY	1935	6	20		

Table 5.2 Virginia long storm list-west of the Appalachians, listed chronologically (continued).

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
NEWCOMERSTOWN	OH	1935	8	6	12.70	OR 9-11
WARDENSVILLE	WV	1936	3	16	8.32	SPAS 1195 Zone 2
MCKENZIE	TN	1937	1	5	22.60	SPAS 1311
CALVIN	OK	1938	2	14	11.00	SW 2-17
CROSSVILLE	TN	1938	5	22	11.00	HMR 45 Table 2.1
LEWISBURG	TN	1938	6	18	9.00	HMR 45 TABLE 2-1
DECHERD	TN	1938	7	8	6.00	HMR 45 TABLE 2-1
PITTMAN CENTER	TN	1938	8	4	11.00	HMR 45 Table 2.1
KOLL	LA	1938	8	12	15.40	LMV 4-23
SIMPSON	KY	1939	7	4	20.82	SPAS 1344
RUCHLANDS	VA	1939	6	9	10.00	HMR 45 Table 2.1
MT MITCHELL	NC	1940	8	10	20.27	SPAS 1342
BLUE RIDGE DIVIDE	NC	1940	8	28	14.09	SPAS 1346
ROCK HOUSE	NC	1940	8	28	14.09	SPAS 1346
HEMPSTEAD	TX	1940	11	22	21.29	SPAS 1430
HALLETT	OK	1940	9	2	24.00	SPAS 1429
IDLEWILD	NC	1940	8	10	20.27	SPAS 1342
GRANT TOWNSHIP	NE	1940	6	3	13.00	MR 4-5
INDEX	AR	1940	6	30	11.50	LMV 4-25
DAVIS	OK	1941	9	30	12.10	UMV 3-20
SMETHPORT	PA	1942	7	17	34.91	SPAS 1345
WARNER	OK	1943	5	6	25.24	SPAS 1431
SILVER LAKE	TX	1943	6	5	16.50	SW 3-3
GLENVILLE	WV	1943	8	4	14.50	OR 3-30
STANTON	NE	1944	6	10	17.30	MR 6-15
CLINTON	TN	1944	9	29	10.08	HMR 45 Table 2.3
VAN	TX	1945	3	28	17.40	SW 3-5
COLLINSVILLE	IL	1946	8	12	19.07	SPAS 1433
COLE CAMP	MO	1946	8	12	19.40	MR 7-2A
MOUNDS	OK	1947	6	18	19.27	SPAS 1432
HOLT	MO	1947	6	18	17.62	SPAS 1434
FLAG BRANCH	TN	1947	6	28	5.40	HMR 45 Table 2.1
WICKES	AR	1947	8	27	15.50	SW 3-7A
TIMBO	AR	1949	1	22	13.00	SW 3-10
SPARTA	TN	1949	6	4	9.50	HMR 45 TABLE 2-1
TVA	TN	1949	6	15		HMR 45 Table 2.3
TVA	TN	1949	10	30		HMR 45 Table 2.3
OKOLONA	KY	1951	3	28	15.07	METSTAT
DUMONT	IA	1951	6	25	12.00	UMV 3-29

Table 5.2 Virginia long storm list-west of the Appalachians, listed chronologically (continued).

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
COUNCIL GROVE	KS	1951	7	9	18.50	MR 10-2
MCMINNVILLE	TN	1952	6	13	10.50	HMR 45 Table 2.1
KELSO	MO	1952	8	11	13.00	UMV 3-30
HARRISONBURG DAM	LA	1953	5	11	25.34	SPAS 1435
CAMP POLK	LA	1953	4	23	21.10	LMV 5-3
RITTER	IA	1953	6	7	11.00	MR 10-8
SEQUATCHIE	TN	1954	8	8	10.00	HMR 45 Table 2.1
PONTOTOC	MS	1955	3	20	11.07	TVA FLOOD REPORT
GOOSE ROCK	KY	1956	6	21	11.70	HMR 45 Table 2.1
CLINGMANS DOME	TN	1957	1	27	12.55	TVA FLOOD REPORT
PARIS WATERWORKS	IN	1957	6	27	12.40	HMB-V18
NEBO	TN	1957	11	18	9.00	HMR 45 TABLE 2-1
PRAGUE	NE	1959	8	1	13.09	SPAS 1031
COLUMBIA	TN	1960	6	16	12.20	HMR 45 Table 2.1
OAK RIDGE	TN	1960	8	10	9.00	HMR 45 TABLE 2-1
IDA GROVE	IA	1962	8	30	12.85	EPRI
SIGNAL MOUNTAIN	TN	1963	3	11	8.94	TVA FLOOD REPORT
COLLEGE HILL	OH	1963	6	3	19.39	SPAS 1226
DAVID CITY	NE	1963	6	24	15.98	SPAS 1030
ROSMAN	NC	1964	9	26	9.22	SPAS 1312A Zone 1
ROSMAN	NC	1964	9	26	17.86	SPAS 1312A Zone 2
ROSMAN	NC	1964	10	3	17.53	SPAS 1312B Zone 2
MADISONVILLE	KY	1964	3	8	11.53	SPAS 1278
ROSEDALE	TN	1965	7	24	13.32	SPAS 1402 Zone 2
EDGERTON	MO	1965	7	18	20.76	SPAS 1183
GLADEWATER	TX	1966	4	27	25.33	SPAS 1181
BURTON DAM	GA	1967	8	21	18.42	SPAS 1380
SCOTTSVILLE	KY	1969	6	23	10.58	METSTAT
WOOSTER	OH	1969	7	4	14.95	SPAS 1209
BIG STONE GAP	KY	1969	12	30	6.31	METSTAT
WELLSVILLE	NY	1972	6	18	15.23	SPAS 1276
BURNSVILLE	TN	1973	3	14	12.15	SPAS 1357
ENID	OK	1973	10	10	19.45	SPAS 1034
CLARKSVILLE SEWAGE	TN	1975	3	12	9.11	METSTAT
COEBURN	VA	1977	4	2	15.66	SPAS 1362
JOHNSTOWN	PA	1977	7	18	12.64	SPAS 1550
TOMPKINSVILLE	KY	1978	12	7	9.90	METSTAT
LOUISVILLE	MS	1979	4	12	22.07	SPAS 1227
DUNLAP	TN	1982	8	17	15.50	HRM 56 TABLE 1

Table 5.2 Virginia long storm list-west of the Appalachians, listed chronologically (continued).

Storm Name	State	Year	Month	Day	Total Rainfall in Inches	Precipitation Source
BIG FORK	AR	1982	12	1	15.92	SPAS 1219
FOREST CITY	MN	1983	6	20	17.00	SPAS 1035
DANDRIDGE	TN	1984	5	7	9.62	SPAS 1376
MONTEBELLO	VA	1985	11	1	19.77	
BIG RAPIDS	MI	1986	9	9	13.42	SPAS 1206
MINNEAPOLIS	MN	1987	7	23	11.55	SPAS 1210
GILBERTSVILLE	KY	1989	2	12	13.20	SPAS 1277
SAVANNAH	TN	1991	5	26	13.04	METSTAT
RIPLEY	MS	1991	12	1	10.29	METSTAT
AMERICUS	GA	1994	7	4	28.09	SPAS 1317
CHATTANOOGA	TN	1994	2	14		
BRYSON CITY	TN	1994	3	27	9.33	METSTAT
AURORA COLLEGE	IL	1996	7	16	18.13	SPAS 1286
REDBANK	PA	1996	7	19	9.42	SPAS 1548
LOUISVILLE	KY	1997	2	28	13.51	SPAS 1244
ELIZABETHON	TN	1998	1	8		
CHATTANOOGA	TN	1998	4	22		
MT MANSFIELD	VT	1999	9	15	11.35	SPAS 1198 Zone 2
COVINGTON	TN	2001	11	26	11.09	Memphis NWS REPORT
CLINTON	TN	2002	3	20		
WARROAD	MN	2002	6	9	14.55	SPAS 1297
UPPER SHERANDO	VA	2003	9	17	20.20	Hurricane Isabelle
ELIZABETHON	TN	2003	11	19		
MONTGOMERY DAM	PA	2004	9	18	8.80	SPAS 1275
FALL RIVER	KS	2007	6	30	25.50	SPAS 1228
HOKAH	MN	2007	8	18	18.32	SPAS 1048
ALLEY SPRING	MO	2008	3	17	15.10	SPAS 1242
LARTO LAKE	LA	2008	9	1	23.31	SPAS 1182
DOUGLASVILLE	GA	2009	9	19	25.37	SPAS 1218
WARNER PARK	TN	2010	4	30	19.71	SPAS 1208
DUBUQUE	IA	2011	7	27	15.14	SPAS 1220
DULUTH	MN	2012	6	19	10.73	SPAS 1296
VALLEY	TN	2013	1	17		
BANKHEAD NF	TN	2013	7	4	9.20	Huntsville NWS Report
EAST TENNESSEE	TN	2013	7	8		

5.4 Developing the Short List of Extreme Storms

The long list of potential storms included hundreds of unique storm events. A multiple step process was followed to determine a list of storms that was comprehensive enough to ensure that major events were identified while eliminating smaller events that would not be significant for determining PMP values at any area size or duration after standard adjustments were applied.

The next step was to determine which of these storms would ultimately need to be fully analyzed using SPAS (see Appendix G for a full description of SPAS). Several steps were taken to compare the magnitude of each of the events at various area sizes and durations with the magnitude of other events on the potential storms to analyze list. Storms were sorted by storm type and location for initial comparison. This helped eliminate several storms which occurred in the same climate region but were of significantly less magnitude compared with others of the same duration in similar locations. The remaining storms were further investigated using various flood reports, discussions with personnel familiar with the storm events, and examination of the synoptic environment surrounding the event. The storms which made it through these final evaluations were placed on the short storm list (Table 5.3). Each of these storms was analyzed with SPAS and considered to potentially affect PMP values for one or more grid points analyzed in this study.

This list contained all the storms analyzed by AWA for this study, a total of 79 individual SPAS DAD zones. SPAS DAD zones were derived by analyzing the timing of the rainfall accumulation and the effect of underlying terrain on "anchoring" the rainfall to terrain. This is a subjective decision made during the SPAS analysis. In highly orographic terrain, numerous DAD zones would be possible. However, delineating those based on data is ultimately subjective. Therefore, AWA applies a more conservative approach in combining storm centers, which produces more volume in the resulting data. In application, the hydrologist can delineate a given basin in sub-basins down to a 1/3rd of a square mile resolution to derive the overall basin average. This would allow for a more refined look at the rainfall depths at the discrete grid point level where multiple centers would provide a more accurate representation of the rainfall and runoff.

Only a small subset of the 79 SPAS DAD zones control PMP values, with most providing support for the PMP values. The reason more storms were analyzed than was ultimately required to derive the PMP values, was to ensure no storms were omitted which could have affected PMP values after all adjustment factors were applied. The magnitude of the adjustment factors is unknown at the beginning of the process. In other words, a storm with large point rainfall values may have a relatively small total adjustment factor, while a storm with a relatively smaller but significant rainfall value may end up with a large total adjustment factor. The combination of these calculations may provide a total adjusted rainfall value for the smaller rainfall event that is greater than the larger rainfall event after all adjustments are applied.

Figure 5.2 displays the locations of all the storms used for PMP development. Figure 5.3 shows the locations of all the local storms, Figure 5.4 shows the locations of all the general storms and Figure 5.5 displays the location of all the tropical storms.

Table 5.3 Short storm list used to derive PMP values, all storms were analyzed with SPAS. APP is short for Appalachian. Storm Type: G is General, L is Local, and T is Tropical.

Storm Name	State	Lat	Lon	Year	Month	Day	Total Rainfall in Inches	Precipitation Source	East or West of App Crest	Storm Type
WELLSBORO	PA	41.704	-77.229	1889	5	30	10.11	SPAS 1339	E	G
JEWELL	MD	38.730	-76.570	1897	7	26	15.88	SPAS 1489	E	L
VADE MECUM	NC	36.310	-80.280	1908	8	23	18.00	SPAS 1514	E	G
ST GEORGE	GA	30.521	-82.020	1911	8	28	19.10	SPAS 1515	E	T
COOPER	MI	42.371	-85.588	1914	8	31	13.39	SPAS 1426	W	L
ALTA PASS	NC	35.879	-81.871	1916	7	13	24.90	SPAS 1299 Zone 1	E	T
KINGSTREE	NC	33.663	-79.829	1916	7	13	16.79	SPAS 1299 Zone 2	E	T
JOHNSON CITY	TN	36.304	-82.063	1924	6	13	16.14	SPAS 1343	W	L
BOYDEN	IA	43.196	-95.996	1926	9	17	24.22	SPAS 1427	W	L
ELBA	AL	31.363	-86.121	1929	3	12	29.73	SPAS 1305	W	G
GLENVILLE	GA	34.860	-84.290	1929	9	23	21.20	SPAS 1516	W	T
GLENVILLE	GA	34.883	-84.283	1929	9	23	20.88	SPAS 1516 Zone 2	W	T
MONCURE	NC	35.600	-79.070	1929	9	29	11.55	SPAS 1517 zone 2	E	T
SETTLE	NC	35.950	-80.700	1929	9	29	9.97	SPAS 1517 zone 3	E	T
FAIRFIELD	TX	31.6792	-96.1292	1932	9	2	19.58	SPAS 1428	W	G
EASTON	MD	38.860	-76.070	1935	9	4	17.00	SPAS 1490	E	T
PINKHAM NOTCH	NH	44.246	-71.221	1936	3	9	9.70	SPAS 1194	E	G
PINKHAM NOTCH	NH	44.246	-71.221	1936	3	16	12.37	SPAS 1195 Zone 1	E	G
PADDY MOUNTAIN	WV	39.020	-78.560	1936	3	16	8.32	SPAS 1195 Zone 2	E	G
MCKENZIE	TN	36.440	-87.910	1937	1	17	19.86	SPAS 1311	W	G
SIMPSON	KY	38.104	-83.296	1939	7	4	20.82	SPAS 1344	W	L
MT MITCHELL	NC	36.300	-81.450	1940	8	10	20.27	SPAS 1342	W	T
BLUE RIDGE DIVIDE	NC	35.038	-83.079	1940	8	28	14.09	SPAS 1346	W	G
EWAN	NJ	39.688	-75.181	1940	9	1	24.30	SPAS 1534	E	L
HALLETT	OK	36.246	-96.613	1940	9	2	24.00	SPAS 1429 Zone 2	W	L
HEMPSTEAD	TX	30.130	-96.054	1940	11	22	21.29	SPAS 1430	W	G
SMETHPORT	PA	41.872	-78.277	1942	7	17	34.91	SPAS 1345	W	L
BIG MEADOWS	VA	38.546	-78.404	1942	10	12	19.77	SPAS 1340	E	G
BIG MEADOWS	VA	38.546	-78.404	1942	10	12	19.77	SPAS 1340	E	L
WARNER	OK	35.479	-95.329	1943	5	6	25.24	SPAS 1431	W	G
MOUNDS	OK	35.846	-96.071	1943	5	15	19.27	SPAS 1432	W	L
GLENVILLE	WV	38.895	-80.771	1943	8	4	15.04	SPAS 1536	W	L
COLLINSVILLE	IL	38.671	-90.004	1946	8	12	19.07	SPAS 1433	W	G
HOLT	MO	39.454	-94.329	1947	6	18	17.62	SPAS 1434	W	L
LITTLE RIVER	VA	38.863	-79.188	1949	6	17	15.13	SPAS 1546	E	L
HARRISONBURG DAM	LA	31.788	-91.813	1953	5	11	25.34	SPAS 1435	W	G
SLIDE MOUNTAIN	NY	42.017	-74.417	1955	8	11	14.70	SPAS 1003	E	T
WESTFIELD	MA	42.120	-72.700	1955	8	17	20.09	SPAS 1243	E	T
WEST SHOKAN	NY	41.950	-74.320	1955	10	14	18.50	SPAS 1006	E	T

Table. 5.3 Short storm list used to derive PMP values, all storms were analyzed with SPAS (continued).

Storm Name	State	Lat	Lon	Year	Month	Day	Total Rainfall in Inches	Precipitation Source	East or West of App Crest	Storm Type
ROSMAN	NC	37.7375	-81.5958	1964	9	26	9.22	SPAS 1312A Zone 1	W	G
ROSMAN	NC	35.1458	-82.8042	1964	9	26	17.86	SPAS 1312A Zone 2	W	G
ROSMAN	NC	35.1375	-82.8375	1964	10	3	17.53	SPAS 1312B Zone 2	W	T
EDGERTON	MO	40.413	-95.513	1965	7	18	20.76	SPAS 1183	W	G
ROSEDALE	TN	36.1792	-84.2292	1965	7	24	13.32	SPAS 1402 Zone 2	W	L
BURTON DAM	GA	34.796	-83.696	1967	8	21	18.42	SPAS 1380	W	G
TYRO	VA	37.8125	-79.0042	1969	8	19	27.23	SPAS 1491	E	T
ZERBE	PA	40.5375	-76.6208	1972	6	18	18.79	SPAS 1276	E	T
BURNSVILLE	TN	34.8375	-88.3958	1973	3	14	12.15	SPAS 1357	W	G
COEBURN	VA	37.2792	-81.8042	1977	4	2	15.66	SPAS 1362	W	L
JOHNSTOWN	PA	40.3958	-78.9542	1977	7	18	12.64	SPAS 1550	W	L
DANDRIDGE	TN	37.2625	-84.9708	1984	5	7	9.62	SPAS 1376	W	L
MONTEBELLO	VA	37.813	-79.163	1985	11	1	22.56	SPAS 1533	E	G
AMERICUS	GA	32.096	-84.229	1994	7	4	28.09	SPAS 1317	W	T
RAPIDAN	VA	38.4150	-78.3350	1995	6	27	28.39	SPAS 1406	E	L
ANTREVILLE	SC	34.855	-82.225	1995	8	26	19.99	SPAS 1373	E	T
REDBANK	PA	41.2600	-79.1600	1996	7	19	9.42	SPAS 1548	W	L
SOUTHPORT 5 N	NC	34.0050	-77.9950	1999	9	14	24.30	SPAS 1552 Zone 1	E	T
YORKTOWN	VA	37.2750	-76.5550	1999	9	14	19.22	SPAS 1552 Zone 2	E	T
PINKHAM NOTCH	NH	44.260	-71.340	1999	9	15	10.55	SPAS 1198 Zone 1	E	T
POMTON LAKE	NJ	40.995	-74.285	1999	9	15	14.62	SPAS 1552 Zone 3	E	T
CAIRO	NY	42.295	-74.005	1999	9	15	11.71	SPAS 1552 Zone 4	E	T
MT MANSFIELD	VT	44.5300	-72.8100	1999	9	15	11.35	SPAS 1198 Zone 2	W	T
SPARTA	NJ	41.030	-74.640	2000	8	11	16.70	SPAS 1017	E	L
EDENTON	NC	35.8625	-76.5042	2003	9	17	7.96	SPAS 1535 Zone 1	E	T
UPPER SHERANDO	VA	37.913	-79.029	2003	9	17	20.22	SPAS 1535 Zone 2	E	T
TABERNACLE	NJ	39.881	-74.690	2004	7	13	15.63	SPAS 1040	E	L
RICHMOND	VA	37.7050	-77.3750	2004	8	30	14.38	SPAS 1551	E	T
MONTGOMERY DAM	PA	40.6450	-80.3850	2004	9	18	8.79	SPAS 1275	W	T
MONTEGOMERY DAM	PA	40.605	-76.465	2004	9	18	8.80	SPAS 1275 Zone 2	E	T
HALIFAX	VT	42.7700	-72.7500	2005	10	7	15.40	SPAS 1201	E	G
RALEIGH	NC	34.340	-81.010	2006	6	13	9.32	SPAS 1526	E	T
TAMAQUA	PA	41.6750	-75.3750	2006	6	26	12.26	SPAS 1047	E	G
DELAWARE COUNTY	NY	42.010	-74.900	2007	6	19	11.69	SPAS 1049	E	L
DOUGLASVILLE	GA	33.870	-84.769	2009	9	19	25.37	SPAS 1218	W	G
WARNER PARK	TN	36.0611	-86.9056	2010	4	30	19.71	SPAS 1208	W	G
NEW BERN	NC	35.1750	-77.2150	2010	9	27	23.44	SPAS 1350	E	G
MAPLECREST	NY	42.300	-74.160	2011	8	27	22.91	SPAS 1224	E	T
HARRISBURG	PA	39.9850	-76.4950	2011	9	4	18.32	SPAS 1298	E	T
ISLIP	NY	40.805	-73.065	2014	8	13	14.23	SPAS 1415	E	L

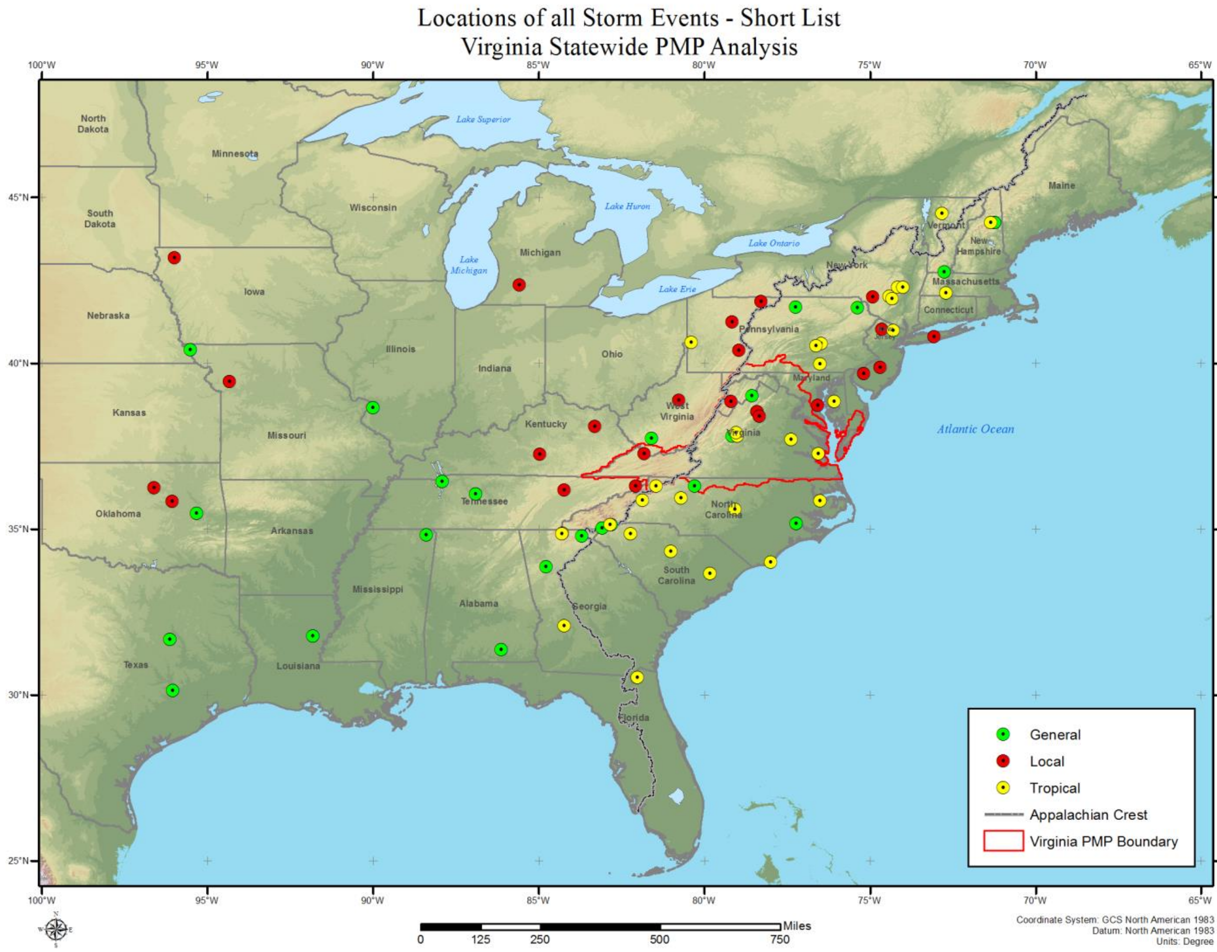

Figure 5.2 Storm locations for storms on the short storm list

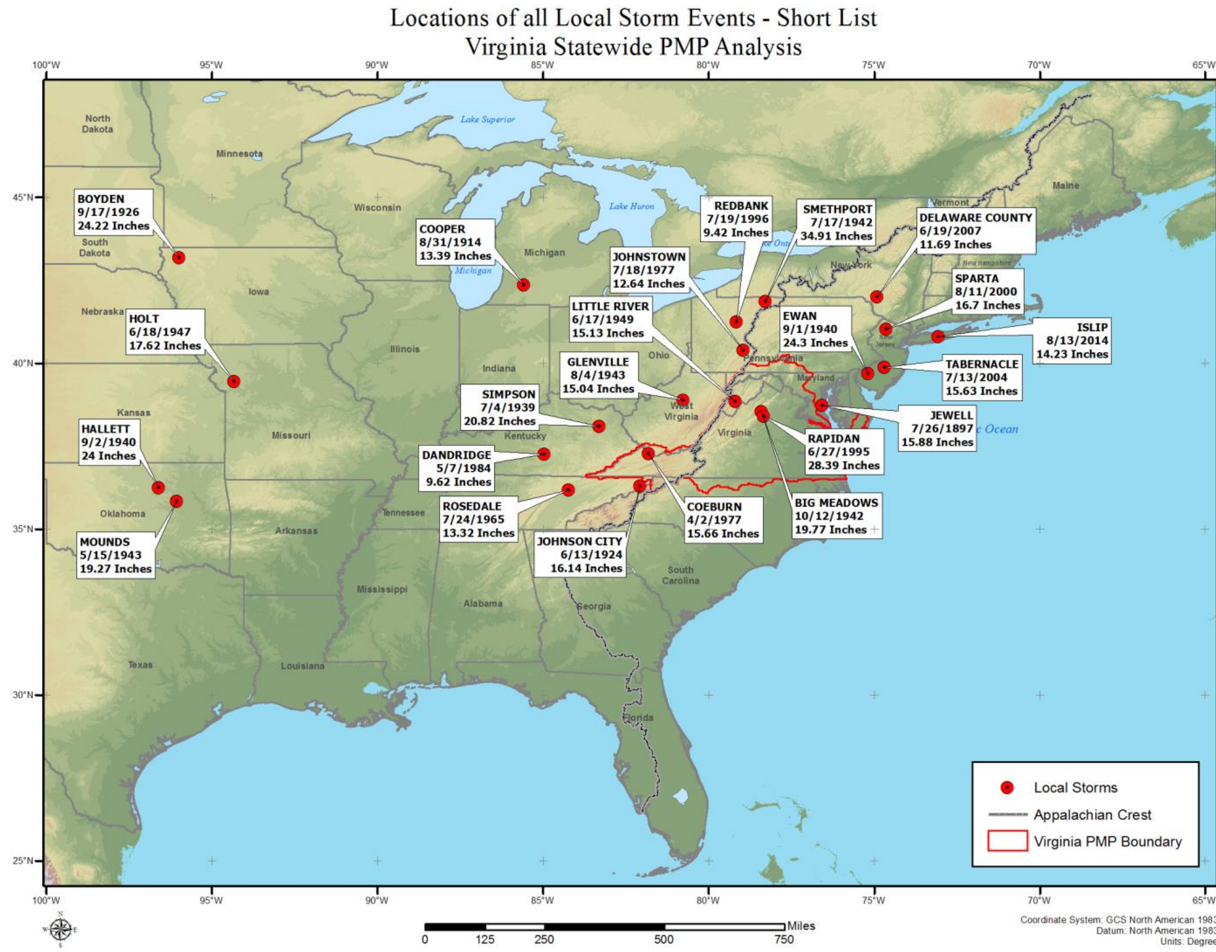

Figure 5.3 Storm locations for local storms on the short storm list

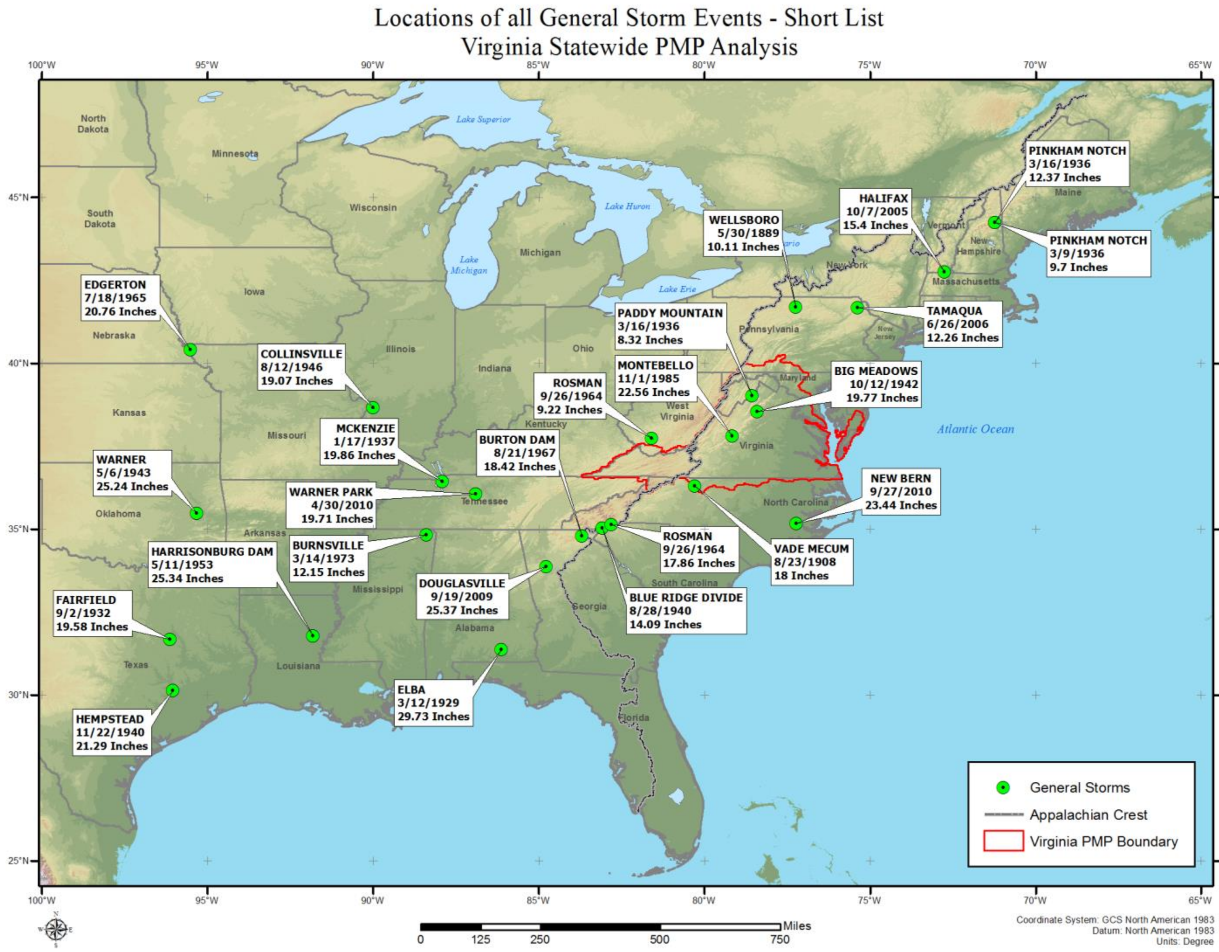

Figure 5.4 Storm locations for general storms on the short storm list

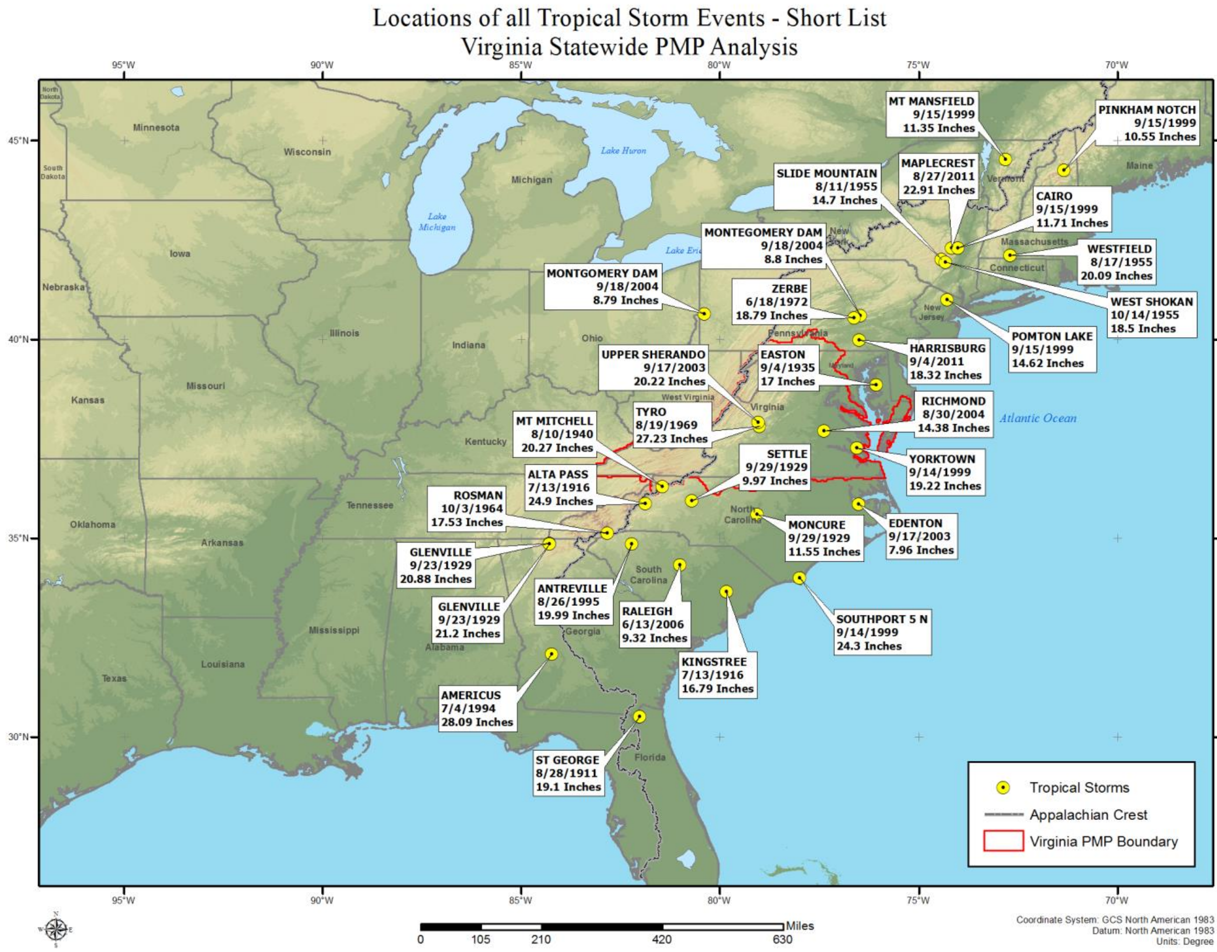

Figure 5.5 Storm locations for tropical storms on the short storm list

6. Storm Maximization

Storm maximization is the process of increasing rainfall associated with an observed extreme rain storm under the potential condition that additional atmospheric moisture could have been available to the storm for rainfall production. This assumes that the storm dynamics, which convert that atmospheric moisture into precipitation, remain constant and therefore an increase of available moisture would result in an increase in rainfall. Maximization is accomplished by increasing surface dew points or SSTs to some climatological maximum and calculating the enhanced rainfall amounts that could potentially be produced. An additional consideration is usually applied that selects the climatological maximum dew point or SST for a date two weeks towards the season with higher amounts of moisture from the date that the storm actually occurred. This procedure assumes that the storm could have occurred with the same storm dynamics two weeks earlier or later in the year when maximum dew points or SSTs could be higher. 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 2.3.4) and in the WMO manual (1986) as well as all AWA PMP studies.

The in-place maximization and moisture transposition factors depend on the determination of storm representative dew points and SSTs, along with maximum historical dew points and SSTs. The magnitude of the maximization factor varies depending on the values used for the storm representative dew point or SST and the maximum dew point or SST value. Holding all other variables constant, the maximization factor is smaller for higher storm representative values as well as for lower maximum values. 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.

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 (6-, 12-, or 24-hour) are used to determine the storm representative dew point. This value is then maximized using the appropriate climatological value representing the 100-year return interval at the same location moved two weeks towards the warm season. To determine which duration period was most appropriate for the storm representative value, the total precipitation accumulation during the duration of the storm was analyzed. The duration (3-, 6-, 12- or 24-hour) closest to when 90% of the rainfall had accumulated during the core precipitation period was used to determine the duration period. The HYSPLIT model (Draxler and Rolph, 2013) provides detailed analyses for assisting in the determination of the upwind trajectories of atmospheric moisture that was advected into the storm systems. HYSPLIT was developed to re-create past weather patterns based on all atmospheric data available. This allows the used to plot what the meteorological conditions were at any location. Using these model results and trajectories, along with ananalysis of the general synoptic weather patterns, the moisture source location is determined. The procedures followed to determine the storm representative location are similar to the approach used in HMRs. However, by utilizing the HYSPLIT model trajectories, much of the subjectivity was eliminated. Further, details of each evaluation can be explicitly provided and the HYSPLIT trajectory results based on the input parameters defined are reproducible. The storm spreadsheets presented in Appendix F list the moisture source region for each storm and dew points values used in the maximization calculations.

6.1 Storm Representative Dew Point Determination Process

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

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

The HYSPLIT model developed by the NOAA Air Resources Laboratory (Draxler and Rolph, 2013) 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 model trajectories have been used to analyze moisture inflow vectors in other PMP studies completed by AWA over the past several years. During these analyses, the model trajectory results were verified and the utility explicitly evaluated (e.g. Tomlinson et al., 2006-2013, Kappel et al., 2012-2015).

In determining the moisture inflow trajectories, the HYSPLIT model was used to compute the trajectory of the atmospheric moisture inflow associated with the storm's rainfall production, both location and altitude, for various levels in the atmosphere. The HYSPLIT model was run for trajectories at several levels of the lower atmosphere to capture the moisture source for each storm event. These included 700mb (approximately 10,000 feet), 850mb (approximately 5,000 feet), and storm center location surface elevation. For the majority of the analyses, a combination of all three levels was determined to be most appropriate for use in evaluation of the upwind moisture source location. It is important to note that the resulting HYSPLIT model 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., 2006-2013; Kappel et al., 2012-2015) and as outlined in the HMRs (e.g. HMR 51 Section 2.3) and WMO manual (Section 2.2).

The process involves deriving the average dew point (or SST) values at all stations with dew point (or SST) data in a large region along the HYSPLIT inflow vectors. Values representing the average 3-, 6-, 12-, and 24-hour dew points or daily SST are analyzed in Excel spreadsheets. The appropriate duration representing the storm being analyzed is determined and data are plotted for evaluation of the storm representative dew point (or SST). This evaluation includes an analysis of the timing of the observed dew point (or SST) values to ensure they occurred in a source region where they would be advected into the storm environment at the time of the rainfall period. Several locations are investigated to find values that are of generally similar magnitude (within a degree or two Fahrenheit). Once these representative locations are identified, an average of the values to the nearest half degree is determined and a location in the center of the stations is identified. This becomes the storm representative dew point (or SST) value and the location provides the inflow vector (direction and distance) connecting that location to the storm center location. This follows the approach used in HMR 51 Section 2, HMR 55A Section 5, and HMR 57 Section 4, with improvements provided by the use of HYSPLIT and updated maximum dew point and SST climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used). Figure 6.1 is an example map used to determine the storm representative dew point for the Tamaqua, PA June 2006, SPAS 1047 storm event.

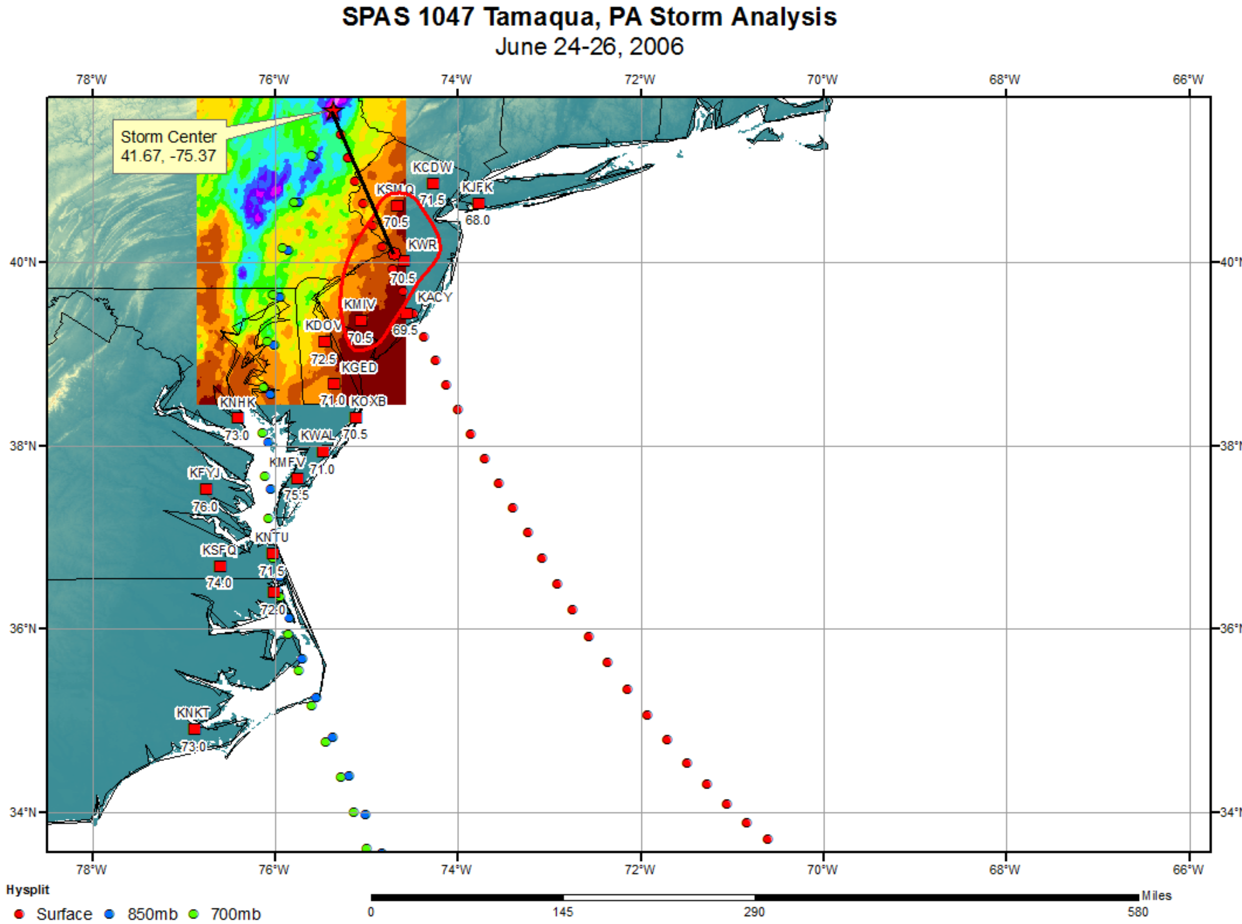

Figure 6.1 Dew point values used to determine the storm representative dew point for Tamaqua, PA, June 2006, SPAS 1047 storm event.

6.1.1 Storm Representative Dew Point Determination Example

As an example, Figure 4.2 shows the HYSPLIT trajectory model results used to analyze the inflow vector for the Madisonville, KY March, 1964 (SPAS 1278) storm. HYSPLIT trajectories showed a general inflow from the Gulf of Mexico flowing north, then northeast into the storm and along the frontal boundary. The turning of the moisture in a clockwise direction was around the western edge of the general high pressure located to the east of the Atlantic (the Bermuda High). This is a common scenario for heavy rains over the region, where moisture is drawn up around the western edge of high pressure from the Gulf of Mexico and forced to lift over a frontal system stalled over the region and then further enhanced by topography of the Appalachian Mountains. In this case, surface dew point values were analyzed for a region starting at the storm center and extending southward to the Gulf of Mexico and from Texas eastward to Georgia/Florida/South Carolina. All the HYSPLIT inflow vectors showed a south to southeast inflow direction from the storm center over Kentucky (the most common direction for general storms west of the Appalachians). The air mass source region supplying the atmospheric moisture for this storm was located over southern Texas/Louisiana/Mississippi/Alabama 24-36 hours prior to the rainfall occurring over Tennessee and Kentucky. Surface dew points were analyzed over this source region, ensuring that the dew point observations were located outside of the area of rainfall to avoid contamination of the dew points by evaporating rainfall. Figure 4.3 displays the stations analyzed and their representative 24-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

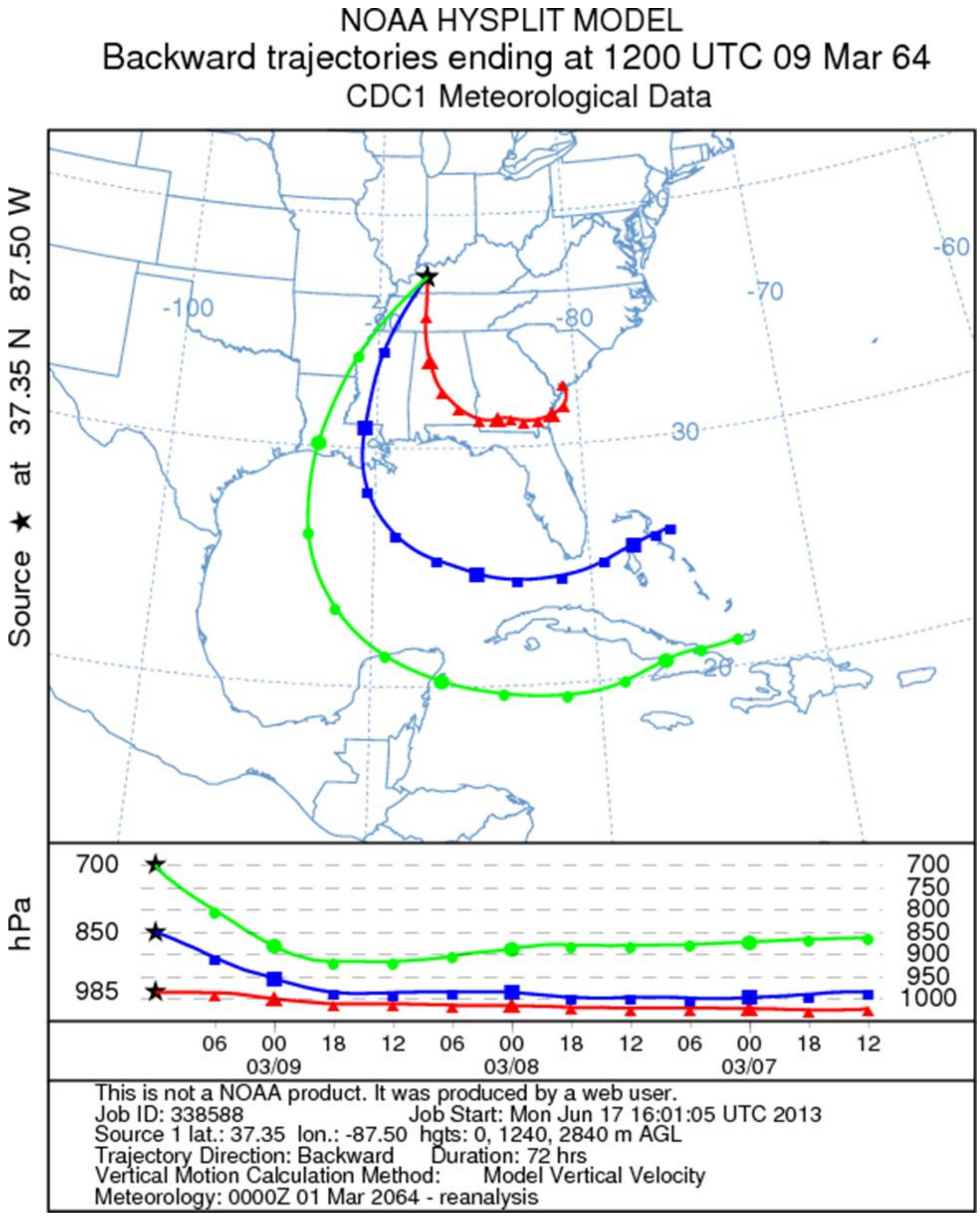

Figure 6.2 HYSPLIT trajectory model results for the Madisonville, KY March, 1964 (SPAS 1278) storm

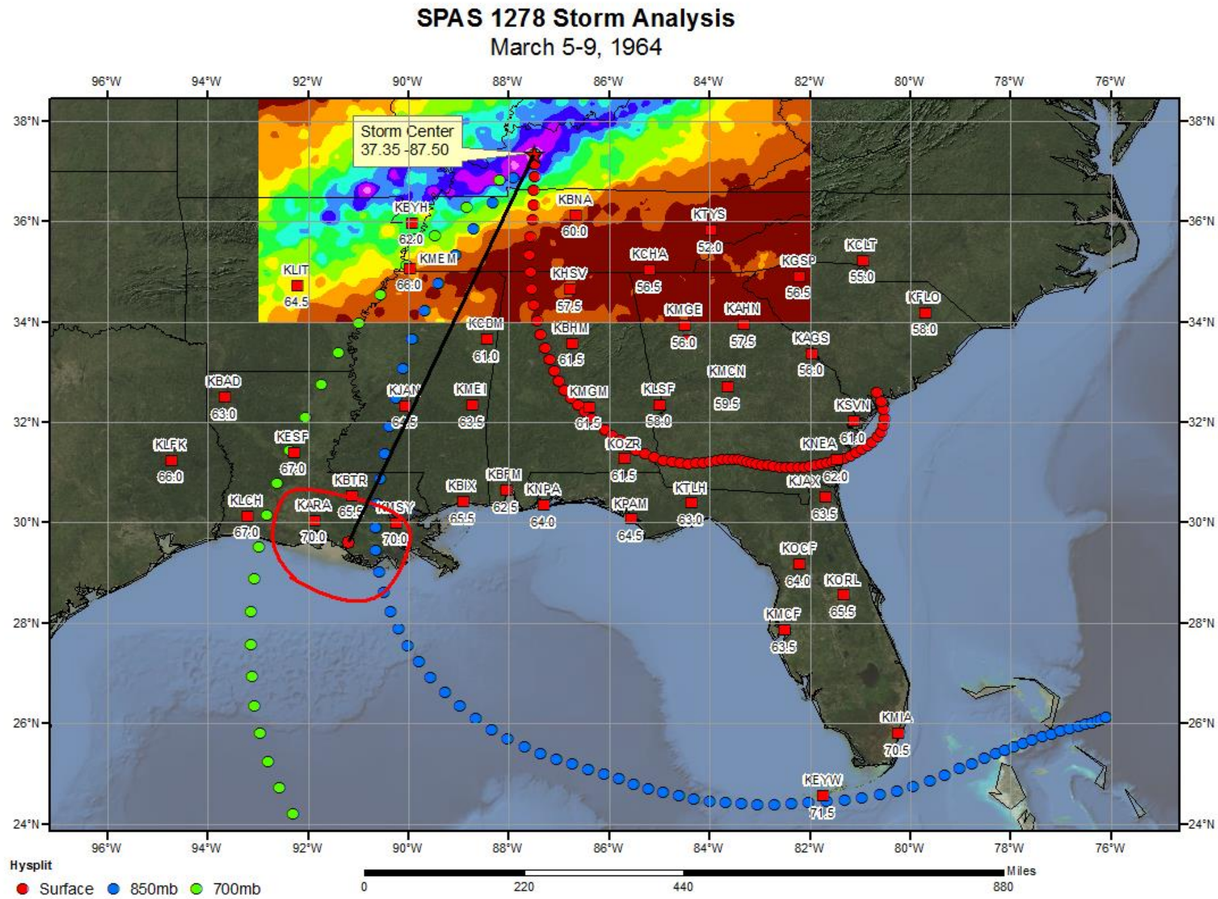

Figure 6.3 Surface stations, 24-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Madisonville, KY March, 1964 (SPAS 1278) storm.

Most storms have maximization factors that are significantly greater than 1.00, with a general average of around 1.20 (or 20%). Exceptions occur when a storm is as close to PMP as can reasonably be expected. Examples are storms like Smethport, PA July, 1942 and Tyro, VA August, 1969. In each case, the amount of atmospheric moisture available to each storm was near its maximum when combined with the extreme storm efficiency. Therefore, when maximizing these storms, the resulting maximization factors are close to 1.00. In the case of Smethport, the IPMF is 1.02 and Tyro is 1.07. 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. For example, for the Smethport storm, a 1.02 IPMF shows that the observed storm representative value was only a half degree from the 100-year value. This is not surprising given the magnitude of the rainfall this storm produced, a world record rainfall from 4.5-6 hours. To produce this much rainfall, the atmospheric environment must have contained an optimum combination of moisture and storm dynamics (both mechanical lift [from topography] and thermodynamic lift). Note that the NWS maximization of these storms was also close to 1.00.

For Smethport the value was 1.10 and for Tyro the value was 1.05 (see HMR 51 Appendix tables). Given that HMR 51 used the 12-hour persisting dew point process to maximize the storms and the fact that a 12-hour persisting data set often underestimates the true storm representative dew point for short duration events, the values are basically the same as AWA's reanalysis when corrections to the 12-hour persisting dew point process are applied as discussed in Section 4.1.

6.1.2 Rationale for Adjusting HMR 51 Persisting Dew Point Values

In previous storm analyses performed by the NWS and the USACE, a 12-hour persisting dew point was used for both the storm representative and maximum dew points. The 12-hour persisting dew point is the value equaled or exceeded at all observations during the 12-hour period (e.g., WMO 2009). However, as was established in previous and ongoing AWA PMP studies, this dew point methodology tends to underestimate and not accurately reflect the available atmospheric moisture associated with the rainfall event.

An excellent example of this (from the Nebraska statewide PMP study but relevant for the local storm type that affects Virginia) is illustrated by the David City, NE 1963 storm. During this extreme storm event, a narrow tongue of moisture was advected into the region by strong southeasterly flow during a short time period. Most of the rain with this event (approximately 15 inches) accumulated in less than 6 hours. For this storm, hourly dew point data were collected from several locations near the rainfall event. These included Omaha, NE; Des Moines, IA; Topeka, KS; and Kansas City, MO. Following standard procedures for determining storm representative dew point location, it was determined that Topeka, KS and Kansas City, MO were the two stations that best represented the air mass that produced the extreme rainfall. Using hourly dew point data for these two stations clearly showed that use of 6-hour average dew point values better represented the atmospheric moisture available to the storm event than did use of 12-hour persisting dew point values. The 6-hour average dew point representing the moisture in the air mass associated with the rainfall was 71.5°F at Kansas City, MO and 71°F at Topeka, KS. Using these dew point values, a 1000mb 6-hour average dew point of 73.5°F was determined for Kansas City, MO and a dew point of 73°F was determined for Topeka, KS. Using the NWS approach, the 12-hour persisting dew point is 63°F (65°F at 1000mb) at Kansas City, MO and 66°F (68°F at 1000mb) at Topeka, KS for an average 12-hour persisting 1000mb adjusted value of 66.5°F (Table 6.1).

Table 6.1 Comparison of 6-hour average storm representative dew point vs. 12-hour persisting storm representative dew point for the David City, NE, 1963 storm

Observed Dew Point Values for David City, NE 1963																								
Kansas City, MO																								
Hour	00Z	01Z	02Z	03Z	04Z	05Z	06Z	07Z	08Z	09Z	10Z	11Z	12Z	13Z	14Z	15Z	16Z	17Z	18Z	19Z	20Z	21Z	22Z	23Z
Dew Point	58	61	62	62	63	63	_63_	64	66	68	69	**71**	**72**	**72**	**72**	**71**	**71**	69	68	67	67	67	67	67
												Air Mass Supplying Rainfall Event												
12-Hour Persisting Td 63 (65 reduced to 1000mb)							***12 Hour Persisting Td Timeframe***																	
6-Hour Average Td 71.5 (73.5 reduced to 1000mb)												**6 Hour Average Td timeframe**												
Topeka, KS																								
Hour	00Z	01Z	02Z	03Z	04Z	05Z	06Z	07Z	08Z	09Z	10Z	11Z	12Z	13Z	14Z	15Z	16Z	17Z	18Z	19Z	20Z	21Z	22Z	23Z
Dew Point	61	62	64	65	65	65	_66_	66	67	68	69	**72**	**71**	**71**	**71**	**70**	**70**	70	69	70	69	68	66	69
												Air Mass Supplying Rainfall Event												
12-Hour Persisting Td 66 (68 reduced to 1000mb)							***12 Hour Persisting Td Timeframe***																	
6-Hour Average Td 71 (73 reduced to 1000mb)												**6 Hour Average Td timeframe**												

The 12-hour persisting dew point analysis included dew point values from a 6-hour period not associated with the rainfall. The hourly dew point value that provides the 12-hour persisting dew point occurred outside of the rainfall period after adjustment for advection time from the dew point observing station to the storm location.

6.1.3 Background on Adjusting HMR 51 Persisting Dew Point Values

In some cases, (e.g., storms on the short storm list previously analyzed in the USACE Storm Studies and used in NWS HMRs), an adjustment factor was applied to provide consistency in storm maximization while utilizing the updated dew point climatology. The adjustment factor was determined using the same procedure used in the FERC Michigan/Wisconsin and subsequent AWA PMP studies.

Results from the dew point analyses showed consistent results for Local/MCS and General type storms for differences between the older method for determining 12-hour persisting storm representative dew points and the approach using average storm representative dew points. The following discussion from the FERC Michigan/Wisconsin report addresses these differences:

The average difference between dew points for the synoptic storms was five degrees less than that for the MCS storms. This may be attributed to the greater homogeneity of inflow moisture associated with the synoptic events. With most of the modern MCS storms, limited-area, short-duration pockets of relatively moist air were found within the inflow moisture at one or two locations. The analyses may indicate that for MCS events, bubbles of extremely moist air interact with storm catalysts to create extreme rainfall events of short duration. A warm humid air mass over a broad area with small moisture gradients more aptly describes the synoptic inflow moisture. Several stations within the air mass may have the same or similar dew points. Much smaller variations in dew points along the inflow moisture vector are expected.

Large spatial and temporal variations in moisture associated with MCS-type storms are not represented well with 12-hour persisting dew points, especially when only two observations a day are available. Average dew point values, temporally consistent with the duration of the storm event provide a much improved description of the inflow moisture available for conversion to precipitation. The more homogeneous moist air masses associated with synoptic storms result in smaller differences between average and persisting values.

This analysis has provided correlations between 12-hour persisting storm dew points and average storm dew points for both MCS and synoptic storms. Despite the small sample size, the consistent results tend to support the reliability of the analysis. However, the small sample size has been considered in making recommendations for adjusting the old storm representative dew points for use in determining PMP estimations. The eight degree difference for MCS-type storms has been decreased to five degrees to provide a conservative adjustment. A similar consideration is made for synoptic-type storms. The three-degree difference is decreased to two degrees to provide a conservative adjustment. The adjusted representative storm dew points are used with the new maximum average dew point climatology to maximize storms.

Similar analyses were completed in the Nebraska, Ohio, and Wyoming statewide PMP studies for storms which were relevant for Virginia. Results of these analyses confirmed what has been found in previous studies, with an average difference of 7°F between the average and 12-hour persisting dew points for Local/MCS storms and an average difference was 2°F for General storms. Therefore, results of the more recent analyses were very consistent with the

FERC Michigan/Wisconsin regional PMP study. This validated the process of adjusting the 12-hour persisting dew points to achieve compliance with using the average dew point climatology.

6.2 Storm Representative Sea Surface Temperatures (SSTs) Calculation Example

The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for many storms where the inflow vector originated over the Atlantic Ocean. The storm spreadsheets presented in Appendix F list the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations. For storm maximization, the value for the maximum SST was determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs were used in the same manner as storm representative dew points and maximum dew point climatology representing the 15th of the month values in the maximization and transpositioning procedure. Figure 7.2 is an example of a daily SST map used to determine the storm representative SST for the SPAS 1276, June 1972 storm event.

In this example, the first decision was whether surface dew points were available to derive the storm representative dew point. However, this was not possible for this storm because there was rainfall to the coast, thereby contaminating the dew point readings along the inflow pathway to the Atlantic. Next, SSTs were investigated to determine regions of homogenous temperatures in a region that was appropriate in time and space according to the HYSPLIT trajectories. Several regions were possibilities in this case. Next, the track of the Hurricane and its relation to advecting moisture into the storm center was considered. This better matched the surface (red dots) HYSPLIT trajectory. Finally, sensitivity calculations were performed using several couplets of storm representative SST values versus the +2-sigma climatological maximum values to ensure the range of maximizations was within a reasonable range (i.e. greater than 1.00). After the investigations were completed, the storm representative location of 36.0°N and 67.0°W was chosen. This was an average of several of the SST values within the red circled area of Figure 6.2 on June 18 and June 19, 1972.

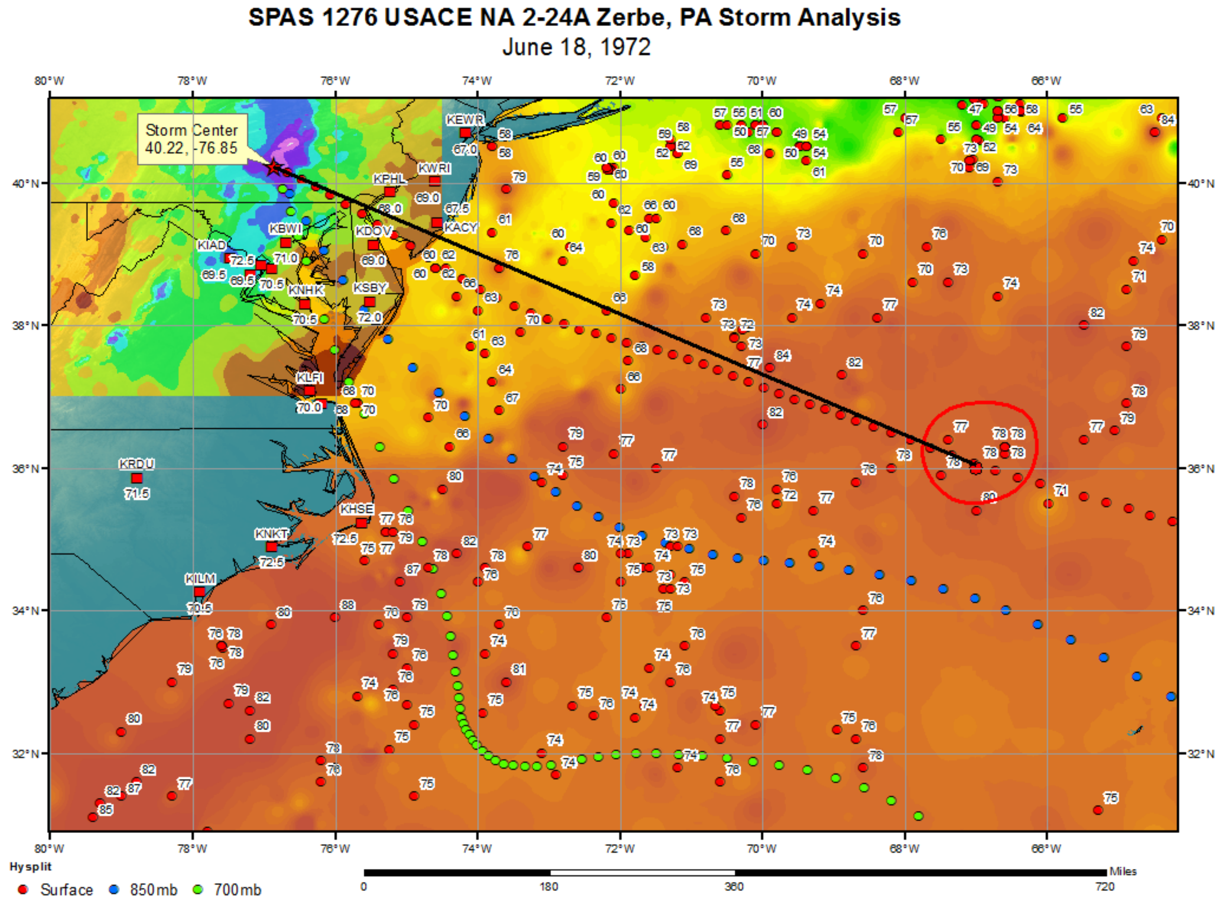

Figure 6.4 Daily SST observations used to determine the storm representative SST value for the SPAS 1276, June 1972 storm event.

7. Storm Transpositioning

Extreme rain events in topographically and meteorologically similar regions surrounding a location are a very important part of the historical evidence on which a PMP estimate for that location 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 another location is called storm transpositioning. The underlying assumption is that storms transposed to the location could have occurred under similar 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 transposing a storm are quantified by using the OTFs and MTFs as discussed in Section 8.

The search for extreme rainfall events identified storms that occurred throughout the New England states, Mid-Atlantic region, Appalachians Mountains and the Great Plains (see Figure 5.1). This region was considered meteorologically and geographically similar to one or more locations within the Virginia study region.

The storms on the eastern side of the Appalachian crest are supplied with low-level atmospheric moisture primarily from the Atlantic Ocean; conversely storms on the western side receive their moisture from the Gulf of Mexico. These air masses cannot cross the Appalachians without significant loss of moisture content and changes to the storm structure. Transposition limits were defined by dividing the state into seven transposition zones. Each transposition zone was delineated after careful consideration of a combination of criteria including; physiographic provinces (defined by the USGS), climatological zones defined by NCDC and the Köppen classification (Ahrens, 2007), variations in topography, and ecological regions. These criteria helped identify regions of similar meteorology and topography. Seven transposition zones were defined as follows (Figure 7.1):

1. Interior Valley
2. Cumberland Plateau
3. Great Valley
4. Blue Ridge West
5. Blue Ridge East
6. Piedmont
7. Coastal Plain

It is recognized that these boundaries are not discrete boundaries in nature, but transitional zones. However, for the purpose of this study, these zones provide a good estimation of acceptable transpositionable extents for each storm.

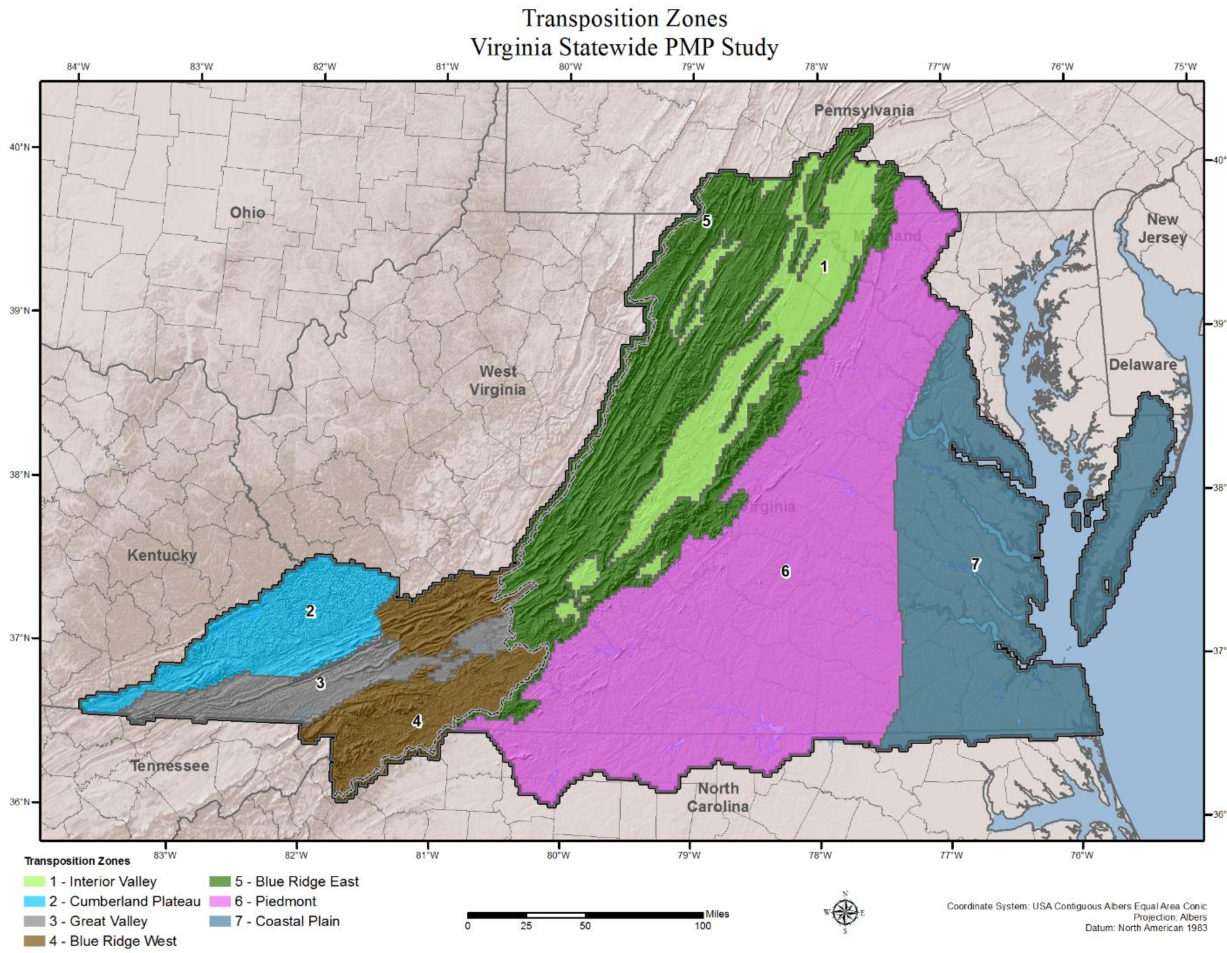

Figure 7.1 Transposition zones used to define transposition limits for individual storms

The 79 SPAS DAD zone centers on the short storm list were individually evaluated to determine their unique transposition limits. Initially, general transposition limits were placed on all storms and their individual DAD zones based on subjective judgments of the meteorology associated with each, the moisture source regions, and the interaction with topography at the original location versus other areas being considered for transpositioning. Initial results were presented at various Review Board meetings and the limits were refined during and between subsequent meetings. During the meetings, discussions with all members present took place to explicitly define transposition limits for each of the 79 SPAS DAD zones. Each storm's meteorological characteristics were evaluated, including the storm type, the seasonality, the storm isohyetal patterns, and the storm's moisture source. These factors were evaluated for each storm to provide reasoning as to where the storm could be transpositioned. Each storm was assigned to one or more of the seven transposition zones across the study domain. It should be noted that conservative transposition limits were employed (i.e., moving storms to larger regions than may be justified if all controlling factors were fully understood) unless there was justification for a more refined analysis. This is because the transposition process involves some subjectivity and although it produces a binary answer (either a storm is transpositionable to a point or not), in actuality there are gradients in meteorology that need to be considered.

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

For all storms, the IPMF does not change during this process. The MTF and OTF change as a storm is moved from its original location to a new location. Further, because the MTF represents the horizontal difference in available moisture between the original location and the new location (i.e. no elevation difference component is applied when used with the OTF), this factor does not vary as much as the OTF across the region. Generally, most MTFs result in less than a +/-10% change. Therefore, the largest contributing factor to the variation of PMP over a specific area in the transposition process is the OTF. This is to be expected, as the topography across Virginia varies significantly in elevation, aspect, and slope, often over very short distances.

Questions regarding whether the MTF process is already accounted for (called "double counting") in the OTF calculation received extensive discussion. In previous PMP studies completed by AWA (e.g. Tomlinson et al., 2013; Kappel et al., 2014; Kappel et al., 2015), this question was also discussed extensively. During this study, further evaluation and discussion demonstrated that the MTF is most likely not being "double counted" in the PMP calculation process. This is because the MTF process is setting the moisture levels for all storms used to their climatological maximum level (using the 100-year recurrence interval climatological maps) in order to compare the difference between the two locations being analyzed assuming all storms had occurred with their maximum moisture instead of what actually occurred. Evaluations of the MTF will continue in future studies. However, including it as a separate calculation was important as this allowed the effect to be explicitly delineated and will allow for explicit correction if needed. Note that the OTF is comparing the differences of the rainfall resulting from both moisture and topography interactions at two locations. The moisture component in the OTF process does not represent the climatological maximum amount, but represents the actual amount of moisture associated with each given event that went into the development of the precipitation frequency climatologies.

The spatial variations in the OTF were useful in making decisions on transposition limits for a storm. As described in Section 6, values larger than 1.50 for a storm's maximization factor exceed reasonable limits. In these situations, changing a storm by this amount is likely also changing the storm characteristics. The same concept applies to the OTF. OTF values greater than 1.50 (or less than 0.50) indicate that transposition limits have most likely been exceeded. Mapping the OTF and MTF values across the region studied provided visual guidance to aid with defining transposition zones allowing areas of excessively large transposition factors to be defined as non-transposable. Therefore, storms were reevaluated for transpositionability in regions which resulted in an OTF greater than 1.50 or less than 0.50. In some high elevation locations where there was a lack of extreme rainfall data and the OTF was greater than 1.50, a cap of 1.50 was applied to be consistent with the IPMF cap. This followed the same process as employed in the Arizona (2013) and Wyoming (2014) statewide studies and the TVA regional PMP study (2015).

From these analyses, refinements such as limiting a storm's transposition location using an elevation constraint or by an OTF amount were applied. An example of the Halifax, VT October, 2005 (SPAS 1201 DAD Zone 1) storm is provided. This storm occurred on the east side of the Appalachians, with a storm center elevation of 1,500 feet. The storm is only transpositionable to transposition zones 1, 5, 6 and 7 (see Figure 7.1 for locations of the transposition zones used). Elevation, terrain, synoptic meteorology, moisture source, storm type, and distance are examined to further refine the transposition limits. Figure 7.2 shows the OTF values for the storm across the statewide domain. In this scenario, in the regions where this storm is considered transpositionable (all of zones 1, 5, 6 and 7) there are many locations where OTF values are above 1.50. This results from both moving this storm a long distance from its location in Vermont to Virginia (over 4° of latitude), and the associated differences in precipitation frequency climatology between the two regions. Therefore, a limitation of the OTF in areas where the value is 1.50 or higher is required. This is because increasing the storm by more than 50% would significantly alter its dynamics, violating the definition of transpositionability.

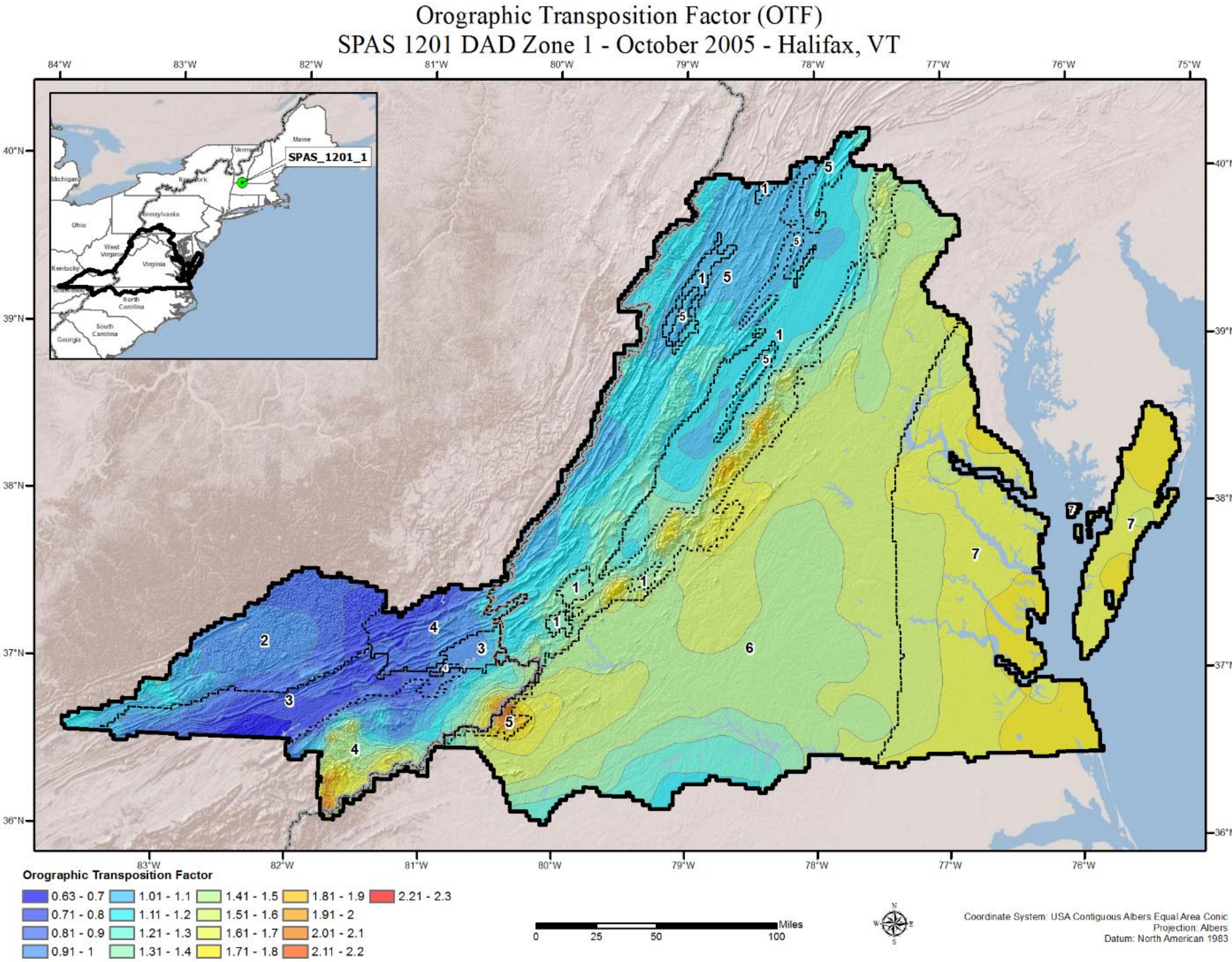

Figure 7.2 Orographic Transposition Factors for Halifax, VT October 2005, SPAS 1201.

8. Development of PMP Values

Gridded PMP depths were calculated by comparing the total adjusted rainfall values for all transpositionable storm events over each grid point and taking the largest value. In this process, all transposable storms are considered independently at each grid point for the analyzed duration and area size. This approach provides a site-specific calculation for each grid point across the analysis domain. During this process, durational envelopment occurs because the largest PMP depth for a given duration is identified after analyzing all the transpositionable storms for each grid point at each location for each duration at the area size(s) specific to the basin being analyzed. In addition, several storms can control the PMP depth at a specific area size for a given basin at various grid points and/or durations. This is similar to the HMR process of envelopment, which encompasses several different storms for each area size.

The adjusted rainfall at a grid point, for a given storm event, was determined by applying a total adjustment factor (TAF) to the SPAS analyzed DAD value corresponding to the area size being analyzed (in square miles) at the appropriate duration. The TAF is the product of the three separate storm adjustment factors; the IPMF, the MTF, and the OTF. In-place maximization and moisture transposition are described in Sections 7 and 8. Orographic transposition is described in Section 3. These calculations were completed for all storms for every grid point analyzed over the entire domain. Several storms have multiple centers analyzed. Each SPAS DAD zone was considered as an independent event for the purpose of PMP calculation. In addition, one of the storms was considered a hybrid-type storm exhibiting characteristics of both local and general storms. In this situation, this storm was analyzed as both a local and general storm type event with separate PMP values developed for each scenario. In total there were 79 separate events analyzed; 22 local storms, 24 general storms, 31 tropical storms, and 1 hybrid type storm.

An Excel spreadsheet with storm adjustments was produced for each of the analyzed events. These spreadsheets are designed to perform the calculation of each of the three adjustment factors, along with the final TAF. The spreadsheet format allows for the large number of calculations to be performed correctly and consistently in an efficient template format. In addition to the IPMF, MTF, and OTF calculations, a Boolean transpositionability flag for each grid point is stored within the spreadsheets, allowing a conditional statement to determine if the given storm is transpositionable to the grid point based on predetermined criteria (see Section 7). Information such as precipitation climatological values, coordinate pairs, grid point elevation values, equations, and the precipitable water lookup table remain constant from storm to storm and remain static within the spreadsheet template. The spreadsheet contains a final adjusted rainfall tab with the adjustment factors, including the TAF, listed for each grid point. For each storm, this table was exported to a GIS feature class to be used as input for the PMP Evaluation Tool, a scripted GIS tool that automates the calculation and production of PMP gridded datasets (see Section 8.7.1). At any point in the future, new storm feature classes could be added, removed, or edited.

The PMP Evaluation Tool receives the storm TAF feature classes and the corresponding DAD tables for each of the storm events as input, along with a basin outline feature layer as a model parameter. The tool then calculates and compares the total adjusted rainfall for each transpositionable storm at each grid point within the statewide analysis domain and determines the PMP depth for each duration separately for all storm types. The durations calculated for general/tropical storms PMP were 1-, 6-, 12-, 24-, 48-, and 72-hours. The durations calculated for local/MCS storms PMP were 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hours. The PMP area sizes calculated for general/tropical storm PMP were 1-, 10-, 100-, 200-, 500-, 1,000-, 5,000-, and 20,000-square miles. The PMP area sizes calculated for local storm PMP were 1-, 10-, 100-, 200-, and 500-square miles.

The following sections describe the procedure for calculating the IPMF, the MTF, the OTF, and the TAF for the creation of the storm adjustment feature classes. Examples of each of these calculations are presented followed by discussion of the implementation and application of the PMP Evaluation Tool to calculate PMP.

8.1 Available Moisture at Source and Target Locations

The available atmospheric moisture, in terms of precipitable water depth, must be determined for the storm center location to calculate both the IPMF and MTF. The IPMF is determined by taking the ratio of the maximum precipitable water depth at the storm representative dew point location to the storm representative precipitable water depth at the same point location. The MTF is determined by taking the ratio of the maximum precipitable water depth at the transposition location to the maximum precipitable water depth at the storm representative location. Identification of storm representative dew point (or SST) values and locations are described in Section 6.1. Note that in the final total adjustment factor calculation, the climatological maximum precipitable water depth at the storm center is used in both the numerator of the IPMF and denominator of the MTF and is ultimately cancelled out of the equation, mathematically having no impact on the total adjustment factor. However, it is still important to calculate the storm center precipitable water, and the MTF and IPMF individually, so that the proportion of each component can be quantified for transparency and quality/error control purposes.

The precipitable water depth is obtained from a lookup table stored within the storm adjustment spreadsheets. The lookup table is a digital version of the precipitable water table found in Appendix C of HMR 55A and Annex I of the WMO PMP Manual (2009). The precipitable water tables provide an equivalent amount of precipitable water based on a dew point temperature starting sea level through the top of the atmosphere. Values are provided for temperatures every 0.5°F through the entire atmospheric column required to represent the amount of precipitable water available for rainfall production (sea level through 30,000 feet).

To determine the temperatures to use from the precipitable water lookup table, GIS was used to extract the values from the appropriate monthly climatological maximum dew point raster files at the appropriate duration. ArcGIS was used to extract the dew point (or SST) temperatures to point features stored within shapefiles. For each storm there was a point feature at the storm center, and a series of 24,372 point features across the domain. Before the extraction, each of these point features was shifted a distance in the *x* and *y* direction equivalent to the moisture inflow vector components for the given storm. This allows for the extraction of dew point (or SST) temperatures that are representative of the moisture source location. The monthly maximum average dew point and SST temperature values were linearly interpolated between the bounding monthly values according to the temporal transposition date. The moisture inflow vectors and temporal transposition date for each storm are in Appendix F.

The precipitable water was calculated for each event, within the storm adjustment spreadsheet, for the storm center grid cell and each of the target grid cells within the project domain using the lookup table with the storm center elevation. Storm center elevations were rounded to the nearest 100 feet, or nearest 500 feet for elevations above 5,000 feet, to coincide with the values in the precipitable water lookup table.

As described in Section 6, the precipitable water depths are adjusted for elevation. This is done 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 be present in the atmospheric column between sea-level and the surface elevation at the storm location using Equation 8.1.

$$W_p = W_{p,30,000'} - W_{p,elev} \qquad \text{Equation 8.1}$$

where,

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

8.2 In-Place Maximization Factor

In-place storm maximization is applied for each storm event using the methodology described in Section 6. Storm maximization is quantified by the IPMF using Equation 8.2.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 8.2}$$

where,

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

8.3 Moisture Transposition Factor

The difference in the climatological maximum amount of available atmospheric moisture between the storm center location and the basin target grid point is quantified as the MTF. This MTF represents the change due to horizontal distance only. The change due to vertical displacement is quantified inherently within the OTF, described in the next section. The MTF is calculated as the ratio of precipitable water for the maximum dew point (or SST) at the target grid point location to precipitable water for the storm maximum dew point (or SST) at the storm center location as described in Equation 8.3.

$$MTF = \frac{W_{p,trans}}{W_{p,max}} \qquad \text{Equation 8.3}$$

where,

$W_{p,trans}$	=	precipitable water at the target location (in.)
$W_{p,max}$	=	precipitable water at the storm center location (in.)

8.4 Orographic Transposition Factor

Section 3.1 provides details on the methods used in this study to define the orographic effect on rainfall. The OTF is calculated by taking the ratio of transposed rainfall to the in-place rainfall.

$$OTF = \frac{P_o}{P_i} \qquad \text{Equation 8.4}$$

where,

P_o	=	transposed rainfall (in.)
P_i	=	SPAS-analyzed in-place rainfall (in.)

The orographically adjusted rainfall is determined by applying the function in Equation 3.1 to SPAS-analyzed rainfall depth for the appropriate duration (24-hour for general/tropical storm and 6-hour for local storm events).

$$P_o = mP_i + b \qquad \text{Equation 8.5 (from Equation 3.1)}$$

where,

P_o	=	target orographically adjusted rainfall (inches)
P_i	=	SPAS-analyzed in-place rainfall (inches)
m	=	slope of least squares line
b	=	origin offset (inches)

8.4.1 OTF Calculations for Smethport, PA and Simpson, KY

The Smethport, PA July, 1942 and Simpson, KY July, 1939 storms were transposed to the orographic regions of the project area in southwestern Virginia; Smethport to zone 4 and Simpson to zones 2, 3, and 4. The resulting OTF in these areas was greater than one due to the positive relationship of the precipitation climatology at the storm center locations to the transposed target location. Each of these events produced rainfall accumulations that were assumed to approach the upper limit of what was possible for the associated meteorological conditions. In the case of Smethport, this produced a world record rainfall at 4.5 and 6 hours. In addition, the highest rainfall accumulations were not recorded in standard rain gauges, but instead were collected during bucket surveys after the storm had occurred. Further, very little to no hourly data were available. Therefore, significant subjective decisions were made to determine rainfall accumulations for durations less than 3 hours for Simpson, KY and less than 4 hours for Smethport, PA. Initial adjustment of these storms to various locations within the transposition zones resulted in unreasonable total adjustment values for many locations. This resulted in total adjusted rainfall values that were much greater than world record rainfalls and produced anomalous patterns when plotted against the world record rainfall curve (Figure 8.1).

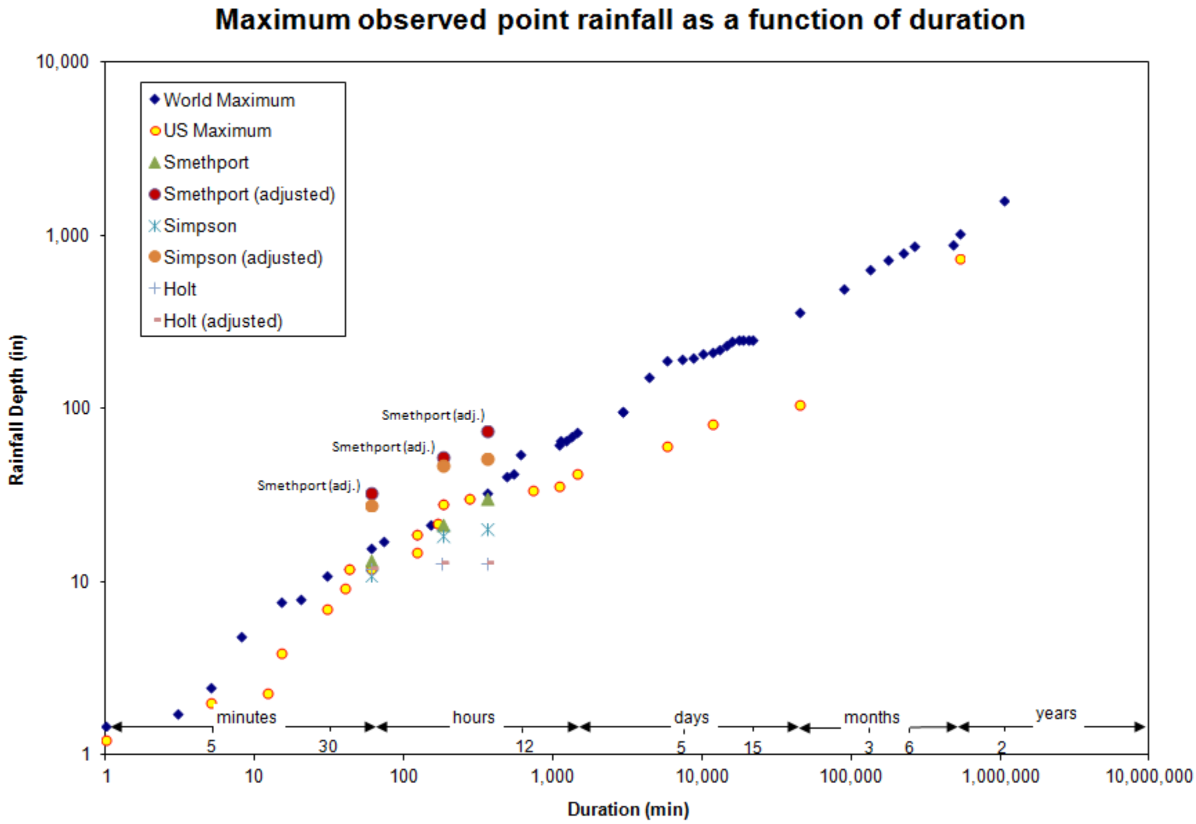

Figure 8.1 Comparison of total adjusted values of the Smethport, PA, Simpson, KY, and Holt, MO storms without constraint compared to the world record rainfalls.

Extensive discussions between AWA and the review board from the TVA PMP study (2015) took place to develop a conservative, yet reasonable way to adjust these events. These discussions and transposition approaches are considered to also be applicable to this study as they are applied to the same location where there is overlap between the TVA study and this study. Although subjectivity was involved in the decisions on how to adjust these storms, meteorological reasoning and comparisons against similar storms were utilized as much as possible.

Evaluations of the meteorological pattern associated with both events were considered and discussed in detail (see daily weather maps in Appendix F and meteorological description by Eisenlohr in USGS Water Supply Paper 1134-B, 1952). It was determined that the factors leading to extreme levels of moisture and instability combined with terrain influences were similar to what could occur over the foothills and mountainous terrain in southwestern Virginia. Because of the similarity to the meteorological conditions and terrain, it was determined to be unreasonable to further adjust the events upward based on the OTF. For the Smethport, PA July, 1942 storm specifically, this was most pronounced because the storm was already moved far from its original location and therefore at the edge of reasonable transposition limits. This distance of transposition from north to south further increased the total adjustment of the storm due to the increase in dew point climatology between the two locations. However, the meteorology of the two events is not adequately reflected in the north to south gradient of dew point climatology. This is due to the low-level moisture inflow coming from the west/northwest and localized sources for both storm events. This meteorological pattern is related to the flow of moisture in a clockwise fashion around the Bermuda High to the east and is also evidenced by the storm representative dew point determination which showed in both cases the storm representative locations was to the west/northwest of each storm center. This westerly flow of low-level moisture was very important in both cases in producing extreme rainfall accumulations as a result of optimal moisture interaction with terrain forcing. This same flow pattern would be required in Virginia for this storm interaction to take place.

The result of these analyses and discussions resulted in a consensus decision that it was not reasonable to apply a further increase in magnitude due to topographical influence. To account for this, the OTF factors for these events were normalized to a maximum of 1.00. This was accomplished by applying a reduction factor to each target grid point based on the ratio of the originally calculated OTF at that grid point to the highest calculated OTF from all grid points. The resulting normalized OTF provides a spatial distribution based on the precipitation climatology without increasing rainfall unrealistically.

8.5 Total Adjusted Rainfall

The TAF is a product of the linear multiplication of the IPMF, MTF, and OTF. 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.

$$TAF = IPMF * MTF * OTF \text{ (from Equation 1.1)}$$

The TAF, along with other data relevant to each grid point, is exported and stored within the storm's adjustment factor feature class. The feature class includes a spatial component, a point feature at each grid cell centroid, and a table component as shown in Figure 8.2. For each feature, the table stores the grid point ID, the storm ID, the latitude and longitude coordinate pair, the transposition zone number, the elevation (in feet), the storm adjustment factors, and the transpositionability flag.

Contents | Preview | Description

OBJECTID *	Shape *	CNT	STORM	LON	LAT	ZONE_	ELEV	IPMF	MTF	OTF	TAF	TRANS
1	Point	1	1211_1	-106.325	40.325	3	10731.62764	1.3	1.359649	0.454047	0.802548	0
2	Point	2	1211_1	-106.3	40.325	3	10669.29168	1.3	1.359649	0.45575	0.805558	0
3	Point	3	1211_1	-106.25	40.325	3	10718.50428	1.3	1.359649	0.451202	0.79752	0
4	Point	4	1211_1	-106.225	40.325	3	10416.667	1.3	1.359649	0.446863	0.78985	0
5	Point	5	1211_1	-106.2	40.325	3	10629.9216	1.3	1.359649	0.446376	0.788989	0
6	Point	6	1211_1	-106.175	40.325	3	9924.541	1.3	1.359649	0.454005	0.802474	0
7	Point	7	1211_1	-106.15	40.325	3	11200.78776	1.3	1.359649	0.489492	0.865199	0
8	Point	8	1211_1	-106.125	40.325	3	11046.58828	1.3	1.359649	0.518222	0.91598	0
9	Point	9	1211_1	-106.45	40.35	3	9589.89532	1.3	1.359649	0.559971	0.989772	0
10	Point	10	1211_1	-106.425	40.35	3	9655.51212	1.3	1.359649	0.546669	0.966262	0
11	Point	11	1211_1	-106.4	40.35	3	10305.11844	1.3	1.359649	0.561633	0.99271	0
12	Point	12	1211_1	-106.375	40.35	3	10698.81924	1.3	1.359649	0.577728	1.02116	0
13	Point	13	1211_1	-106.35	40.35	3	10859.5804	1.3	1.359649	0.586313	1.036334	0
14	Point	14	1211_1	-106.325	40.35	3	10725.06596	1.3	1.359649	0.597527	1.056155	0
15	Point	15	1211_1	-106.3	40.35	3	11174.54104	1.3	1.359649	0.605827	1.070825	0
16	Point	16	1211_1	-106.275	40.35	3	10725.06596	1.3	1.359649	0.601789	1.063688	0
17	Point	17	1211_1	-106.25	40.35	3	10528.21556	1.3	1.359649	0.59197	1.046334	0
18	Point	18	1211_1	-106.225	40.35	3	9927.82184	1.3	1.359649	0.572856	1.012548	0
19	Point	19	1211_1	-106.2	40.35	3	9652.23128	1.3	1.359649	0.567762	1.003544	0
20	Point	20	1211_1	-106.175	40.35	3	10882.54628	1.3	1.359649	0.584418	1.032985	0
21	Point	21	1211_1	-106.15	40.35	3	10364.17356	1.3	1.359649	0.595843	1.053179	0
22	Point	22	1211_1	-106.125	40.35	3	10419.94784	1.3	1.359649	0.595564	1.052685	0
23	Point	23	1211_1	-106.1	40.35	3	9803.14992	1.3	1.359649	0.575382	1.017014	0
24	Point	24	1211_1	-106.075	40.35	3	9996.71948	1.3	1.359649	0.559648	0.989202	0
25	Point	25	1211_1	-106.05	40.35	3	9885.17092	1.3	1.359649	0.557122	0.984738	0
26	Point	26	1211_1	-106	40.35	3	9763.77984	1.3	1.394737	0.571341	1.035932	0
27	Point	27	1211_1	-105.975	40.35	3	11286.0896	1.3	1.394737	0.638412	1.157541	0
28	Point	28	1211_1	-105.95	40.35	3	11466.5358	1.3	1.394737	0.665938	1.207451	0
29	Point	29	1211_1	-106.6	40.375	3	9596.457	1.3	1.359649	0.672087	1.187942	0
30	Point	30	1211_1	-106.575	40.375	3	8671.26012	1.3	1.359649	0.662267	1.170585	0
31	Point	31	1211_1	-106.55	40.375	3	8897.63808	1.3	1.359649	0.659118	1.165019	0

1 (of 48343)

Figure 8.2 Example of a storm adjustment factor feature class table

For a grid point, the total adjusted rainfall depths for all storms transposable to that grid point are compared and the largest is stored as the PMP depth for that grid point location for that duration. It is important to understand that PMP depths are calculated for specific area sizes and are a representation of average PMP over that area size for a given duration and are not point rainfall values. *Therefore no areal reduction factors should be applied to the calculated PMP depths*. The depth-area relationships in the PMP values are directly related to the gridded SPAS analyses from the controlling storm events.

8.6 Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Warner Park, TN April, 2010 (SPAS 1208) general storm event when transposed to a randomly chosen location of 36.825° N, 81.30° W (grid point #4,898). The target location is about 320 miles northeast of the storm location at an elevation of 2,545 feet. (Figure 8.3). This event produced nearly 20 inches of rain and flooding across middle and western Tennessee.

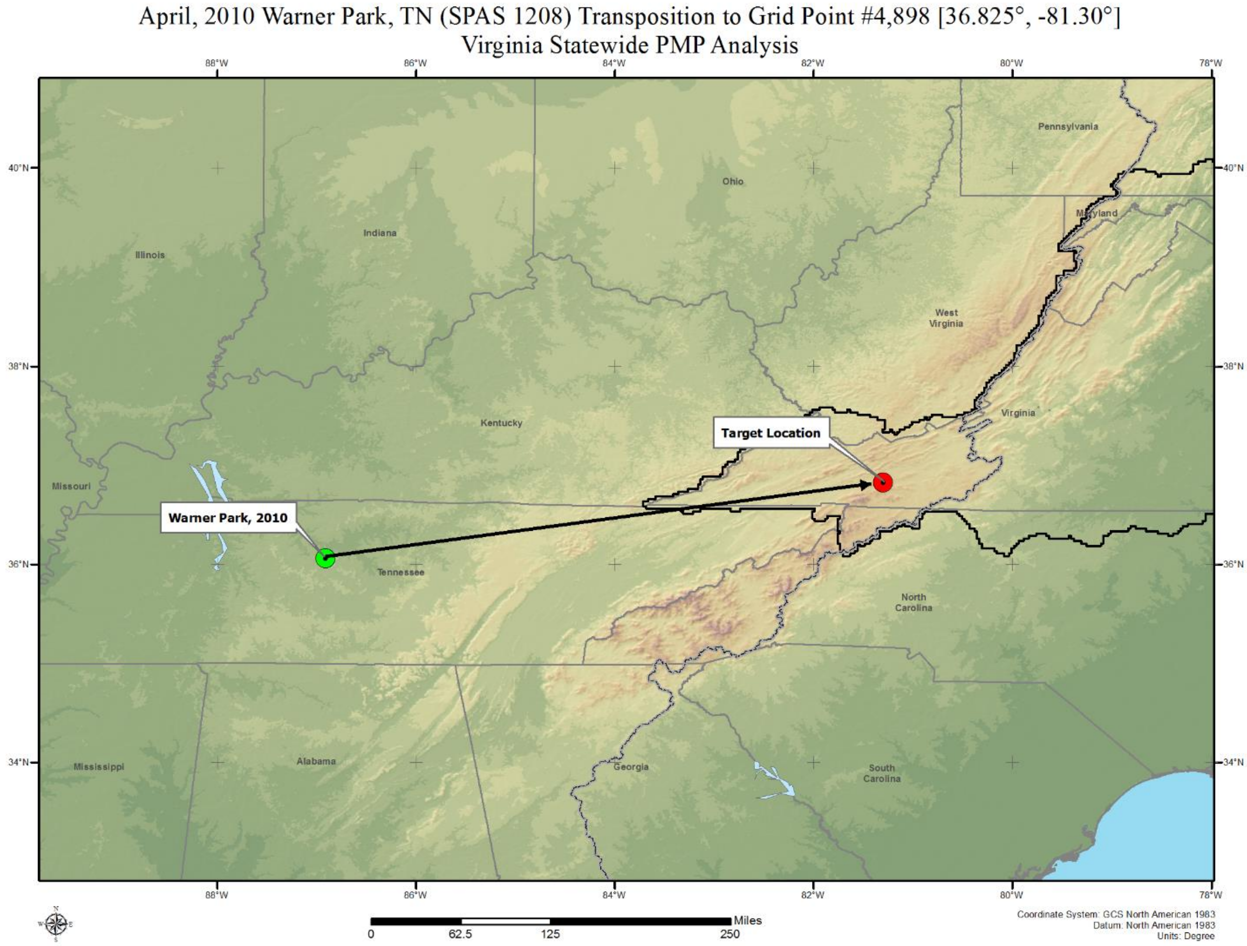

Figure 8.3 Location of Warner Park, TN, April 2010 (SPAS 1208) transposition to grid point #4,898.

8.6.1 Example of Precipitable Water Calculations – Reducing MTF Factor

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 8.1. The 24-hour storm representative dew point temperature is 75°F at the storm representative dew point location 360 miles southwest of the storm center (see Appendix F for the detailed storm maximization and analysis information). The 24-hour duration was chosen as the appropriate duration for this storm because the rainfall accumulation period of when 90% of the rainfall had accumulated was closest to this duration. The storm center elevation is approximated at 600 feet at the storm center location of 36.061° N, 86.906° W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 8.1:

$$W_{p,rep} = W(@75°)_{p,30{,}000'} - W(@75°)_{p,600'}$$

or,

$$W_{p,rep} = 2.85" - 0.15"$$

$$\boldsymbol{W_{p,rep} = 2.70"}$$

The storm occurred at the beginning of May and was adjusted 15 days toward the warm season to a temporal transposition date of May 15th. The May climatological 100-year maximum 24-hour average dew point at the storm representative dew point location is 76.5°F at the in-place elevation of 600 feet. The in-place climatological maximum available moisture ($W_{p,max}$) is calculated.

$$W_{p,max} = W(@76.5°)_{p,30,000'} - W(@76.5°)_{p,600'}$$

$$W_{p,max} = 3.065" - 0.16"$$

$$\boldsymbol{W_{p,max} = 2.91"}$$

The climatological maximum available moisture was determined for the target grid point. The May climatological 100-year maximum 24-hour average dew point for the target grid point location using the 360 miles southwest offset is 75.0 °F at the elevation of 600 feet[1]. The horizontally transpositioned climatological maximum available moisture ($W_{p,\,trans}$) is calculated.

$$W_{p,trans} = W(@75.0°)_{p,30,000'} - W(@75.0°)_{p,600'}$$

$$W_{p,trans} = 2.85" - 0.15"$$

$$\boldsymbol{W_{p,trans} = 2.70"}$$

8.6.2 In-place Maximization Factor

Using Equation 8.2:

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

$$IPMF = \frac{2.905"}{2.70"}$$

$$\boldsymbol{IPMF = 1.08}$$

8.6.3 Moisture Transposition Factor

Using Equation 8.3:

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$

$$MTF = \frac{2.70"}{2.905"}$$

$$\boldsymbol{MTF = 0.93}$$

[1] Note: Although the elevation at grid cell #4,898 is at 2,545 feet, the elevation of the storm center is used to remove the vertical component of the moisture transposition which will be included in the orographic transposition factor.

8.6.4 Supplemental Calculation – Enlarging MTF Factor

The following sections provide sample calculations for the storm adjustment factors for the Wellsboro, PA May, 1889 (SPAS 1339) general storm event when transposed to randomly chosen location of 37.750° N, 79.500° W (grid point #13,697). The target location is about 300 miles southwest of the storm location at an elevation of 1,115 feet (Figure 8.4).

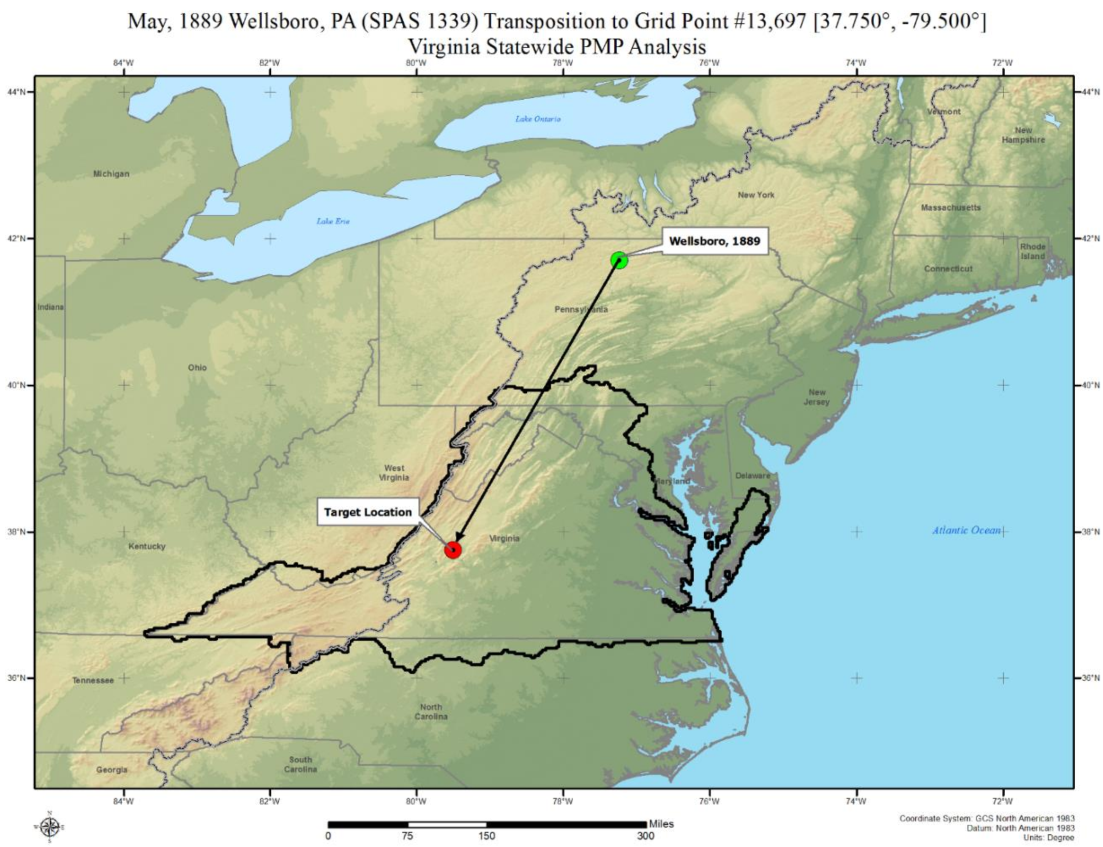

Figure 8.4 Location of Wellsboro, PA, May 1889 (SPAS 1339) transposition to grid point #13,697.

Using the storm representative SST temperature and storm center elevation as input, the precipitable water lookup table returns the depth, in inches, used in Equation 8.1. The 24-hour storm representative SST temperature is 76°F at the storm representative SST location 535 miles southeast of the storm center (see Appendix F for the detailed storm maximization and analysis information). The 24-hour duration was chosen as the appropriate duration for this storm because the rainfall accumulation period of when 90% of the rainfall had accumulated was closest to this duration. The storm center elevation is approximated at 1,800 feet at the storm center location of 41.704° N, 77.229° W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 8.1:

$$W_{p,rep} = W(@76°)_{p,30{,}000'} - W(@76°)_{p,1800'}$$

or,

$$W_{p,rep} = 2.99" - 0.45"$$

$$\boldsymbol{W_{p,rep} = 2.54"}$$

The storm occurred at the end of May and was adjusted 15 days toward the warm season to a temporal transposition date of June 15th. The June mean +2-sigma SST at the storm representative dew point location is 80°F at the in-place elevation of 1,800 feet. The in-place climatological maximum available moisture ($W_{p,\, max}$) is calculated.

$$W_{p,max} = W(@80°)_{p,30,000'} - W(@80°)_{p,1,800'}$$

$$W_{p,max} = 3.60" - 0.52"$$

$$\boldsymbol{W_{p,max} = 3.08"}$$

The climatological maximum available moisture was determined for the target grid point. The June mean +2-sigma SST for the target grid point location using the 535 miles southeast offset is 82 °F at the elevation of 1,800 feet[2]. The horizontally transpositioned climatological maximum available moisture ($W_{p,\, trans}$) is calculated.

$$W_{p,trans} = W(@82°)_{p,30,000'} - W(@82°)_{p,1,800'}$$

$$W_{p,trans} = 3.92" - 0.54"$$

$$\boldsymbol{W_{p,trans} = 3.38"}$$

8.6.4.1 In-place Maximization Factor

Using Equation 8.2:

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

$$\mathrm{IPMF} = \frac{3.08"}{2.54"}$$

$$\boldsymbol{IPMF = 1.21}$$

8.6.4.1 Moisture Transposition Factor

Using Equation 8.3:

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$

$$MTF = \frac{3.38"}{3.08"}$$

$$\boldsymbol{MTF = 1.10}$$

[2] Note: Although the elevation at grid cell #13,697 is at 1,115 feet, the elevation of the storm center is used to remove the vertical component of the moisture transposition which will be included in the orographic transposition factor.

8.6.5 Orographic Transposition Factor

Table 8.1 gives an example of 24-hour precipitation frequency values at both the Warner Park, TN, April 2010 storm center location (source) grid point and the target grid point location used to determine the orographic relationship.

Table 8.1 10-year through 1,000-year precipitation frequency depths from the precipitation frequency climatology developed during this study for the storm center and target locations.

	24-hour Precipitation Frequency Depths (in)						
	10 year	25 year	50 year	100 year	200 year	500 year	1000 year
SOURCE (X-axis)	5.01	5.89	6.61	7.35	8.12	9.18	10.00
TARGET (Y-axis)	4.01	4.65	5.16	5.68	6.22	6.95	7.52

When the precipitation frequency values are plotted (Figure 8.5), a best fit trendline can be constructed to provide a visualization of the relationship between the precipitation frequency values at the source and target locations. In this example, the values for the source grid point nearest the Warner Park, TN, April 2010 storm center are plotted on the *x*-axis while the target values for the target grid point are plotted on the *y*-axis.

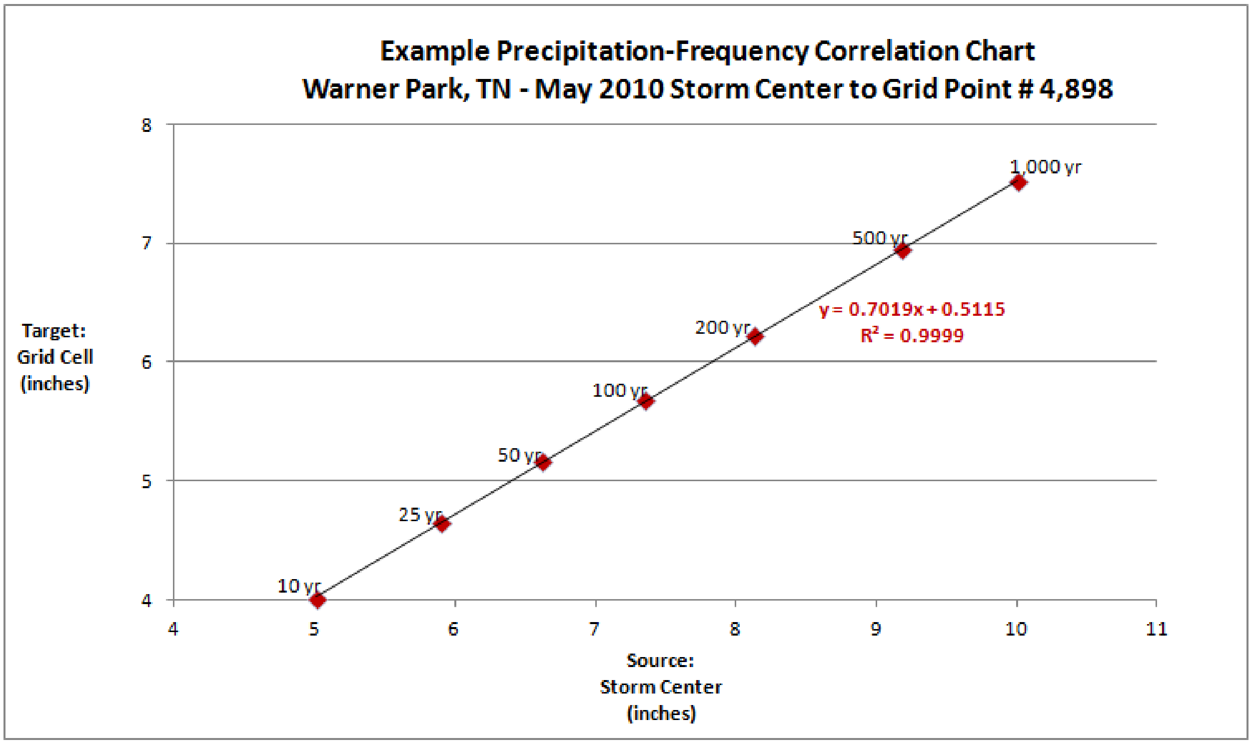

Figure 8.5 Example of precipitation frequency values linear correlation between the storm center and target locations

The orographically adjusted rainfall at the target location can be computed using the equation of the trendline in slope-intercept form.

$$y = mx + b \qquad \text{Equation 8.6}$$

The slope, m is the slope of the least squares line, representing the direct relationship between the source and target points. The y-intercept, b, adjusts for offset at the origin (x = 0) and is a result of the disproportionality between the source and target locations within precipitation frequency datasets. The equation for the Warner Park, TN, April 2010 (SPAS 1208) 24-hour orographically adjusted rainfall transpositioned to the target grid point, using the linear trendline in Figure 8.5 is:

$$y = 0.7019x + 0.5115$$

The maximum SPAS analyzed 24-hour point rainfall value of 18.39" is entered as the x value to compute the target y-value, or orographically adjusted rainfall (P_o) of 13.41".

$$P_o = .7019(18.39) + 0.5115$$

$$\boldsymbol{P_o = 13.41"}$$

The ratio of the orographically adjusted rainfall (P_o) to the in-place SPAS analyzed 24-hour rainfall (P_i) is the orographic transposition factor (OTF) using Equation 8.4:

$$OTF = \frac{13.41"}{18.39"}$$

$$\boldsymbol{OTF = .729}$$

The OTF at grid #4,898 is 0.729, or a 30% rainfall decrease from the storm center location due to terrain and elevation effects. The OTF 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 then be applied to the other durations for that storm.

8.6.6 Total Adjustment Factor

Total Adjustment Factor = IPMF * MTF * OTF from Equation 1.1

$$TAF = 1.076 * 0.929 * 0.729$$

$$\boldsymbol{TAF = 0.73}$$

The TAF for Warner Park, 2010 (SPAS 1208) when moved to the grid point at 36.825° N, 81.30° W, representing storm maximization and transposition, is 0.73. This is an overall decrease of 27% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the DAD value for a given area size and duration 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.

8.6.7 Supplemental Calculation Orographic Transposition Factor – Enlarging Factor

Table 8.2 gives an example of 24-hour precipitation frequency values at both the Wellsboro, PA, May 1889 storm center location (source) grid point and the target grid point location used to determine the orographic relationship.

Table 8.2 10-year through 1,000-year precipitation frequency depths from the precipitation frequency climatology developed during this study for the storm center and target locations.

	24-hour Precipitation Frequency Depths (in)						
	10 year	25 year	50 year	100 year	200 year	500 year	1000 year
SOURCE (X-axis)	3.36	4.05	4.66	5.36	6.17	7.42	8.54
TARGET (Y-axis)	4.34	5.27	6.05	6.88	7.77	9.05	10.09

When the precipitation frequency values are plotted (Figure 8.6), a best fit trendline can be constructed to provide a visualization of the relationship between the precipitation frequency values at the source and target locations. In this example, the values for the source grid point nearest the Wellsboro, PA, May, 1889 storm center are plotted on the *x*-axis while the target values for the target grid point are plotted on the *y*-axis.

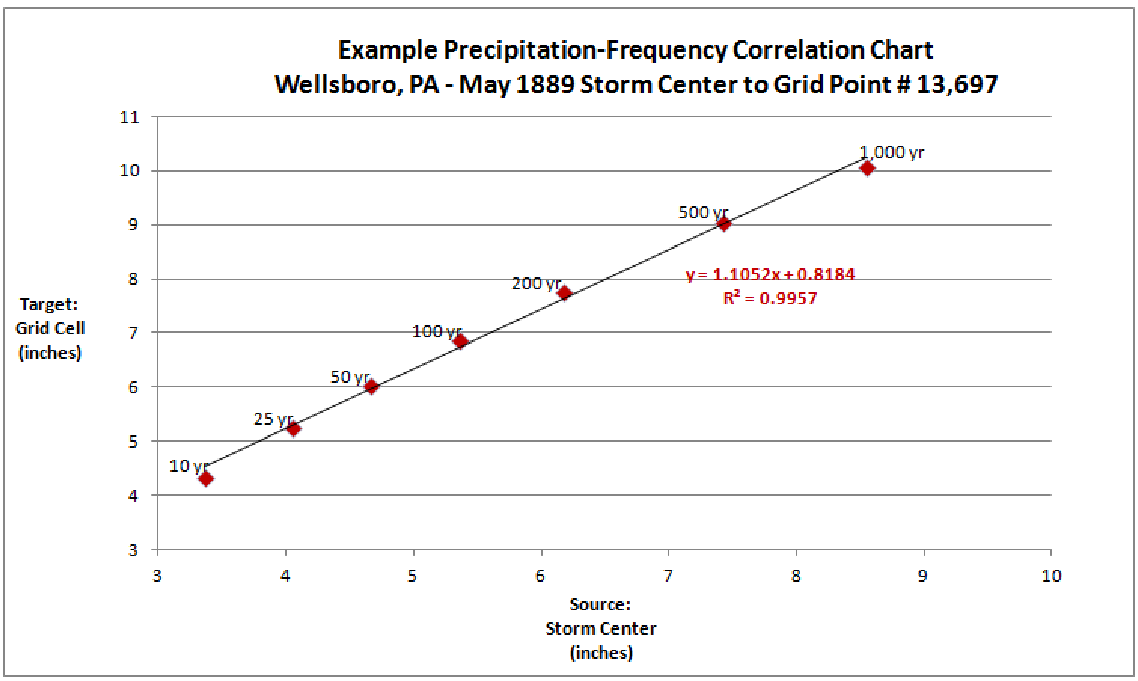

Figure 8.6 Example of precipitation frequency values linear correlation between the storm center and target locations

The orographically adjusted rainfall at the target location can be computed using the equation of the trendline in slope-intercept form.

$$y = mx + b \qquad \text{Equation 8.6}$$

The slope, *m* is the correlation coefficient, representing the direct relationship between the source and target points. The y-intercept, *b*, adjusts for disproportionality between the source and target locations within precipitation frequency datasets. The equation for the Wellsboro, PA, May, 1889 (SPAS 1339) 24-hour orographically adjusted rainfall transpositioned to the target grid point, using the linear trendline in Figure 8.6 is:

$$y = 1.1052x + 0.8184$$

The maximum SPAS analyzed 24-hour point rainfall value of 9.44” is entered as the *x* value to compute the target *y*-value, or orographically adjusted rainfall (P_o) of 11.25”.

$$P_o = 1.1052(9.44) + 0.8184$$

$$\boldsymbol{P_o = 11.25''}$$

The ratio of the orographically adjusted rainfall (P_o) to the in-place SPAS analyzed 24-hour rainfall (P_i) is the orographic transposition factor (OTF) using Equation 8.4:

$$OTF = 11.25''/9.44''$$

$$\boldsymbol{OTF = 1.19}$$

The OTF at grid #13,697 is 1.19, or a 19% rainfall increase from the storm center location due to terrain and elevation effects. The OTF 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 then be applied to the other durations for that storm.

8.6.8 Total Adjustment Factor

Total Adjustment Factor = IPMF * MTF * OTF from Equation 1.1

$$TAF = 1.213 * 1.097 * 1.192$$

$$\boldsymbol{TAF = 1.59}$$

The TAF for Wellsboro, 1889 (SPAS 1339) when moved to the grid point at 37.750° N, 79.500° W, representing storm maximization and transposition, is 1.59. This is an overall increase of 59% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the DAD value for a given area size and duration 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.

8.7 PMP Calculation Process

To calculate PMP, the TAF for each storm must be applied to the storm's SPAS analyzed DAD value for the area size and duration of interest to yield a total adjusted rainfall value. The storm's total adjusted rainfall value is then compared with the adjusted rainfall values of every storm in the database transposable to the target grid point. This process must be repeated for each of the 24,372 grid points within the statewide domain and for each duration for each storm type.

8.7.1 PMP Evaluation Tool Description and Usage

The PMP Evaluation Tool provided with this study uses a Python-based script designed to run within the ArcGIS environment. ESRI's ArcGIS 10.x (or later) software (ESRI, 2012) is required to run the tool and it is recommended that the user have a basic familiarity with the operation of this software. The tool provides gridded PMP values at a spatial resolution of 90 arc-seconds (equivalent to .025 x .025 dd) for a user-designated drainage basin or area at user-specified durations.

8.7.1.1 File Structure

The tool, source script, and all input data are stored within the 'PMP_Evaluation_Tool' project folder. The file and directory structure within the 'PMP_Evaluation_Tool' folder should be maintained as it is provided – as the script will locate various data based on its relative location within the project folder. If the subfolders or geodatabases within are relocated or renamed, then the script must be updated to account for these changes.

The file structure consists of only three subfolders: Input, Output, and Script. The 'Input' folder contains all input GIS files (Figure 8.7). There are three ArcGIS file geodatabase containers within the 'Input' folder: DAD_Tables.gdb, Storm_Adj_Factors.gdb, and Non_Storm_Data.gdb. The DAD_Tables.gdb contains the DAD tables (in file geodatabase table format) for each of the 79 SPAS analyzed storm DAD zones. The Storm_Adj_Factors.gdb contains a feature class for each analyzed event and stores the adjustment factors for each grid point as a separate feature. These feature classes are organized into feature datasets, according to storm type (General, Local, and Tropical). The storm adjustment factor feature classes share their name with their DAD Table counterpart. The naming convention is SPAS_XXXX_Y, where XXXX is the SPAS storm ID number and Y is the DAD zone number. Finally, the Non_Storm_Data.gdb contains spatial data not directly relating to the input storms: Grid_Points, a point feature class, and Vector_Grid, a polygon feature class representing the grid cells for each of 24,372 grid points.

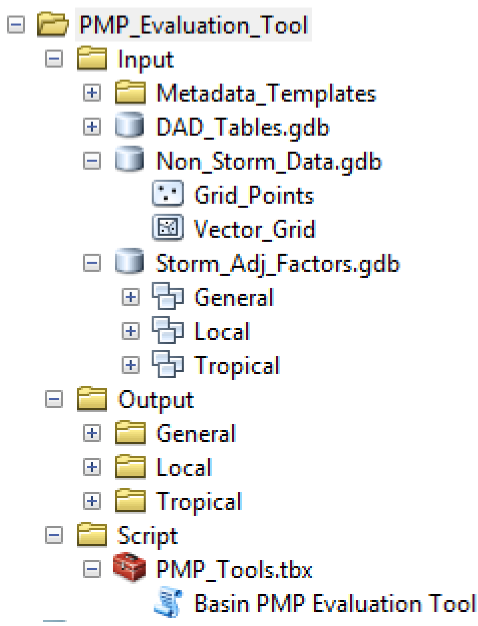

Figure 8.7 PMP tool file structure

The 'Script' folder contains an ArcToolbox called PMP_Tools.tbx. The toolbox contains a Script Tool called 'Basin PMP Evaluation Tool' that is used to calculate basin PMP. ArcCatalog should be used for viewing the GIS tool file structure and interacting with the input and output geospatial data and metadata. A typical operating system's file browser does not allow access to the geodatabase containers and cannot be used to directly run the tool.

8.7.1.2 Python Script

Due to the large number of storm datasets and grid points within the project domain, a scripted process is necessary to compare each value efficiently and accurately for a given area of interest and make the necessary calculations. ArcGIS has adopted the Python scripting language as the viable option for compiling powerful geoprocessing operations as clearly and concisely as possible.

The Python scripts are imported and stored internally within the Script Tools and can be exported to .py files within ArcGIS Catalog. A hardcopy version of the code is given in Appendix D. The Python code can be opened and edited within any text editor. The python script uses the arcpy, arcpy.management, and arcpy.conversion modules. After the input parameters are provided, the script runs the pmpAnalysis() three times, once for each storm type. To shorten and simplify the code, repeatable functions are designed and called within the code when needed. Within the broader pmpAnalysis() function, several smaller functions are called to perform various tasks:

createPMPfc() Creates the PMP_Points feature class to store vector (point) results.

getAOIarea() Calculates the area of the input basin

dadLookup() Gets the DAD value for the current storm based on basin area

updatePMP()	Writes the largest adjusted rainfall value (PMP) to the PMP_Points feature class
outputPMP()	Produces output PMP raster files for each duration and applies metadata to output GIS files

There is extensive documentation within the code in the form of '# comments'. These comments provide guidance toward its functionality and describe the code.

While the script performs many actions, its primary purpose is to iterate through both the storm list and the grid points within the area of interest (AOI), comparing each, and creating output based on the maximum values. To accomplish this, several layers of nested iterative "for" loops are used.

The following high-level algorithm broadly describes the script process:

- Calculate Basin Area (in mi^2)
- For each Storm Type (general, tropical, and local)
    - For each duration
        - For each storm in database
            - Lookup storm's depth-area-duration (DAD) value for basin size
            - For each grid point in basin
                - Calculate total adjusted rainfall (TAR) by multiplying DAD value by total adjustment factor for the grid point
                - If TAR > PMP, the TAR becomes the new PMP value for that grid point
    - Create Point feature class for the storm type
    - Create raster GRID files for each duration
    - Attach metadata to each output file

8.7.1.3 Usage

The 'PMP_Evaluation_Tool' Script Tool within the PMP_Tools.tbx ArcToolbox opens and runs the script within the ArcGIS environment. The Script Tool has validation code that allows the user to override the basin area and provide input for the PMP area to be analyzed. In addition to running as a standalone tool, the script tool can be incorporated into Model Builder or be called as a sub-function of another script. The 'PMP_Evaluation_Tool' project folder should be stored locally at a location that can be accessed (both read/write) by ArcGIS desktop.

8.7.1.4 Input Parameters

The tool requires several parameters as input to define the area and durations to be analyzed. The first parameter required by the tool dialogue is a feature layer, such as a basin shapefile or feature class, designed to outline the area of interest for the PMP analysis. The basin shapefile must have a map surface projection spatial reference, with units of either feet or meters (e.g. Universal Transverse Mercator or State Plane). If the feature layer has multiple features (or polygons), the tool will use the combined area as the analysis region. Only the selected polygons will be used if the tool is run from the ArcMap environment with selected features highlighted. If the basin shapefile extends beyond the project analysis domain, only the grid cells within the domain will be analyzed, although the PMP depths will be calculated for the area of the entire basin.

The dialogue also requires the path of the 'PMP_Evaluation_Tool' and an 'Output Folder' path which provide the tool with the location of the input geodatabases and the location to write the output geodatabases, respectively. Figure 8.8 shows the input dialogue window.

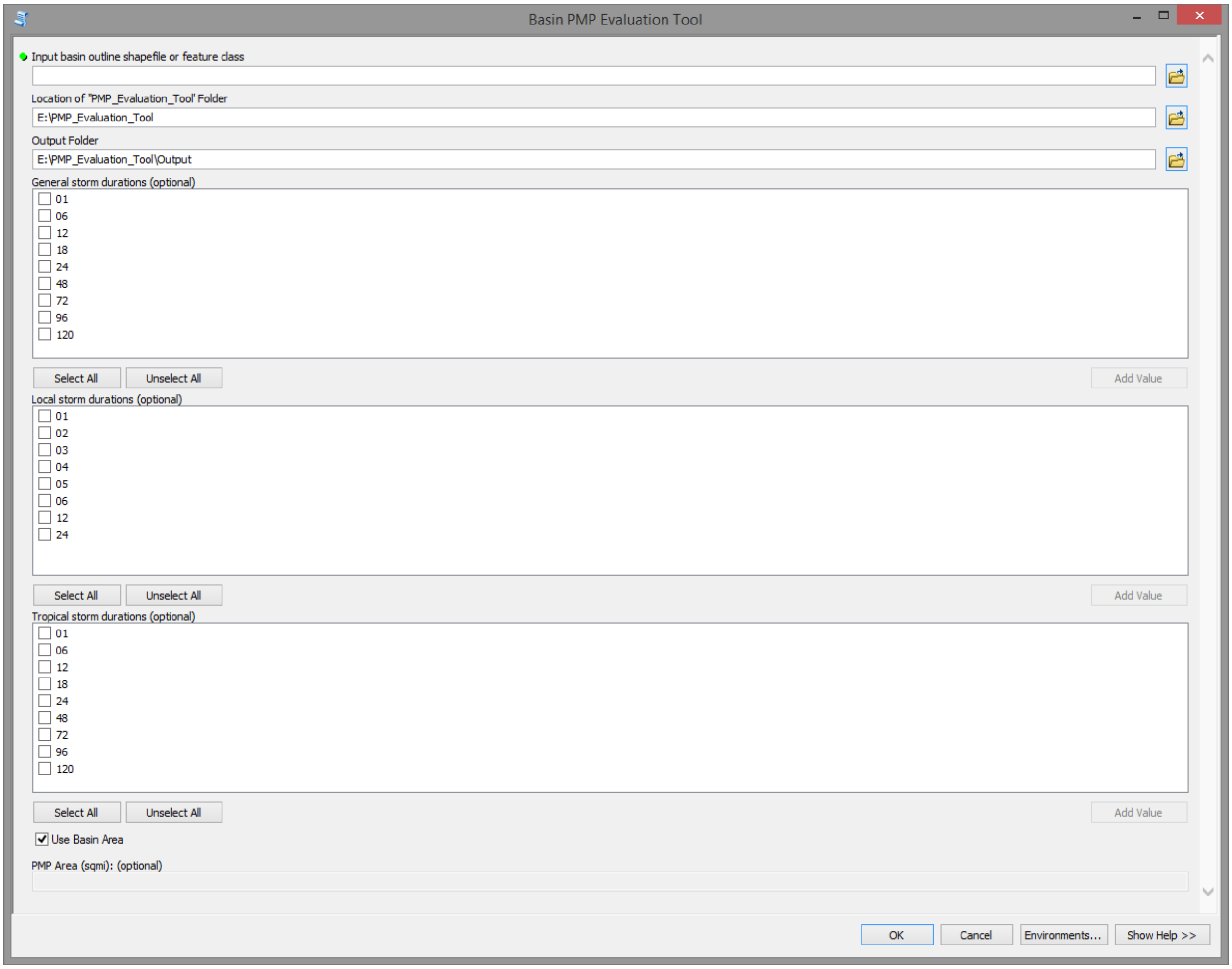

Figure 8.8 The PMP Evaluation Tool input dialogue

8.7.1.5 Tool Output

Once the tool has been run, the output folders and geodatabases will be populated with the model results (Figure 8.9). The GIS files can then be brought into an ArcMap, or other compatible GIS environment, for mapping and analysis. The tool is set to have overwrite capabilities; if output data exists, it will be overwritten the next time the tool is run. Output data should be moved to an alternate permanent storage location before the tool is run again, if the user wants the output data to be preserved.

For each storm type, the output is organized within file geodatabases and named according to the analyzed PMP area. An output geodatabase named "PMP_21.gdb" holds PMP values for a 21 square-mile basin. Each file geodatabase contains a feature class which stores each grid point centroid within the basin as a separate feature. Each feature has a field for the grid ID, latitude, longitude, analysis zone, elevation, PMP (for each duration), and the contributing storm ID. The PMP GRID files are also stored within the file geodatabase. The naming convention for the GRID files is T_XX_YYYYY, where T is the storm type (L for local convective, G for general, and T for Tropical), XX is the duration in hours, and YYYYY is the analyzed area size. For example, a GRID named "G_06_00021" would be the 21-square mile 6-hour general storm PMP. An example of the output file structure is shown in Figure 8.9.

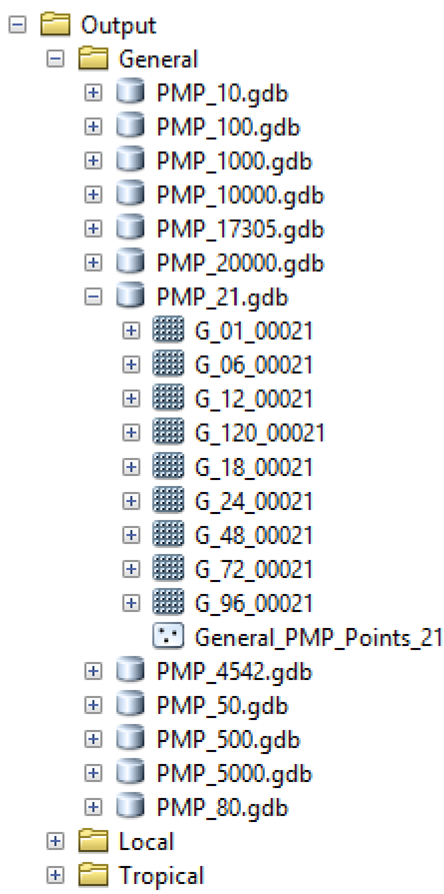

Figure 8.9 Example of the PMP Evaluation Tool output file structure

Full descriptions of each field are provided in the metadata for each GIS dataset.

8.7.1.6 GIS Dataset Metadata

Comprehensive metadata have been included for every data element within the project folder. The metadata were compiled using the Federal Geographic Data Committee (FGDC) .xml format standard and are attached to each GRID file. The metadata can be viewed in ArcCatalog under the description tab (the FGDC metadata style may need to be enabled under ArcCatalog 'options' for proper viewing). The output metadata originates from templates stored within each storm type's 'Metadata_Templates' sub-folder within the 'Input' folder.

The final PMP datasets are stored in ESRI GRID raster format and have been provided to the state of Virginia (All data are included as part of the digital Appendix J). The GRID files are stored within a file geodatabase specific to the PMP area-size analyzed. The geodatabase follows a naming convention of PMP_X.gdb, where X is the area size of the analysis. Within each geodatabase there is a separate GRID file for each duration. The naming convention for the GRID files is T_XX_YYYYY, where T is the storm type (L for local convective, T for Tropical, and G for general), XX is the duration in hours, and YYYYY is the analyzed area size. For example, a GRID named "L_06_00025" would be the 25-square mile 6-hour local storm PMP. The following PMP maps are provided in Appendix A:

Local Storm PMP

- 1-hour 1-square mile
- 1-hour 10-square mile
- 1-hour 100-square mile
- 1-hour 200-square mile
- 1-hour 500-square mile
- 6-hour 1-square mile
- 6-hour 10-square mile
- 6-hour 100-square mile
- 6-hour 200-square mile
- 6-hour 500-square mile
- 12-hour 1-square mile
- 12-hour 10-square mile
- 12-hour 100-square mile
- 12-hour 200-square mile
- 12-hour 500-square mile
- 24-hour 1-square mile
- 24-hour 10-square mile
- 24-hour 100-square mile
- 24-hour 200-square mile
- 24-hour 500-square mile

General/Tropical Storm PMP

- 6-hour 1-square mile
- 6-hour 10-square mile
- 6-hour 100-square mile
- 6-hour 200-square mile
- 6-hour 500-square mile
- 6-hour 1,000-square mile
- 6-hour 5,000-square mile
- 6-hour 20,000-square mile

- 12-hour 1-square mile
- 12-hour 10-square mile
- 12-hour 100-square mile
- 12-hour 200-square mile
- 12-hour 500-square mile
- 12-hour 1,000-square mile
- 12-hour 5,000-square mile
- 12-hour 20,000-square mile
- 24-hour 1-square mile
- 24-hour 10-square mile
- 24-hour 100-square mile
- 24-hour 200-square mile
- 24-hour 500-square mile
- 24-hour 1,000-square mile
- 24-hour 5,000-square mile
- 24-hour 20,000-square mile
- 48-hour 1-square mile
- 48-hour 10-square mile
- 48-hour 100-square mile
- 48-hour 200-square mile
- 48-hour 500-square mile
- 48-hour 1,000-square mile
- 48-hour 5,000-square mile
- 48-hour 20,000-square mile
- 72-hour 1-square mile
- 72-hour 10-square mile
- 72-hour 100-square mile
- 72-hour 200-square mile
- 72-hour 500-square mile
- 72-hour 1,000-square mile
- 72-hour 5,000-square mile
- 72-hour 20,000-square mile

High-resolution PDF files for each of these maps are provided in the Digital Appendix J.

8.8 Temporal Distribution of PMP Values

This study does not include guidance for applying temporal distributions to PMP values. The authors recognize that temporal distributions should vary with storm type and potentially basin size and location. For this study, 66 storms (total of 78 SPAS DAD zones) were analyzed with SPAS at 1-hour or higher temporal resolutions and mass curves were produced for each analyzed DAD zone. These individual temporal storm distributions could be applied in hydrologic models and greatly aid in the development of storm type specific and/or region specific temporal distribution patterns. The mass curves showing the accumulation of rainfall through time for each event are included in Appendix F or this report. Until an updated analysis of the temporal accumulation patterns is completed, it is recommended that patterns provided in HMR 40, 52, and/or 56 or by the NRCS be used to temporal distribute the PMP depths.

9. Procedure for Calculating Basin-Specific PMP

The gridded PMP datasets provided with this study are designed to allow for the calculation of basin-average PMP depths for drainage basins within the project domain. Although not required, it is recommended that ESRI's ArcGIS 10.x (or later) software be used to aid in the extraction of the gridded data for a given drainage basin. It is also recommended that the user have a basic familiarity with the operation of this software.

Since PMP is calculated at specific standard area sizes, the user may need to interpolate depths for their basin size using the available bounding area size PMP depths. For example, consider a 125-square mile drainage basin. PMP for 100- and 200-square miles are provided, but not specifically for 125-square miles. The 125-square mile PMP can be interpolated from the bounding 100- and 200-square mile values. In this example, the user would take 75% of the 100-square mile PMP and 25% of the 200-square mile PMP and derive the 125-square mile value. In addition, PMP values on a Depth-Area graph are not always linear. Therefore, it may be useful to do a non-linear curve fit to the surrounding PMP values for four or more area sizes. This would be most useful when there is a large difference in area size between the two bounding area sizes available. These data are readily available from the PMP data base.

The following steps are followed to obtain basin average PMP:

1) Create or obtain a polygon shapefile of the drainage basin outline and calculate the basin area. The calculated PMP is the average depth for the area of the basin. The areal reduction is inherent within the PMP development process and *no further areal reduction should be applied*.
2) Using ArcMap, for a given duration import the two PMP GRID datasets for standard area sizes that bound the basin area size from step 1.
3) Extract the PMP GRID data to the basin shapefile for both of the bounding area sizes. There are numerous methods for extracting data using ArcGIS and the best approach depends on the experience level and needs of the user and the basin itself. For example, the Extract by Mask tool will effectively clip the GRID to the basin shapefile but will not include any grid cells with their centroids outside the basin boundary. If the basin is very small, the user may want to extract all cells touching the boundary and include part or all of them in the PMP average. The PMP GRIDs can be resampled to a higher spatial resolution before extraction to obtain an extracted dataset that adheres more closely to the basin outline. It is recommended that the user gain a sufficient understanding of the extraction method used.
4) Obtain the mean raster value for the extracted area from the GRID layers at both of the bounding area sizes. These values are the basin-average PMP depth for each of the bounding standard area sizes.
5) Interpolate the basin-size PMP depth from the basin average values obtained in Step 4 for both bounding area sizes. The user can apply a linear interpolation or plot four or more data points and apply a non-linear curve fit using a Depth-Area analysis. The linear interpolation can be done using equation 9.1:

$$P = \frac{(A-A_1)(P_2-P_1)}{(A_2-A_1)} + P_1 \qquad \text{Equation 9.1}$$

Where,
A_1= smaller-bounding area size (sq. mi.)
P_1 = basin-average PMP for smaller-bounding area size (in.)
A_2 = larger-bounding area size (sq. mi.)
P_2 = basin-average PMP for larger-bounding area size (in.)
A = target basin area size (sq. mi.)
P = interpolated basin-average PMP (in.)

In the event that GIS software cannot be used, basin average PMP depth can be obtained from hard-copy maps by tracing the basin outline and manually estimating an average over the basin domain for the bounding area sizes then following the interpolation process in step 5. Interpolation may not be as accurate as what can be obtained from the GIS datasets, due to the fewer number of standard area sized hard copy maps available.

9.1 Basin Average PMP Calculation

The following steps provide a sample application of the above steps for the calculation of basin average local convective PMP depths at the 1-hour duration for a sample drainage basin.

1) A basin outline shapefile is obtained for the North Anna Dam drainage basin. The basin area is calculated to be 341-square miles (Figure 9.1).

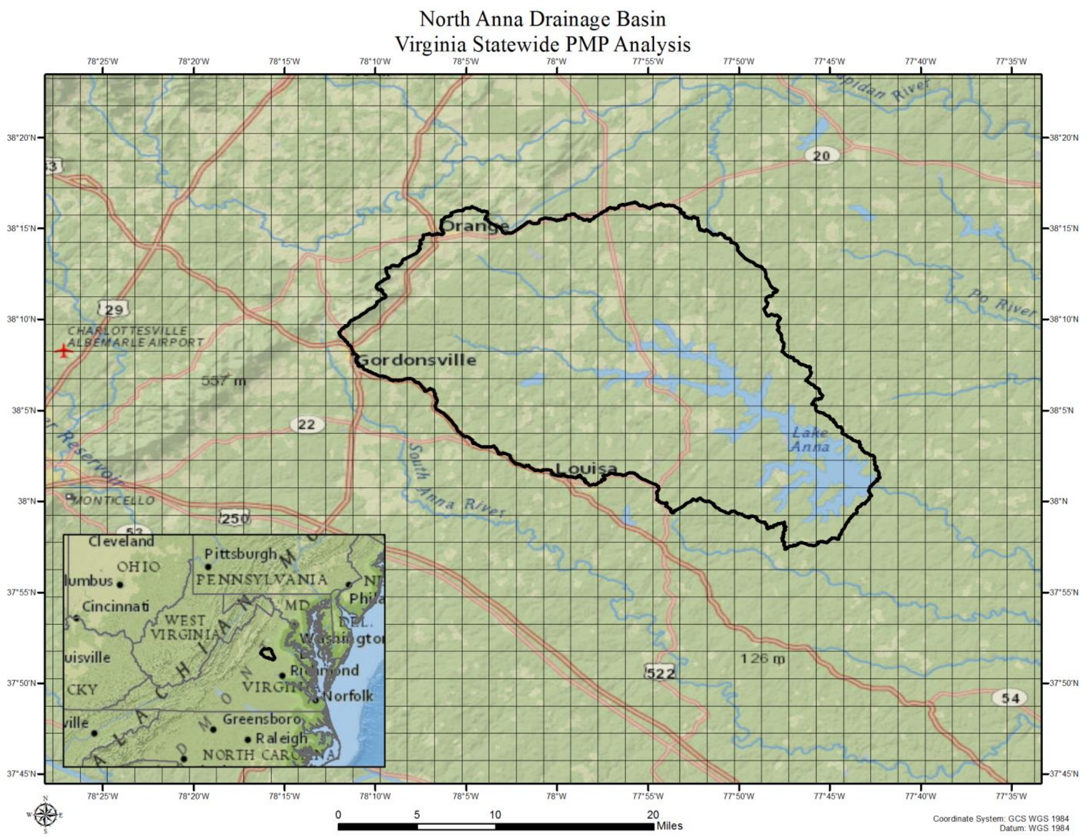

Figure 9.1 North Anna Dam drainage basin (341-square miles)

2) The 1-hour PMP GRID layers for the bounding standard area sizes of 200-square miles and 500-square miles are added to ArcMap; “L_01_00200” and “L_01_00500”.
3) The Spatial Analyst *Extract by Mask* tool is run for both the 200- and 500-square mile bounding GRID layers using each PMP GRID as the input raster and the basin shapefile as the feature mask (Figure 9.2). The output rasters are ‘snapped’ to original rasters to maintain spatial alignment (Figure 9.3).

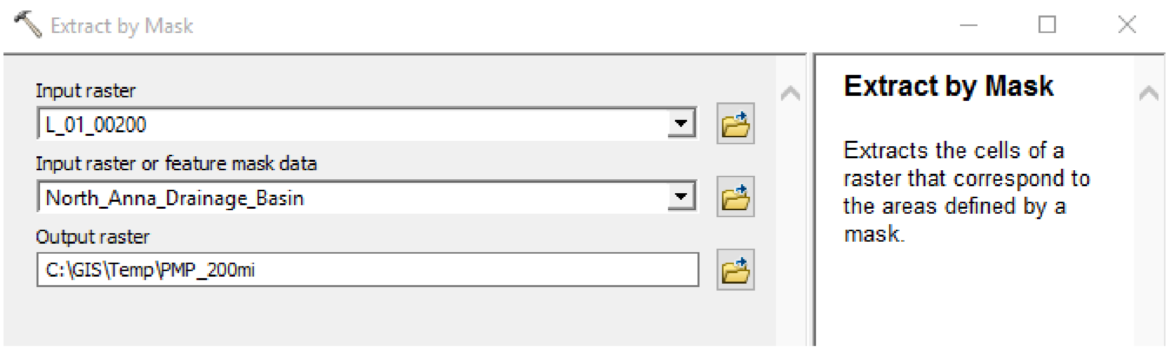

Figure 9.2 Extract by Mask tool dialogue

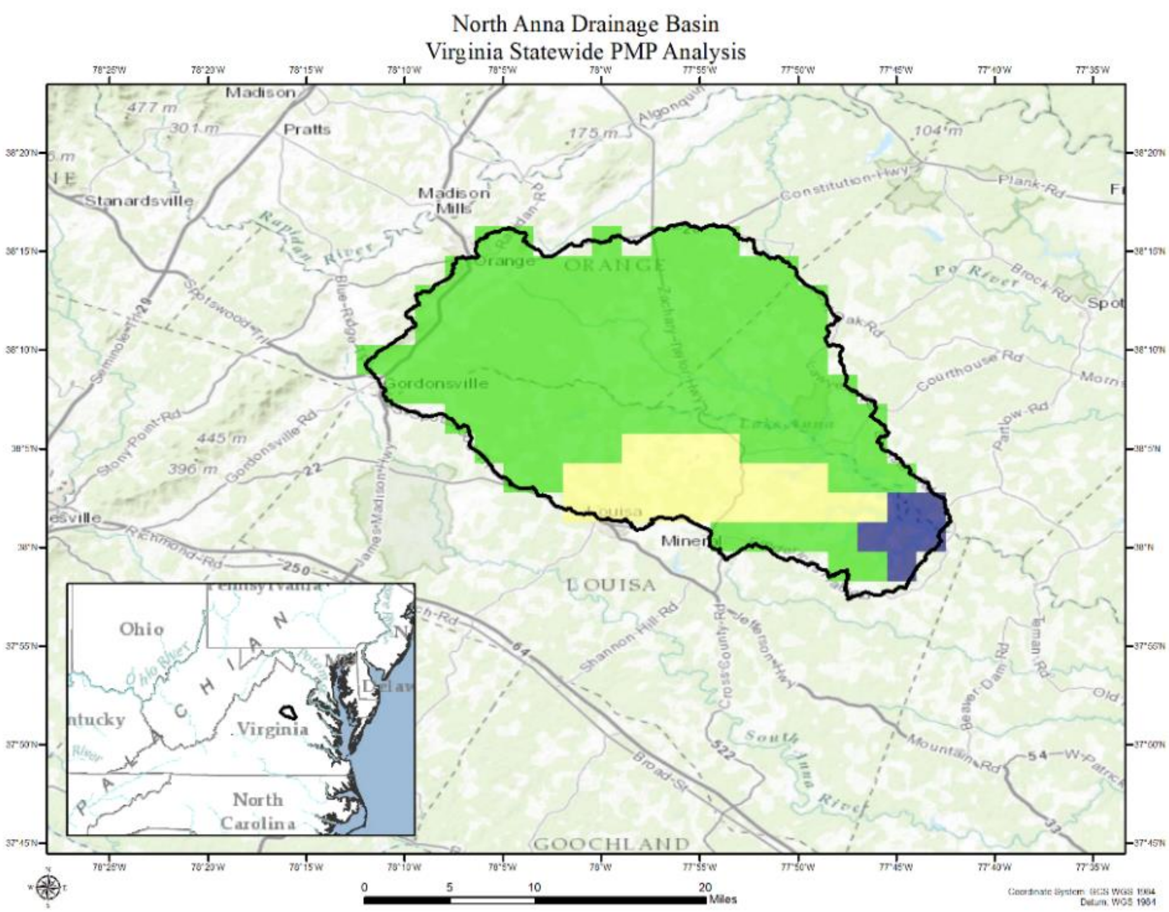

Figure 9.3 Gridded data extracted to basin

4) The gridded mean value is taken from the layer properties for both of the extracted bounding layers. The 200-square mile basin average PMP is 5.09” and the 500-square mile basin average PMP is 3.71”.
5) Equation 10.1 is used to interpolate to the 32-square mile area size:

$$P = \frac{(341mi^2 - 200mi^2)(3.71" - 5.09")}{(500mi^2 - 200mi^2)} + 5.09"$$

$$P = 4.26"$$

The North Anna Dam 1-hour local storm basin average PMP is 4.26”.

10. PMP Sensitivity and Comparisons

The PMP and intermediate data produced for this study was 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. Comparisons of the PMP values against the 100-year recurrence interval values were made to ensure all PMP values were at least two times as large. Many iterations of maps were produced that helped 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. As expected, several different storms controlled PMP values at various durations and area sizes. In some instances, a discontinuity of PMP depths between adjacent grid point locations resulted. This occurs when a transposition zone bisects an area of interest. In these cases, storms that are transpositionable to one transposition zone may not be transpositionable to the other. Therefore, different storms are affecting adjacent grid points and often result in a shift in values over a short distance. This occurs because of the requirement to assign specific transposition limits to each storm that result in a storm being either transpositionable to a grid point or not, with no allowance for gradients of transpositionability. In reality, there would be some transition for a given storm, but the process and definition of transpositionability does not allow for this. However, it is important to note that these discontinuities make little difference in the overall basin average PMP values for most basins and is only seen when analyzing data at the highest resolution (e.g. individual grid points). This issue could potentially have the most significant effect for small basins where there are a small number of grid points representing the drainage and therefore each grid point value would have an exaggerated effect on the basin average PMP.

PMP values are highest near the coast and along the Blue Ridge. These regions have exhibited past extreme rainfall accumulations that are the result of both moisture availability and topographic enhancement (see Smith et al., 2011 for an in-depth discussion on extreme rainfall in the region and the effects of topography). Regions along and near the coast are also affected by coastal convergence processes which act to enhance lift and provide an additional mechanism for enhanced rainfall production versus other locations in the study domain. Minimum values are seen in the most protected interior valleys. This is expected because of the lack of sustained low-level moisture that can make it to these regions and the downslope effect of topography to act to dry out the atmosphere as the air descends in elevation (rain shadow).

Figures 10.1, 10.2, 10.3 display sample statewide PMP maps used in this evaluation for 6-hour local storm at the 10-square mile area size, 48-hour tropical storm at 1,000-square miles, and 72-hour general storm at the 100-square mile area size, respectively. Figures 10.4, 10.5, and 10.6 display the controlling storms by storm type across the entire domain. Often a transposition zone is entirely controlled by a single storm. However, in Figure 10.6 Zones 2 and 3, there are more than one storm controlling these zones. This is caused when two storms produce total adjusted rainfall values that are very close and the controlling storm can alternate based on small fluctuations in the orographic or moisture adjustment factors (OTF and MTF). Because these alternations only occur when adjusted rainfall values are very close for both storms, there is no noticeable variation in the final PMP values.

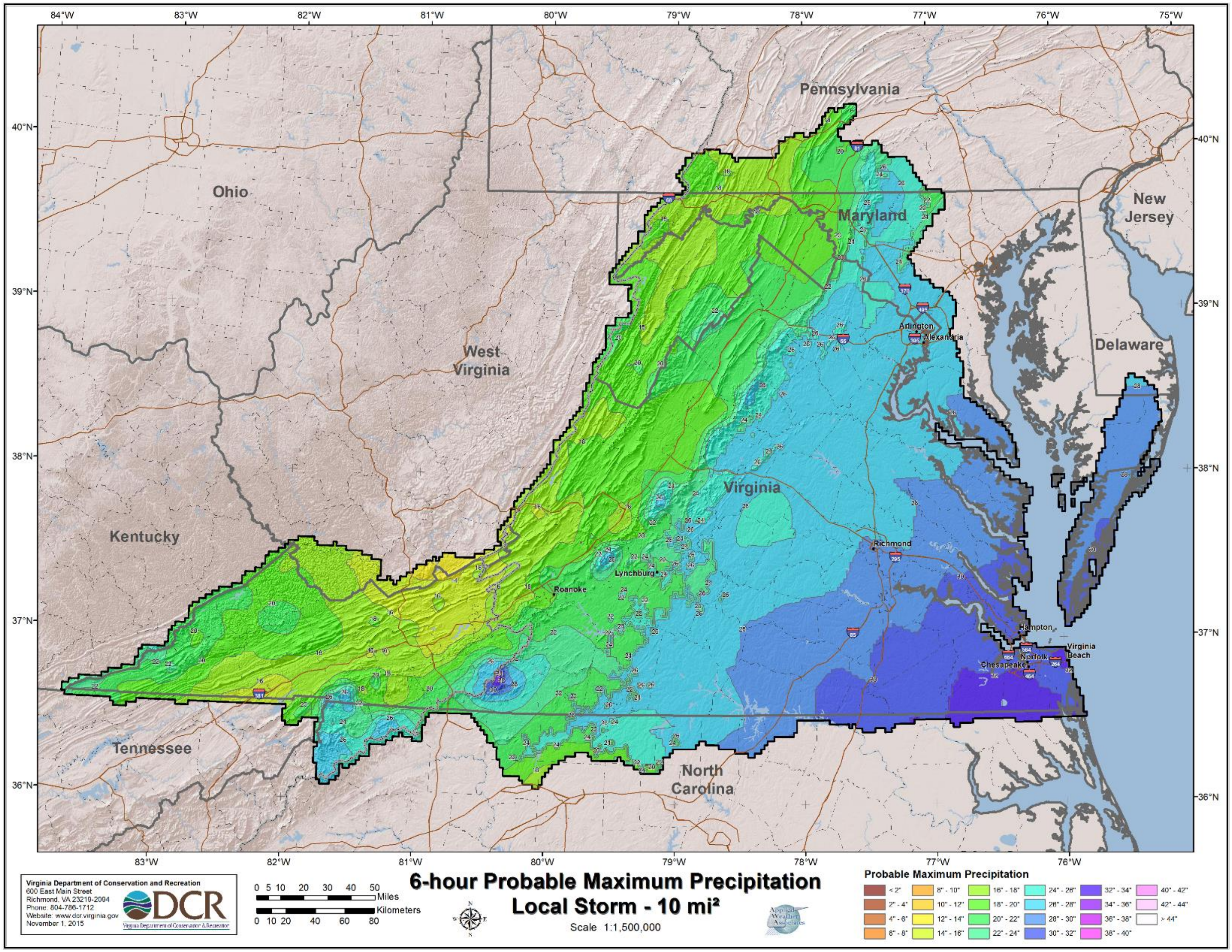

Figure 10.1 Statewide map of the 6-hour, 10-square mile PMP values derived from local storms.

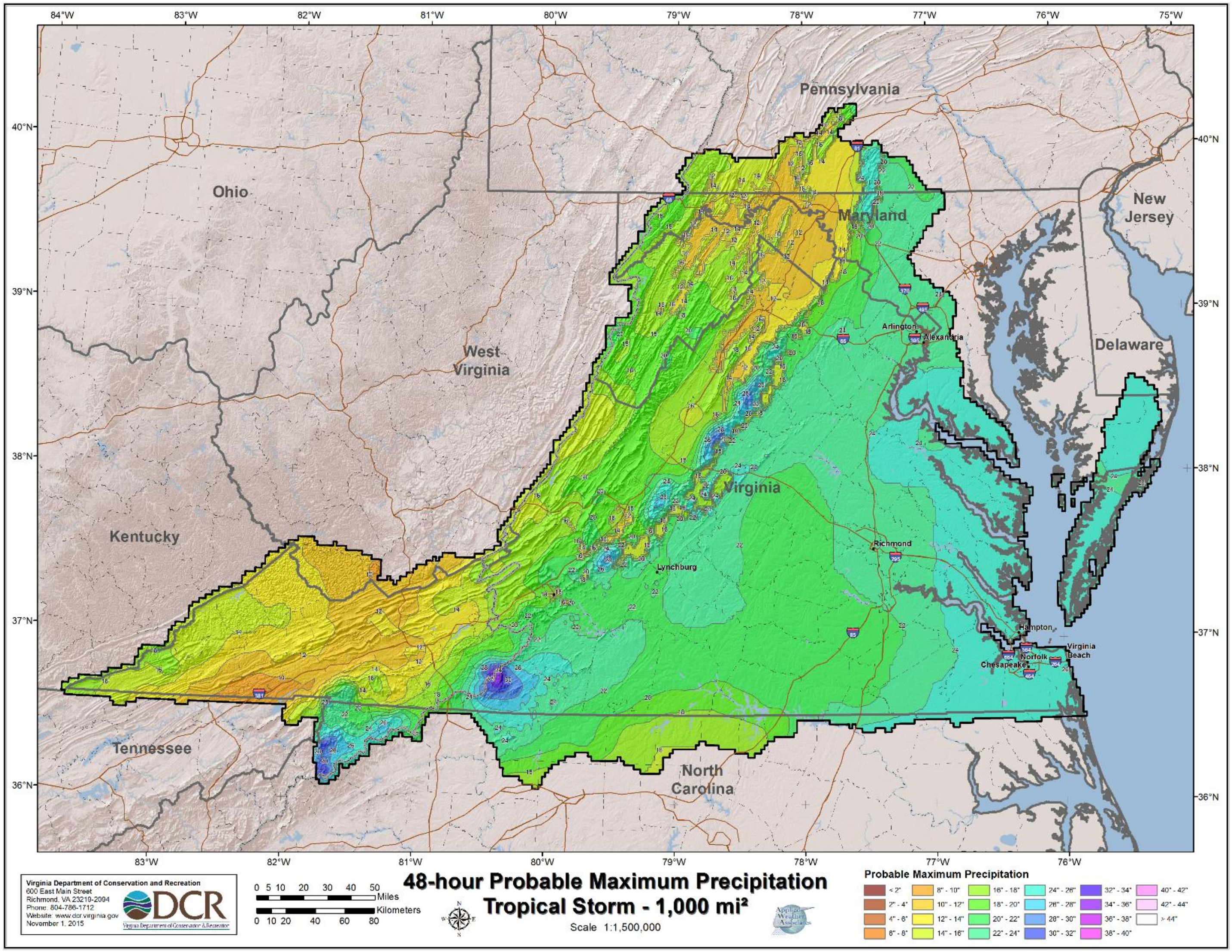

Figure 10.2 Statewide map of the 48-hour, 1,000-square mile PMP values derived from tropical storms.

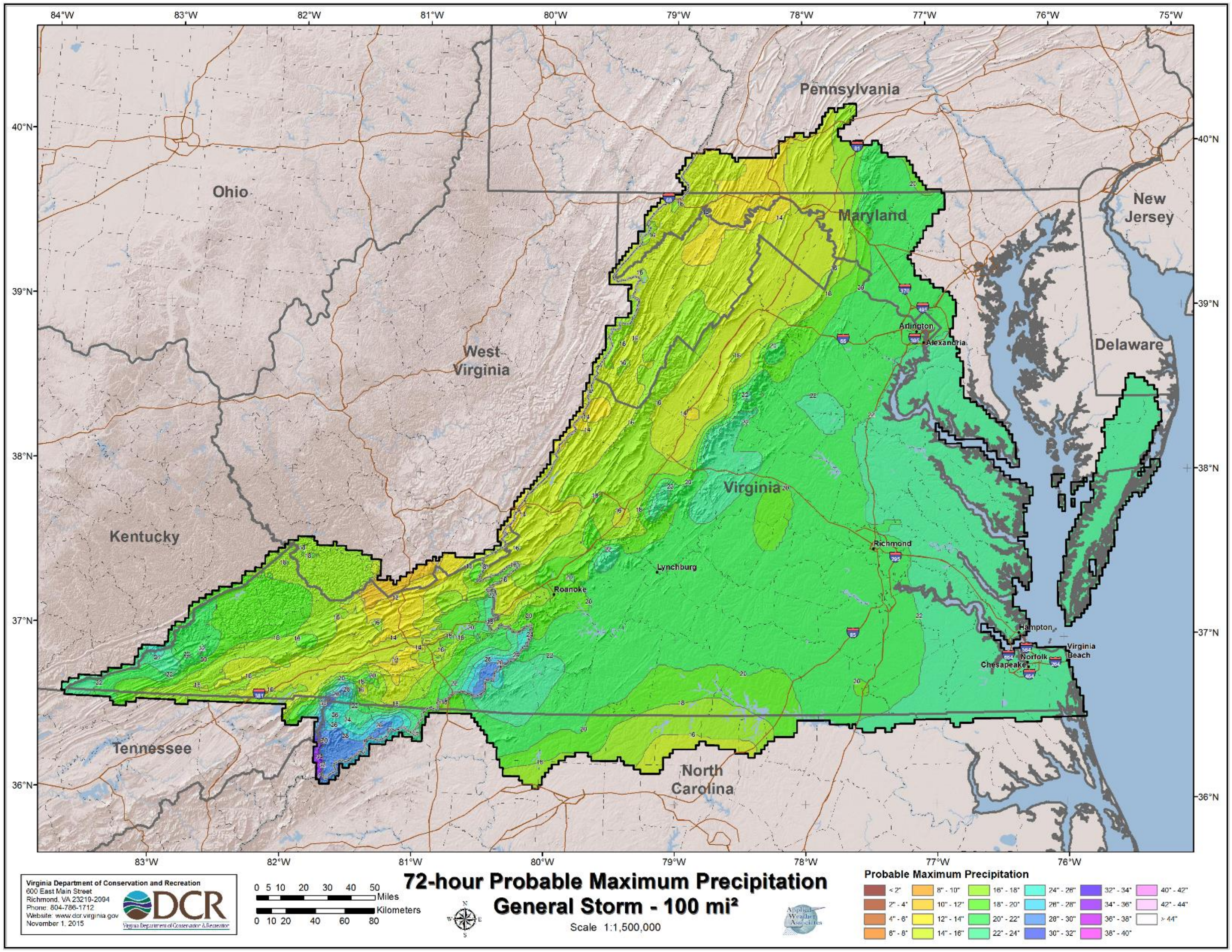

Figure 10.3 Statewide map of the 72-hour, 100-square mile PMP values derived from general storms.

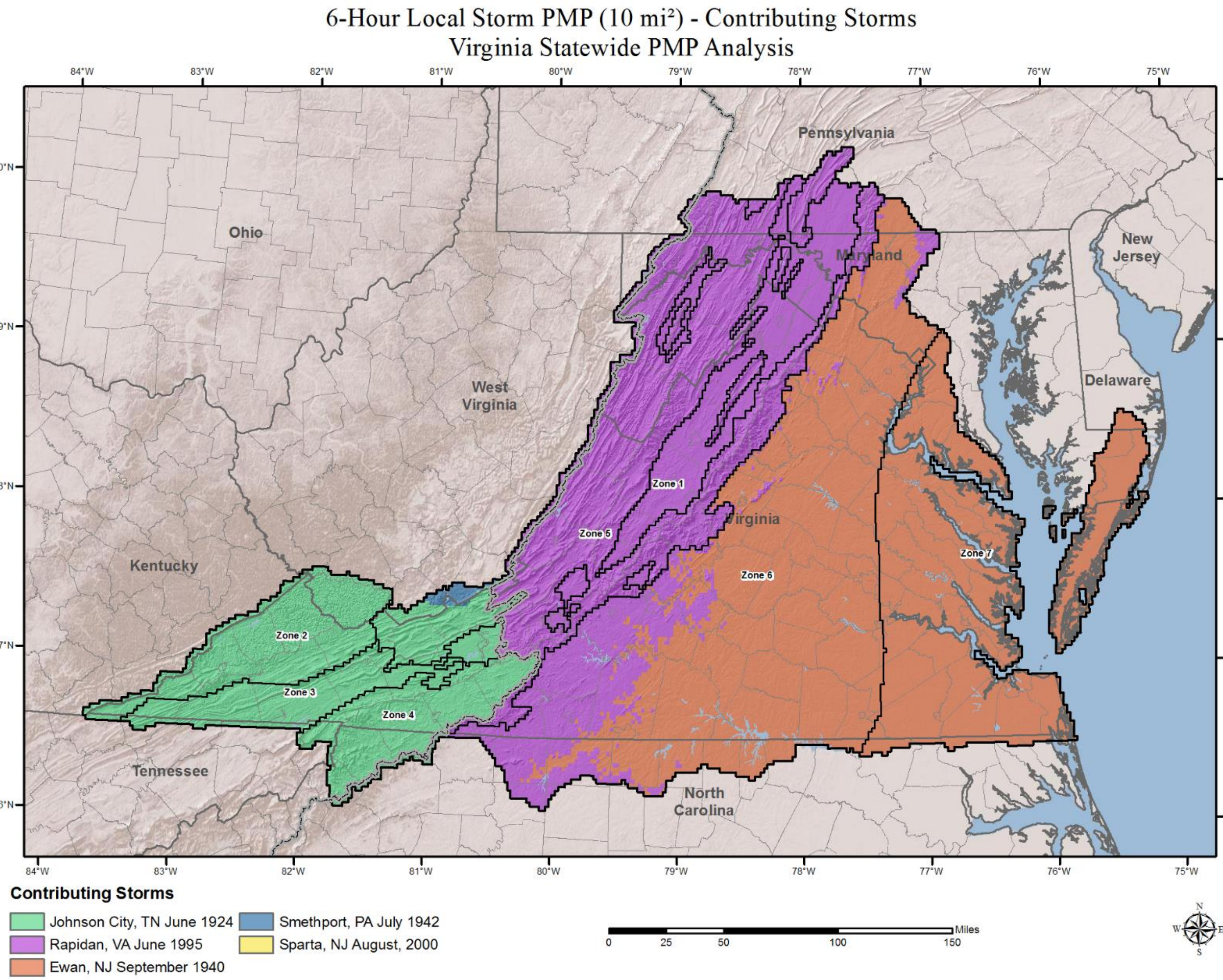

Figure 10.4 Statewide map of the controlling storms of the local storm type for the 6-hour 10-square mile PMP.

48-Hour Tropical Storm PMP (1,000 mi²) - Contributing Storms
Virginia Statewide PMP Analysis

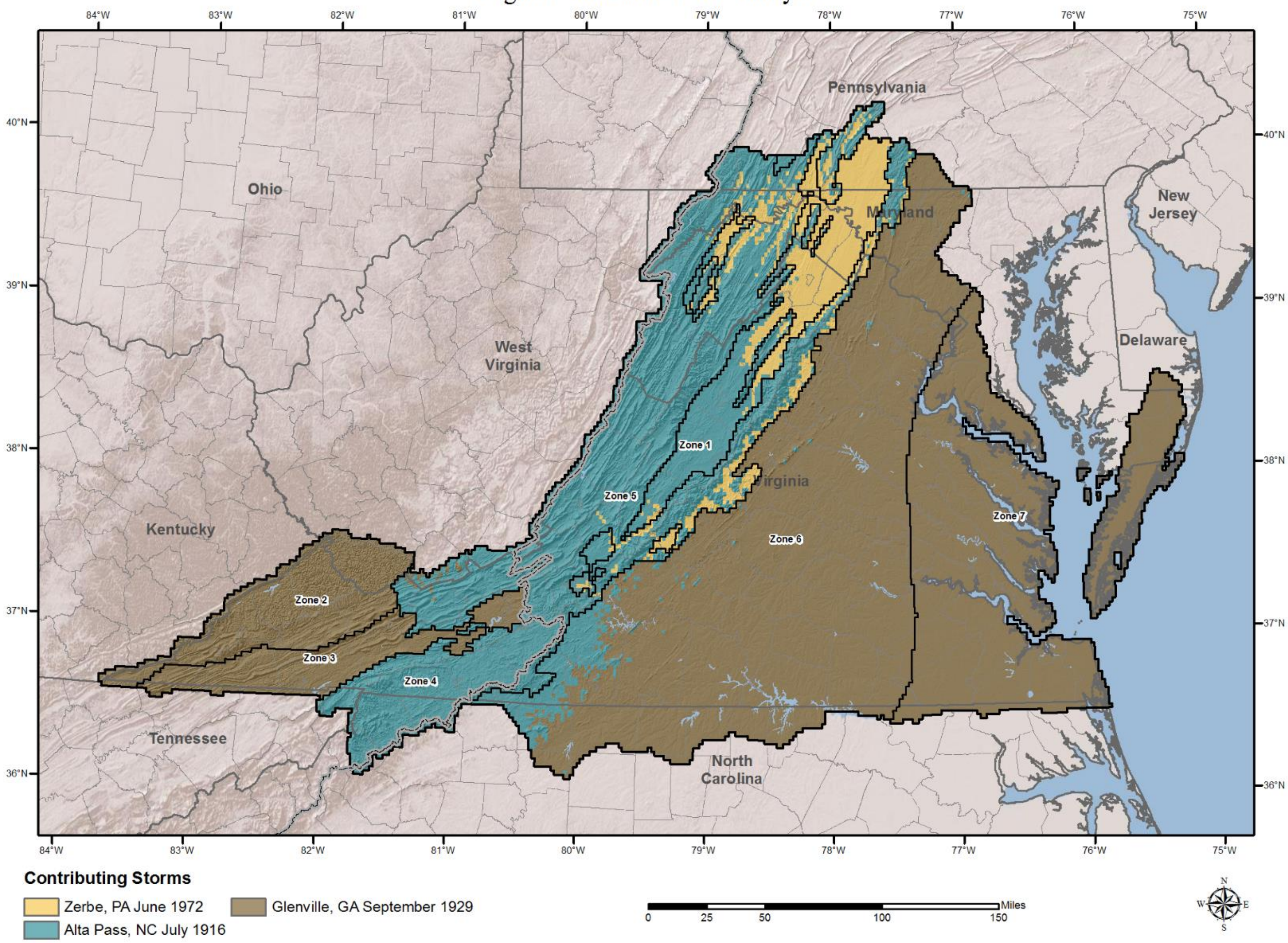

Figure 10.5 Statewide map of the controlling storms of the tropical storm type 48-hour 1,000-square mile PMP.

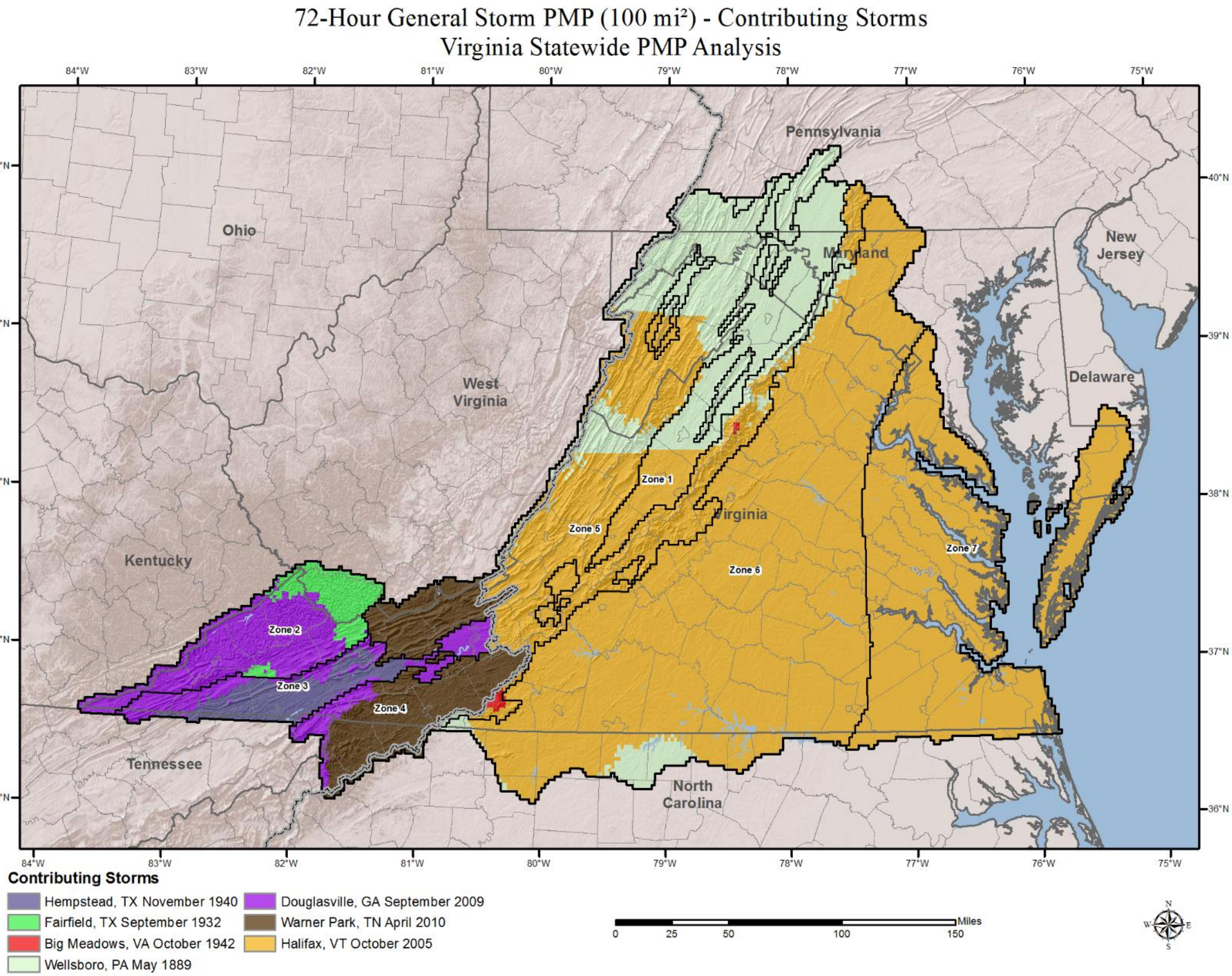

Figure 10.6 Statewide map of the controlling storms of the general storm type 72-hour 100-square mile PMP.

10.1 Evaluation of Basin-Specific PMP

PMP was calculated for three sample drainage basins: The Claytor Dam Basin, The Goshen Dam Basin, and the North Anna Dam Basin. The 2,387 square mile Claytor Dam basin is on the west side of the Appalachian crest and lies within transposition zones 3 and 4. The 82 square mile Goshen Dam basin is on the east side of the Appalachian crest and is completely within zone 5. The 341 square mile North Anna Dam basin lies within the Piedmont region of zone 6. The basin locations are shown in Figure 10.7.

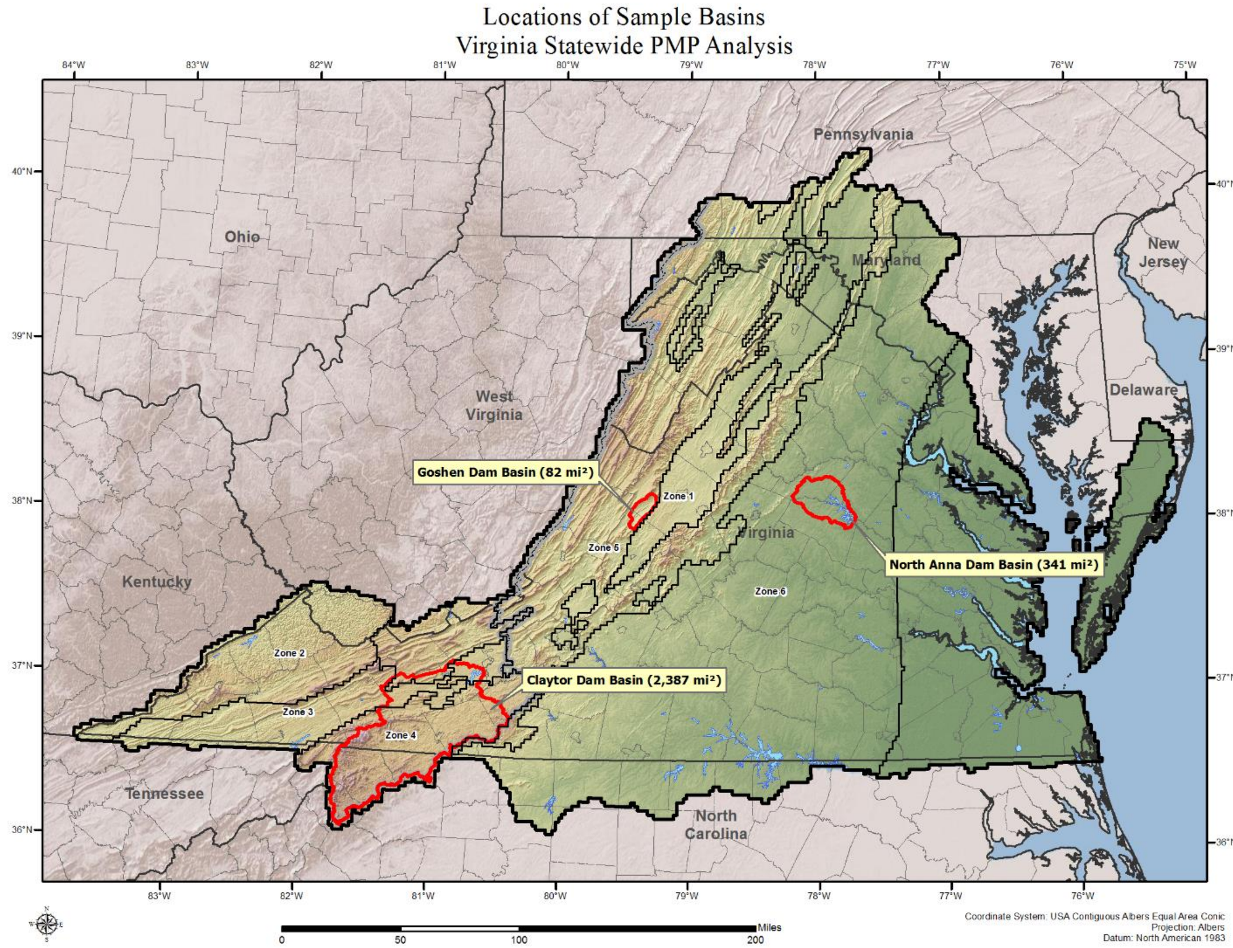

Figure 10.7 Sample basin locations

Gridded PMP values were determined for each basin at their precise area sizes following the methods described in Section 9.1 and tabulated for local storms at 1-, 6-, and 24-hour durations, and general and tropical storms at 6-, 24-, and 72-hour durations (Tables 10.1, 10.2, and 10.3). The basin area size PMP depths were calculated using the methods described in the beginning of this section. The PMP magnitudes at all durations are within the reasonable range for each storm type.

Table 10.1 2,387-square mile basin average PMP depths and the controlling storms for the Claytor Dam basin

		6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	72-hour PMP (in)
General	PMP (in)	7.7	11.7	13.4	17.6
	Source Storm(s)	Warner Park, TN 2010 Wellsboro, PA 1889	Warner Park, TN 2010 Wellsboro, PA 1889	Warner Park, TN 2010 Wellsboro, PA 1889 Hempstead, TX 1940	Warner Park, TN 2010 Wellsboro, PA 1889 Hempstead, TX 1940 Vade Mecum, NC 1908
Tropical	PMP (in)	7.0	10.4	12.7	17.1
	Source Storm(s)	Montgomery Dam, PA 2004 Americus, GA 1994 Tyro, VA 1969 Glenville, GA 1929	Montgomery Dam, PA 2004 Alta Pass, NC 1916 Glenville, GA 1929	Montgomery Dam, PA 2004 Alta Pass, NC 1916 Glenville, GA 1929	Alta Pass, NC 1916 Americus, GA 1994 Glenville, GA 1929
		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	2.1	6.7	7.7	8.3
	Source Storm(s)	Johnson City, TN 1924 Holt, MO 1947 Little River, VA 1949 Redbank, PA 1996	Tabernacle, NJ 2004 Johnson City, TN 1924 Little River, VA 1949 Redbank, PA 1996	Big Meadows, VA 1942 Boyden, IA 1926 Little River, VA 1949 Johnstown, PA 1977 Redbank, PA 1996	Big Meadows, VA 1942 Coeburn, VA 1977 Redbank, PA 1996

Table 10.2 82-square mile basin average PMP depths and the controlling storms for the Goshen Dam basin

	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	72-hour PMP (in)
PMP (in)	13.6	15.8	16.0	17.7
Source Storm(s)	Wellsboro, PA 1889	Wellsboro, PA 1889	Wellsboro, PA 1889	Halifax, VT 2005
PMP (in)	11.3	19.9	22.1	23.9
Source Storm(s)	Tyro, VA 1969	Tyro, VA 1969	Alta Pass, NC 1916	Alta Pass, NC 1916
	1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
PMP (in)	5.5	14.8	15.8	17.7
Source Storm(s)	Rapidan, VA 1995	Rapidan, VA 1995	Rapidan, VA 1995	Little River, VA 1949

Table 10.3 341-square mile basin average PMP depths and controlling storms for the North Anna Dam basin

		6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	72-hour PMP (in)
General	PMP (in)	15.2	17.5	17.9	19.2
	Source Storm(s)	Wellsboro, PA 1889	Wellsboro, PA 1889	Wellsboro, PA 1889	Halifax, VT 2005 Wellsboro, PA 1889
Tropical	PMP (in)	11.5	18.7	19.6	26.4
	Source Storm(s)	Tyro, VA 1969	Tyro, VA 1969	Alta Pass, NC 1916 Glenville, GA 1929	Alta Pass, NC 1916 Glenville, GA 1929
		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	4.5	15.8	18.2	18.2
	Source Storm(s)	Rapidan, VA 1995 Ewan, NJ 1940	Rapidan, VA 1995 Jewell, MD 1897 Ewan, NJ 1940	Jewell, MD 1897 Ewan, NJ 1940 Little River, VA 1949	Jewell, MD 1897 Ewan, NJ 1940 Little River, VA 1949

10.2 Comparison of the PMP Values with Precipitation Frequency

The ratio of the 1-square mile 24-hour PMP to 24-hour 100-year return period rainfall 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 HMRs 57 and 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 24-hour 1-square mile PMP was compared directly to the 100-year 24-hour precipitation frequency values from NOAA Atlas 14 Volume 2 (Bonin et al., 2004) on a grid-by-grid basis for the entire analysis domain using a GIS. The comparison was presented as a percent of PMP and ratio of PMP to precipitation, and was determined for each grid point. Average zonal statistics were summarized for each transposition zone. Table 10.4 provides the statistics for the comparison with 100-year 24-hour precipitation frequency depths.

The PMP to 100-year return period precipitation ratios for storm controlling PMP vary from 3.5 to 4.0 and are in reasonable proportion expected for the study area. The ratios that are not controlling of PMP are grayed out in the table. This explicitly shows that the PMP values are sufficiently larger than the 100-year values as to provide the necessary conservatism required for use in dam safety. The values are controlled by the local storm type for all transposition zones, with the tropical storm equal to the local storm in the highly orographic Blue Ridge East, transposition zone 5. This is expected, as the comparison is between the 1-square mile area size value, which is most often controlled by the local storm type storm.

Table 10.4 Comparison of 24-hour 1-square mile PMP with 100-year 24-hour precipitation values. Value in bold are the controlling values for a given transposition zone. Grayed values are not controlling.

Local Storm Gridded Average by Transposition Zone				
Transposition Zone	24hr 1 mi² Local PMP (inches)	100yr 24hr NOAA 14 Precip (inches)	Percent of PMP	Ratio of PMP to 100yr 24hr Precip
1 - Interior Valley	24.1	6.6	28%	**3.6**
2 - Cumberland Plateau	22.0	5.6	26%	**3.9**
3 - Great Valley	19.6	5.3	27%	**3.7**
4 - Blue Ridge West	23.1	6.9	30%	**3.4**
5 - Blue Ridge East	24.2	6.9	29%	**3.5**
6 - Piedmont	31.4	8.2	26%	**3.8**
7 - Coastal Plain	35.6	8.9	25%	**4.0**
Statewide Domain	**28.6**	**7.6**	**27%**	**3.8**

Tropical Storm Gridded Average by Transposition Zone				
Transposition Zone	24hr 1 mi² Tropical PMP (inches)	100yr 24hr NOAA 14 Precip (inches)	Percent of PMP	Ratio of PMP to 100yr 24hr Precip
1 - Interior Valley	22.5	6.6	30%	3.4
2 - Cumberland Plateau	13.7	5.6	41%	2.4
3 - Great Valley	12.0	5.3	44%	2.3
4 - Blue Ridge West	20.4	6.9	35%	2.9
5 - Blue Ridge East	24.3	6.9	29%	**3.5**
6 - Piedmont	30.0	8.2	27%	3.7
7 - Coastal Plain	35.1	8.9	25%	3.9
Statewide Domain	**26.9**	**7.6**	**29%**	**3.5**

General Storm Gridded Average by Transposition Zone				
Transposition Zone	24hr 1 mi² General PMP (inches)	100yr 24hr NOAA 14 Precip (inches)	Percent of PMP	Ratio of PMP to 100yr 24hr Precip
1 - Interior Valley	15.4	6.6	43%	2.3
2 - Cumberland Plateau	18.3	5.6	31%	3.3
3 - Great Valley	16.0	5.3	33%	3.0
4 - Blue Ridge West	18.8	6.9	37%	2.7
5 - Blue Ridge East	16.5	6.9	42%	2.4
6 - Piedmont	20.4	8.2	40%	2.5
7 - Coastal Plain	22.4	8.9	40%	2.5
Statewide Domain	**19.2**	**7.6**	**40%**	**2.5**

10.3 Annual Exceedance Probability of Short List Storms

Annual Exceedance Probabilities (AEP) were estimated for each storm's unadjusted maximum rainfall using the NOAA Atlas 14 precipitation frequency climatologies. The AEPs were calculated at the 6-hour duration for local storms and 24-hour and 72-hour durations for general and tropical storms. The SPAS analyzed maximum rainfall at the storm center location was compared to the NOAA Atlas 14 precipitation values obtained from the Precipitation

Frequency Data Server (PFDS) at the same location. The AEP was estimated by locating the SPAS analyzed rainfall depth on the range of precipitation values reported on the PFDS and linearly interpolating between the two bounding average recurrence intervals. The reciprocal of the return period is the AEP. NOAA Atlas 14 provides precipitation estimates up to the 1,000-year average recurrence interval. In many cases, the return period of the analyzed storms was beyond 1,000-years. When this occurred, the AEP was expressed as < 0.10%. Table 10.5 lists the AEP for each local storm, Table 10.6 lists the AEP for each general storm, Table 10.7 lists the AEP for each tropical storm.

Table 10.5 Annual Exceedance Probability for local storms

Storm Name	State	Lat	Lon	Year	Month	Day	Max Rainfall	NOAA Atlas 14 AEP (6hr)
JEWELL	MD	38.73	-76.57	1897	7	26	15.88	<0.10%
COOPER	MI	42.37	-85.59	1914	8	31	13.39	<0.10%
JOHNSON CITY	TN	36.30	-82.06	1924	6	13	16.14	<0.10%
BOYDEN	IA	43.20	-96.00	1926	9	17	24.22	<0.10%
SIMPSON	KY	38.10	-83.30	1939	7	4	20.82	<0.10%
EWAN	NJ	39.69	-75.18	1940	9	1	24.30	<0.10%
HALLETT	OK	36.25	-96.61	1940	9	2	24.00	<0.10%
SMETHPORT	PA	41.87	-78.28	1942	7	17	34.91	<0.10%
BIG MEADOWS	VA	38.55	-78.40	1942	10	12	19.77	1.27%
MOUNDS	OK	35.85	-96.07	1943	5	15	19.27	<0.10%
GLENVILLE	WV	38.90	-80.77	1943	8	4	15.04	<0.10%
HOLT	MO	39.45	-94.33	1947	6	18	17.62	<0.10%
LITTLE RIVER	VA	38.86	-79.19	1949	6	17	15.13	<0.10%
ROSEDALE	TN	36.18	-84.23	1965	7	24	13.32	<0.10%
COEBURN	VA	37.28	-81.80	1977	4	2	15.66	1.15%
JOHNSTOWN	PA	40.40	-78.95	1977	7	18	12.64	<0.10%
DANDRIDGE	TN	37.26	-84.97	1984	5	7	9.62	0.49%
RAPIDAN	VA	38.42	-78.34	1995	6	27	28.39	<0.10%
REDBANK	PA	41.26	-79.16	1996	7	19	9.42	<0.10%
SPARTA	NJ	41.03	-74.64	2000	8	11	16.70	<0.10%
TABERNACLE	NJ	39.88	-74.69	2004	7	13	15.63	<0.10%
DELAWARE COUNTY	NY	42.01	-74.90	2007	6	19	11.69	<0.10%
ISLIP	NY	40.81	-73.07	2014	8	13	14.23	<0.10%

Table 10.6 Annual Exceedance Probability for general storms

Storm Name	State	Lat	Lon	Year	Month	Day	Max Rainfall	NOAA Atlas 14 AEP (24hr)	NOAA Atlas 14 AEP (72hr)
WELLSBORO	PA	41.70	-77.23	1844	5	30	10.11	< 0.10%	0.12%
VADE MECUM	NC	36.31	-80.28	1908	8	23	18.00	< 0.10%	< 0.10%
ELBA	AL	31.36	-86.12	1929	3	12	29.73	0.21%	< 0.10%
FAIRFIELD	TX	31.6792	-96.1292	1932	9	2	19.58	< 0.10%	N/A
PINKHAM NOTCH	NH	44.25	-71.22	1936	3	9	9.70	3.33%	4.76%
PADDY MOUNTAIN	WV	39.02	-78.56	1936	3	16	8.32	1.46%	0.93%
PINKHAM NOTCH	NH	44.25	-71.22	1936	3	16	12.37	2.86%	2.08%
MCKENZIE	TN	36.44	-87.91	1937	1	17	19.86	3.56%	0.15%
BLUE RIDGE DIVIDE	NC	35.04	-83.08	1940	8	28	14.09	0.37%	1.08%
HEMPSTEAD	TX	30.1292	-96.0542	1940	11	22	21.29	< 0.10 %	N/A
BIG MEADOWS	VA	38.55	-78.40	1942	10	12	19.77	0.22%	< 0.10%
WARNER	OK	35.48	-95.33	1943	5	6	25.24	< 0.10%	< 0.10%
COLLINSVILLE	IL	38.67	-90.00	1946	8	12	19.07	0.11%	< 0.10%
HARRISONBURG DAM	LA	31.79	-91.81	1953	5	11	25.34	0.14%	0.19%
ROSMAN	NC	37.74	-81.60	1964	9	26	9.22	0.12%	0.12%
ROSMAN	NC	35.15	-82.80	1964	9	26	17.86	0.12%	0.11%
EDGERTON	MO	40.41	-95.51	1965	7	18	20.76	< 0.10%	< 0.10%
BURTON DAM	GA	34.80	-83.70	1967	8	21	18.42	1.31%	1.12%
BURNSVILLE	TN	34.84	-88.40	1973	3	14	12.15	0.47%	0.72%
MONTEBELLO	VA	37.81	-79.16	1985	11	1	22.56	0.25%	0.11%
HALIFAX	VT	42.77	-72.75	2005	10	7	15.40	< 0.10%	< 0.10%
TAMAQUA	PA	41.68	-75.38	2006	6	26	12.26	0.24%	0.20%
DOUGLASVILLE	GA	33.87	-84.77	2009	9	19	25.37	< 0.10%	< 0.10%
WARNER PARK	TN	36.06	-86.91	2010	4	30	19.71	< 0.10%	< 0.10%
PORTSMOUTH	VA	35.18	-77.22	2010	9	27	23.44	0.33%	< 0.10%

Table 10.7 Annual Exceedance Probability for tropical storms

Storm Name	State	Lat	Lon	Year	Month	Day	Max Rainfall	NOAA Atlas 14 AEP (24hr)	NOAA Atlas 14 AEP (72hr)
ST GEORGE	GA	30.52	-82.02	1911	8	28	19.10	< 0.10%	0.16%
ALTA PASS	NC	35.88	-81.87	1916	7	13	24.90	< 0.10%	< 0.10%
KINGSTREE	NC	33.66	-79.83	1916	7	13	16.79	0.13%	0.15%
GLENVILLE	GA	34.88	-84.28	1929	9	23	20.88	< 0.10%	< 0.10%
GLENVILLE	GA	34.86	-84.29	1929	9	23	21.20	< 0.10%	< 0.10%
MONCURE	NC	35.60	-79.07	1929	9	29	11.55	0.10%	0.17%
SETTLE	NC	35.95	-80.70	1929	9	29	9.97	0.70%	0.49%
EASTON	MD	38.86	-76.07	1935	9	4	17.00	0.19%	< 0.10%
MT MITCHELL	NC	36.30	-81.45	1940	8	10	20.27	0.12%	< 0.10%
SLIDE MOUNTAIN	NY	42.02	-74.42	1955	8	11	14.70	0.94%	1.03%
WESTFIELD	MA	42.12	-72.70	1955	8	17	20.09	< 0.10%	< 0.10%
WEST SHOKAN	NY	41.95	-74.32	1955	10	14	18.50	1.19%	0.23%
ROSMAN	NC	35.14	-82.84	1964	10	3	17.53	< 0.10%	< 0.10%
TYRO	VA	37.81	-79.00	1969	8	19	27.23	< 0.10%	< 0.10%
ZERBE	PA	40.54	-76.62	1972	6	18	18.79	< 0.10%	< 0.10%
AMERICUS	GA	32.10	-84.23	1994	7	4	28.09	< 0.10%	< 0.10%
ANTREVILLE	SC	34.86	-82.23	1995	8	26	19.99	< 0.10%	< 0.10%
SOUTHPORT 5 N	NC	34.01	-78.00	1999	9	14	24.30	0.18%	< 0.10%
YORKTOWN	VA	37.28	-76.56	1999	9	14	19.22	< 0.10%	< 0.10%
MT MANSFIELD	VT	44.53	-72.81	1999	9	15	11.35	0.28%	0.42%
POMTON LAKE	NJ	41.00	-74.29	1999	9	15	14.62	< 0.10%	0.11%
CAIRO	NY	42.30	-74.01	1999	9	15	11.71	0.21%	0.39%
PINKHAM NOTCH	NH	44.26	-71.34	1999	9	15	10.55	3.33%	5.55%
EDENTON	NC	35.86	-76.50	2003	9	17	7.96	3.03%	6.67%
UPPER SHERANDO	VA	37.91	-79.03	2003	9	17	20.22	< 0.10%	< 0.10%
RICHMOND	VA	37.71	-77.38	2004	8	30	14.38	< 0.10%	0.15%
MONTEGOMERY DAM	PA	40.61	-76.47	2004	9	18	8.80	< 0.10%	< 0.10%
MONTGOMERY DAM	PA	40.65	-80.39	2004	9	18	8.79	< 0.10%	< 0.10%
RALEIGH	NC	34.34	-81.01	2006	6	13	9.32	0.56%	1.12%
MAPLECREST	NY	42.30	-74.16	2011	8	27	22.91	< 0.10%	< 0.10%
HARRISBURG	PA	39.99	-76.50	2011	9	4	18.32	< 0.10%	< 0.10%

10.4 Comparison of the PMP Values with HMR PMP Values

Previous PMP values from HMR 51 and HMR 56 are unable to accurately account for the effect of terrain. This study employs a variety of improved methods when compared to previous HMRs studies including 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; use of updated precipitation frequency climatologies (NOAA Atlas 14) to more accurate resolve and compare variations across terrain; gridded PMP calculations which result in higher spatial and temporal resolutions; and a greatly expanded storm record. Unfortunately, working papers and notes from the HMRs are not available in most cases, therefore direct PMP comparisons between the HMRs and the values from this study are somewhat limited. Furthermore, due to the generalization of the regionallybased HMR studies, comparisons to the detailed gridded PMP of this study can vary greatly over short distances. However, comparisons were made for sensitivity purposes. The PMP values in this study resulted in a wide range of both reductions and some minor increases as compared to the HMRs.

A gridded statewide comparison was made by averaging the updated PMP values over each transposition zone. Figures 10.8 through 10.16 show the highest PMP values of all three storm types compared to HMR 51 as a percent difference from the original HMR 51 values. Table 10.8 provides the results of those comparisons to HMR 51 for the local storms using the 10- and 200 square miles, at 6-, and 24 hour durations. Table 10.9 provides the results of those comparisons for the general storms using the 10-, 200-, and 1,000 square miles, at 6-, 24-, and 72-hour durations. Table 10.10 provides the results of those comparisons for the tropical storms using the 10-, 200-, and 1,000 square miles, at 6-, 24-, and 72-hour durations. The Virginia PMP domain also overlaps and was compared to HMR 56. Figure 10.14 compares PMP values derived during this analysis to the 6-hour 1-square mile values from Figure 23 of HMR 56.

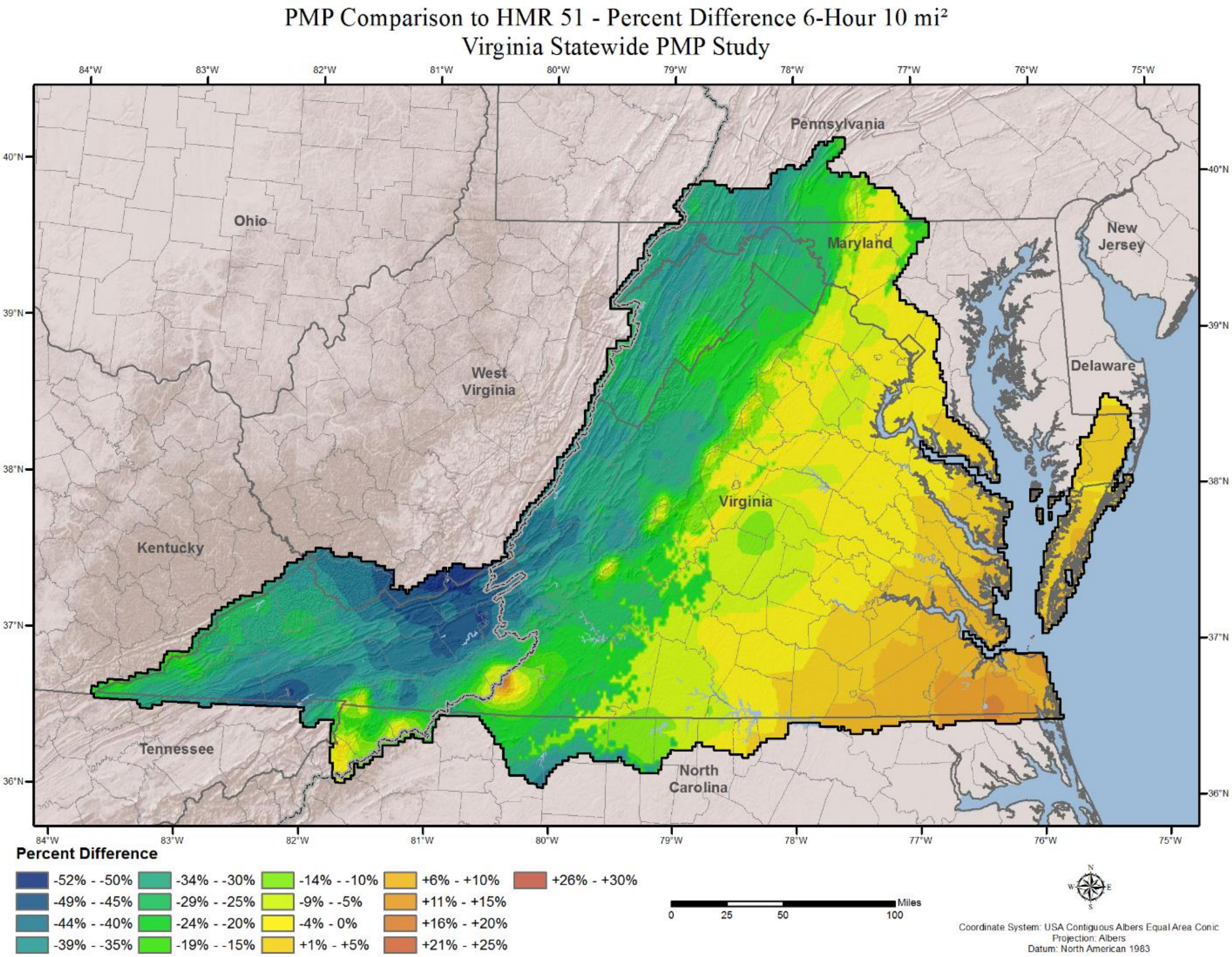

Figure 10.8 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 6-hour 10 square miles. Note the scale in the legend is specific to the image.

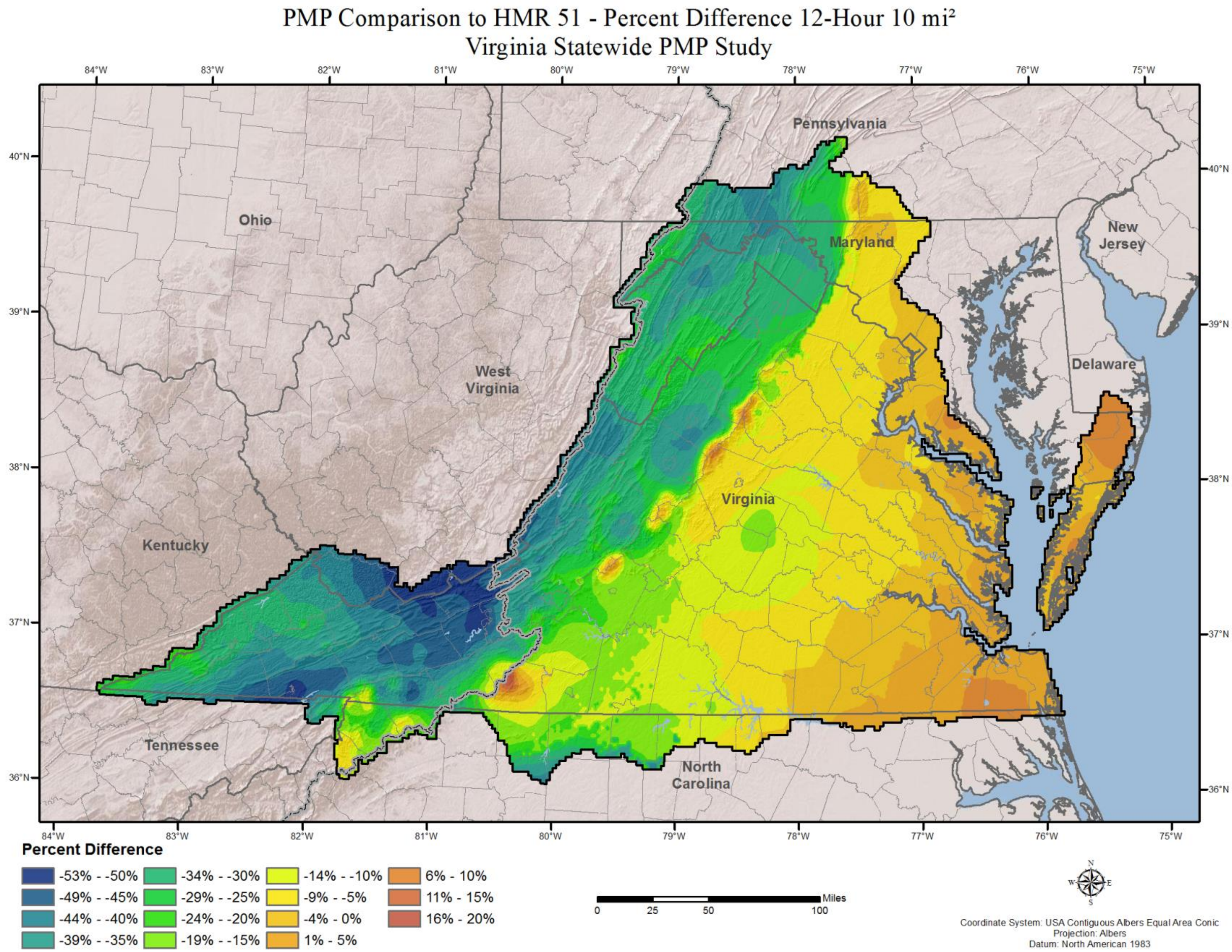

Figure 10.9 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 12-hour 10 square miles. Note the scale in the legend is specific to the image.

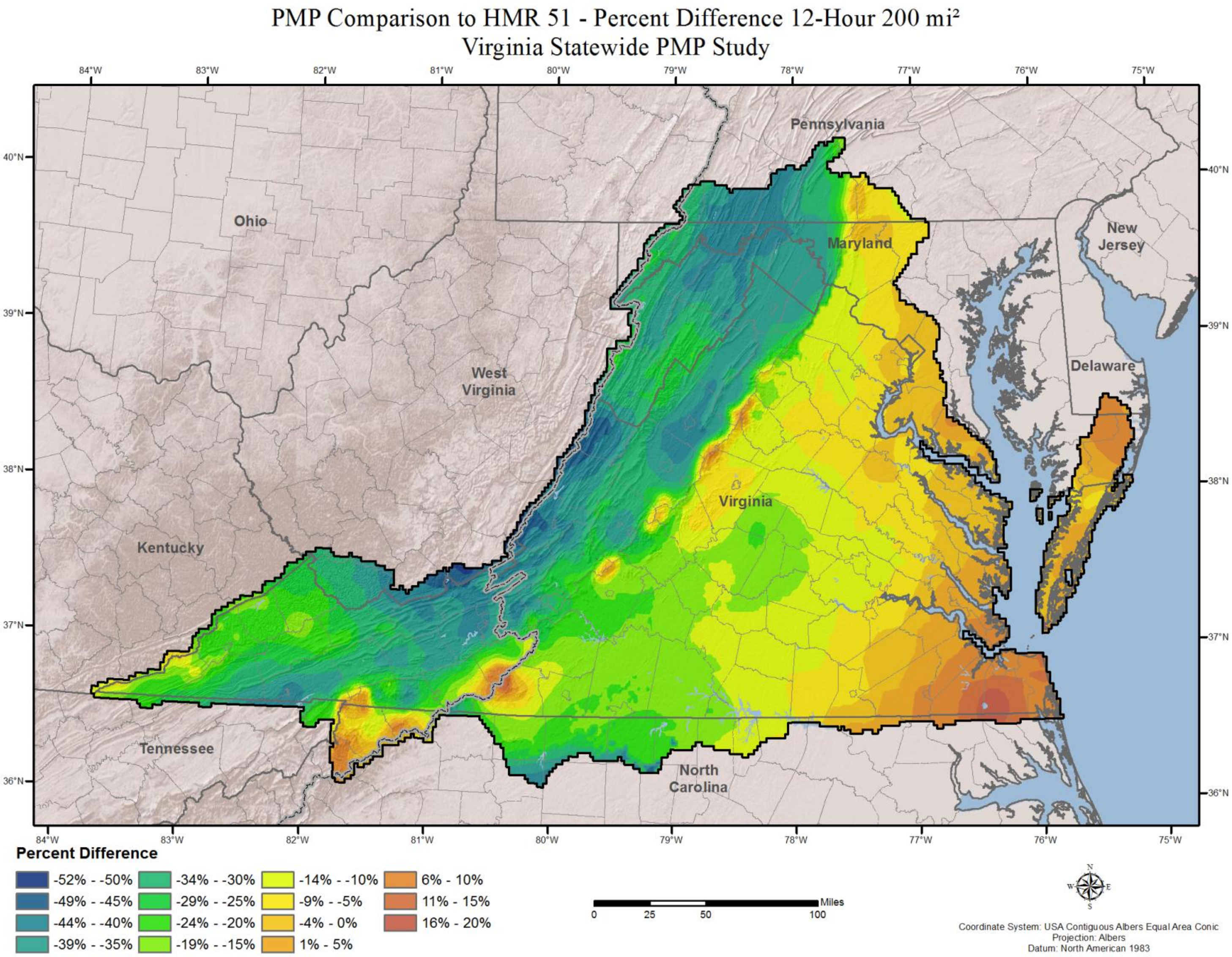

Figure 10.10 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 12-hour 200 square miles. Note the scale in the legend is specific to the image.

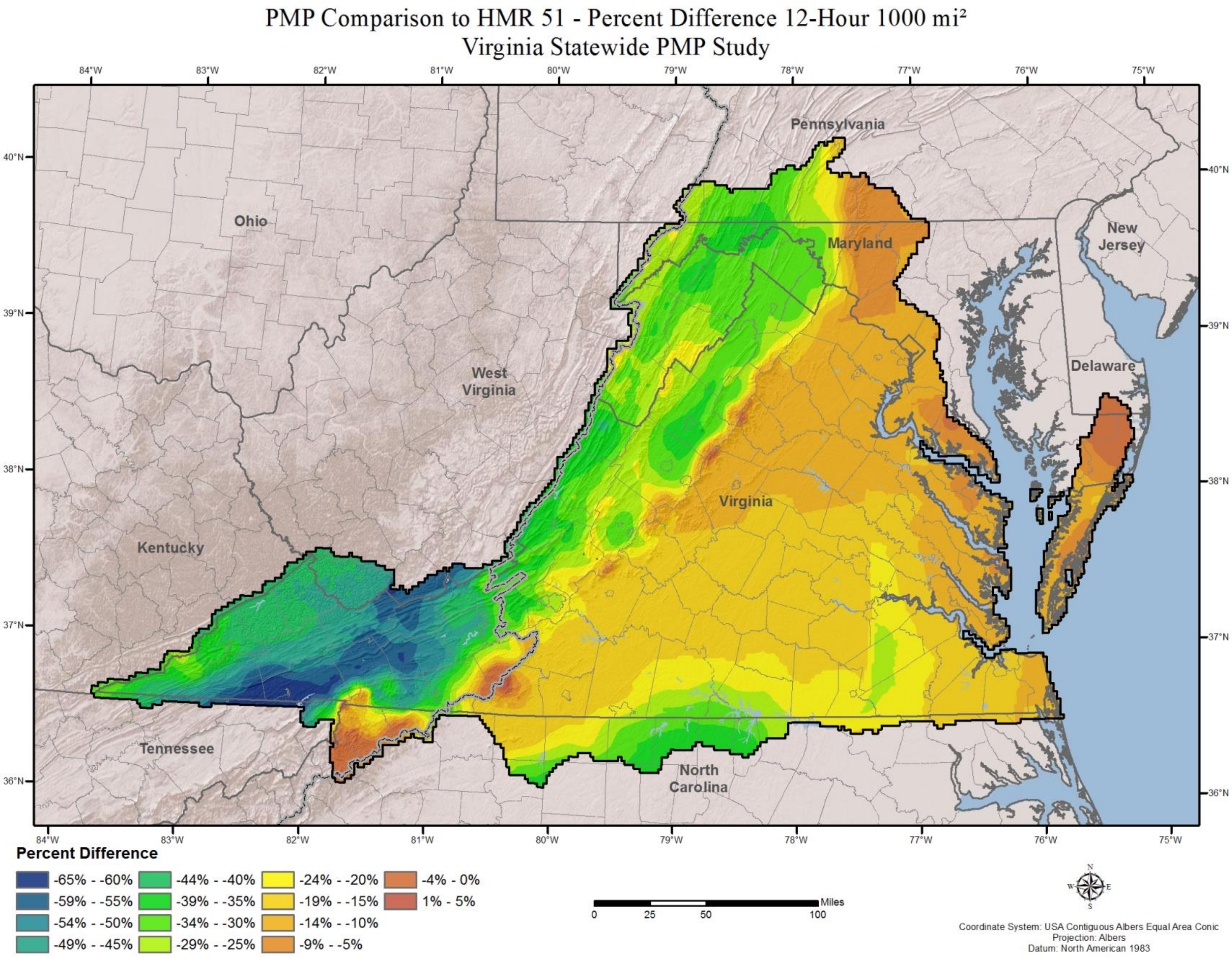

Figure 10.11 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 12-hour 1,000 square miles. Note the scale in the legend is specific to the image.

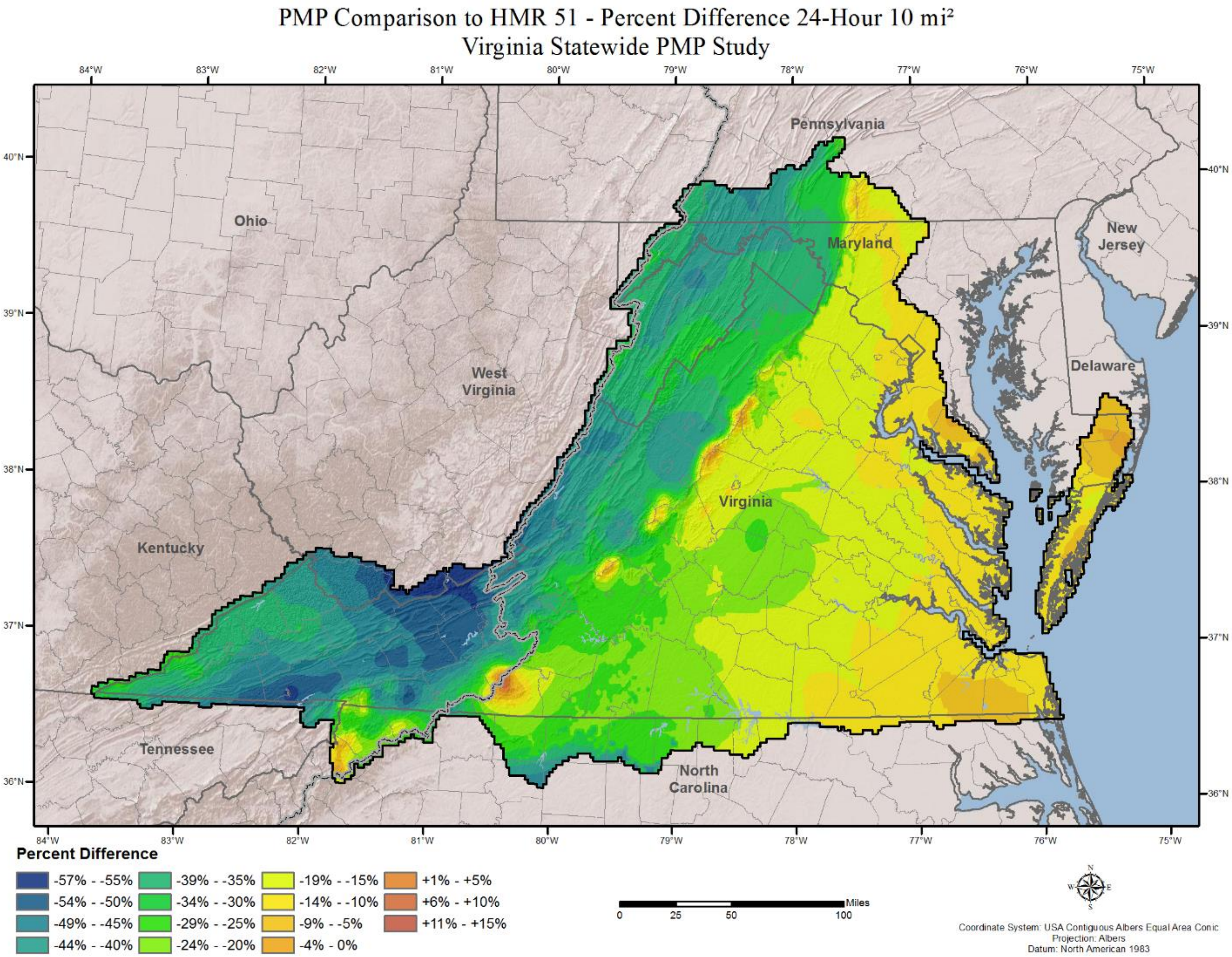

Figure 10.12 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 24-hour 10 square miles. Note the scale in the legend is specific to the image.

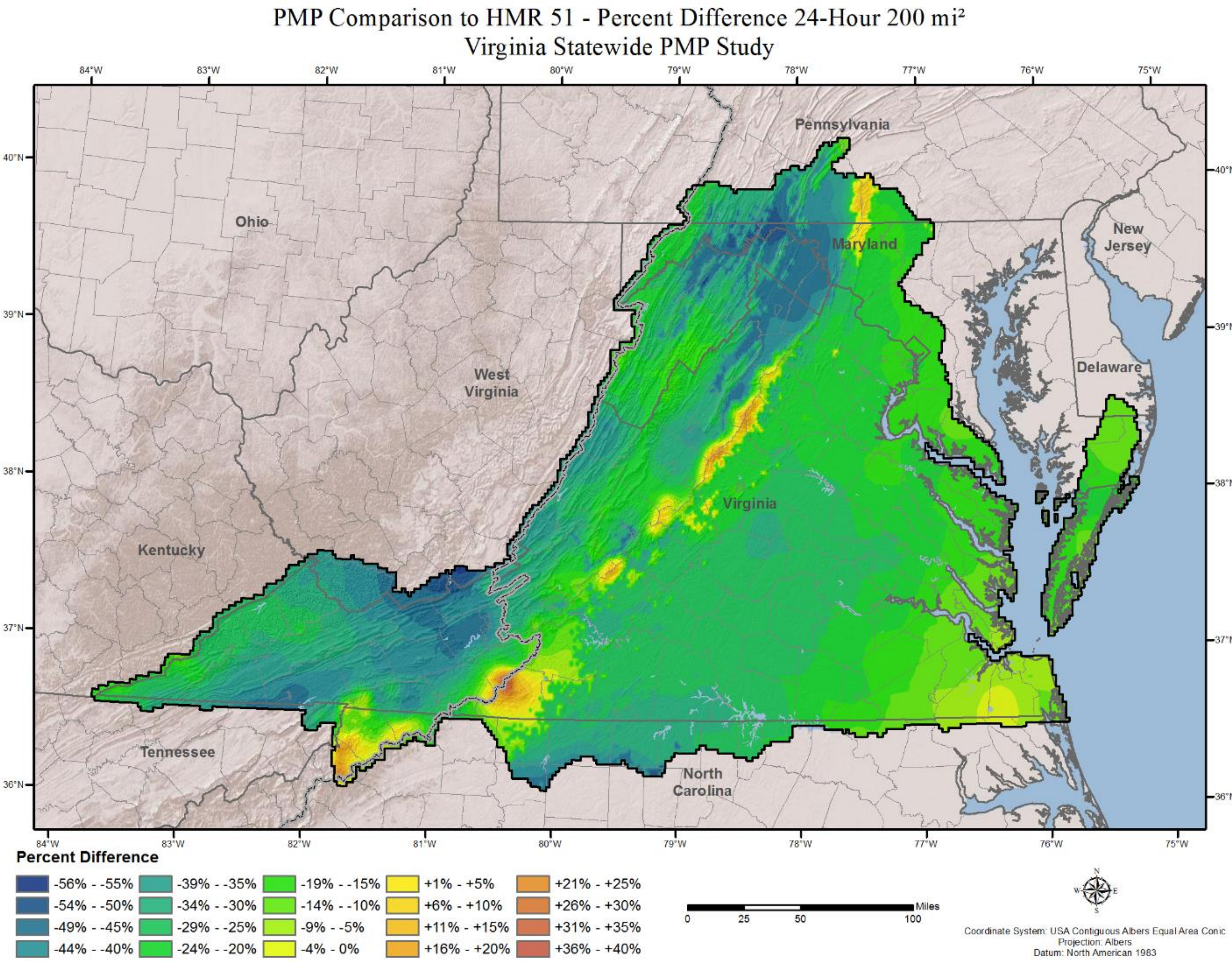

Figure 10.13 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 24-hour 200 square miles. Note the scale in the legend is specific to the image.

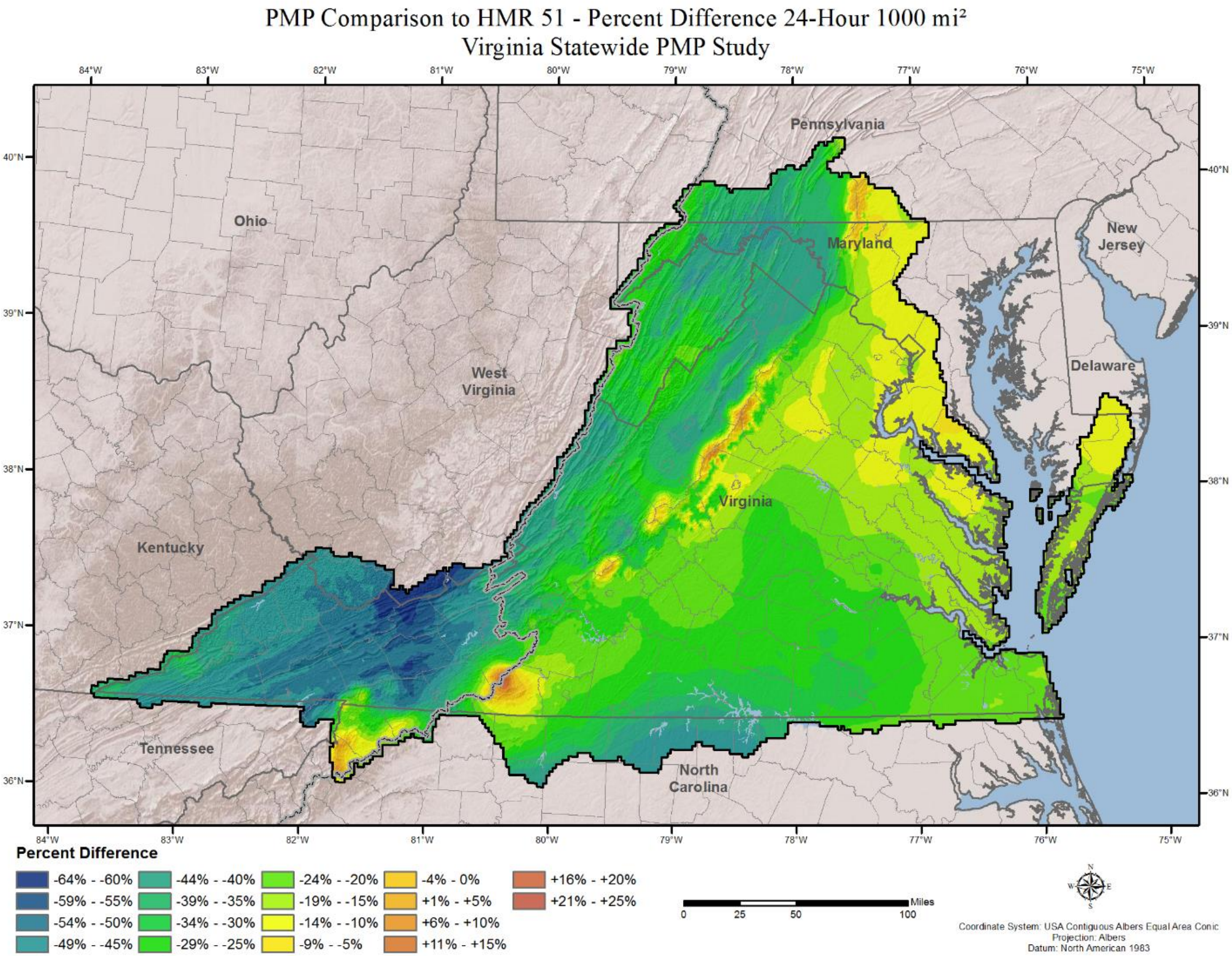

Figure 10.14 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 24-hour 1,000 square miles. Note the scale in the legend is specific to the image.

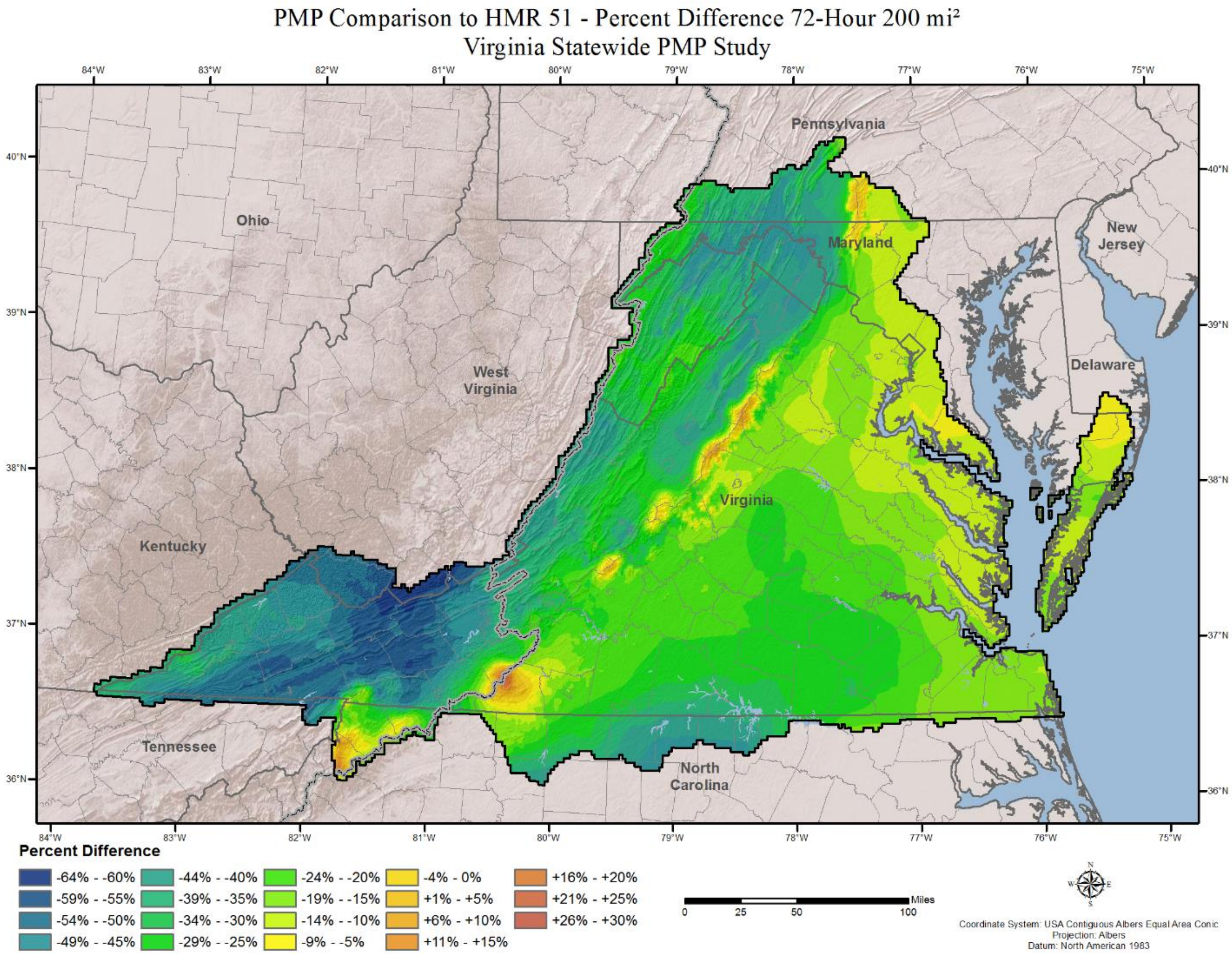

Figure 10.15 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 72-hour 200 square miles. Note the scale in the legend is specific to the image.

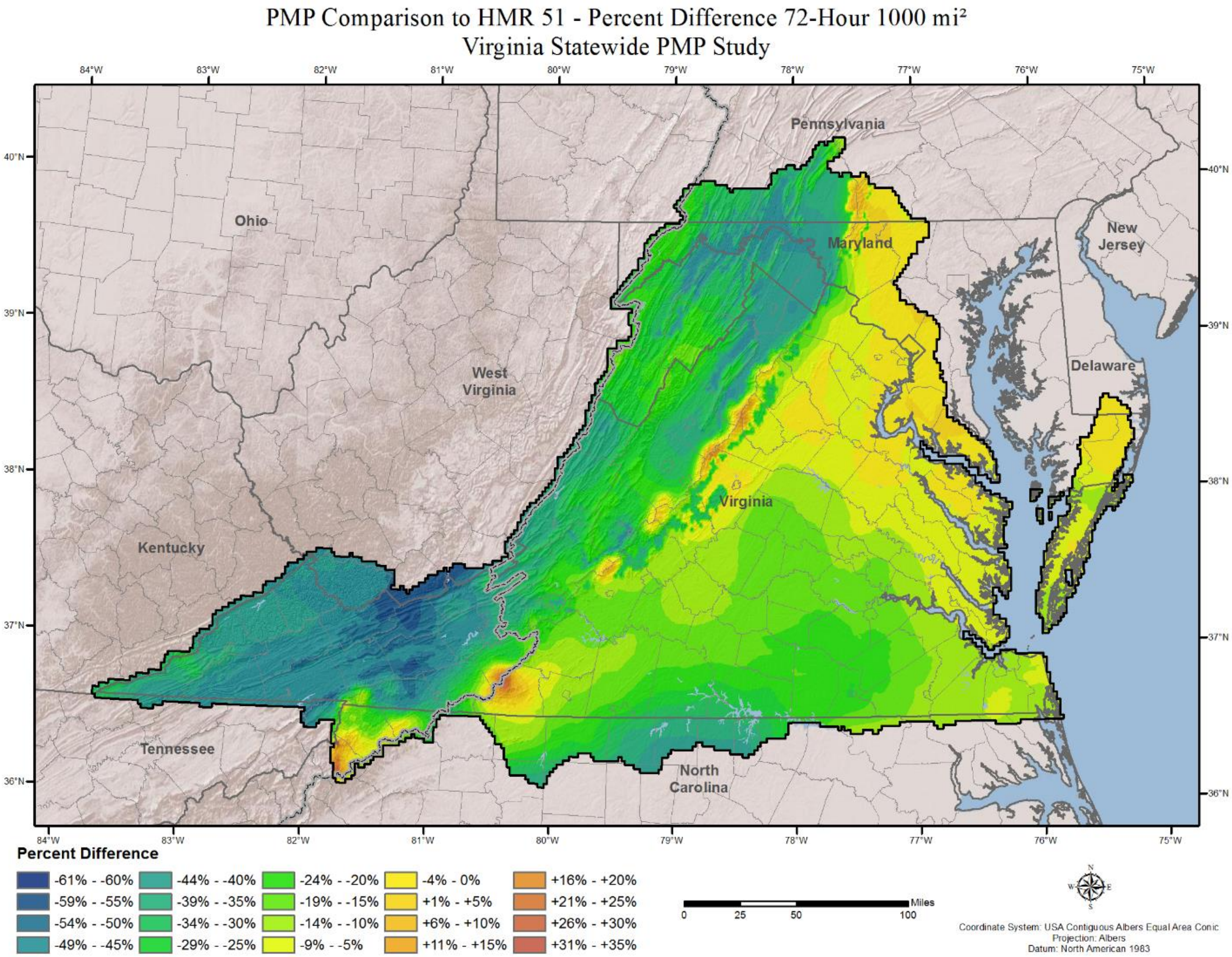

Figure 10.16 Percent difference of HMR 51 values compared to largest PMP values from all three storm types 72-hour 1,000 square miles. Note the scale in the legend is specific to the image.

Table 10.8 Comparisons of local storm PMP values versus the HMR 51 PMP values. Grayed out rows signify where one of the other storm types is controlling.

Local Storm 10 Sq Mi Average PMP									
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr
1 - Interior Valley	27.6	19.7	-28.7%	32.2	21.2	-34.3%	35.5	21.8	-38.5%
2 - Cumberland Plateau	28.7	19.2	-33.2%	33.8	21.5	-36.6%	36.9	21.7	-41.3%
3 - Great Valley	28.9	17.1	-40.7%	34.1	19.2	-43.9%	37.4	19.4	-48.3%
4 - Blue Ridge West	28.9	19.7	-31.8%	34.1	22.1	-35.5%	37.6	22.3	-40.8%
5 - Blue Ridge East	27.8	19.8	-28.8%	32.5	21.3	-34.5%	35.8	22.0	-38.6%
6 - Piedmont	28.5	26.1	-8.5%	33.7	29.0	-13.9%	37.7	29.1	-22.7%
7 - Coastal Plain	28.6	29.6	3.7%	33.8	33.1	-2.1%	38.5	33.1	-14.0%
Statewide Domain	**28.4**	**23.8**	**-16.2%**	**33.4**	**26.3**	**-21.4%**	**37.2**	**26.6**	**-28.9%**

Local Storm 200 Sq Mi Average PMP									
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr
1 - Interior Valley	19.2	11.5	-40.2%	22.9	12.5	-45.5%	26.5	14.3	-46.0%
2 - Cumberland Plateau	20.4	16.7	-18.1%	24.3	18.4	-24.6%	27.4	18.7	-31.7%
3 - Great Valley	20.5	14.9	-27.5%	24.6	16.4	-33.3%	27.8	16.7	-39.9%
4 - Blue Ridge West	20.5	17.1	-16.8%	24.5	18.8	-23.5%	28.1	19.2	-31.8%
5 - Blue Ridge East	19.4	11.6	-40.4%	23.1	12.8	-44.6%	26.7	15.5	-41.8%
6 - Piedmont	20.2	17.4	-14.1%	24.2	19.4	-19.7%	28.4	19.8	-30.4%
7 - Coastal Plain	20.4	21.2	3.6%	24.4	23.8	-2.5%	29.3	24.2	-17.7%
Statewide Domain	**20.1**	**16.3**	**-19.0%**	**24.0**	**18.2**	**-24.5%**	**28.0**	**19.1**	**-32.0%**

Table 10.9 Comparisons of general storm PMP values versus the HMR 51 PMP values. Grayed out rows signify where one of the other storm types is controlling.

General Storm 10 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	27.6	12.5	-54.6%	32.2	14.5	-55.0%	35.5	14.9	-58.0%	40.8	18.0	-56.0%
2 - Cumberland Plateau	28.7	12.6	-56.0%	33.8	15.9	-53.1%	36.9	17.9	-51.6%	42.3	20.7	-51.1%
3 - Great Valley	28.9	10.9	-62.3%	34.1	13.7	-59.9%	37.4	15.7	-58.1%	43.0	18.3	-57.5%
4 - Blue Ridge West	28.9	15.3	-47.1%	34.1	17.8	-47.9%	37.6	18.7	-50.4%	43.3	20.4	-53.1%
5 - Blue Ridge East	27.8	13.1	-52.8%	32.5	15.2	-53.3%	35.8	16.0	-55.4%	41.1	19.2	-53.3%
6 - Piedmont	28.5	15.7	-45.1%	33.7	18.2	-46.0%	37.7	19.7	-47.6%	43.5	23.8	-45.2%
7 - Coastal Plain	28.6	8.1	-71.8%	33.8	14.5	-57.2%	38.5	21.7	-43.7%	44.5	26.1	-41.3%
Statewide Domain	**28.4**	**13.0**	**-54.0%**	**33.4**	**16.2**	**-51.4%**	**37.2**	**18.6**	**-50.1%**	**42.9**	**22.2**	**-48.3%**

General Storm 200 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	19.2	12.2	-36.8%	22.9	13.9	-39.5%	26.5	14.3	-46.1%	31.5	14.9	-52.6%
2 - Cumberland Plateau	20.4	10.1	-50.4%	24.3	12.9	-47.1%	27.4	16.0	-41.5%	33.1	17.9	-46.0%
3 - Great Valley	20.5	8.7	-57.7%	24.6	10.7	-56.4%	27.8	13.7	-50.6%	33.6	16.1	-52.2%
4 - Blue Ridge West	20.5	12.4	-39.7%	24.5	15.3	-38.0%	28.1	16.2	-42.4%	33.8	18.9	-44.3%
5 - Blue Ridge East	19.4	12.7	-34.5%	23.1	14.5	-37.4%	26.7	14.9	-44.0%	31.7	15.8	-50.2%
6 - Piedmont	20.2	15.2	-24.6%	24.2	17.3	-28.2%	28.4	17.9	-37.0%	33.8	19.3	-42.8%
7 - Coastal Plain	20.4	6.6	-67.6%	24.4	11.6	-52.4%	29.3	17.6	-39.9%	34.7	21.3	-38.7%
Statewide Domain	**20.1**	**12.1**	**-39.7%**	**24.0**	**14.7**	**-38.5%**	**28.0**	**16.6**	**-40.9%**	**33.3**	**18.4**	**-44.9%**

General Storm 1000 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	13.9	10.9	-21.9%	17.6	12.3	-29.9%	21.2	12.5	-41.1%	25.0	14.2	-43.2%
2 - Cumberland Plateau	15.0	7.7	-48.5%	18.9	10.8	-43.0%	22.2	13.3	-40.0%	26.5	14.9	-44.0%
3 - Great Valley	15.1	6.4	-57.4%	19.2	9.0	-53.3%	22.8	11.4	-50.0%	27.1	14.3	-47.1%
4 - Blue Ridge West	15.1	9.2	-39.6%	19.2	12.8	-33.8%	23.1	13.7	-40.9%	27.3	17.4	-36.8%
5 - Blue Ridge East	14.1	11.4	-19.3%	17.8	12.9	-27.6%	21.3	13.1	-38.9%	25.2	14.9	-41.0%
6 - Piedmont	14.7	13.6	-7.5%	18.9	15.4	-18.0%	23.4	15.6	-32.9%	27.5	17.8	-35.1%
7 - Coastal Plain	14.8	5.7	-61.3%	19.1	10.4	-45.2%	24.3	15.7	-35.3%	28.6	18.3	-35.9%
Statewide Domain	**14.6**	**10.5**	**-28.0%**	**18.6**	**13.0**	**-30.0%**	**22.9**	**14.4**	**-36.9%**	**27.0**	**16.7**	**-38.2%**

Table 10.10 Comparisons of tropical storm PMP values versus the HMR 51 PMP values. Grayed out rows signify where one of the other storm types is controlling.

Tropical Storm 10 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	27.6	13.3	-51.7%	32.2	21.0	-34.8%	35.5	21.0	-40.8%	40.8	21.4	-47.5%
2 - Cumberland Plateau	28.7	8.4	-70.7%	33.8	11.7	-65.6%	36.9	13.6	-63.2%	42.3	16.5	-61.1%
3 - Great Valley	28.9	7.5	-74.2%	34.1	10.3	-69.7%	37.4	11.9	-68.2%	43.0	14.4	-66.5%
4 - Blue Ridge West	28.9	9.8	-66.3%	34.1	14.1	-58.9%	37.6	20.4	-46.0%	43.3	21.9	-49.6%
5 - Blue Ridge East	27.8	14.4	-48.2%	32.5	22.7	-30.2%	35.8	22.7	-36.6%	41.1	23.5	-42.9%
6 - Piedmont	28.5	17.7	-37.7%	33.7	28.0	-16.8%	37.7	28.0	-25.6%	43.5	28.0	-35.3%
7 - Coastal Plain	28.6	20.7	-27.4%	33.8	32.7	-3.3%	38.5	32.7	-15.0%	44.5	32.7	-26.4%
Statewide Domain	**28.4**	**15.8**	**-44.3%**	**33.4**	**24.6**	**-26.2%**	**37.2**	**25.3**	**-32.3%**	**42.9**	**25.8**	**-39.9%**

Tropical Storm 200 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	19.2	8.7	-54.6%	22.9	14.8	-35.6%	26.5	16.7	-37.1%	31.5	19.3	-38.8%
2 - Cumberland Plateau	20.4	7.7	-62.0%	24.3	10.7	-56.2%	27.4	12.3	-54.9%	33.1	16.0	-51.7%
3 - Great Valley	20.5	6.9	-66.6%	24.6	9.4	-61.5%	27.8	10.8	-61.1%	33.6	14.0	-58.4%
4 - Blue Ridge West	20.5	9.0	-56.4%	24.5	12.9	-47.4%	28.1	19.2	-31.9%	33.8	21.0	-38.2%
5 - Blue Ridge East	19.4	9.4	-51.5%	23.1	15.9	-31.3%	26.7	20.0	-25.0%	31.7	22.1	-30.4%
6 - Piedmont	20.2	11.6	-42.4%	24.2	19.6	-18.6%	28.4	20.3	-28.5%	33.8	25.9	-23.3%
7 - Coastal Plain	20.4	13.6	-33.3%	24.4	22.9	-5.7%	29.3	22.9	-21.6%	34.7	29.1	-16.1%
Statewide Domain	**20.1**	**10.7**	**-46.5%**	**24.0**	**17.7**	**-25.9%**	**28.0**	**19.5**	**-30.3%**	**33.3**	**23.8**	**-28.7%**

Tropical Storm 1000 Sq Mi Average PMP												
Transposition Zone	HMR 51 6hr	PMP 6hr	Change 6hr	HMR 51 12hr	PMP 12hr	Change 12hr	HMR 51 24hr	PMP 24hr	Change 24hr	HMR 51 72hr	PMP 72hr	Change 72hr
1 - Interior Valley	13.9	6.6	-52.7%	17.6	10.5	-40.5%	21.2	12.0	-43.5%	25.0	14.8	-41.1%
2 - Cumberland Plateau	15.0	6.2	-59.0%	18.9	8.8	-53.7%	22.2	10.8	-51.2%	26.5	14.3	-46.0%
3 - Great Valley	15.1	5.5	-63.9%	19.2	7.8	-59.6%	22.8	9.5	-58.1%	27.1	12.5	-53.8%
4 - Blue Ridge West	15.1	7.3	-51.5%	19.2	11.0	-43.1%	23.1	13.9	-40.1%	27.3	18.0	-34.4%
5 - Blue Ridge East	14.1	7.1	-49.5%	17.8	11.3	-36.6%	21.3	14.5	-32.2%	25.2	18.3	-27.8%
6 - Piedmont	14.7	9.0	-38.7%	18.9	14.2	-24.7%	23.4	17.5	-24.7%	27.5	23.1	-15.5%
7 - Coastal Plain	14.8	10.3	-30.2%	19.1	16.3	-14.4%	24.3	19.7	-18.6%	28.6	26.1	-8.6%
Statewide Domain	**14.6**	**8.3**	**-43.4%**	**18.6**	**12.9**	**-30.7%**	**22.9**	**15.9**	**-30.5%**	**27.0**	**20.8**	**-23.3%**

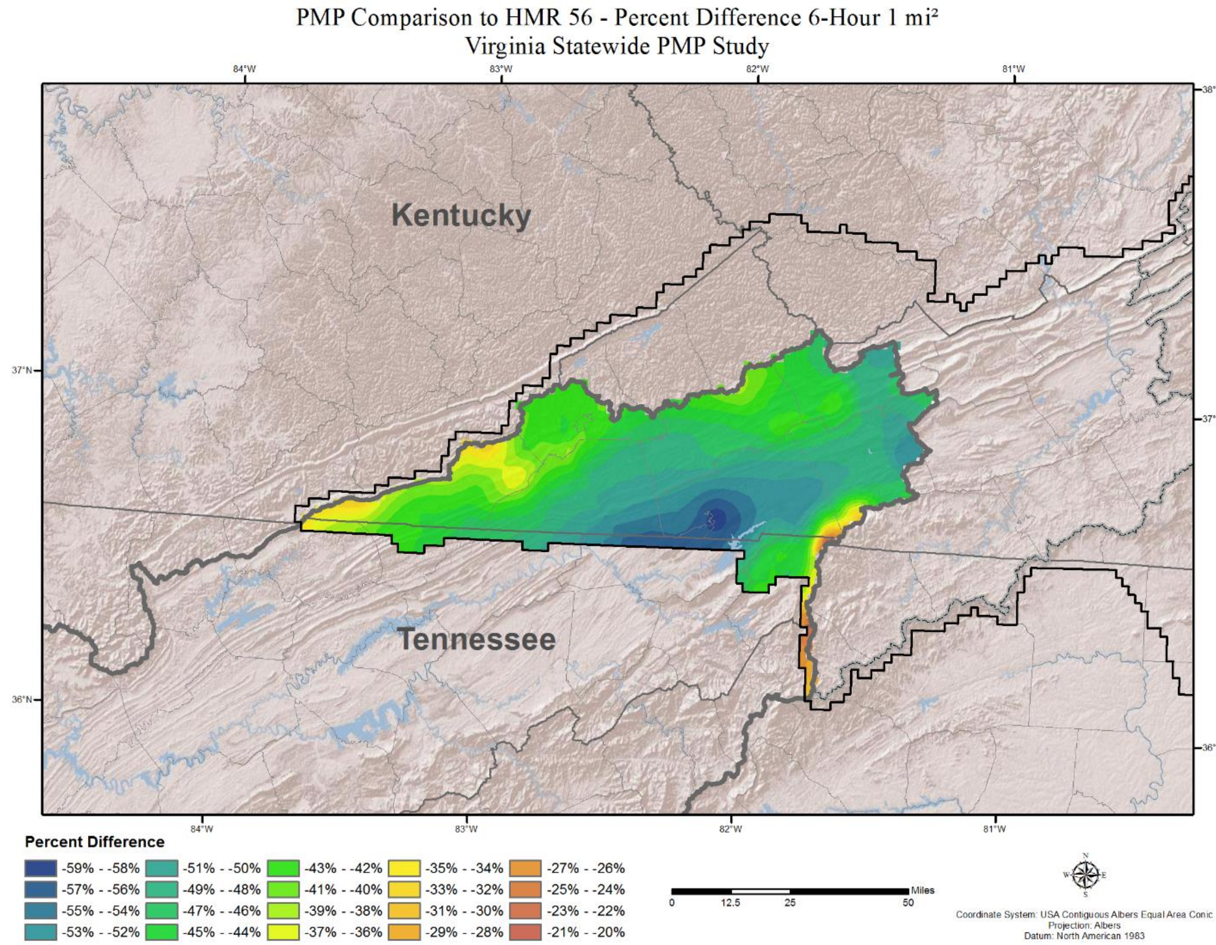

Figure 10.17 Percent difference of HMR 56 values compared to largest PMP values from all three storm types 6-hour 1-square miles. Note the scale in the legend is specific to the image.

10.4.1 Discussion of Comparison Results

In topographic regions (areas stippled in HMR 51), there are significant changes from HMR PMP values, both much lower and greater. This is expected given the lack of analysis that was employed in HMR 51 in these regions. HMR 51 smoothed the PMP contours across this area without detailed consideration for the effects of topography on the spatial distribution or magnitude of PMP. The updated approach employed in this study explicitly accounted for those spatial variations and provided values at a much higher resolution. This is demonstrated by the highly variable values between the Blue Ridge, interior valleys, and Appalachians ridge. Value range from 20% greater than HMR 51 to 50% less than HMR 51 over a small distance. This is because there is no variation in the HMR 51 values, yet the updated PMP varies greater over small distances in the areas. This is a direct reflection of the effect of topography in these areas and how that controls rainfall accumulations. Rainfall is enhanced significantly in areas exposed to moisture inflow with increasing topography (upslope regions). While in areas that are in protected/lower valleys and/or inland where barriers to moisture exist, the rainfall is depleted significantly (leeward slopes).

In contrast, over non-orographic regions in the piedmont through the coastal regions, the gradient between AWA PMP values and HMR 51 is minimal and changes gradually from the first upslopes of the Blue Ridge eastward, and in some places AWA is greater than HMR 51. This reflects the consistency of processes between this study and HMR 51 in non-orographic locations. In this case, HMR 51 more accurately reflected PMP in these areas where topography wasn't a major factor and in which they had sufficient storm data to analyze. Areas where the PMP values increased versus HMR 51 (e.g. by 5-10% in the eastern piedmont and coastal zones of Figure 10.7) resulted from a significant number of storms being added to the database that were not used in HMR 51, allowing AWA more conservative transposition limits. Examples include allowing Ewan, NJ September, 1940 to be used through 700 feet in elevation versus the 500 foot limitation employed by the NWS; and Tyro, VA August, 1969 allowed to influence PMP for regions through the piedmont and costal transposition zones versus the 1,000 to 500 foot range employed by the NWS. The application of more conservative transposition limits was applied to ensure proper spatial continuity of PMP values across the domain, and because the application of transposition limits is a subjective process, it does not allow for gradients to be properly analyzed (see Section 7).

These variations closely match the observed rainfall patterns in the region as displayed by the mean annual precipitation (Figure 10.15) and the precipitation frequency climatologies (Figure 10.16). Due to the fact that PMP is required to represent a physically possible scenario, these variations caused by a combination of meteorology and topography should be reflected accurately in the PMP values.

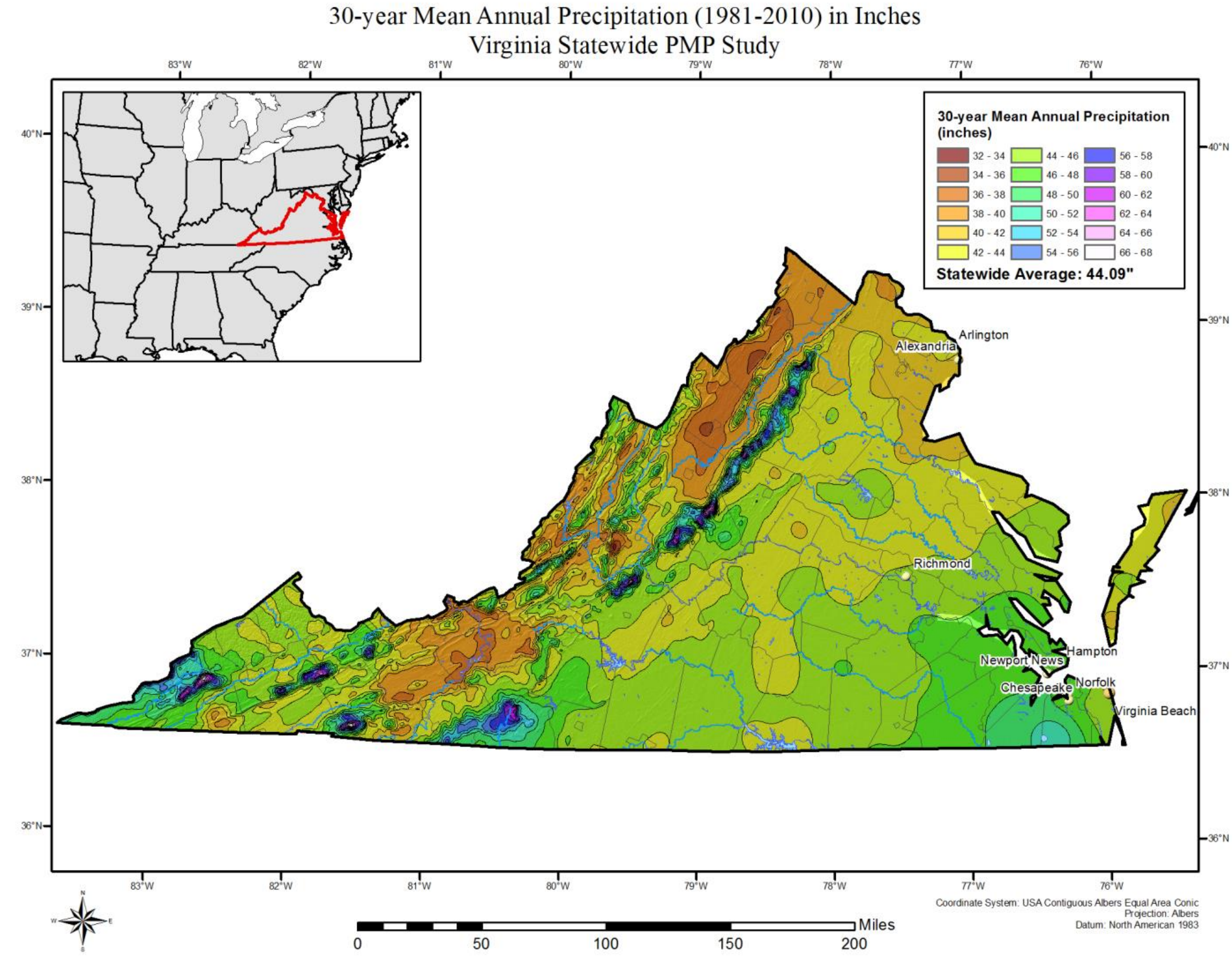

Figure 10.18 Mean annual precipitation representing the 30-year period from 1981-2010

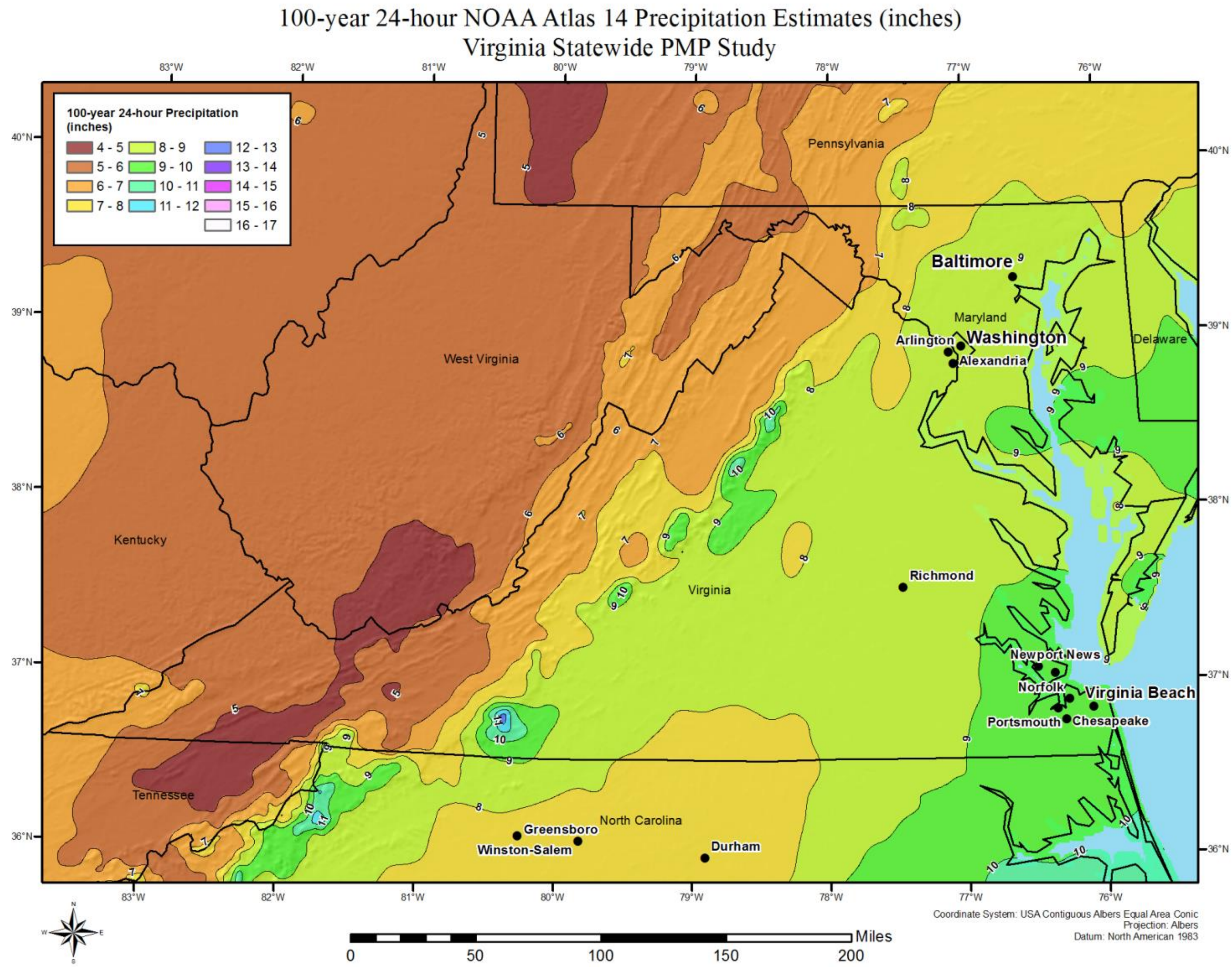

Figure 10.19 Precipitation frequency climatology showing 24-hour 100-year data

11. Sensitivity Discussions Related to PMP Derivations

In the process of deriving site-specific PMP values, various assumptions were made and explicit procedures were adopted for use. Additionally, various parameters and derived values are used in the calculations. It is of interest to assess the sensitivity of PMP values to assumptions that were made and to the variability of parameter values.

11.1 Assumptions

11.1.1 Saturated Storm Atmosphere

The atmospheric air masses that provide available moisture to both the historic storm and the PMP storm are assumed to be saturated through the entire depth of the atmosphere and to contain the maximum moisture possible based on the surface dew point. This assumes moist pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm. Limited evaluation 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 are generally not entirely saturated and contain somewhat less precipitable water than is assumed in the PMP procedure. It follows that the PMP storm (if it were to occur) would also have somewhat less precipitable water available than the assumed saturated PMP atmosphere would contain. The *ratio* of precipitable water associated with each storm is used in the PMP calculation procedure. If the precipitable water values for each storm are both slightly overestimated, the ratio of these values will be essentially unchanged. For example, consider the case where instead of a historic storm with a storm representative dew point of 70°F 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 assumes the same type of storm with similar atmospheric characteristics for the maximized storm but with a higher dew point of 76°F. The maximized storm, having similar atmospheric conditions, would have about 2.69 inches of precipitable water instead of the 2.99 inches associated with a saturated atmosphere with a dew point of 76°F. 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, 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.

11.1.2 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 the actual rainfall amounts would be the same as the ratio of the precipitable water in the atmosphere associated with each storm.

There are two issues to be considered. First is the assumption that a storm has occurred that 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 is 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 is accepted.

11.2 Parameters

11.2.1 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^{o}F difference between the storm representative and maximum dew point values. The same sensitivity applies to the transposition factor, with about a 5% change for every 1^{o}F change in either the in-place maximum dew point or the transposition maximum dew point.

For example, consider the following case:

Storm representative dew point:	75^{o}F	Precipitable water:	2.85"
Maximum dew point:	79^{o}F	Precipitable water:	3.44"

Maximization factor = 3.44"/2.85" = 1.21

If the storm's representative dew point were 74^{o}F with precipitable water of 2.73",
Maximization factor = 3.44"/2.73" = 1.26 (an increase of approximately 5%)

If the maximum dew point were 78^{o}F with precipitable water of 3.29",
Maximization factor = 3.29"/2.85" = 1.15 (a decrease of approximately 5%)

11.2.2 Sensitivity of the Elevation Adjustment Factor to Changes in Storm Elevation

Elevated topographic features remove atmospheric moisture from an air mass as it moves over the terrain. When storms are transpositioned, the elevation of the original storm is used in this study to compute the amount of atmospheric moisture depleted from or added to the storm atmosphere. The absolute amount of moisture depletion or addition is somewhat dependent on the dew point values, but is primarily dependent on the elevation at the original storm location and the elevation of the study basin. The elevation adjustment is slightly less than 1% for every 100 feet of elevation change between the original storm location and the study basin elevation.

For example, consider the following case:

Maximum dew point:	79°F
Study basin elevation:	100 feet
Historic storm location elevation:	500 feet
Precipitable water between 1000mb and the top of the atmosphere:	3.44 inches
Precipitable water between 1000mb and 100':	0.03 inches
Precipitable water between 1000mb and 500':	0.15 inches

Elevation Adjustment Factor = (3.44"-0.03")/(3.44"-0.15") = 1.04 (about 1% per 100 feet)

If the historic storm location elevation were 1,000', the precipitable water between 1000mb and 1,000' is 0.28"

Elevation Adjustment Factor = (3.44"-0.03")/(3.44"-0.28") = 1.08 (about 1% per 100 feet)

12. Recommendations for Application

12.1 Site-Specific PMP Applications

Site-specific PMP values provide rainfall amounts for use in computing the Probable Maximum Flood (PMF). This study addressed several issues that could potentially affect the magnitude of the PMP storm over any drainage basin within the project area covering the state of Virginia. It is important to remember that the methods used to derive PMP and subsequently the methods used to derive the PMF from those data, adhere to the caveat of being "physically possible" as described in the definition of PMP (see Section 1.1). In other words, various levels of conservatism and/or extreme aspects of storms that would not occur/co-occur in a PMP storm environment should not be compounded together to generate unrealistic results in either the PMP values or the hydrologic applications of those values to derive the PMF.

The storm search process and selection of storms analyzed in this study only considered events that occurred over areas that are both meteorologically and topographically similar to locations within the overall project domain. Each storm type (local, tropical, and general) that occurs in the overall project domain was analyzed. Therefore, results of this study should not be used for watersheds where meteorological and/or topographical parameters are different from those found within the project domain without further evaluation.

12.2 Climate Change Assumptions

The effect of climate change on the number and intensity of extreme rainfall events in the state of Virginia 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.

It is recognized that the climate is in a constant state of change and there is uncertainty whether the state will be wetter or drier, warmer or colder, and/or experience more or less extreme precipitation events with any quantitative and statistically significant certainty, particularly for the region specific to this study. The PMP values derived in this study have a useful life of approximately 30 years before they would require re-evaluation. In general, most projected changes expected occur within the Earth's climate system would be unlikely to significantly affect the project's PMP related hydrology beyond the bounds of the PMP/PMF values derived using values from this project. 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).

12.3 Future Work Requirements

Although this study was comprehensive in its development and calculation of PMP values, there remain several related areas which could use further analysis and study.

Temporal distributions can be thought of as the time order in which incremental PMP amounts are arranged within a PMP storm. Initial analysis of the temporal accumulations of the PMP rainfall began during this work. This is an important aspect for properly determining the PMF where PMP values are distributed over time and the total analysis duration in question. Analysis should continue using the storm data derived in this study to determine whether any adjustments to current guidelines are warranted. This could potentially be by storm type and storm location and vary east and west of the Appalachian crest. The underlying principal would be that the guidelines would be storm-based using the storms in this study and therefore most accurately represent temporal distributions expected to occur with Virginia PMP-type storms.

Further study is required to fully analyze temporal distributions and determine applicability for use in Virginia as design criteria. Storms that are found to be controlling PMP values must be analyzed in terms of their original temporal distributions and potential applicability for use in Virginia as specified design criteria. Previously used curves must also be re-examined in terms of continual use and updated as needed. The project team should consist of a broad oversight committee including AWA, DCR, NRCS, and design engineers each having experience and expertise in performing hydrologic studies in Virginia. The goal of the project would be to appropriately capture reasonable temporal distributions based on controlling PMP storms, storm types, and storm durations that could be used by Virginia as design criteria

Finally, increasing the number of meteorological and hydrological observation locations across the state is critical to capturing the rainfall and flood events that will occur in the future. These data are the foundation for being able to assess storms and floods in relation to PMP and to update and add to the database developed during this work.

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