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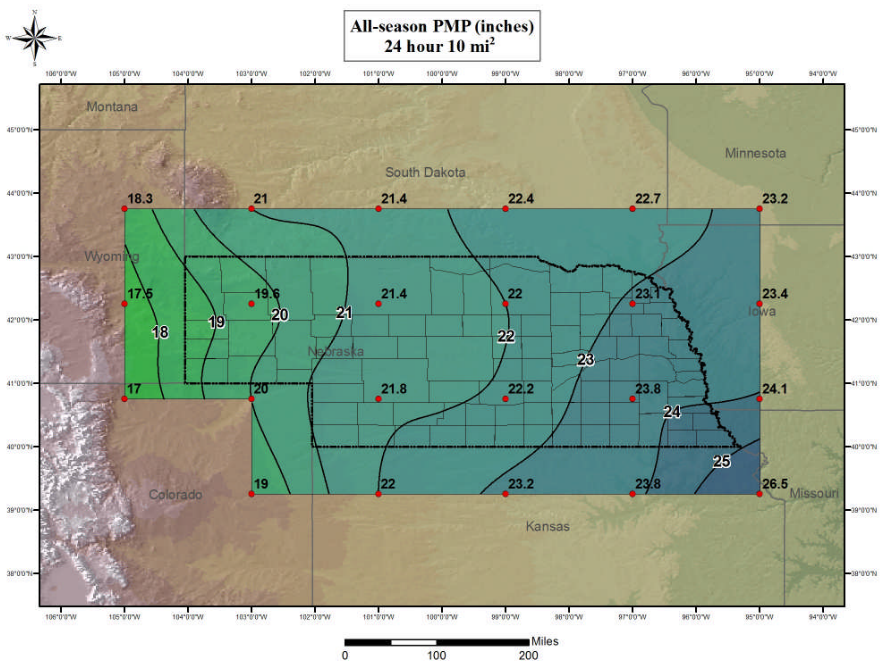
Site-Specific Probable Maximum Precipitation (PMP) Study for Nebraska



Prepared for

Lower Platte North NRD

Wahoo, Nebraska

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NOTICE

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Nebraska Statewide PMP Peer Review Committee

November 20, 2008

Mr. John Miyoshi, General Manager
Lower Platte North Natural Resources District
P.O. Box 126
Wahoo, NE 68066-0126

Subject: Approval of the Estimates for Probable Maximum Precipitation for Nebraska

Dear Mr. Miyoshi,

The Nebraska Statewide PMP Peer Review Committee herewith formerly accepts the results of the Probable Maximum Precipitation (PMP) study conducted for the State by Applied Weather Associates (AWA). The primary purpose for this investigation stems from the need to update the National Weather Service document – *Hydrometeorological Report No. 51* (HMR 51). HMR 51 was published in 1978, with the most recent storm included in the analysis from 1972, and the most recent storm in the Midwest from 1953. Thus a more comprehensive search and analysis of storms over the last 50-60 years was needed to ensure that all relevant events were investigated.

Standard PMP procedures were followed by AWA, along with some improved techniques. Standard procedures include storm maximization, storm transpositioning, and development of depth-area-duration curves. These procedures were then followed by envelopment of the relevant storms to determine the PMP values for the basin. The text of the report details the complete procedure, including where this report deviated from HMR 51, including use of radar estimated rainfall that was unavailable when HMR 51 was produced, use of dew points (over various durations) that better represent moisture inflow into the storm, and use of a 100-year return period climatology of dew points for storm maximization.

Based on thorough examination of the procedures used therein, the Nebraska Statewide PMP Peer Review Committee approves use of these values. Results and conclusions in this report are based upon AWA analysis, and we, the Peer Review Committee, used our best professional judgment in evaluating their work. We note that the final PMP estimates are based on the historical record of the past century and more, with the underlying assumption that this record across the Midwest region yields insight into the PMP across Nebraska. As such, the Nebraska Statewide PMP Peer Review Committee does not make any warranty, express or implied, regarding use of any information or method shown in the report or assume any future liability regarding use of any information contained in the report.

Respectfully,

Mark R. Anderson

Pat Diederich, P.E.

Barry D. Keim

Barry Keim

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Abstract

Applied Weather Associates (AWA) initiated a statewide Probable Maximum Precipitation (PMP) study for Nebraska in January 2007. The purpose of the study is to build on results of the Wanahoo, Nebraska site-specific PMP study results and develop PMP values for the entire state, taking into account topography, and climate and storm types that affect Nebraska.

This project received support and funding from a variety of agencies in Nebraska. These include the U. S. Army Corps of Engineers; Lower Platte North, Central Platte, Lower Elkhorn, Lower Platte South, and the Papio-Missouri River Natural Resource Districts; Central Nebraska Public Power and Irrigation District; and the Nebraska Department of Natural Resources. The study was administered by the Lower Platte North NRD.

Nebraska lies within the domain of Hydrometeorological Report No. 51 (HMR 51). This study is similar to other site-specific PMP studies conducted with HMR 51 domain such as the Upper Deerfield drainage basin above Harriman Dam in Vermont (Harriman Study, 1987), the Upper and Middle Dams drainage basins in Maine (Tomlinson 2002), the Stewarts Bridge drainage basin in New York (Tomlinson et al 2003), the Wanahoo drainage basin study in Nebraska (Tomlinson et al 2007), and the Blenheim Gilboa drainage basin in New York (Tomlinson et al 2008). Additionally, a regional study managed by the Electric Power Research Institute (EPRI) for the two state region of Wisconsin and Michigan was completed in 1993 (Tomlinson 1993). Those studies have been accepted for use in computing the Probable Maximum Flood (PMF) by the Federal Energy Regulatory Commission (FERC) and state dam regulators.

The approach used in this study is basically the same as that used in the previous studies, i.e., a storm-based approach that utilizes the same procedures used by the National Weather Service (NWS) in the development of the HMRs. These same procedures are recommended by the World Meteorological Organization (WMO) for PMP determination (WMO Operational Hydrology Report No.1, 1986). This approach identifies extreme rainfall events that have occurred over the central United States that have meteorological characteristics similar to extreme rain storms that could occur over Nebraska. The largest of these rainfall events are selected for detailed analyses.

Thirty-six extreme storm events are identified as storms having similar characteristics to extreme rainfall events that could potentially occur over some portion of the state of Nebraska and received detailed storm analyses. These storms comprised the Short Storm List. Twenty-one of these storms were considered in the development of HMR 51, six were identified in the EPRI Wisconsin/Michigan study, and nine storms are completely new, with no prior storm analysis before this study. These new storm analyses used AWA’s Storm Precipitation Analysis System (SPAS) and SPAS-NEXRAD (NEXt generation RADar) software. Depth-area-duration (DAD) tables, total storm isohyetal maps, and mass curve plots were produced for each storm.

When available, results are used from DAD analyses of storms completed by the National Weather Service (NWS) and/or the US Army Corps of Engineers (USCOE). One of the previously analyzed storms from HMR 51 is re-analyzed in this study with the new DAD used in this study (Hale, CO 1935). The HMR procedures for maximization, transposition, and elevation moisture adjustment are

used. New techniques and databases are used in the study to increase accuracy and reliability, while adhering to the basic procedures used in the HMRs and in the WMO Manual.

For storms that have previously had storm maximization factors determined, those maximization factors are used (with some adjusted for use with the new maximum average dew point climatology based on results of the EPRI Michigan/Wisconsin study and discussions with the Board of Consultants for this study). For the most recent storms, maximization factors are determined in this study. A parcel trajectory model (HYSPLIT) was used along with the National Center for Environmental Prediction (NCEP) Reanalysis (Mesinger 2006) database to assist in the determination of inflow moisture vectors.

Each storm on the short storm list was maximized, transpositioned, and elevation adjusted to the appropriate grid point(s). Depth-area plots were made for durations of 6-hour, 12-hour, 24-hour, 48-hour, and 72-hour for area sizes of 10-square miles, 200-square miles, 1000-square miles, 5000-sqaure miles, 10000-square miles, and 20000-square miles. Enveloping curves were constructed at each of the 23 grid points. Depth-duration plots were then made and enveloping curves constructed at each grid point. These final enveloping curves provide PMP values for each grid point and were plotted in GIS. The maps produced within GIS were then examined to ensure continuity in space and time among the grid points.

The site-specific PMP values provide reductions in the PMP provided in HMR 51 for all grid points within the study domain. Within the state of Nebraska, these reductions ranged from 56% to 3% (see Section 12.2). The statewide PMP maps produced in this study are intended to replace HMR 51 PMP maps for Nebraska, Figures 18-47 in that report.

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 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.

Average basin elevation: The average elevation of all pixels within a drainage basin outline as determined by geographical information system calculations.

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

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

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

Cirrus shield: In this study, the area of cirrus cloud that covers a mesoscale convective complex.

Cirrus anvil: The cirrus cloud that is advected downwind from the top of a cumulonimbus cloud.

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

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

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

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

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 systems can be either tropical or extra-tropical, and transform between the two. 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 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 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 in order for saturation (100% relative humidity) to occur.

Effective Barrier Height: The height of a barrier determined from elevation analysis that reflects the effect of the barrier on the precipitation process for a storm event. The actual barrier height may be either higher or lower than the effective barrier height.

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

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

First-order NWS station: A weather station typically found at airports across the United States and records observations on a continuous basis. Most of these stations include an Automated Surface Observing System (ASOS), which is overseen by the National Weather Service.

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, which 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.

Gulf Stream current: A warm, well-defined, swift, relatively narrow, ocean current in the western North Atlantic that originates where the Florida Current and the Antilles Current begin to curve eastward from the continental slope of Cape Hatteras, North Carolina. East of the Grand Banks, the Gulf Stream meets the cold Labrador Current, and the two flow eastward separated by the cold wall.

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.

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

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

Jet Stream: A strong, narrow current concentrated along a quasi-horizontal axis (with respect to the earth's surface) in the upper troposphere or in the lower stratosphere, characterized by strong vertical and lateral wind shears. Along this axis it features at least one velocity maximum (jet streak). Typical jet streams are thousands of kilometers long, and 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 Jetstream: 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) and 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.

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

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

Observational day: The 24-hour time period represented by a daily observation at a cooperative weather station. For example, if a cooperative station observes at 7:00 AM, data gathered at that time represents the period from 7:00 AM on the previous day up until 7:00 AM on the day of the observation.

One-hundred year rainfall event: The point rainfall amount that has a one-percent probability of occurrence in any year. Also referred to as the rainfall amount that *on average* occurs once in a hundred years.

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 300-mb level 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 over some specified duration. Commonly, durations of 12 or 24 hours are used, though other durations can sometimes be implemented.

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 the drainage basin under study.

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.

Pseudo-adiabatic: Referring to the process described by the pseudo-adiabat.

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

PMP storm pattern: The isohyetal shape that encloses the PMP area, plus the isohyets of residual precipitation outside the PMP portion of the pattern.

Saturation: Upper limit of water-vapor content in a given space; solely a function of temperature. The condition in which vapor pressure is equal to the equilibrium vapor pressure over a plane surface of pure liquid water or sometimes ice.

Shortwave: A small wave or disturbance in the atmosphere that moves around longwaves in the same direction as the air flow in the middle and upper troposphere. Also called shortwave troughs.
Spatial distribution: The geographic distribution of precipitation over a drainage, according to an idealized storm pattern of the PMP for the storm area.

Stationary front: A front that is nearly stationary with winds blowing almost parallel and from opposite directions on each side of the front.

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 is totally embedded in maritime tropical air, hence no frontal boundaries, and derives its energy from the ocean surface.

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

Transposition limits: The defined region surrounding an actual storm location that has similar climatic and topographic characteristics throughout, whereby it is assumed that the storm dynamics could have also occurred . The storm can be transpositioned – or theoretically relocated - within the transposition limits.

Undercutting: The process of placing an envelopment curve somewhat lower than the highest rainfall amounts on depth-area and depth-duration plots.

Warm front: Front where relatively warmer air replaces colder air.

Warm sector: Sector of warm air bounded on two sides by the cold and warm fronts extending from a center of low pressure known as a mid-latitude cyclone.

1 INTRODUCTION

This study defines the probable maximum precipitation (PMP) for use in the computation of the probable maximum flood (PMF) for the entire state of Nebraska.

1.1 Background

Definitions of probable maximum precipitation (PMP) are found in most of the Hydrometeorological Reports (HMRs) issued by the National Weather Service (NWS). The definition used in the most recently published HMR (HMR 59, p. 5) 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." Since the mid-1940s or earlier, several government agencies have been developing methods to calculate PMP in various regions of the United States. The National Weather Service (formerly the U.S. Weather Bureau) and the Bureau of Reclamation have been the primary agencies involved in this activity. PMP values from their reports are used to calculate the probable maximum flood (PMF) which, in turn, is often used for the design of significant hydraulic structures.

The generalized PMP studies currently in use in the conterminous United States include HMR 49 (1977) for the Colorado River and Great Basin drainage; HMRs 51 (1978), 52 (1982) and 53 (1980) for all of 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. Clearly, the Midwest and eastern and southern portions of the U.S. constitute the largest area covered by a single generalized PMP study--HMR 51. Figure 1.1 shows an example of a HMR 51 PMP map.

In addition to these HMRs, numerous Technical Papers and Reports deal with specific subjects concerning precipitation. Examples are NOAA Technical Report NWS 25 (1980) and NOAA Technical Memorandum NWS HYDRO 45 (1995). Topics include maximum observed rainfall amounts; return periods for various rainfall amounts, and specific storm studies. Climatological atlases (Technical Paper No. 40, 1961; NOAA Atlas 2, 1973; and NOAA Atlas 14, 2003) are available for use in determining precipitation amounts for specified return periods.

A number of specialized and regional PMP studies (Harriman Study, 1987; Tomlinson, 1993; and Tomlinson et al, 2002) augment generalized HMR. These studies are for specific regions within the large area addressed by HMR 51 (over half of the conterminous United States). The meteorological conditions producing extreme rainfall events are significantly different in different regions within this large geographic area. Along the Gulf Coast and much of the eastern seaboard, hurricanes are a major contributor. In much of the Midwest, extreme events are usually linked to either Mesoscale Convective Systems (MCSs) or synoptic storms with embedded convection.

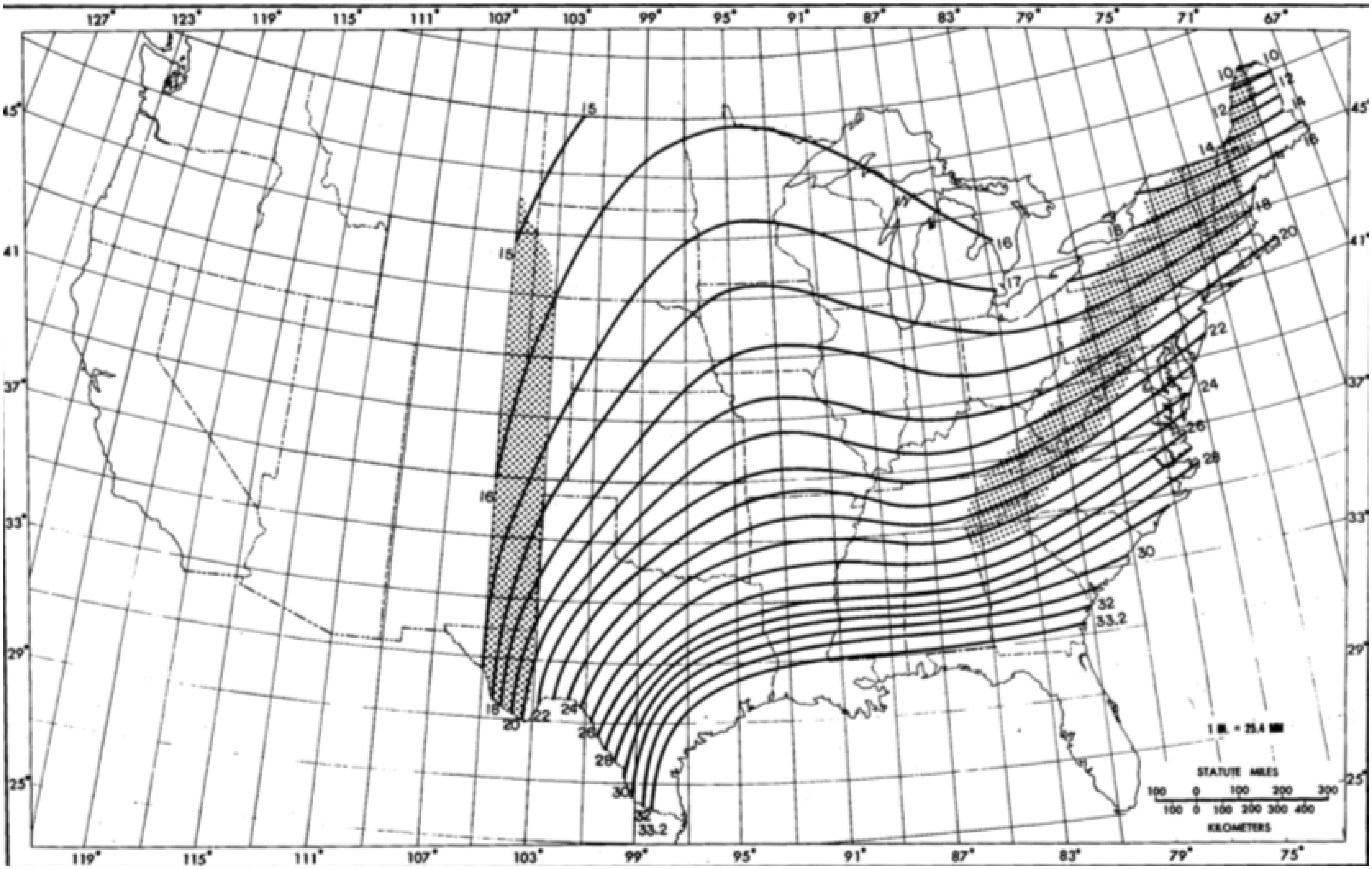

Figure 1.1 Example of a HMR 51 PMP map for 24-hour rainfall over 1,000 square miles (Schreiner and Riedel 1978)

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. By periodically reviewing storm data and advances in meteorological concepts, PMP analysts can identify relevant new data and approaches for use in determining PMP estimates.

Several site-specific PMP studies have been completed in the northeastern US; the Upper Deerfield River drainage above Harriman Dam in Vermont (Board of Consultants to New England Power Company 1987), the Upper and Middle Dams drainage basin in Maine (Tomlinson 2002), and the Great Sacandaga Lake drainage basin in New York (Tomlinson 2003). Additionally, a regional study for the two state regions of Wisconsin and Michigan, managed by the Electric Power Research Institute (EPRI) was completed in 1993 (Tomlinson 1993). These are good examples of PMP studies that explicitly consider the meteorology and topography of the basins and characteristics of historic extreme storms over climatically similar regions surrounding the basins. These regional and site-specific PMP studies have received extensive review and the results have been used in computing the PMF for individual watersheds.

This project received support and funding from a variety of agencies in Nebraska. These include the U. S. Army Corps of Engineers; Lower Platte North, Central Platte, Lower Elkhorn, Lower Platte South, and the Papio-Missouri River Natural Resource Districts; Central Nebraska Public Power and Irrigation District; and the Nebraska Department of Natural Resources. The study was administered by the Lower Platte North NRD.

A Review Committee was involved in this study with periodic review meetings, technical reviews of the data and storm analyses, and review of the Final Report. The members of the Review Committee are listed below.

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This final report presents details of the Nebraska statewide PMP study. Section 1 provides an overview of the study. The geography and climate of the state are discussed in Section 2. The steps involved with identifying extreme storms are discussed in Sections 3 and 4. Procedures used to analyze storms are discussed in Section 5. Development of the new maximum dew point climatology is provided in Section 6. The grid point analysis process is discussed in Section 7. Adjustments for storm maximization, storm transpositioning, and elevation adjustments are presented in Section 8. The final procedure of developing PMP values from the adjusted rainfall amounts at each of the 23 grid points is provided in Section 9 with storm characteristics discussed in Section 10. Section 11 provides discussions related to the sensitivity analysis of the parameters used in the study. Results are discussed in Section 12 and the recommended application of results are given in Section 13.

1.2 Objectives

The objectives of this study were:

1. To perform a Probable Maximum Precipitation (PMP) study to determine PMP values for the state of Nebraska using the most reliable methods and data available.

2. To coordinate the study with oversight from the Review Committee, thereby producing a credible report acceptable to the Nebraska Department of Natural Resources.

1.3 Approach

The approach used in this study follows the same basic procedures that were used in the development of the HMRs. These procedures were applied considering the meteorological and topographic characteristics of Nebraska.

The study maintains as much consistency as possible with the general method used in HMR 51 and the EPRI Wisconsin/Michigan study. Deviations are incorporated where justified by developments in meteorological analyses and available data. The basic approach identifies major storms that occurred within the central US from eastern Colorado and Wyoming eastward to western Michigan and Ohio, and from northern Oklahoma northward to the Canadian border (Figure 4.1). The moisture content of each of these storms is maximized to provide a worst-case rainfall estimation for each storm at the location where it occurred. This is accomplished by computing the ratio of the *maximum possible* amount of atmospheric moisture that could have been entrained into the storm at that time of year to the *actual* atmospheric moisture entrained into the storm. After maximization, the storms are transpositioned to each appropriate grid point throughout the domain to the extent supportable by similarity of meteorological conditions and topography (see Section 7 for a description of the grid system). Maximum precipitation values are enveloped at each grid point to provide PMP estimates for various area sizes and durations.

For some applications, this study applied standard methods (e.g. WMO Operational Hydrology Report No. 1, 1986), while for other applications, new techniques were developed. Advanced computer-based technologies were used for storm analyses along with new meteorological data sources. New technology and data were incorporated into the study when they provided improved reliability, while maintaining as much consistency as possible with previous studies. This approach incorporated the best scientific applications that provided consistency and reliability of PMP values.

Moisture analyses have historically used monthly maximum observed 12-hour persisting dew points to quantify atmospheric moisture. Maximum dew point values have been provided by *Climatic Atlas of the United States,* published by the Environmental Data Services, Department of Commerce (1968). This study, however, used an updated maximum dew point return frequency analysis. This dew point analyses incorporated data sets with longer periods of record than were available for use in HMR 51and the EPRI study, and produced 20-year, 50-year and 100-year return frequencies for maximum average dew point values for 6-hour, 12-hour and 24-hour duration periods. The ESRI Geographic Information System (GIS) was used extensively in the development of the new maximum dew point climatology.

Along with this updated dew point climatology, a set of 23 grid points (Figure 1.2) were placed over the region. A reanalysis of transposition limits was completed which used areal rainfall distributions for storms that occurred over the higher, more western areas of Nebraska versus storms that occurred over the lower, eastern areas of the state. It was determined from this analysis that storms that occur east of the 105th meridian and west of the Mississippi River should not be transpositioned more than +/- 1000 feet in elevation from their original storm elevations (see Section 8.2 and Appendix J) This procedure provided precise guidance and constraints on the regions of influence for individual storms. The gridded analysis procedure was used with the contribution of each transpositioned storm applied across a grid that not only covers the state of Nebraska, but extended into bordering states to insure continuity near state borders and across state lines. PMP values were analyzed at each grid point using standard procedures. Envelopment of the largest rainfall totals was applied to insure spatial and temporal continuity of the final PMP values. Once values were derived for each area size and duration, values were spatially and temporally distributed using GIS technologies. This process produced the final set of PMP maps for the state of Nebraska.

As was completed in HMR 51 and the EPRI study, a preferred storm orientation analysis was completed using storm isohyetal patterns. Recommendations for orientation constraints for HMR 52 applications are made.

Results of this study are considered to provide reliable estimates of PMP values for Nebraska. The basic approach in this study follows methods used in the development of the Hydrometeorological Reports. The approach also includes updates to climatologies, use of new data sources and more sophisticated storm analysis techniques.

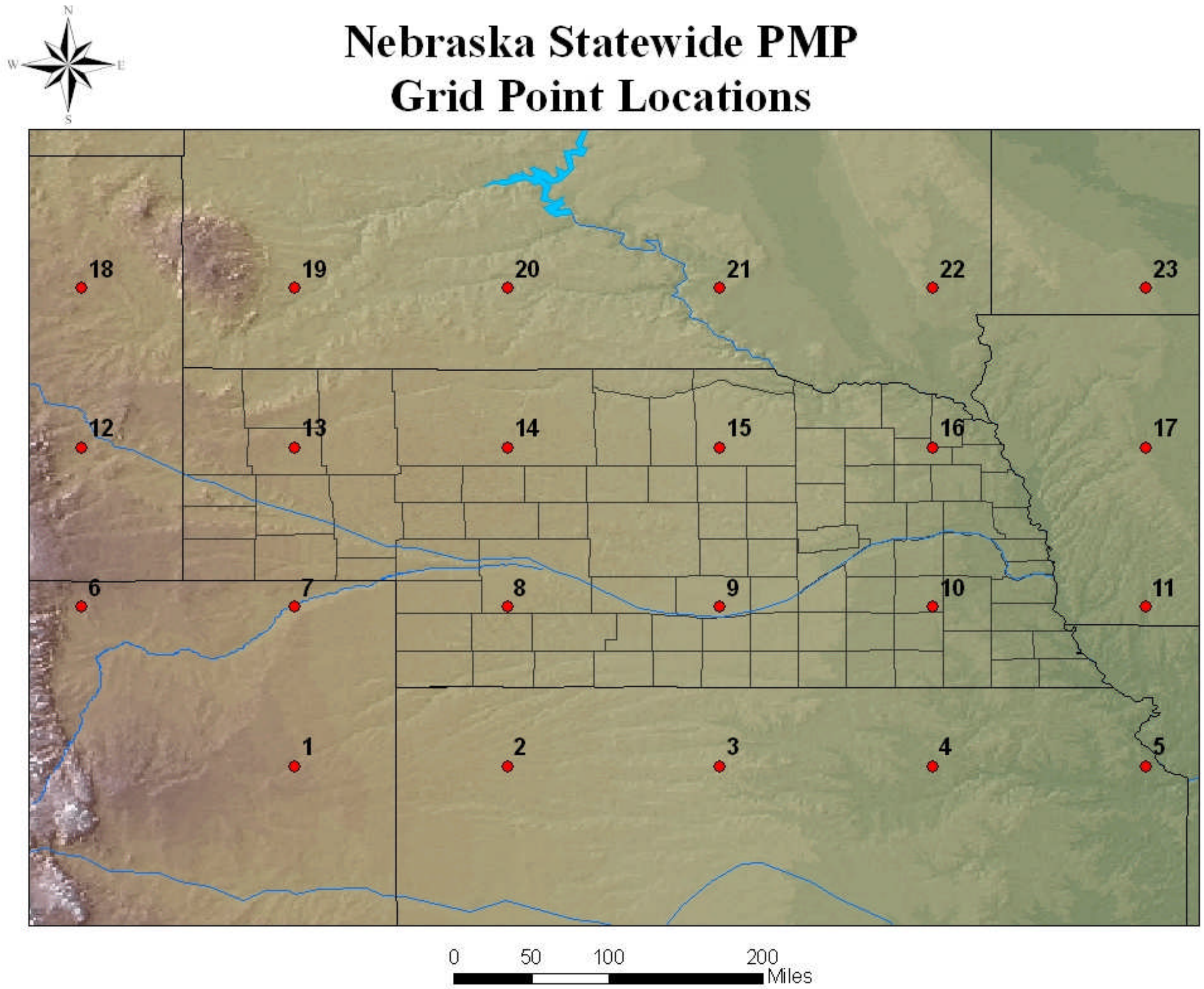

Figure1.2 Grid points used in the study

1.4 State of Nebraska Location and Description

The state of Nebraska extends from the High Plains just to the east of the Front Range of the Rocky Mountains of Wyoming at 104°W longitude to the east where the Missouri River forms the eastern border between 96° and 95° W longitude (Figure 1.3). Most of the northern border follows the 43°N latitude line until it intersects the Missouri River. To the south, the border starts at the intersection of Colorado at 41°N latitude, then drops down to 40°N latitude as it follows the Kansas border. Nebraska's northerly latitude along with it location in the center of the United States greatly affects the variety of weather patterns that affect the state (Section 2.0).

Figure 1.3 Nebraska regional setting

Elevation changes across the state range from 840 feet at the far southeastern border in Richardson County to 5424 feet at Panorama Point near Kimball in the southwestern panhandle (Figure 1.4). Although these elevation changes seem gradual moving east to west across the state, this large elevation change has a profound effect on moisture availability and storm dynamics. Therefore separate sets of storms were transpositioned to various grid points based on elevation. Several rivers traverse the state, including the North and South Platte Rivers and the Missouri River.

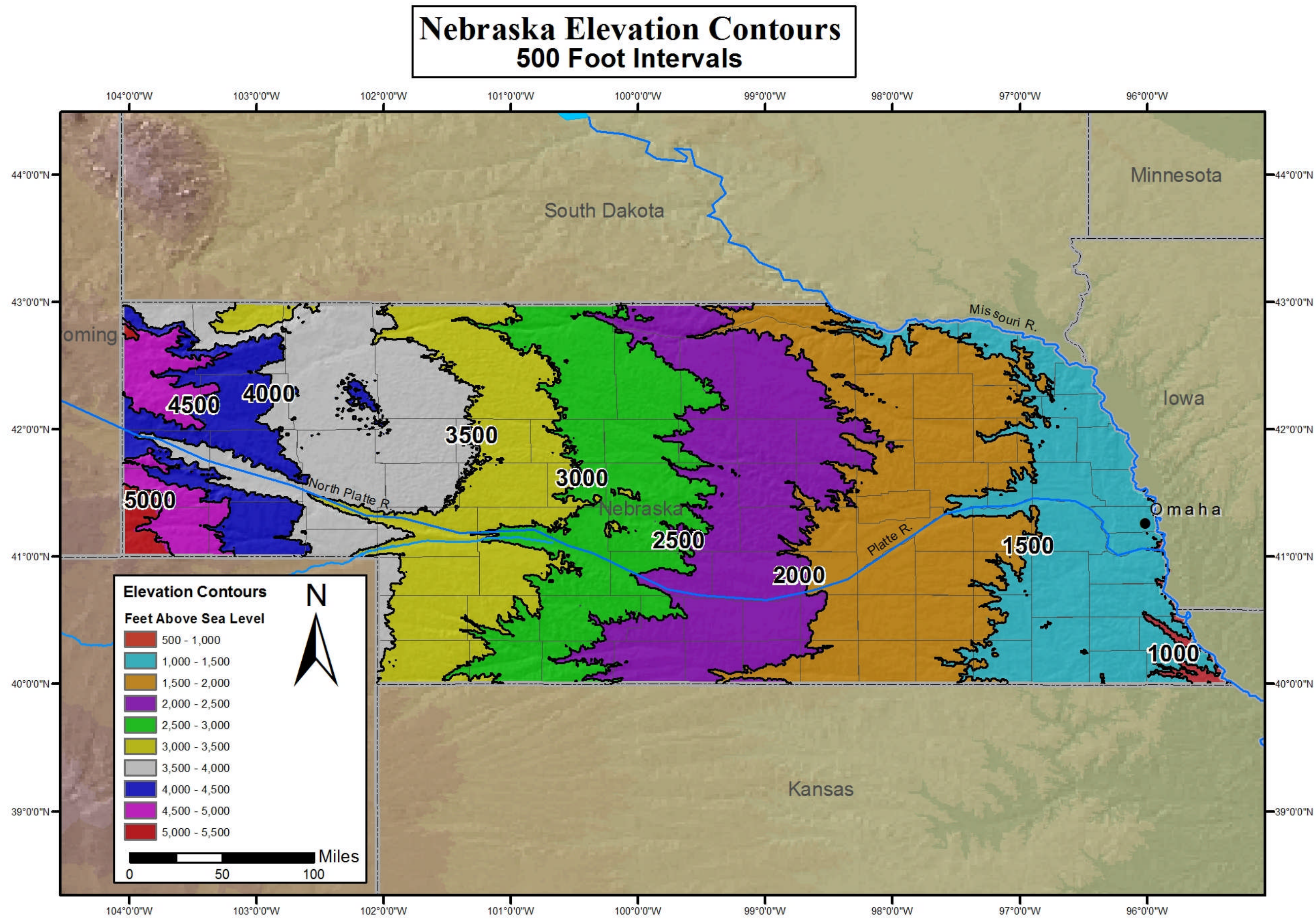

Figure 1.4 Elevations contours across the state of Nebraska 500 foot intervals

2 Geography and Climate of Nebraska

2.1 Nebraska Climate

Nebraska has a continental climate, with highly variable temperatures from season to season and year to year. Average yearly precipitation (1971–2000) in Omaha was 30 inches. In the semiarid panhandle in the west the average yearly precipitation was 17 inches. Snowfall in the state varies from about 21 in (53 cm) in the southeast to about 45 in (114 cm) in the northwest corner. Blizzards, droughts, and windstorms have plagued Nebraskans throughout their history.

The weather patterns in the region are characterized by frequent passages of differing air masses that lead to large ranges in temperatures and large differences in rainfall produced by precipitation events. There are no large bodies of water to help moderate the climate and the region is open to cold surges from the north, humid air masses from the south/southeast, and dry air from the Rocky Mountains to the west. These differing air masses often converge over the region, creating winter blizzards and flood producing rainstorms. The four main air mass types that affect the weather and climate of Nebraska include the continental polar (cP) air mass with origins from the Arctic regions of Canada and Alaska. This air mass is most common in the winter and early spring and is often associated with stratiform snowfall events and extremely cold temperatures. When this air mass type arrives in spring and collides with a more humid air mass from warmer regions, low pressure (rising air) often results, and when combined with strong winds aloft, severe thunderstorms and flood producing rain storms can result.

The second type of air mass observed in the region is the maritime polar (mP) which originates in the Gulf of Alaska and North Pacific Ocean. This airmass often arrives on strong winds from the west and northwest, but is usually devoid of moisture because it has traveled over several mountain ranges where it has dropped its precipitation and lost its low level moisture on its way to Nebraska.

The third type of air mass that affects Nebraska is comprised of dry, warm air and originates off of the high plateaus to the southwest in Arizona, New Mexico, and northern Mexico. This air mass, called continental tropical (cT), will often provide a cap on the atmosphere five to fifteen thousand feet above the surface. This serves to bottle up large amounts of potential energy that when released can result in explosive growth of thunderstorms and heavy rain.

The fourth type of air mass common to the region originates from the Gulf of Mexico and contains copious amounts of atmospheric moisture in a conditionally unstable state. This type of air mass is called maritime tropical (mT) and is most directly responsible for producing heavy rainfall in the region. Figure 2.1 shows the general source regions for the air masses described above.

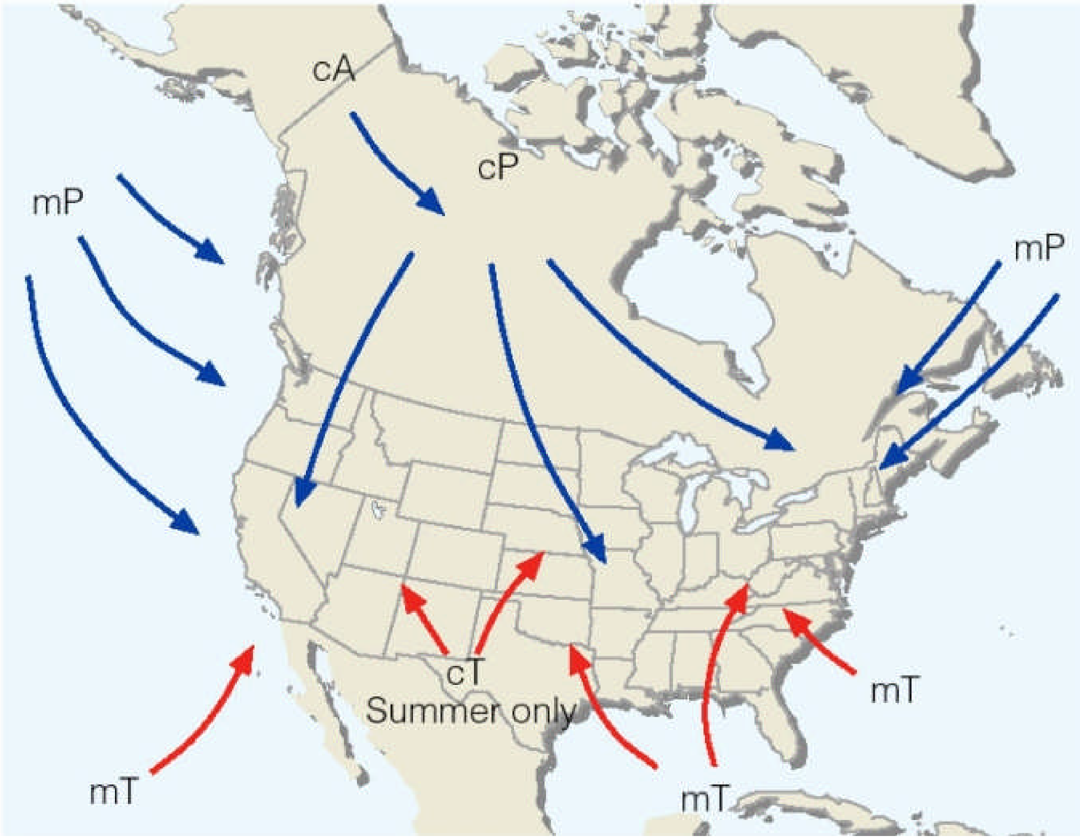

Figure 2.1 Airmass source regions affecting Nebraska (Ahrens 2007)

The most important large scale weather feature affecting the region is the polar front and associated jet stream. The polar front represents the boundary between a dry, polar air mass and a moist, tropical air mass. The polar front is usually oriented west to east across Nebraska when the weather pattern is relatively quiet, and more southwest to northeast during stormy periods. The polar front will shift its mean position throughout the year, being most southerly during winter and retreating north during summer. Synoptic fronts are associated with contrasting air masses that meet at the polar front and have strengths relative to the temperature gradient between the two air masses. This often results in strong fronts during winter and early spring. Dynamic lifting of the atmosphere is enhanced along these fronts, often leading to clouds and precipitation. During the time of the year when higher amounts of moisture are available (May through October), the fronts can aid in producing large amounts of rainfall. Because steering winds aloft can be light in the warm season, the area of lift associated with the synoptic front can remain over the same region for a protracted period of time. This can result in heavy rainfall over the same general area for durations up to three days or more, often leading to widespread flooding over large areas.

For smaller spatial scales (generally less than 500 square miles), diurnal heating patterns, upper air disturbances, and a low-level jet (LLJ) supplying large amounts of moisture combine to produce strong thunderstorms and may lead to Mesoscale Convective Systems (MCSs). In these situations, maritime tropical air from the Gulf of Mexico provides copious amounts of water vapor just waiting to be released as clouds and rainfall, while upper air disturbances (shortwaves) provide additional lift and instability. Finally, the continental tropical air mass serves to bottle up this energy until it can overcome the cap and be released explosively in the form of strong thunderstorms and heavy rains.

A representative weather station in eastern Nebraska is Omaha/Valley, NE. Figures 2.2 and 2.3 display the annual precipitation and temperature. Notice the maximum in precipitation occurs in late spring and summer. The monthly maximum occurs in May as the convective potential energy in the atmosphere coincides with strong jet stream/upper level dynamics, and increasing amounts of atmospheric moisture. The most common type of heavy rain producing events occurs with MCSs (see Section 3 for more details on storm types). This type of storm is reflected strongly in the PMP numbers for the state at areas sizes less than 500 square miles and duration less than 24 hours.

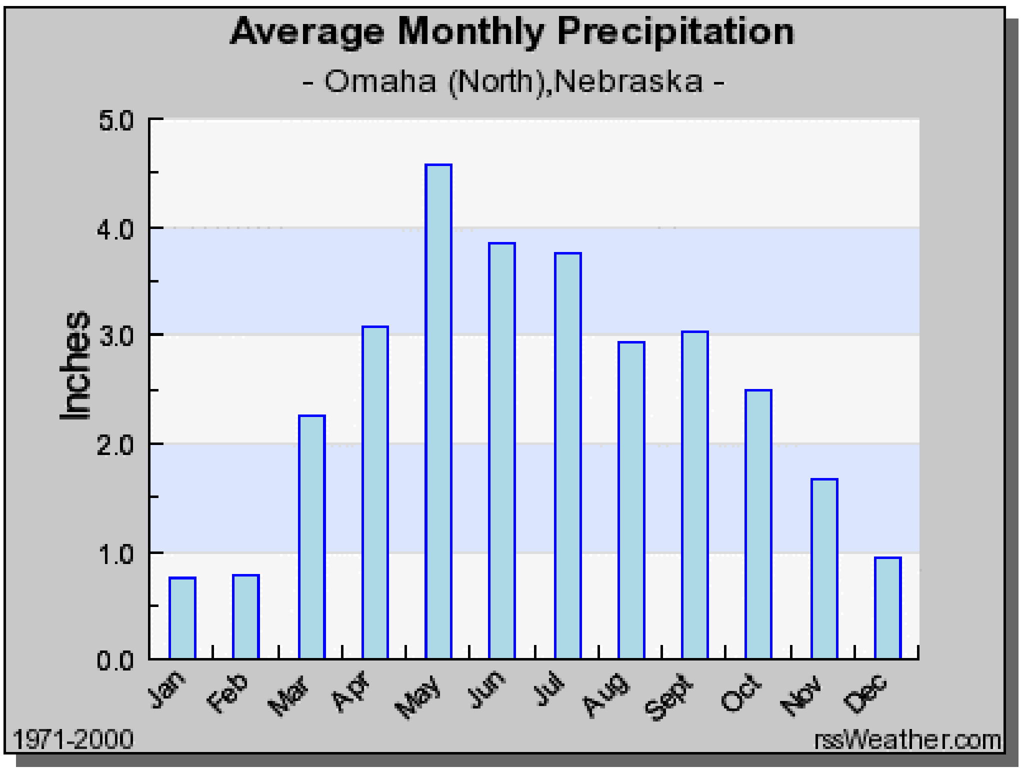

Figure 2.2 Average monthly precipitation at Omaha/Valley, NE 1971-2000 (Weather.com)

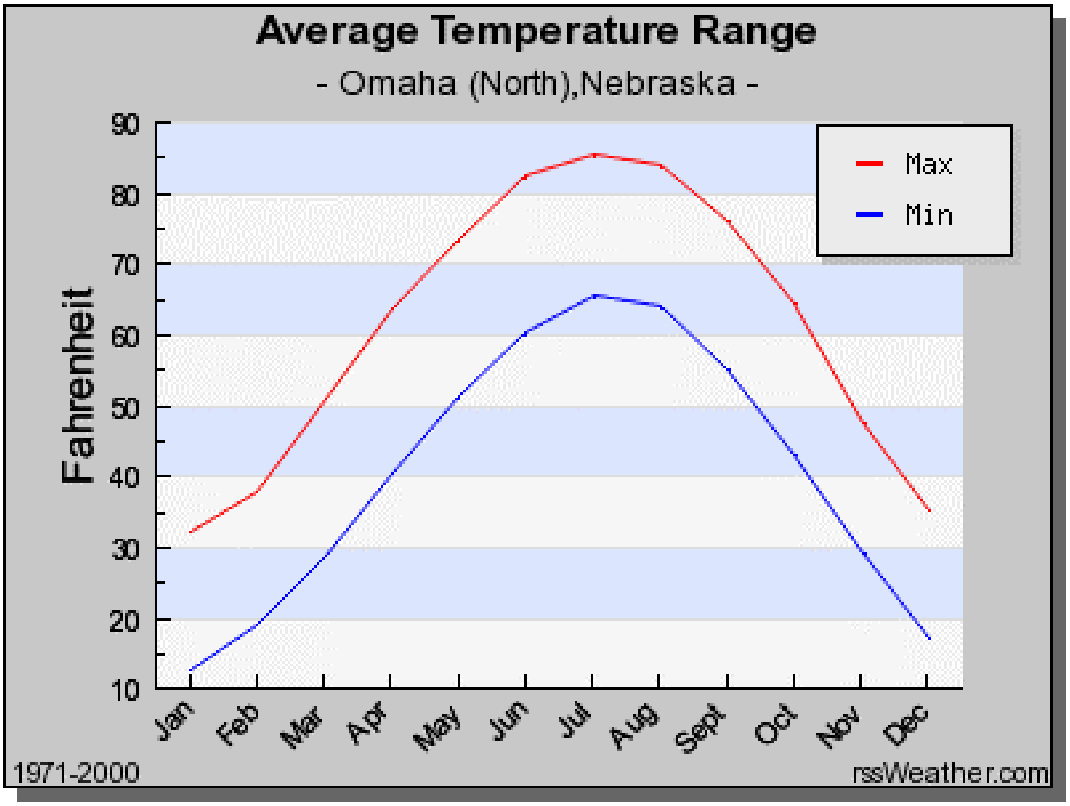

Figure 2.3 Yearly temperature graph at Omaha/Valley, NE 1971-2000 (Weather.com)

2.2 Nebraska Geography

Much of the discussion in this section is derived from the following source http://www.netstate.com/states/geography/ne_geography.htm. Nebraska covers 77,358 square miles, making it the 16th largest of the 50 states, 481 square miles of Nebraska is covered by water. The major rivers in Nebraska are the Missouri River, Niobrara River, Platte River, and Republican River. The major lakes are Lewis and Clark Lake, Harlan County Lake, and Lake C.W. McConaughy.

In the center of the continental United States, Nebraska is a land of plains; the Dissected Till Plains in the eastern part of the state rise to the Great Plains in the north central and northwest parts of the state.

The Dissected Till Plains cover the eastern fifth of Nebraska. This area consists of rolling hills crossed by streams and rivers. The Dissected Till Plains are farm country and fields of corn, soybeans, sorghum grain, and other crops blanket the region. The northern section is referred to as the Loess Hills. Loess is a buff to yellowish-brown loamy dust that is found in North America. Loess is distributed across an area by the wind.

The Great Plains of Nebraska lie to the west of the Till Plains and extends across the state into Wyoming and Colorado. Loess covers the central and south-central Great Plains. This area can be rough and hilly. A relatively flat area in the southeastern section, interspersed with lakes and wetlands, is farmed intensely. This area, about 7,000 square miles, is called The Loess Plains. This region is also sometimes referred to as the Rainwater Basin or the Rain basin.

One might think of sand dunes as belonging near an ocean or one of the Great Lakes. But, north of the Platte River in central Nebraska lays the largest area of sand dunes in North America. This area, about 20,000 square miles, is created of fine sand formed into hills by the wind. Most of the sand in the so-called Sand Hills is held in place by grass. Exceptions occur due to overgrazing by cattle.

North and west of the Sand Hills are the High Plains, characterized by rising land up to over a mile above sea level in the west along the Wyoming border. This area receives little rainfall although some farming is accomplished with irrigation techniques. Rougher sections of the High Plains are used for cattle grazing. The beautiful Wildcat and Pine Ridges are covered with evergreen trees. The highest point in Nebraska, at 5,426 feet above sea level is found in southwestern Kimball County.

In the northwestern corner of Nebraska is a small area of Badlands. In this area of Nebraska, wind and water have sculpted the sandstone and clay into strange and beautiful natural formations. This unusual landscape is characterized by steep hills laid bare by the wind to reveal sandstone and siltstone structures including pedestals shaped like mushrooms. Toadstool Park, in the Ogallala National Grasslands, is an attraction of the Nebraska Badlands.

Because of its relatively dry climate, Nebraska has vegetation that is primarily grasslands, with about 2% of the total area under forest cover. Trees exist along the river valleys and on the higher sandstone escarpments of the northwest. In the east the river valleys are dominated by oak, hickory, and elm trees. Farther west the river valleys are lined with cottonwood, willow, and elm trees. Ponderosa pines grow on the Great Plains escarpments of the northwest. The prairie of the west, once covered with tall bluestem grass, is now mostly cultivated, although the Sand Hills still have much natural grass cover. The dry Panhandle region has a shorter and sparser grama and buffalo grass cover with occasional sagebrush. The sandy plains of the southwest have sand sage mixed with grasses.

The Ogallala Aquifer, a vast underground reservoir, underlies a major portion of Nebraska. Development of the Ogallala Aquifer has brought prosperity to farms and communities throughout the High Plains region of the United States. The documented drawdown of the Ogallala Aquifer, and the resulting Six-State High Plains Ogallala Aquifer Study, indicate that Nebraska's groundwater reserves are more plentiful and stable than other High Plains states.

3. Extreme Storm types

Nebraska and the surrounding region have a very active and varied weather regime throughout the year. Consequently heavy rainfall events at both short and long durations are common. By far, the largest amount of moisture available for precipitation over the region comes from the Gulf of Mexico. Additional moisture is sometimes drawn up around the semi-permanent area of high pressure over the eastern Pacific Ocean, especially at the middle and upper levels of the atmosphere. The major types of extreme precipitation events in the region are produced by Mesoscale Convective Systems (short durations and small area sizes), synoptic events (large areas sizes and longer durations), and/or a combination of the two.

3.1 Mesoscale Convective Systems

Mesoscale Convective Systems (MCSs) are capable of producing extreme amounts of precipitation for short durations and over small area sizes. The current understanding of MCS type storms has progressed tremendously with the advent of satellite technology in the 1970s and early 1980s. The current name of MCS was first applied in the late 1970s to these type of "flood producing", strong thunderstorm complexes (Maddox 1980). Mesoscale systems are so named because they are small in areal extent (10s to 100s of square miles), whereas synoptic storm events are 100s to 1000s of square miles. MCSs also exhibit a distinctive signature on satellite imagery where they show rapidly growing cirrus shields with very high cloud tops. Furthermore, MCSs usually take on a nearly circular pattern about the size of the state of Iowa with constantly regenerating thunderstorms fed by moist low level jet inflow.

MCSs 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 and tropical cyclones, and MCSs that don't 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, becoming most common around Nebraska from May through September, but have been known to occur as early as the beginning of April or as late as the middle of October.

The vast majority of MCSs have distinctive features and evolve in a standard pattern. 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 these storms 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 – situated at around 3000-5000 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 low level moisture transport 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.

Many of the storms previously analyzed by the Army Corps of Engineers and NWS Hydrometeorological Branch in support of pre-1979 PMP research have features that indicate they were most likely MCCs or MCSs, only this nomenclature had not yet been introduced into the scientific literature, nor were the events fully understood. For Nebraska, twenty-one of the thirty-six storms identified for the short storm list produced the classic MCS storm signature (Table 4.2). These are very important storms for determining PMP for small area sizes and short durations across the state.

Some examples of this type of storm which were important to the PMP development for Nebraska include Boyden, IA 1926; Grant Township, NE 1940; Hallett, OK 1940; and David City, NE 1963 (see Section 4 and Appendixes B and F for complete descriptions).

3.2 Synoptic Fronts

The polar front and jet stream, which separate cool, dry Canadian air to the north from warm, moist air to the south, is a major weather maker in the region. This contributes large amounts of energy and storm dynamics to storm systems that move through the region. These features are strongest and most active over the region from late Fall through late 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 edge of the Bermuda High circulation encounters the frontal zone and is forced to rise over the cooler, drier air mass to the north of the front. This forced ascent condenses moisture in the air mass into clouds and precipitation, while releasing latent heat. This process most often results in widespread rainfall over longer durations, but can also help enhance convection. Air that arrives at the frontal location is conditionally unstable, where the lower layers are much warmer and more humid than the air above. This conditionally unstable air mass is just waiting for an uplifting mechnism to lift the airmass ever so slightly to begin an energy release, which will foster more instability and further uplift. This is where the forced ascent over the polar front initiates the lifting of the air mass and release of its energy.

A stationary polar front located near Nebraska will often provide the mechanism necessary for this warm, humid air mass to release its convective potential. When this occurs, rainfall occurs, sometimes associated with pockets of convection and heavy rainfall. The 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 instead add to the storm dynamics and energy available for producing precipitation.

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 heavy to moderate rain continues to fall over the same regions for an extended period of time. Warner, OK 1943, Cole Camp 1946, MO, Collinsville 1946, IL, and Edgerton, MO 1965 are classic examples of this type of storm that generated large amounts of rainfall over longer durations and larger area sizes (see Section 4 and Appendixes B and F for complete storm descriptions).

3.2.1 Tropical Storms

It is important to note that the HMRs do not have decaying tropical storms directly affecting the central US as far north as Nebraska. By the time this type of storm moves this far inland away from its energy source in the Gulf of Mexico, it has lost its tropical characteristics, and therefore this type of storm is not considered to be explicitly relevant to the region (see Section 2.4.2 in HMR 55A). However, remnant air mass from a tropical storm can add high levels of moisture and potential convective energy to the atmosphere over the central plains but tropical circulations are constrained to regions south of Nebraska (HMR 51, HMR 55A and EPRI).

3.3 Hybrid Storms

This storm type contains characteristics of both synoptic frontal storms and intense convection. Generally, this type of storm lasts for a duration of at least 24 hours, but includes periods of intense rainfall for shorter durations associated with strong imbedded convective cells within the overall storm environment that produce large amounts of rain over smaller areas within the larger storm environment. Examples of this type of storm relevant to Nebraska include Aurora College, IL 1996 and Hokah, MN 2007 (see Section 4 and Appendix B and F for complete descriptions).

4 Extreme Storm Identification

4.1 Storm Search Area

The initial storm search for this study included regions of the country that were considered meteorologically and topographically similar to Nebraska, where extreme rainfall storms similar to those that could occur over some part of Nebraska may have been observed. This region covered the United States from 49°N 108°W to 35°N 108°W and 49°N 85°W to 35°N 85°W. Figure 4.1 shows the storm search domain used to identify extreme rainfall events. Over the western edges of this search domain, storms were eliminated that occurred in the orographically significant regions of the Black Hills, the Front Range of Colorado and the Rocky Mountains.

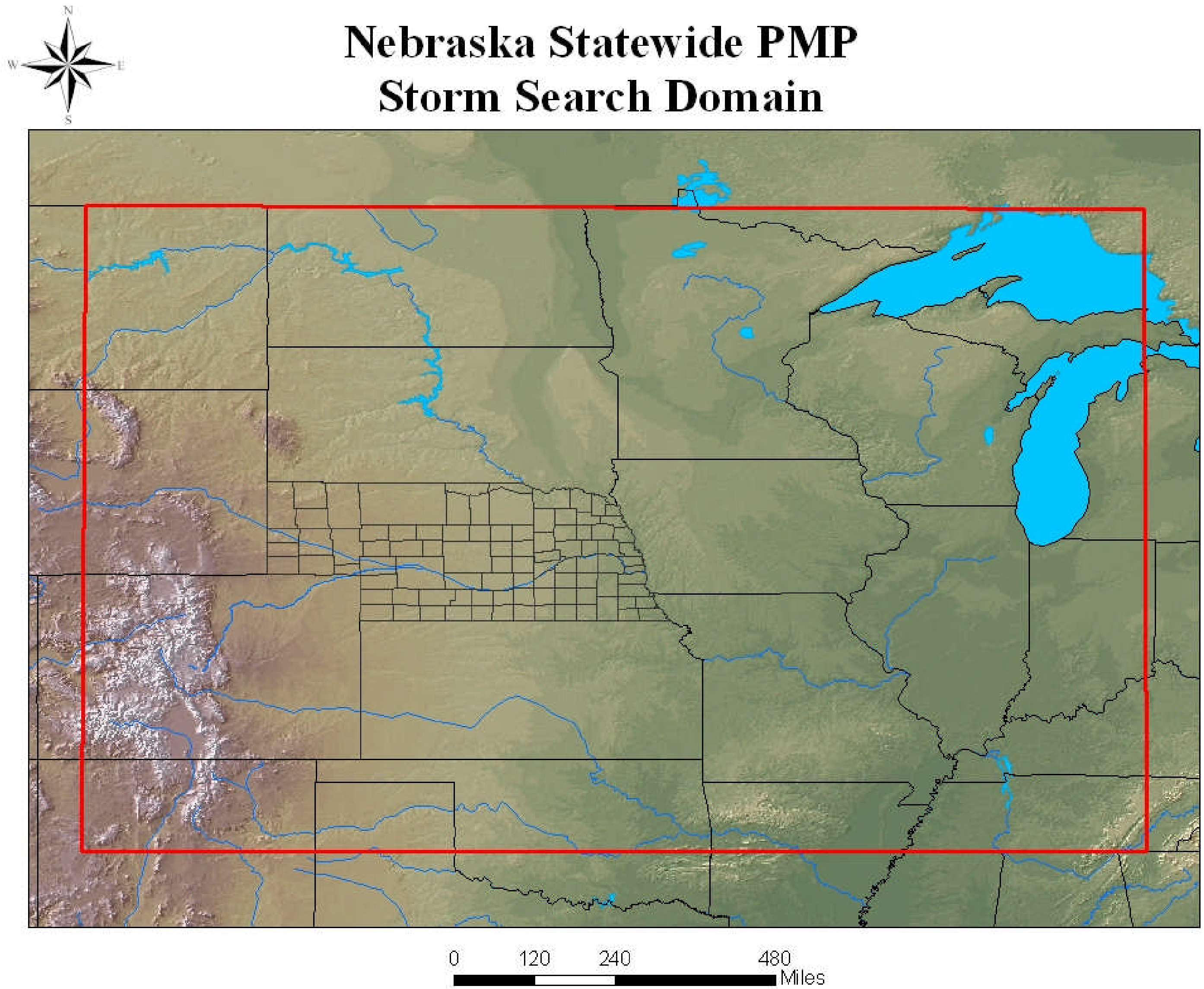

Figure 4.1 Nebraska storm search domain

4.2 Data Sources

The storm search was conducted by searching the National Climatic Data Center (NCDC) hourly and daily rainfall records for maximum rainfall amounts that occurred during a 6-hr, 24-hr/1-day, and 72-hr/3-day period within the storm search domain. Further searches were conducted from several sources listed below:

1. Cooperative Summary of the Day / TD3200 through 2006. These data are published by the National Climatic Data Center (NCDC).
2. Hourly Weather Observations published by NCDC, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory).
3. NCDC Recovery Disk
4. Other data published by state climate offices.
5. Data from supplemental sources, such as Community Collaborative rain, Snow, and Hail Network (CoCoRaHS), Nebraska Rainfall Assessment and Information Network (NeRAIN), Weather Underground, Forecast Systems Laboratories, RAWS, and various Google searches.

4.3 Storm Search Method

The initial task was the identification of extreme rainfall events that occurred within the storm search domain (see Figure 4.1). The climate and weather of Nebraska is fairly uniform with most of the Midwest, extending from the southern Great Plains northward to the upper Mississippi River Valley and Missouri River Valley. The storm search domain extended from the Rockies to the western edges of the Ohio River Valley, south to central Oklahoma and north to the Canadian border. Figure 4.2 shows the locations of the storms that were initially identified. This large storm search domain ensured that all relevant extreme storm events that could potentially have occurred over portions of Nebraska were identified.

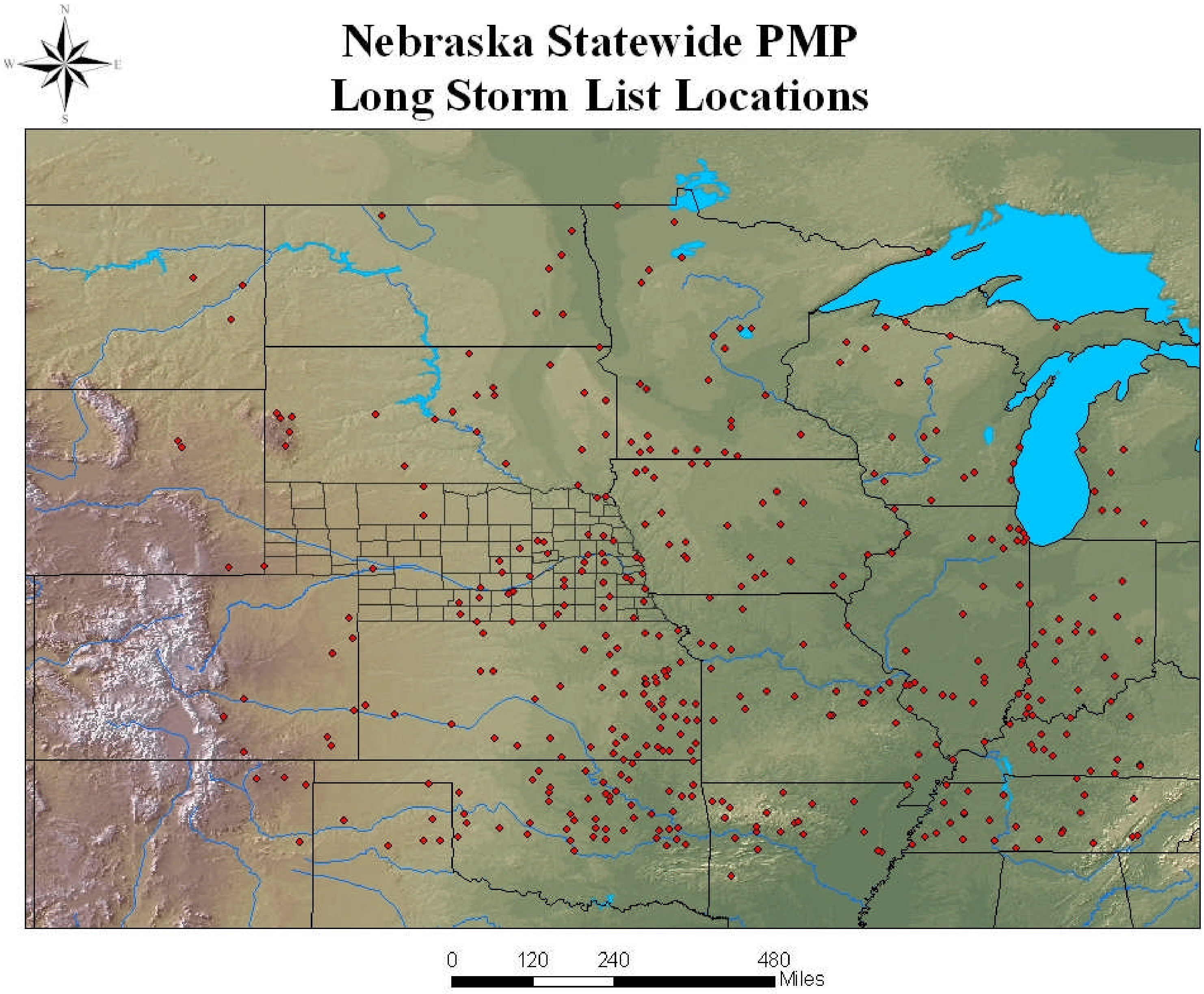

Figure 4.2 Nebraska long list storm locations

The initial storm search used all rainfall observations in the National Climatic Data Center (NCDC) archives in three different categories; 6-hours (MCS), 24-hours or 1-observation day (Hybrid), and 3-days (Synoptic). Additional data mining was done using the National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), and NCDC web services, various American Meteorological Society (AMS) journals, and previous PMP studies in the region. These data were sorted and organized in each of the three categories from largest to smallest rainfall amounts. This initial data extraction procedure produced over 1,200 storm events through all three durations. An initial quality control (QC) process eliminated numerous duplicates and several storms were eliminated because of clearly incorrect precipitation values.

After the initial QC process, a procedure was initiated to eliminate storms that were too small to be significant in the PMP development. All storm events that had greater than some minimum rainfall amount (dependent of storm duration) went through further QC procedures.

For the 6-hour duration, the Web Search Store Retrieve Display (WSSRD) website was used to QC the hourly rainfall values and to view the storm data documentation. The final maximum 6-hr rainfall dataset included in 172 storm events greater than 4.5 inches. Figure 4.3 shows the locations of the 6-hour (MCS) extreme storm events.

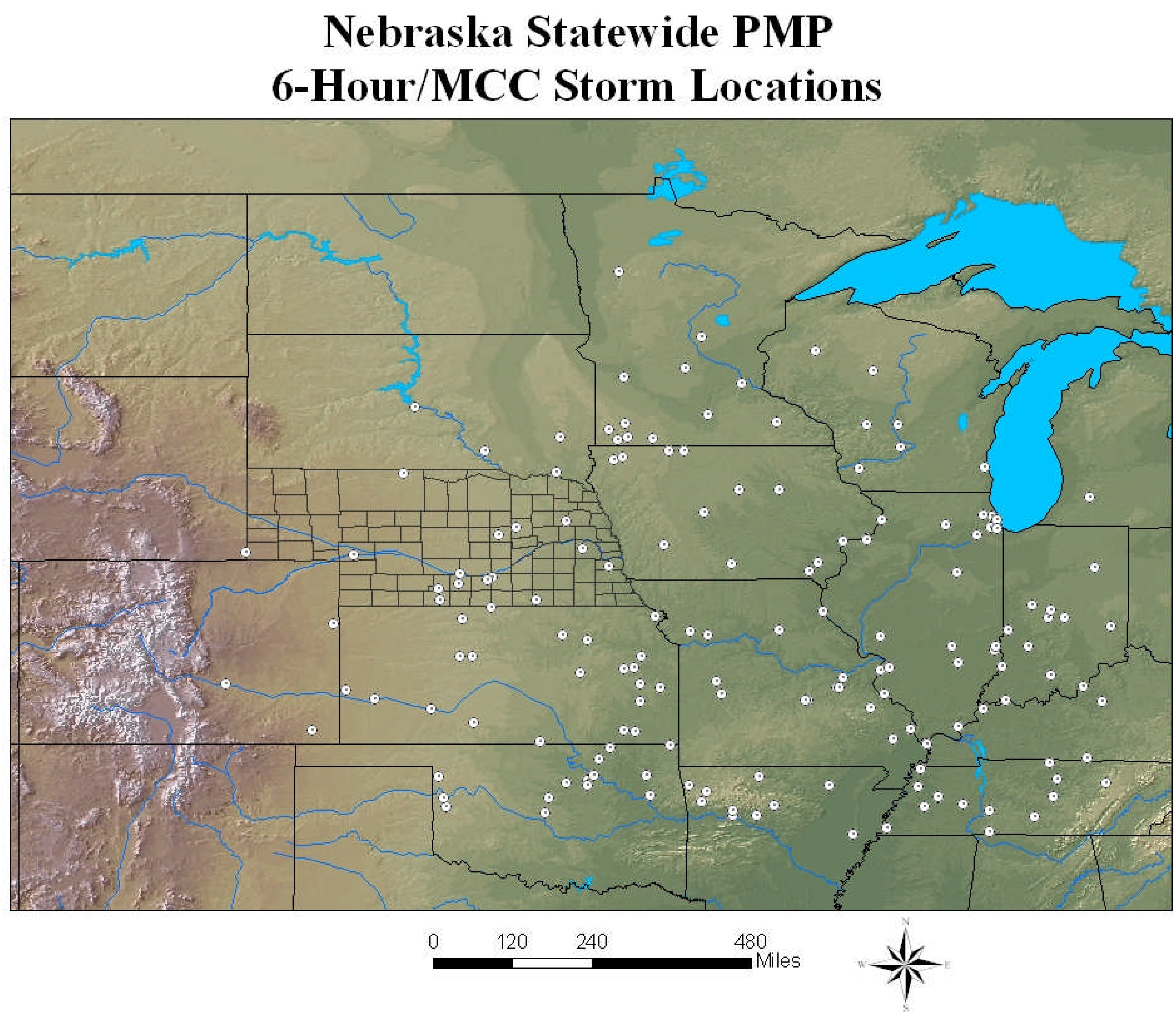

Figure 4.3 Nebraska 6-Hour/MCS storm locations

For the 24-hour or 1-observation day duration, storms with 24-hour or 1-observation day totals of 6 inches or greater were evaluated. The 6 inch limitation was because this represented the largest 20 percent of the storms. Therefore all the potentially significant storms that could affect the final PMP values at some area size or duration were included. Data were sorted by rainfall amount for the 24-hours or 1-observation day periods. Extreme rainfall values that occurred on the same day were sorted and only the highest value of that day was retained on the 24-hours or 1-observation day storm list. This left just over 2,300 storm events. To further delineate the list, the maximum Precipitable Water (PW) values for each of the states in the study region were determined using data from the Rapid City, South Dakota-NWS office. This allowed a ratio method to be used to eliminate storms on the lower end of the spectrum that even after maximization would not be significant storms for PMP development. This procedure provided realistic cutoff values for storms in each state. This procedure reduced the number of storms on the 24-hours or 1-observation day list to just over 950.

The next step was accomplished by scrutinizing the storms in each state and determining the ratio of each storm's rainfall value in comparison to the 24-hour storm of record for that state. This procedure ensured that no storms were left off that could be significant after maximization and transposition in the PMP development procedure. The final step was to ensure all previous storms analyzed as part of the NWS Hydrometeorological Studies (HMR 51) for the region, the PMP Study for Michigan and Wisconsin (Tomlinson et al, 1993) and Lake Wanahoo Study (Tomlinson et al, 2008) were included. This final step brought the number of storms on the 24-hour list to 155. Figure 4.4 shows the locations of the 24-hour storm events

Nebraska Statewide PMP
24-Hour/1-Day Storm Locations

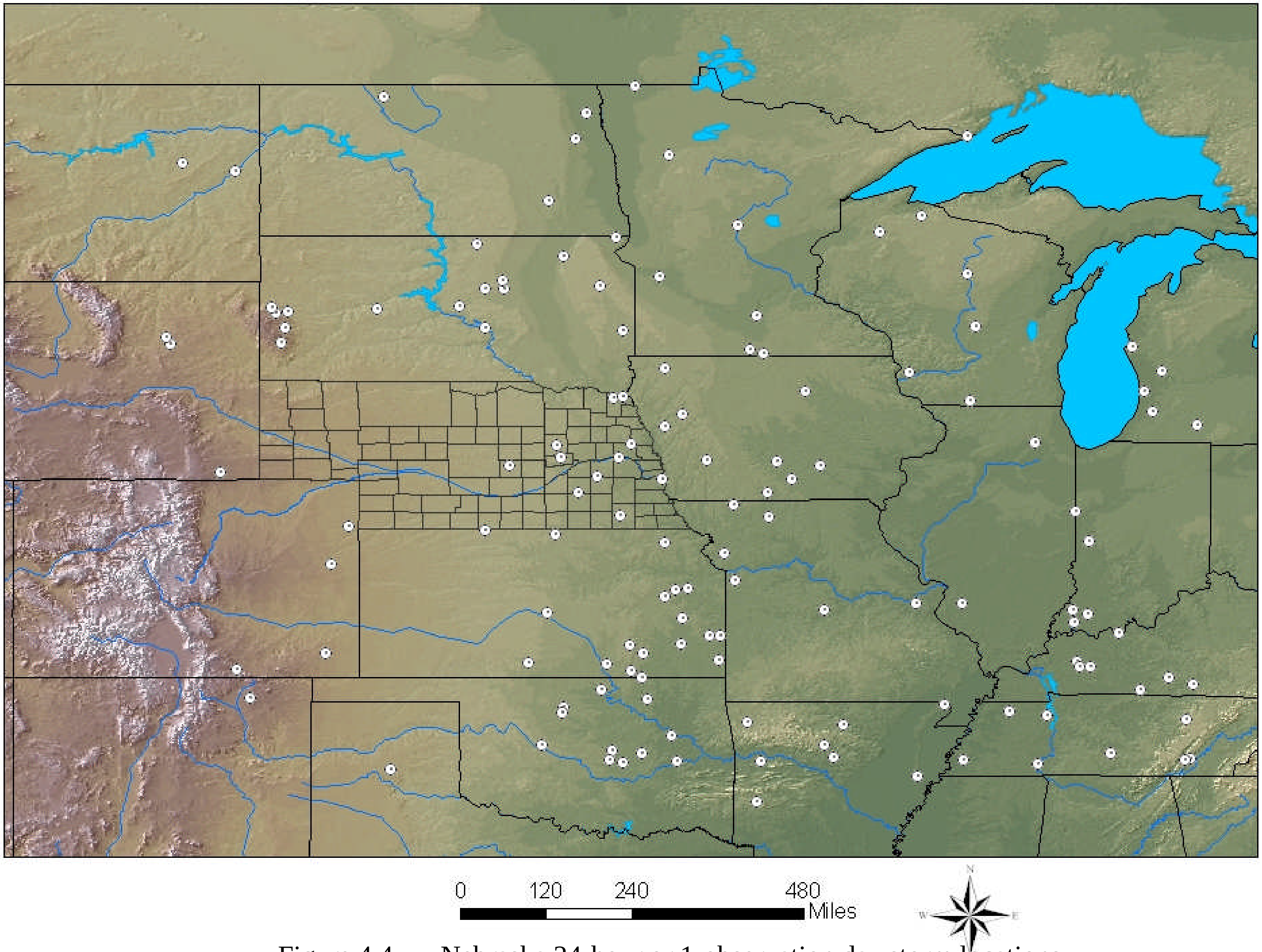

Figure 4.4 Nebraska 24-hour or 1-observation day storm locations

For the 3-day duration, data were sorted by greatest amount. Once this was completed, each storm was screened for data that was not probable. By far the largest number of rainfall observations removed were due to multiple large precipitation reports occurring at several stations during the same storm event. In these cases only the largest amount was kept for purposes of developing a long list warranting further analysis. After this procedure was completed there were 993 entries on the 3-day storm list.

Each state's storm list was evaluated using the ratio of each storm's value in comparison to the storm of record for each state. Storms within approximately 35% of the maximum 3-day value were kept. The final step was to ensure all previous storms analyzed as part of the NWS Hydrometeorological Studies (HMR 51) for the region, the PMP Study for Michigan and Wisconsin (Tomlinson et al, 1993) and Lake Wanahoo (Tomlinson et al, 2008) were included. This final step brought the number of storms on the 3-day long list to 137. Figure 4.5 shows the locations of the 3-day storm events.

The final step was to determine the significance of all the major storms by using a first look tool, the Depth-Area Estimator (DA Estimator). This program produces a high level view of each storm's significance at various area sizes, a much more informative tool than just looking at the maximum point rainfall amount. The DA Estimator was run for all Nebraska storms and for the top 20% of the storms from the other states. Figure 4.6 shows a typical result of the DA estimator program.

Nebraska Statewide PMP
3-Day Storm Locations

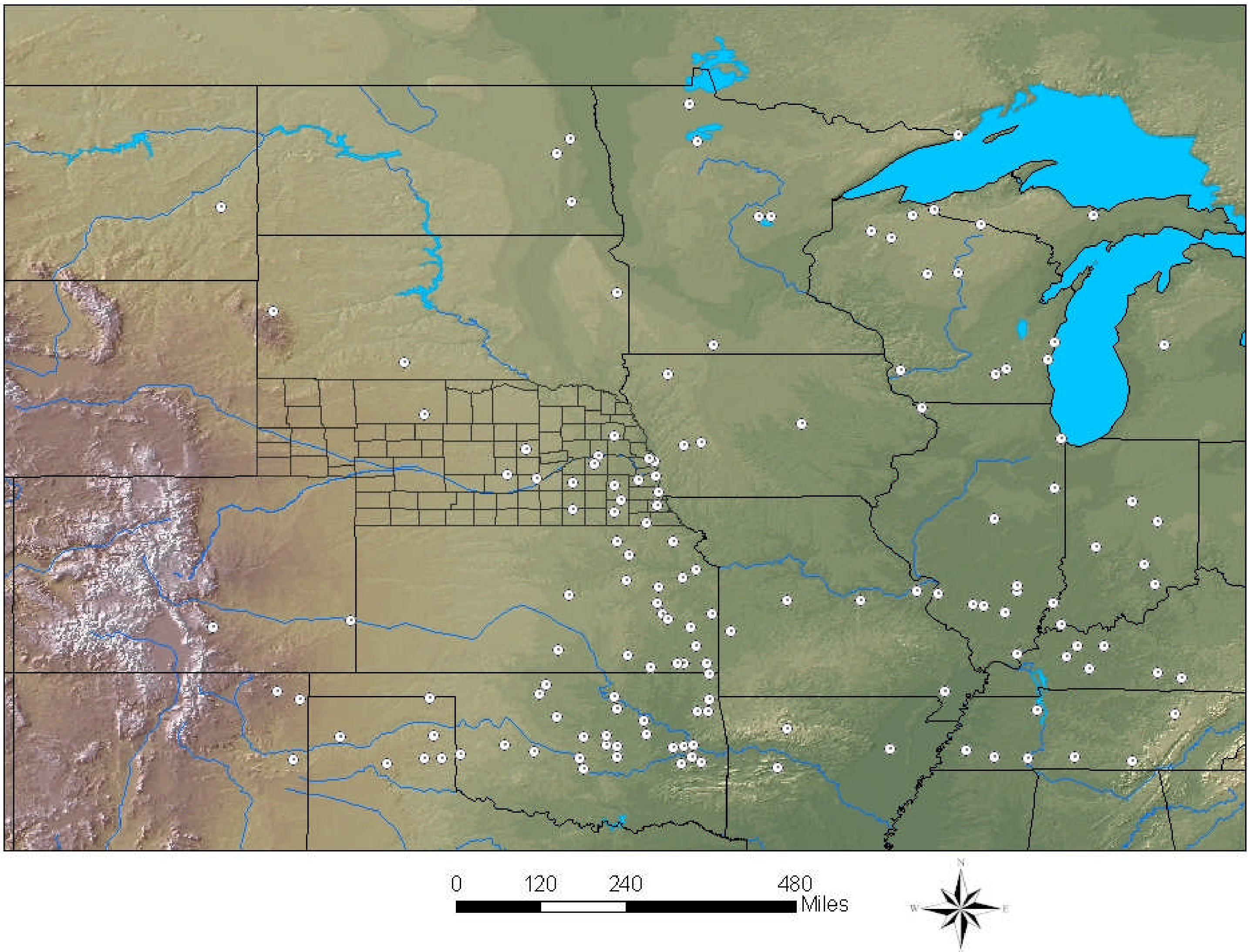

Figure 4.5 Nebraska 3-Day/Synoptic storm locations

Once these lists were finalized, subsequent steps involved determining which were the most significant for the development of the PMP for the state of Nebraska. Results of this analysis produced the short list of storms. Each of the storms on the final short storm list had a full storm analysis completed that includes a storm Depth-Area-Duration (DAD) table and maximization adjustments using standard procedures, as documented by the WMO (1986).

All storms that have been previously analyzed in HMRs and/or US Army Corps of Engineers Storm Studies (USACE) were included. Appropriate storms that were analyzed in the EPRI Michigan/Wisconsin regional PMP study and the Lake Wanahoo PMP study were included as well. This produced 25 storms, each of which had been previously analyzed with a full DAD and storm adjustments. Each of these storms was placed into the standard Applied Weather Associates storm adjustment spreadsheet where storm maximization, transposition and other adjustments were applied based on transpositioning each of these storms to the appropriate grid point(s) throughout the region.

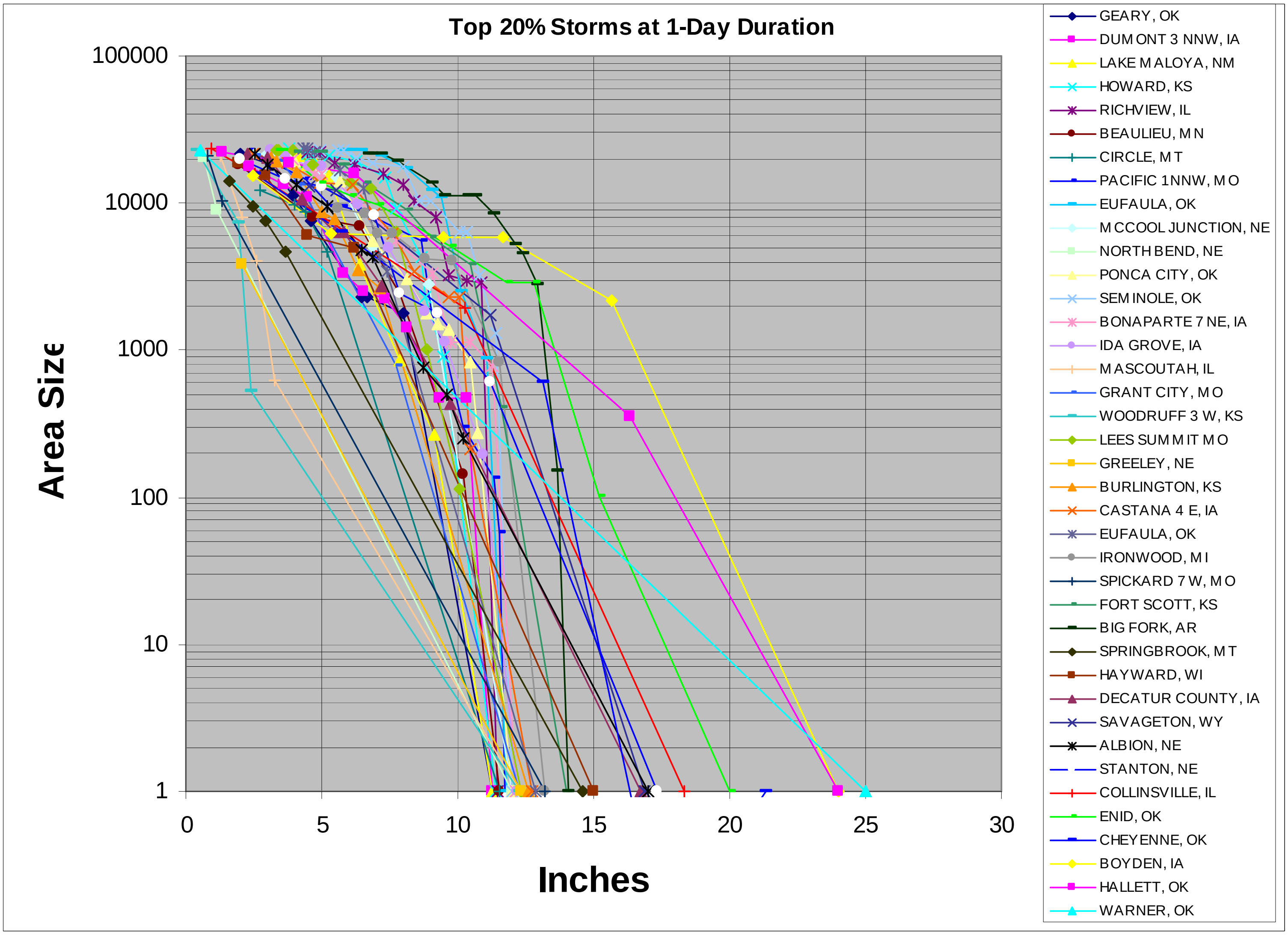

Figure 4.6 Example Depth-Area graphical output from the DA estimator

This procedure produced 140 DA estimator results. This number of storms was determined to be sufficiently large as to ensure all potentially significant storms were identified and evaluated. Once this was completed, the most significant of these storm events that could potentially become a driver storm in the estimates of PMP were determined and compiled into the short storm list. These storms are then further analyzed.

4.4 Long List of Extreme Storms

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount.

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
DANVILLE	AR	35.05	-93.40	3-day	1982	12	2	22.03
DEER	AR	35.83	-93.20	3-day	1994	11	4	15.75
BEEDEVILLE	AR	35.43	-91.10	3-day	1978	9	12	14.42
BIG FORK	AR	34.49	-93.97	1-day	1982	12	3	14.06
DAMASCUS	AR	35.37	-92.42	1-day	1957	8	13	11.00
CHIMES 9 SE	AR	35.63	-92.58	1-day	1998	10	6	10.46
MADISON	AR	35.00	-90.72	1-day	1980	7	22	10.45
GREEN MOUNTA	AR	36.03	-92.20	1-day	1949	1	24	9.89
FAYETTEVILLE	AR	36.10	-94.17	1-day	1960	7	25	9.60
RATCLIFF	AR	35.30	-93.88	1-day	1945	2	13	9.58
ST FRANCIS	AR	36.45	-90.15	1-day	1999	4	3	9.30
APPLETON	AR	35.42	-92.88	6hrs	1957	8	13	7.13
CLARKSVILLE	AR	35.43	-93.42	6hrs	1950	7	17	6.39
CLARKSVILLE	AR	35.53	-93.42	6hrs	1975	9	19	6.21
BOTKINBURG	AR	35.65	-92.50	6hrs	1945	6	9	6.08
WEDINGTON LAKE	AR	36.10	-94.38	6hrs	1950	5	9	5.47
DURHAM	AR	35.95	-93.98	6hrs	1946	5	24	5.40
SMITHVILLE	AR	36.08	-91.30	6hrs	1949	1	24	5.23
PYATT	AR	36.27	-92.85	6hrs	1961	5	7	5.09
WINFREY	AR	35.73	-94.10	6hrs	1945	9	12	4.91
FORREST CITY	AR	35.02	-90.78	6hrs	1947	12	31	4.60
HALE	CO	39.63	-102.14	6hrs	1935	5	30	24.00
HOLLY	CO	38.05	-102.12	3-day	1965	6	16	15.54
PAWNEE CREEK	CO	40.67	-103.83	1-day	1998	7	28	13.70
TRINIDAD	CO	37.17	-104.50	1-day	1910	3	6	10.00
RYE	CO	37.92	-104.93	3-day	1955	5	17	9.92
WRAY	CO	40.07	-102.22	1-day	1921	2	7	9.00
STRATTON	CO	39.30	-102.58	1-day	1969	8	23	8.00
HARMON RANCH	CO	37.48	-102.68	1-day	1951	5	15	7.13
SPRINGFIELD	CO	37.28	-102.62	6hrs	1965	6	16	5.37
SAND CREEK	CO	38.30	-104.50	6hrs	1998	7	22	4.50
BOYDEN	IA	43.19	-96.01	1-day	1926	9	17	24.00
MARSHALLTOWN	IA	42.07	-92.90	3-day	1954	8	3	19.93
MARSHALLTOWN	IA	42.07	-92.90	3-day	1954	8	16	17.36
DECATUR COUNTY	IA	40.74	-93.75	1-day	1959	8	6	16.70
HARLAN	IA	41.65	-95.32	3-day	1972	9	10	15.25
AUDUBON	IA	41.70	-94.95	3-day	1958	7	1	14.81
ATLANTIC 1E	IA	41.40	-94.98	1-day	1998	6	13	14.02
PRIMGHAR	IA	43.08	-95.63	3-day	1900	7	14	13.70
IDA GROVE	IA	42.32	-95.47	1-day	1962	8	30	12.85
CASTANA 4 E	IA	42.07	-95.82	1-day	1996	7	17	12.75
BONAPARTE 7	IA	40.77	-91.75	6hrs	1905	6	10	12.10
DUMONT 3 NNW	IA	42.78	-92.98	1-day	1968	7	17	11.28
CHARITON 3 E	IA	41.00	-93.25	1-day	1903	8	27	11.23
INDIANOLA	IA	41.37	-93.55	1-day	1931	9	19	11.21
OSKALOOSA	IA	41.28	-92.67	1-day	1947	10	11	11.07
RITTER	IA	43.24	-95.82	6hrs	1953	6	7	11.00
ARMSTRONG	IA	43.40	-94.48	6hrs	1993	6	23	10.00
DERBY	IA	40.93	-93.45	6hrs	1992	9	15	8.90
DICKINSON & EMMET CTYS	IA	43.40	-94.80	6hrs	1993	6	30	7.00
IOWA FALLS	IA	42.53	-93.27	6hrs	1964	7	31	6.17
OGDEN	IA	42.05	-94.03	6hrs	1954	6	20	5.92
MOUNT PLEASANT	IA	40.95	-91.56	6hrs	1973	9	18	5.50
CASS COUNTY	IA	41.33	-94.93	6hrs	1998	6	5	5.00
WATERLOO LSO	IA	42.55	-92.40	6hrs	1968	7	16	7.28

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
COLLINSVILLE	IL	38.67	-90.54	3-day	1946	8	12	18.70
AURORA COLLEGE	IL	41.75	-88.33	1-day	1996	7	16	18.24
NASHVILLE 3	IL	38.38	-89.40	3-day	1946	8	14	16.13
GOLCONDA DAM	IL	37.37	-88.48	3-day	1910	10	4	15.18
CLINTON	IL	40.15	-88.97	3-day	1961	5	6	15.00
CHICAGO UNIV	IL	41.78	-87.60	3-day	1982	11	11	14.61
BELLE RIVE	IL	38.23	-88.75	3-day	1978	1	16	13.00
EAST ST LOUI	IL	38.62	-90.12	3-day	1957	6	13	12.74
MASCOUTAH	IL	38.48	-89.80	1-day	1919	10	29	12.25
GALENA	IL	42.42	-90.43	3-day	2002	8	22	12.19
MOUNT CARMEL	IL	38.42	-87.75	3-day	1949	1	18	12.07
FLORA	IL	38.67	-88.48	3-day	1931	3	6	11.96
WATSEKA	IL	40.77	-87.73	3-day	1893	5	9	11.79
RICHVIEW	IL	38.37	-89.18	3-day	1949	1	4	11.59
LOUISVILLE	IL	38.77	-88.50	3-day	1949	1	27	11.54
FAIRBURY WATERWWORK	IL	40.74	-88.52	6hrs	1951	7	8	7.10
CHICAGO MAYFAIR PUMP	IL	41.97	-87.75	6hrs	1957	7	12	6.47
CHICAGO O'HARE WSO ARP	IL	42.00	-87.93	6hrs	1987	8	13	5.95
COLLINSVILLE	IL	38.67	-89.98	6hrs	1942	7	8	5.92
CHICAGO WB CITY 2	IL	41.88	-87.63	6hrs	1967	6	10	5.87
QUINCY DAM	IL	39.90	-91.43	6hrs	1949	7	20	5.70
ILLINOIS CITY DAM 16	IL	41.43	-91.02	6hrs	1965	4	24	5.69
EFFINGHAM	IL	39.12	-88.62	6hrs	1973	8	12	5.65
LOUISVILLE	IL	38.77	-88.50	6hrs	1963	6	30	5.65
CAIRO WB CIT	IL	37.00	-89.17	6hrs	1967	5	14	5.41
CAIRO WB CITY	IL	37.00	-89.17	6hrs	1938	3	13	5.36
CHICAGO MIDWAY AP 3 SW	IL	41.74	-87.78	6hrs	1996	7	17	5.30
LOCKPORT, LOCK & DAM	IL	41.57	-88.08	6hrs	1942	9	7	5.23
MOLINE WSO	IL	41.47	-90.52	6hrs	1963	7	18	5.20
PRAIRIE DU ROCHER	IL	38.08	-90.10	6hrs	1946	8	5	5.18
MOLINE WB AI	IL	41.45	-90.50	6hrs	1971	7	10	5.08
CHICAGO ROSE	IL	41.70	-87.63	6hrs	1954	10	3	5.04
CAIRO WB CITY	IL	37.00	-89.17	6hrs	1925	6	13	4.94
GREENFIELD	IL	39.33	-90.20	6hrs	1942	6	25	4.92
FULTON LOCK & DAM #13	IL	41.90	-90.15	6hrs	1967	8	6	4.80
HUTSONVILLE	IL	39.12	-87.67	6hrs	1947	8	25	4.63
GOLCONDA DAM	IL	37.37	-88.48	6hrs	1942	8	23	4.62
LOUISVILLE	IL	38.77	-88.50	6hrs	1967	12	21	4.57
WATERMAN	IL	41.77	-88.77	6hrs	1946	8	17	4.57
SOUTH CENTRAI/SOUTH EAST	IN	38.50	-86.45	6hrs	1992	8	8	13.00
PUTNAMVILLE	IN	39.57	-86.87	3-day	1948	11	5	12.82
PARIS WATERWORKS	IN	39.05	-87.70	6hrs	1957	6	27	12.40
COLUMBUS 2	IN	39.22	-85.90	3-day	1981	3	6	10.90
EVANSVILLE F	IN	37.97	-87.58	3-day	1910	10	4	10.85
KOKOMO POST	IN	40.48	-86.13	3-day	2003	7	5	10.81
ANDERSON MOU	IN	40.08	-85.62	3-day	1948	11	11	10.65
PRINCETON	IN	38.37	-87.57	1-day	1905	8	6	10.50
DEPUTY 1 NW	IN	38.80	-85.67	3-day	1992	8	8	10.41
MCCUTCHANVIL	IN	38.12	-87.53	1-day	1996	4	29	8.79
ROCKVILLE	IN	39.77	-87.23	1-day	1957	6	28	8.74
PENCE 1 SW	IN	40.35	-87.50	1-day	2002	8	20	8.35
PRINCETON	IN	38.37	-87.57	1-day	1979	7	26	8.29
CANNELTON	IN	37.90	-86.63	1-day	1997	3	2	8.25
SPURGEON 2 N	IN	38.28	-87.25	1-day	1979	6	9	8.10
ROCKVILLE	IN	39.77	-87.23	1-day	1989	5	26	8.05

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
INDIANAPOLIS	IN	39.77	-86.17	6hrs	1895	9	4	6.55
WORTHINGTON	IN	39.12	-86.97	6hrs	1947	8	15	5.51
HUNTINGTON	IN	40.86	-85.50	6hrs	1959	6	25	5.24
CRAWFORDSVILLE	IN	40.03	-86.88	6hrs	1950	8	31	5.10
TERRE HAUTE WB CITY	IN	39.48	-87.40	6hrs	1926	9	8	4.89
ALPINE 2 NE	IN	39.57	-85.16	6hrs	1983	4	30	4.78
DANVILLE	IN	39.77	-86.52	6hrs	1962	7	19	4.72
NEWBURGH ARCHAEOL	IN	37.95	-87.45	6hrs	1950	7	31	4.70
JAMESTOWN	IN	39.92	-86.46	6hrs	1962	7	14	4.55
VINCENNES	IN	38.68	-87.53	6hrs	1945	9	27	4.53
COUNCIL GROVE	KS	38.40	-96.30	3-day	1951	7	9	18.50
ALTAMONT	KS	37.18	-95.30	3-day	1948	6	21	16.20
MOUND VALLEY	KS	37.18	-95.45	3-day	1976	7	1	16.07
ALTA VISTA	KS	38.87	-96.48	3-day	1951	7	10	13.19
BURLINGTON	KS	38.20	-95.75	3-day	1941	5	31	13.11
WORDEN	KS	38.80	-95.37	1-day	1988	6	30	13.07
GRENOLA	KS	37.35	-96.45	3-day	1977	6	23	12.80
BURLINGTON	KS	38.19	-95.47	1-day	1941	6	1	12.59
FORT SCOTT	KS	37.85	-94.70	1-day	1998	9	15	12.50
LINDSBORG	KS	38.57	-97.67	3-day	1941	10	20	12.44
BLUE RAPIDS	KS	39.68	-96.67	3-day	1981	7	26	12.35
WOODRUFF 3 W	KS	39.98	-99.47	1-day	1967	6	29	12.29
HAYS	KS	38.91	-99.39	6hrs	1951	5	21	12.00
HORTON	KS	39.67	-95.52	3-day	1984	6	9	12.00
WALNUT 4 S	KS	37.55	-95.07	3-day	1998	9	12	11.62
HOWARD	KS	37.48	-96.27	1-day	1976	7	3	11.40
NORWICH	KS	37.47	-97.87	3-day	1998	10	31	11.38
PLEASANTON	KS	38.18	-94.72	3-day	1927	9	30	11.35
HAVANA 2 W	KS	37.10	-95.98	3-day	1972	7	17	11.32
MORAN	KS	37.93	-95.17	3-day	1915	9	5	11.23
LEBO	KS	38.42	-95.85	3-day	1928	11	16	11.20
CLINTON DAM	KS	38.93	-95.33	3-day	1996	6	5	10.95
WESTMORELAND	KS	39.40	-96.42	3-day	1968	7	24	10.94
BURLINGAME 1	KS	38.75	-95.82	3-day	1977	7	2	10.90
LE ROY	KS	38.08	-95.63	3-day	1926	9	12	10.84
COLUMBUS	KS	37.18	-94.85	3-day	1996	8	16	10.66
TONGANOXIE 2	KS	39.10	-95.05	3-day	1977	9	12	10.53
BELVIDERE	KS	37.45	-99.08	6hrs	1997	5	18	10.00
DODGE CITY 6NW	KS	37.75	-100.02	6hrs	2003	8	29	10.00
OSAGE CITY	KS	38.63	-95.83	1-day	1909	7	7	9.65
ELGIN	KS	37.00	-96.28	1-day	1979	11	21	9.60
UNIONTOWN 2	KS	37.85	-94.93	1-day	1986	10	5	9.50
LOVEWELL DAM	KS	39.90	-98.03	1-day	2003	6	23	9.39
ELGIN	KS	37.00	-96.28	1-day	1984	10	13	9.20
WINFIELD NO.	KS	37.25	-97.00	1-day	1973	10	11	9.12
CEDAR VALE	KS	37.12	-96.50	1-day	1995	7	3	9.05
LYONS 3 S	KS	38.32	-98.20	1-day	1973	9	26	9.00
MEDICINE LOD	KS	37.28	-98.58	1-day	1923	9	30	9.00
WOMER	KS	39.97	-98.71	6hrs	1998	7	4	9.00
CHANUTE FAA	KS	37.67	-95.48	1-day	1927	4	8	8.92
BEAUMONT	KS	37.65	-96.53	1-day	1945	9	24	8.83
PITTSBURG 4	KS	37.33	-94.73	1-day	1993	9	25	8.77
OVERBROOK 2	KS	38.77	-95.60	1-day	1988	6	29	8.72
WOODLAWN 4 S	KS	39.73	-95.83	1-day	1977	5	20	8.54
PITTSBURG 4	KS	37.33	-94.73	1-day	1957	6	9	8.52
IOLA 1 W	KS	37.92	-95.43	6hrs	1984	7	2	7.40
CLAY CENTER	KS	39.38	-97.12	6hrs	1998	9	20	7.00

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
OSAGE CITY	KS	38.63	-95.80	6hrs	2005	6	3	7.00
PHILLIPSBURG 13N	KS	39.74	-99.32	6hrs	2003	4	29	7.00
TUTTLE CREEK	KS	39.25	-96.60	6hrs	1972	9	6	6.52
DIAMOND SPRI	KS	38.55	-96.75	6hrs	1959	7	14	6.04
CENTERVILLE & MOUND CITY	KS	38.22	-95.01	6hrs	1998	6	24	6.00
IOLA 1 W	KS	37.92	-95.43	6hrs	1985	8	22	5.80
TROY 2	KS	39.78	-95.10	6hrs	1984	6	7	5.80
VICTORIA 5NE	KS	38.90	-99.10	6hrs	2004	5	11	5.50
LEWIS 3S	KS	38.17	-101.87	6hrs	2005	7	3	5.24
CALDWELL	KS	37.03	-97.62	6hrs	1969	9	15	5.20
ELK CITY DAM	KS	37.28	-95.80	6hrs	1984	5	27	5.20
CLINTON	KS	38.92	-95.40	6hrs	1988	6	29	5.10
POMONA LAKE	KS	38.65	-95.57	6hrs	1981	6	11	4.75
HARRIS	KS	38.32	-95.43	6hrs	1961	9	13	4.64
LAKIN	KS	37.97	-101.25	6hrs	2004	6	19	4.50
CHERRYVALE 5S	KS	37.27	-95.55	6hrs	1998	10	4	4.47
RUMSEY LOCK	KY	37.53	-87.27	3-day	1980	10	3	17.00
DUNDEE	KY	37.55	-86.72	3-day	1997	3	1	13.44
DUNDEE	KY	37.55	-86.72	3-day	1949	3	10	12.05
EDMONTON	KY	37.00	-85.62	3-day	1948	11	29	11.67
MADISONVILLE	KY	37.32	-87.48	3-day	1964	3	10	11.53
WOLF CREEK D	KY	36.88	-85.13	3-day	1949	7	11	11.44
DUNMOR	KY	37.08	-87.00	3-day	1960	6	28	11.25
MADISONVILLE	KY	37.32	-87.48	1-day	1997	3	2	10.25
GREENVILLE 2	KY	37.20	-87.20	1-day	1935	6	21	10.10
JAMESTOWN 8	KY	36.87	-85.12	1-day	1994	1	17	10.00
SCOTTSVILLE	KY	36.75	-86.20	1-day	1969	6	23	9.68
MADISONVILLE	KY	37.22	-87.42	1-day	1998	7	11	9.50
EDMONTON	KY	37.00	-85.62	1-day	1911	4	30	9.05
ST. MARY	KY	37.92	-85.35	6hrs	1950	6	14	6.18
TOMPKINSVILLE	KY	36.70	-85.68	6hrs	1949	6	15	4.98
LOUISVILLE WB CITY	KY	38.25	-85.77	6hrs	1896	7	4	4.66
UNIONTOWN DAM 49	KY	37.77	-87.95	6hrs	1943	3	19	4.60
BIG RAPIDS	MI	43.70	-85.48	3-day	1986	9	9	13.42
IRONWOOD	MI	46.45	-90.18	3-day	1909	7	21	13.20
COOPER	MI	42.38	-85.61	6hrs	1914	8	31	12.60
CHATHAM EXPE	MI	46.35	-86.93	3-day	1901	4	29	11.75
BLOOMINGDALE	MI	42.38	-85.95	1-day	1914	9	1	9.78
BURLINGTON	MI	42.10	-85.03	1-day	1978	6	26	8.62
HART	MI	43.70	-86.37	1-day	1905	6	6	8.50
KENT CITY 2	MI	43.20	-85.77	1-day	1986	9	11	8.03
HOLLAND	MI	42.78	-86.12	1-day	1982	7	17	7.99
HOKAH	MN	43.812	-91.363	1-day	2007	8	19	18.93
FOREST CITY	MN	45.21	-94.47	6hrs	1983	6	21	17.00
ISLE 12 N	MN	46.33	-93.52	3-day	1972	7	21	13.70
SHERBURN 3 N	MN	43.68	-94.70	3-day	1948	9	21	12.36
GARRISON 4 N	MN	46.33	-93.77	3-day	1995	3	27	12.00
CAMP NORRIS	MN	48.61	-95.18	3-day	2002	6	9	11.95
BEAULIEU[b]	MN	47.30	-95.90	1-day	1909	7	18	11.50
RED LAKE IND	MN	47.87	-95.03	3-day	1980	6	6	11.20
PIGEON RIVER	MN	48.00	-89.70	3-day	1948	12	7	11.17
FORT RIPLEY	MN	46.17	-94.35	1-day	1972	7	22	10.84
MINNEAPOLIS	MN	44.88	-93.22	6hrs	1987	7	23	10.55
CARIBOU 2 S	MN	48.97	-96.43	1-day	1941	3	26	10.50
ROCHESTER 10SW	MN	44.02	-92.47	6hrs	1981	7	11	10.00
MILAN	MN	45.12	-95.93	1-day	1995	7	4	9.78
BRICELYN	MN	43.57	-93.82	1-day	2004	9	14	9.22

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
BLUE EARTH	MN	43.65	-94.10	1-day	1996	1	25	9.20
GRAND PORTAG	MN	47.97	-89.68	1-day	1897	3	7	9.20
FOSSTON POWER	MN	47.57	-95.73	1-day	1909	7	19	8.97
ST PETER 2 S	MN	44.32	-93.97	1-day	1968	8	7	8.62
EDGERTON	MN	43.87	-96.13	6hrs	1997	6	27	8.00
READING	MN	43.70	-95.71	6hrs	2001	5	20	8.00
LIME TOWNSHIP	MN	44.20	-93.95	6hrs	2004	6	8	7.05
ADRIAN	MN	43.63	-95.93	6hrs	1993	7	10	7.00
LAKEFIELD	MN	43.67	-95.17	6hrs	1969	6	28	6.40
WATSON	MN	45.00	-95.80	6hrs	1992	6	16	5.70
BUCKMAN	MN	45.90	-94.09	6hrs	2005	8	16	5.60
SLAYTON	MN	43.99	-95.76	6hrs	1996	6	17	5.00
MALDEN 3 N	MO	36.60	-89.97	3-day	1970	3	3	22.10
EDGERTON	MO	39.50	-94.62	1-day	1965	7	18	20.02
COLE CAMP	MO	38.46	-93.20	3-day	1946	8	12	19.40
MALDEN 3 N	MO	36.60	-89.97	3-day	1970	3	17	17.00
FREEDOM	MO	38.47	-91.70	3-day	1993	8	10	14.70
NEVADA	MO	37.83	-94.35	3-day	1994	4	11	14.40
UNION	MO	38.45	-91.01	6hrs	2000	5	7	13.40
SPICKARD 7 W	MO	40.25	-93.72	1-day	1958	1	21	13.20
SE QUADRANT	MO	38.60	-90.20	6hrs	1977	3	27	13.00
LEES SUMMIT	MO	38.95	-94.40	1-day	1982	8	12	12.30
GRANT CITY	MO	40.48	-94.42	1-day	1922	7	10	12.25
HOLT	MO	39.45	-94.34	6hrs	1947	6	22	12.00
PACIFIC 1 NN	MO	38.48	-90.73	1-day	1957	6	15	11.75
ELDON	MO	38.35	-92.58	1-day	1925	10	16	11.19
CAPE GIRARDEAU	MO	37.31	-89.52	6hrs	1973	5	26	10.00
FARMINGTON	MO	37.79	-90.41	6hrs	1969	6	30	8.50
RICHMOND 7 N	MO	39.38	-93.97	6hrs	1993	8	12	8.00
ROLLA UNIV	MO	37.96	-91.78	6hrs	1988	7	26	6.90
OSCEOLA 3 NE	MO	38.08	-93.65	6hrs	1975	8	25	6.19
ROLLA 3 W	MO	37.95	-91.83	6hrs	1958	6	10	5.80
SULLIVAN 3 SE	MO	38.21	-91.15	6hrs	1975	8	17	5.30
MOBERLY AIRP	MO	39.47	-92.42	6hrs	1973	4	20	5.10
SULLIVAN 3 E	MO	38.22	-91.10	6hrs	1970	8	9	5.02
ADVANCE	MO	37.10	-89.91	6hrs	2005	8	30	5.00
CLINTON	MO	38.37	-93.77	6hrs	1955	8	29	4.66
CLINTON	MO	38.37	-93.77	6hrs	1962	10	13	4.65
SPRINGBROOK	MT	47.25	-104.52	1-day	1921	6	17	14.60
CIRCLE	MT	47.42	-105.59	1-day	1921	6	20	11.50
ISMAY	MT	46.52	-104.78	3-day	1950	9	12	10.25
ENDERLIN	ND	46.62	-97.60	3-day	1975	6	29	11.80
SHARON	ND	47.60	-97.90	3-day	1946	8	26	10.82
LITCHVILLE	ND	46.65	-98.18	1-day	1975	6	29	10.28
LARIMORE	ND	47.90	-97.63	3-day	1957	9	1	10.19
MOHALL	ND	48.77	-101.52	1-day	1897	6	15	7.70
GRAFTON	ND	48.42	-97.42	1-day	1957	9	2	7.42
LARIMORE	ND	47.90	-97.63	1-day	2000	6	13	6.48
STANTON	NE	41.87	-97.05	6hrs	1944	6	10	17.30
DAVID CITY	NE	41.25	-97.13	3-day	1951	5	31	9.15
DESHLER 5N	NE	40.14	-97.72	6hrs	2003	6	22	15.00
OGALLALA	NE	41.12	-101.72	6hrs	2002	7	6	14.92
YORK	NE	40.87	-97.58	3-day	1950	7	9	13.22
BEATRICE	NE	40.27	-96.73	3-day	1979	11	22	13.20
PRAGUE	NE	41.358	-96.879	6hrs	1959	8	1	13.09
GRANT TOWNSHIP	NE	40.39	-99.85	6hrs	1940	6	3	13.00
GREELEY	NE	41.55	-98.53	6hrs	1896	6	4	12.30

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
PAWNEE CITY	NE	40.07	-96.08	3-day	1958	9	5	12.13
GREELEY	NE	41.55	-98.53	6hrs	1996	6	4	12.00
MCCOOL JUNCT	NE	40.75	-97.58	1-day	1950	7	9	12.00
NORTH BEND	NE	41.45	-96.77	1-day	1975	1	10	12.00
NEBRASKA CIT	NE	40.68	-95.83	3-day	1993	7	22	11.37
KENESAW 2.4W	NE	40.62	-98.66	6hrs	2005	5	12	11.33
BEATRICE	NE	40.27	-96.73	1-day	1911	7	23	11.05
WEEPING WATER	NE	40.92	-96.23	3-day	1965	6	3	11.00
ULYSSES	NE	41.07	-97.20	1-day	1961	12	11	11.00
PLATTSMOUTH	NE	41.02	-95.88	1-day	1898	7	6	10.69
AUBURN	NE	40.40	-95.85	3-day	1929	7	5	10.55
OMAHA WB ARP	NE	41.30	-95.90	3-day	1999	8	7	10.48
ALBION	NE	41.68	-98.00	1-day	1966	8	13	10.29
GREELEY	NE	41.55	-98.53	3-day	1966	8	12	10.06
LOUP CITY	NE	41.28	-98.97	1-day	1896	6	5	10.05
SCHUYLER	NE	41.43	-97.05	3-day	1959	7	31	9.77
GRAND ISLAND	NE	40.97	-98.32	3-day	1977	8	30	9.74
PAWNEE CITY	NE	40.07	-96.08	3-day	1965	6	29	9.69
OMAHA	NE	41.37	-96.02	3-day	1965	9	6	9.35
FIRTH	NE	40.53	-96.60	3-day	1950	5	6	9.31
BRUNING	NE	40.33	-97.57	3-day	1919	9	16	9.20
PLATTSMOUTH	NE	41.02	-95.88	3-day	1993	8	28	9.09
BROWNLEE	NE	42.28	-100.62	3-day	1977	3	10	9.05
SE YORK COUNTY	NE	42.90	-100.60	6hrs	1997	7	10	9.00
NEWCASTLE	NE	42.65	-96.87	1-day	1996	7	17	8.92
RAVENNA	NE	41.03	-98.92	3-day	1968	6	24	8.88
UEHLING	NE	41.73	-96.50	1-day	1999	8	6	8.72
WEST POINT	NE	41.83	-96.72	3-day	1891	6	24	8.65
GENOA[e]	NE	41.45	-97.93	1-day	1887	9	2	8.60
LINCOLN UNIV	NE	40.83	-96.73	3-day	1910	8	29	8.60
MALMO 1 E	NE	41.27	-96.70	6hrs	1963	6	24	7.07
BEAVER CITY 3N	NE	40.14	-99.83	6hrs	2001	9	14	6.00
WEEPING WATE	NE	40.88	-96.13	6hrs	1990	7	25	5.70
MALMO 1 E	NE	41.27	-96.70	6hrs	1959	8	2	5.07
ELM CREEK	NE	40.72	-99.37	6hrs	2002	8	24	5.00
ELM CREEK	NE	40.72	-99.37	6hrs	2003	5	24	5.00
HEARTWELL & KENESAW	NE	40.57	-98.79	6hrs	2000	7	6	5.00
PHELPS COUNTY	NE	40.50	-99.41	6hrs	2000	6	19	5.00
ALBION 7 WNW	NE	41.73	-98.15	6hrs	1966	8	12	4.78
LAKE MALOYA	NM	36.59	-104.22	1-day	1955	5	18	11.29
GRENVILLE	NM	36.60	-103.62	3-day	1941	9	21	10.42
PORTER	NM	35.22	-103.28	3-day	1930	10	9	9.91
CLAYTON WSO	NM	36.45	-103.15	3-day	1914	4	29	9.55
WARNER	OK	35.49	-95.31	3-day	1943	5	6	25.00
HALLETT	OK	36.20	-96.60	6hrs	1940	9	2	24.00
CHEYENNE	OK	35.61	-99.67	6hrs	1934	4	3	23.00
ENID	OK	36.40	-97.88	1-day	1973	10	11	20.00
ROSE	OK	36.20	-95.03	3-day	1964	6	14	16.54
SAPULPA 1W	OK	36.00	-96.13	3-day	1940	9	2	16.30
MEEKER	OK	35.50	-96.90	1-day	1908	10	19	16.23
KANSAS	OK	36.20	-94.80	3-day	1986	9	30	16.11
CHECOTAH	OK	35.47	-95.53	3-day	1960	7	23	15.73
PURCELL	OK	35.02	-97.35	3-day	1950	5	9	15.55
SEMINOLE	OK	35.27	-96.67	3-day	1945	4	13	14.93
MEEKER	OK	35.50	-96.90	3-day	1932	6	1	14.33
NORMAN	OK	35.23	-97.43	3-day	1908	10	22	14.31
PRAGUE	OK	35.48	-96.68	3-day	1983	10	18	14.19

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
MARAMEC	OK	36.25	-96.68	3-day	1959	10	2	13.77
HENNESSEY	OK	36.10	-97.90	3-day	1957	5	15	13.32
STIGLER	OK	35.27	-95.13	3-day	1943	5	10	13.16
WEBBERS FALL	OK	35.52	-95.12	3-day	1945	6	10	13.16
HELENA	OK	36.55	-98.27	3-day	1997	7	19	13.13
EUFAULA	OK	35.28	-95.58	1-day	1941	10	31	12.86
ARCADIA 2 W	OK	35.67	-97.37	3-day	1993	5	8	12.51
RALSTON	OK	36.50	-96.73	3-day	1943	5	17	12.48
BEGGS	OK	35.73	-96.07	3-day	1985	10	13	12.47
CHANDLER	OK	35.70	-96.88	3-day	1983	9	16	12.40
MAYFIELD	OK	35.33	-99.87	3-day	1949	1	12	12.33
CHECOTAH	OK	35.47	-95.53	3-day	1969	10	11	12.17
QUAPAW	OK	36.95	-94.78	3-day	1945	9	24	12.12
MAYFIELD	OK	35.33	-99.87	3-day	1949	1	25	12.01
SEMINOLE	OK	35.27	-96.67	1-day	1948	6	22	12.00
EUFAULA	OK	35.28	-95.58	1-day	1943	5	11	11.77
MC CURTAIN	OK	35.15	-94.95	3-day	1973	11	23	11.64
JAY	OK	36.43	-94.78	3-day	1972	10	30	11.43
GEARY	OK	35.63	-98.32	1-day	1948	6	23	11.25
PONCA CITY F	OK	36.73	-97.10	1-day	1979	11	20	11.11
GREAT SALT P	OK	36.75	-98.12	3-day	1995	8	1	11.09
QUINTON	OK	35.12	-95.37	3-day	1943	9	30	11.01
CLINTON	OK	35.52	-98.98	3-day	1955	10	2	10.85
LOOKEBA	OK	35.37	-98.37	3-day	1965	9	19	10.80
OKEMAH 2	OK	35.45	-96.30	1-day	1945	4	14	10.65
SHAWNEE	OK	35.32	-96.93	1-day	1983	10	20	10.62
BARNSDALL	OK	36.55	-96.17	1-day	1986	9	29	10.42
HASKELL	OK	35.82	-95.68	1-day	1985	10	14	10.33
WAUKOMIS	OK	36.28	-97.90	1-day	1957	5	16	10.23
OKLAHOMA CITY WBC	OK	35.48	-97.53	6hrs	1932	6	3	6.48
GUTHRIE	OK	35.80	-97.43	6hrs	1949	5	18	6.37
SHATTUCK	OK	36.27	-99.85	6hrs	1942	8	11	6.10
CLEVELAND	OK	36.32	-96.47	6hrs	1971	9	4	5.99
STILLWATER	OK	36.13	-97.07	6hrs	1959	10	2	5.65
PAWHUSKA	OK	36.67	-96.35	6hrs	1985	6	10	5.50
PRYOR	OK	36.30	-95.32	6hrs	1996	9	26	5.40
FORT GIBSON	OK	35.87	-95.23	6hrs	1981	10	13	5.20
ROLL	OK	35.80	-99.75	6hrs	1954	4	29	5.20
HULAH DAM	OK	36.92	-96.10	6hrs	1945	9	24	5.04
QUAPAW	OK	36.95	-94.78	6hrs	1943	5	17	5.04
OILTON	OK	36.08	-96.60	6hrs	1982	5	12	4.80
CLEAR LAKE	SD	44.75	-96.68	3-day	1992	6	15	11.53
PLATTE 6 EAST	SD	43.39	-98.84	6hrs	1998	8	19	9.50
DEADWOOD	SD	44.38	-103.72	3-day	1982	5	14	9.28
PARMELEE	SD	43.33	-101.03	3-day	1967	6	11	9.09
ANDOVER 7 N	SD	45.52	-97.88	1-day	1964	4	5	8.00
DEADWOOD	SD	44.38	-103.72	1-day	1994	10	8	8.00
ELK POINT	SD	42.68	-96.68	1-day	1900	9	10	8.00
VICTOR 3 NE	SD	45.92	-96.80	1-day	1941	6	21	7.94
PACTOLA RANG	SD	44.07	-103.50	1-day	1972	6	10	7.16
LAKE SHARPE	SD	44.07	-99.47	1-day	1999	8	30	7.14
WATERTOWN FA	SD	44.92	-97.15	1-day	1931	5	27	7.14
CUSTER	SD	43.77	-103.60	1-day	1920	4	17	7.10
FORT MEADE	SD	44.40	-103.47	1-day	1907	5	13	7.10
FLANDREAU 4	SD	44.02	-96.67	1-day	1957	6	16	7.09
HIGHMORE 25	SD	44.87	-99.45	1-day	1994	7	8	6.94
BLUNT	SD	44.52	-99.98	1-day	1953	8	2	6.89

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
ORIENT	SD	44.88	-99.08	1-day	1994	7	7	6.80
EUREKA	SD	45.77	-99.62	1-day	1964	6	18	6.73
FAULKTON 6 S	SD	45.03	-99.10	1-day	1994	7	7	6.70
MILESVILLE	SD	44.45	-101.65	1-day	1987	7	18	6.49
SPEARFISH AI	SD	44.48	-103.78	1-day	1922	5	11	6.49
SPEARFISH AI	SD	44.48	-103.78	1-day	1976	6	15	6.46
MISSION HILL	SD	42.92	-97.28	6hrs	1995	5	27	6.00
PIERRE & FORT PIERRE	SD	44.35	-100.37	6hrs	1994	7	6	6.00
MCCOOK COUNTY	SD	43.70	-97.20	6hrs	1993	7	3	5.00
BIG SANDY	TN	36.24	-88.09	3-day	2001	11	27	15.19
SAVANNAH	TN	35.25	-88.27	3-day	1991	5	25	13.47
BOLIVAR 2 NE	TN	35.27	-88.95	3-day	1935	1	19	12.70
MASON	TN	35.40	-89.53	3-day	1987	12	26	12.60
WINCHESTER 2	TN	35.18	-86.15	3-day	1990	12	21	12.28
LAWRENCEBURG	TN	35.27	-87.32	3-day	1998	7	12	12.26
MONTEREY	TN	36.15	-85.27	3-day	1992	1	2	12.10
SODDY DAISY	TN	35.35	-85.18	1-day	2004	9	17	11.00
SAVANNAH	TN	35.25	-88.27	1-day	2002	9	27	10.40
HUMBOLDT	TN	35.82	-88.93	6hrs	1982	7	5	9.60
BIG SANDY	TN	36.24	-88.09	1-day	2002	9	27	9.50
MARTIN UNIV	TN	36.32	-88.85	1-day	1975	7	20	9.20
BOLTON	TN	35.32	-89.77	1-day	1987	12	25	9.00
LEWISBURG EX	TN	35.45	-86.80	1-day	1902	3	28	9.00
LEWIS CHAPEL	TN	35.33	-85.30	1-day	1954	8	9	8.87
SUGAR HILL	TN	35.55	-87.82	6hrs	1944	8	26	8.16
MEMPHIS WB CITY	TN	35.15	-90.05	6hrs	1934	11	21	7.03
LEWISBURG EXP STN	TN	35.41	-86.81	6hrs	1989	7	11	6.40
SAMBURG WILDLIFE REF	TN	36.45	-89.30	6hrs	1972	7	16	5.70
MEMPHIS WB CITY	TN	35.15	-90.05	6hrs	1919	3	16	5.43
MEMPHIS WB CITY	TN	35.15	-90.05	6hrs	1935	10	22	5.41
BROWNSVILLE	TN	35.63	-89.22	6hrs	1945	11	2	5.40
LEBANON 3 W	TN	36.23	-86.32	6hrs	1979	9	13	5.30
MONTEREY 1 E	TN	36.15	-85.26	6hrs	1969	6	23	5.18
LEXINGTON	TN	35.68	-88.38	6hrs	2002	9	26	5.10
PORTLAND	TN	36.58	-86.50	6hrs	1944	10	5	5.08
VICTORY	TN	35.08	-87.82	6hrs	1970	9	5	5.01
MEMPHIS WB CITY	TN	35.15	-90.05	6hrs	1929	7	16	5.00
DYERSBURG	TN	36.05	-89.37	6hrs	1985	7	5	4.90
HUMBOLDT	TN	35.83	-88.92	6hrs	1984	10	2	4.80
MURFREESBORO	TN	35.85	-86.40	6hrs	1944	8	31	4.58
CHANNING	TX	35.68	-102.33	3-day	1941	7	26	11.76
CLAUDE	TX	35.12	-101.37	3-day	1951	5	16	10.86
SHAMROCK RAD	TX	35.23	-100.25	3-day	1995	6	3	10.51
CLAUDE	TX	35.12	-101.37	1-day	1982	5	27	10.27
CANADIAN 15	TX	35.71	-100.42	3-day	2005	6	11	9.22
MC LEAN	TX	35.23	-100.60	3-day	1997	4	3	9.20
BOOKER MOUNS	TX	36.47	-100.50	3-day	1997	6	9	8.10
HAYWARD	WI	46.01	-91.48	3-day	1941	8	28	15.00
PORT WASHING	WI	43.38	-87.87	3-day	1996	6	16	13.52
LAKE MILLS	WI	43.08	-88.92	3-day	1996	1	26	13.12
STEUBEN 1 NW	WI	43.18	-90.88	3-day	1949	7	15	12.35
MELLEN POWER	WI	46.35	-90.62	3-day	1946	6	23	12.33
BARABOO	WI	43.47	-89.74	6hrs	1993	7	17	12.00
WINTER P K R	WI	45.88	-91.07	3-day	1941	8	29	11.84
SHEBOYGAN	WI	43.75	-87.72	3-day	1998	8	5	11.75
LAND O LAKES	WI	46.17	-89.22	3-day	1942	3	15	11.66
WATERTOWN	WI	43.20	-88.72	3-day	1929	1	21	11.33

Table 4.1 Long list of storms. Maximum rainfall values shown are point values. The list is sorted by state, then precipitation amount. (Continued)

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
MERRILL	WI	45.18	-89.68	3-day	1912	7	22	11.25
MEDFORD	WI	45.13	-90.33	3-day	1905	6	4	11.20
MERRILL	WI	45.18	-89.68	3-day	1957	11	15	11.03
MONROE	WI	42.60	-89.65	1-day	1996	7	18	10.10
MIKANA	WI	45.59	-91.60	6hrs	2005	10	4	9.80
HANCOCK EXP	WI	44.12	-89.52	1-day	2002	6	22	9.43
TOMAH	WI	43.98	-90.50	6hrs	1990	8	17	9.17
MEDFORD	WI	45.14	-90.34	6hrs	1906	6	3	7.20
FENNIMORE 1 NE	WI	43.00	-90.65	6hrs	1950	7	15	7.16
MILWAUKEE	WI	43.04	-87.91	6hrs	1987	8	6	6.24
FRIENDSHIP	WI	43.97	-89.82	6hrs	2005	7	25	6.00
SAVAGETON	WY	43.75	-105.83	1-day	1923	9	27	16.90
CHEYENNE WB	WY	41.15	-104.82	1-day	1985	8	1	6.06
PINE BLUFFS	WY	41.18	-104.07	6hrs	1983	7	22	4.90

4.4.1 New Storm Analysis Evaluation Procedures

A major task for the Nebraska statewide PMP study was to identify potential storm events that have not been previously analyzed in HMR 51 or the EPRI study. AWA evaluated the most significant of these events to determine which needed to be fully analyzed as part of the PMP development for the Lake Wanahoo site-specific PMP study.

This was accomplished by sorting the data contained on the initial long list of storms, including 6-hour, 24-hour or 1-observation day, and 3-day storm totals to determine potential storms that were sufficiently large to be candidates, based on the possibility that they could be the largest at some area size and/or duration after maximization and transpositioning. The first step in this process was to identify maximum storm totals which exceeded 10 inches and recent storms that caused widespread damage. The list of potential storms was then further analyzed using several criteria, including the following:

1. Date of storm occurrence (storms that have occurred since 1993 and therefore could potentially be analyzed with a NEXRAD basemap)

2. Major storms that occurred near Nebraska that were not previously analyzed in PMP studies including those that have produced the floods of record around the basin

3. Location of storm center (preference given to storms that occurred in NE, CO, KS, SD, IA, OK)

4. Amount of maximum precipitation with extra emphasis given to durations shorter than 24 hours

5. DA Estimator[1] results and area size comparisons to published DADs relevant to the region.

[1] A description of how the DA estimator was developed, its uses, and potential limitations can be found Appendix H "Depth-Area (DA) Estimator Program Development and Description"

6. Other storm information from secondary sources, such as first hand reports, newspaper accounts, Internet searches, scholarly articles, and climate center discussions

The DA Estimator program was run on candidate storms to assist in determining which events should be considered for the final short list. These storms would then undergo full storm analyses. From this process, each storm's specific characteristics were delineated, allowing AWA to estimate each storm's significance at various area sizes and their potential relevance to Nebraska. This step allowed the initial list to be cut down to 9 new storms that were never before analyzed and 2 storms in need of reanalysis. Figure 4.7 shows the locations of these events.

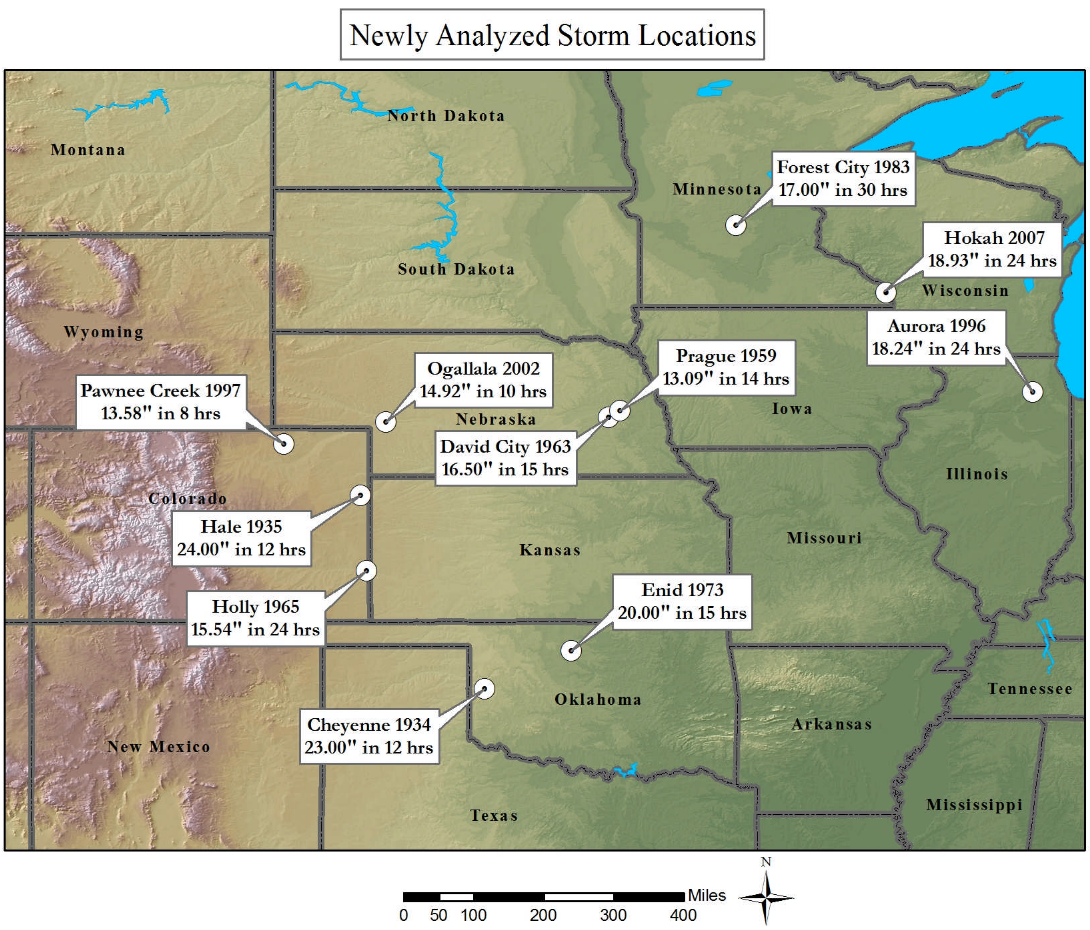

Figure 4.7 Newly analyzed or reanalyzed storms

Further evaluation of these storms was conducted by comparing results to the previously analyzed MCS type events from HMR 51 and the EPRI studies. The DA Estimator was run on these previously-analyzed storms to provide a graphical comparison. From this analysis, it became clear which of these storms was significant enough to have of a full storm analysis and DAD development.

Eleven storms were considered to be significant enough to be analyzed or re-analyzed using SPAS, either as part of the Lake Wanahoo PMP study or the Nebraska statewide PMP study.

4.5 Short List Evaluation Methodology

All storms included on the short storm list for the Wanahoo site-specific PMP study were included as part of the Nebraska statewide PMP study. In addition to these storms, several were added that were not on the Wanahoo short storm list due to elevation differences that limited their transposition limits to the higher elevations of Nebraska. This included Springbrook, MT in 1921, Savageton, WY in 1923, Hale, CO in 1935, Holly, CO in 1965, Pawnee Creek, CO in 1997, and Ogallala, NE in 2002. In addition to these storms being added to the list, the Hokah, MN in 2007 storm was included.

4.5.1 Short List Evaluation Methodology Used in the Wanahoo Study

This section describes the processes used to determine the short list of storms during the Wanahoo site-specific PMP study. These processes are directly relevant to the Nebraska statewide PMP study and in addition to the storms listed in the previous paragraph, details how the short list of storms used to determine the PMP values were evaluated at each of the grid points.

The largest 20% of the long list of storms at each of the three durations (6 hours-MCS, 24-hour-Hybrid, and 3 day-Synoptic) was initially evaluated using the AWA Depth Area Estimator (DA estimator) program. This produced DA estimator results for 95 storms. Figure 4.6 shows an example of results from this process.

The DA estimator was also run against the top 20% of storms that occurred within the state of Nebraska that were not included in the initial run against the top 20% of storms on the entire long list. As such, 35 additional DA estimator results were examined from storms on the long storm list. Identification and analysis of storms in this manner was considered adequate to identify all relevant storms for the determination of the PMP for Nebraska.

In conjunction with DA estimator results, all storms on the long storm list were sorted to delineate those that have been previously analyzed as part of HMR 51 and/or the EPRI Michigan Wisconsin study. All of the HMR 51/EPRI storms that were considered transpositionable to Nebraska were placed on the initial short storm list. Next, all storms were sorted according to their appropriate duration (6-hour, 24-hours or 1-observation day and 3-day). Significant storms that occurred but did not meet the above criteria were then analyzed and evaluated to determine whether inclusion on the initial short storm list was appropriate.

Further evaluation to eliminate non-significant storms for PMP development was accomplished by sorting each duration by state and maximum precipitation. This provided a way to eliminate storms that were smaller than other storms in the same climatic region.

All storms that made the initial short storm list were then analyzed to determine their 100-square mile, 500-square mile, and 1000-square mile depth-area value at the most appropriate duration. This allowed another objective way to evaluate the significance of each of these storms in the final determination of the PMP. Several storms were eliminated from the initial short storm list at this step based on their depth-area values in relation to other storms in similar climatic regions and of similar durations. After this analysis, 48 storms were left on the list.

A final analysis of the remaining storms was completed by AWA in which each storm (not previously analyzed but possibly significant for PMP development) was closely scrutinized against other storms on the list at similar durations and/or locations. From this analysis, 12 more storms were eliminated. This produced the final short storm list with 36 storms; 18 at the 6-hour duration, 9 at the 24-hour duration, and 9 at the 3-day duration. Table 4.2 gives the relevant details of these storms and Figure 4.8 shows the locations of each storm.

Table 4.2 Short storm list for Nebraska sorted alphabetically

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip
AURORA COLLEGE	IL	41.75	-88.3333	1-day	1996	7	17	18.24
BEAULIEU	MN	47.3	-95.9	6hrs	1909	7	18	11.50
BONAPARTE	IA	40.7667	-91.75	6hrs	1905	6	10	12.10
BOYDEN	IA	43.19	-96.01	6hrs	1926	9	17	24.00
CHEYENNE	OK	35.61	-99.67	6hrs	1934	4	3	23.00
COLE CAMP	MO	38.46	-93.2027	3-day	1946	8	12	19.40
COLLINSVILLE	IL	38.6717	-90.5392	3-day	1946	8	12	18.70
COOPER	MI	42.376	-85.610	6hrs	1914	8	31	12.60
COUNCIL GROVE	KS	38.400	-96.300	3-day	1951	7	9	18.50
DAVID CITY	NE	41.228	-97.109	6hrs	1963	6	24	16.50
EDGERTON	MO	39.5	-94.6167	1-day	1965	7	18	20.02
ENID	OK	36.4	-97.8833	1-day	1973	10	10	20.00
FOREST CITY	MN	45.206	-94.466	6hrs	1983	6	20	17.00
GRANT TOWNSHIP	NE	40.390	-99.850	6hrs	1940	6	3	13.00
GREELEY	NE	41.55	-98.5333	6hrs	1896	6	4	12.30
HALE	CO	39.609	-102.246	6hrs	1935	5	30	18.00
HALLETT	OK	36.2	-96.6	6hrs	1940	9	2	24.00
HAYWARD	WI	46.013	-91.485	1-day	1941	8	28	15.00
HOKAH	MN	43.812	-91.363	1-day	2007	8	19	18.93
HOLLY	CO	38.05	-102.117	3-day	1965	6	16	15.54
IDA GROVE	IA	42.3167	-95.4667	1-day	1962	8	30	12.85
IRONWOOD	MI	46.45	-90.1833	3-day	1909	7	21	13.20
LAMBERT	MN	44.230	-95.260	3-day	1897	7	18	8.00
MEDFORD	WI	45.1333	-90.3333	3-day	1905	6	4	11.20
MEEKER	OK	35.503	-96.903	1-day	1908	10	19	16.23
MINNEAPOLIS	MN	44.8833	-93.2167	6hrs	1987	7	23	10.55
OGALLALA	NE	41.125	-101.717	6hrs	2002	7	6	14.92
PARIS WATERWORKS	IN	39.05	-87.7	6hrs	1957	6	27	13.19
PAWNEE CREEK	CO	40.67	-103.83	1-day	1997	7	28	13.70
PRAGUE	NE	41.358	-96.879	6hrs	1959	8	1	13.09
RITTER	IA	43.244	-95.823	6hrs	1953	6	7	11.00
SAVAGETON	WY	43.88	-105.93	1-day	1923	9	27	17.10
SPRINGBROOK	MT	47.25	-104.52	1-day	1921	6	17	14.60
STANTON	NE	41.867	-97.05	6hrs	1944	6	10	17.30
TOMAH	WI	43.98	-90.5	6hrs	1990	8	17	9.17
WARNER	OK	35.49	-95.31	3-day	1943	5	6	25.00

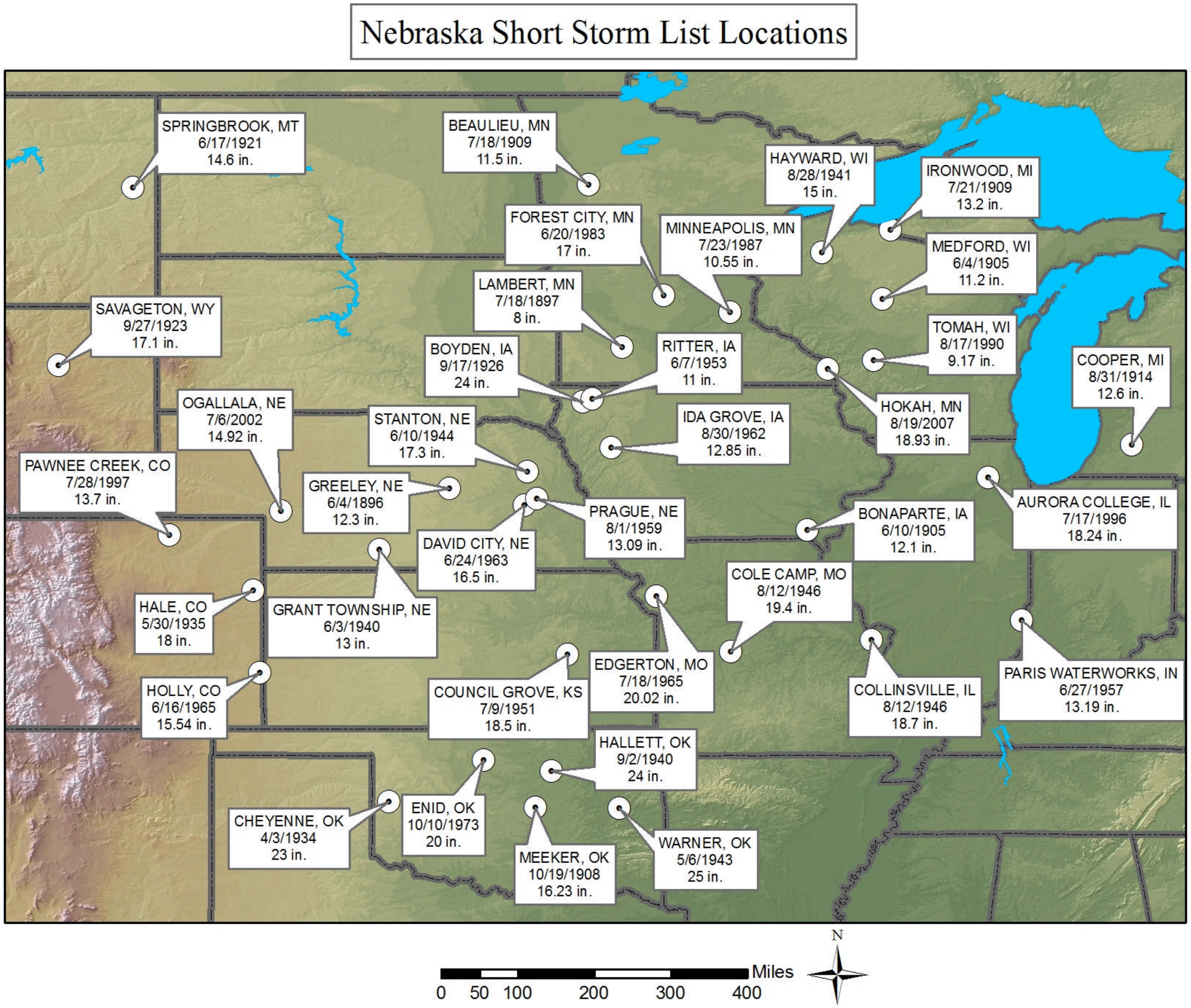

Figure 4.8 Nebraska short storm list locations

4.6 Use of Published Depth-Area-Duration Analyses

Published Depth-Area-Duration (DAD) analysis results were used for all storms when they were available. For events not previously analyzed, as well as the HMR 51 storm that were re-analyzed (Hale 1935), DAD, storm isohyetal pattern, and mass curves were produced and used in the storm spreadsheets calculations. Storm analysis results are provided in Appendix F.

5 Storm Depth-Area-Duration (DAD) Analyses for New Storms

For newly identified extreme rainfall events without published depth-area-duration (DAD) analyses, DADs needed to be computed. The Storm Precipitation Analysis System (SPAS) was used to compute DADs for these storms.

There are two main steps in a DAD analysis: 1) Creation of high-resolution hourly precipitation grids and 2) computation of depth-area rainfall amounts for various durations. Reliability of results from step 2) depends on the accuracy of step 1). Historically the process has been very labor intensive. SPAS utilizes Geographic Information Systems (GIS) concepts to create more spatially-oriented and accurate results in a more efficient manner (step 1). Furthermore, the availability of NEXRAD (NEXt Generation RADar) data allows SPAS to better account for the spatial and temporal variability of storm precipitation for events occurring since the early 1990s. Prior to NEXRAD, the National Weather Service (NWS) developed and used a method based on the research of several scientists (Corps of Engineers 1954-1973). Because this process has been the standard for many years and holds merit, the DAD analysis process developed for this study attempts to mimic it as much as possible. See Appendix H for a full description of SPAS. By adopting this approach, some level of consistency between the newly analyzed storms and the hundreds of storms already analyzed can be achieved. Comparisons between the NWS DAD results and those computed using the new method for two storms (Westfield, MA 1955 and Ritter, IA 1953) indicated very similar results.

5.1 Data Collection

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

The daily database is comprised of data from National Climatic Data Center (NCDC) TD-3206 (pre 1948) and TD-3200 (generally 1948 through present). The hourly database is comprised of data from NCDC TD-3240. The daily supplemental database is largely comprised of data from "bucket surveys," local rain gauge networks (e.g. ALERT, USGS, etc.) and daily gauges with accumulated data.

5.2 Mass Curves

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

5.3 Hourly or Sub-hourly Precipitation Maps

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

5.3.1 NEXRAD mode

Radar has been in use by meteorologists since the 1960s to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the equation (1) below:

(1) $Z = aR^b$

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

The National Weather Service (NWS) uses this relationship to estimate rainfall through use of their network of Doppler radars (NEXRAD) located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ is the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and DND, and differing air mass characteristics across the United States (Dickens 2003). The DSD and DND are determined by a complex interaction of microphysical processes in a cloud. They fluctuate hourly, daily, seasonally, regionally, and even within the same cloud. Other factors that affect radar rainfall computations include occultation or blockage of the radar beam due to terrain features and range effects that are the result of the radar beam passing through the cloud at elevations too high in the cloud to observe the main precipitation portion of the cloud.

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

Issues are sometimes encountered in the radar-rainfall calculation process that can contribute to a less than perfect correlation between radar rainfall depth calculations and rainfall depth observations at the rainfall observation sites. These issues include the following:

1. Area average radar-rainfall depth estimates vs. observed point rainfall depths: A rain gauge observation represents a much smaller area than the area sampled by the radar. The area that the radar is sampling is approximately 1 km^2. Radar data provide the average reflectivity (Z) within the area being sampled. This average reflectivity is used to convert Z to Rcalc for the sample area. This radar-derived rainfall value is compared to a point rainfall depth measured by a rain gauge located within the radar sample area. This area vs point issue contributes to correlations greater than or less than 1.0 within the project area.

2. Rain gauge catch: Precipitation gauges, shielded and unshielded, inherently underestimate total precipitation due to local airflow, wind undercatch, wetting, and evaporation. The wind undercatch errors are usually around 5% but can be as large as 40% in high winds (Mather 1974). In addition, tipping buckets miss a small amount of rainfall during each tip of the bucket due to the bucket travel and tip time. As rainfall intensities increase, the volumetric loss of rainfall due to tipping tends to increase. At rainfall intensities greater than 152 mm per hour, 1 mm tipping buckets will under report rainfall in the range of 0-5% depending on how the gauge was calibrated (Duchon 2001). Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies.

3. Radar Calibration: NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a problem with the calibration and precipitation estimates could be significantly in error. The calibration test is supposed to maintain a reflectivity precision of 1 dBZ. A 1 dBZ error results in an error of 17% in Rcalc, using the default Z-R relationship $Z=300^{1.4}$. Higher calibration errors will result in higher Rcalc errors. However, by performing correlations each hour, the calibration issue is minimized.

4. Attenuation: Attenuation is the reduction in power of the radar beams energy as it travels from the antenna to the target and back and is caused by the absorption and the scattering of power from the beam by precipitation. Attenuation can result in errors in Z as large as 1 dBZ especially when the radar beam is sampling a large area of heavy precipitation.

5. Range effects: Earth’s curvature and standard refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar beam not sampling the main precipitation portion of the cloud. A correction scheme is used for this issue.

6. Radar Beam Occultation/Ground Clutter: Radar occultation (beam blockage) results when the radar beam’s energy intersects terrain features. The result is an increase in radar reflectivity values that can result in higher then normal rainfall estimates.

7. Use of the standard hail cap employed by the NWS of 54 dBZ, where all dBZ values above 54 are calculated as a rain rate of 54 dBZ.

5.3.2 SPAS mode-non NEXRAD

The standard SPAS mode requires a full listing of all the actual hourly precipitation values, as well as the newly created estimated hourly data from daily and daily supplemental stations (pseudo stations are not included). This is done by creating an hourly file that contains the newly created hourly mass curve precipitation data (from the daily and supplemental stations) and the “true” hourly mass curve precipitation (not percent). The option of incorporating base maps was not used in this study. If not using a base map, the individual hourly precipitation values are simply plotted and interpolated to a raster with an IDW interpolation routine in a GIS. For the Nebraska study, no base maps were used.

5.4 Depth-Area-Duration (DAD) Program

The DAD extension of SPAS runs from within a GRASS 6.2 GIS environment and utilizes many of the built-in functions for calculation of area sizes and average depths. The following is the general outline of the procedure:

1. Given a duration (e.g. x-hours) and cumulative precipitation, sum up the appropriate hourly or sub-hourly precipitation grids to obtain an x-hour total precipitation grid starting with the first x-hour moving window.

2. Determine x-hour precipitation total and its associated areal coverage. Store these values. Repeat for various lower rainfall thresholds. Store the average rainfall depths and area sizes. Determine if the x-hour window includes the last hour of the CPP, if it does not, move the x-hour window forward one hour and return to step 1.

3. The result is a table of depth of precipitation and associated area sizes for each x-hour window location. Summarize results by moving through each of the area sizes and choosing the maximum precipitation amount. A log-linear plot of these values provides the depth-area curve for the x-hour duration.

4. Based on the log-linear plot of the rainfall depth-area curve for the x-hour duration, determine rainfall amounts for the standard area sizes for the final DAD table. Store these values as the rainfall amounts for the standard sizes for the x-duration period. Determine if the x-hour duration period is the longest duration period being analyzed, if it is not, analyze the next longest duration period and return to step 1.

5. Construct the final DAD table with the stored rainfall values for each standard area for each duration period.

5.5 New Storms Analyzed

Storm analysis results using SPAS were produced for nine new storms for the Wanahoo and statewide studies. These included Prague, NE, August, 1959; David City, NE, 1963; Enid, OK, 1973; Forest City, MN, 1983; Aurora College, IL, 1996; Pawnee Creek, CO, 1997; Ogallala, NE, 2002; and Hokah, MN, 2007. A complete description of each of the new storms analyzed, along with the DAD, mass curve, and total storm precipitation map, are included in Appendix F.

6 New Return Frequency Dew Point Climatology

As part of the Wanahoo site-specific and Nebraska statewide PMP studies, a new dew point climatology was developed which produced 20-year, 50-year, and 100-year return frequency values at durations of 6-hours, 12-hours, and 24-hours. For the Nebraska statewide PMP study the same procedure of using the 100-year value for the appropriate duration for each storm analyzed on the short storm list was continued. The process used to develop the new climatology is discussed below and details are provided in Appendix C.

6.1 Dew Point Temperature Interpolation Methodology

An updated dew point climatology was developed for use in determining PMP values as part of the storm maximization process. Sophisticated interpolation procedures were applied to dew point data to smooth the isodrosotherms. This procedure was coded into a script file and run in a GRASS GIS environment. The complete set of the updated dew point climatology maps used for storm maximization in this study are provided in Appendix C.

Construction of the dew point climatology began with a search of NCDC hourly datasets for the 6-hour, 12-hour, and 24-hour maximum dew point temperatures for each reporting station within the pre-defined search box (49.0/-108.0, 49.0/-85.0, 32.5/-108.0, and 32.5/-85.0). A total of 77 hourly stations met the 30 year or greater data requirement as applied by AWA. This ensured a sufficient period of record to create reasonably reliable statistics for the return frequency analysis of dew point temperature (Figure 6.1). A program was written to extract and quality control (QC) the stations' monthly maximum average dew point temperatures for each duration (6-hour, 12-hour, and 24-hour) for each year, known as the annual maximum series (AMS). The AMS for each month, at each station, served as input to an Excel spreadsheet that calculated L-moment statistics. Using the generalized-extreme-value (GEV) distribution, the 20-yr, 50-yr, and 100-yr dew point temperature values were computed for each duration for each month for each station.

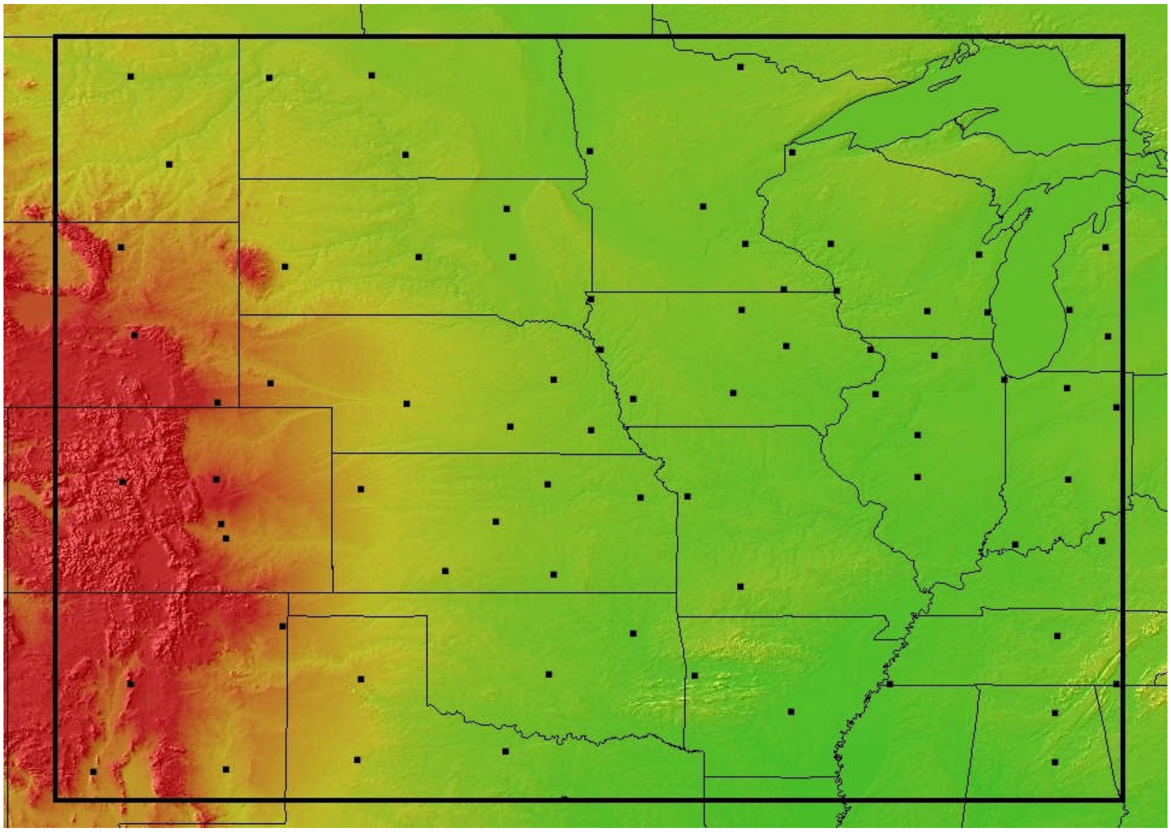

Figure 6.1 Hourly dew point temperature station locations used for this analysis.

6.2 Dew Point Adjustments to Mid-Month and to 1000mb

Once the dew point station data were gathered and organized, the next step reduced all data to a standard level for comparison and analysis purposes. This was done following the accepted methodology of reducing the dew point data moist pseudo-adiabatically to a standard level - in this case 1000mb. Furthermore, dew point data were adjusted to the 15th of each month so the dew point climatology maps represented the mid-month values (see Appendix C for a step-by-step example of how this was completed). The June 24-hour dew point data for Omaha, NE are shown in Table 6.1. The table shows the original station data, the data adjusted to the 15th, and the data adjusted to 1,000 mb.

Table 6.1 Original station dew point data (°F), the adjusted 15th data, and the 1000 mb data for the 20-yr, 50-yr, and 100-yr frequencies.

	20-year	50-year	100-year
Station Data	73.76	74.89	75.60
15th Data	72.95	74.11	74.83
1000 mb Data	76.02	77.18	77.90

7 Use of Grid Points to Spatially Distribute Rainfall Values

To appropriately distribute rainfall values spatially and temporally across the state of Nebraska, a series of grid points were used. The grid consisted of 23 points and was extended across state boundaries into bordering regions (Figure 7.1). The spacing of the grid points was two degrees longitude and one and a half degrees latitude. These grid point locations provided approximately 100 miles between grid points.

All appropriate storm rainfall values for each of the 23 grid points were maximized and transpositioned to the grid point locations (see Section 8 for details). Depth-Area (DA) curves for each duration (6-hours to 72-hours) were created at each grid point. Using results from the DA analyses, Depth-Duration (DD) curves were constructed for each grid point (see Section 9 for details). Results from the DD analysis were input into GIS where the values for each duration and area size at each grid point were spatially analyzed. The final PMP maps derived using the grid point methodologies are given in Appendix A.

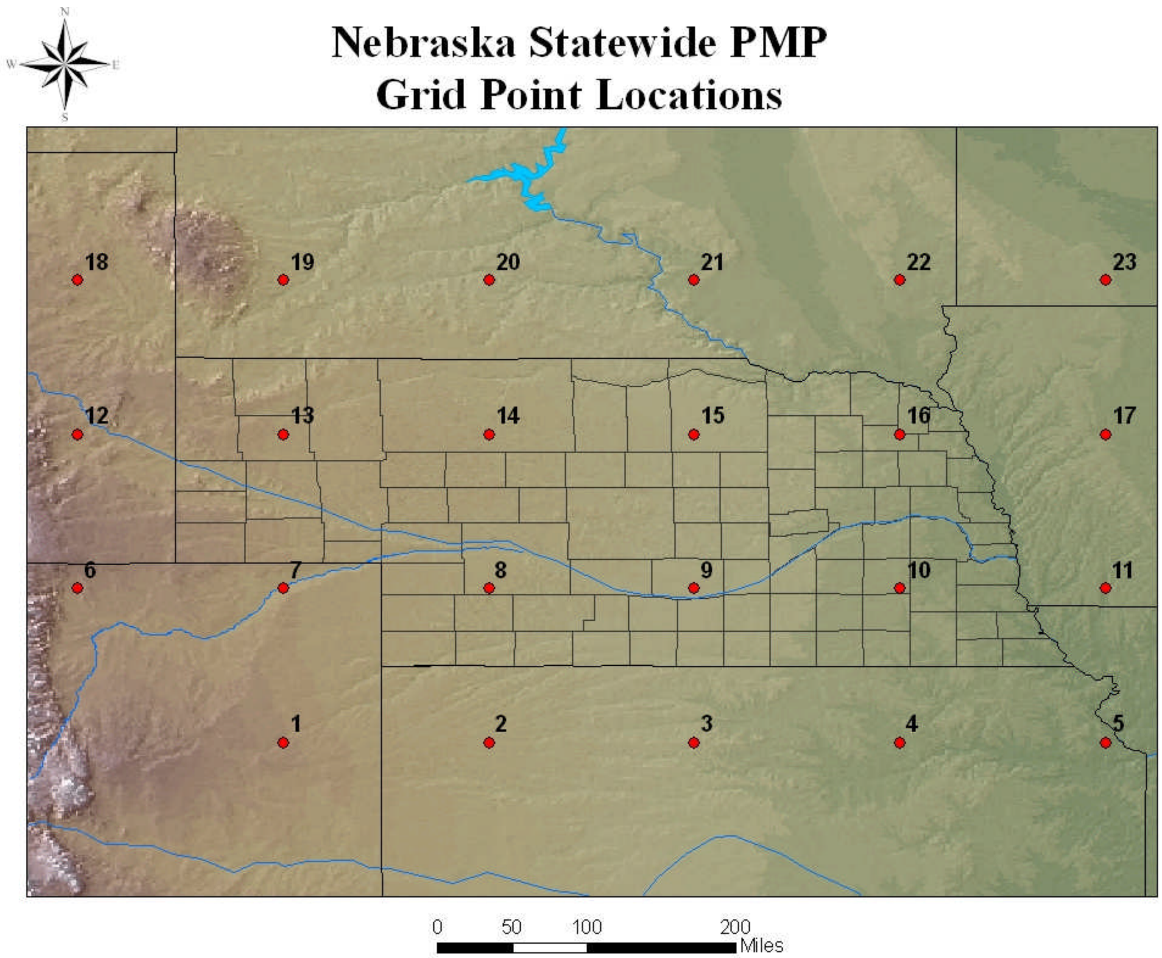

Figure 7.1 Grid point locations used to spatially distribute (or transposition) rainfall values over the region surrounding Nebraska

8 Storm Maximization and Transpositioning

8.1 Storm Maximization

Storm maximization is the process of increasing rainfall associated with an observed extreme storm under the potential condition that additional atmospheric moisture could have been available to the storm for rainfall production. Maximization is accomplished by increasing surface dew points to some climatological maximum and calculating the enhanced rainfall amounts that could potentially be produced. The 1.50 limitation on in-place storm maximization as detailed in HMRs 51 and 55A was followed in the report and is noted in several of the storm spreadsheets where this limitation was applied in Appendix F. An additional consideration is usually applied that selects the climatological maximum dew point for a date 15 days towards the warm season from the date that the storm actually occurred. This procedure assumes that the storm could have occurred with the same storm dynamics 15 days earlier or later in the year when maximum dew points could be higher.

8.1.1 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 dew point values from the *Climatic Atlas of the United States* (1968) were the source for maximum dew point values. HMR 55A published in 1988 updated maximum dew point values for a portion of United States from the Continental Divide eastward into the central plains (Hansen 1988). A regional PMP study for Michigan and Wisconsin produced return frequency maps using the L-moments method (Tomlinson 1993). The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year return frequency values were appropriate for use in PMP calculations. HMR 57 was published in 1994 and HMR 59 in 1999. These more recent NWS publications also updated the maximum dew point climatology, but used maximum observed dew points instead of return frequency values. For the Nebraska statewide study, the Review Committee agreed that the 100-year return frequency dew point climatology maps were appropriate because this added a layer of conservatism over 50-year return periods. This study added 15 years of data available since the EPRI study, hence adding reliability to the 100-year return frequency analyses. Storm precipitation amounts are 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. This procedure was followed in this study using the updated maximum dew point climatology developed and described in Section 6. A more detailed discussion, along with examples of this procedure, is provided in Appendix C.

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

In previous storm analyses performed by the National Weather Service (formally the Weather Bureau) and the US Army Corps of Engineers, 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 period (WMO 1986). However, as was established in the EPRI study, this dew point methodology tends to underestimate the storm representative dew point value associated with the rainfall event.

An excellent example of this - specific to the Nebraska statewide PMP study - is illustrated by the David City, NE 1963 storm. This storm produced one of the largest floods of record at the Ithaca gage on Wahoo Creek (77,400 cfs). 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 (Figure 8.1). 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 1000mb adjusted value of 66.5°F (Table 8.1).

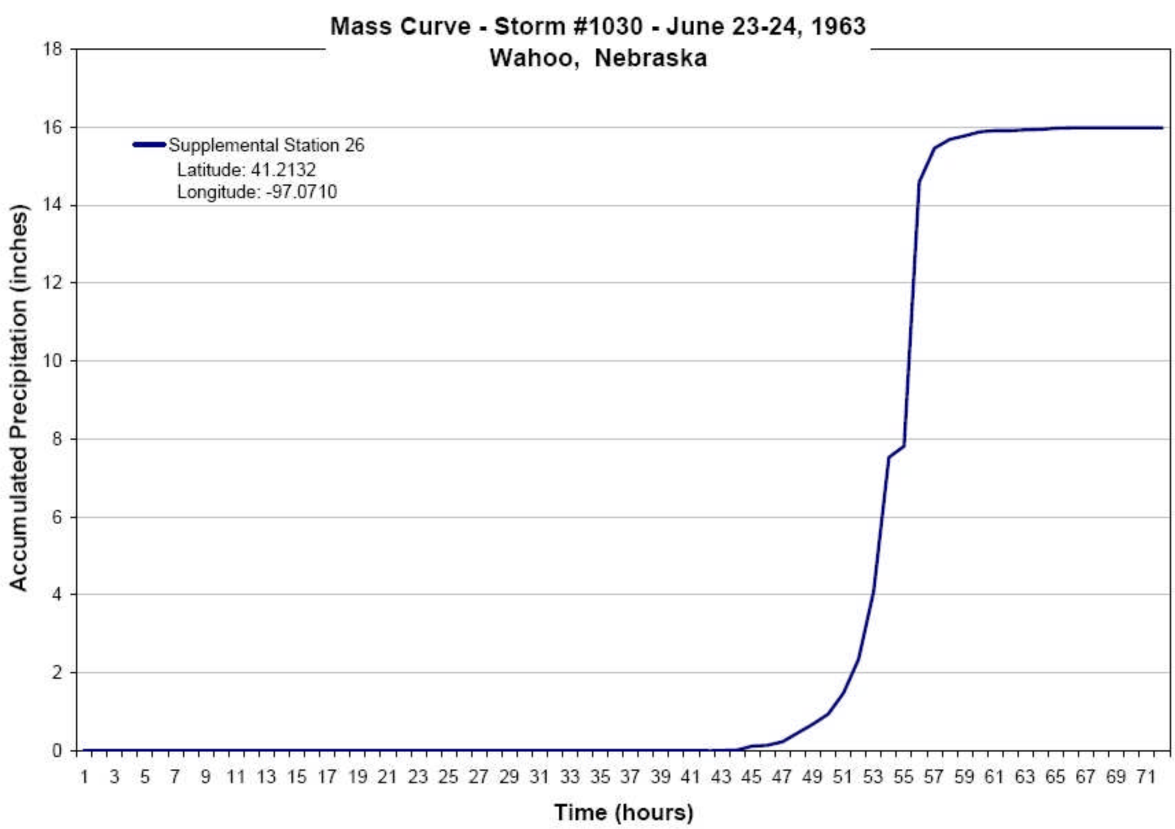

Figure 8.1 Mass Curve as analyzed by SPAS for David City, NE 1963 storm event

Table 8.1 Comparison of 6-hour *average* storm representative dew point vs. 12-hour *persisting* storm representative dew point for David City, NE 1963

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 six 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 dewpoint observing station(s) to the storm location.

For older storms previously analyzed in the US Army Corps of Engineers Storm Studies and used in NWS Hydrometeorological Reports, 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 EPRI study. The discussion on the development of the adjustment factor from the EPRI report is provided below:

When using average dew points to describe the storm inflow moisture, an inconsistency existed between the older storms and the modern storms. The earlier storms used 12-hour persisting dew points to characterize moisture inflow. However, the approach used in this study was to derive storm inflow moisture based on average rather than persisting dew points. Furthermore, new maximum average dew point climatologies for the various temporal periods (i.e. 6-, 12-, and 24-hour periods) were created expressly for use in the maximization process. The older storms, which used 12-hour persisting dew points, are inconsistent with the use of the average maximum dew point climatology. Since our storm list is much smaller than desired, eliminating the older storms was not considered feasible. Instead, a procedure to provide average dew point values of the older storms was developed.

The best solution would be to re-evaluate the older storms to determine storm representative dew points based on the storm duration period and average dew point values. Unfortunately, the data required for the re-evaluation were not available. Hence the best approach was to establish correlations between the 12-hour persisting and the 6-, 12-, and 24-hour average storm dew points for each storm type, i.e. MCS and synoptic. (Although older storms were not analyzed as MCS or synoptic storms, the investigators believe their type can be determined using the DAD analyses, surface analyses, and mass curves available for the older storms.)

To quantify the differences between the average and 12-hour persisting storm dew points, each modern storm was analyzed in a manner consistent with the procedure used with the older storms to determine the 12-hour persisting dew points (HMR 23, HMR 25A). Only limited dew point data were available for periods in which the older storms occurred, because dew point temperatures were normally taken just twice a day and occasionally at noon at certain locations.

The readings were taken at 7:00 or 8:00 in the morning and 7:00 or 8:00 in the evening. The 12-hour persisting dew point determination procedure involved using two dew point temperatures, spaced 12 hours apart, and taking the lowest one. Assuming the timing of the 12-hour period chosen was consistent with the surface wind flow (data on upper-air winds were not available before 1945), the 12-hour persisting dew point at two or more stations were then averaged to determine the representative storm dew point (HMR 23, HMR 25A). This process was copied for modern storms.

Results from the dew point analyses in the EPRI study showed consistent results for MCS 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 analysis of MCS storm data provided an average difference of eight degrees between the average and 12-hour persisting dew points. For synoptic storms, the average difference was three degrees. The following discussion from the EPRI 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 Wanahoo site-specific PMP study for the additional modern storms included on the short storm list. Six of these were MCS type storms and one was a synoptic type storm. Results were very consistent with the EPRI study. As a result of finding the same correlations with a larger storm sample size, a less conservative adjustment factor is being used in this study for MCS type storms. A seven degree adjustment is applied for MCS type storms. For the synoptic type storms, the two degree adjustment from the EPRI study is being retained.

8.2 Storm Transpositioning

Extreme rain events that have occurred over geographically and climatically similar regions surrounding a study area are a very important part of the historical evidence on which PMP estimates for a drainage basin are based. Study locations usually have a limited period of record for rainfall data collected within the boundaries and hence have a limited number of extreme storms that have been observed over the area. Storms observed regionally with a similar climate are analyzed and adjusted to provide information describing the storm rainfall as if the storm had occurred over the study area. Transfer of a storm from where it occurred to a location that is meteorologically and geographically similar is called *storm transpositioning*. The underlying assumption is that storms transposed to the study area could occur over the basin under similar meteorological conditions. To properly relocate such storms, it is necessary to address issues of similarity as they relate to topography and meteorological conditions.

The search for extreme rainfall events identified storms that occurred east of the Rocky Mountain upslope regions and east to the first upslopes of the Appalachians (see Figure 4.1). This region was considered meteorologically and geographically homogenous and therefore the climatological settings of the basin and the locations of each of the transposed storms are similar. Further analysis of storm patterns on both a temporal and spatial scale within this region revealed that only storms that occurred within a +/- 1000 feet of elevation of a particular location possessed similar enough storm dynamics to be transpositionable to that location (see Appendix J for a complete description of how the transposition limitations were derived).

8.2.1 Use of Maximum Dew point

The procedure for storm maximization has been discussed. The same maps used for maximum dew points were used in the storm transpositioning procedure. The procedure was the same for dew points once the storm representative dew point location had been identified. The wind inflow vector connecting the storm location with the storm representative dew point location was transpositioned to each appropriate grid point location based on transposition limitations already discussed. The value of the maximum dew point at that upwind location provided the transpositioned maximum dew point value used to compute the transposition adjustment factor for relocating the storm to the appropriate grid point. The primary effect of storm transpositioning was to adjust storm rainfall amounts to account for enhanced or reduced atmospheric moisture made available to the storm at the transposed inflow location. A more detailed discussion of this procedure is provided in Appendix C.

8.2.2 Storm transpositioning with the HMR 51 Gentle Upslope Region

AWA evaluated the limitations of transpositioning storms throughout the study region based on elevation changes between each grid point and the storm center locations. A comprehensive discussion has been prepared and is presented in Appendix J, with a summary presented here.

The general procedure used in HMR 51 is to not make elevation adjustments when transpositioning storms from their in-place location to other locations within their transposition limits. The one exception to this procedure is when transpositioning storms within the "Gentle

Upslope Region". Figure 3 in HMR 51 shows the gentle upslope region on a map of the central United States. The map is shown here in Figure 8.2 of this report. Discussions on storm transpositioning in this region are given in Section 2.4.5 of HMR 51.

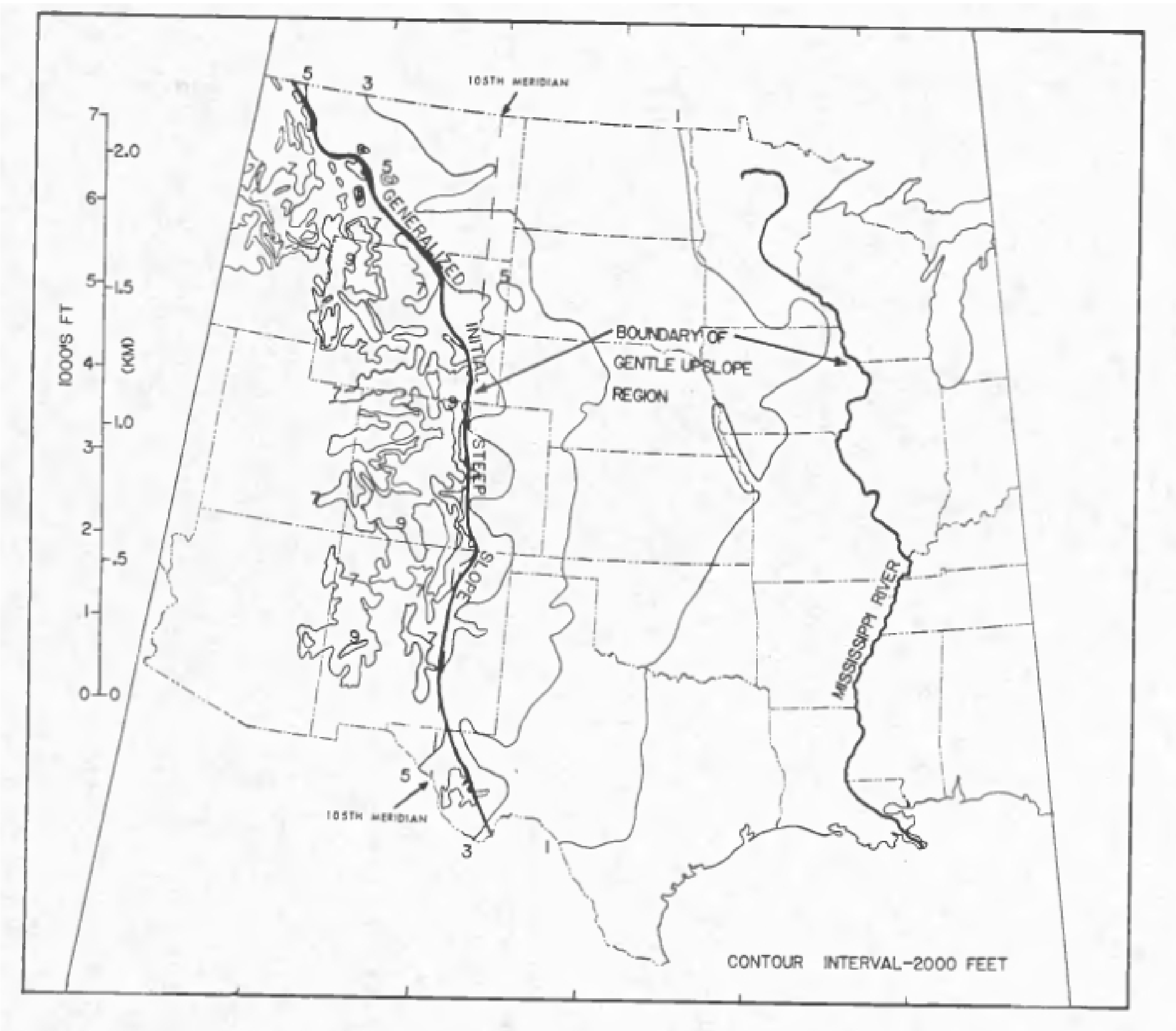

Figure 8.2 HMR 51 Gentle Upslope Region (reproduced from HMR 51 Figure 3, page 13)

Important guidelines to storm transposition in HMR 51 that affect storms within and surrounding Nebraska are found on pages 10-11 and include the following::

2.4.2 c. In regions of large elevation differences, transpositions were restricted to a narrow elevation band (usually within 1000 ft of the elevation of the storm)

2.4.2 e. Westward transposition limits of storms located in Central United States were related to elevation. This varied from storm-to-storm but in most cases the 3000- or 4000-ft contour.

2.4.5 This report did not apply an elevation adjustment when transposing storms within limited differences in elevation. However, in the gently rising terrain west of the

> *Mississippi River to the generalized initial steep slopes in the western portion of the study region (fig 3) patterns of tentative PMP were not consistent with the patterns in the guidance material. The guidance material indicated a greater decrease in areal rainfall towards the west in the gentle upslope region….*
>
> *Stratification of the rainfall by area size showed a decided trend toward greater decrease for large-area rainfall than for small….*
>
> *With the evidence from rainfall data of various kinds and meteorological analyses within the gentle upslope region, we decreased large-area rainfalls when transposing to higher elevations and increased them when transposing to lower elevations. Storm depths for 1,000 mi^2 or less were not adjusted….*
>
> *Any discontinuity introduced in PMP at 1,000 mi^2 was eliminated by the various consistency checks.*
>
> *There are a number of major large-area storms in the gentle upslope region with limits of transposition east of the Mississippi River – beyond the boundaries of the gentle upslope region. In calculating the adjusted rainfall for the eastward transposition of these storms, the adjustment for gentle upslope was not applied.*

What was explicitly done when transpositioning storms within the gentle upslope region i.e. how the elevation adjustments were computed and applied, and what consistency checks were used to modify storm data in HMR 51 is not known. However, the authors did recognize and tried to address what they described as a "decided trend toward greater decreases for large-area rainfall than for small" as storms were transpositioned towards the west. The discussion in HMR 51 also indicates that rainfall values were increased when transposing to lower elevations but only for area sizes larger than 1,000 mi^2.

A site-specific PMP study was completed in 2003 by Applied Weather Associates for the Cherry Creek drainage basin south of Denver, Colorado (Tomlinson et al. 2003). The issue of differences in the spatial distribution of rainfall between eastern Colorado storms and Midwestern storms was also identified in that study. In particular, the same storm rainfall spatial distribution issue was identified and a conclusion consistent with the HMR 51 discussions was reached. That study concluded that although the storms in eastern Colorado and Midwestern storms have some similar characteristics, storms from the Midwestern states should not be transpositioned into Colorado because of significant differences in spatial rainfall distributions. Hence, the Cherry Creek study used only Colorado storms in its PMP analysis.

Both the site-specific Cherry Creek PMP study and HMR 51 recognized differences between high plains storms and lower elevation central plains storms. However, the approaches taken to address these differences in storm transpositioning procedures varied. The approach taken in HMR 51 was to constrain the transposition limits of storms, often within regions with elevation that differs from the in-place storm elevation by 1,000 feet or less (HMR 51, Section 2.4.2.c.). Westward transposition limits of storms located in the central United States were related to elevation. This varied from storm to storm but in most cases the 3,000- or 4,000- contours were used (HMR 51, Section 2.4.2.e.). For transpositioning within these limits, the spatial distribution of storm rainfall was modified as storms were transpositioned to locations with differing elevations (HMR 51, Section 2.4.5). Discontinuities introduced by this modification were eliminated by "various consistency checks" (HMR 51, Section 2.4.5). Smoothing appears to be the primary tool used in applying the consistency checks (HMR 51, Section 3.3).

This procedure is unique to HMR 51 and has not been used in any other HMR or site-specific or regional PMP studies. Storms are transpositioned to regions where storms with similar characteristics have occurred. When adjustments are applied during the transpositioning process (moisture, elevation and/or barrier adjustments), the adjustments are applied at all durations and all area sizes. To selectively apply these adjustments distorts the storms' temporal and/or spatial rainfall pattern, thereby creating a storm with different characteristics at the transpositioned location than it had at its in-place location.

Appendix J contains discussions and figures related to storm areal rainfall distributions. The figures show differences between the spatial rainfall distributions of Colorado eastern plains storms, and storms east of Colorado used in HMR 52 to construct the within/without storm rainfall curves. The most dramatic differences appear for short durations and small area size comparisons (e.g. 10 square mile, 6-hour). Plots and discussions are also presented on analyses of rainfall distributions for the most significant central and eastern Nebraska storms used in this study. Similar results to the analysis using Colorado storms were found.

Based on the above discussions, AWA revisited the storm transposition procedure. The transpositioning procedure should ensure an adequate storm database for each region while insuring to the maximum extent possible that storms are not transpositioned beyond appropriate limits.

During the Wanahoo study, AWA implemented the procedure that constrains storm's being transpostioned beyond + or -1,000 feet of their in-place elevation. This limitation was validated during the Wanahoo study and used for the Nebraska statewide PMP study. This procedure, although not completely consistent with the NWS transposition limits, maintains some consistency with the limits that apparently were used in HMR 51, while maintaining the integrity of the within storm rainfall distributions of individual storms.

8.3 Storm Spreadsheet Development Process

AWA developed Excel spreadsheets that incorporate relevant storm information, determines appropriate adjustment factors, and computes the adjusted rainfall DAD tables. Storm spreadsheets were developed for each of the new storms analyzed by AWA, the Army Corps of Engineers Storm Studies, HMR 51 storms, and the EPRI storms. These storm spreadsheets used the storm DADs, storm representative dew points, maximum dew points (both in-place and transposition), storm elevation and transposition location elevation information either as published in the Army Corps of Engineers Storm Studies reports, HRM 51 tables, the EPRI storm analysis, or as developed during AWA storm analysis procedures. This information was entered into each individual storm spreadsheet. Using the storm center location and inflow vector, the in-place maximum dew point was determined. The same inflow vector was then moved to each of the appropriate grid point(s) based on transposition limits to determine the transpositioned maximum dew point value and total adjustment factor for that storm at that grid point. This information was entered into the storm spreadsheet to calculate the in-place maximization factor, the transposition factor, and finally the total adjustment factor. This total adjustment factor was applied to the storm DAD table values to provide the final adjusted DAD table for the maximized transpositioned storm rainfall values at each grid point. The dew point values used to calculate the maximization and transposition factors were taken from the 100-year dew point climatology maps, using the 6-hour, 12-hour, and 24-hour dew point map appropriate for the storm's duration.

All data were crossed checked to ensure that no errors or omissions were made. DA and DD plots for all standard area sizes and durations were produced for each grid point based on storm spreadsheet results. Maps were created in GIS using the grid point adjusted rainfall values.

8.4 Deriving the Final PMP Values

Once this set of maps was produced, AWA evaluated each map by duration and area size. Inconsistencies among grid points were evaluated based on meteorological and topographic considerations across the region. Each iteration (there were six total) of this process identified and corrected various errors and/or inconsistencies. The initial set of maps used the transpositioning guidelines discussed earlier of limiting any individual storm to within +/- 1000 feet of the elevation of its storm center location (location of the highest recorded point rainfall-not the center of storm dynamics-although they may be co-located). However, these criteria allowed several storms to be transpositioned to inappropriate locations based on meteorological considerations. Examples are storms that occurred in Oklahoma (Enid, Cheyenne, Hallett, Meeker, Warner). Transpositioning of these storms were constrained only to Grid Point 5, the most southeastern grid point. Precedence was set for this through examining the transposition limits set on the Hallett, OK storm by the NWS, where the storm was not transpositioned further north than Wichita or Kansas City. The reasoning behind this limitation was that the maximized values from these storms increased beyond reasonable limits and produced much higher adjusted rainfall amounts than other storms at grid points further to the north and west. This revealed that these storms were not reflecting homogenous meteorological characteristics. Furthermore, the rainfall gradients could not be attributed to topographic effects. Another example was the Springbrook, MT event. It was transpositioned only to the most northern grid points. This storm occurred in eastern Montana. Moving as far south (over 500 miles) as southern Nebraska and/or northern Kansas was meteorologically inconsistent because the storm dynamics (e.g. coriolis force, moisture sources) involved would have varied enough at those location to make the storm non-transpositionable.

Another issue encountered occurred where the elevations changes from east to west across the state of Nebraska led to a variation in the set of storms available to be properly transpositioned at adjacent grid points (Figure 2.1). An example of this occurs between Grid Points 8 and 9. Therefore, the contours between the two grid points initially showed gradients that were unrealistic based on the meteorological characteristics that could be expected in the region. In these cases, AWA enveloped the DA values to produce a more realistic representation of the expected characteristics of the PMP contours. At no point did AWA undercut storm DA values. Furthermore, at the higher elevation grid points, i.e. those above 3000 feet, the number of storms that could be used in development of the DA values was limited, sometimes as few as two storms (Grid Points 1, 6). This limited number of storms often did not represent a robust set of synoptic and/or MCS type events. Because of this, large amounts of envelopment were applied to ensure spatial and temporal continuity among adjacent grid points. This also allowed for a better transition between grid point values from west to east across the state.

8.5 Meteorological Characteristics Inferred from the PMP Maps

Several interesting meteorological characteristics became evident during the grid point PMP analysis process. One was the obvious transition from MCS storms to synoptic events as the PMP driver storm-type between 500 and 1000-square mile area sizes. This was especially evident on the 12-hour 500-square mile and 1000-square mile maps in eastern Nebraska. The effect of the elevation changes across the state, generally from east to west, became very evident not only in the number of storms that affected a given grid point, but also the transition of PMP values. This is most evident during the transition between Grid Points 2, 8, and 13 and Grid Points 3, 9, and 15. During this transition, elevations go from the lower 3000 foot elevations at Grid Points 2, 8, and 13 to the low 2000 foot elevations at 3, 9, and 15. This caused the set of storms used to determine the PMP values to change. This led to a high gradient between these grid points based on the differing storm dynamics associated with storms that occur at varying elevations.

It was observed in the Cherry Creek PMP study (Tomlinson et al, 2003) that point rainfall amounts from extreme rainfall events will often be comparable to those observed at lower elevations in the Great Plains. However, the rainfall amounts decrease much more dramatically as the areal sizes and durations increase. The conclusion is that storms over higher elevations have a more efficient release of instability through forced ascent (i.e. are more efficient in producing rainfall), thereby are capable of producing large rainfall amounts over small areas and short durations from very efficient convective cells, even with less atmospheric moisture than is available to convective cells at lower elevations to the east. But the lack of overall atmospheric moisture content and replenishment that allow for heavy rains to fall over larger area sizes and longer durations constrains rainfall amounts over larger areas.

Overall, having the contoured PMP maps to analyze on a regional basis proved to be a very valuable asset vs having only rainfall values at a single location. The ability to look at the relationships among grid points at various spatial and temporal scales as a whole proved very insightful and was of great importance in deriving the final PMP values across the state.

9 Development of PMP Values from Adjusted Storm DADs

Storm maximization and transpositioning provided an indication of the maximum amount of precipitation that a particular storm could have produced at any of the individual grid point locations used in this study. Use of these values alone did not ensure that PMP values were provided for all of the particular area sizes and durations since some of the maximized values could be less than the PMP. It seems reasonable to expect that by enveloping the values resulting from maximizing and transposing the rainfall amounts from all the major storms, rainfall values indicative of the PMP magnitude will result (WMO 1986).

Enveloping is a process for selecting the largest values from a set of data. This technique provides continuous smooth curves based on the largest precipitation values from the set of maximized and transposed storm rainfall data values. The largest precipitation amounts provide guidance for drawing the curves.

During the enveloping process, values which are not consistent (are either high or low) are re-evaluated to ensure reliability. High values are enveloped unless an explanation can be provided to justify undercutting the value. However, undercutting of values was not necessary in the development of the enveloping curves at any of the grid points. Low values are also re-evaluated for reliability and then enveloped to maintain consistency with surrounding values. This enveloping procedure addresses the possibility that for certain area sizes and durations, no significantly large storms have been observed which provide large enough values after being maximized and transposed to represent the PMP. Results of this procedure provide a set of smooth curves that maintain continuity among temporal periods and areal sizes. This smoothing process was further enhanced by ensuring continuity in space and time among grid points and throughout the iso-PMP lines represented on the final PMP maps.

The envelopment process was used in developing the DA curves at each grid point and the DD curves at each grid point. Curves for each storm were plotted using the adjusted storm values at each of the 23 grid points. An enveloping curve using all of the storm curves was drawn for each duration. An example of the enveloped DA curve for Grid Point 15, for 24-hours is given in Figure 9.1. Notice the envelopment of the largest storm values. This envelopment was necessary to ensure continuity both spatially and temporally not only at this grid point but among adjacent grid points. This allowed the final iso-PMP lines to remain meteorologically consistent and physically possible, as the definition of PMP requires. The envelopment procedure used in constructing those curves was such that low values for particular area sizes were increased to provide a smooth transition from one area size to another and when necessary between grid points. Although there were some situations that required enveloping, there were no cases that involved undercutting, primarily because the maximized and transposed data points were reasonably consistent. The DA envelopment procedure was performed to provide smooth curves with continuity among area sizes, thereby providing continuity in space. The DA curves were constructed in such a way as to ensure that, for a given duration, the depth for any area did not exceed the depth for a smaller area.

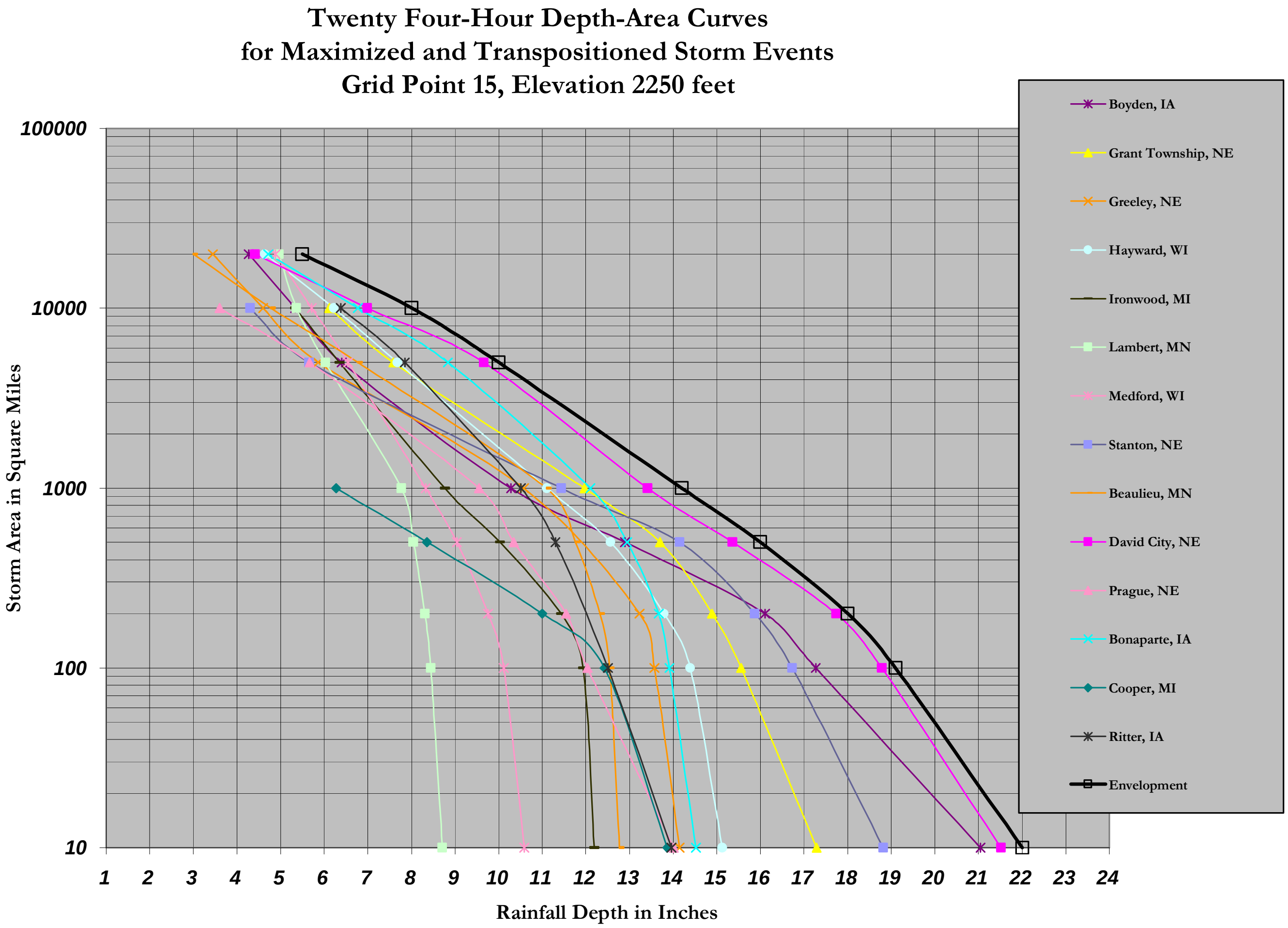

Figure 9.1 24-hour depth-area curves for Grid Point 15

The second application of the envelopment process was used with the DD curves at each grid point. Curves for each of the area sizes were constructed using results from the depth-area analysis described above. Enveloping curves were drawn to produce smooth curves that provide continuity in time. Figure 9.2 gives an example of the DD curves for Grid Point 15.

The final curves at each grid point define PMP values for that individual grid point location. These values were then plotted in GIS to derive the final iso-PMP lines across the study region. The envelopment of the adjusted storms together with the curve smoothing process ensured that all storm data were included and that the resulting set of PMP values provides rainfall values that are consistent spatially and temporally.

Appendix E provides more detailed discussions on the envelopment and smoothing procedure and Appendix G provides further discussion regarding the development and use of the depth-area and depth-duration plots for this study.

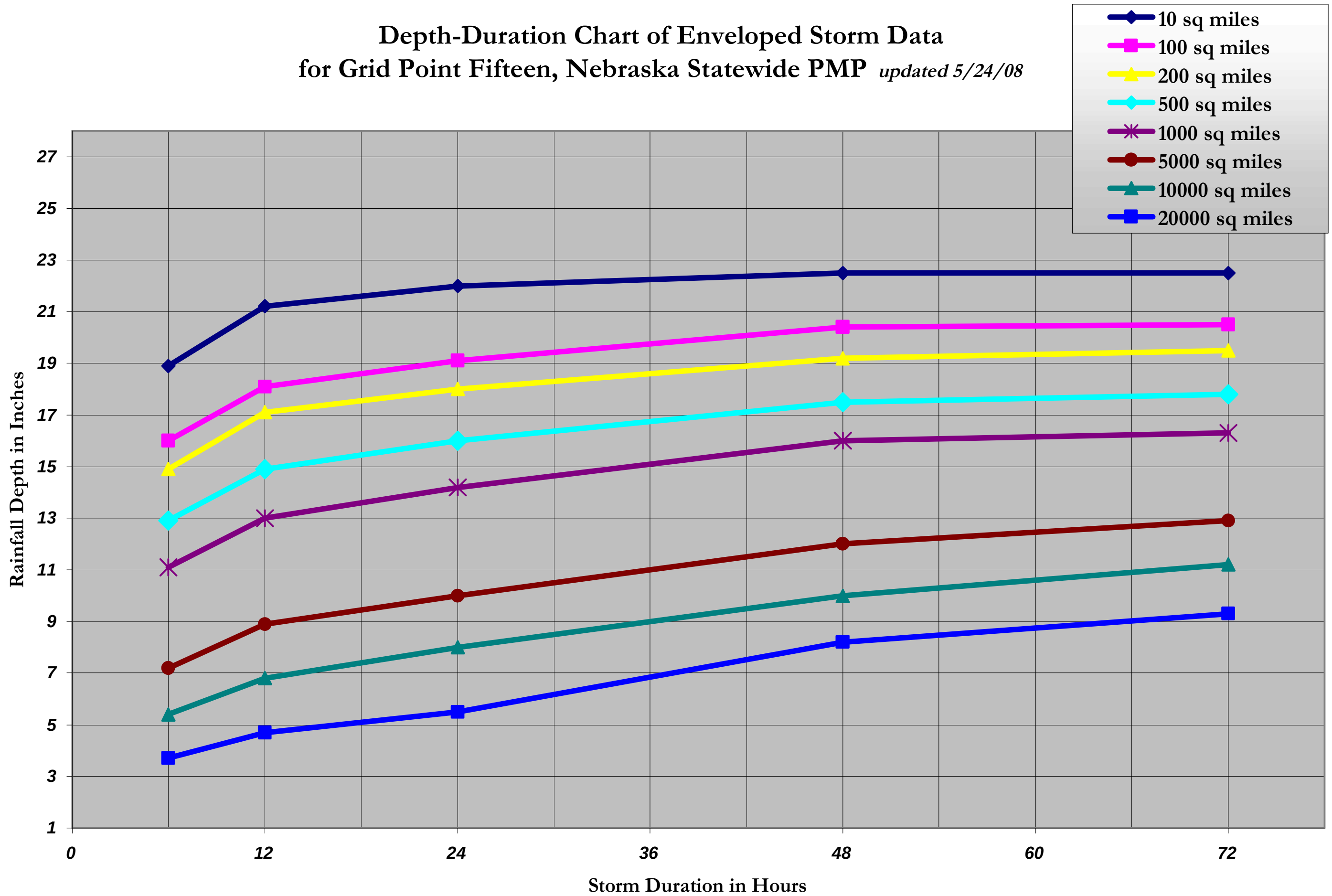

Figure 9.2 Depth-Duration curves for Grid Point 15

10 Storm Dimensions

10.1 Storm Shape

Storm isohyetal patterns for 34 of the 36 storms on the short list were analyzed to determine their general shape (no isohyetal pattern was given for Paris Waterworks USACE Storm Studies sheet HMB V-18 and EPRI storm 18. Furthermore, the Cole Camp, MO and Collinsville, IL storm events were given as one isohyetal pattern as part of USACE Storm Studies sheets MR 7-2A and MR 7-2B). Ellipses were fit to the storm isohyetal patterns and provided a standard geometric pattern for use in describing the spatial shape of the storm's precipitation. Storm patterns (ratio of the major to the minor axis) ranged from 1.07 to 4.33 with all storms showing a definable major and minor axis such that a ratio could be determined objectively. Table 10.1 details the shape ratios for the 34 analyzed storm events.

Table 10.1 Shape ratios derived for the short list of storms

Station Name	St	Lat	Lon	Year	Month	Day	Max Precip	Shape Ratio
AURORA COLLEGE	IL	41.75	-88.33	1996	7	17	18.24	1.91
BEAULIEU	MN	47.30	-95.90	1909	7	18	11.50	1.60
BONAPARTE	IA	40.77	-91.75	1905	6	10	12.10	2.50
BOYDEN	IA	43.19	-96.01	1926	9	17	24.00	2.00
CHEYENNE	OK	35.61	-99.67	1934	4	3	23.00	4.33
COLE CAMP	MO	38.46	-93.20	1946	8	12	19.40	2.00
COOPER	MI	42.38	-85.61	1914	8	31	12.60	1.75
COUNCIL GROVE	KS	38.40	-96.30	1951	7	9	18.50	2.00
DAVID CITY	NE	41.23	-97.11	1963	6	24	16.50	1.07
EDGERTON	MO	39.50	-94.62	1965	7	18	20.02	3.60
ENID	OK	36.40	-97.88	1973	10	10	20.00	1.30
FOREST CITY	MN	45.21	-94.47	1983	6	20	17.00	3.00
GRANT TOWNSHIP	NE	40.39	-99.85	1940	6	3	13.00	2.00
GREELEY	NE	41.55	-98.53	1896	6	4	12.30	1.50
HALE	CO	39.61	-102.25	1935	5	30	18.00	1.85
HALLETT	OK	36.20	-96.60	1940	9	2	24.00	2.50
HAYWARD	WI	46.01	-91.48	1941	8	28	15.00	2.55
HOKAH	MN	43.81	-91.36	2007	8	19	18.93	3.75
HOLLY	CO	38.05	-102.12	1965	6	16	15.54	1.85
IDA GROVE	IA	42.32	-95.47	1962	8	30	12.85	3.60
IRONWOOD	MI	46.45	-90.18	1909	7	21	13.20	2.50
LAMBERT	MN	44.23	-95.26	1897	7	18	8.00	2.00
MEDFORD	WI	45.13	-90.33	1905	6	4	11.20	2.50
MEEKER	OK	35.50	-96.90	1908	10	19	16.23	2.00
MINNEAPOLIS	MN	44.88	-93.22	1987	7	23	10.55	2.70
OGALLALA	NE	41.12	-101.72	2002	7	6	14.92	2.00
PAWNEE CREEK	CO	40.67	-103.83	1997	7	28	13.70	2.50
PRAGUE	NE	41.36	-96.88	1959	8	1	13.09	2.00
RITTER	IA	43.24	-95.82	1953	6	7	11.00	2.50
SAVAGETON	WY	43.88	-105.93	1923	9	27	17.10	1.74
SPRINGBROOK	MT	47.25	-104.52	1921	6	17	14.60	1.33
STANTON	NE	41.87	-97.05	1944	6	10	17.30	2.67
TOMAH	WI	43.98	-90.50	1990	8	17	9.17	1.60
WARNER	OK	35.49	-95.31	1943	5	6	25.00	2.35

Figure 10.1 shows an example of how a storm isohyetal pattern was analyzed to determine its shape (ratio) and orientations.

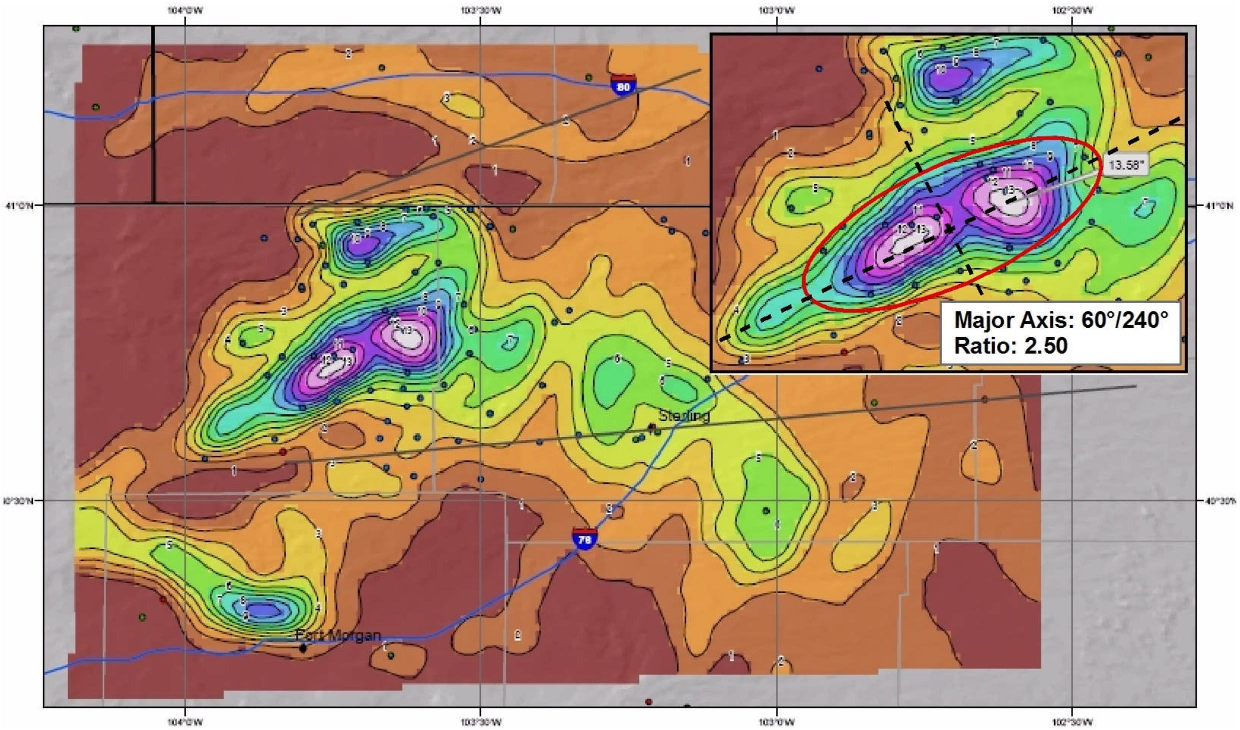

Figure 10.1 Storm isohyetal analyses to determine storm shape and orientation

The average shape ratio for the 34 events analyzed was 2.27. This is very similar to values derived in HMR 52 as well as the EPRI study. Overall, 65% of the events had shape ratios between 2 and 4, with 53% of the events between 2 and 3.

The smaller area size and short duration events (MCS storms) had a smaller shape ratio (more circular pattern) compared to synoptic events. Of the 34 events analyzed, 20 were considered MCS events and had an average shape ratio of 2.16. This included two significant outliers, the Cheyenne, OK 1934 event with a shape ratio of 4.33 and the Forest City, MN 1983 event with a shape ratio of 3.00. Without these two events included, the average shape ratio for the MCS-type events would be 1.99.

A similar relationship exists between the shape ratio and the larger area size longer duration events (synoptic storms). The remaining 14 synoptic events have an average shape ratio of 2.42. Huff (1979) and Huff and Vogel (1976) found similar results.

10.2 Storm Orientation

Storm orientation is an important aspect when considering the placement of an isohyetal pattern over a basin. The orientations of the short list storm events were evaluated to determine a preferred storm orientation to use when applying a storm pattern over a basin. The shape of each storm was examined to determine the orientation of the major axis. Storm orientations are described by an angle of 180° to 359°, where 180° is equivalent to south-to-north and 270° is equivalent to west-to-east orientation. The rainfall pattern images used for this analysis were taken from the USACE Storm Studies isohyetal images, EPRI isohyetal image, and from SPAS storm analyses.

The orientation and major/semi-major axis ratio was estimated for each storm using a carefully drawn ellipse oriented with the isohyetal pattern. The ellipses were drawn to envelope the majority of the storm's precipitation with the orientation axis drawn through the location of highest precipitation.

Although each axis is two-valued, the orientation of the major axis was measured and recorded using the 180° section between 135° and 315°. The average orientation for all 35 storms was obtained by using the appropriate value for each two-value axis orientation resulting in a minimum range for all values. This procedure is outlined in HMR 52, Section 4.2.1 (Hansen et al 1982).

The average orientation of the 35 storms analyzed was 259°, with a range from 330° to 200° (see Table 10.2). This result is consistent with the meteorology involved in producing extreme rainfall events during the warm season. In these situations, a front is often in the vicinity of the rainfall event and usually oriented in a west-to-east direction, where convection often fires along this boundary. Therefore, it would be expected that the isohyetal pattern would follow a similar delineation.

Based on these results, the following storm orientation for the major axis of ellipses used to describe PMP storm patterns is recommended:

260° +/-70

Table 10.2 Storm orientations for the major axis of the short list of storms

Station Name	St	Lat	Lon	Duration	Year	Month	Day	Max Precip	Storm Orientation in Degrees
AURORA COLLEGE	IL	41.75	-88.33	1-day	1996	7	17	18.24	290
BEAULIEU	MN	47.30	-95.90	6hrs	1909	7	18	11.50	290
BONAPARTE	IA	40.77	-91.75	6hrs	1905	6	10	12.10	285
BOYDEN	IA	43.19	-96.01	6hrs	1926	9	17	24.00	225
CHEYENNE	OK	35.61	-99.67	6hrs	1934	4	3	23.00	225
COLE CAMP	MO	38.46	-93.20	3-day	1946	8	12	19.40	295
COOPER	MI	42.38	-85.61	6hrs	1914	8	31	12.60	295
COUNCIL GROVE	KS	38.40	-96.30	3-day	1951	7	9	18.50	285
DAVID CITY	NE	41.23	-97.11	6hrs	1963	6	24	16.50	205
EDGERTON	MO	39.50	-94.62	1-day	1965	7	18	20.02	325
ENID	OK	36.40	-97.88	1-day	1973	10	10	20.00	205
FOREST CITY	MN	45.21	-94.47	6hrs	1983	6	20	17.00	265
GRANT TOWNSHIP	NE	40.39	-99.85	6hrs	1940	6	3	13.00	255
GREELEY	NE	41.55	-98.53	6hrs	1896	6	4	12.30	220
HALE	CO	39.61	-102.25	6hrs	1935	5	30	18.00	230
HALLETT	OK	36.20	-96.60	6hrs	1940	9	2	24.00	330
HAYWARD	WI	46.01	-91.48	1-day	1941	8	28	15.00	275
HOKAH	MN	43.81	-91.36	1-day	2007	8	19	18.93	290
HOLLY	CO	38.05	-102.12	3-day	1965	6	16	15.54	215
IDA GROVE	IA	42.32	-95.47	1-day	1962	8	30	12.85	250
IRONWOOD	MI	46.45	-90.18	3-day	1909	7	21	13.20	295
LAMBERT	MN	44.23	-95.26	3-day	1897	7	18	8.00	300
MEDFORD	WI	45.13	-90.33	3-day	1905	6	4	11.20	310
MEEKER	OK	35.50	-96.90	1-day	1908	10	19	16.23	210
MINNEAPOLIS	MN	44.88	-93.22	6hrs	1987	7	23	10.55	275
OGALLALA	NE	41.12	-101.72	6hrs	2002	7	6	14.92	225
PARIS WATERWORKS	IN	39.05	-87.70	6hrs	1957	6	27	13.19	220
PAWNEE CREEK	CO	40.67	-103.83	1-day	1997	7	28	13.70	240
PRAGUE	NE	41.36	-96.88	6hrs	1959	8	1	13.09	305
RITTER	IA	43.24	-95.82	6hrs	1953	6	7	11.00	225
SAVAGETON	WY	43.88	-105.93	1-day	1923	9	27	17.10	215
SPRINGBROOK	MT	47.25	-104.52	1-day	1921	6	17	14.60	200
STANTON	NE	41.87	-97.05	6hrs	1944	6	10	17.30	275
TOMAH	WI	43.98	-90.50	6hrs	1990	8	17	9.17	275
WARNER	OK	35.49	-95.31	3-day	1943	5	6	25.00	230
								MAX:	**330**
								MIN:	**200**
								Range:	**130**
								Average	**259**

10.3 Comparison with the HMR 52 and EPRI

Shape ratios and storm orientation derived using the short list of storm for the Nebraska statewide PMP study were compared against results derived in HMR 52 and in the EPRI study. For the most part, the values agree very well, adding a high level of confidence. Table 10.3 details the values of each study versus what was derived by AWA in this study.

Table 10.3 Comparison of the Nebraska site-specific PMP Processes vs HMR 51

Study Name	Storm Orientation
Nebraska Statewide	260° +/- 70°
EPRI	280° +/- 50°
HMR 52-Table 11 Storms	275° +/- 40°
HMR 52-Nebraska	235° +/- 40°

11 Sensitivity Analysis

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 Atmospheres

The atmospheric air masses that provide moisture to both the historic storm and the maximized 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 maximized storm. Limited evaluation of this assumption in the EPRI Michigan/Wisconsin PMP study, as well as several current studies, indicates that historic storm atmospheric profiles are generally not entirely saturated and contain somewhat less precipitable water (PW) than is assumed in the PMP procedure. It follows that the PMP storm (if it were to occur) would also have somewhat less PW available than the assumed saturated PMP atmosphere would contain. It is important to realize that what is important in the PMP maximization procedure is the ratio of the PW associated with each storm, i.e. with the historic storm and with the maximized storm. If the PW values for the storms are both slightly overestimated, the ratio of these values will be essentially unchanged. For example, consider the inflow to a storm that has only 90% of the PW that it would have if it were saturated through the entire depth**.** Assume a storm representative dew point of 70^{o} F. The PW for a saturated atmosphere would be 2.25 inches but the PW for the actual storm is 2.03 inches or 90% of the saturated value. The maximization procedure assumes the same type of storm with similar atmospheric characteristics for the maximized storm but with a higher dew point, say 76^{o} F. The maximized storm, having similar atmospheric conditions, would have about 2.69 inches of PW instead of the 2.99 inches associated with a saturated atmosphere (90% of 2.99 = 2.69). The maximization factor computed using the assumed saturated atmospheric values would be 2.99/2.25 = 1.329. But the air mass associated with the inflow which provides the moisture to both storms is really 90% saturated so the maximization factor is 2.69/2.03 = 1.325, effectively the same as for the saturated atmosphere. Therefore the potential inaccuracy of assuming saturated atmospheres (where in reality 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 over 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 atmospheres associated with each storm, i.e. for both the in-place and transpositioned storms.

There are two issues to be considered. First is the assumption that a storm has occurred that has 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 assumed that there should have been at least one storm with storm dynamics that approach the maximum efficiency for rainfall production.

The other issue is the assumption that storm efficiency does not change if additional atmospheric moisture is available. A theoretical evaluation is not yet available although there are some numerical models that are approaching the reliability needed to make such evaluations. Furthermore, recent research points to the possibility that storm efficiency does change, and more importantly, at differing rates. This would therefore affect the ratio assumption that both the historic storms and the assumed PMP storm are changing at the same rate. Storm dynamics could potentially become more efficient or possibly less efficient depending on the interaction of cloud microphysical processes with the storm dynamics. Off-setting effects could indeed lead to the storm efficiency remaining essentially unchanged. For the present, the assumption of no change in storm efficiency is accepted until further scientific research shows definitively otherwise and is accepted in the meteorological community.

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 "worst-case" historical dew point values, occurring near the same of year as the storm in question. 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 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 4%)

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 topography removes atmospheric moisture from an air mass as it moves over the terrain. Atmospheric moisture available to a storm above a given elevation is quantified by subtracting the moisture in the lower portion of the atmosphere below the elevation at the storm location (sea level to storm elevation) from the total atmospheric moisture in the air mass (sea level to 30,000 feet). This procedure quantifies the moisture in the atmosphere above the terrain.

When storms are transpositioned into Nebraska, the elevation of the original storm and the elevation of each individual grid point are used to compute the amount of atmospheric moisture depleted (or added if the grid point is at a lower elevation) from the storm atmosphere. The absolute amount of moisture depletion is slightly dependent on the dew point values, but is primarily dependent on the elevation differences between the original storm location and each grid point. The elevation adjustment varies approximately 0.8% for every 100 feet of storm elevation change for the range of dew point values used in this study.

For example, consider the following case:

Maximum dew point:	79 ^{o} F
Storm Elevation Difference (1000mb to 1,000 feet)	1,000’
Precipitable water between 1000-mb and the top of the atmosphere:	3.44"
Precipitable water between 1000-mb and 1,000':	0.28"

Elevation Adjustment Factor = (3.44"-0.28")/3.44" = 0.92 (approximately 0.8% per 100 feet)

If the elevation difference were 2,000'
Precipitable water between 1000-mb and 2,000': 0.55"
Elevation Adjustment Factor = (3.44"-0.55")/3.44" = 0.84 (approximately 0.8% per 100 feet)

12 Results

This statewide PMP study provides PMP values for use in computing the PMF at any point within the state of Nebraska. Although grid points and contours extend beyond Nebraska, results are only considered applicable within the state of Nebraska. Values for all durations up to 72 hours and areal sizes up to 20,000 square miles have been computed. Section 12.1 contains the PMP maps to be used in determining basin specific PMP values throughout the state. The accompanying CD also contains the maps in GIS format so that an exact value can be determined from any PMP map by a user who has the software to read shapefiles.

The study was designed to retain as much continuity as possible with the methodology used in HMR 51 and the EPRI Michigan/Wisconsin studies, while incorporating improvements based on changes in technology, meteorological understanding, and availability of new data.

DAD analyses were completed for 10 storms not analyzed in either HMR 51 or the EPRI study. These analyses used the same basic approach but updated technology to analyze these storms utilizing the SPAS program (see Appendix H). The study continued use of surface dew point data to quantify moisture inflow to storms. However, instead of using the 12-hour persisting value as in HMR 51, an average dew point value for a duration (6, 12, or 24-hours) consistent with the storm precipitation was used. This approach, first used in the EPRI study, provides a more representative parameterization of the moisture available to the storm.

A new dew point climatology was developed and used in this study (see Appendix C). This allows use of average dew point values for several durations to be used for storm maximization and transposition.

Storms were maximized and transpositioned to a set of grid points that covered the state and provided a margin for boundary conditions (see Figure 1.2). For storms analyzed in HMR 51, 12-hour persisting dew points had been used to characterize moisture inflow and available data did not provide sufficient basis for readily developing average dew point moisture inflow values for those storms. Correlations were established in the EPRI study between average values for storms that had adequate data and storms for which only 12-hour persisting values were available. These correlations were validated further as part of the Wanahoo site-specific PMP study and utilized in this study. This procedure added 7°F to the 12-hour persisting storm representative dew point for MCS-type storms and 2°F to the 12-hour persisting storm representative dew point for synoptic-type storm events.

12.1 All-Season Probable Maximum Precipitation (PMP) Maps

Figures 12.1 – 12.30 present maps of the all-season PMP values for each duration and area size analyzed in this project. These are the same durations and area sizes provided in HMR 51. The maps should be used to determine PMP values for any location within the state of Nebraska. Alternately, the companion CD contains the same maps in GIS format. These maps can be used with appropriate GIS software to determine PMP values for any location within the state.

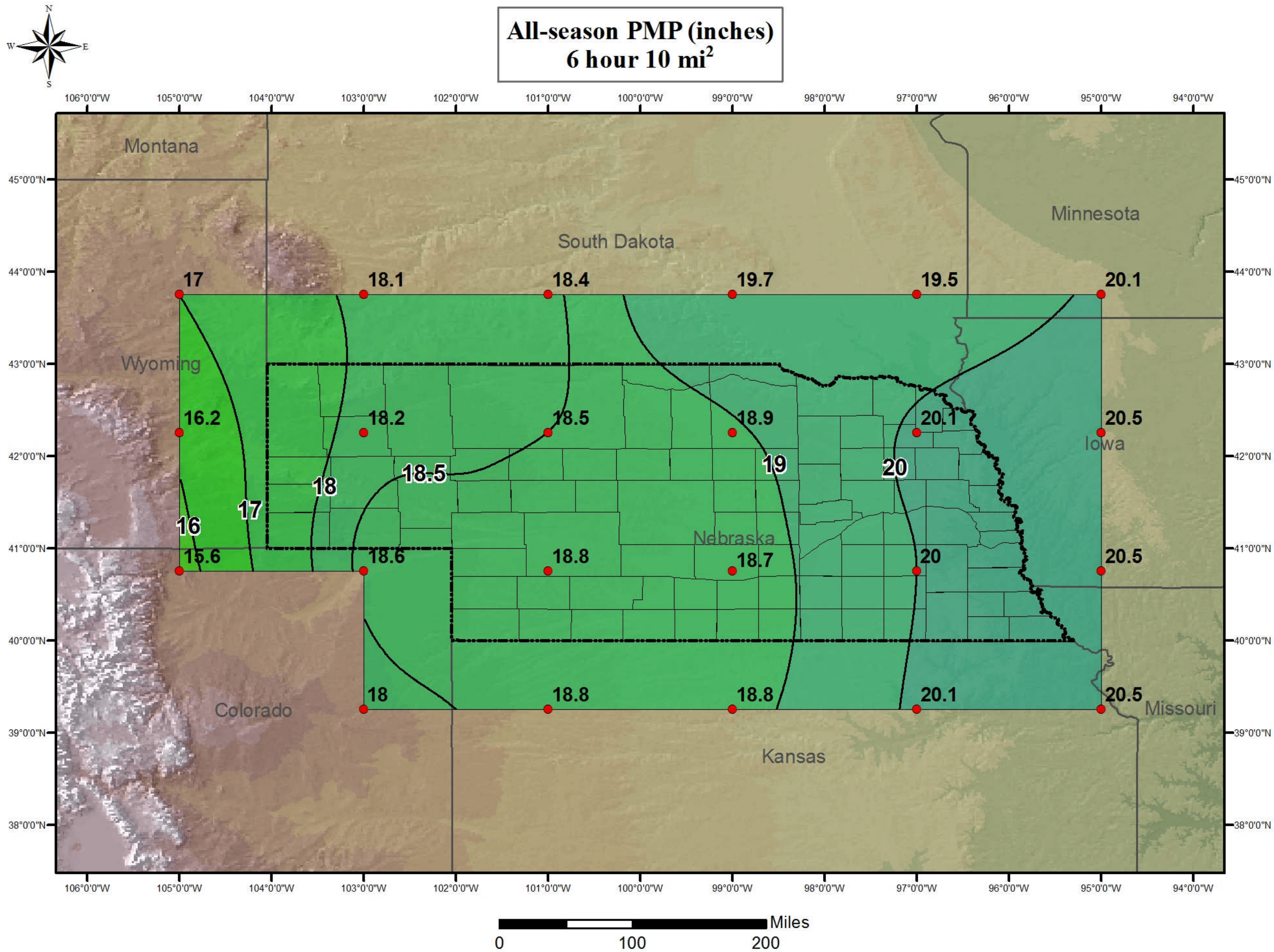

Figure 12.1 6-hour 10-square mile Nebraska statewide All-Season PMP (inches)

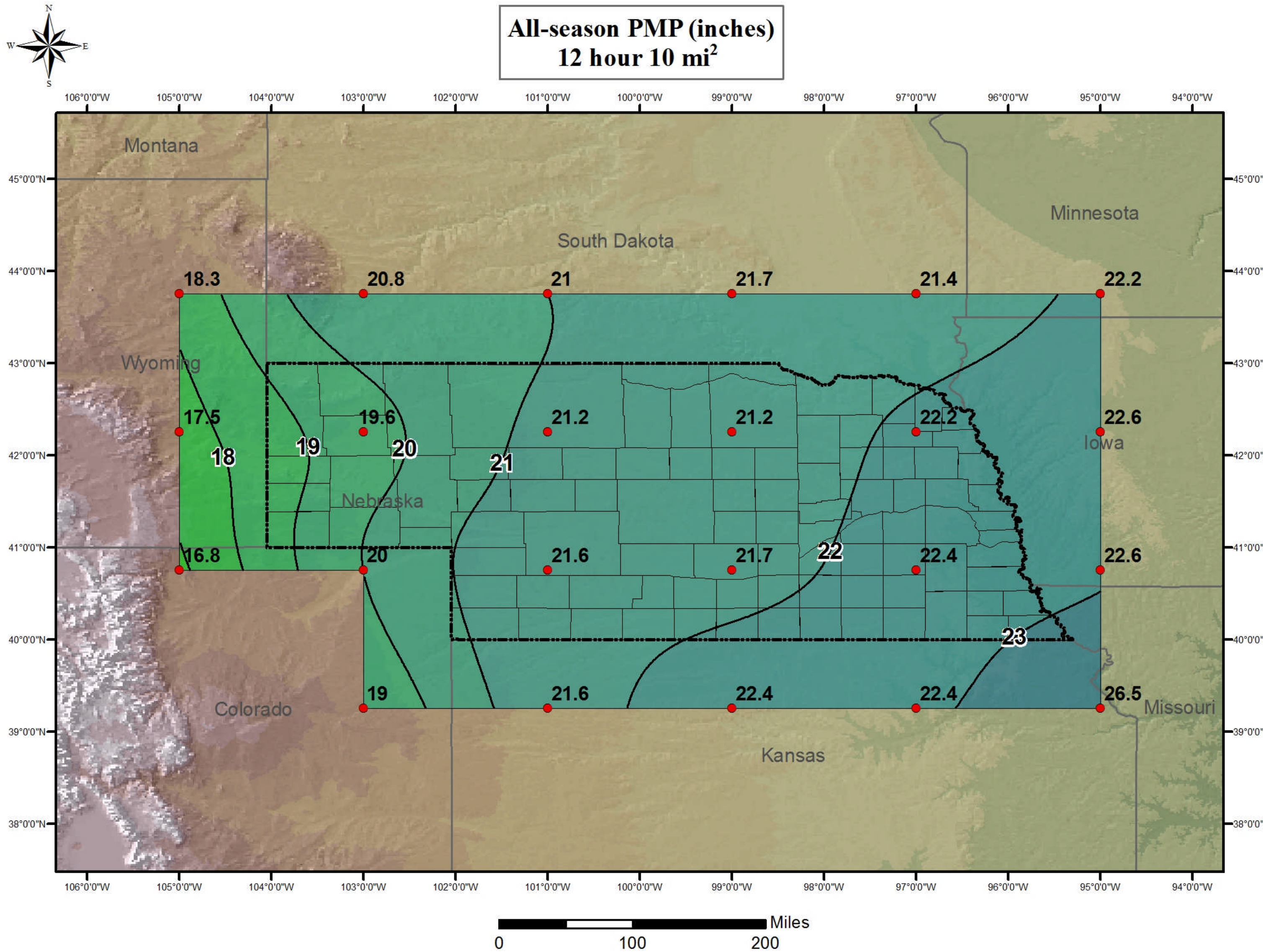

Figure 12.2 12-hour 10-square mile Nebraska statewide All-Season PMP (inches)

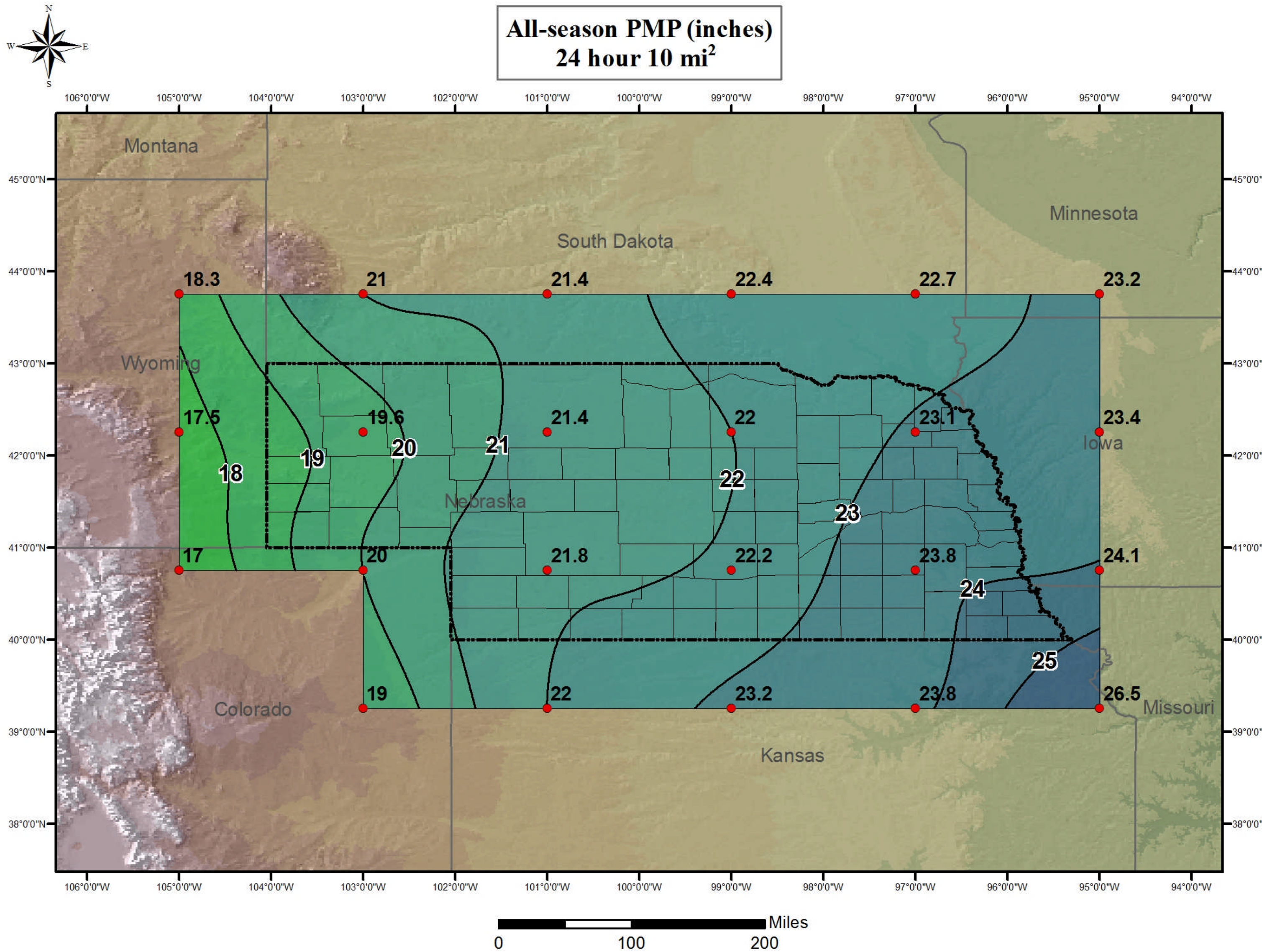

Figure 12.3 24-hour 10-square mile Nebraska statewide All-Season PMP (inches)

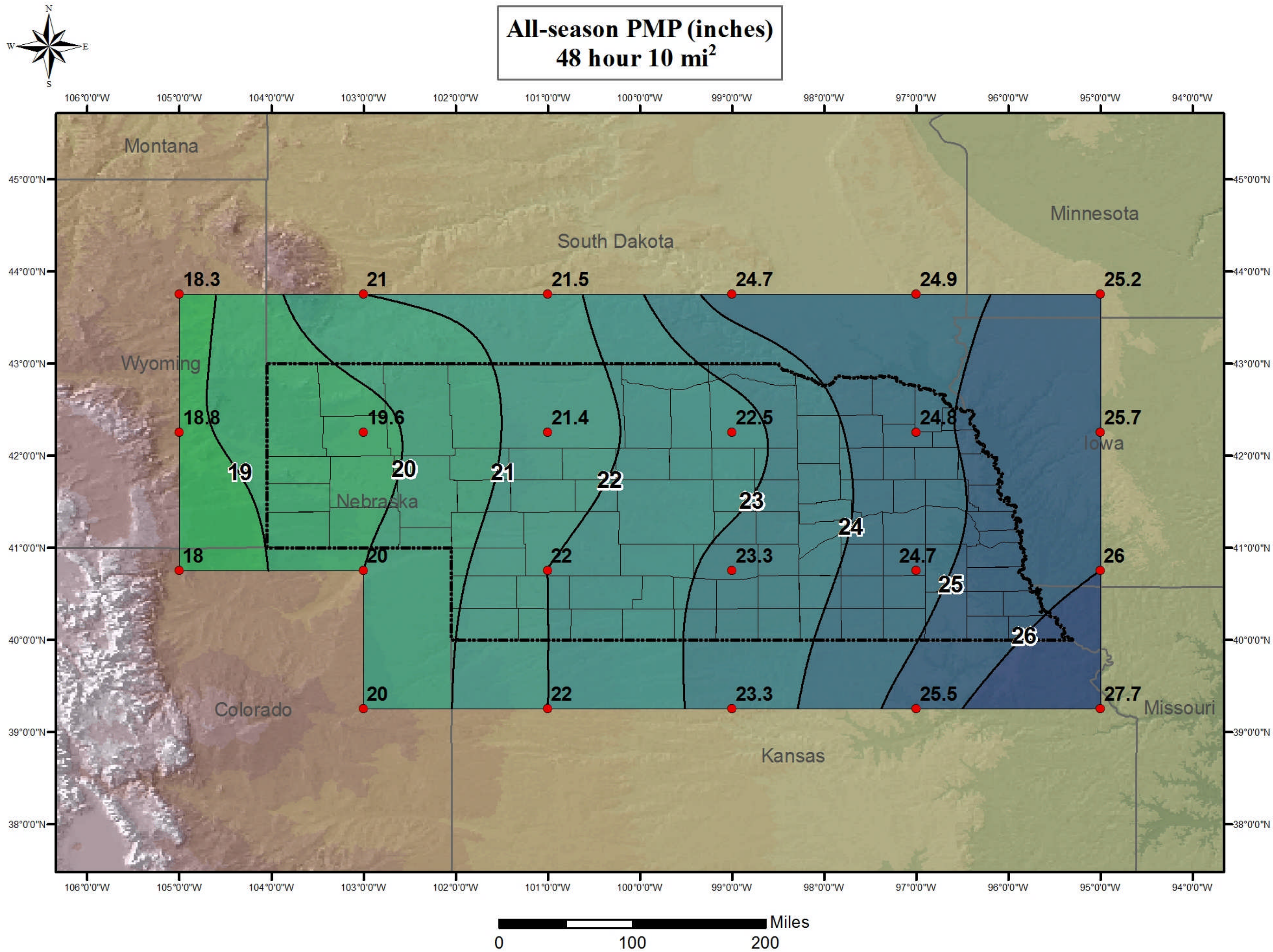

Figure 12.4 48-hour 10-square mile Nebraska statewide All-Season PMP (inches)

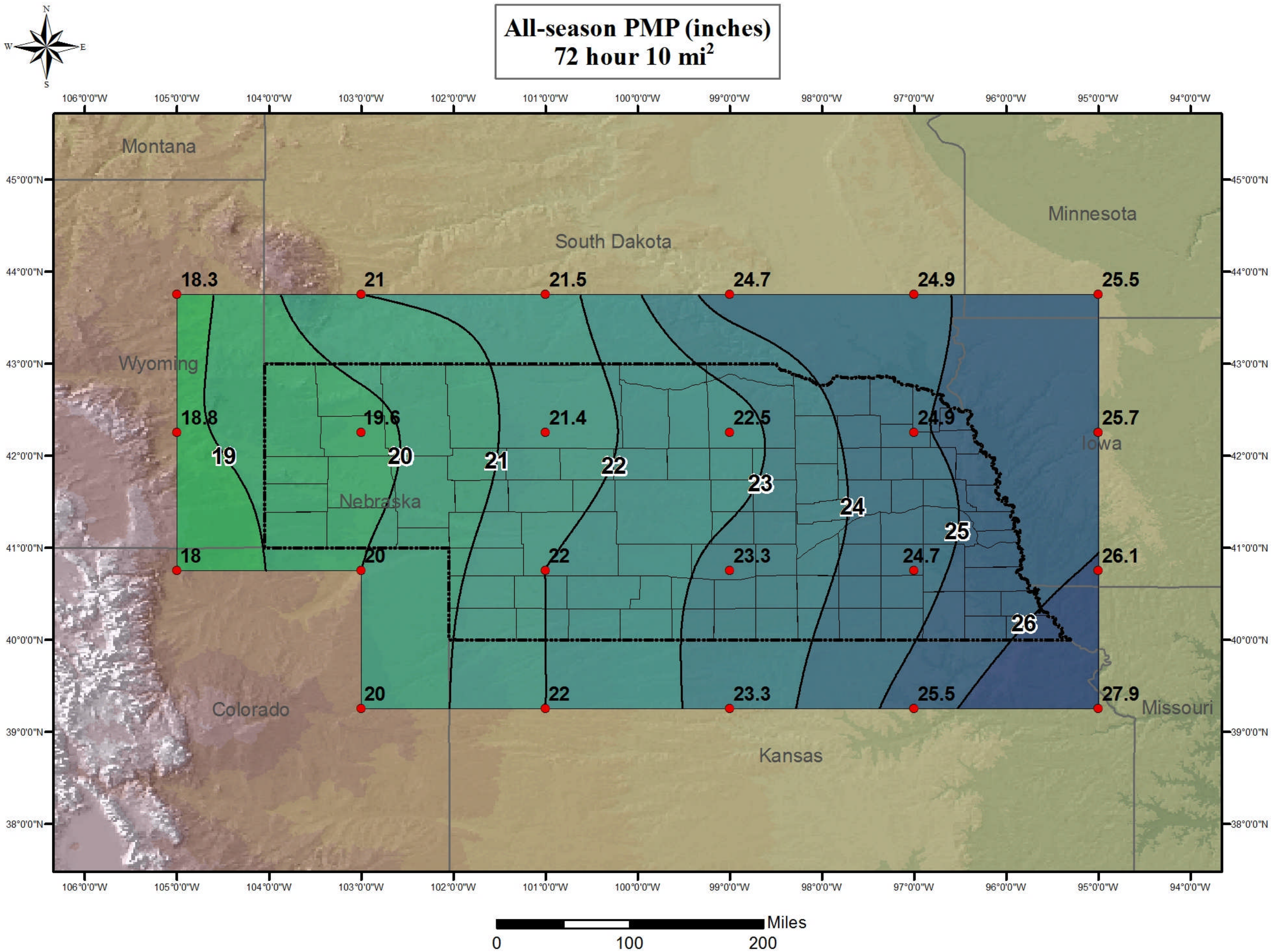

Figure 12.5 72-hour 10-square mile Nebraska statewide All-Season PMP (inches)

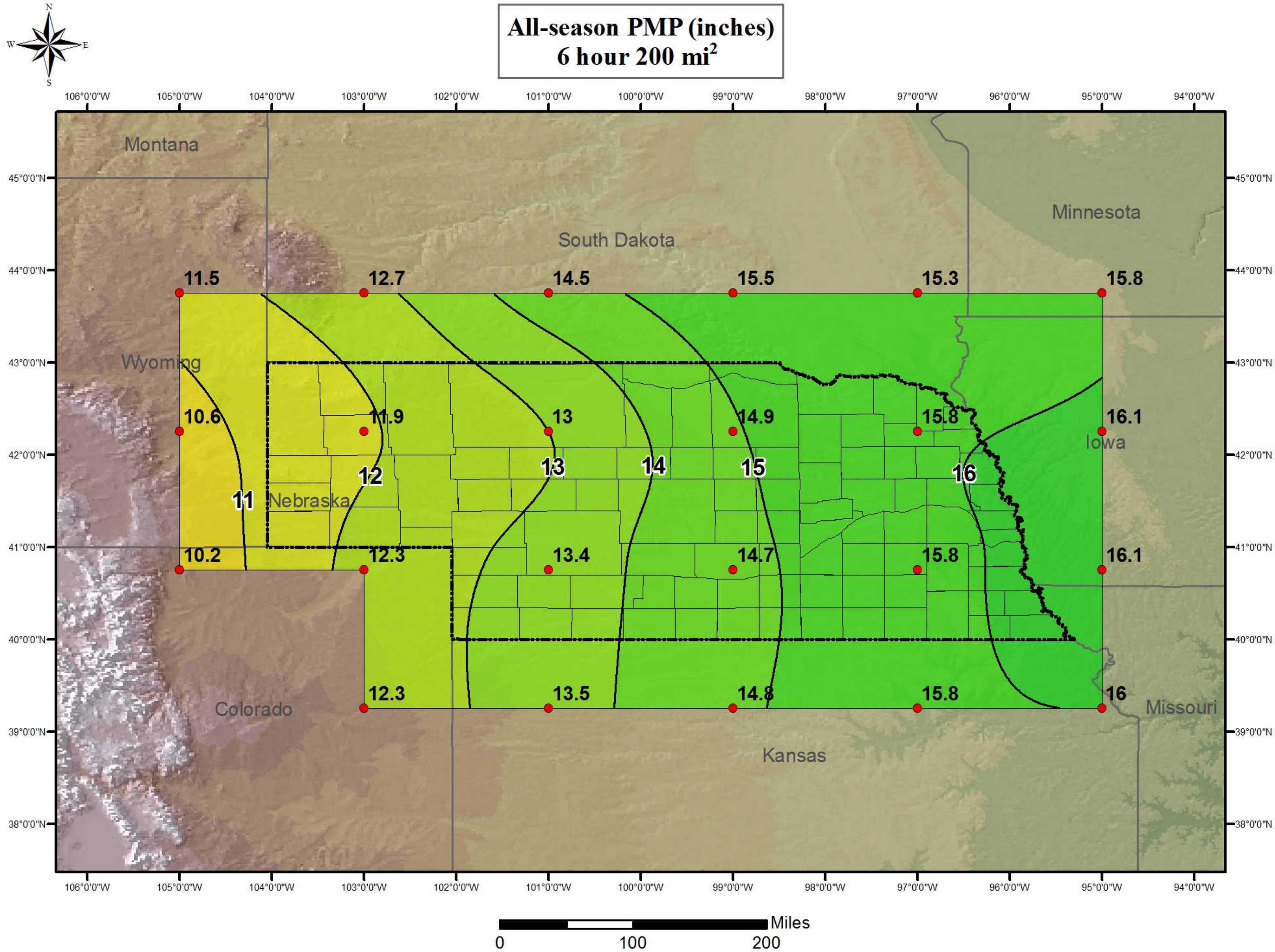

Figure 12.6 6-hour 200-square mile Nebraska statewide All-Season PMP (inches)

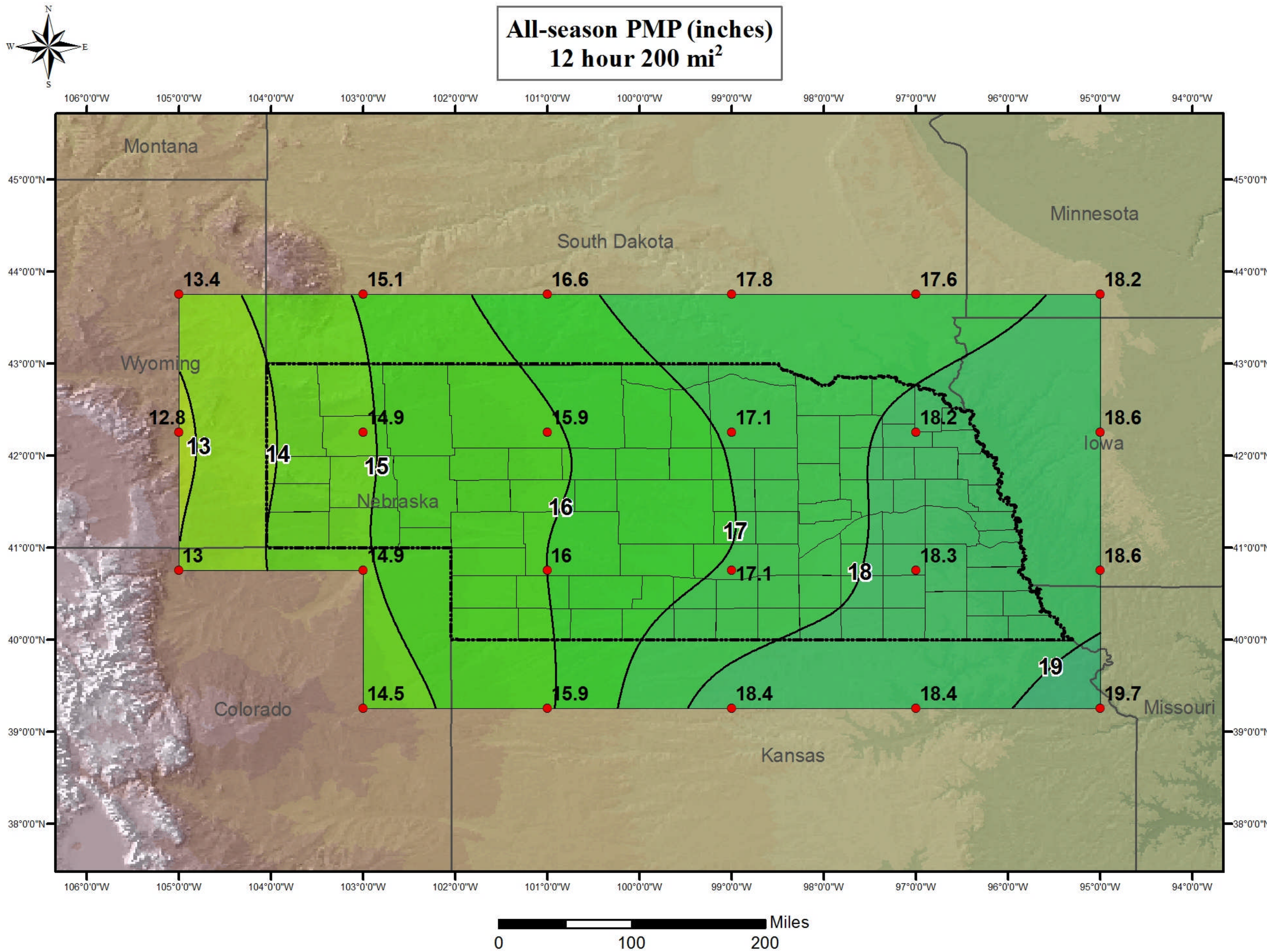

Figure 12.7 12-hour 200-square mile Nebraska statewide All-Season PMP (inches)

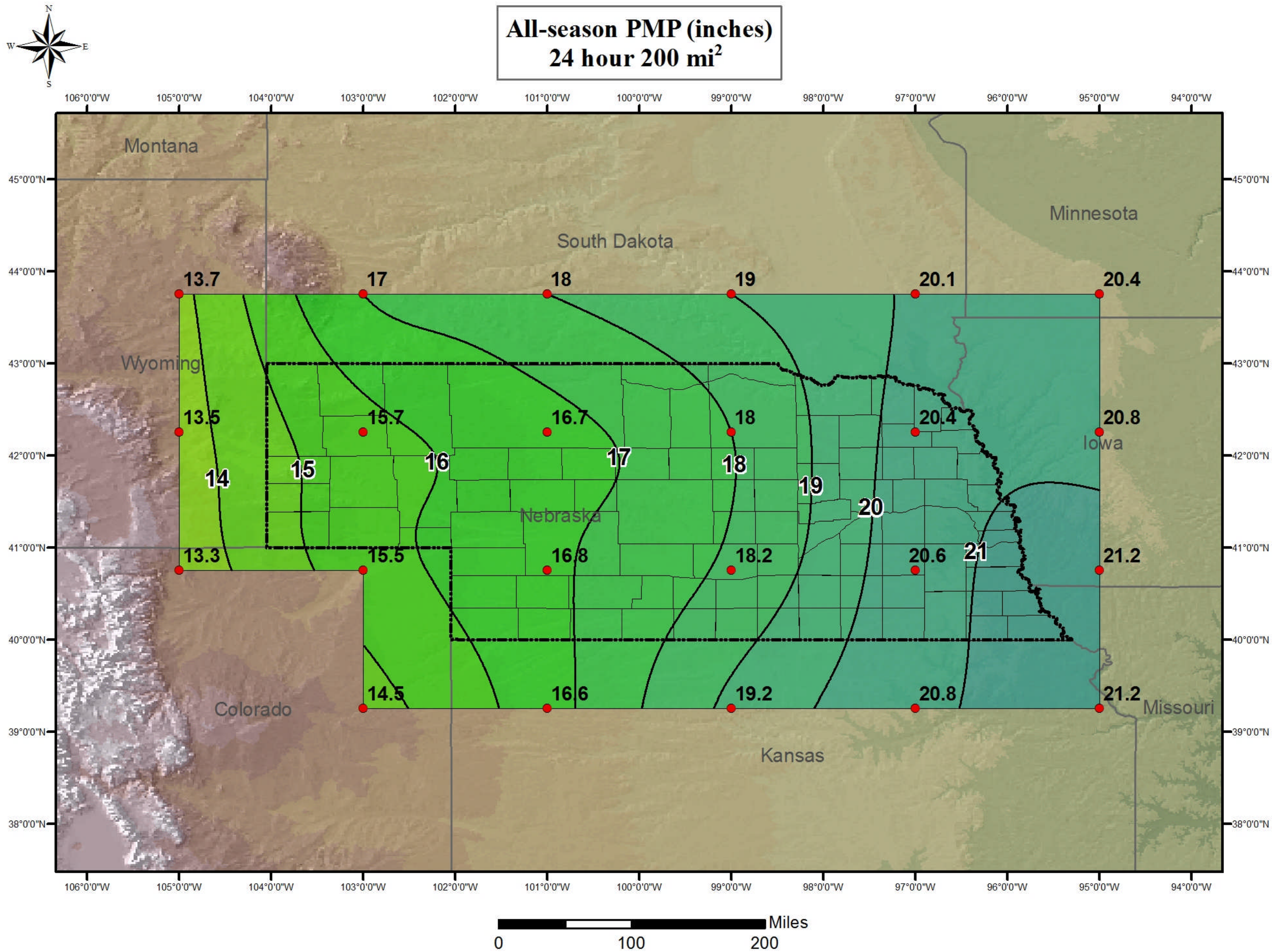

Figure 12.8 24-hour 200-square mile Nebraska statewide All-Season PMP (inches)

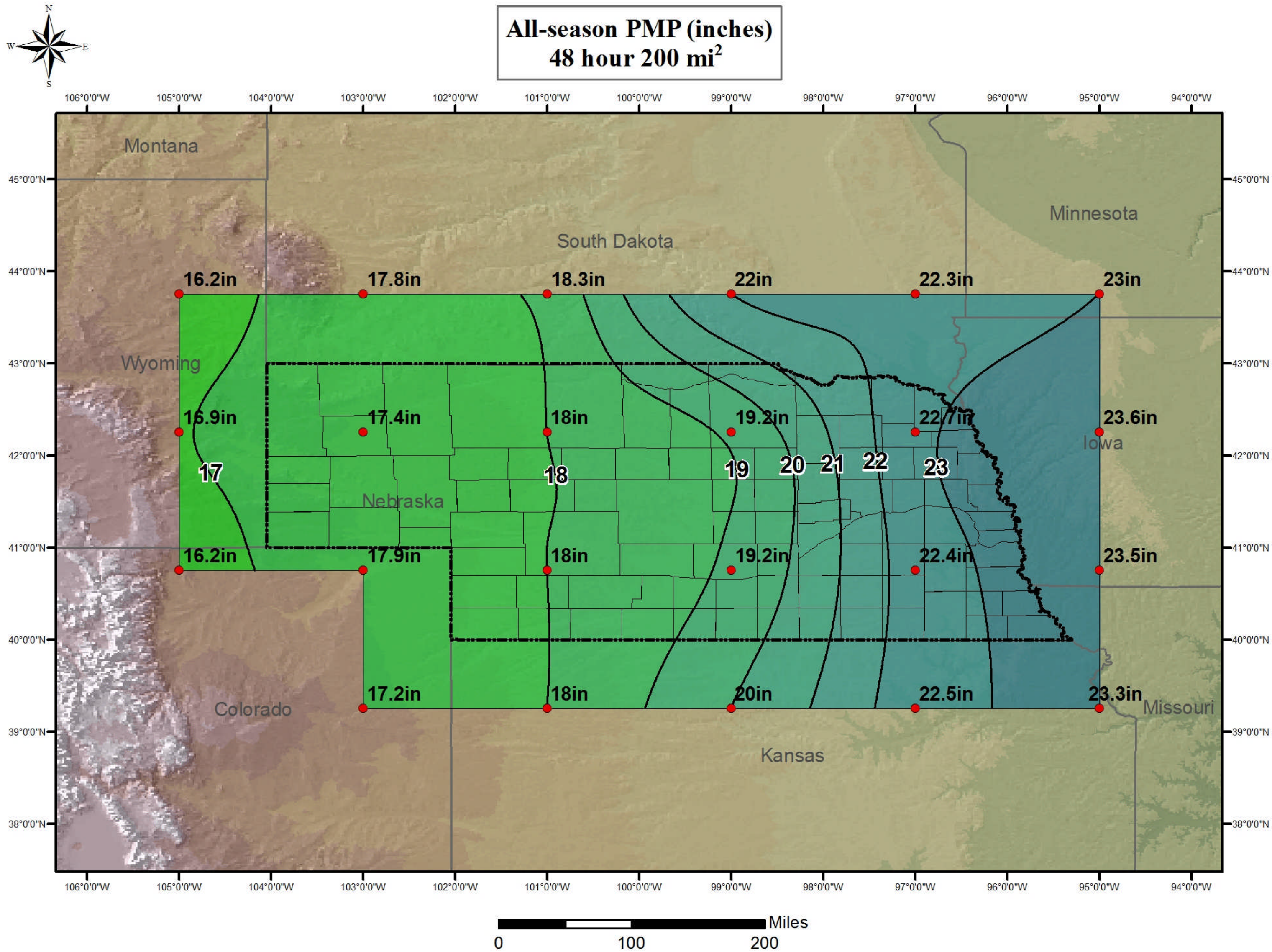

Figure 12.9 48-hour 200-square mile Nebraska statewide All-Season PMP (inches)

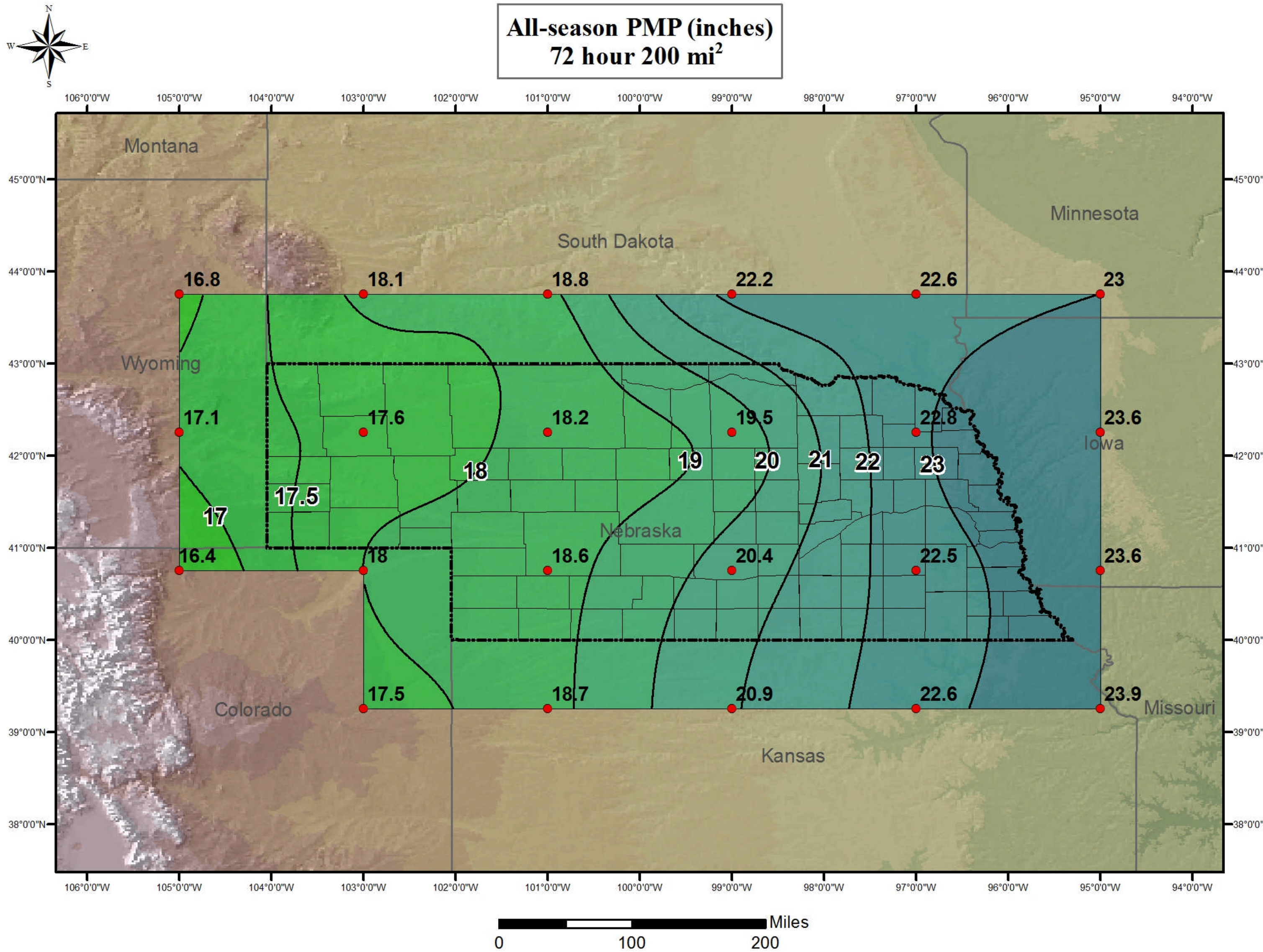

Figure 12.10 72-hour 200-square mile Nebraska statewide All-Season PMP (inches)

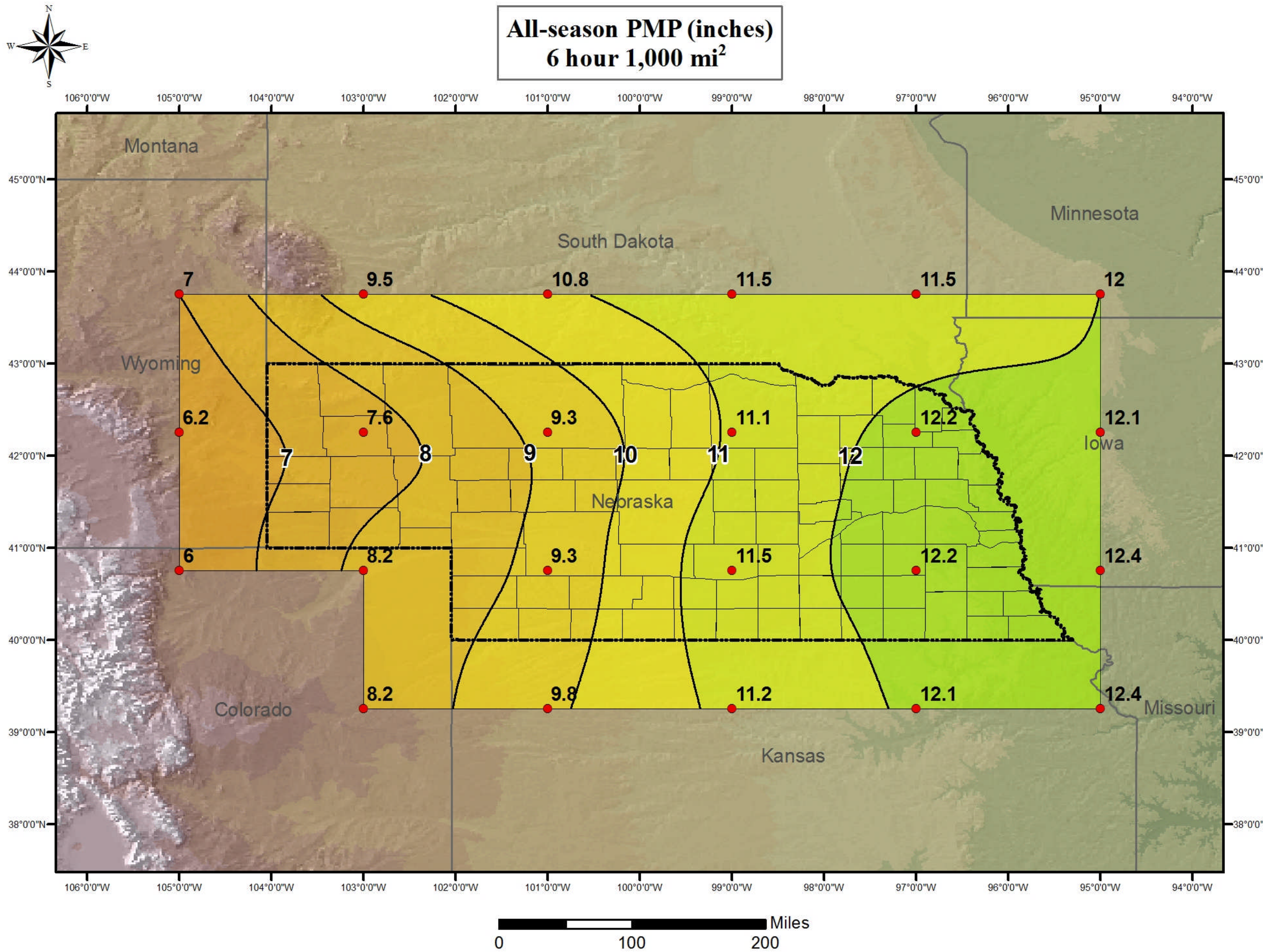

Figure 12.11 6-hour 1,000-square mile Nebraska statewide All-Season PMP (inches)

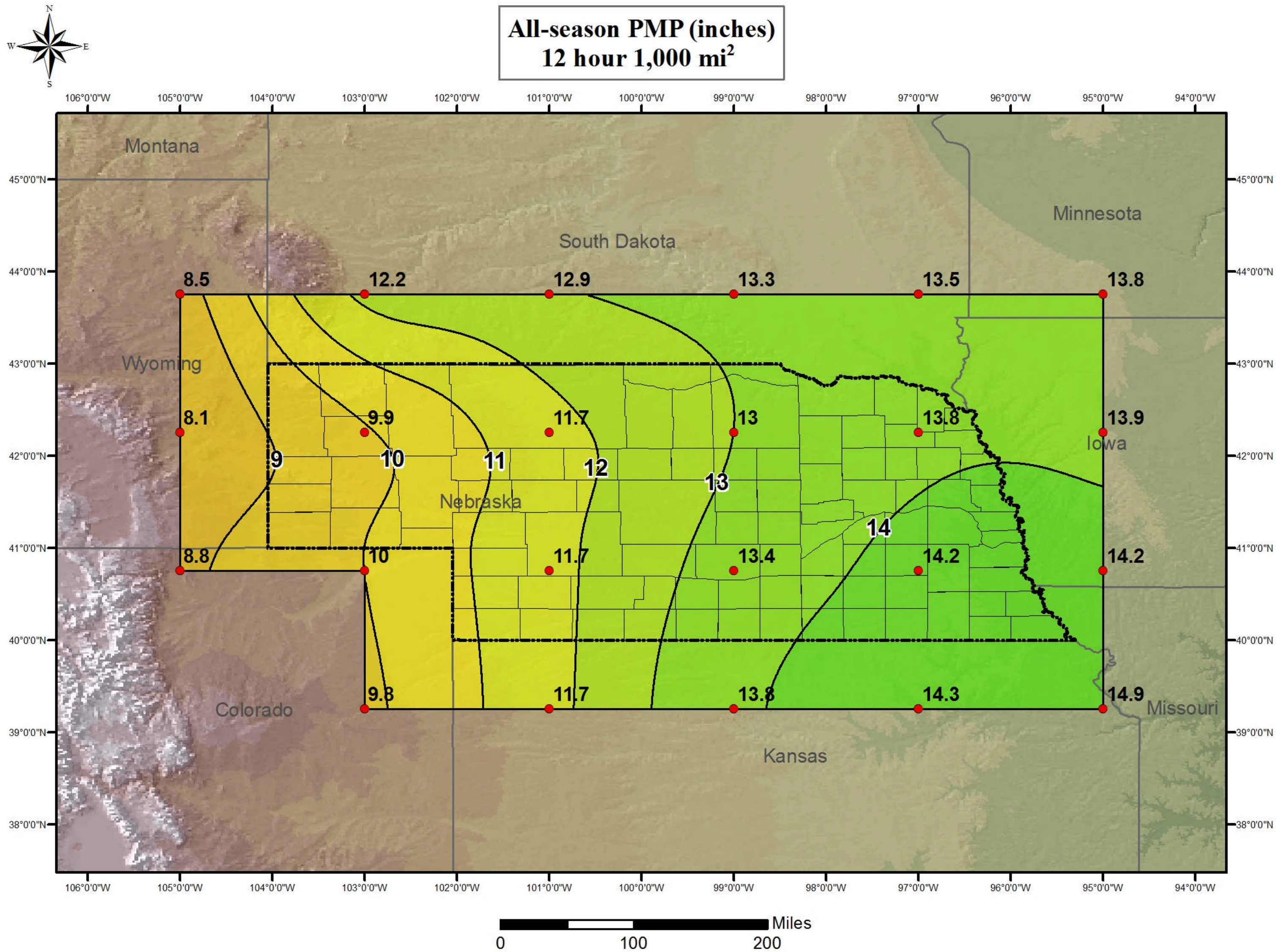

Figure 12.12 12-hour 1,000-square mile Nebraska statewide All-Season PMP (inches)

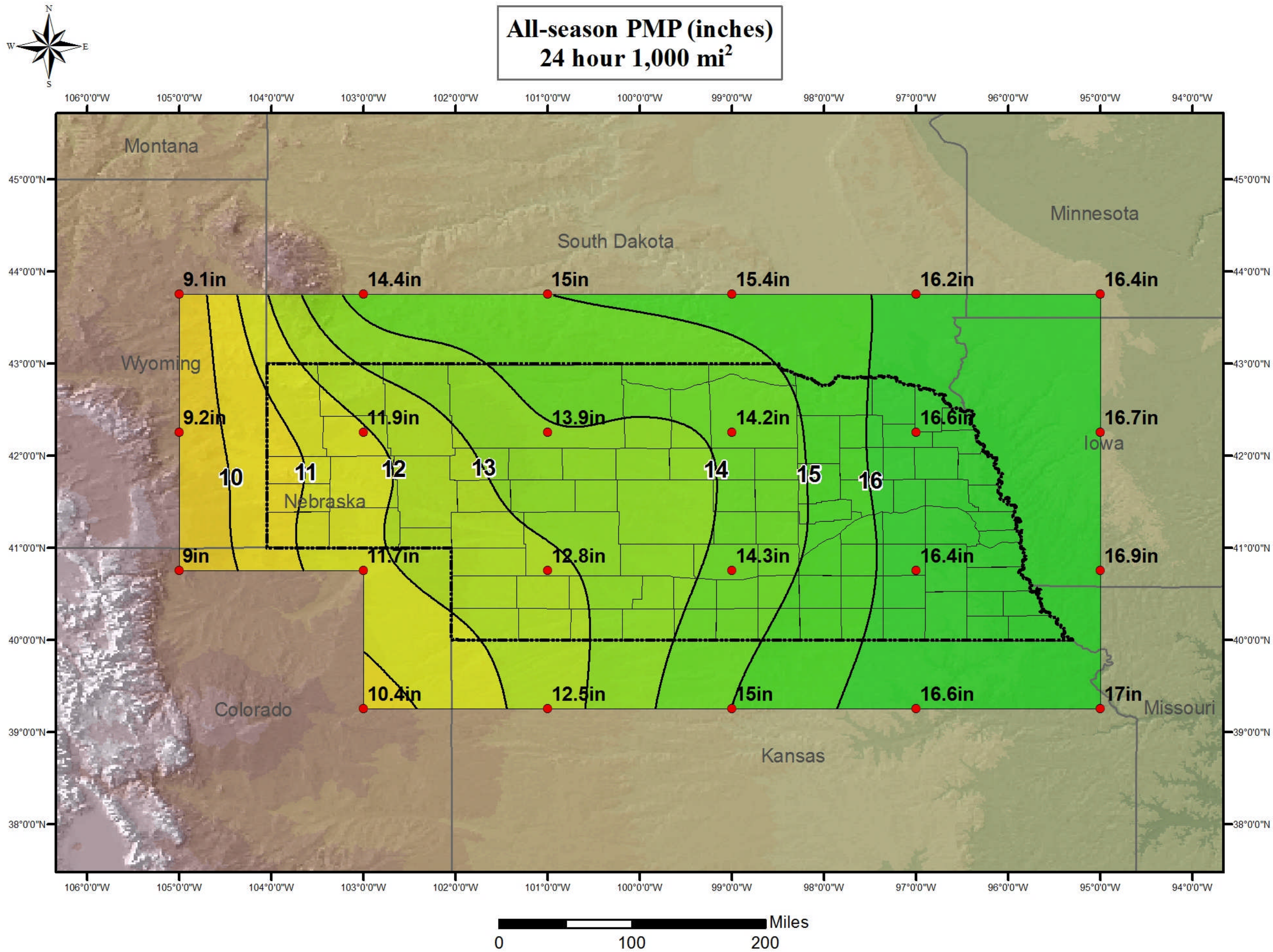

Figure 12.13 24-hour 1,000-square mile Nebraska statewide All-Season PMP (inches)

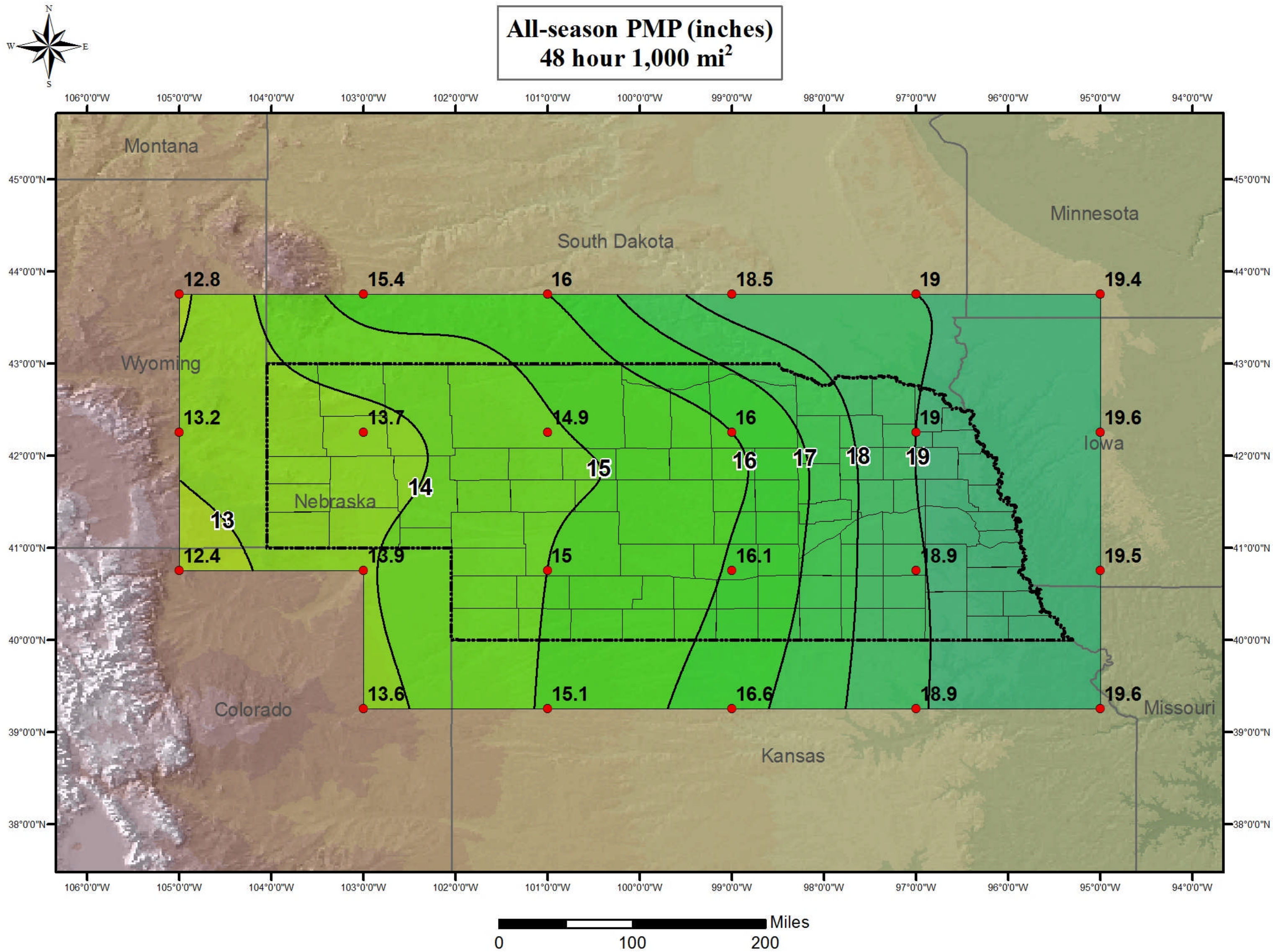

Figure 12.14 48-hour 1,000-square mile Nebraska statewide All-Season PMP (inches)

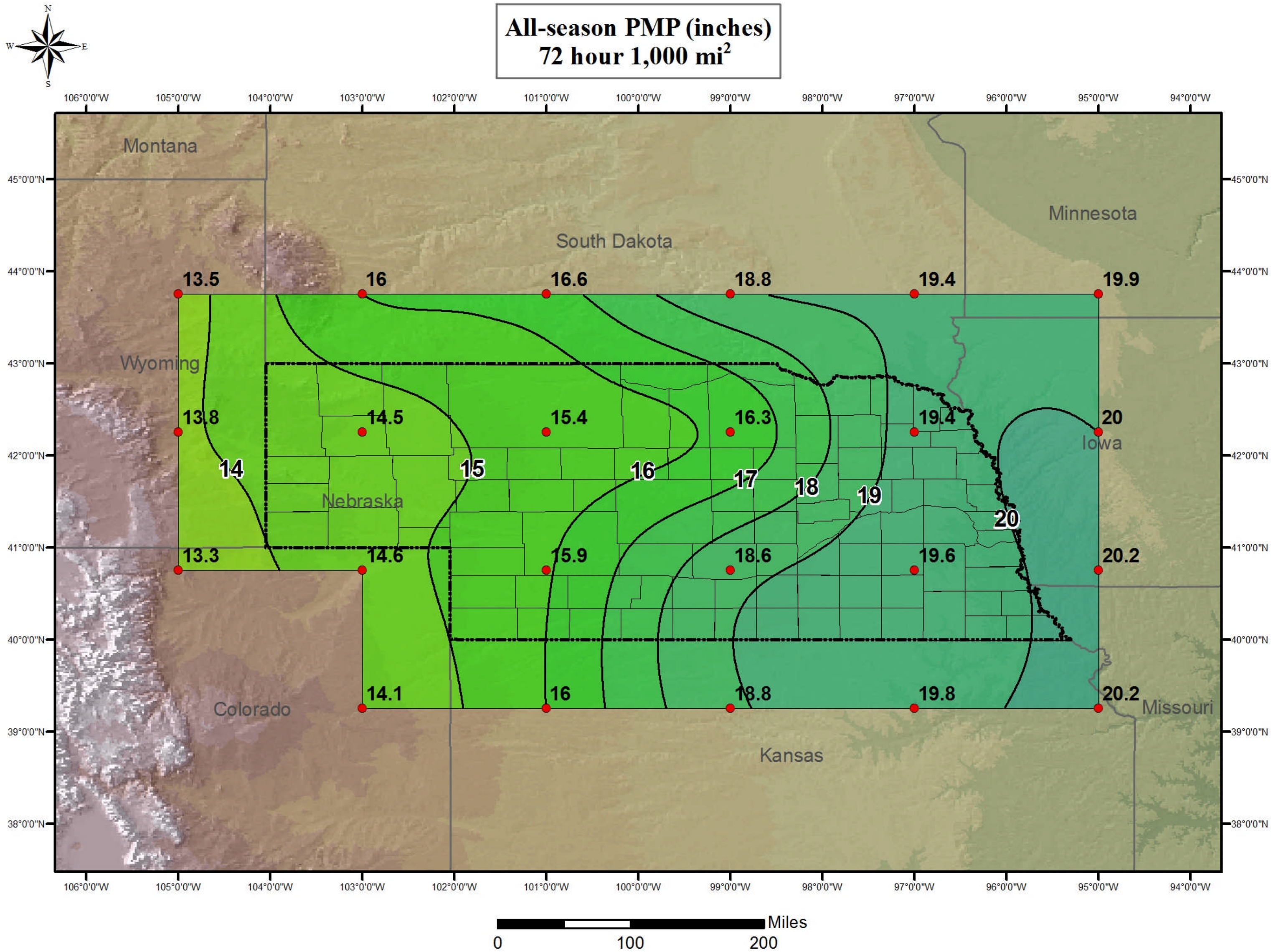

Figure 12.15   72-hour 1,000-square mile Nebraska statewide All-Season PMP (inches)

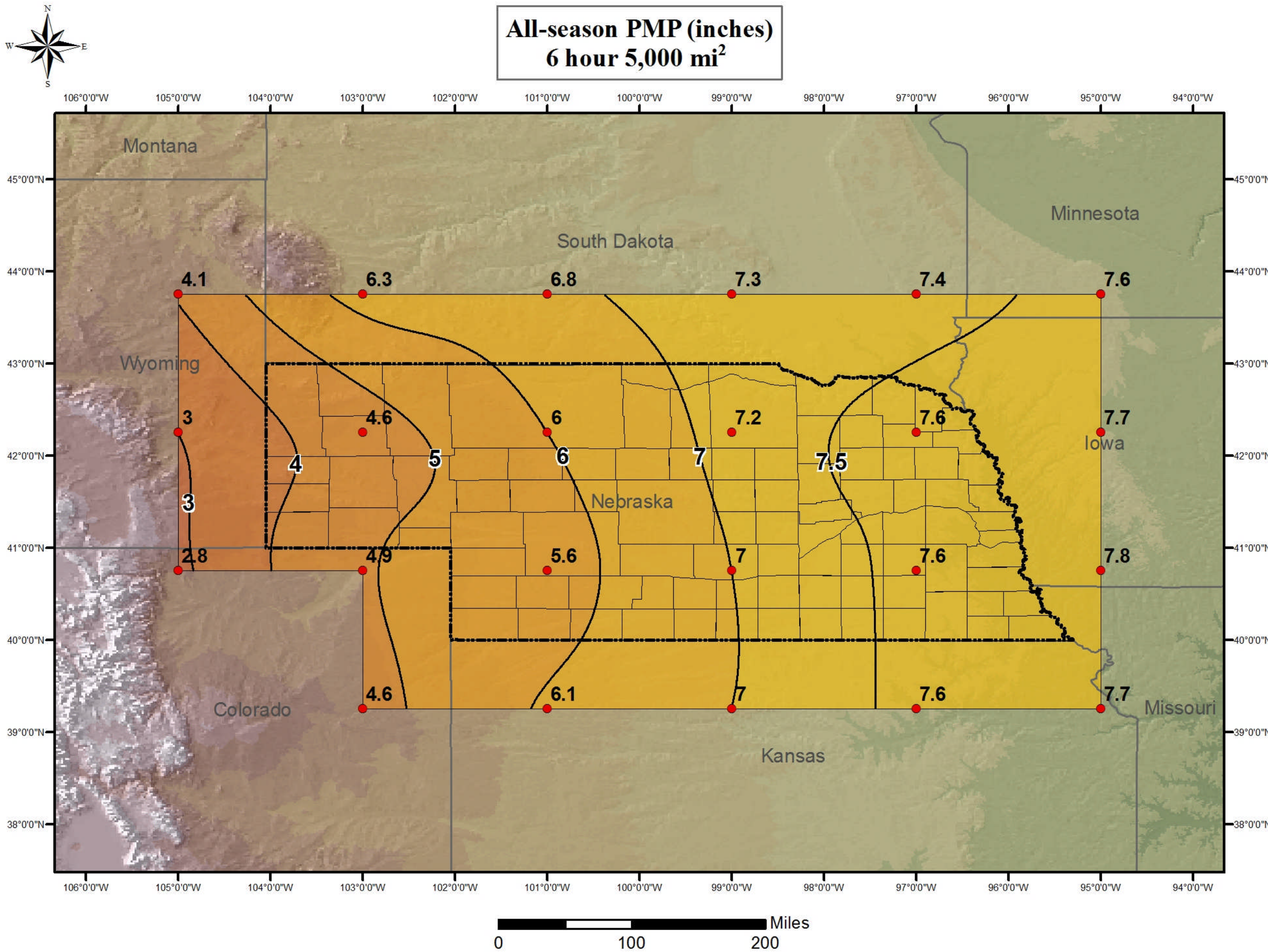

Figure 12.16   6-hour 5,000-square mile Nebraska statewide All-Season PMP (inches)

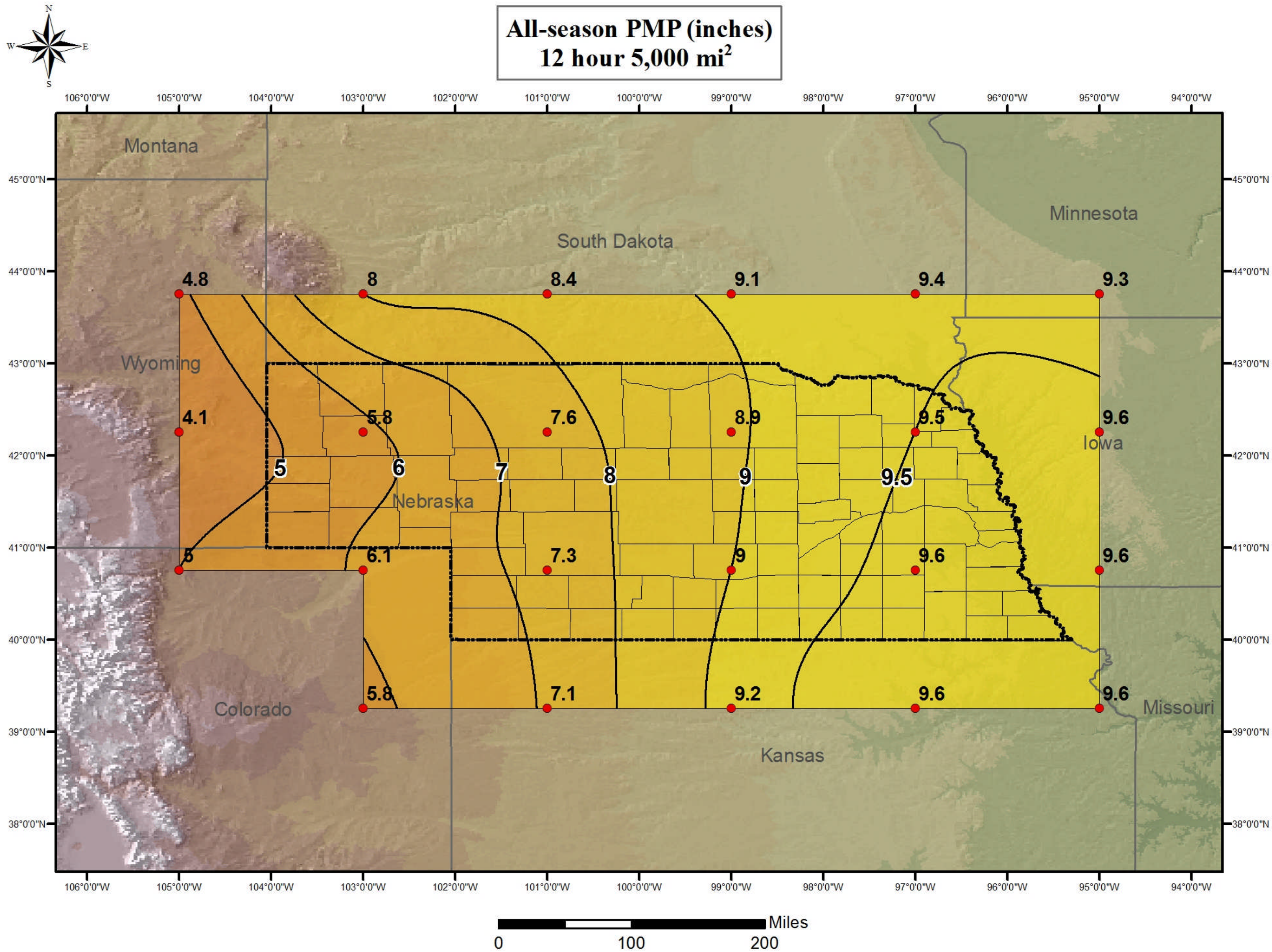

Figure 12.17 12-hour 5,000-square mile Nebraska statewide All-Season PMP (inches)

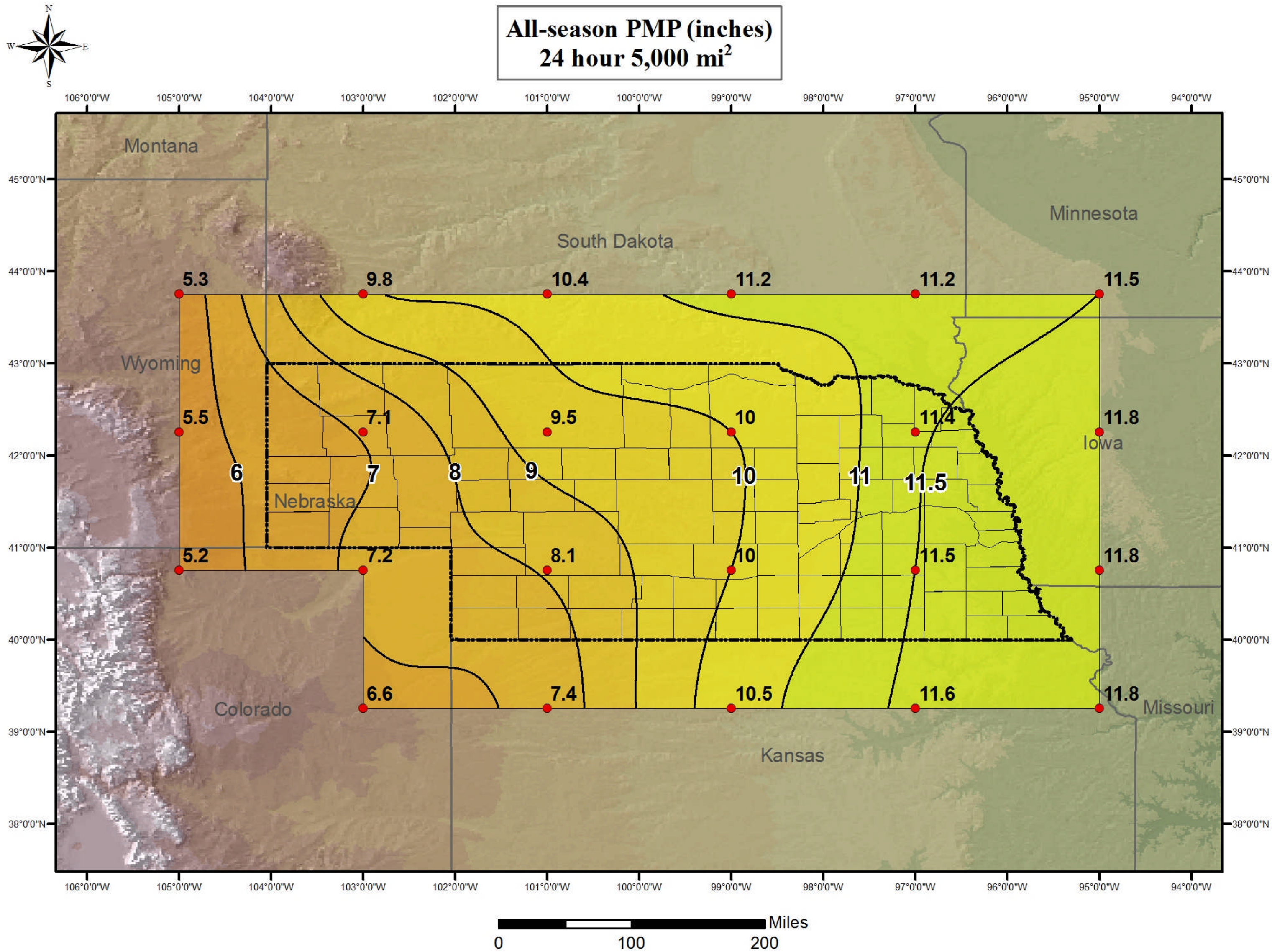

Figure 12.18 24-hour 5,000-square mile Nebraska statewide All-Season PMP (inches)

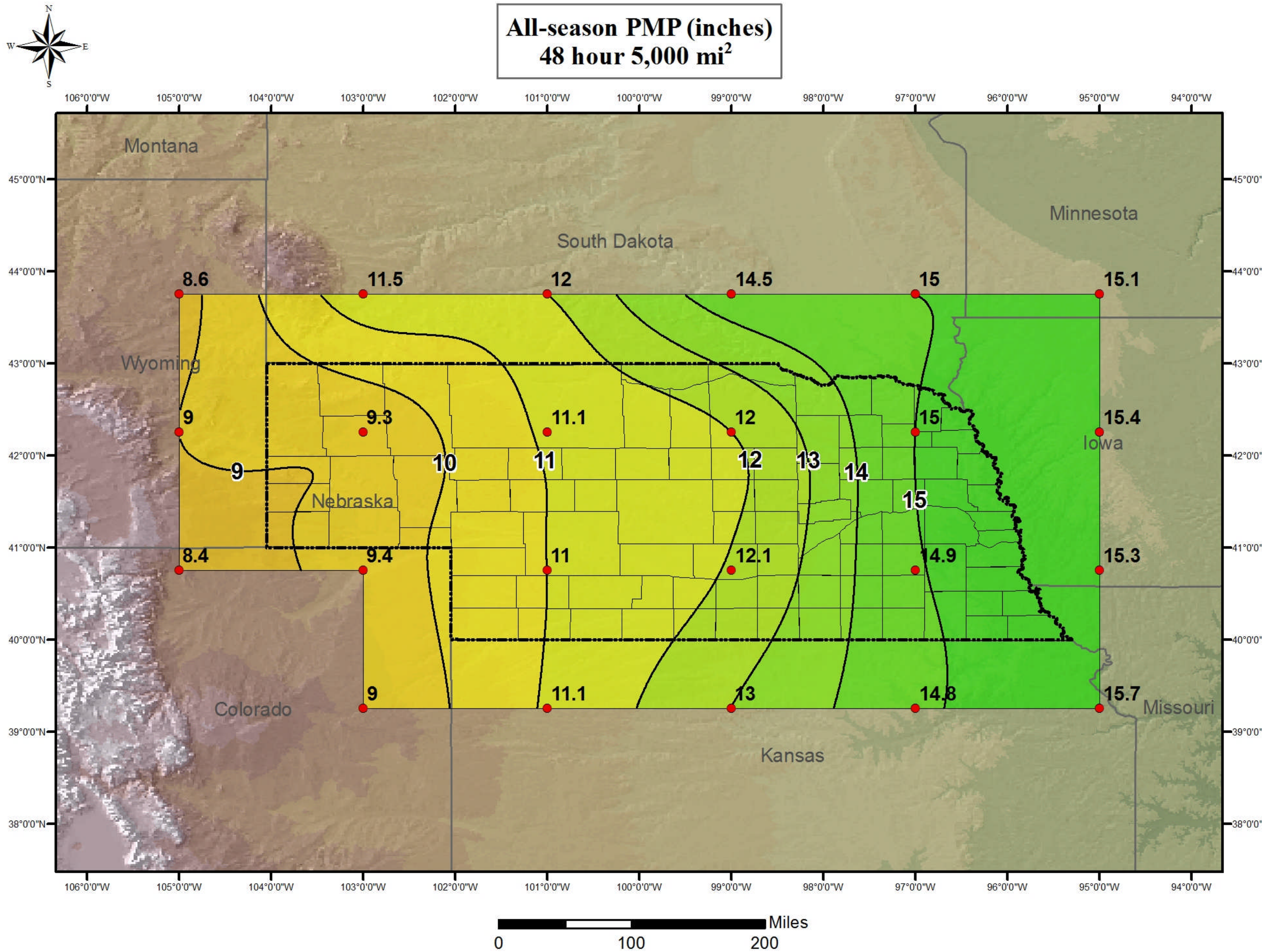

Figure 12.19 48-hour 5,000-square mile Nebraska statewide All-Season PMP (inches)

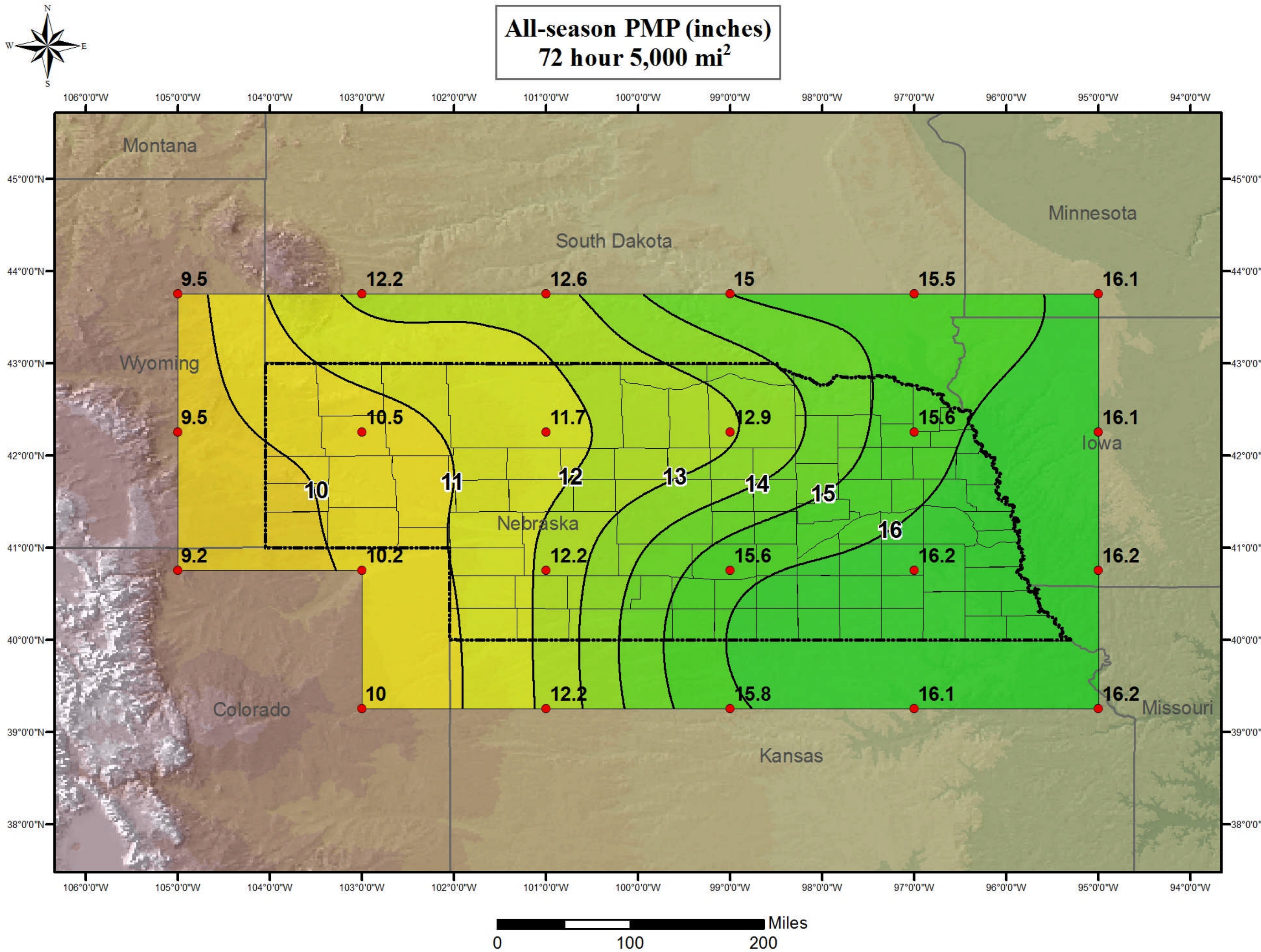

Figure 12.20 72-hour 5,000-square mile Nebraska statewide All-Season PMP (inches)

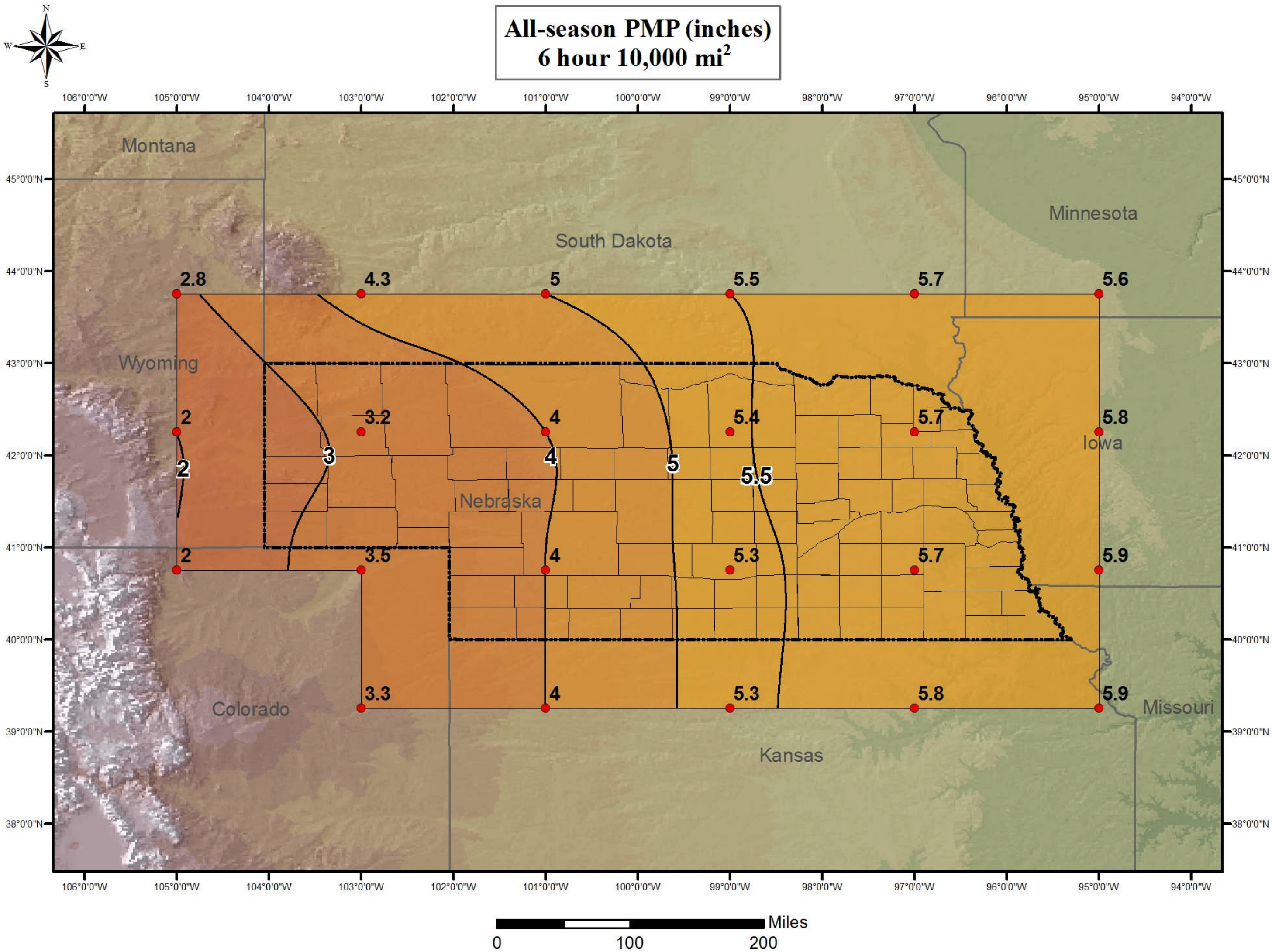

Figure 12.21 6-hour 10,000-square mile Nebraska statewide All-Season PMP (inches)

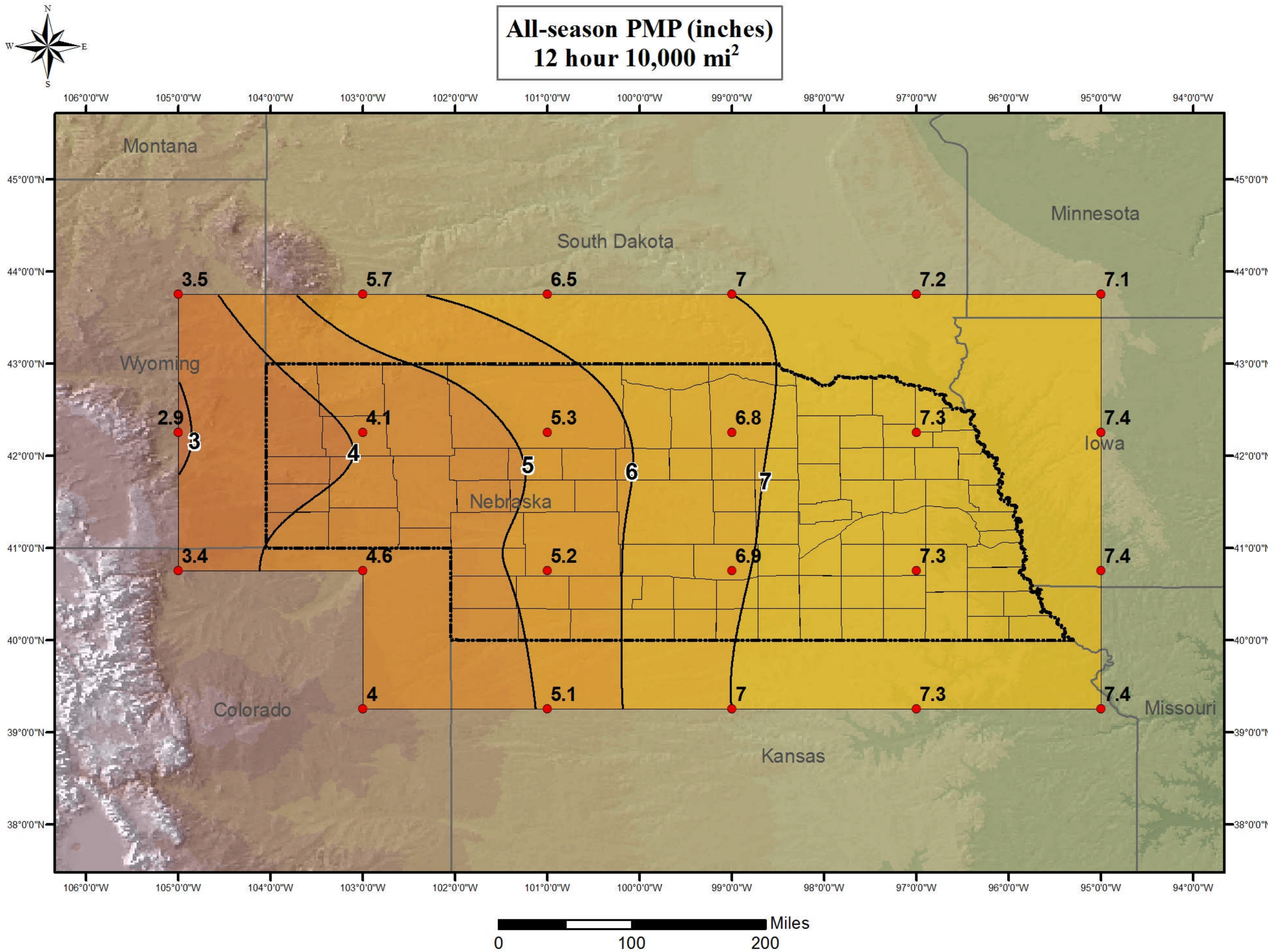

Figure 12.22 12-hour 10,000-square mile Nebraska statewide All-Season PMP (inches)

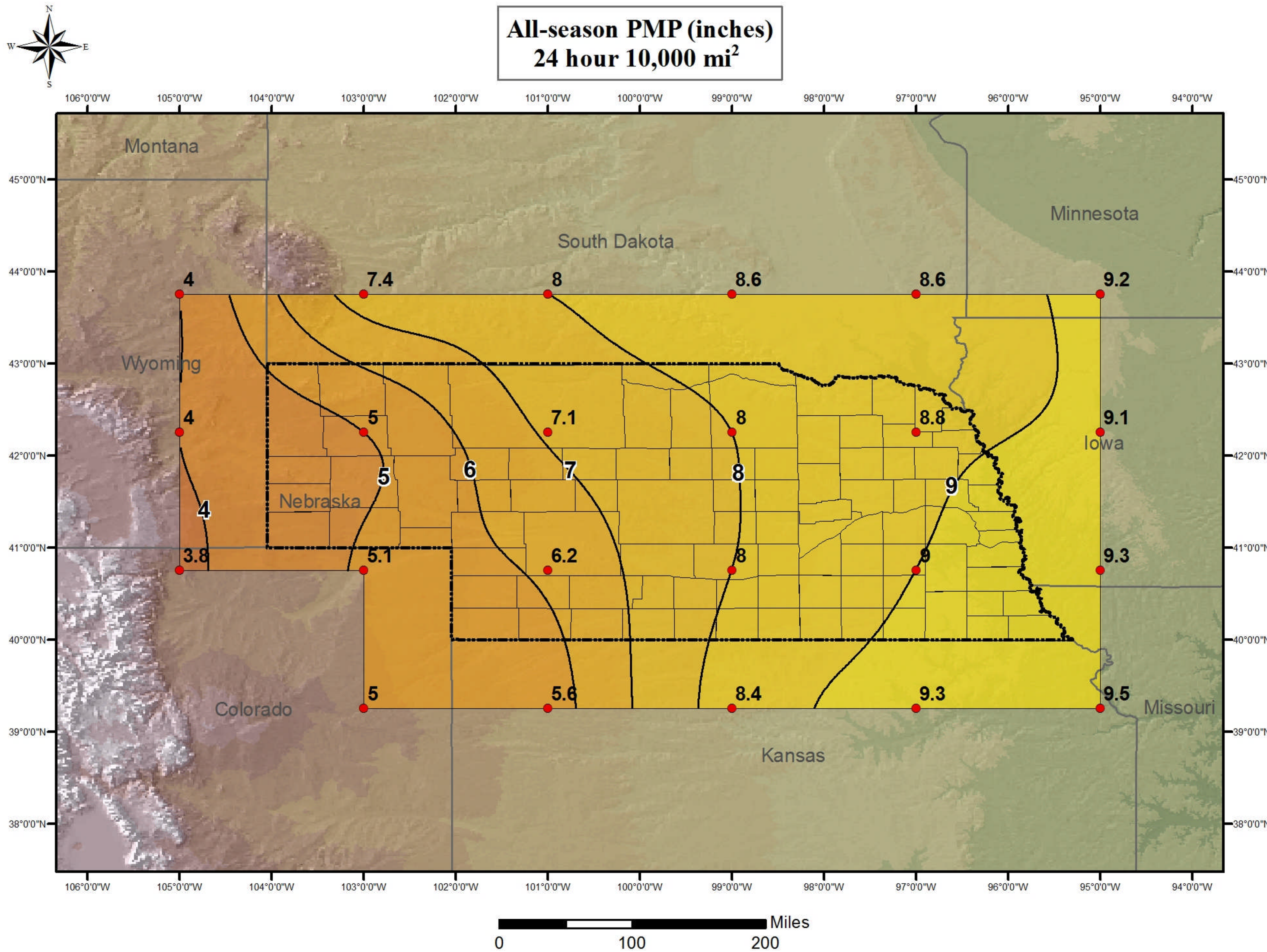

Figure 12.23 24-hour 10,000-square mile Nebraska statewide All-Season PMP (inches)

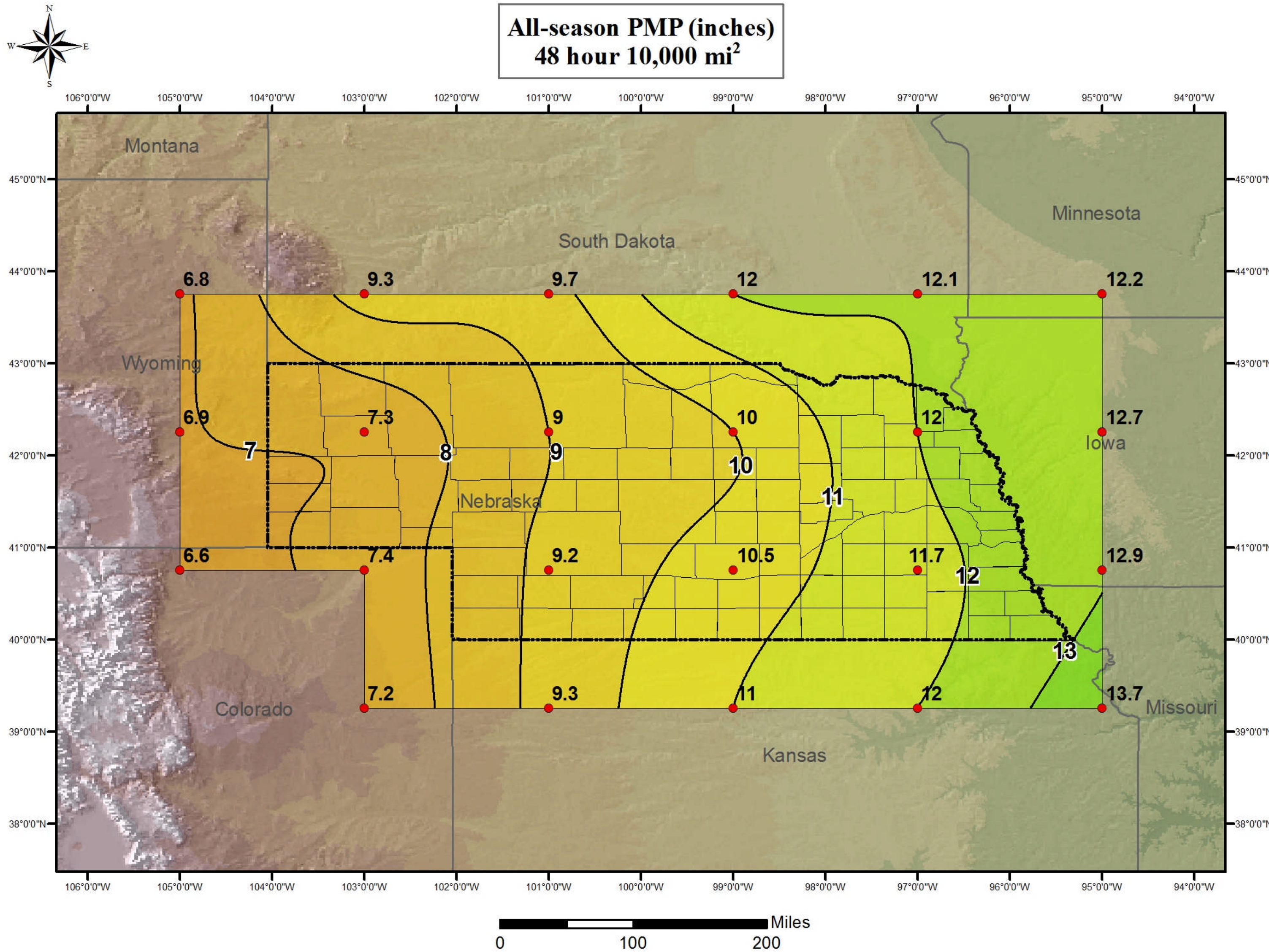

Figure 12.24 48-hour 10,000-square mile Nebraska statewide All-Season PMP (inches)

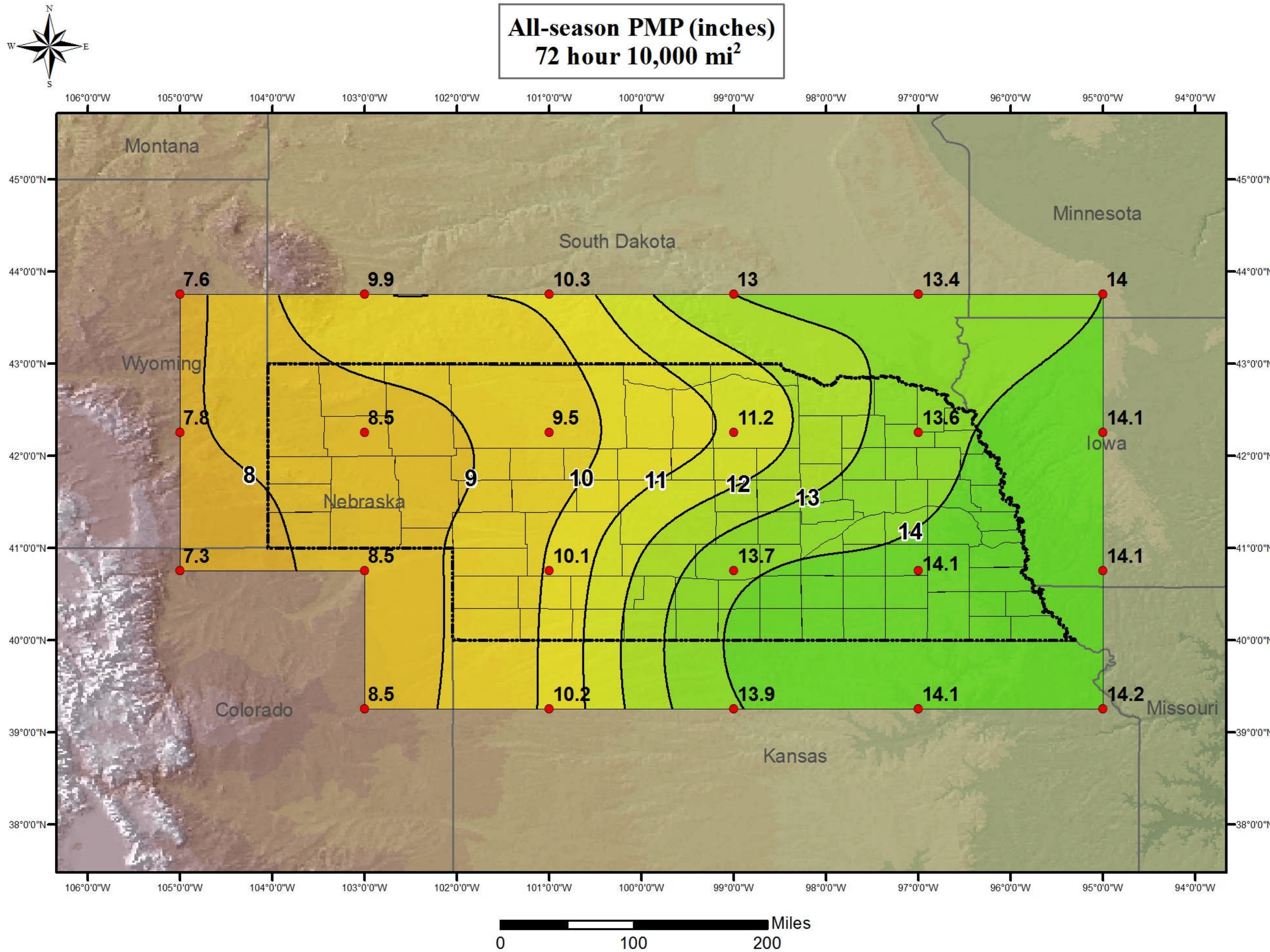

Figure 12.25 72-hour 10,000-square mile Nebraska statewide All-Season PMP (inches)

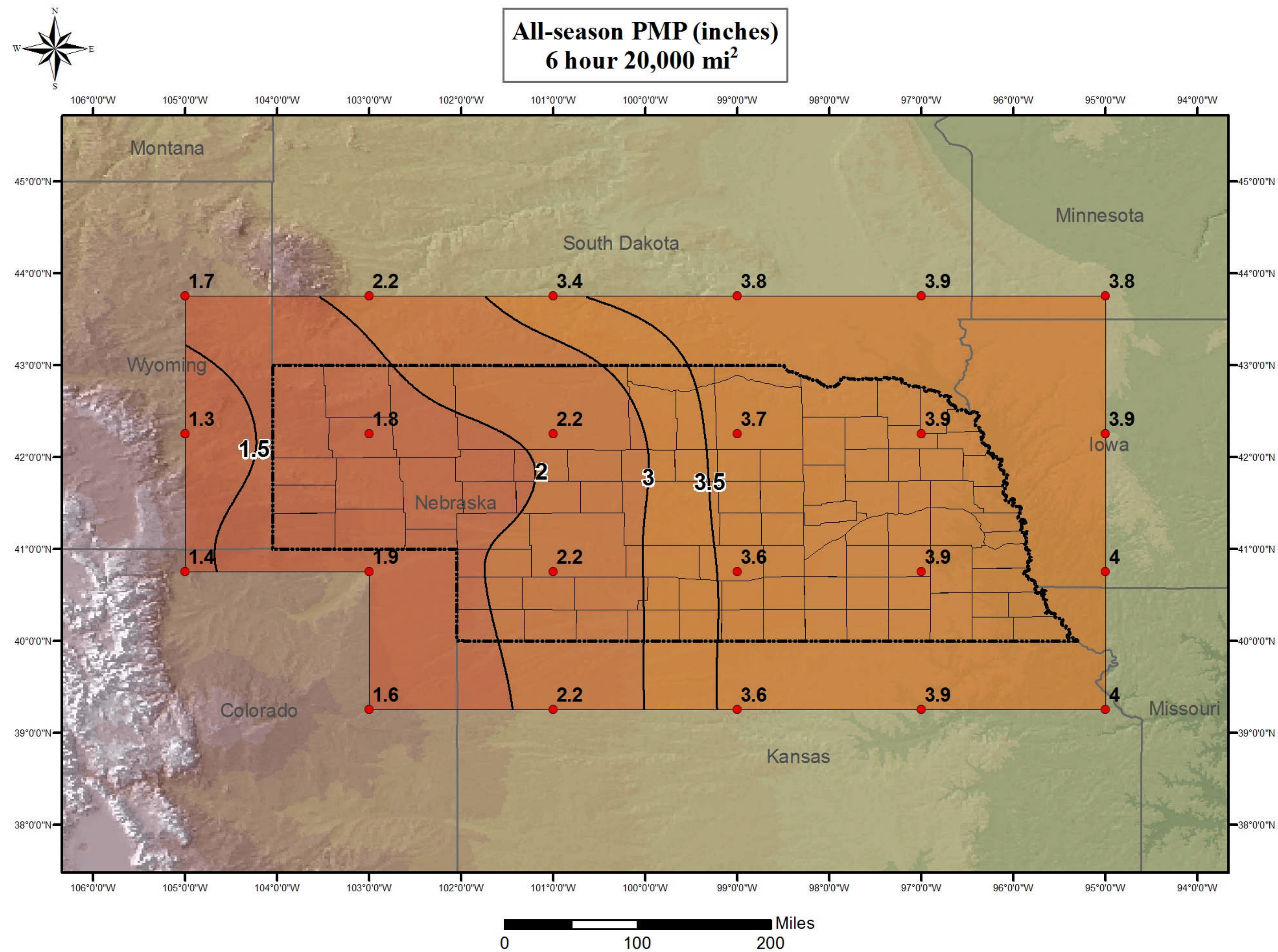

Figure 12.26 6-hour 20,000-square mile Nebraska statewide All-Season PMP (inches)

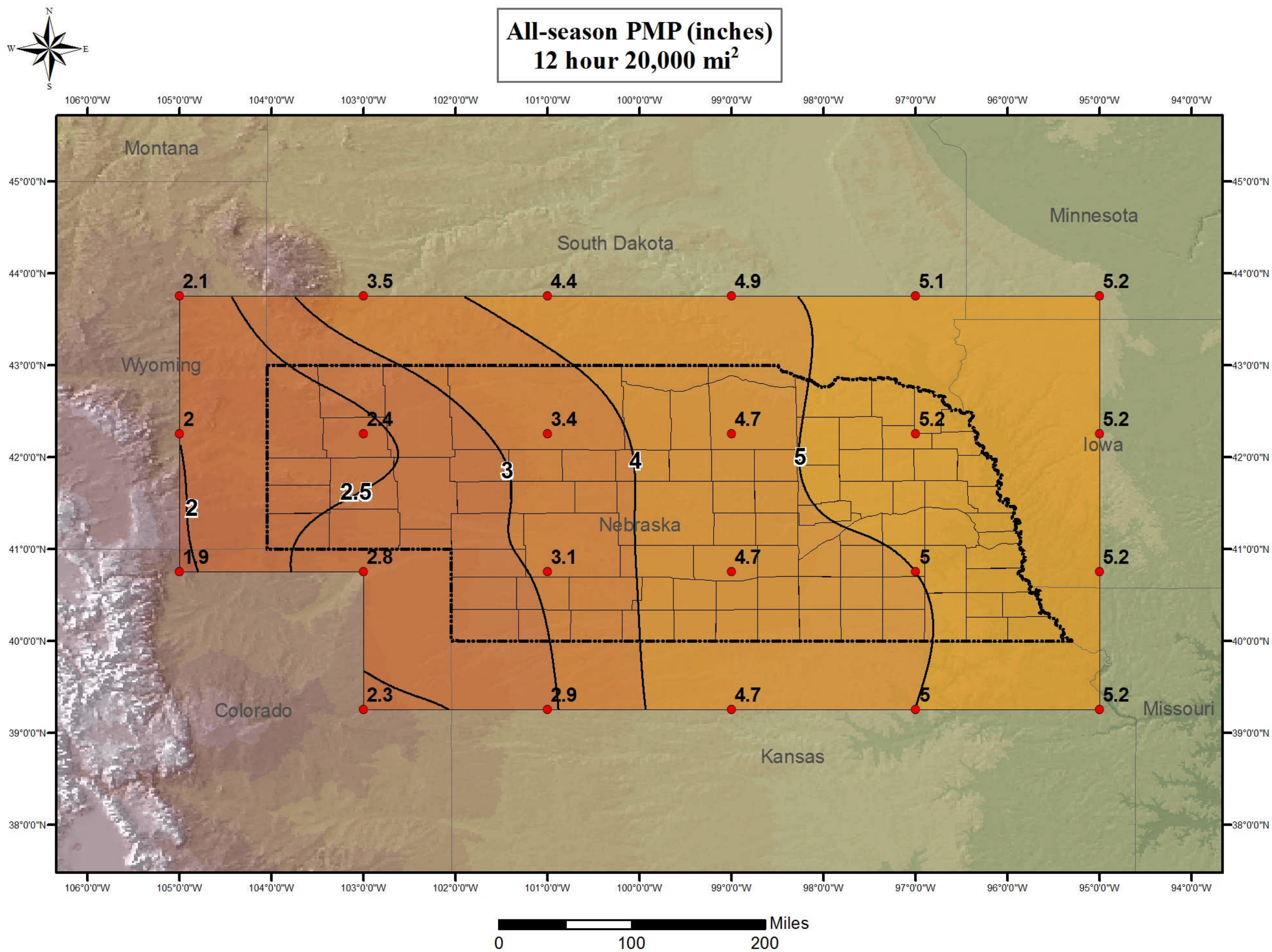

Figure 12.27 12-hour 20,000-square mile Nebraska statewide All-Season PMP (inches)

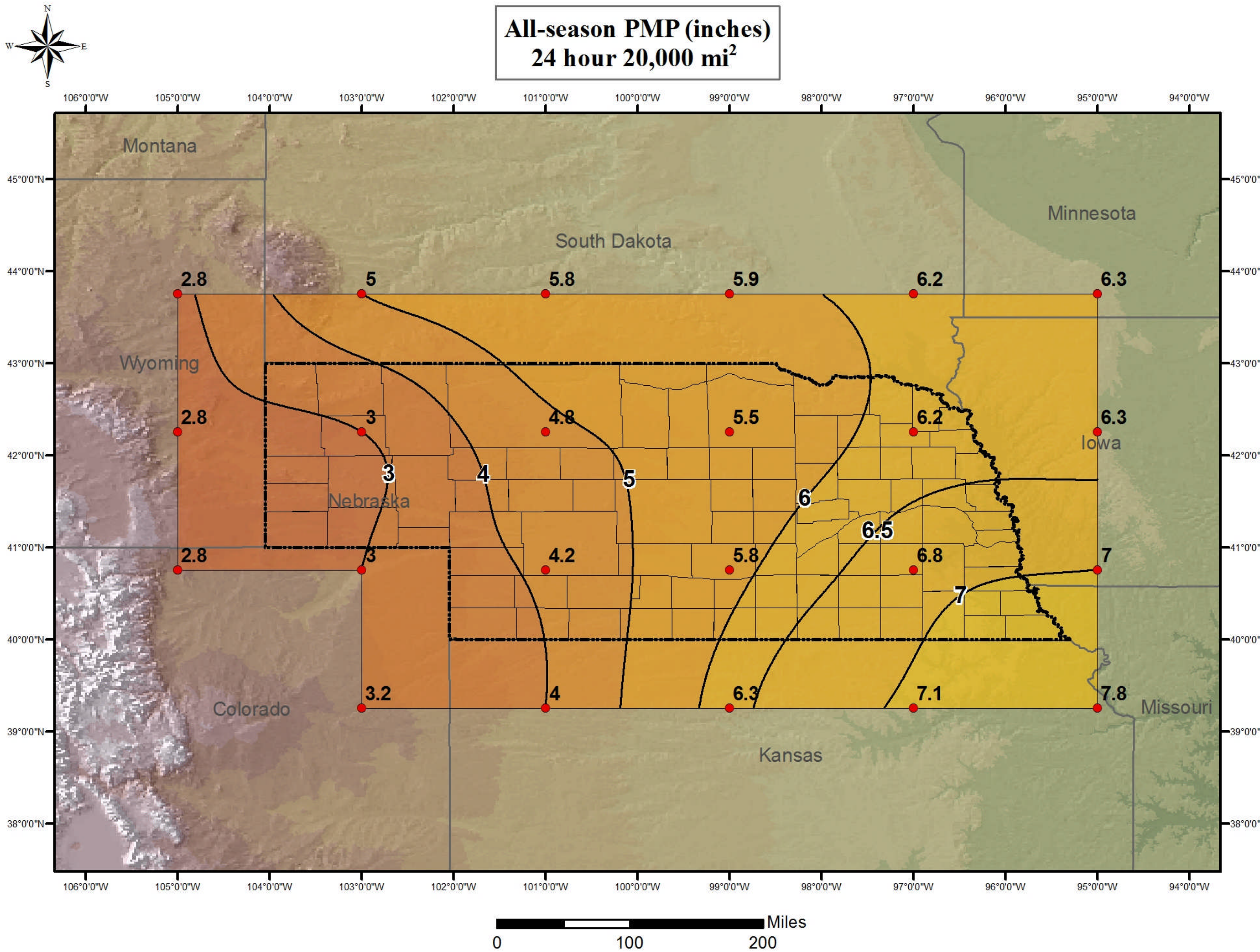

Figure 12.28 24-hour 20,000-square mile Nebraska statewide All-Season PMP (inches)

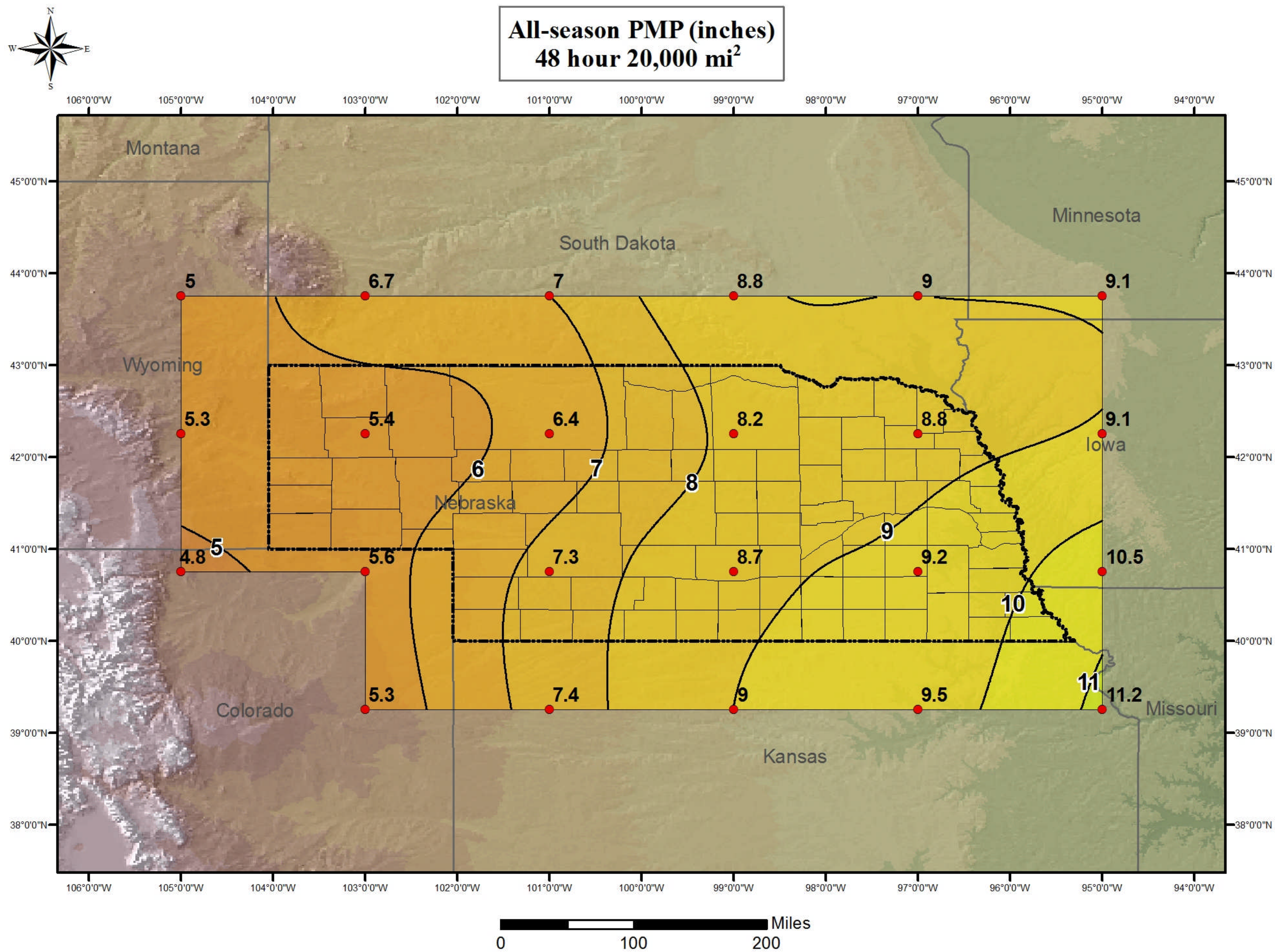

Figure 12.29   48-hour 20,000-square mile Nebraska statewide All-Season PMP (inches)

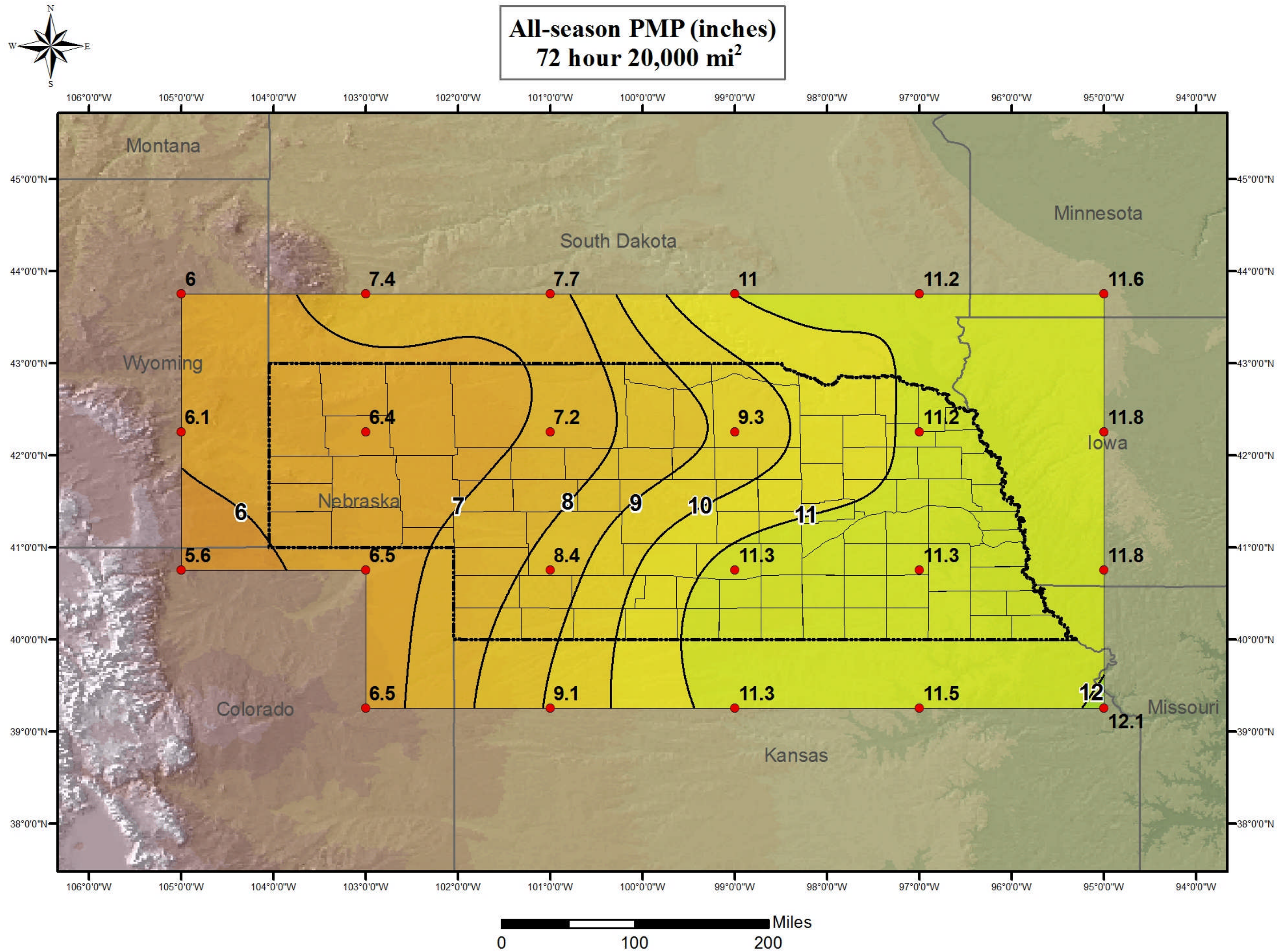

Figure 12.30 72-hour 20,000-square mile Nebraska statewide All-Season PMP (inches)

12.2 Comparison of the Nebraska Statewide PMP Values with HMR 51 PMP Values

A comparison was made at various area sizes and durations to determine the difference between results of this PMP study vs. HMR 51 values. Within the state of Nebraska, reductions ranged from a high of 56% at Grid Point 13 (Northwestern Nebraska) 24-hour 20,000-square miles to a low of 3% at Grid Point 16 (Northeastern Nebraska) 48-hour 5,000-square miles. Tables 12.1a - 12.1e provide the percent reductions from HMR 51 PMP values throughout the state of Nebraska at each area size and duration for all grid point located within the state boundary. Figures 12.31a – 12.31d show several maps with the variations in percent reduction versus HMR 51 across the state of Nebraska plotted using GIS. In order to provide further comparison and reference, HMR 51 PMP maps for durations of 6-hours, 12-hours, and 24-hours for the 10-square miles area size are provided in Figures 12.32a - 12.32c. These maps were digitized from the HMR 51 maps and have been incorporated and displayed in GIS.

Table 12.1a Comparison of the Nebraska PMP values at each grid point within the state at the 6-hour durations vs HMR 51 PMP values

Nebraska Statewide Study Derived 6-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	18.8	13.4	9.3	5.6	4.0	2.2
9	40.75	-99.00	18.7	14.7	11.5	7.0	5.3	3.6
10	40.75	-97.00	20.0	15.8	12.2	7.6	5.7	3.9
13	42.25	-103.00	18.2	11.9	7.6	4.6	3.2	1.8
14	42.25	-101.00	18.5	13.0	9.3	6.0	4.0	2.2
15	42.25	-99.00	18.9	14.9	11.1	7.2	5.4	3.7
16	42.25	-97.00	20.1	15.8	12.2	7.6	5.7	3.9

HMR 51 6-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	24.7	18.0	13.1	7.7	5.7	4.2
9	40.75	-99.00	25.5	18.7	13.6	8.1	6.2	4.9
10	40.75	-97.00	26.2	19.1	13.9	8.4	6.4	5.4
13	42.25	-103.00	23.1	16.6	12.1	7.1	5.1	3.6
14	42.25	-101.00	24.0	17.5	12.8	7.5	5.6	4.1
15	42.25	-99.00	24.8	18.1	13.2	7.9	6.0	4.6
16	42.25	-97.00	25.4	18.6	13.5	8.1	6.3	5.0

Nebraska Statewide Study 6-hour Percent Reduction from HMR 51 Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	24%	25%	29%	27%	30%	48%
9	40.75	-99.00	27%	21%	15%	13%	14%	26%
10	40.75	-97.00	24%	17%	12%	9%	12%	28%
13	42.25	-103.00	21%	28%	37%	36%	38%	50%
14	42.25	-101.00	23%	26%	27%	20%	29%	46%
15	42.25	-99.00	24%	18%	16%	9%	10%	19%
16	42.25	-97.00	21%	15%	10%	7%	9%	22%

Table 12.1b Comparison of the Nebraska PMP values at each grid point within the state at the 12-hour durations vs HMR 51 PMP values

Nebraska Statewide Study Derived 12-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	21.6	16.0	11.7	7.3	5.2	3.1
9	40.75	-99.00	21.7	17.1	13.4	9.0	6.9	4.7
10	40.75	-97.00	22.4	18.3	14.2	9.6	7.3	5.0
13	42.25	-103.00	19.6	14.9	9.9	5.8	4.1	2.4
14	42.25	-101.00	21.2	15.9	11.7	7.6	5.3	3.4
15	42.25	-99.00	21.2	17.1	13.0	8.9	6.8	4.7
16	42.25	-97.00	22.2	18.2	13.8	9.5	7.3	5.2

HMR 51 12-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	29.1	21.0	15.6	9.9	7.7	5.9
9	40.75	-99.00	30.0	22.0	16.3	10.3	8.2	6.3
10	40.75	-97.00	30.8	22.7	17.0	10.8	8.7	6.8
13	42.25	-103.00	27.2	19.3	14.3	9.1	7.0	5.3
14	42.25	-101.00	28.1	20.5	15.1	9.6	7.6	5.7
15	42.25	-99.00	29.0	21.3	15.8	10.1	8.0	6.1
16	42.25	-97.00	29.7	21.9	16.3	10.4	8.4	6.4

Nebraska Statewide Study 12-hour Percent Reduction from HMR 51 Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	26%	24%	25%	26%	33%	47%
9	40.75	-99.00	28%	22%	18%	13%	16%	26%
10	40.75	-97.00	27%	19%	17%	11%	16%	26%
13	42.25	-103.00	28%	23%	31%	36%	42%	55%
14	42.25	-101.00	25%	22%	23%	21%	30%	40%
15	42.25	-99.00	27%	20%	18%	12%	15%	22%
16	42.25	-97.00	25%	17%	15%	9%	13%	19%

Table 12.1c Comparison of the Nebraska PMP values at each grid point within the state at the 24-hour durations vs HMR 51 PMP values

Nebraska Statewide Study Derived 24-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	21.8	16.8	12.8	8.1	6.2	4.2
9	40.75	-99.00	22.2	18.2	14.3	10.0	8.0	5.8
10	40.75	-97.00	23.8	20.6	16.4	11.5	9.0	6.8
13	42.25	-103.00	19.6	15.7	11.9	7.1	5.0	3.0
14	42.25	-101.00	21.4	16.7	13.9	9.5	7.1	4.8
15	42.25	-99.00	22.0	18.0	14.2	10.0	8.0	5.5
16	42.25	-97.00	23.1	20.4	16.6	11.4	8.8	6.2

HMR 51 24-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	30.7	22.9	17.2	11.6	9.5	7.3
9	40.75	-99.00	31.7	23.7	18.0	12.2	9.9	7.8
10	40.75	-97.00	32.5	24.4	18.8	12.8	10.4	8.2
13	42.25	-103.00	29.2	21.2	17.0	10.9	9.0	6.8
14	42.25	-101.00	29.9	22.2	17.0	11.3	9.3	7.1
15	42.25	-99.00	30.7	23.2	17.4	11.8	9.6	7.5
16	42.25	-97.00	31.4	23.7	18.0	12.3	9.9	7.9

Nebraska Statewide Study 24-hour Percent Reduction from HMR 51 Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	29%	27%	25%	30%	35%	43%
9	40.75	-99.00	30%	23%	21%	18%	19%	25%
10	40.75	-97.00	27%	16%	13%	10%	13%	17%
13	42.25	-103.00	33%	26%	30%	35%	44%	56%
14	42.25	-101.00	28%	25%	18%	16%	23%	33%
15	42.25	-99.00	28%	22%	18%	16%	17%	27%
16	42.25	-97.00	26%	14%	8%	7%	11%	21%

Table 12.1d Comparison of the Nebraska PMP values at each grid point within the state at the 48-hour durations vs HMR 51 PMP values

Nebraska Statewide Study Derived 48-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	22.0	18.0	15.0	11.0	9.2	7.3
9	40.75	-99.00	23.3	19.2	16.1	12.1	10.5	8.7
10	40.75	-97.00	24.7	22.4	18.9	14.9	11.7	9.2
13	42.25	-103.00	19.6	17.4	13.7	9.3	7.3	5.4
14	42.25	-101.00	21.4	18.0	14.9	11.1	9.0	6.4
15	42.25	-99.00	22.5	19.2	16.0	12.0	10.0	8.2
16	42.25	-97.00	24.8	22.7	19.0	15.0	12.0	8.8

HMR 51 48-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	34.1	26.2	20.5	14.7	12.4	10.4
9	40.75	-99.00	35.1	27.1	21.3	15.5	13.2	10.9
10	40.75	-97.00	36.0	27.9	21.8	16.1	13.8	11.4
13	42.25	-103.00	31.9	24.1	18.9	13.5	11.1	9.3
14	42.25	-101.00	32.9	25.4	19.9	14.2	12.0	10.0
15	42.25	-99.00	33.9	26.3	20.6	14.9	12.6	10.5
16	42.25	-97.00	34.6	26.9	21.2	15.4	13.1	10.9

Nebraska Statewide Study 48-hour Percent Reduction from HMR 51 Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	35%	31%	27%	25%	26%	30%
9	40.75	-99.00	34%	29%	24%	22%	21%	21%
10	40.75	-97.00	31%	20%	13%	7%	15%	19%
13	42.25	-103.00	38%	28%	28%	31%	34%	42%
14	42.25	-101.00	35%	29%	25%	22%	25%	36%
15	42.25	-99.00	34%	27%	22%	20%	21%	22%
16	42.25	-97.00	28%	16%	10%	3%	8%	19%

Table 12.1e Comparison of the Nebraska PMP values at each grid point within the state at the 72-hour durations vs HMR 51 PMP values

Nebraska Statewide Study Derived 72-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	22.0	18.6	15.9	12.2	10.1	8.4
9	40.75	-99.00	23.3	20.4	18.6	15.6	13.7	11.3
10	40.75	-97.00	24.7	22.5	19.6	16.2	14.1	11.3
13	42.25	-103.00	19.6	17.6	14.5	10.5	8.5	6.4
14	42.25	-101.00	21.4	18.2	15.4	11.7	9.5	7.2
15	42.25	-99.00	22.5	19.5	16.3	12.9	11.2	9.3
16	42.25	-97.00	24.9	22.8	19.4	15.6	13.6	11.2

HMR 51 72-hour PMP Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	35.6	27.4	21.8	16.1	13.7	11.7
9	40.75	-99.00	36.8	28.5	22.9	16.8	14.3	12.3
10	40.75	-97.00	37.8	29.5	23.7	17.6	15.0	12.9
13	42.25	-103.00	33.3	25.4	20.0	14.9	12.6	10.6
14	42.25	-101.00	34.6	26.4	21.1	15.7	13.4	11.3
15	42.25	-99.00	35.5	27.6	22.1	16.3	13.9	11.9
16	42.25	-97.00	36.4	28.5	22.8	16.9	14.4	12.4

Nebraska Statewide Study 72-hour Percent Reduction from HMR 51 Values

Grid Point	Lat	lon	10-mi^2	200-mi^2	1k-mi^2	5k-mi^2	10k-mi^2	20k-mi^2
8	40.75	-101.00	38%	32%	27%	24%	27%	28%
9	40.75	-99.00	37%	29%	19%	7%	4%	8%
10	40.75	-97.00	35%	24%	17%	8%	6%	12%
13	42.25	-103.00	41%	31%	28%	29%	33%	40%
14	42.25	-101.00	38%	31%	27%	25%	29%	36%
15	42.25	-99.00	37%	29%	26%	21%	20%	22%
16	42.25	-97.00	32%	20%	15%	8%	6%	10%

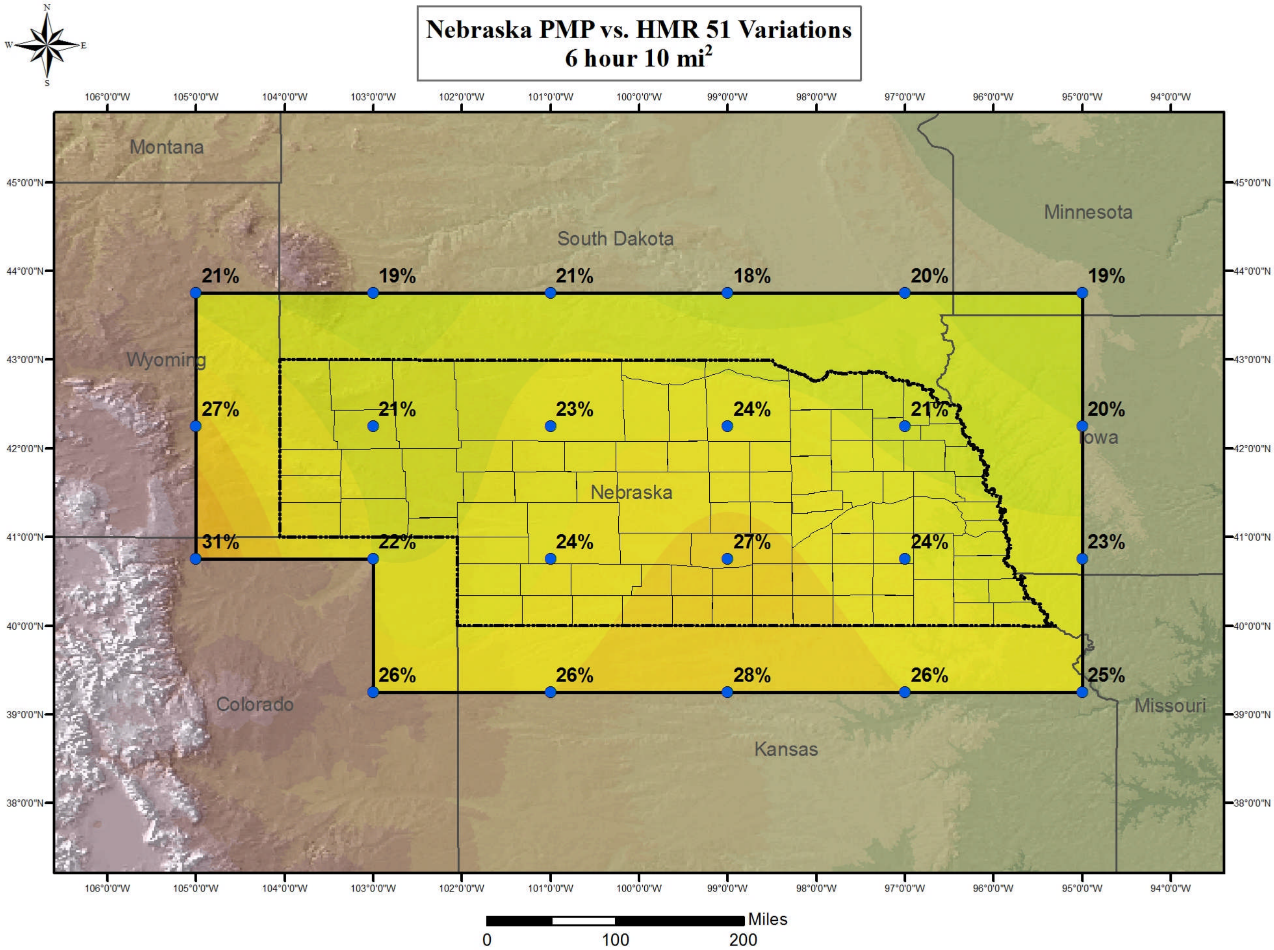

Figure 12.31a 6-hour 10-square mile Nebraska statewide PMP values versus HMR 51 PMP values

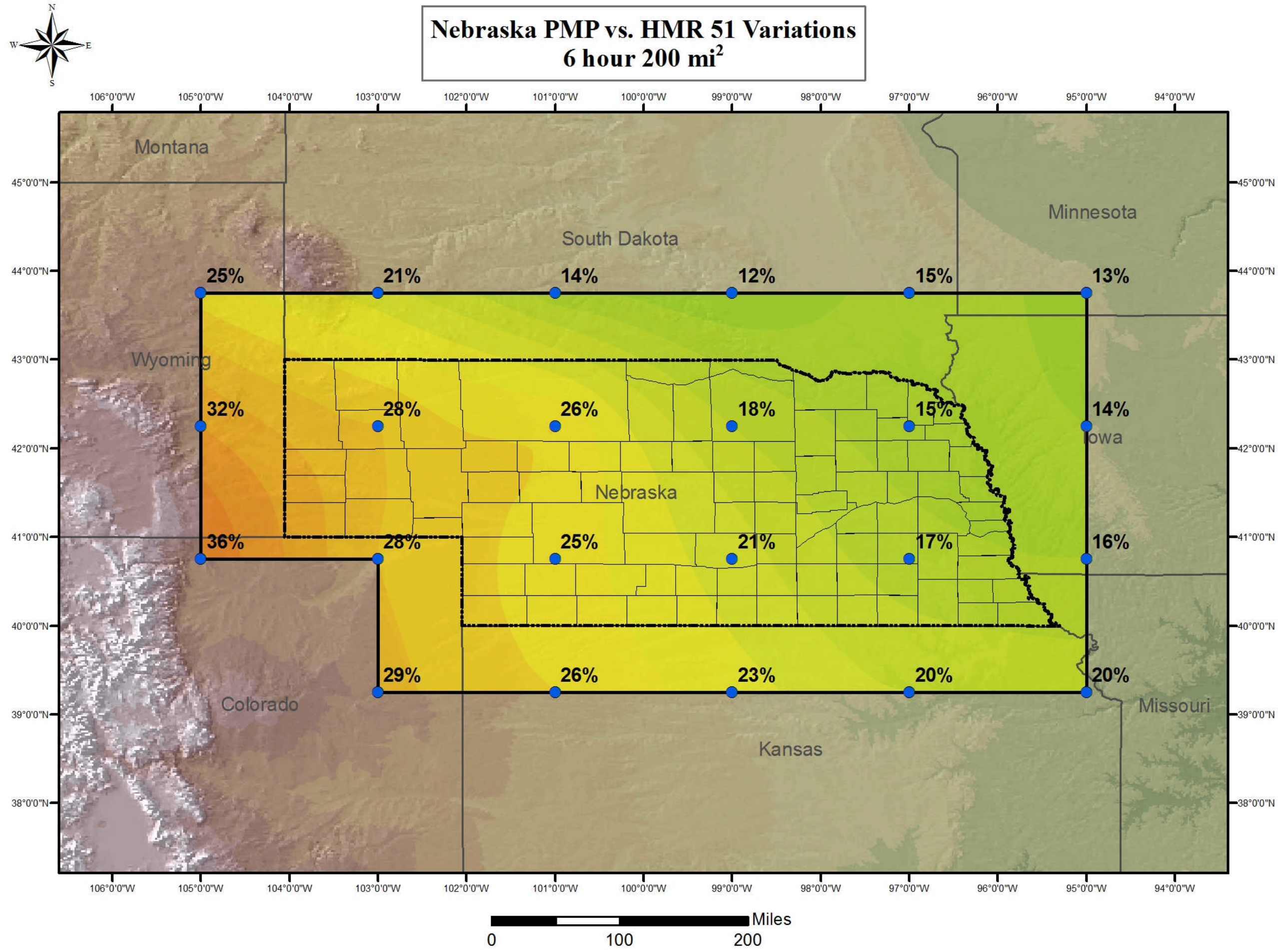

Figure 12.31b 6-hour 200-square mile Nebraska statewide PMP values versus HMR 51 PMP values

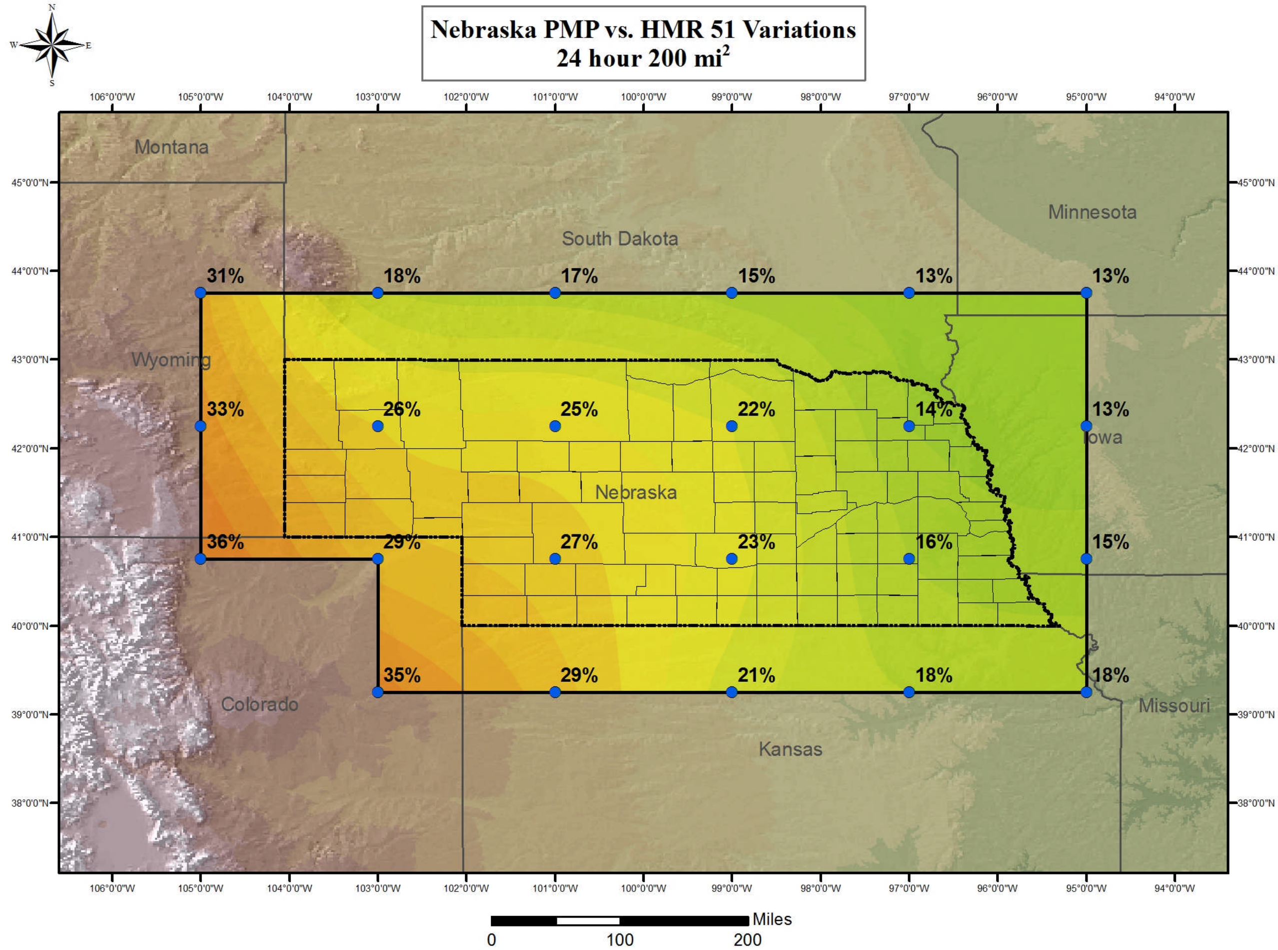

Figure 12.31c 24-hour 200-square mile Nebraska statewide PMP values versus HMR 51 PMP values

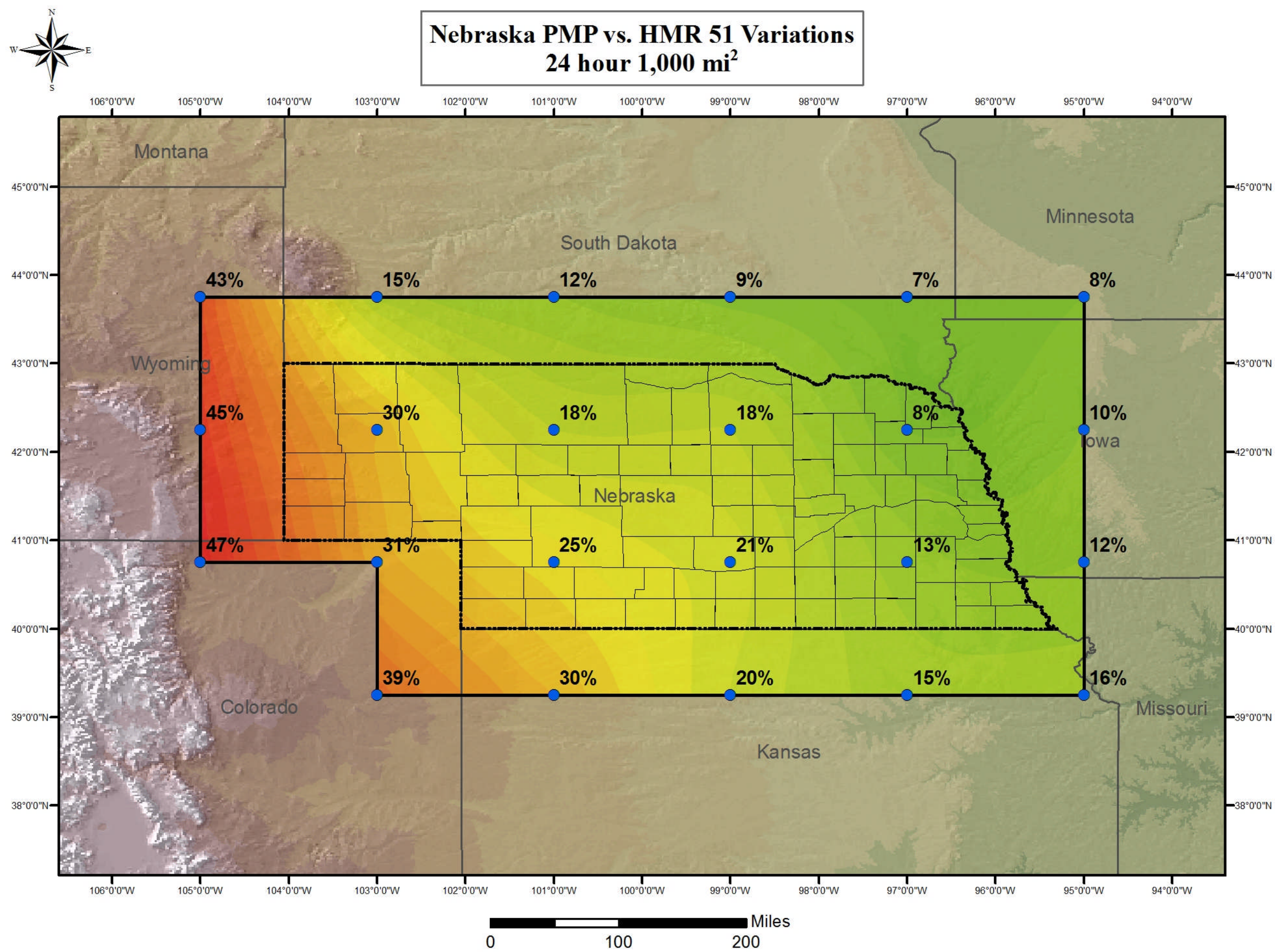

Figure 12.31d 24-hour 1000-square mile Nebraska statewide PMP values versus HMR 51 PMP values

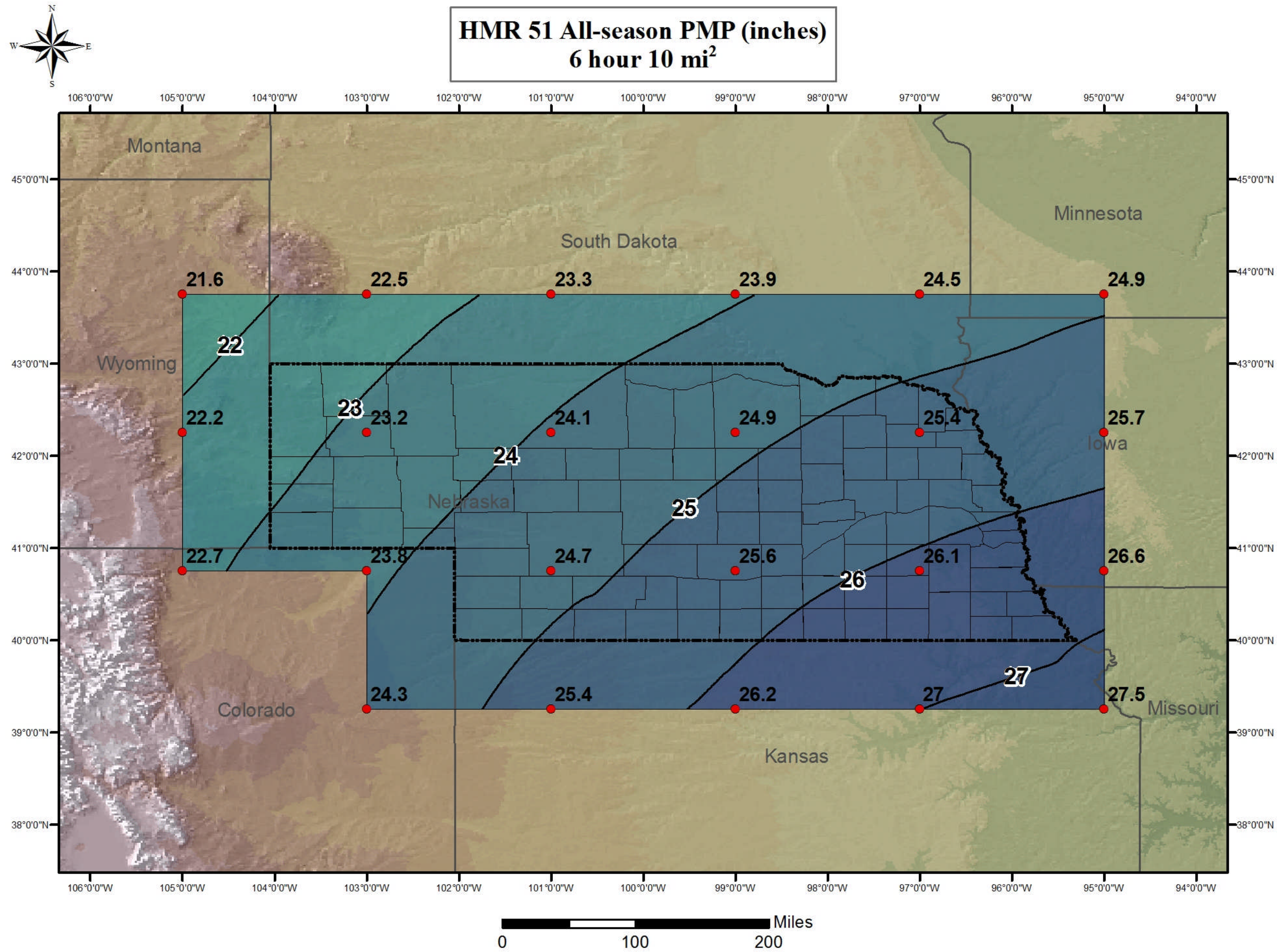

Figure 12.32a HMR 51 6-hour 10-square mile PMP values over the Nebraska statewide PMP grid point domain

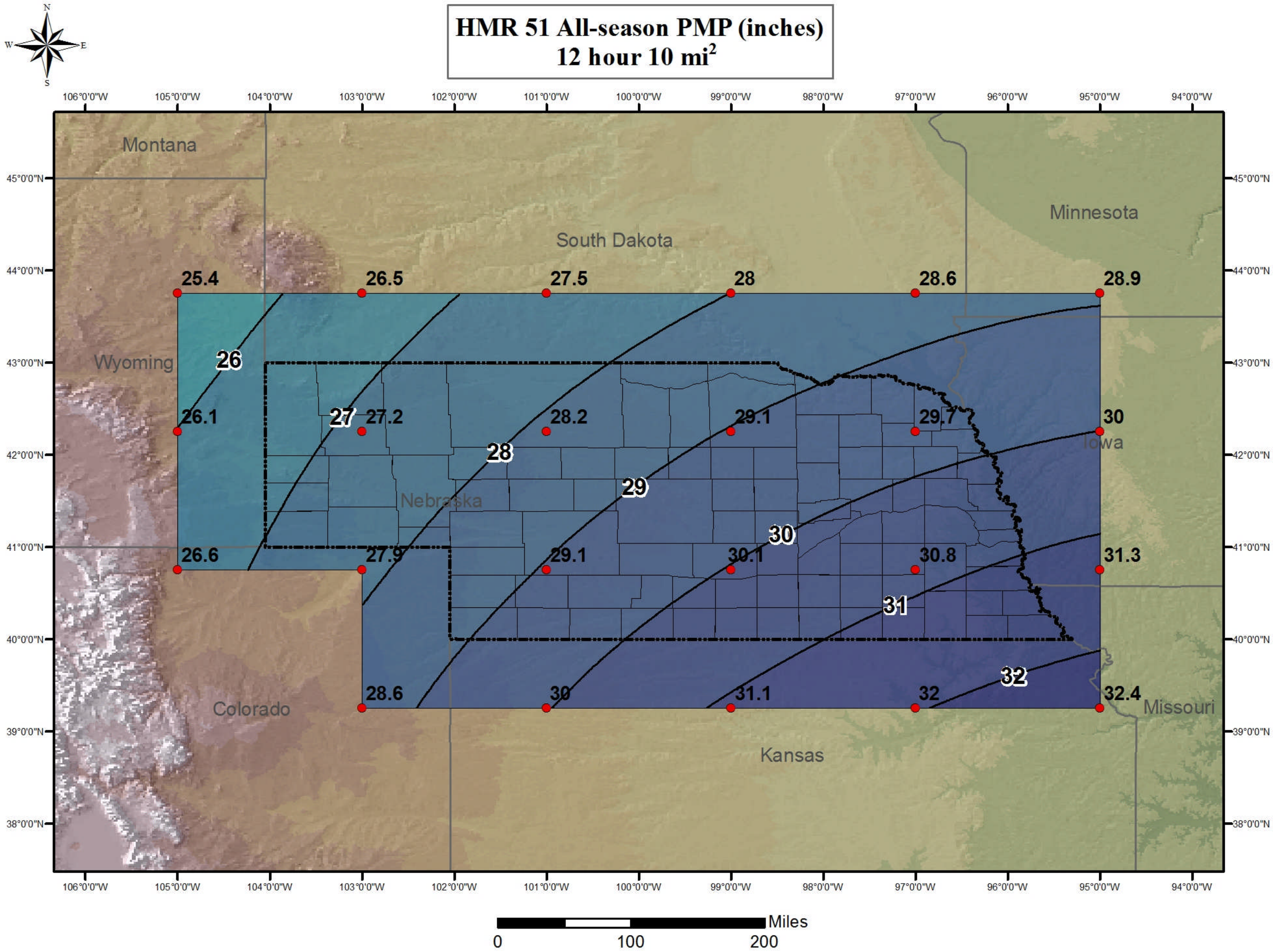

Figure 12.32b HMR 51 12-hour 10-square mile PMP values over the Nebraska statewide PMP grid point domain

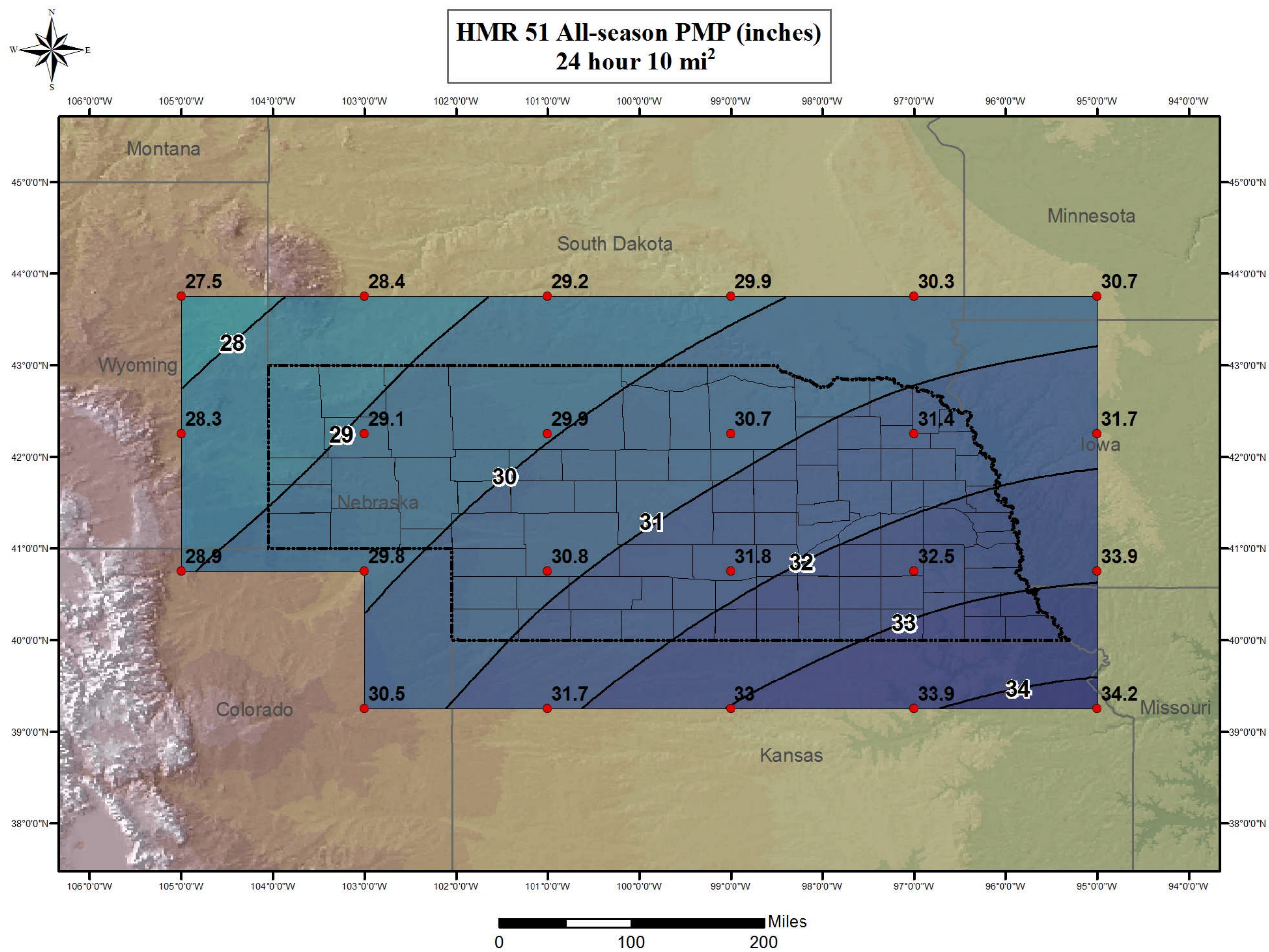

Figure 12.32c HMR 51 24-hour 10-square mile PMP values over the Nebraska statewide PMP grid point domain

12.3 Nebraska Statewide Study and HMR 51 Differences in Procedures

This statewide PMP study provided reduced PMP values from those obtained from HMR 51 across the state of Nebraska which ranged from 56% to 3%. This study explicitly addressed elevations, transposition limitations, and meteorological issues with the most up to date state-of-the-science techniques available, improving on methods used in HMR 51. Additionally, the storm data base was significantly expanded.

Since the study followed the same basic storm rainfall adjustment procedures as HMR 51, it would be useful to understand the reasons for the differences in PMP values. Detailed working papers are not available for HMR 51, so explicit differences in calculations and procedures cannot be compared. However, the following issues were treated differently in the two studies:

1. Previously analyzed storm events that occurred prior to 1948 that used 12-hour persisting dew points were adjusted using storm representative dew point adjustments of 2°F for synoptic type storm events and 7°F for MCS type storm events. This was done to adjust for using average dew point values for varying durations vs. 12-hour persisting dew point values. Recent evaluations of 12-hour persisting storm representative dew points show those used in HMR 51 underestimated the storm representative values (Tomlinson et al, 1993). An updated set of maximum dew point climatology maps were produced. These maps have higher maximum dew point values than those used in HMR studies and therefore compensate to some extent for the higher storm representative dew points.

2. A larger set of storm events, including eight newly analyze storms were used to developed the PMP values. Storms that occurred in meteorologically and geographically homogenous locations similar to one or more of the 23 grid points were transpositioned to appropriate grid point locations. Several of these storms appear to have been previously treated as non-transpositionable to parts of Nebraska. Considering these storms to be transpositionable to various locations in Nebraska adds a level of conservatism to this study by using more storms in Nebraska than appears to have been done in HMR 51. This produces a larger sample set of storms for developing PMP values for the state, thereby giving a higher level of confidence in the reliability of the final PMP values.

3. The HYSPLIT trajectory model was used to evaluate and verify moisture inflow vectors for storms on the short storm list. Trajectory models were not available in previous studies and allowed for a high degree of confidence when evaluating moisture inflow vectors and storm representative dew points.

4. The Storm Precipitation Analysis System (SPAS) was used in conjunction with NEXRAD data (when available) to evaluate the spatial and temporal distribution of rainfall. Use of NEXRAD data produced higher point rainfall amounts than were observed using only rain gauge observations and provides objective spatial distributions of storm rainfall. SPAS results provided storm DADs, total storm precipitation patterns, and mass curves for the newly analyzed storms and the re-analyzed HMR storms. Using these technologies, significant improvements of the storm rainfall analyses were achieved.

12.4 Comparison of the Site-Specific PMP Values with 24-Hour 100-Year Rainfall Values

PMP values at two grid point locations (Grid Points 10 and 13) were compared with 100-year rainfall values as a general check for reasonableness. The ratio of the 10-square mile 24-hour PMP to 24-hour 100-year return period point rainfall amounts is generally expected to be around a value of three, but recent studies have found ratios ranging from 2 to 5. The most current rainfall frequency analysis available for Nebraska is from Weather Bureau Technical Paper-40 (TP-40), produced by the NWS (1961). The 100-year, 24-hour return frequency values for Nebraska were taken from this document. Figure 12.33 shows the graphical representation from TP-40 for the United States. The Nebraska values used for comparison were taken from this graphic. Once these values were determined, a comparison of the 10-square mile 24-hour site-specific PMP value for the two grid points to the 100-year 24-hour rainfall return frequency value was made.

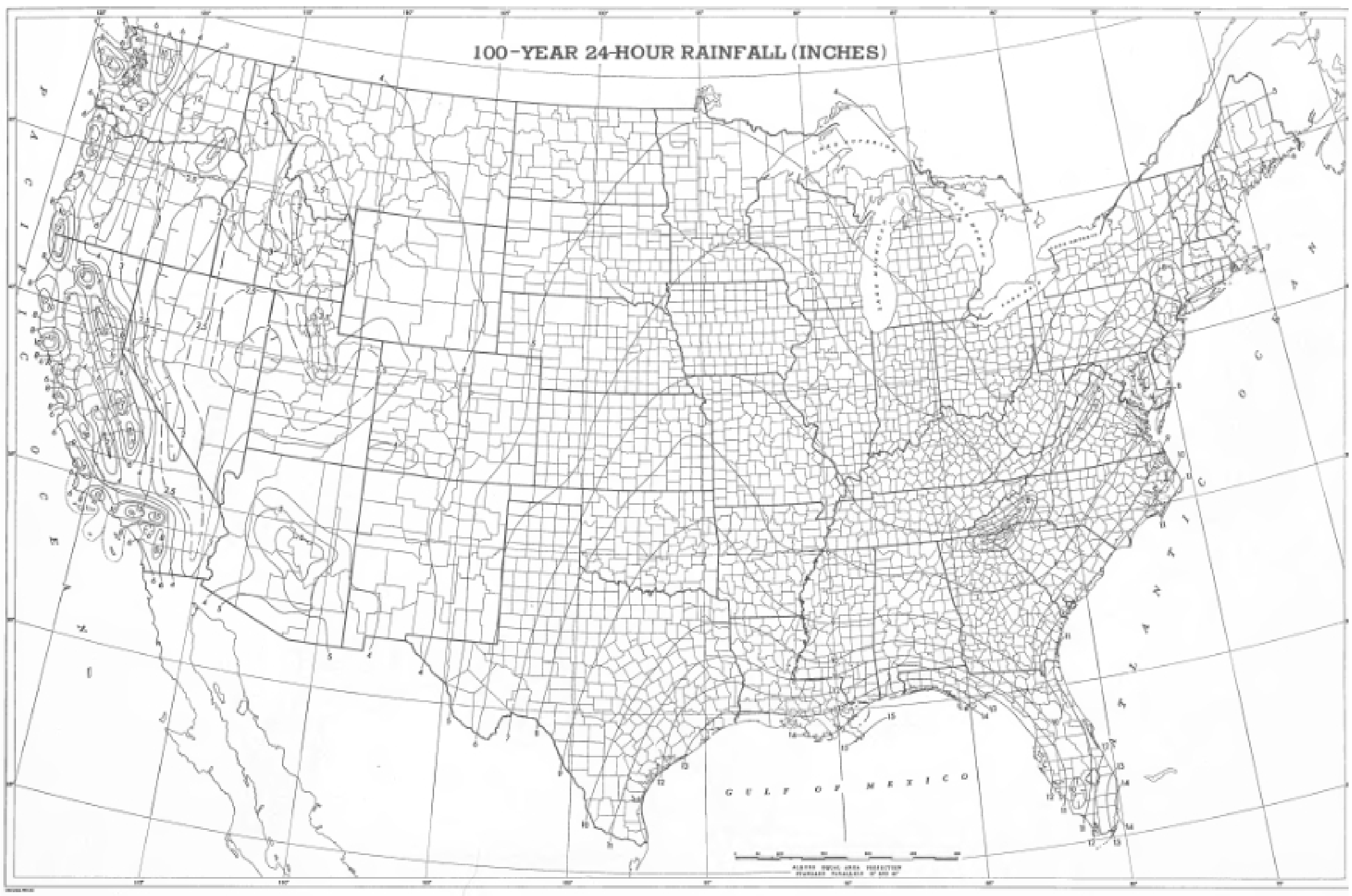

Figure 12.33 TP-40 100-Year 24-Hour return frequency map (Hershfield 1961)

Comparison of PMP values with rainfall frequencies is generally made for point locations, i.e., individual locations. Sufficient data are not available to make the comparison at other area sizes. The 10-square mile, 24-hour PMP value at each grid point was divided by the 100-year, 24-hour return frequency value for that location. Tables 12.2a and 12.2b show the results of this analysis.

The two grid points used in this comparison are Grid Points 10 and 13. These grid points were chosen because they both are located within the state of Nebraska and represent different meteorological and topographical regions within the state.

Grid Point 10 97.00°W 40.75°N Approx. 20 miles west of Lincoln Elevation 1,500 feet

Grid Point 13 103.00°W 42.25°N Approx 40 miles northeast of Scottsbluff Elevation 4,000 feet

Table 12.2a Comparison of the 10-square mile 24-hour PMP with the 24-hour 100-Year Point Rainfall Frequencies at Grid Point 10

10-square mile 24-hour PMP:	23.8 inches
TP-40 100-year rainfall:	6.7 inches
Ratio of PMP to the average 100-year rainfall:	3.6

Table 12.2b Comparison of the10-square mile 24-hour PMP with the 24-hour 100-Year Point Rainfall Frequencies at Grid Point 13

10-square mile 24-hour PMP:	19.6 inches
TP-40 100-year rainfall:	4.7 inches
Ratio of PMP to the average 100-year rainfall:	4.2

13 Recommendations for Application

PMP values have been computed that provide maximum rainfall amounts for use in computing the PMF at any point within the state of Nebraska. The study addressed several issues that could potentially affect the magnitude of the PMP storm over Nebraska as compared with HMR 51.

Analysis of moisture availability for previously analyzed storms and analysis of recent extreme storms with up to date state-of-the-science techniques resulted in decreased PMP values throughout the state from previously published HMR 51 values. These represent the most current PMP values that should be used together with the procedures in HMR 52 to provide PMP rainfall at any location within the state Nebraska.

13.1 Discussion on the Spatial Limits of the PMP Values

The grid system used in this study was designed such that no regions within the state of Nebraska required extrapolation of storm data but allowed for interpolation between rainfall values. The grid extended beyond the geographic boundaries of Nebraska. The emphasis was to provide the most reliable and consistent analysis within the geographic region. PMP maps are provided to allow for PMP values to be extracted for any location in Nebraska. As an option, a user who has GIS software can use the included CD to determine PMP values at any location within the state.

The distance of the grid points located outside the state boundaries varies (see Figure 1.2). For each of the storms analyzed, appropriate transposition grid points were defined (see Appendix B). After all the storms were analyzed, the largest rainfall values were determined for each grid point for each duration and area size. These largest values were enveloped to insure both spatial and temporal continuity.

Once the enveloped values were finalized, lines of constant PMP values were drawn using GIS interpolation software for each duration and area size. These iso-PMP lines were extended beyond the state boundary such that PMP values could be interpolated at all locations within the state of Nebraska. Hence, the reason that some iso-PMP lines extend beyond the state boundary is to allow for gradients to be determined between lines for all locations within Nebraska.

Since the grid used in the analysis was larger than the state of Nebraska, these lines should produce reliable PMP values within the state, even near state boundaries with other states. The extended PMP lines across state boundaries are provided to aid in the determination of PMP values within the state of Nebraska and not to provide PMP values outside of the state. For regions outside of Nebraska where extrapolation would be required, the gradient is uncertain. There are probably regions where the extended lines provide reasonable PMP values while for other regions outside the state, PMP values are less reliable. This study provides PMP values only for locations within the state boundaries of Nebraska.

The final PMP maps are also included on a companion CD in GIS format. These can be directly imported and analyzed in ESRI ArcView software and allow for exact evaluation of PMP values for all area sizes and durations at any latitude and longitude point within the state of Nebraska. A tool is included in the program which allows the user to enter in a latitude longitude pair and receive any or all PMP values for that point. The values can then be directly imported as comma-delimited text files (.csv) file into an HMR 52 program. The instructions on how to perform this function are included in the ReadMe file on the CD.

13.2 Discussion on Potential Climate Change

Climate change has occurred in the past, is now occurring, and undoubtedly will continue in the future. This is and has always been a natural part of earth's climate cycles. Much attention has been given to anthropogenic increases in atmospheric greenhouse gases and their potential impact on global temperature and/or accentuating natural climate variability (IPCC 2007). How the climate will change and how this will affect the number and intensity of extreme rainfall events is unknown as of the date of this report.

With a warming of the atmosphere, there can potentially be an increase in the available atmospheric moisture for storms to convert to rainfall. However, storm dynamics play a significant role in that conversion process and the result of a warming or cooling climate on storm dynamics is not well understood. A warmer or cooler 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 (Taylor, 2008).

Newly analyzed storms in this study provide rainfall values that determine PMP values for some durations and area sizes. There are also older storms that provide the most significant rainfall values for other area sizes and durations.

AWA recognizes that the climate is in a constant state of change. However, the current scientific consensus and understanding cannot agree how climate is changing and more importantly what those changes will be for the region (www.icecap.us). Recent research raises further issues with respect to the inability of the IPCC multi-decadal global models to predict future climate (Koutsoyiannis et al 2008). The main findings of the research as stated in the abstract "Geographically distributed predictions of future climate, obtained through climate models, are widely used in hydrology and many other disciplines, typically without assessing their reliability. Here we compare the output of various models to temperature and precipitation observations from eight stations with long (over 100 years) records from around the globe. Results show that models *perform poorly*, even at a climatic (30-year) scale. Thus *local model projections cannot be credible*, whereas a common argument that models can perform better at larger spatial scales is unsupported."

Therefore, one cannot say whether any or all of Nebraska will be wetter or drier, warmer or colder and/or experience more or less extreme precipitation events with any quantitative and statistically significant certainty. Furthermore, most projects which would utilize the PMP values presented in this report have a projected life between 50 to 100 years before they are re-evaluated. In general, any significant projected changes that *may* occur within earth's climate system would be unlikely to significantly affect any particular project's hydrology evaluation during its useful life.

Based on these discussions, AWA recommends 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, Section 1.1.1).

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Appendix A

Short List Storm Discussions

Greeley, NE June 4, 1896
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 19-23

Little synoptic information was available for the Greeley storm, but the mass curve and areal distributions were used to type the storm as an MCS event. Almost all of the rain fell between approximately 8pm and noon the following day, with the heaviest rain falling in a four hour period. This is a common signature of an MCS type storm event, where a cluster of thunderstorms enhanced by abundant low level moisture advected in on a low-level jet produces heavy amounts of rain over a short duration and relatively small area sizes.

Lambert, MN July 18, 1897
Storm Type: Synoptic
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

A slow moving cold front moving in from the east stalled in far western Wisconsin. Several short rain events along and east of the front contributed to the rainfall total over 72 hours. A weak low pressure deepened over the area enhancing the precipitation. Once this low moved away from the area, the precipitation came to an end. This was a synoptic type storm event.

Medford, WI June 4, 1905
Storm Type: Synoptic
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

Heavy rains fell across central Wisconsin as an area of low pressure over South Dakota moved east. A warm front ahead of the low stretched across Wisconsin just south of the heavy rain. Several widespread rain events over a three day period led to the excessive rainfalls. This occurred as waves of moisture road over the warm front, condensing the moisture laden air into rainfall over the region. A strong southerly inflow of moisture provided the necessary dynamics to cause the storms responsible for the flooding rains. The rain event ended as the low pressure moved out of the region and the warm front shifted east. This was a synoptic type storm event.

Bonaparte, IA June 10, 1905
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This was a nocturnal event where most of the rainfall fell within the first six hours, a classic MCS signature. The convection with this storm was triggered by a warm front that had edged north to the Iowa-Missouri border. A total of 12.1 inches of rain fell in 12 hours, and then once the warm front and its associated area of low pressure moved out of the region, the rains came to an end. During the heavy rain period a strong southerly inflow of moisture was advected into the region on a low-level jet.

Meeker, OK October 19, 1908
Storm Type: Hybrid
Transpositioned Grid Points: 5

A strong and slow moving cold front moving east through the Great Plains was responsible for the 16.23 inches of rainfall over the three day storm period. Two events occurred in the three day storm period that makes this a hybrid type event with both MCS and synoptic characteristics. First, the evening before the synoptic rain event took place, a short duration MCS storm moved through the region. This MCS ended as the cold front moved into the region and caused widespread precipitation from north Texas to southern Minnesota.

Beaulieu, MN July 18, 1909
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

A strong MCS storm moved through the area during the overnight hours just north of a stationary front that extended from central Minnesota to north Wisconsin, all while a low pressure system was moving to the east out of Iowa. Very moist air was advected from the south-southwest on a strong low-level jet to the stationary front. This front acted as an area of convergence adding extra lift and dynamics to the MCS storm environment, where 10.5 inches of rain fell in less than six hours.

Ironwood, MI July 21, 1909
Storm Type: Synoptic
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

Immediately following the Beaulieu, MN storm another storm developed in association with the same piece of energy and low pressure, but lasted much longer. Rain fell over a three day period as a stationary front associated with the storm complex wavered over the same general area and an area of low pressure moved along this boundary. The front and waves of low pressure all aided in the lift and storm dynamics of the environment with the southerly flow of moisture along the front advected in large amounts of moist air.

Cooper, MI August 31, 1914
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This was a nocturnal, short duration, heavy rain event that affected a limited area size, classic signatures of an MCS type storm. It formed ahead of a cold front moving through the Great Lakes region. The ascending air ahead of the front acted as the catalyst that started the convective processes. Once the cold front moved through the area, the MCS broke down and the heavy rainfall ended. A total of 12.6 inches of rain fell in six hours with this event.

Springbrook, MT June 17, 1921
Storm Type: Hybrid
Transpositioned Grid Points: 2-3, 8-10, 14-16, 22-23

This extreme rainfall event occurred as an area of low pressure moved out of the Rockies and into the Midwest. The counterclockwise flow around this area of low pressure advected in large amounts of moisture. This moisture was then lifted in association with the low pressure causing the heavy rains to fall. This synoptic pattern was in place for several days in the same general area as the area of low pressure lifted to the northeast from Colorado over the Dakotas. Its progress was slowed by an area of high pressure moving out of the Prairie Provinces of Canada. The clockwise flow around this high pressure added to the east/northeasterly flow into the system and eastern Montana, aiding in the lifting mechanisms already associated with this storm and helping to produce maximum rainfall production. The low pressure system continued it north/northeast trek into southern Canada, producing the heaviest period of rain late on the 19th and into the morning of the 20th, when nearly 12 inches accumulated in approximately 12 hours. As the storm continued to move away from the region, then rain fall quickly came to an end.

Savageton, WY September 27, 1923
Storm Type: Hybrid
Transpositioned Grid Points: 1, 6-7, 12-13, 18

This storm event occurred in a very similar fashion to the Springbrook, MT 1921 storm as an area of low pressure developed along the lee of the Rocky Mountain front in Colorado and moved north/northeast into the Great Plains. This was ahead of a deep trough moving through the Intermountain West, which added extra lift and energy to the storm environment. Ahead of the area of low pressure, the counterclockwise flow advected high levels of moisture into the eastern plains of Wyoming where it produced heavy rainfall over a three day period. Again, an area of high pressure moving south from Canada helped to slow the progress of this storm system and keep the heavy rains falling in the same region for an extended period of time.

Boyden, IA September 17, 1926
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

A powerful cold front swept through northwest Iowa causing this extreme event. An amazing 24 inches of rain fell in 12 hours, with 18.4 inches in only 6 hours. Moist air was uplifted ahead of the front and thunderstorms continued to develop over the same area for the entire rain event. These storms tapped into very moist air being advected into the region ahead of the front along a strong low-level jet and helped form the MCS event during the evening o the 17th.

Cheyenne, OK April 3, 1934
Storm Type: MCS
Transpositioned Grid Points: 5

This intense burst of rain occurred out ahead of a cold front that approached from the west. This front was associated with an area of low pressure that moved out of southern Colorado to the northeast across the central Plains. Out ahead of this low, moist air was drawn into western and central Oklahoma and turned into heavy rain as an area of intense thunderstorms formed over the Cheyenne, OK area. These storms dropped 23 inches of rain in as little as 12 hours. Once the cold front moved into the region, the moisture source was cut off and the rain fall ended.

Hale, CO May 30, 1935
Storm Type: MCC
Transpositioned Grid Points: 1-2, 6-8, 12-14, 18

This extremely heavy rainfall developed just east of the Front Range of Colorado along and north of the crest of the Palmer Divide, which separate the Platte River drainage from the Arkansas River drainage. The intense line of thunderstorms initially developed during the morning of the 30th to the north/northwest of Colorado Springs and continued to form to the northeast throughout the rest of the afternoon. As these storms moved further to the east, they encountered a moisture rich environment and plenty of lift provided by a front lying across eastern Colorado. An area of low pressure moving into Colorado from the west and an area of high pressure moving in from the north caused an area of convergence over a very localized region along the I-70 corridor in eastern Colorado. Several intense rainfall centers developed along this boundary, with very little rain accumulating only a couple of miles to either side. The Hale center occurred just west of the Kansas border with Colorado when the heavy rains inundated the headwaters of the Republican River drainage form late in the evening to early the next morning.

The main characteristics of this event are 1) the presence of a persistent warm and very moist low level air mass which originated over the Gulf of Mexico and moved into eastern Colorado from the southeast, b) a low pressure center over northern New Mexico which moved east-northeastward during the storm period, and c) the presence of cold and warm fronts immediately to the west and south of the precipitation centers. The result was heavily embedded convective rainfall which occurred over several locations along a line oriented southwest-northeast from the foothills of the Rocky Mountains to the Kansas border.

Grant Township, NE June 3, 1940
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This was another short duration, nocturnal MCS event. The storm occurred well ahead of an approaching cold front and low pressure system along the leading edge of the warm front. Moist air was advected into the region from the south/southeast on a strong low-level jet and forced to lift over the warm front forming an intense cluster of thunderstorms. Once the low pressure and cold front moved through the thunderstorm forming environment dissipated.

Hallett, OK September 2, 1940
Storm Type: MCS
Transpositioned Grid Points: 5

This extremely heavy rain fell during the evening of the 3rd and continued into the early morning of the 4th as an area of high pressure was anchored over the Ohio Valley and southern Appalachians. The clockwise flow around this area of high pressure advected large amounts of moist air into Oklahoma from the Gulf of Mexico. This moisture was turned into heavy rains as thunderstorms that had developed along the Front Range of the Rockies in southern Colorado and New Mexico moved into this moisture rich environment. Because a general area of high pressure was influencing the region, these storms moved very slowly over the Hallett, OK area, producing 24 inches of rain in 12 hours.

Hayward, WI August 28, 1941
Storm Type: Hybrid
Transpositioned Grid Points: 3-5, 9-11, 15-17, 21-23

A warm front moving slowly north over Wisconsin triggered a series of heavy rains across the region. A weak low pressure system helped to advect moisture north across the warm front. Imbedded areas of convection produced short bursts of heavy rainfall within the overall synoptic storm environment.

Warner, OK May 6, 1943
Storm Type: Synoptic
Transpositioned Grid Points: 5

A large, cold late season Canadian air mass sinking south into the Great Plains caused this intense storm event. The associated cold front stalled from the Great Lakes back to the southwest into north Texas. Along this stationary front warm, moist air was drawn up from the Gulf of Mexico and forced to rise. Two shortwaves rode along this boundary further enhancing the lift and storm dynamics, helping to produce the heavy rainfall through embedded convection over the three day period.

Stanton, NE June 10, 1944
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This intense cluster of thunderstorms displayed all the expected characteristics of an MCS type storm event, with rainfall occurring overnight as a strong low-level jet advected very moist air into the region from the south/southeast, feeding the storm environment. The heavy rains fell over a relatively small area and for a short duration. One unusual factor with this event is that the low-level jet feeding the moisture into the storm from the south stayed intact through the following day, keeping the thunderstorm complex active and producing heavy rains as it moved across Nebraska and into Iowa over a two day period. However, over 15 inches of rain fell overnight on the 10^{th} into the morning of the 11^{th} near Stanton, NE.

Collinsville/Cole Camp, IL/MO August 12, 1946
Storm Type: Synoptic
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

An approaching warm front where moist air from the south was forced to rise, causing an overrunning event, was enhanced by several shortwaves of energy adding extra lift and heavy bursts of rain. This occurred as an area of low pressure to the west helped supply the moisture around its counterclockwise flow. Both nights of the 15^{th} and 16^{th} experienced heavy rainfall as this synoptic pattern stalled over the region.

Council Grove, KS July 9, 1951
Storm Type: Synoptic
Transpositioned Grid Points: 3-5, 9-11, 16-17, 21-23

Over a period of five days, two cold fronts pushed south over the northern Plains and stalled over Kansas. With moisture advected into the region from the Gulf of Mexico during the period and shortwaves moving along the front laying west to east over the region precipitation was frequent and heavy. Up to 18.5 inches fell over 3.5 days near Council Grove, KS.

Ritter, IA June 6, 1953
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This short duration, heavy rainfall event was fed by a strong low-level jet by southerly winds advecting moisture into the storm environment. An area of low pressure also enhanced the storm dynamics as a warm front approached the region and helped to initiate and sustain the convection.

Paris Waterworks, IN June 27, 1957
Storm Type: Synoptic
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

This rain event occurred as the remains of a tropical system moved into the lower Mississippi River valley and interacted with a cold front. Heavy rain fell in central Illinois through central Indiana from the afternoon of the 21st to the morning of the 28th as thunderstorms formed in an east-west oriented line. These storms developed in the warm sector of an approaching area of low pressure, where moisture was enhanced by the remnants of the departed tropical system.

Prague, NE August 1, 1959
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This storm was characterized by a short duration heavy rain event over a small area with the rain following during the overnight hours. This was a classic MCS type storm event and the storm environment was fed by a low-level jet advecting moisture in from the south/southeast. This storm is a newly analyzed storm as part of the Nebraska study and produced the second largest flood of record at the Ithaca gauge near Wahoo, NE of 45,300 cfs. This storm produced over 90% of its rainfall in a 6 hour period.

Ida Grove, IA August 30, 1962
Storm Type: Hybrid
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This storm produced heavy rainfall over northern Iowa, southeast Minnesota, and west central Wisconsin. This storm combined a synoptic level area of low pressure with Mesoscale features that enhanced rainfall over shorter durations along localized areas within the overall storm environment. The heaviest rain accumulated near Ida Grove, IA from the morning through early evening of the 30th. During this time, the synoptic scale low pressure system moved slowly across Kansas and a trough of low pressure extended northeastward from the low across Iowa and into Wisconsin. Along this boundary a series of intense thunderstorms developed as several shortwaves provided enhanced dynamics to the storm environment.

David City, NE June 24, 1963
Storm Type: MCS
Transpositioned Grid Points: 3-5, 9-11, 15-17, 20-23

This storm was characterized by a short duration heavy rain event over a small area with the rain accumulating during the overnight hours. This was a classic MCS type storm event and the storm environment was fed by a low-level jet advecting moisture in from the south/southeast. This storm is a newly analyzed storm as part of the Nebraska study and produced the largest flood of record at the Ithaca gauge near Wahoo, NE of

77,000 cfs. Nearly the entire storm total rainfall amount of 16.50 inches fell in a 6 hour period.

Holly, CO June 16, 1965
Storm Type: Synoptic
Transpositioned Grid Points: 1-2, 7-8, 13-14, 18-19

During the period of June 13-20, 1965, heavy rains fell over the eastern foothills of Colorado. The heaviest rains during the storm period occurred primarily from severe convective storms during the afternoons and evenings. Strong advection of unstable moist air from the Gulf of Mexico provided low Level moisture for the storms (HMR 55A, 1988). The Holly, CO center developed near the Colorado-Kansas border on the evening and early morning of the 17th and 18th. The heavy rainfall center here is supported by numerous cooperative weather station reports, including a two-day report from Holly of over 15 inches.

On the 13th through the 16th, weak frontal systems were present in the Colorado region. The convective storms developed in the warm moist southerly airflow. The cold front to the west gradually ceased its eastward movement and became stationary by the evening of the 15th. The warm front gradually dissipated as a high-pressure system moved rapidly southward from Canada. By the morning of the 16th, the center of the high was near the northern edge of the Great Lakes. The 500-mb charts showed a trough over the west slowly intensifying as a closed low center moved southward to a position over the California-Nevada border (HMR 55A, 1988).

During the 17th, 18th, and 19th, the surface high continued to move southward and by the morning of the 19th, it was centered over eastern Tennessee. The circulation around the high continued to bring warm moist air northward over the Great Plains and eastern Colorado. The weak stationary front, located along the east-facing slopes of the Rocky Mountains, marked the westward extent of the moist air. At 500 mb, the closed low over the California-Nevada border weakened, but an elongated trough remained over the western United States, while through the Great Plains, a weak ridge extended from the Gulf of Mexico northward to the Canadian border. The airflow over the western and central United States was southerly from the surface to 500 mb. Moisture was flowing into the region through a deep layer of the atmosphere (HMR 55A, 1988).

Edgerton, MO July 18, 1965
Storm Type: Hybrid
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

This storm is responsible for the official 24-hour rainfall record for the state of Missouri and was caused by a stationary front stretching across southern Nebraska and into northern Missouri. Very strong temperature and moisture contrasts were evident across this boundary and this helped enhance the dynamics of the storm environment. The synoptic environment had an area of low pressure over eastern Colorado and high pressure over Arkansas. The flow around the circulations brought high amounts of moisture into the region from the Gulf of Mexico. From the 17^{th} through the 20^{th} the front wavered over the same region, providing lift to the moist air mass. Thunderstorms developed and slowly moved to the southeast following the winds across the boundary. A pronounced diurnal effect was noted in the mass curve which shows the heavy rain occurring in the late afternoon and nighttime hours. This coincided with the low-level jet maximums pushing moisture and instability into the region.

Enid, OK October 10, 1973
Storm Type: Hybrid
Transpositioned Grid Points: 5

This intense storm system displayed characteristics of both an MCS type event and a synoptic event. This heavy rain was associated with a cold front moving into the region from the west and moist air advecting in from the south/southeast. Aloft, a deep trough of low pressure was moving into the Four Corners region at 500mb, adding extra lift to the storm environment. An area of low pressure intensified on the morning of the 4^{th} over Kansas and as this low moved off to the northeast, the heavy rains came to an end. The heavy rain fell from the afternoon of the 10^{th} through the morning of the 11^{th}, causing extensive flooding and several deaths along Boggy Creek, just south of Enid, OK.

Forest City, MN June 20, 1983
Storm Type: MCS
Transpositioned Grid Points: 3-5, 10-11, 16-17, 21-23

This storm was characterized by a short duration heavy rain event over a small area with the rain accumulating during the morning hours of the 21^{st}. This was a classic MCS type storm event where an approaching cold front from the west caused the winds to turn from the south/southeast, advecting large amounts of moisture up the Mississippi river valley into the storm environment. This fed the thunderstorms and allowed them to produced large amounts of rain over a small area in a short duration. Once this cold front moved through the storms dissipated and the rains came to an end.

Minneapolis, MN July 23, 1987
Storm Type: MCS
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

Heavy rainfall and severe flooding occurred over an area centered near the Twin Cities starting on the evening of the 23^{rd}. Rainfall continued overnight and accumulated 10.50 inches by early the next morning. An area of low pressure moved east across South Dakota advecting high amounts of moisture into the region. Thunderstorms that had formed earlier that afternoon helped produce Mesoscale boundaries that led to further thunderstorms, which were enhanced by the fetch of moisture along the low-level jet from the south. Where this moisture intersected the cold front, moisture was concentrated and enhanced the storm environment over southern Minnesota. These thunderstorms formed repeatedly over the same region during the night, producing the extreme rainfall.

Tomah, WI August 17, 1990
Storm Type: MCS
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

This storm affected a very small area (~100 square miles) with rainfall of 9.17 inches in four hours, from the evening of the 17th through the early morning of the 18th, a classic MCS signature. The storm developed north of a warm front stretched east-west across southern Wisconsin. The small scale of the thunderstorm points to a supercell type thunderstorm environment, where this particular cell was in the prime location to receive the necessary moisture to produce the extreme rainfall.

Aurora College, IL July 17, 1996
Storm Type: Hybrid
Transpositioned Grid Points: 4-5, 10-11, 16-17, 21-23

This storm was characterized by two separate heavy bursts of rain during the 17th, setting the official 24-hour rainfall record for the state of Illinois. The heavy rains were the results of two large MCS events, one in the afternoon and one in the evening. These systems formed to the north of a stationary front as moist air was located over Iowa and western Illinois. This moist air was enhanced by surface evaporation from heavy rains during the preceding days, adding instability to the storm environment. At the same time, easterly winds off of Lake Michigan slowed eastward progression of the front and allowed the storm to affect the same area. A low-level jet was present and transported moisture over the front from the southwest, enhancing the storm dynamics.

Pawnee Creek, CO July 29, 1997
Storm Type: MCC
Transpositioned Grid Points: 1, 6-7, 12-13, 18

This storm followed the heavy rains that fell the night before in Ft Collins, CO, as an extremely moist air mass lay over northeastern Colorado. Thunderstorms developed during the afternoon along a boundary in the region, and weak upper level winds allowed the storm to produce heavy rainfall over the same area during the entire storm event. This resulted in widespread flooding of the surrounding farm and ranch lands. A bucket survey for this storm was conducted by the Colorado Climate Center for the Colorado Water Conservation Board in August 1998 and was the results were published in a report titled *A Post-Evaluation of Rainfall Reports Associated with the Pawnee Creek Flood of July 29-30, 1997 in Eastern Weld and Western Logan Counties in Northeast Colorado*. The storm isohyetal pattern was reanalyzed through SPAS using the observations contained within this report, new data mined from various sources, National Weather Service NEXRAD radar data.

Ogallala, NE July 6, 2002
Storm Type: Hybrid
Transpositioned Grid Points: 1-2, 7-8, 13-14, 18-19

This storm produced over 14" in 9 hours over western Nebraska during the morning of July 6th producing devastating flash flood and severe damage to I-80. This is one of the most severe rainfall events that have occurred over western Nebraska. This storm displayed characteristics of both an MCC type event and a synoptic event. A strong area of low pressure moved north out of southeastern Colorado late on the 5th and was accompanied by several shortwaves in the flow (Radell 2002). At the upper levels, the winds were very weak, allowing the thunderstorms to remain in the same region for an extended period of time. Further, a very moist air mass extended from the storm location in southern Nebraska back into northern Texas. This long fetch of moisture continually feed the storm environment and enhanced the storm dynamics on south/southeasterly winds rotating around an area o high pressure near the Great Lakes. At the same time a low-level jet developed and helped feed the storm environment with moisture rich air and instability. At the same time a weak trough of low pressure was nearly stationary from north central Nebraska through northeastern Colorado and served as a focal point for convective initiation.

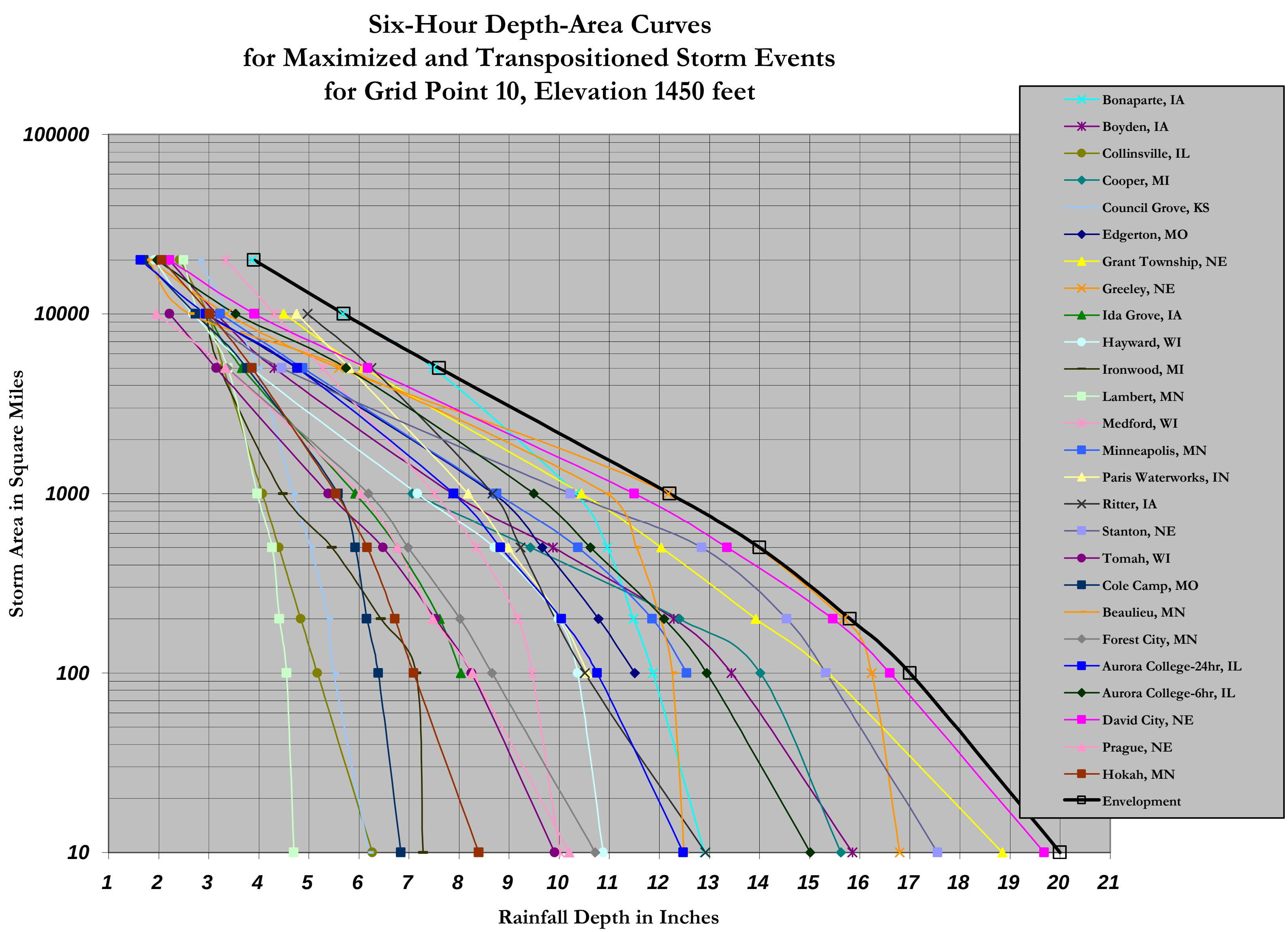
Appendix B

Depth-Area and Depth-Duration Curves

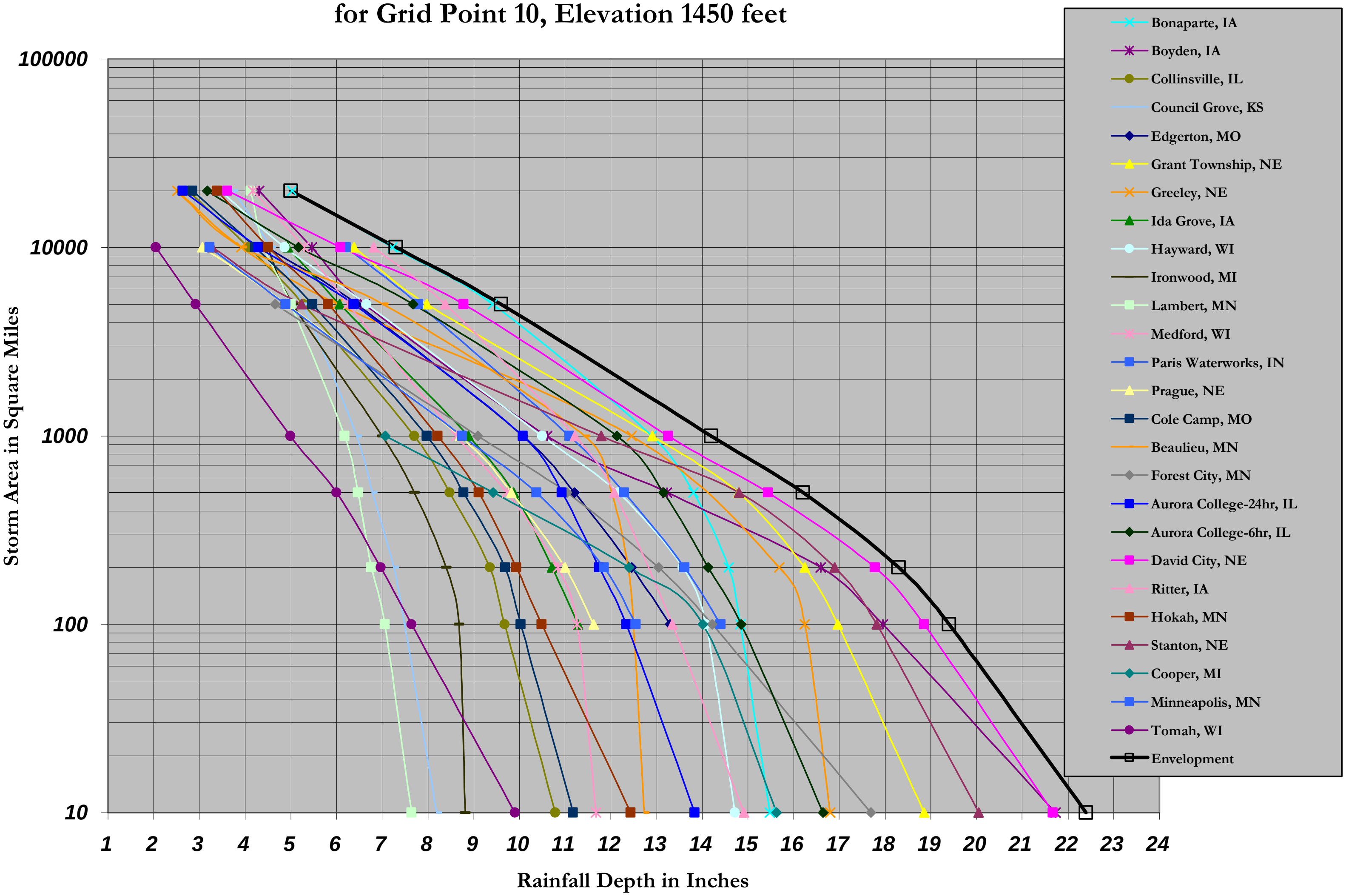
Rainfall amounts from the largest storms, after being adjusted to each of the 23 grid points, were plotted on depth-area plots. Plots were made for each duration period, i.e., 6-, 12-, 24-, 48-, and 72-hour duration periods. Enveloping curves were drawn using the maximum rainfall values and smoothing was applied to provide smooth transitions among area sizes.

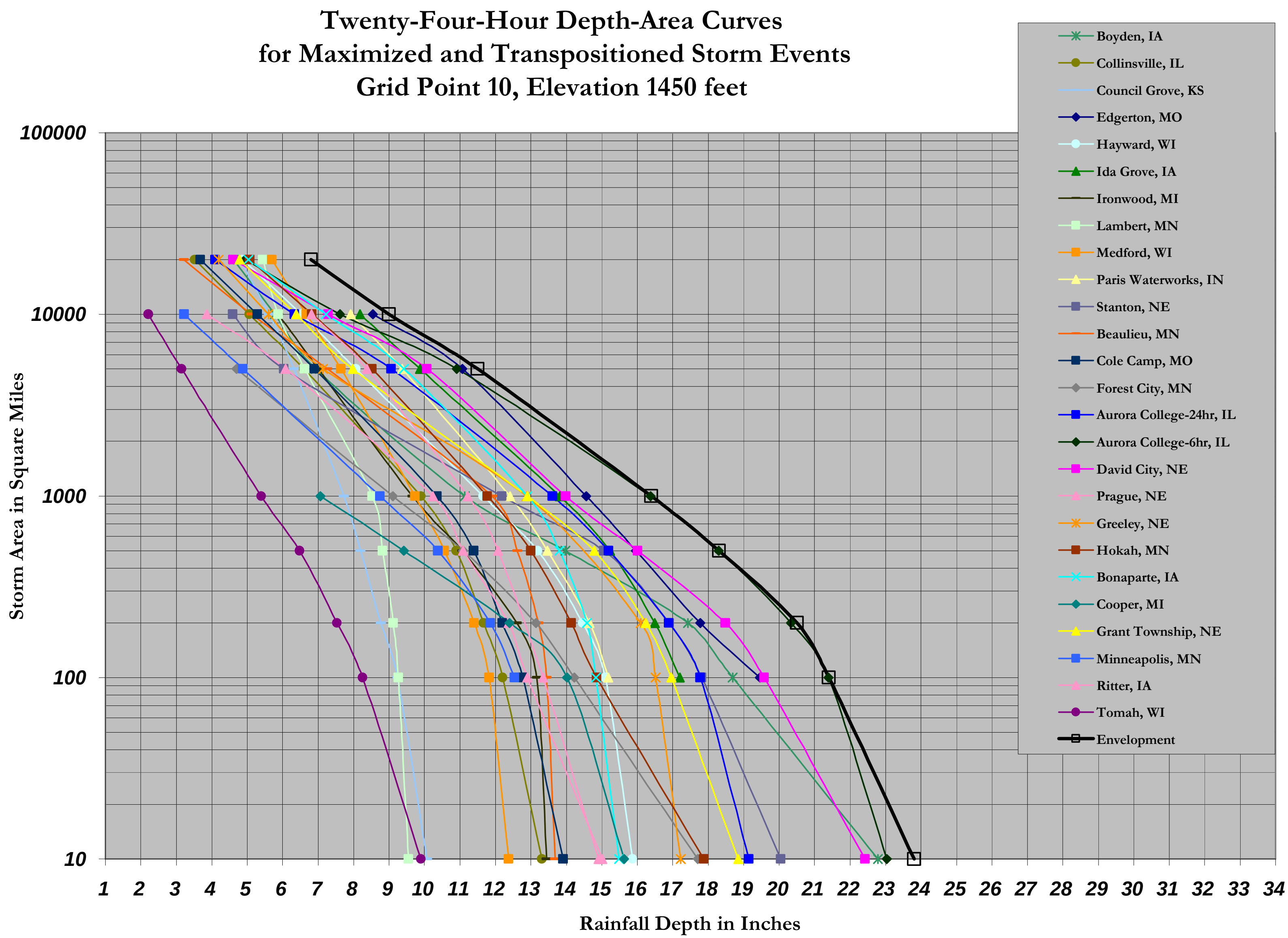
Enveloped rainfall values were taken from the depth-area plots and used to construct the depth-duration plots. A curve was constructed for each area size, i.e., 10-; 100-; 200-; 500-; 1,000-; 5,000-; 10,000-; and 20,000-square mile area sizes. Enveloping curves were drawn with smoothing to provide smooth transitions among duration periods.

This procedure of enveloping and smoothing produces maximum rainfall amounts that have continuity in both time and space. Final plots of the depth-area and depth-duration curves from Grid Point 10 are provided in this appendix as typical examples. The final PMP values for the study were taken from the depth-duration curves and used to derive the all-season PMP maps for the state of Nebraska.

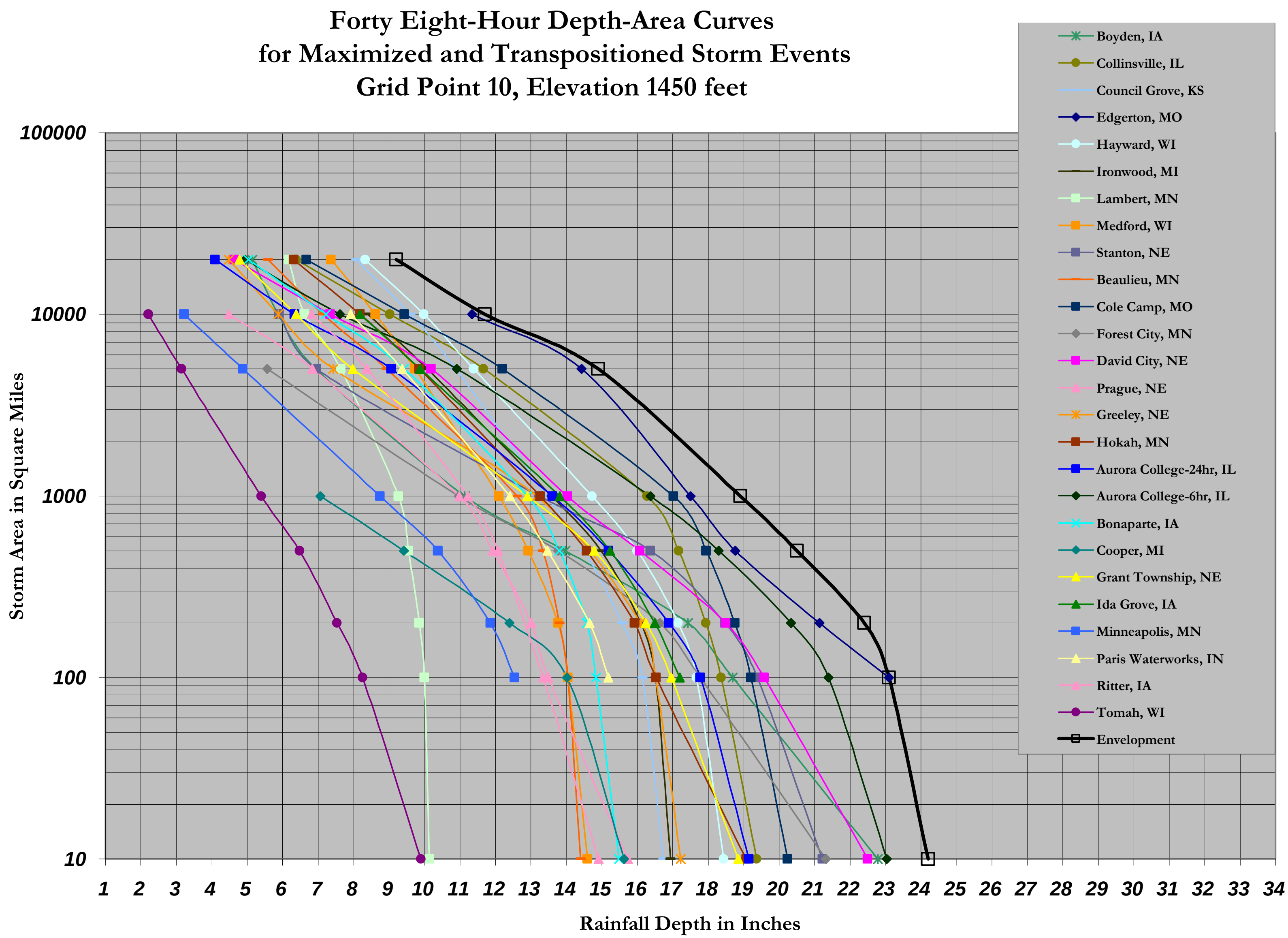

Six-Hour Depth-Area Curves
for Maximized and Transpositioned Storm Events
for Grid Point 10, Elevation 1450 feet
Storm Area in Square Miles
100000
10000
1000
100
10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Rainfall Depth in Inches
Bonaparte, IA
Boyden, IA
Collinsville, IL
Cooper, MI
Council Grove, KS
Edgerton, MO
Grant Township, NE
Greeley, NE
Ida Grove, IA
Hayward, WI
Ironwood, MI
Lambert, MN
Medford, WI
Minneapolis, MN
Paris Waterworks, IN
Ritter, IA
Stanton, NE
Tomah, WI
Cole Camp, MO
Beaulieu, MN
Forest City, MN
Aurora College-24hr, IL
Aurora College-6hr, IL
David City, NE
Prague, NE
Hokah, MN
Envelopment

Twelve-Hour Depth-Area Curves
for Maximized and Transpositioned Storm Events
for Grid Point 10, Elevation 1450 feet

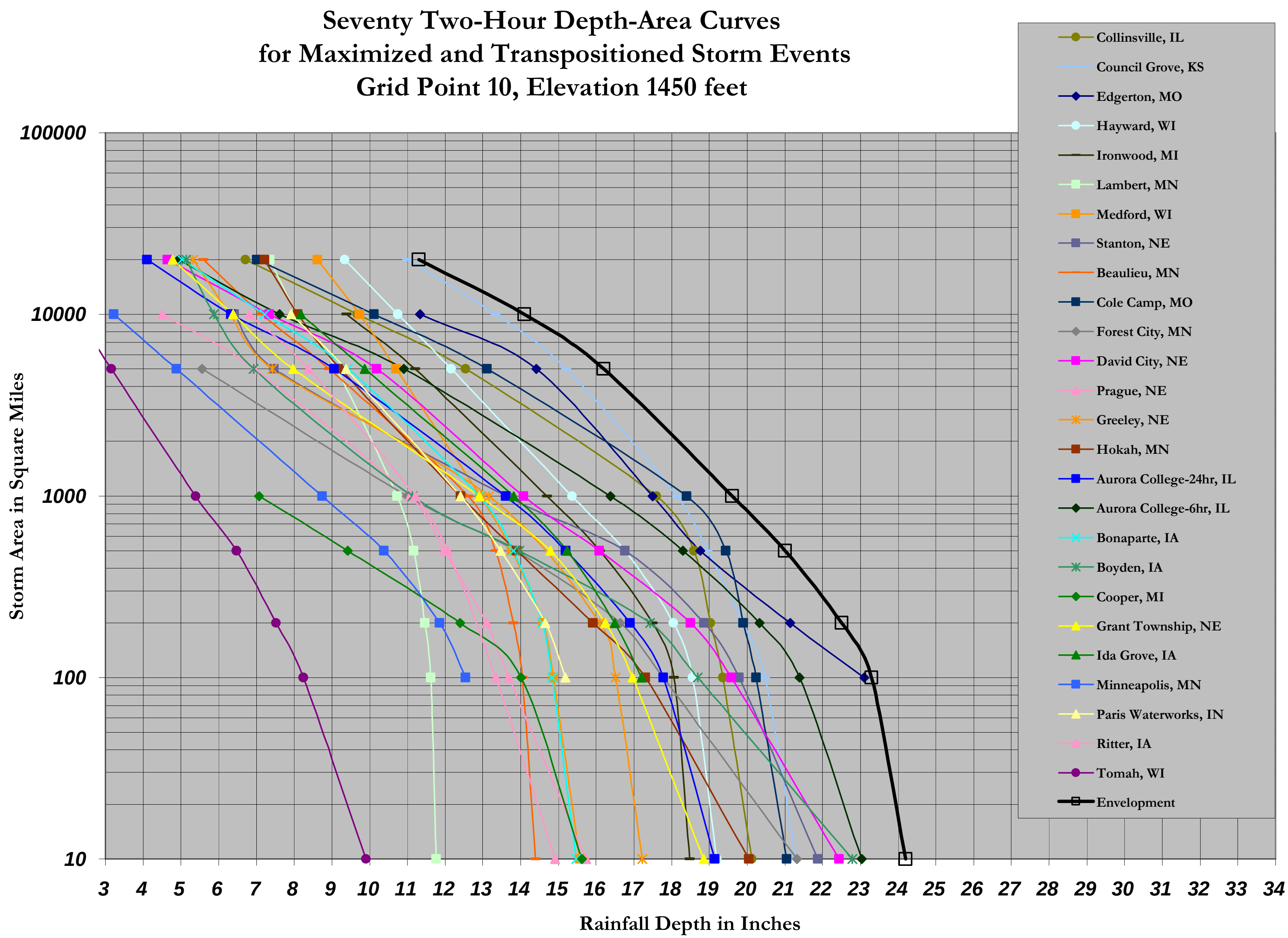




Twenty-Four-Hour Depth-Area Curves
for Maximized and Transpositioned Storm Events
Grid Point 10, Elevation 1450 feet
Storm Area in Square Miles
Rainfall Depth in Inches
100000
10000
1000
100
10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
Boyden, IA
Collinsville, IL
Council Grove, KS
Edgerton, MO
Hayward, WI
Ida Grove, IA
Ironwood, MI
Lambert, MN
Medford, WI
Paris Waterworks, IN
Stanton, NE
Beaulieu, MN
Cole Camp, MO
Forest City, MN
Aurora College-24hr, IL
Aurora College-6hr, IL
David City, NE
Prague, NE
Greeley, NE
Hokah, MN
Bonaparte, IA
Cooper, MI
Grant Township, NE
Minneapolis, MN
Ritter, IA
Tomah, WI
Envelopment

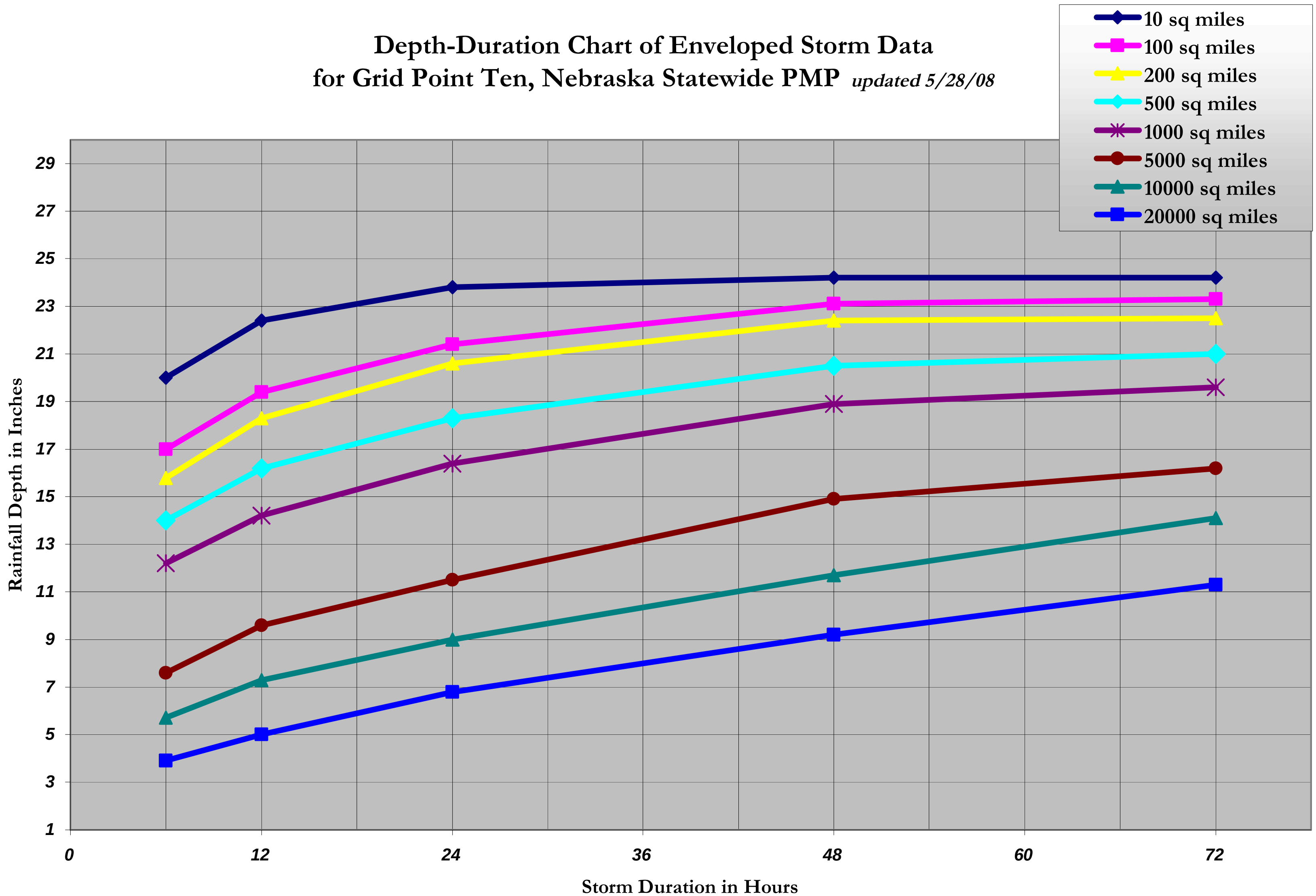


Forty Eight-Hour Depth-Area Curves
for Maximized and Transpositioned Storm Events
Grid Point 10, Elevation 1450 feet
Storm Area in Square Miles
100000
10000
1000
100
10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
Rainfall Depth in Inches
Boyden, IA
Collinsville, IL
Council Grove, KS
Edgerton, MO
Hayward, WI
Ironwood, MI
Lambert, MN
Medford, WI
Stanton, NE
Beaulieu, MN
Cole Camp, MO
Forest City, MN
David City, NE
Prague, NE
Greeley, NE
Hokah, MN
Aurora College-24hr, IL
Aurora College-6hr, IL
Bonaparte, IA
Cooper, MI
Grant Township, NE
Ida Grove, IA
Minneapolis, MN
Paris Waterworks, IN
Ritter, IA
Tomah, WI
Envelopment



Seventy Two-Hour Depth-Area Curves
for Maximized and Transpositioned Storm Events
Grid Point 10, Elevation 1450 feet
Storm Area in Square Miles
Rainfall Depth in Inches
100000
10000
1000
100
10
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
Collinsville, IL
Council Grove, KS
Edgerton, MO
Hayward, WI
Ironwood, MI
Lambert, MN
Medford, WI
Stanton, NE
Beaulieu, MN
Cole Camp, MO
Forest City, MN
David City, NE
Prague, NE
Greeley, NE
Hokah, MN
Aurora College-24hr, IL
Aurora College-6hr, IL
Bonaparte, IA
Boyden, IA
Cooper, MI
Grant Township, NE
Ida Grove, IA
Minneapolis, MN
Paris Waterworks, IN
Ritter, IA
Tomah, WI
Envelopment

Depth-Duration Chart of Enveloped Storm Data for Grid Point Ten, Nebraska Statewide PMP *updated 5/28/08*



Appendix C

New Return Frequency Dew Point Climatology Development and 100-Year, 6-Hour, 12-Hour, and 24-Hour Return Frequency Maximum Average Dew Point Maps

Dew Point Temperature Interpolation Methodology

An updated dew point climatology from those used in the EPRI Michigan Wisconsin (Tomlinson 1993) and HMR 55A studies (Hansen 1988) was developed as part of the Wanahoo site-specific PMP study and are used in determining PMP values for the Nebraska statewide PMP study. A complete set of the updated dew point climatology maps used for storm maximization in this study can be found at the end of this Appendix.

The process started by searching for and extracting the archived NCDC hourly datasets for the 6-hour, 12-hour, and 24-hour maximum dew point temperatures for each reporting station within the defined search box (49.0/-108.0, 49.0/-85.0, 32.5/-108.0, and 32.5/-85.0). A total of 77 hourly stations met the 30 year or greater data requirement as applied by AWA. This ensured a sufficient period of record was used to create reliable statistics for the return frequency analysis and these stations were used for the dew point temperature analysis (Figure C.1). A program was written to extract and quality control (QC) the stations' monthly maximum average dew point temperatures for each duration (6-hour, 12-hour, and 24-hour) for each year, known as the annual maximum series (AMS). The AMS for each month, at each station, served as input to an Excel spreadsheet that calculated L-moment statistics. Using the generalized-extreme-value (GEV) distribution, the 20-yr, 50-yr, and 100-yr dew point temperature values were computed for each duration for each month for each station. These dew point values were adjusted to represent the 15th of each month and adjusted to represent 1,000 mb dew point values. Sophisticated interpolation procedures were applied to dew point data to smooth the isodrosotherms and to incorporate terrain characteristics; this methodology has been coded into a script file and run in a GRASS GIS environment.

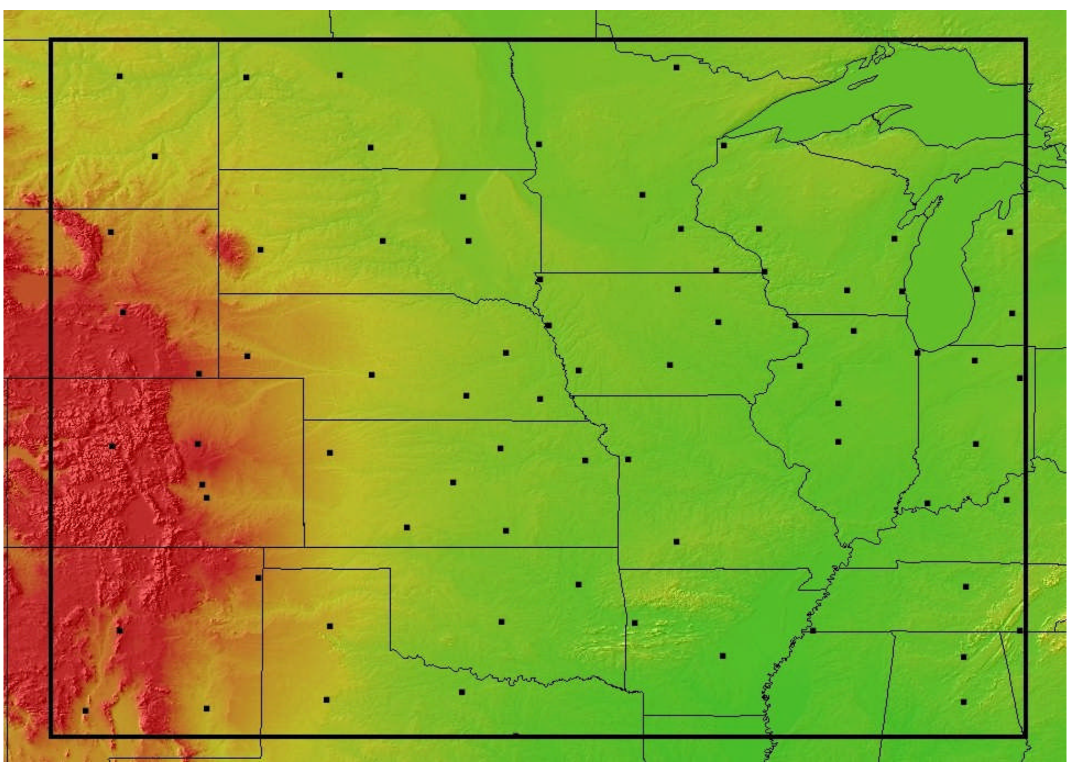


Figure C.1. Hourly dew point temperature station locations used for this analysis.

Dew Point Adjustments to Mid-Month and to 1000mb

Once the dew point station data were gathered and organized, the next step was to reduce all data to a standard level for comparison and analysis purposes. This was done following the accepted methodology of reducing the dew point data moist pseudo-adiabatically to a standard level, in this case 1000mb. Further, the dew point data were adjusted to the 15th of each month so the dew point climatology maps represented the mid-month values.

Dew Point 1000mb reduction Process

A moist pseudo-adiabatic lapse rate (2.7°F/1000 ft) was used to adjust the mid-month dew point temperatures at the station elevations to 1,000 mb (assumed to be at sea level). A linear relationship between elevation and lapse rate was created and applied to each station. The biggest change occurred along the western edge of the domain where elevation is greatest. A majority of the dew point stations were between 800 and 1,400 ft elevation which had adjustments of approximately 2°F to 4°F. The largest adjustment was at the Eagle, CO station (approximately 17°F) and the smallest adjustment was at the Little Rock, AR station (0.68 °F).

Dew Point 15th of the Month Adjustment

The station data were corrected to the 15th of each month using a linear relationship between the previous month, current month, and the next month. Steps are listed below:

1. Calculate the difference in days between the observed average maximum dew point date and the 15th.

Example: May 29th, so 29 -15 = 14 days (positive). Using Julian days, May is 135 and June is 166, 166-135 = 31, where unadjusted 100-year value for May is 62°F and June is 70°F

2. Depending whether the difference in step 1 is positive or negative (direction of adjustment) calculate the ratio/difference between the non-adjusted dew point temperature (for the months of interest) and the number of days between the dates.

Example continued: Since the 29th is after the 15th, take current month and following month, so May 62°F – June 70°F = 8

3. Apply the ratio calculated in step 2 to the difference calculated in step 1.

Example continued: 8/31 = .258 x 14 days = 3.6, add this to the month's value, so 62 + 3.6 = 65.6 or 66°F.

4. Check the adjusted dew point value with the previous and next month values, and the other two durations

5. Calculate the difference between the original dew point value and the adjusted dew point value.

6. Create station plots of the duration and frequency for additional QC measure.

7. Create a list of the adjusted dew point values for each station in a GIS format.

A majority of these steps were performed using Excel macros. The biggest dew point difference (~ <5 °F) was in the winter and transition months of May and September. A majority of the data were adjusted less than +/- 2 °F. The June 24-hour dew point data for Omaha, NE are shown in Table C.1. The table shows the original station data, the data adjusted to the 15th, and the data adjusted to 1,000 mb.

Table C.1 Original station dew point data (°F), the adjusted 15th data, and the 1000 mb data for the 20-yr, 50-yr, and 100-yr frequencies.

	20-year	50-year	100-year
Station Data	73.76	74.89	75.60
15th Data	72.95	74.11	74.83
1000 mb Data	76.02	77.18	77.90

Spatial Interpolation

PRISM Data

Maximum and minimum monthly dew point temperature PRISM grids were downloaded for the continental United States for the time period of 1971-2000. PRISM grids were used to calculate the mean monthly dew point temperature $\overline{td}_m$ for this time period:

$$\overline{td}_m = \frac{\sum_{i=1}^{n} x_i}{n}$$

where m is the month of interest, n is the number months and x_i are the monthly dew point temperature values. The PRISM data were converted from degrees Celsius to degrees Fahrenheit. The mean monthly PRISM dew point data were extracted for each of the 77 dew point stations.

PRISM Station Relationship

Calculate linear relationships between PRISM data and the station data (1000 mb) for each duration (6-, 12-, and 24-hour) and frequency (20, 50, and 100 year). Table B.2 shows each of the derived linear relationships between the PRISM data and station data, where y equals the stations dew point temperature (°F) value, and x equals the stations mean monthly PRISM dew point temperature (°F) value. The linear relationships between mean monthly PRISM dew point data and the 100-year 24-hour dew point data for June, July, August, and September are shown in Figure C.2.

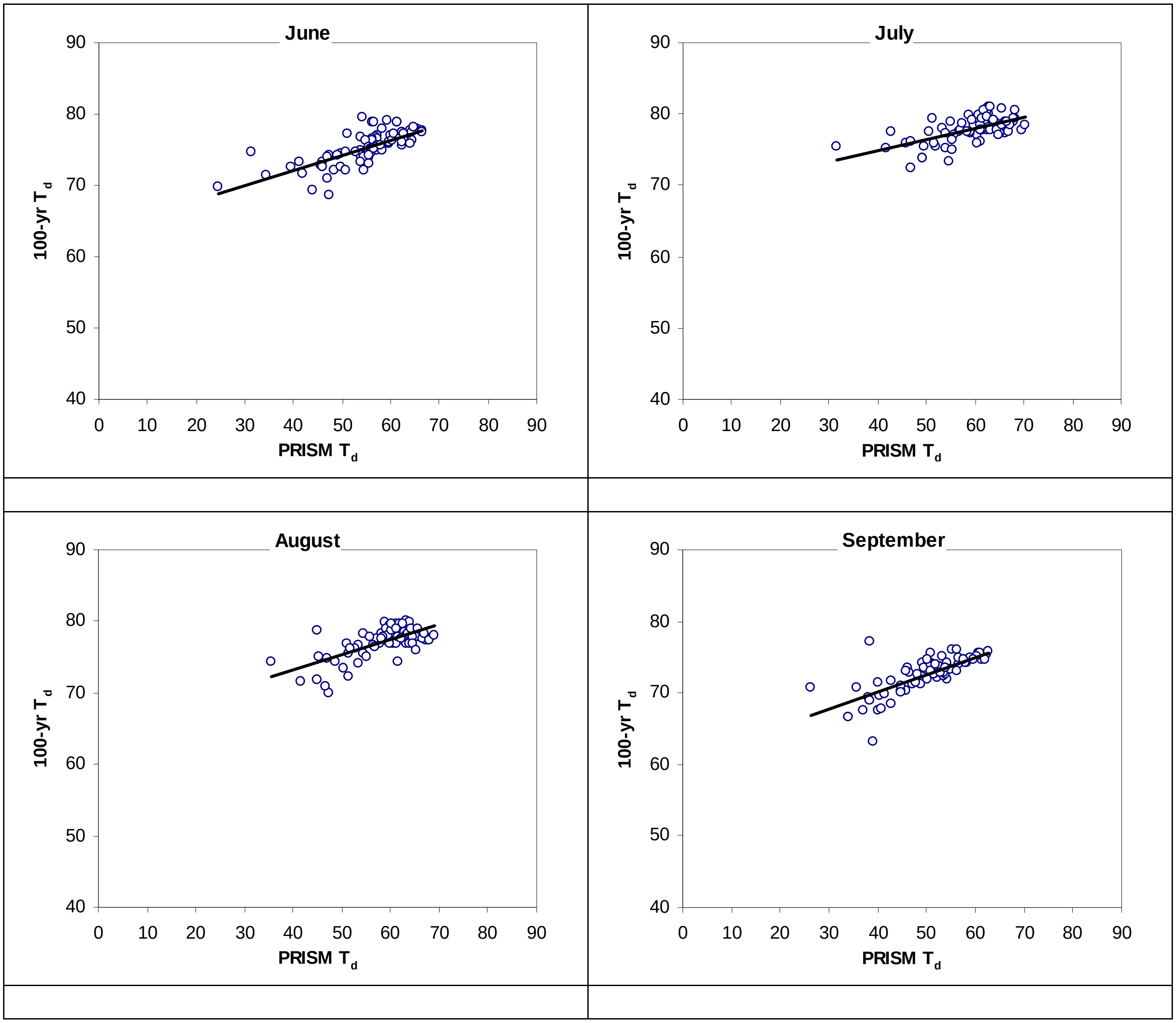


Figure C.2 Linear relationships between mean monthly PRISM dew point data and the 100-year 24-hour dew point data for June, July, August, and September

The derived linear relationships were applied to the mean monthly dew point PRISM grids, which provided a first estimate of the dew point temperature distribution. Residuals (actual – predicted) between the station and the first estimate were calculated at each station. The 100-year 24-hour dew point residuals for June, July, August, and September are shown in Figure C.3.

The residuals were spatially distributed across the search domain using an inverse-distance algorithm. The spatially distributed residual grids were smoothed. The smoothed residual grid was added to the first estimate grid to create the second estimate grid (Figure C.4). The second estimate grids were smoothed further to give a more realistic representation of the isodrosotherms found in the natural environment (Figure C.5). The smoothed second estimate grids represent the final dew point temperature distribution.

The spatial interpolation method was first applied and tested using ArcGIS. Script files of the final ArcGIS interpolation procedure were created to automate the process within the GRASS GIS environment. The GRASS GIS script also created 1°F dew point contours from the final interpolated dew point grid. The GRASS GIS dew point analysis and 1°F contours for the April, June, August, and October 100-year 6-hour are shown in Figure C.6. The GRASS GIS dew point raster and contour shapefile are exported from the GRASS GIS environment and used to create a final dew point layout (Figure C.7)[2].

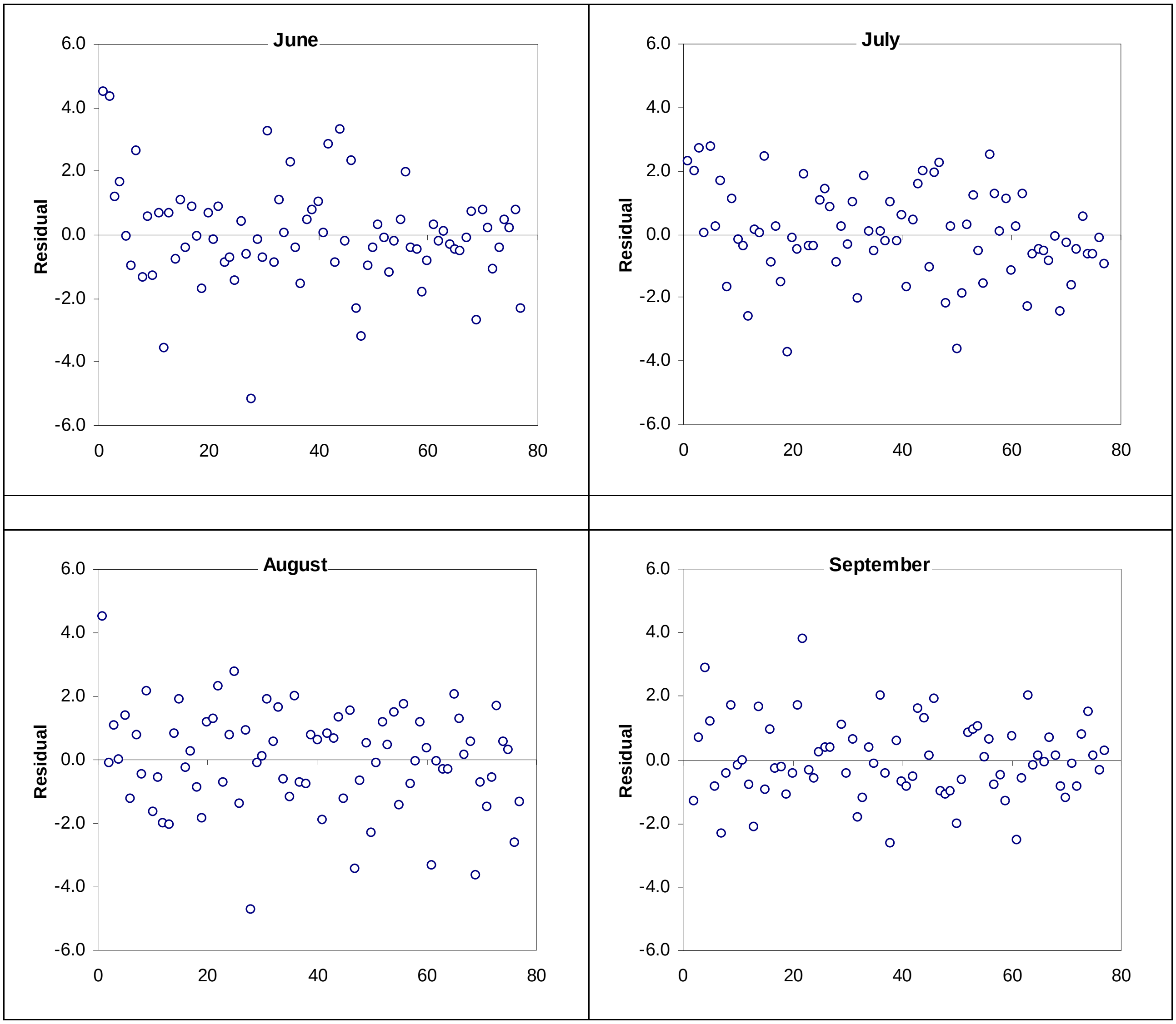


Figure C.3 Calculated residuals between mean monthly PRISM dew point data and the 100-year 24-hour dew point data for June, July, August, and September

[2] The final dew point data values, GIS grids/shapefiles and map layouts, are only representative within the Nebraska search domain. The outer edges of the domain may not represent the actual dew point pattern as no data beyond the search domain were used in the analysis.

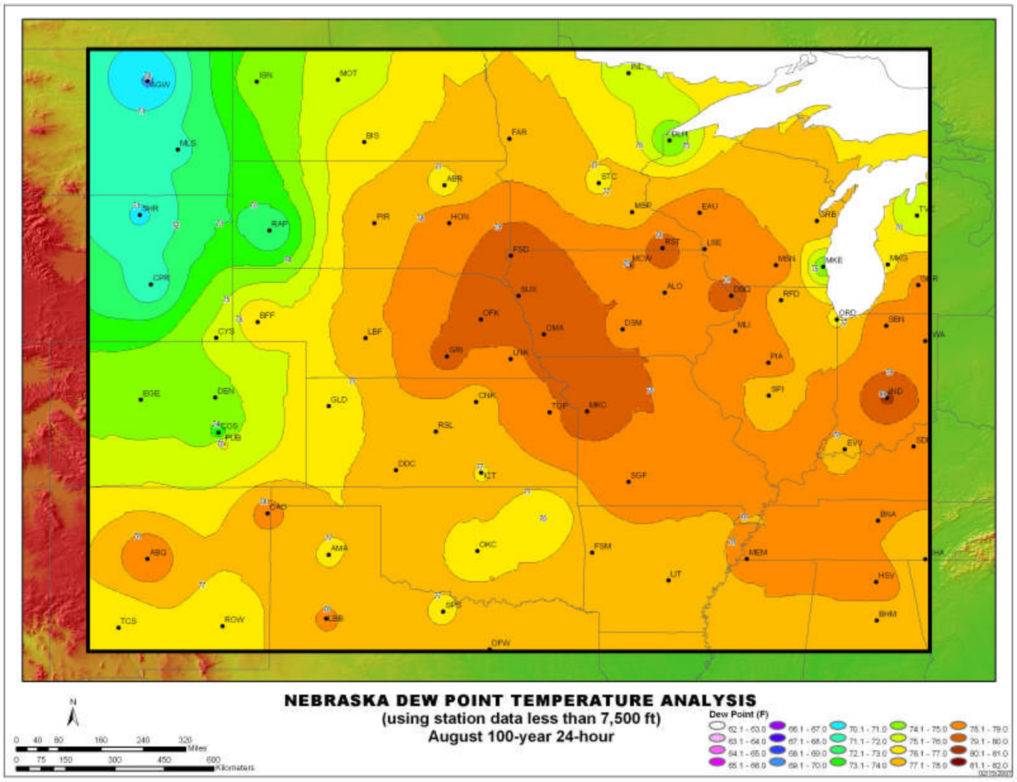


Figure C.4 ArcGIS's inverse distance weighting on August 100-year 24-hour data

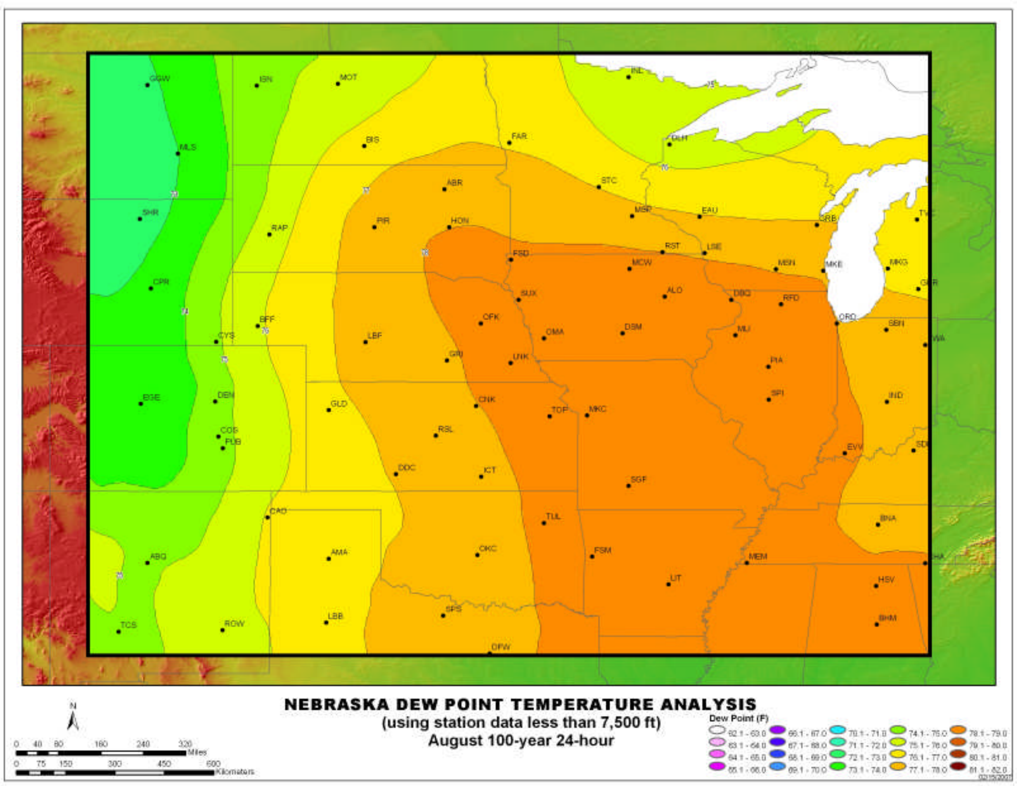


Figure C.5 Smoothing procedure presented in paper on August 100-year 24-hour data

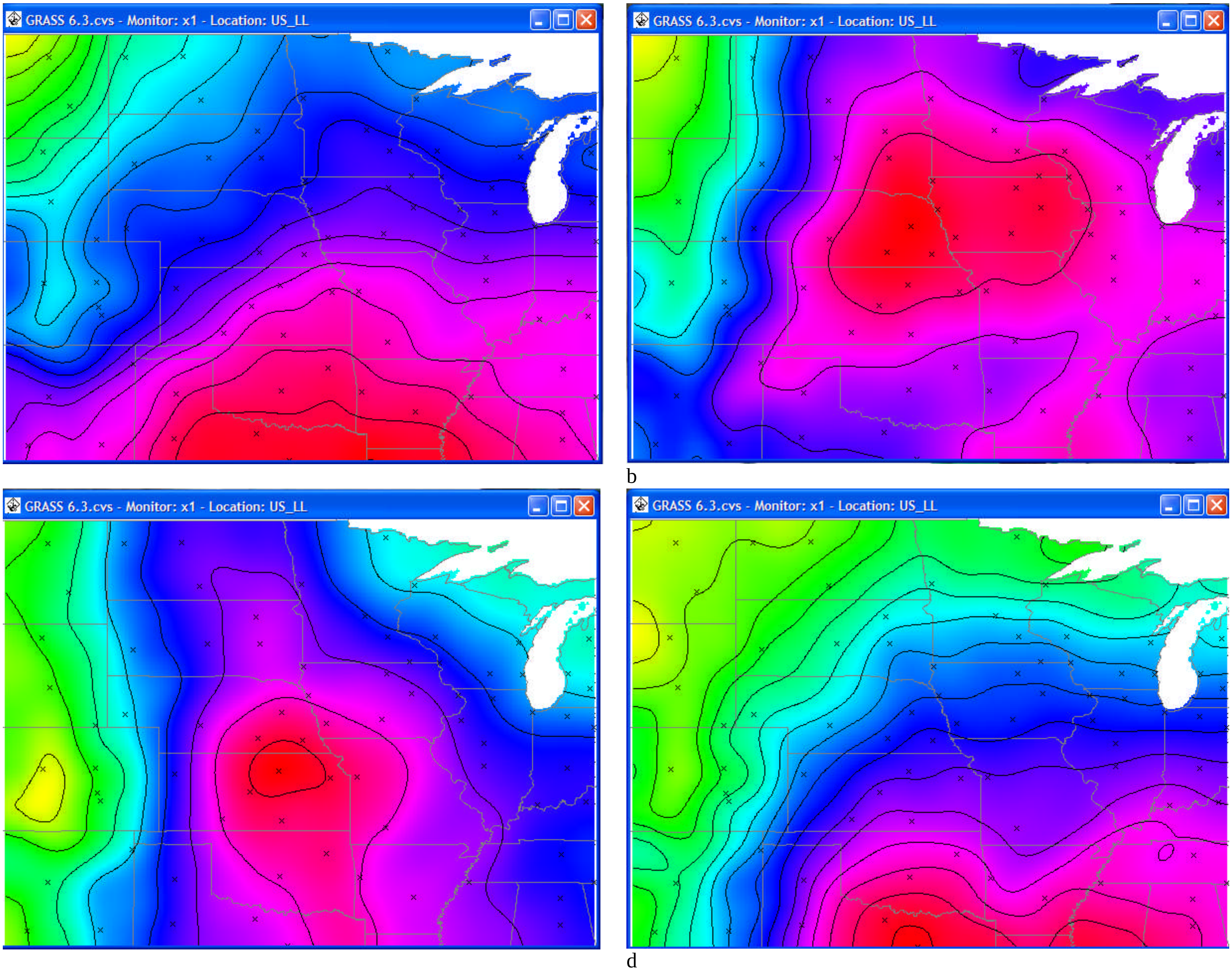


Figure C.6 Dew point analysis using GRASS GIS, contours are at 1°F intervals. a) October 100-year 6-hour dew point b) August 100-year 6-hour dew point c) June 100-year 6-hour dew point d) April 100-year 6-hour dew point.

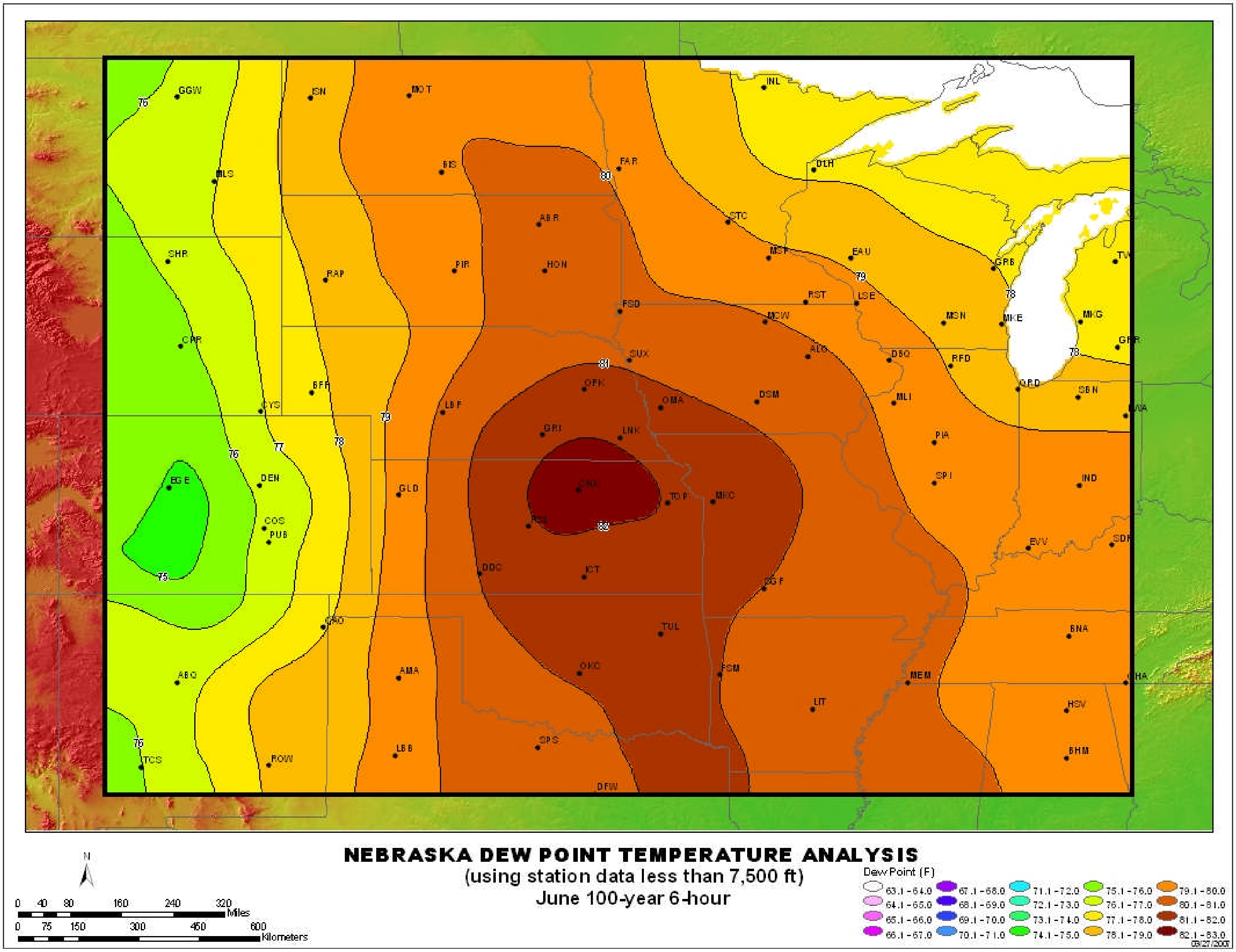
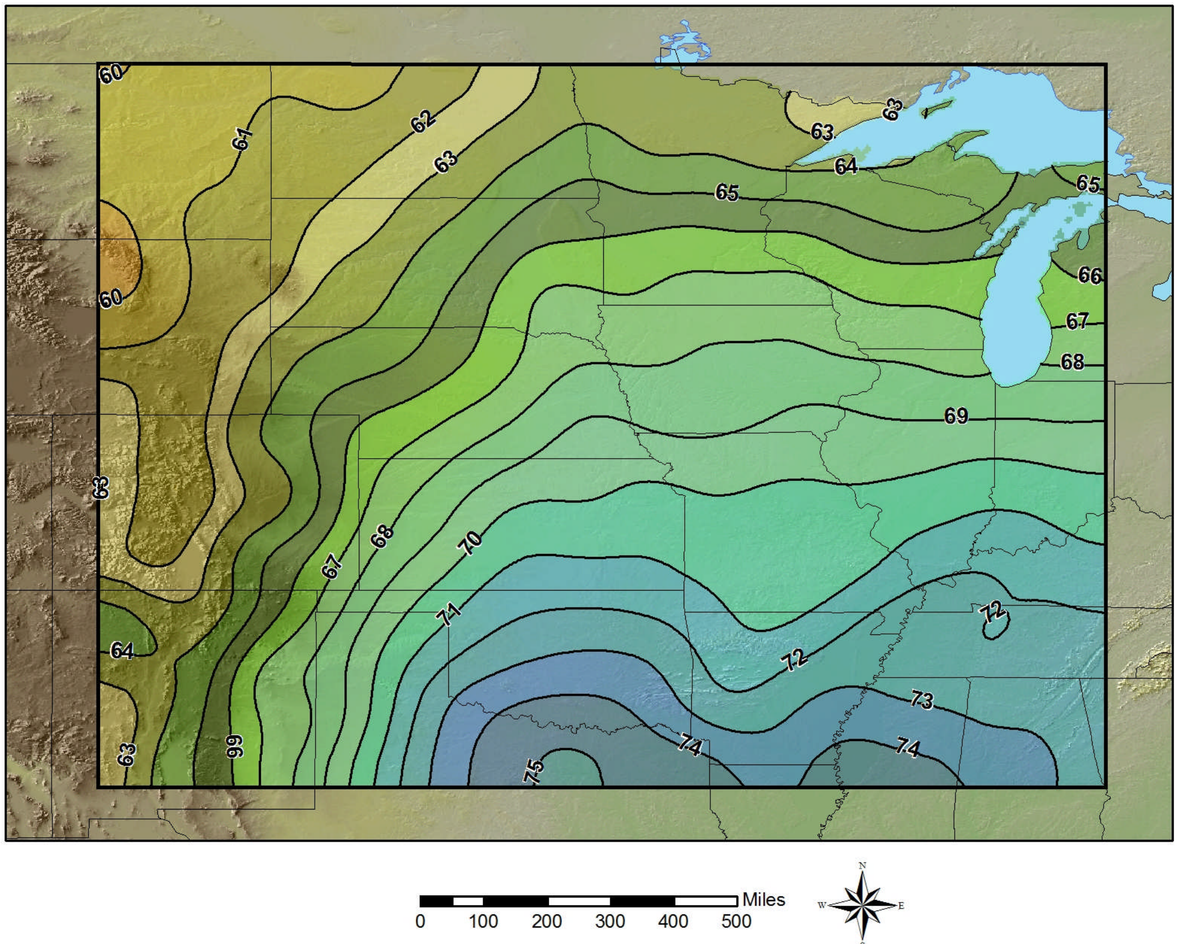


Figure C.7 Dew point analysis using GRASS GIS, the June 100-year 6-hour dew point grid and shapefile were exported from GRASS GIS and plotted using ArcGIS.

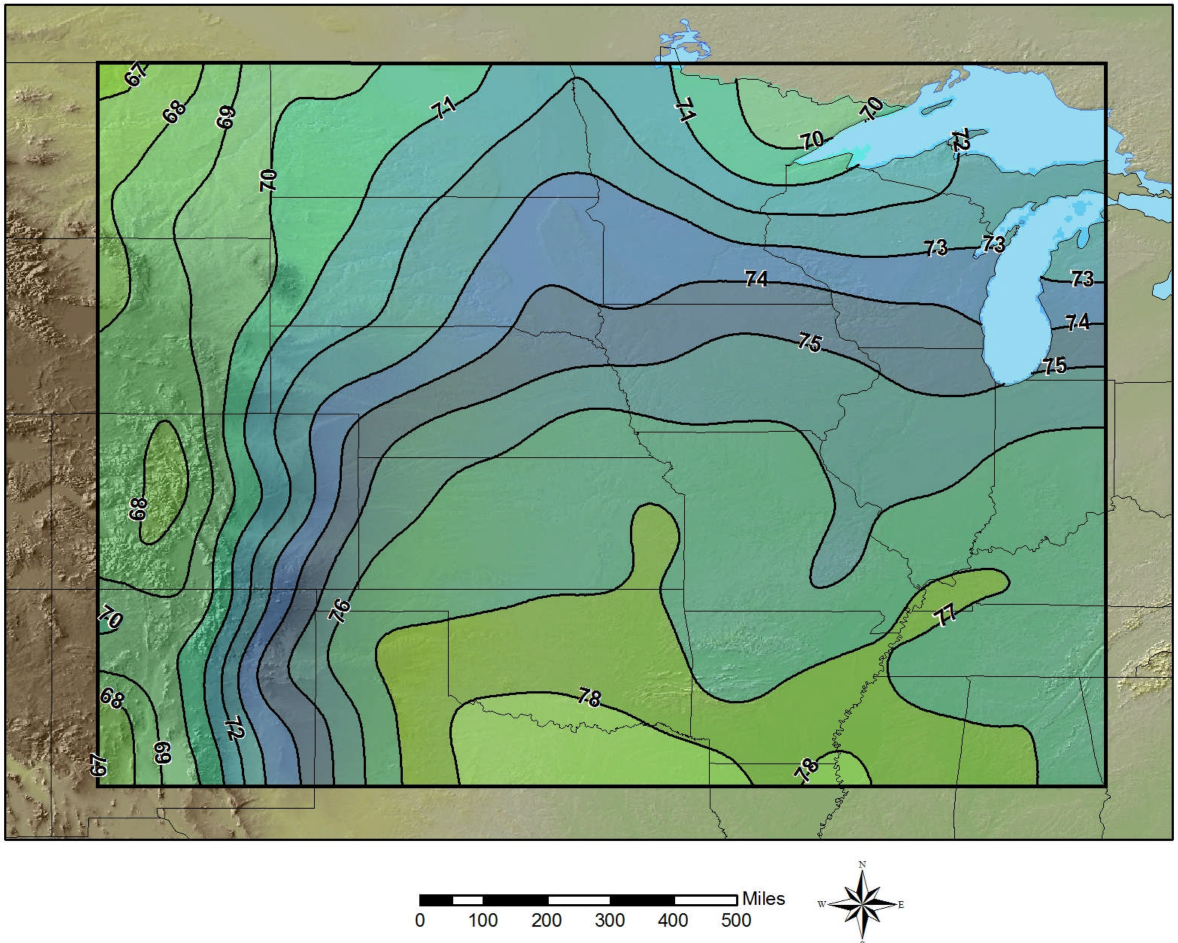
Table C.2 Derived linear relationships between the PRISM data and station data, where *y* equals the stations dew point temperature (°F) value, and *x* equals the stations mean monthly PRISM dew point temperature (°F) value.

	100-yr 6-hr equation	R^2		100-yr 12-hr equation	R^2		100-yr 24-hr equation	R^2
January	-		January	-		January	y = 1.0143x + 35.432	0.77
February	-		February	-		February	y = 0.8982x + 35.385	0.75
March	-		March	-		March	y = 0.7128x + 40.122	0.61
April	y = 0.4319x + 52.032	0.687	April	y = 0.4657x + 49.24	0.73	April	y = 0.4842x + 47.044	0.75
May	y = 0.3152x + 59.14	0.564	May	y = 0.3368x + 56.22	0.68	May	y = 0.366x + 53.073	0.72
June	y = 0.1634x + 69.711	0.368	June	y = 0.1793x + 67.289	0.45	June	y = 0.2113x + 63.637	0.52
July	y = 0.1395x + 72.781	0.233	July	y = 0.1596x + 70.065	0.33	July	y = 0.1534x + 68.746	0.37
August	y = 0.1818x + 69.44	0.303	August	y = 0.1882x + 67.714	0.38	August	y = 0.2145x + 64.552	0.45
September	y = 0.2024x + 65.483	0.424	September	y = 0.2223x + 63.122	0.5	September	y = 0.2442x + 60.393	0.55
October	y = 0.3472x + 57.941	0.444	October	y = 0.3939x + 54.382	0.49	October	y = 0.4361x + 51.225	0.54
November	-		November	-		November	y = 0.6714x + 42.028	0.67
December	-		December	-		December	y = 0.9603x + 36.715	0.73
	50-yr 6-hr equation	R^2		50-yr 12-hr equation	R^2		50-yr 24-hr equation	R^2
January	-		January	-		January	y = 1.0034x + 34.689	0.78
February	-		February	-		February	y = 0.9139x + 34.139	0.78
March	-		March	-		March	y = 0.7431x + 38.138	0.67
April	y = 0.4422x + 51.144	0.701	April	y = 0.4774x + 48.274	0.74	April	y = 0.5x + 45.86	0.76
May	y = 0.3196x + 58.329	0.61	May	y = 0.3425x + 55.4	0.7	May	y = 0.3711x + 52.296	0.73
June	y = 0.167x + 69.014	0.43	June	y = 0.185x + 66.458	0.51	June	y = 0.2175x + 62.853	0.58
July	y = 0.1416x + 72.277	0.276	July	y = 0.1606x + 69.606	0.37	July	y = 0.1568x + 68.178	0.42
August	y = 0.1857x + 68.857	0.352	August	y = 0.1942x + 66.986	0.43	August	y = 0.2202x + 63.839	0.49
September	y = 0.2172x + 64.446	0.474	September	y = 0.2411x + 61.831	0.55	September	y = 0.2679x + 58.873	0.6
October	y = 0.3842x + 55.845	0.504	October	y = 0.4272x + 52.469	0.53	October	y = 0.4716x + 49.164	0.58
November	-		November	-		November	y = 0.7169x + 39.776	0.72
December	-		December	-		December	y = 0.962x + 35.391	0.78
	20-yr 6-hr equation	R^2		20-yr 12-hr equation	R^2		20-yr 24-hr equation	R^2
January	-		January	-		January	y = 0.9839x + 33.419	0.8
February	-		February	-		February	y = 0.9338x + 32.146	0.81
March	-		March	-		March	y = 0.7856x + 35.05	0.73
April	y = 0.4635x + 49.413	0.712	April	y = 0.4997x + 46.439	0.74	April	y = 0.5268x + 43.718	0.75
May	y = 0.3282x + 56.904	0.654	May	y = 0.354x + 53.9	0.71	May	y = 0.3817x + 50.814	0.73
June	y = 0.1762x + 67.658	0.511	June	y = 0.1967x + 64.93	0.58	June	y = 0.2302x + 61.354	0.64
July	y = 0.1461x + 71.324	0.341	July	y = 0.1641x + 68.684	0.43	July	y = 0.1639x + 67.079	0.47
August	y = 0.1942x + 67.743	0.421	August	y = 0.204x + 65.729	0.49	August	y = 0.233x + 62.414	0.54
September	y = 0.2436x + 62.563	0.541	September	y = 0.274x + 59.543	0.61	September	y = 0.3086x + 56.195	0.64
October	y = 0.4372x + 52.625	0.572	October	y = 0.4791x + 49.332	0.59	October	y = 0.5239x + 45.894	0.63
November	-		November	-		November	y = 0.7774x + 36.455	0.75
December	-		December	-		December	y = 0.9598x + 33.323	0.82

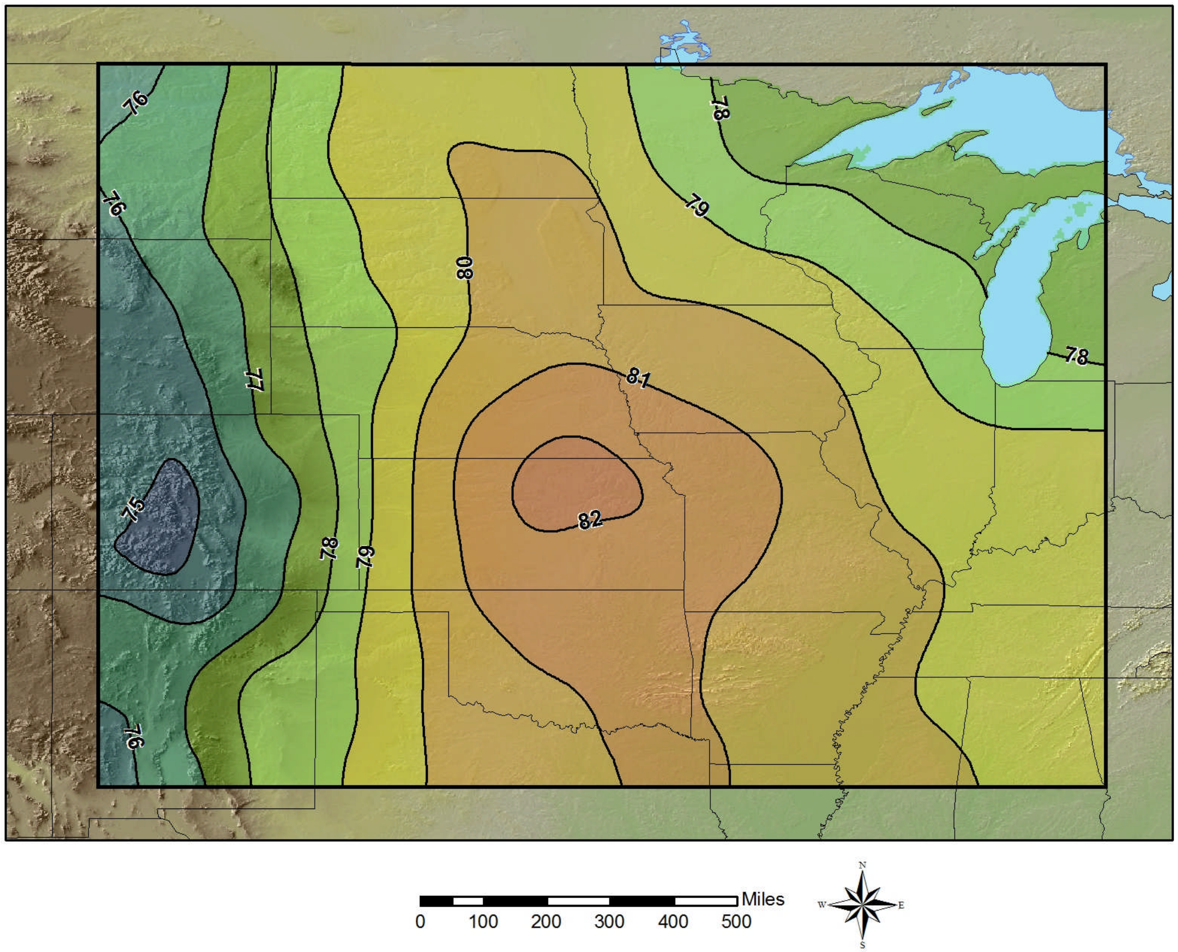
April 100-Year 6-Hour
Dew Point Climatology (°F)



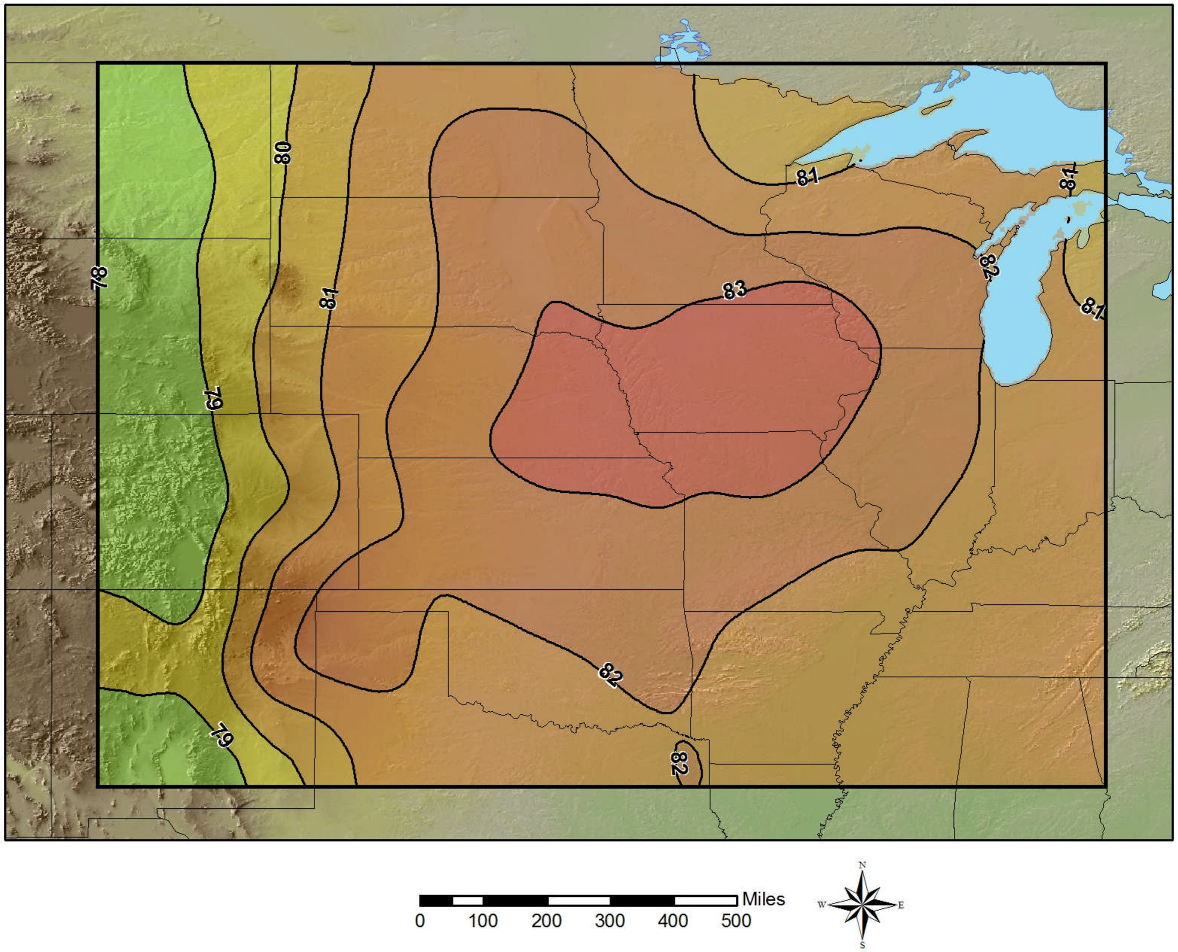
May 100-Year 6-Hour Dew Point Climatology (°F)



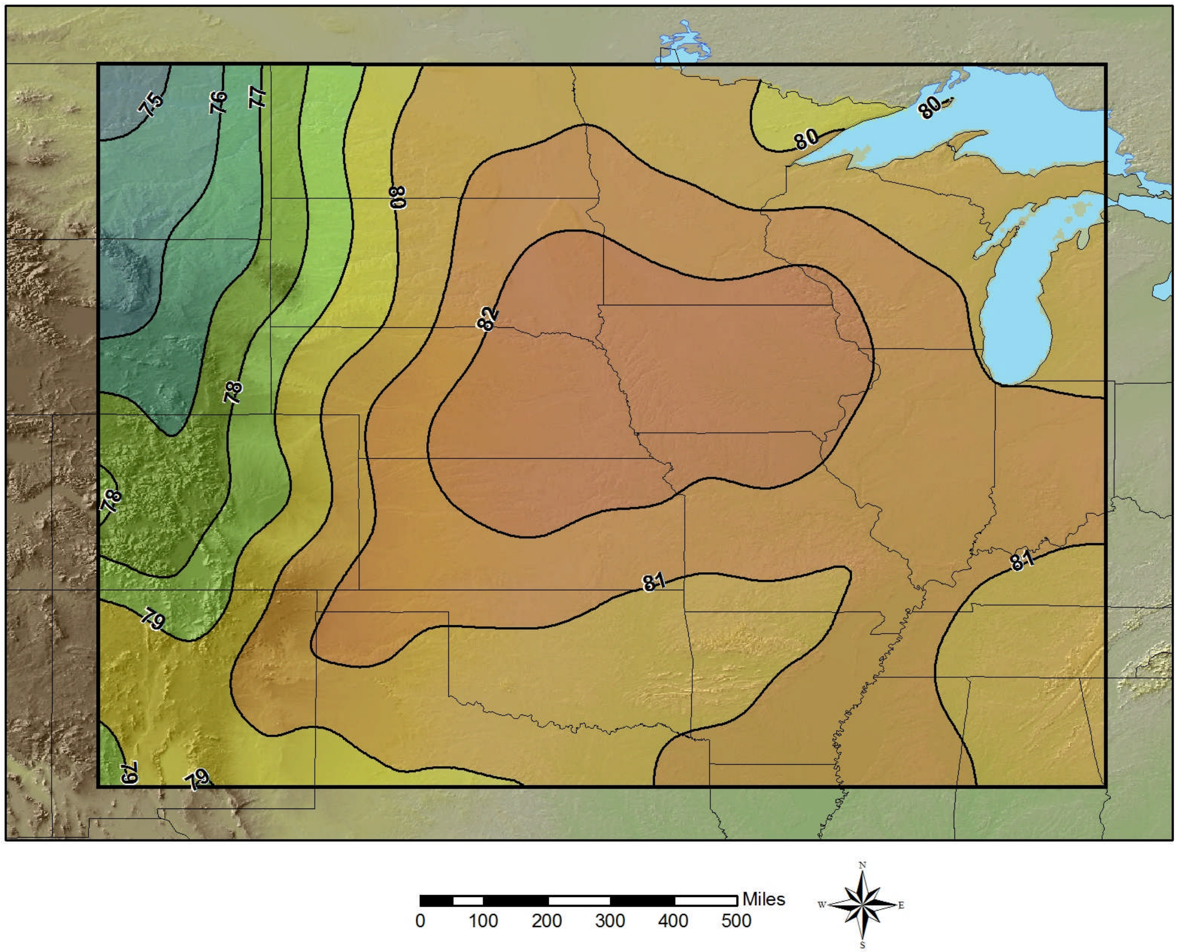
June 100-Year 6-Hour
Dew Point Climatology (°F)



July 100-Year 6-Hour
Dew Point Climatology (°F)



August 100-Year 6-Hour Dew Point Climatology (°F)



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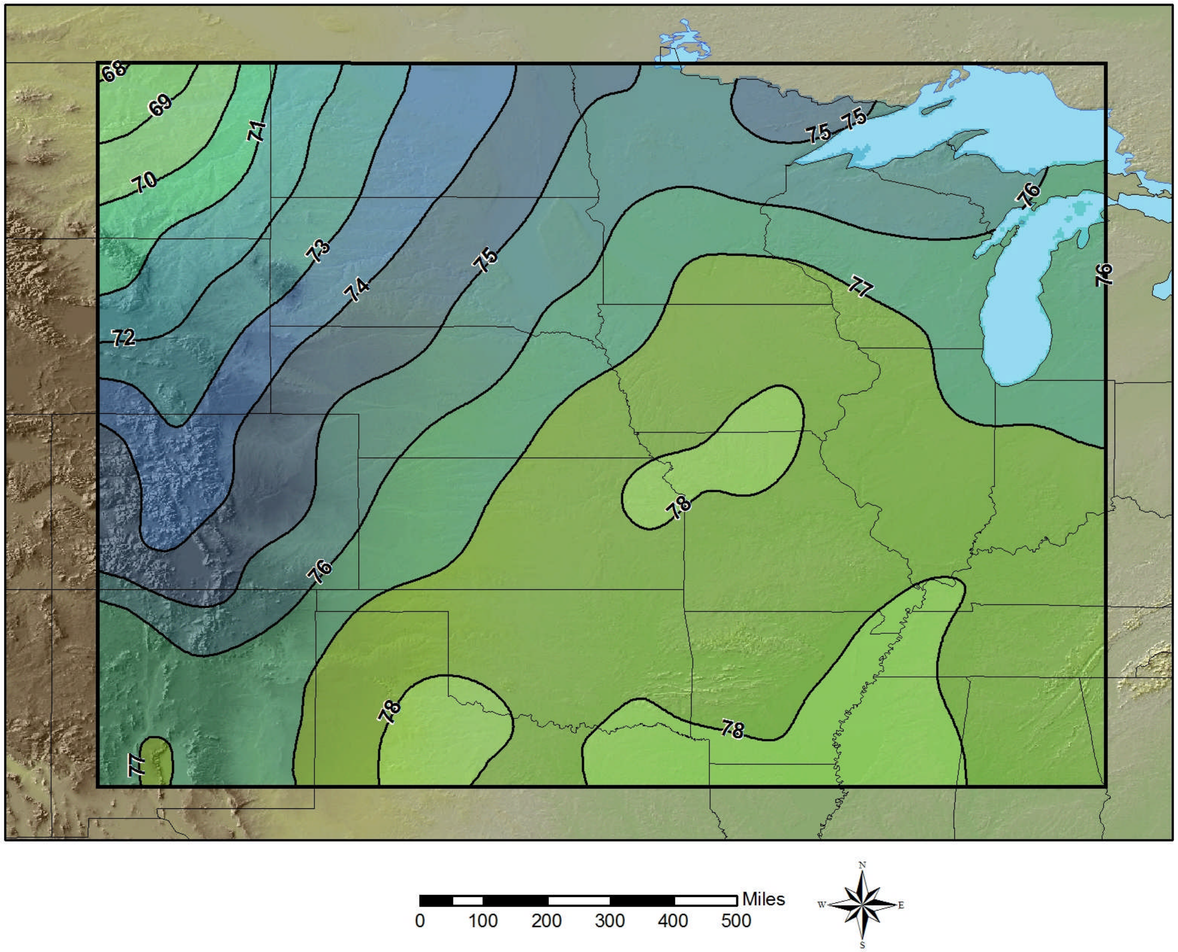
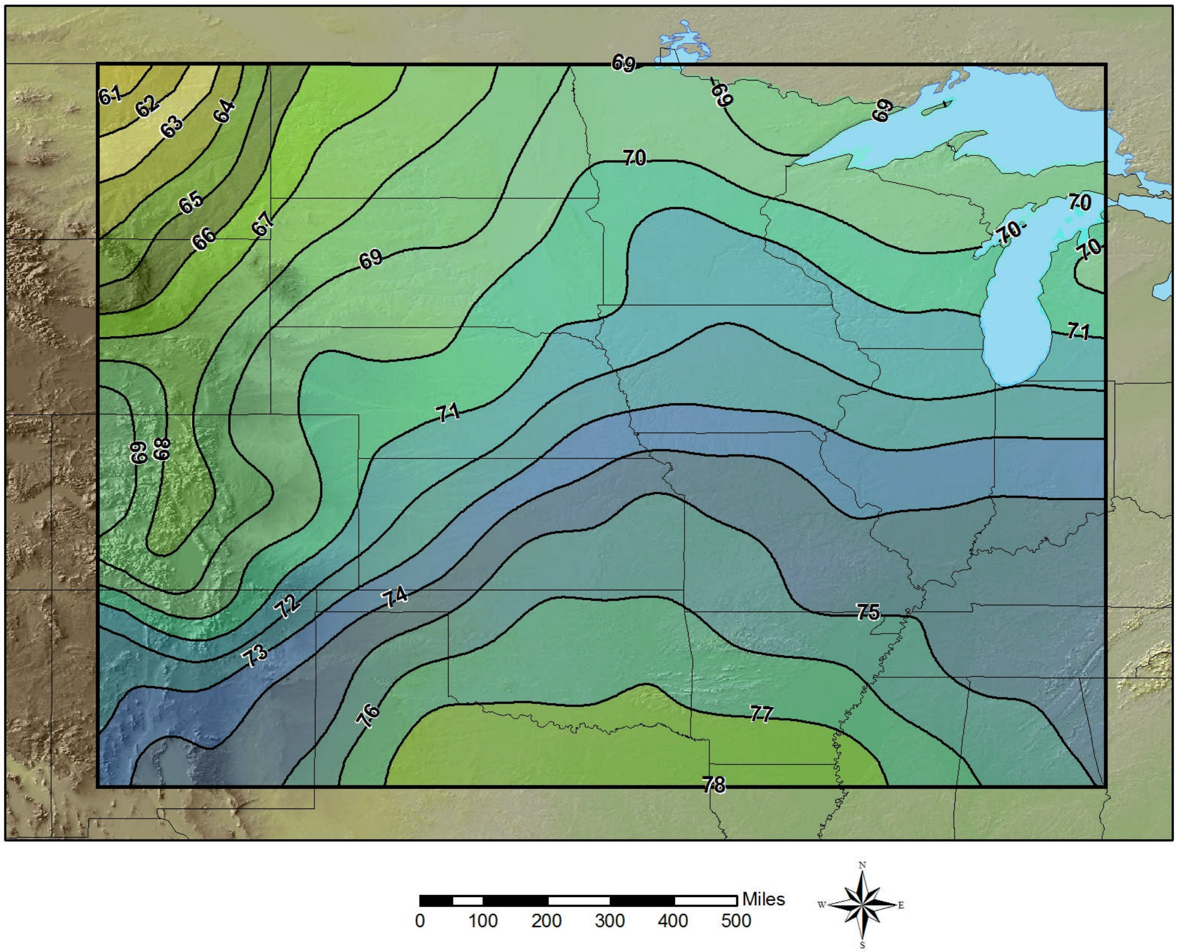
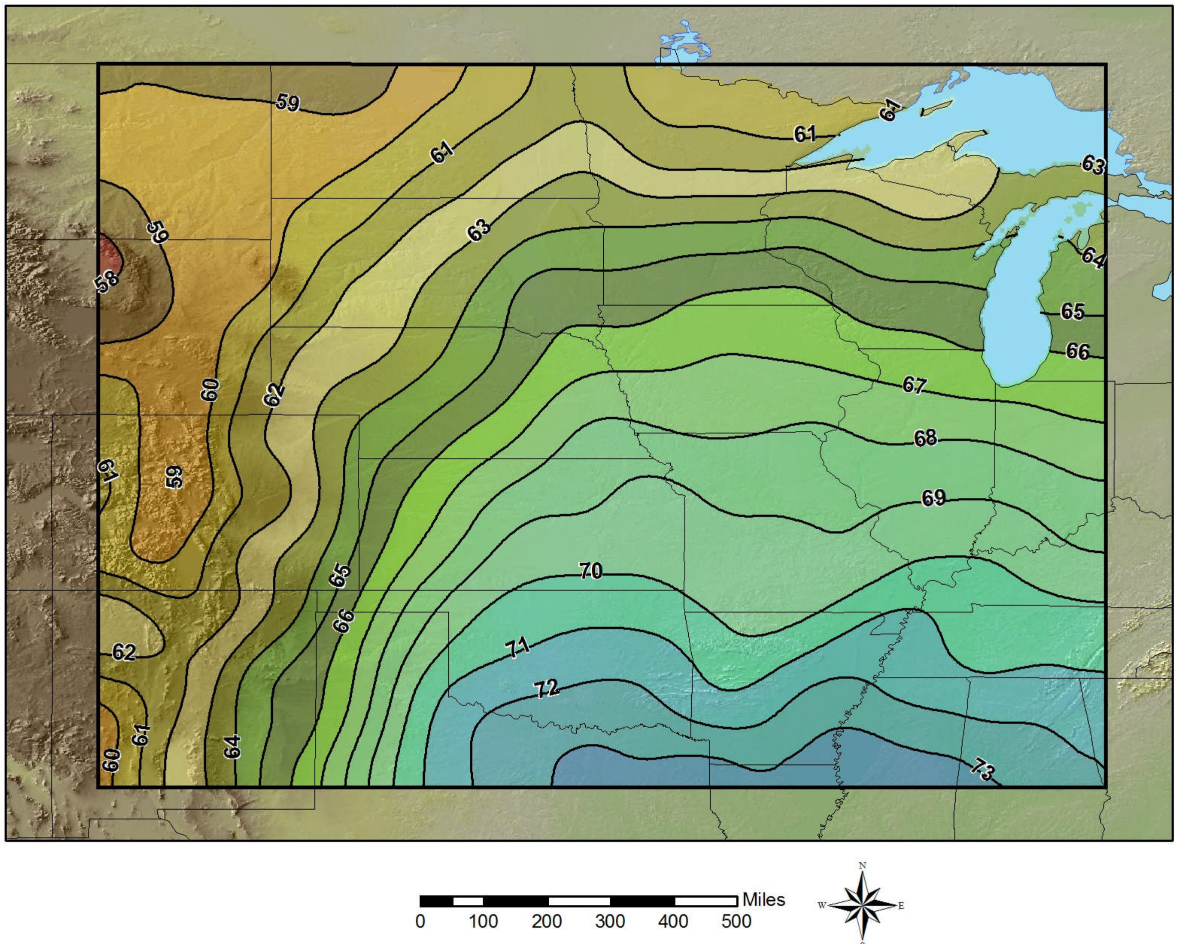


October 100-Year 6-Hour Dew Point Climatology (°F)



April 100-Year 12-Hour
Dew Point Climatology (°F)



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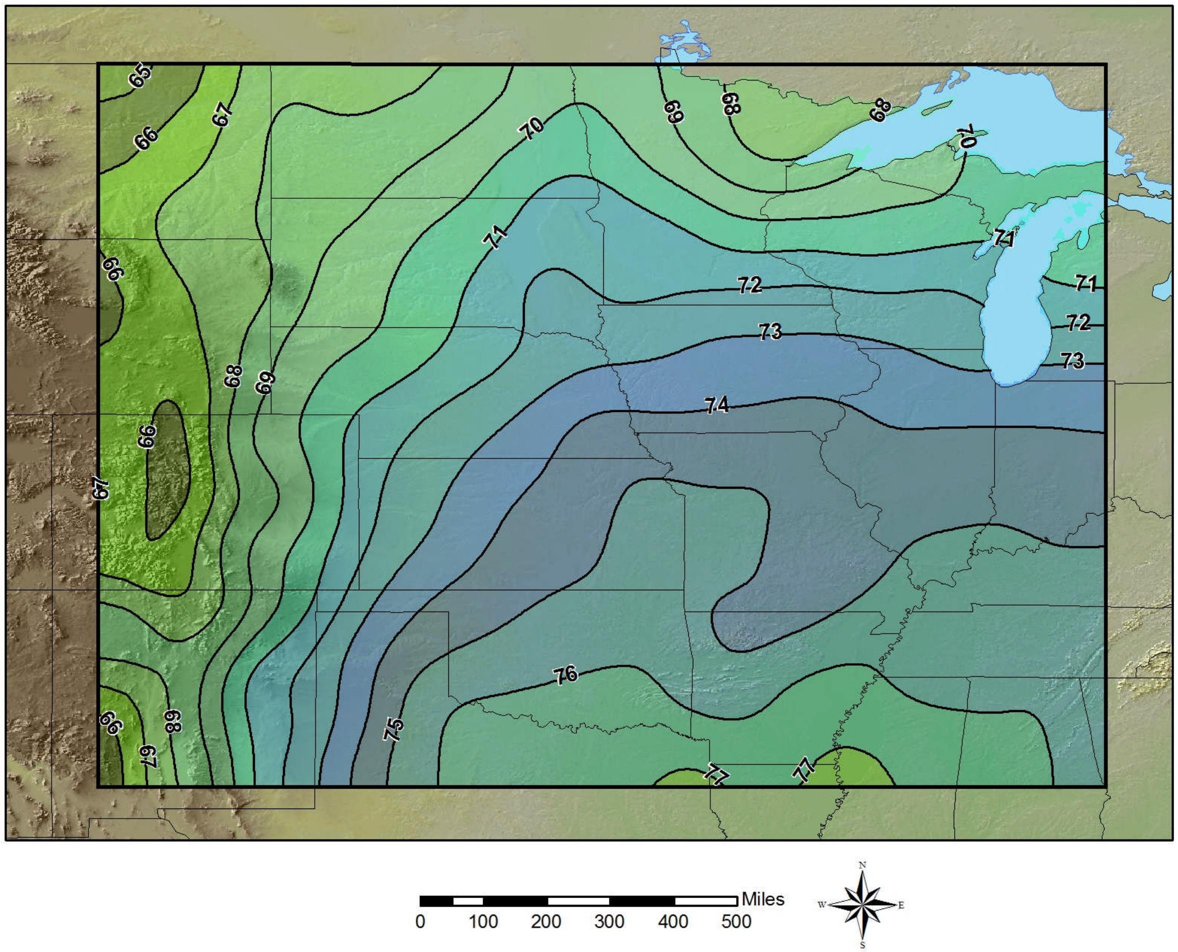

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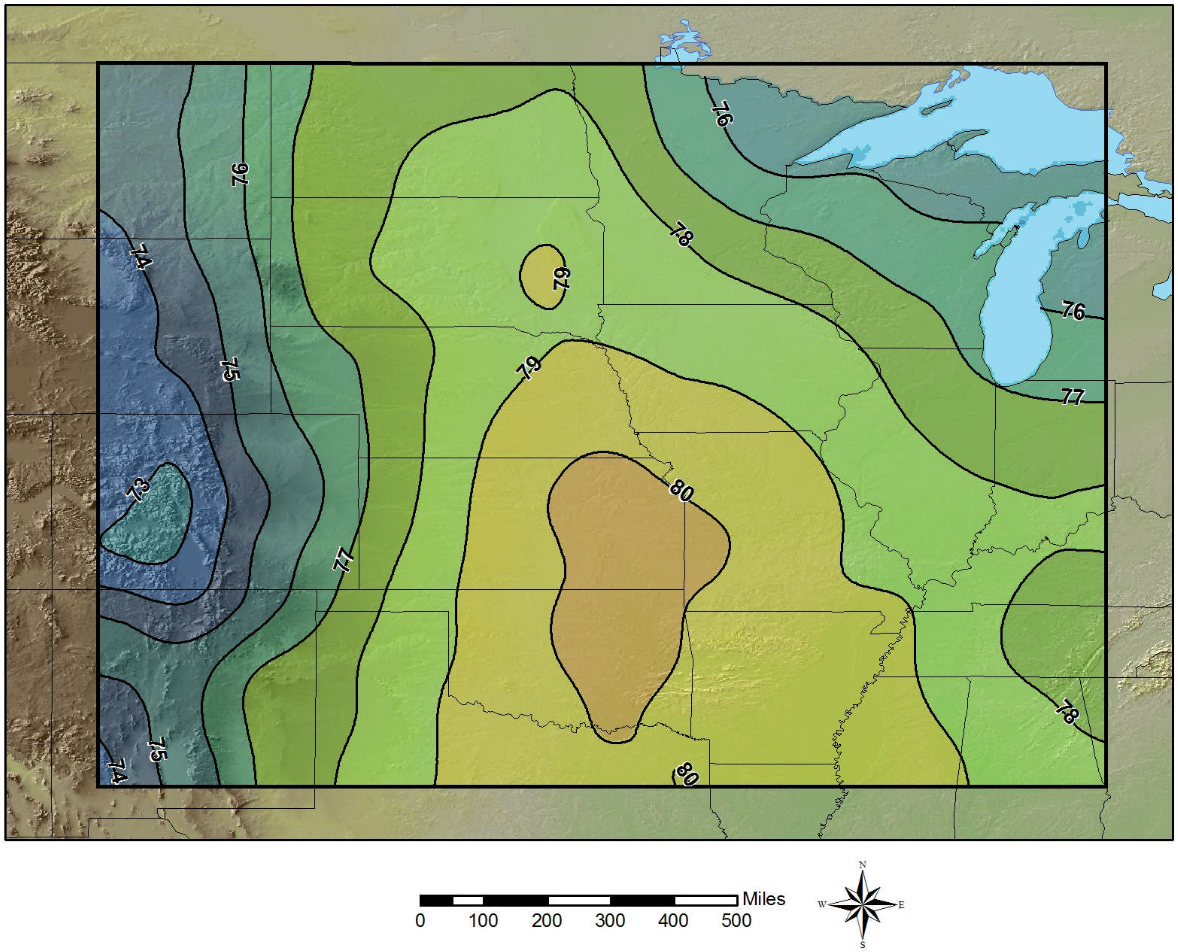

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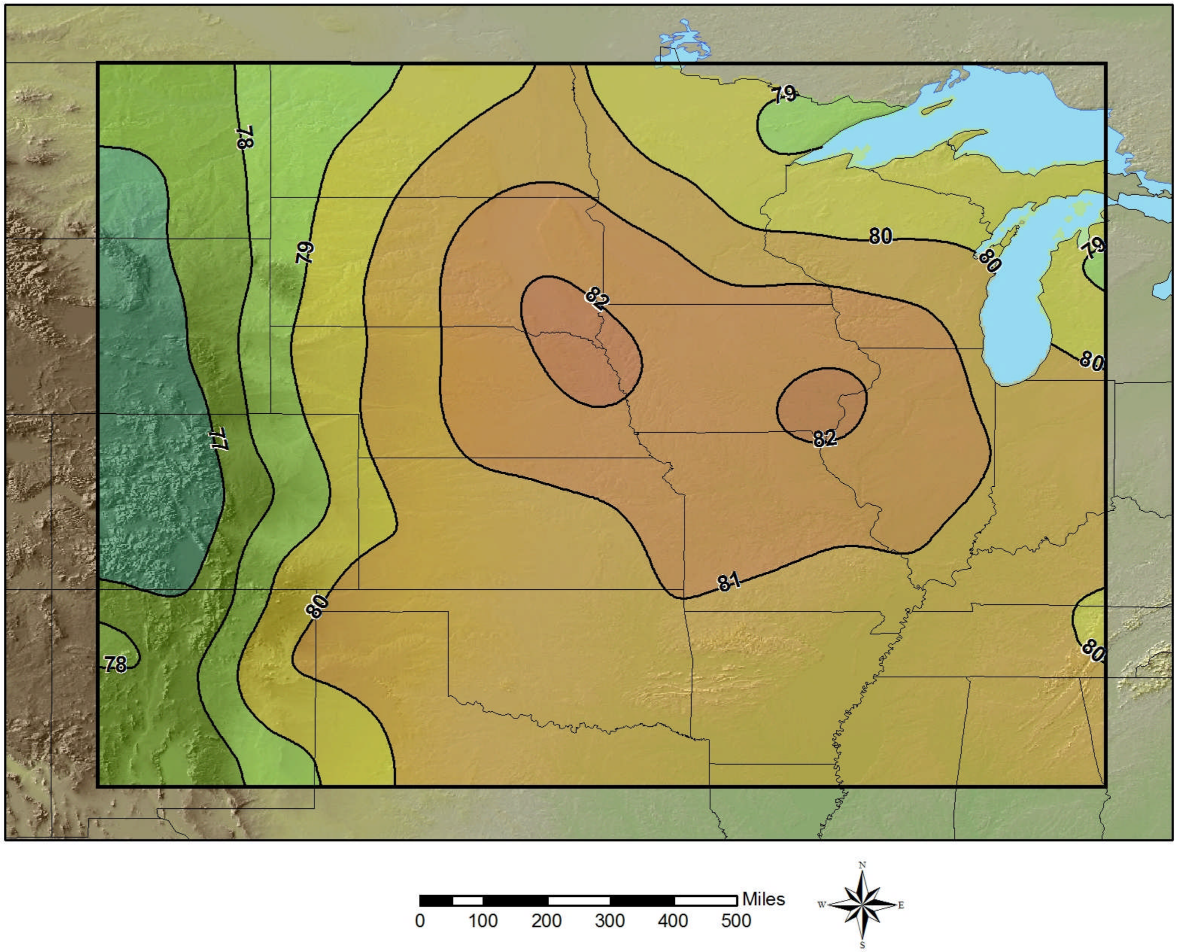
Dew Point Climatology (°F)



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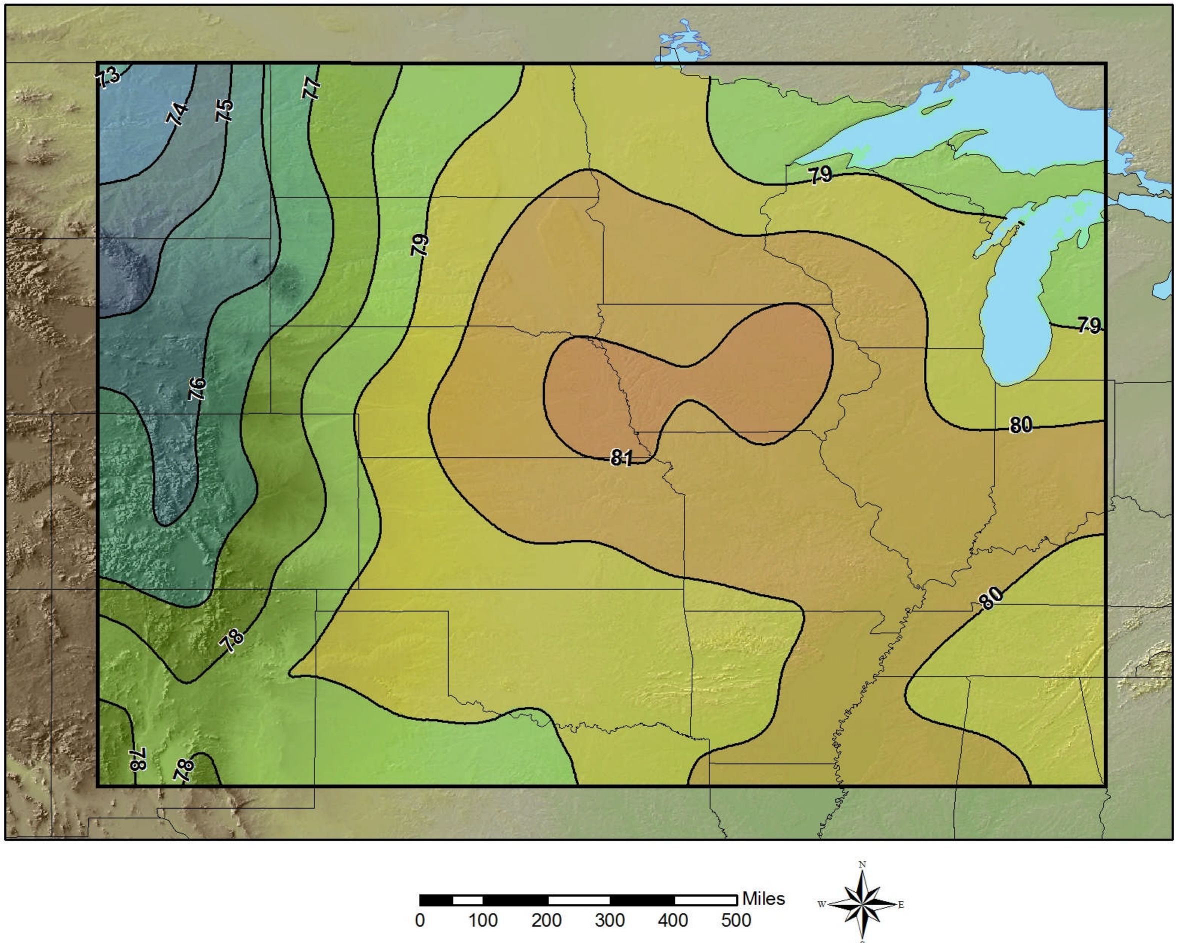

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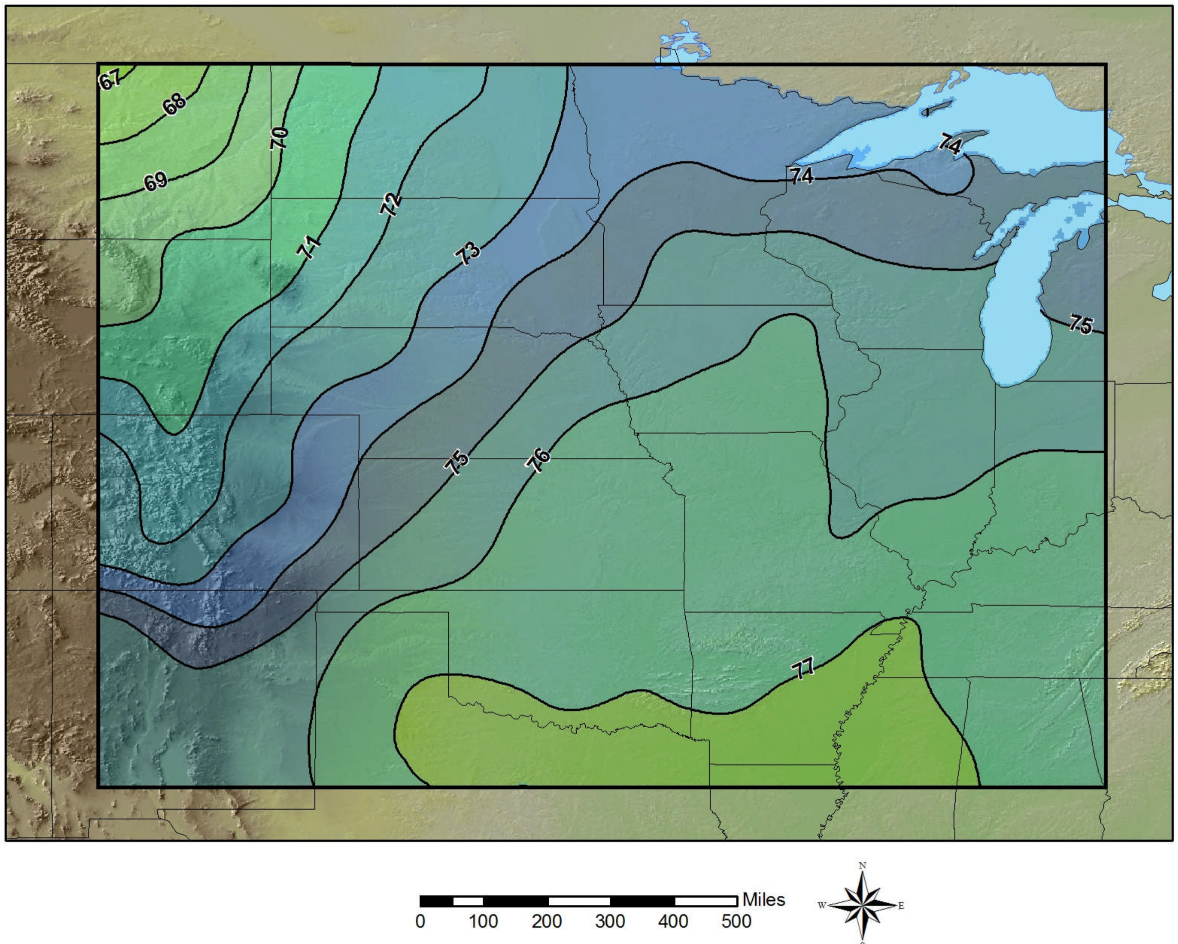
Dew Point Climatology (°F)



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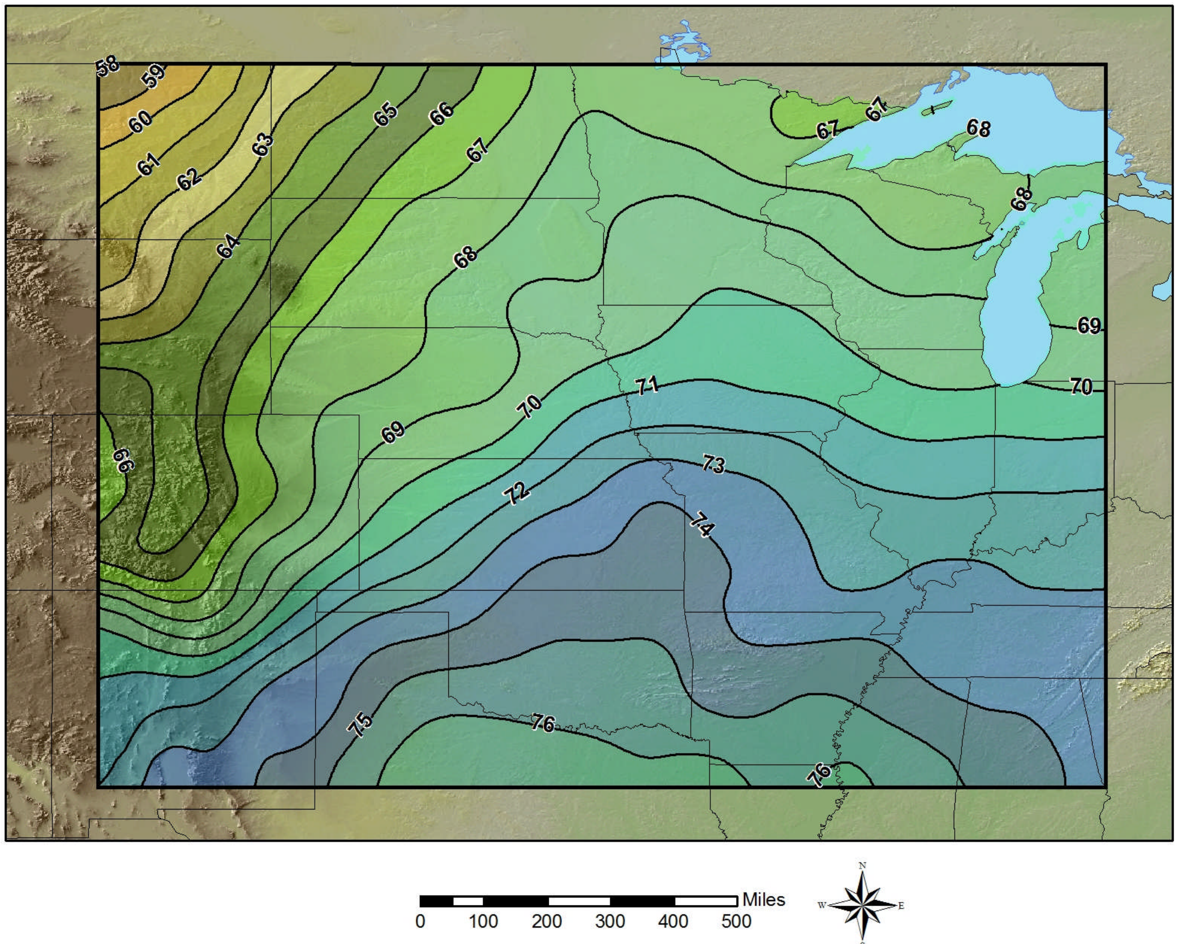
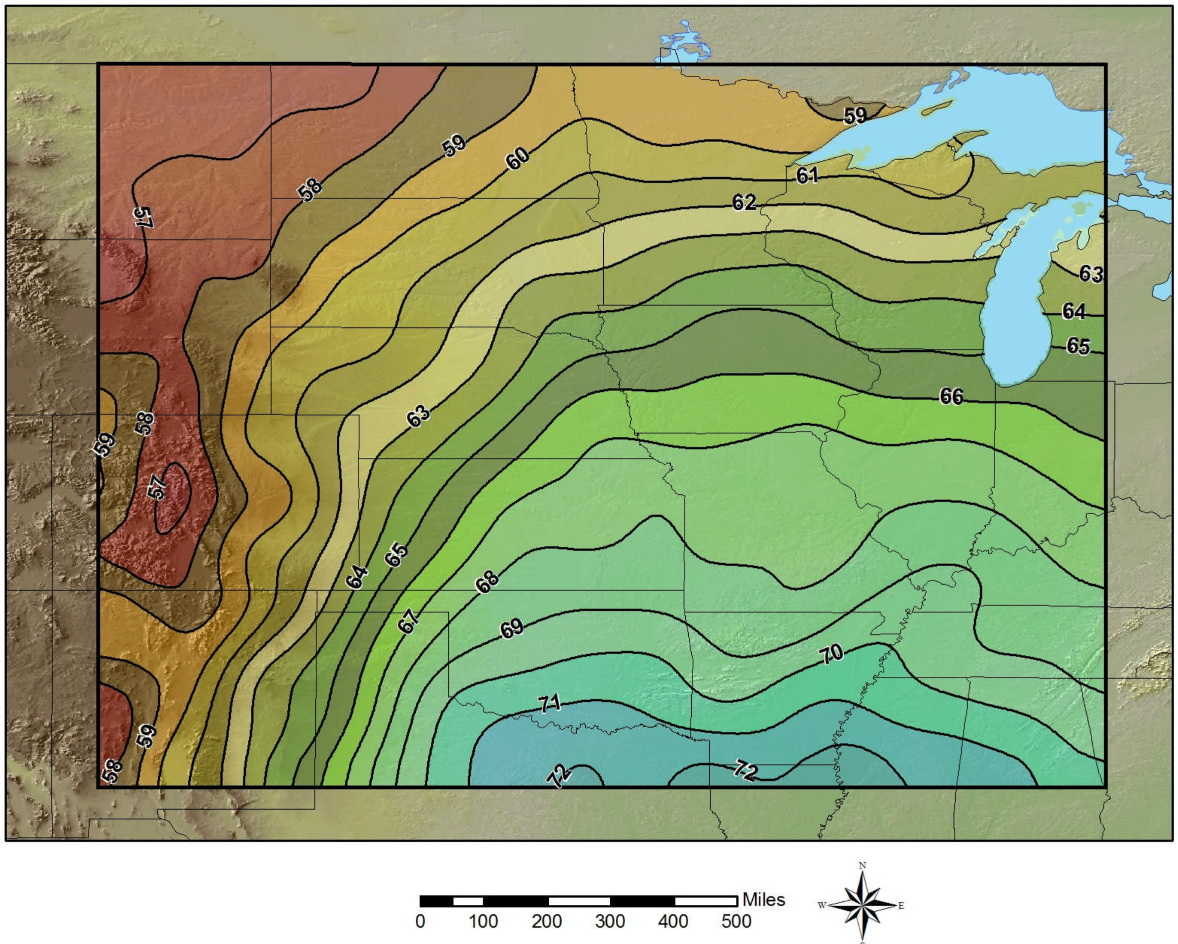
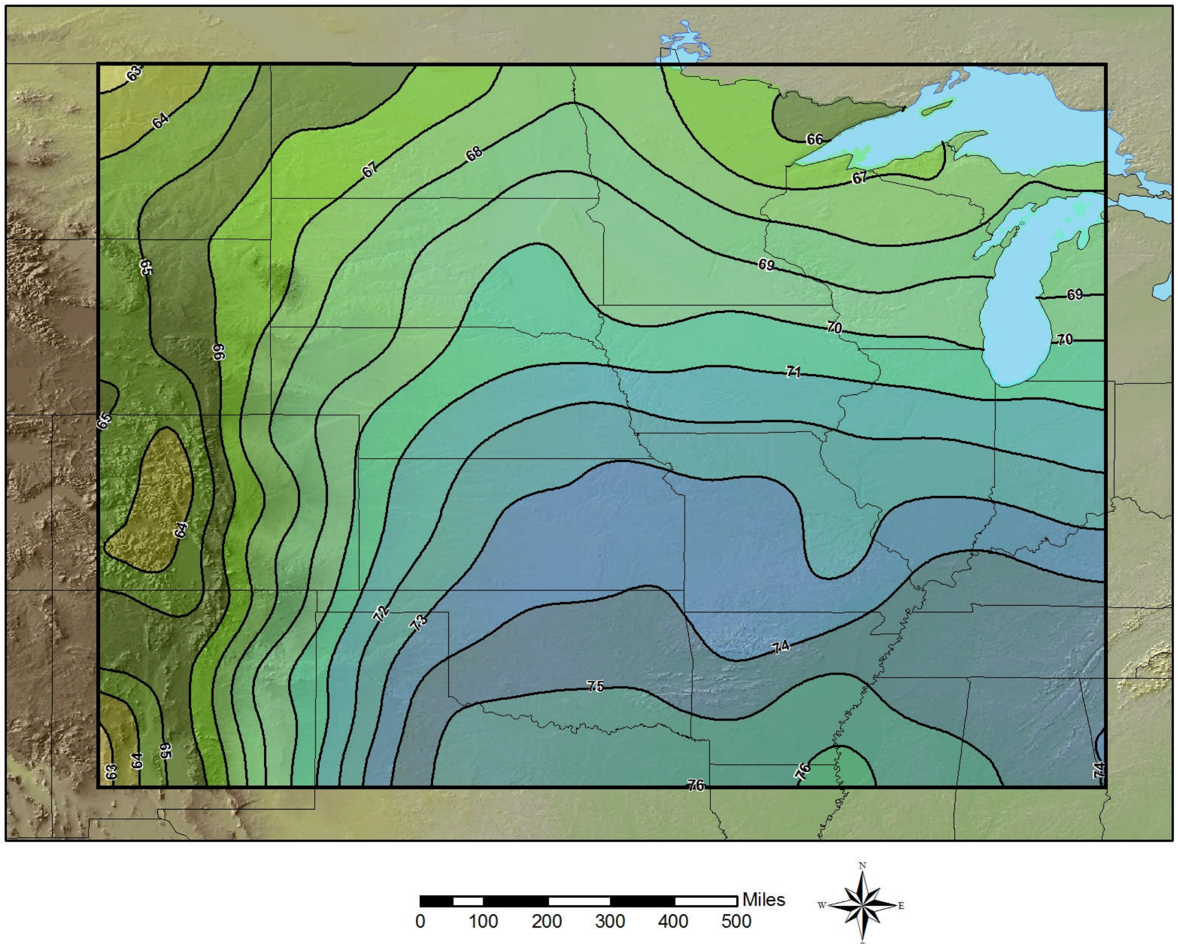
Dew Point Climatology (°F)



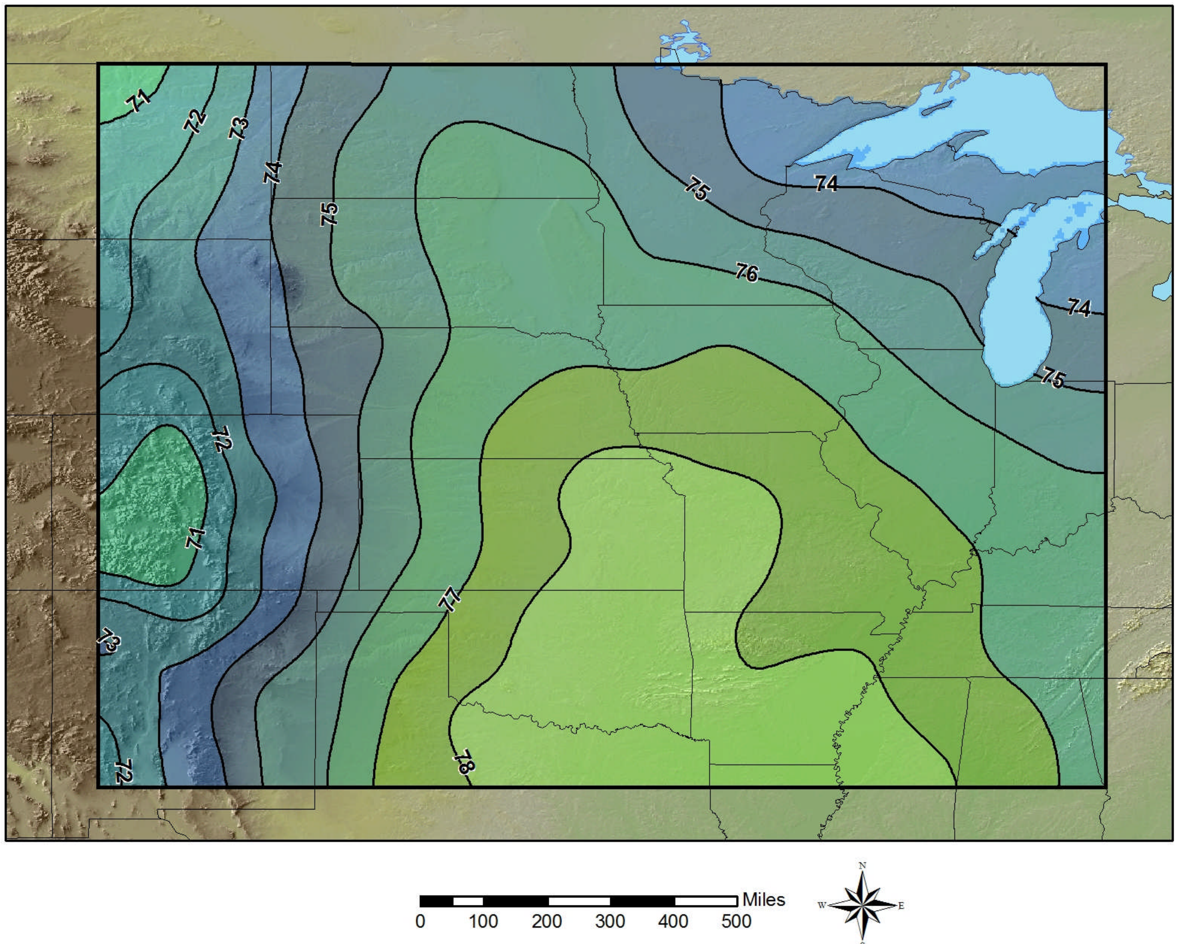
April 100-Year 24-Hour
Dew Point Climatology (°F)



May 100-Year 24-Hour
Dew Point Climatology (°F)



June 10-Year 24-Hour Dew Point Climatology (°F)



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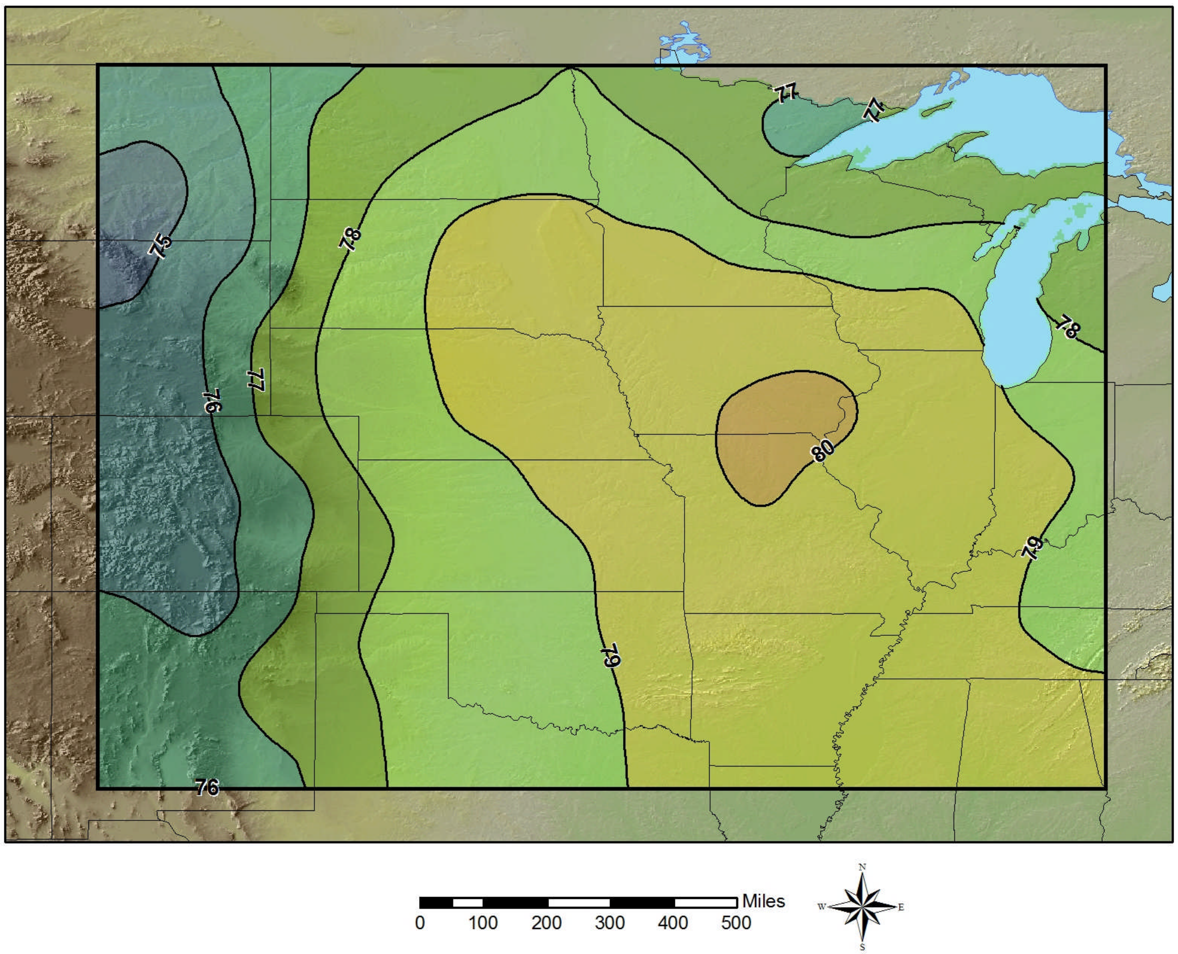
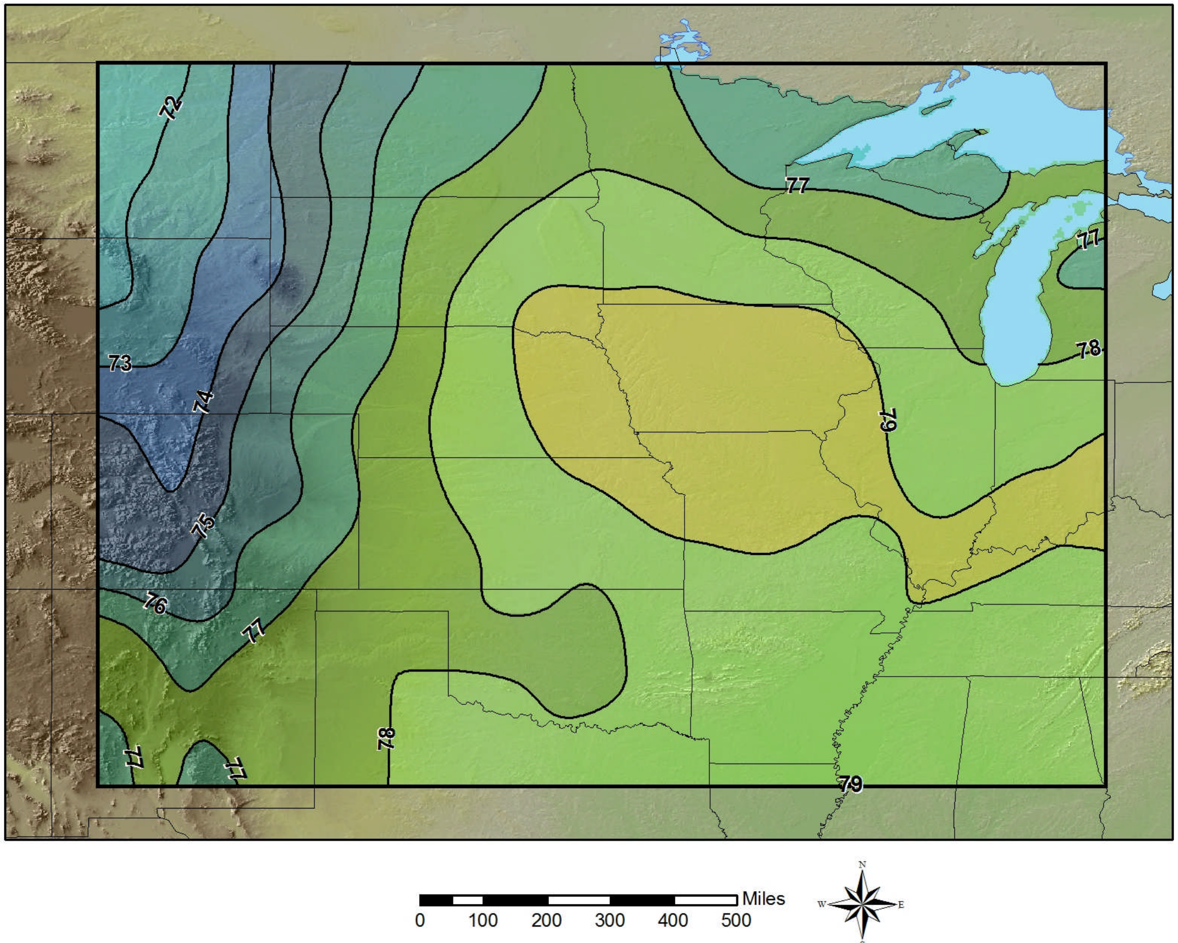
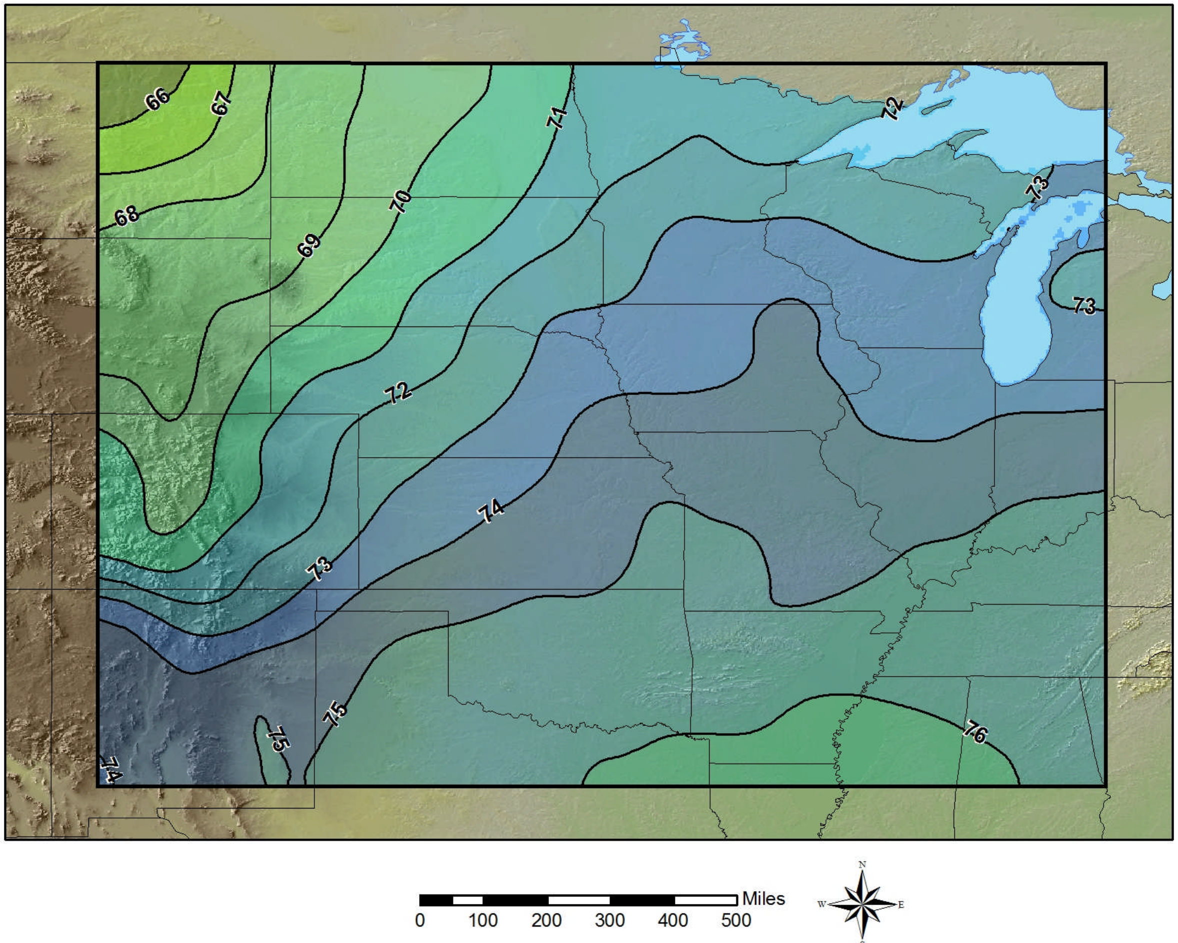
Dew Point Climatology (°F)



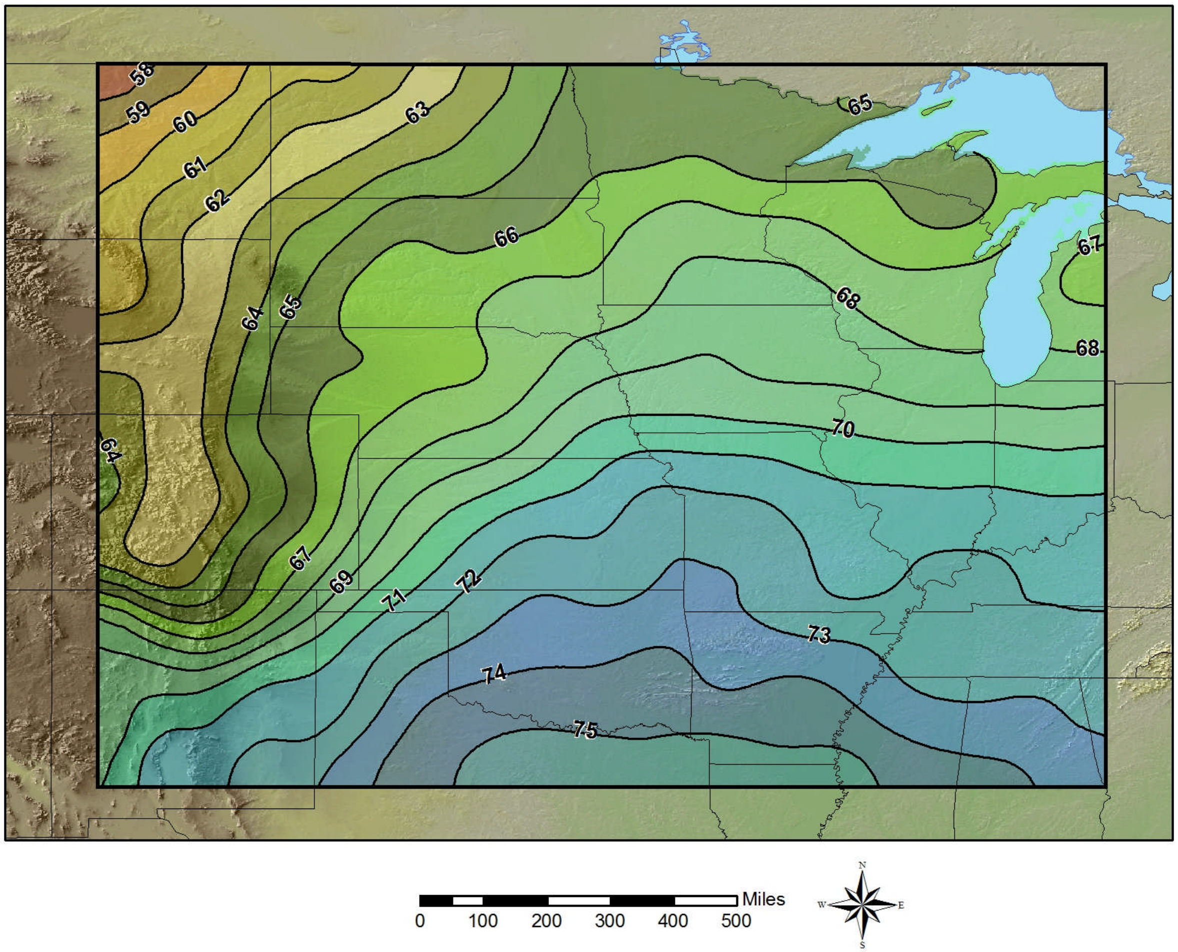
August 100-Year 24-Hour Dew Point Climatology (°F)



September 100-Year 24-Hour
Dew Point Climatology (°F)



October 100-Year 24-Hour
Dew Point Climatology (°F)



Appendix D

Procedure for using Dew Point Temperatures for Storm Maximization and Transposition

Maximum dew point temperatures (hereafter referred to as dew points) have historically been used for two primary purposes in the PMP computation process:

1. Increase the observed rainfall amounts to a maximum value based on a potential increase in atmospheric moisture available to the storm.
2. Adjust the available atmospheric moisture to account for any increases or decreases associated with the maximized storm potentially occurring at another location within the transposition limits for that storm.

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 dew point values from the *Climatic Atlas of the United States*, Environmental Data Services, Department of Commerce (1968), were the source for maximum dew point values. HMR 55 published in 1984 updated maximum dew point values for a portion of United States from the Continental Divide eastward into the central plains. A regional PMP study for Michigan and Wisconsin produced return frequency maps using the L-moments method (Tomlinson 1993). The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year return frequency values were appropriate for use in PMP calculations. HMR 57 was published in 1994 and HMR 59 in 1999. These latest NWS publications also update the maximum dew point climatology but use maximum observed dew points instead of return frequency values. For this study, the Review Committee agreed that the 100-year return frequency dew point climatology maps were appropriate because this added a layer of conservatism and the extra 15 years of data available since the EPRI study allow the 100-year return frequency to be more reliable. Storm precipitation amounts are maximized using the ratio of precipitable water for the maximum observed dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere. This procedure was followed in this study using the updated maximum dew point climatology developed and described in section 6.

The procedure for determining a storm representative dew point begins with the determination of the inflow wind vector (direction and magnitude) for the air mass that contains the atmospheric moisture available to the storm. Beginning and ending times of the rainfall event at locations of the most extreme rainfall amounts are determined using rainfall mass curves from those locations.

The storm inflow wind vector is determined using available wind data. The inflow wind vector has historically been determined using winds reported by weather stations, together with upper air winds, when available. Recently, gridded wind field analyses have become available for four times a day for various levels in the atmosphere from the National Center for Environmental Prediction (NCEP). These analyses are available back to approximately 1948. Use of these wind fields in the lower portion of the atmosphere provides much improved reliability in the determination of the storm inflow wind vectors. The program is available through an online interface through the

Air Resources Laboratory section of NOAA and is called HYSPLIT. Users are able to enter in specific parameters that then out put a wind inflow from a starting point going backwards (or forwards) for a specified amount of time. Users can define variables such as the starting point (using latitude and longitude or a map interface), the date and time to start the trajectory, the length of time to run the trajectory, and the pressure level at which to delineate the inflow vector. Figures D.1 to D.3 show example inflow vectors generated by HYSPLIT at three levels; surface, 925mb, and 850mb for the Aurora College, IL 1996 extreme rainfall event. The data generated from the HYSPLIT runs is then used in conjunction with standard methods to help delineate the source region of the air mass responsible for the storm precipitation. Also, this serves as another tool from which to determine which weather stations to derive hourly dew point data for storm representative dew point analysis.

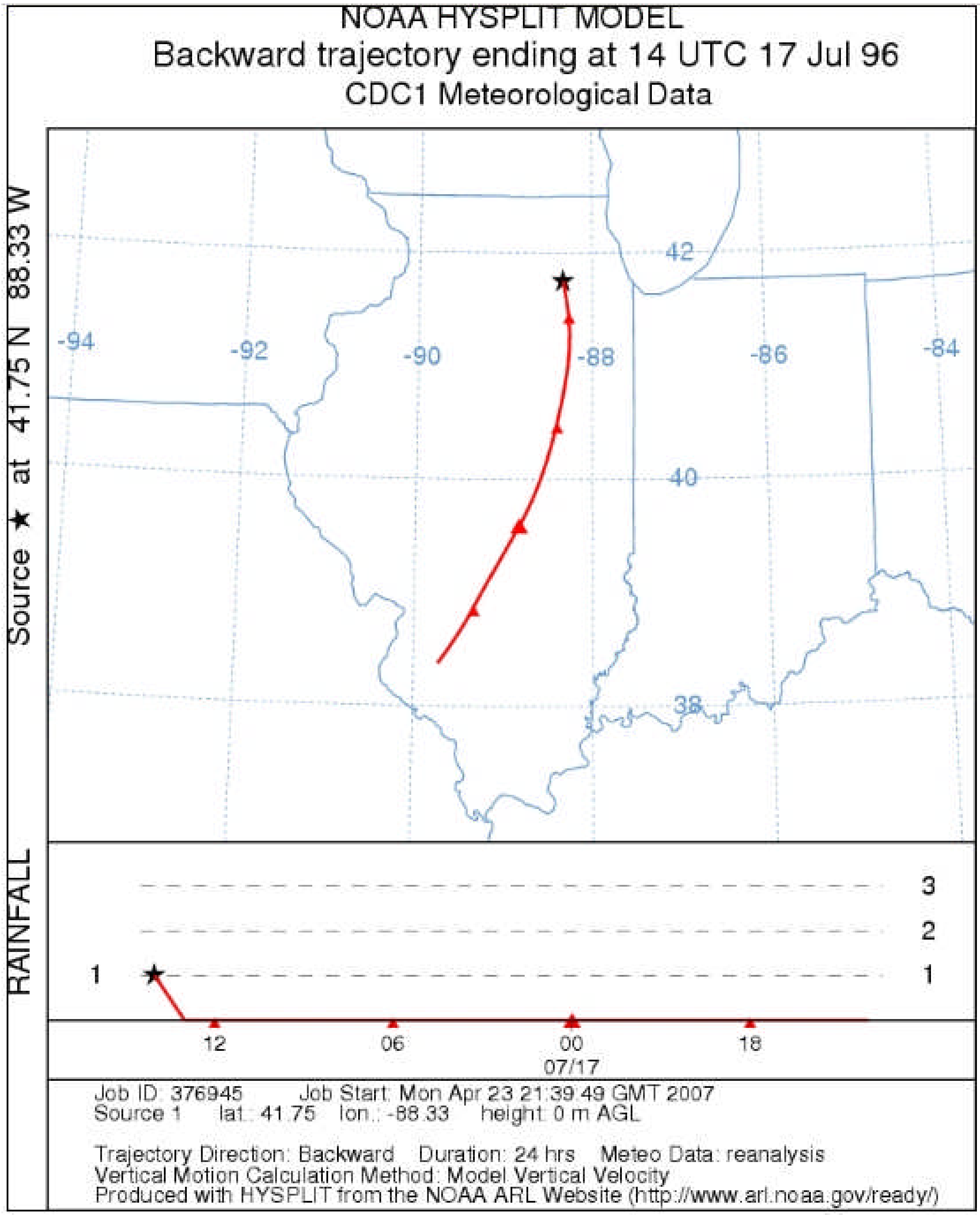


Figure D.1 HYSPLIT model results for Aurora College, IL 1996 storm-surface

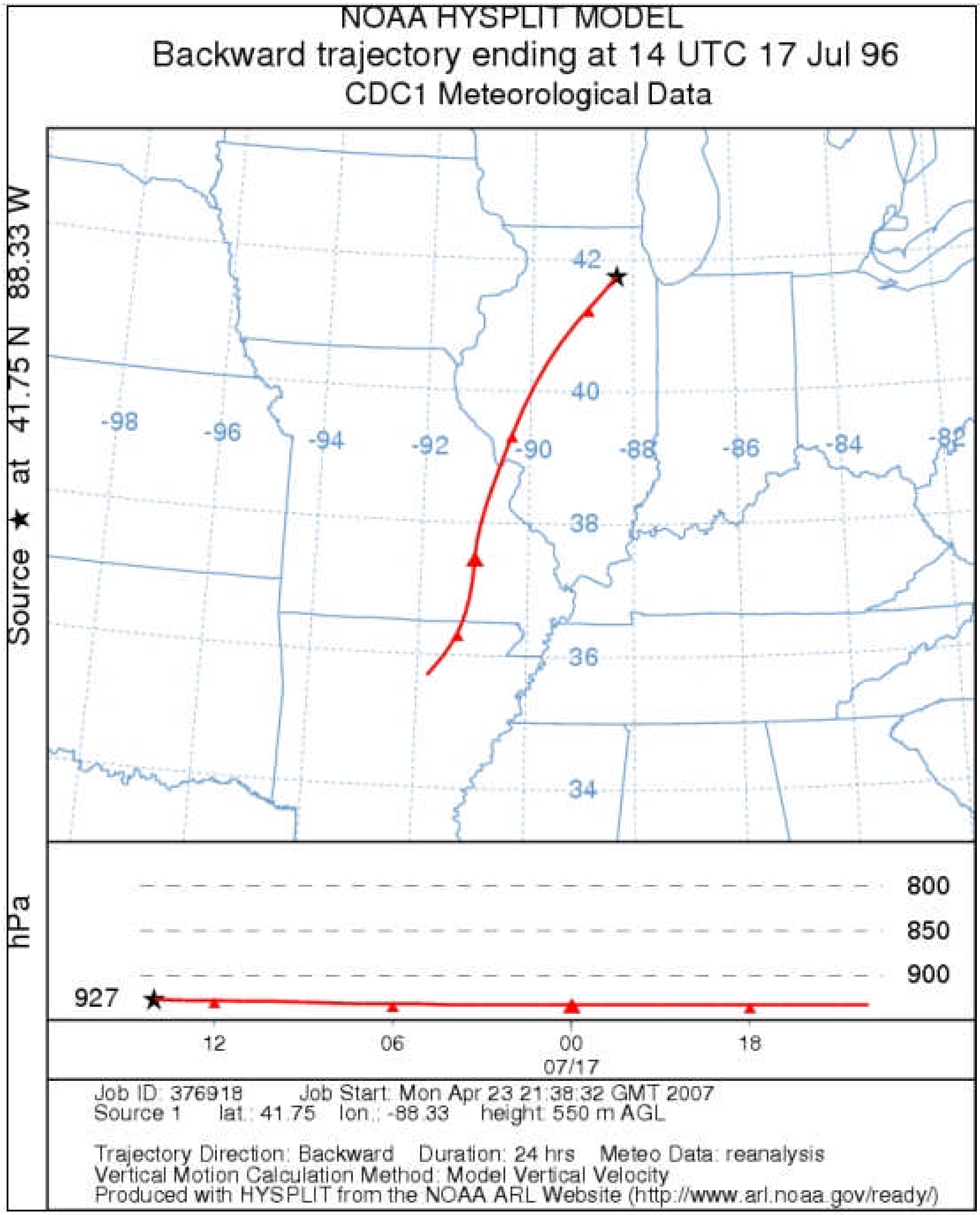


Figure D.2 HYSPLIT model results for Aurora College, IL 1996 storm-925mb

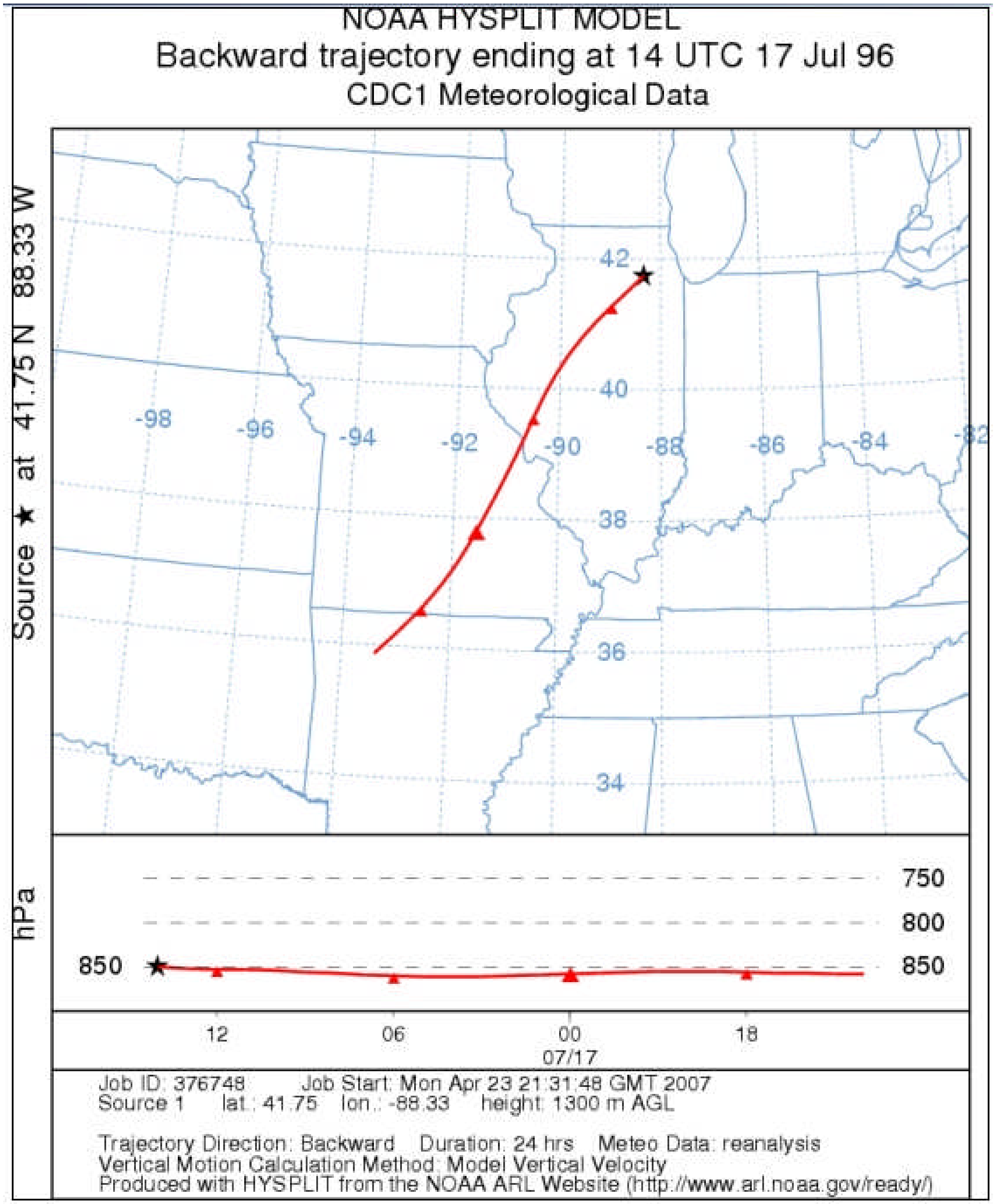


Figure D.3 HYSPLIT model results for Aurora College, IL 1996 storm-850mb

The inflow wind vector is followed upwind until a location is reached that is outside of the storm rainfall. The nearest weather stations that report dew point values are identified. At least two stations are desired but a single station with reliable dew points observations can be used. The time period used to identify the appropriate dew point values is determined by computing the time required for the air mass to be transported from the location of the weather station(s) to the location of maximum rainfall. The start time of the extreme rainfall is then adjusted back in time to account for transit time from the dew point observing station(s) to the maximum rainfall location.

For example, consider the following case:

1. Rainfall begins at 11:00am and ends at 6:00pm the following day at the location of maximum rainfall,
2. The storm representative dew point location (the location of the weather stations observing the dew points) is 100 miles from the maximum rainfall location in the direction of the inflow wind vector, and
3. The inflow wind speed of 20 mph.

The transit time for the air mass from the weather stations to the maximum rainfall location is five hours (100 miles divided by 20 mph). The time to begin using the dew point observations is five hours before the rainfall began (11:00am minus 5 hours = 6:00am) and the time to stop using the dew point observations is five hours before the rainfall ended (6:00pm minus 5 hours = 1:00pm the following day). Dew point observations taken between these times are used to determine the storm representative average 24-hour 1000mb dew point value. The storm representative dew point location can come from a single location if only one station is used or from a location between the reporting weather stations if more than one station is used. The vector connecting this location and the location of maximum rainfall becomes the wind inflow vector used for storm transpositioning.

The storm representative dew point determined from the weather dew point observations needs to be corrected to the 1000mb level. The elevation of the storm representative dew point location is used in this correction. The correction factor of 2.4^{o}F per 1,000 feet of elevation is used. This is the same correction factor used in the *Climatic Atlas of the United States* (Environmental Data Services, Department of Commerce, 1968). For example, a storm representative dew point of 72^{o}F at a station location with an elevation of 800 feet above sea level is corrected with a factor of 800 X 2.4 /1000 = 1.9^{o}F. The dew point value corrected to 1000mb (sea level) is 72^{o}F + 1.9^{o}F = 74^{o}F after rounding.

The procedure that computes the in-place maximized rainfall for a storm provides an estimate of the maximum amount of rainfall that could have been produced by the same storm at the same location if the maximum amount of atmospheric moisture had been available. This procedure requires that a maximum value for the storm representative dew point be determined. The maximum dew point value is selected at the same location where the storm dew point was determined using a maximum dew point climatology. The maximum dew point values must be corrected to 1000mb. The precipitable water in the atmosphere is determined using the storm representative and maximum dew point values. Precipitable water is defined in this study as the total amount of moisture in a column of the atmosphere from sea level to 30,000 feet assuming a vertically saturated atmosphere. Values of atmospheric precipitable water are determined using the moist pseudo-adiabatic assumption, i.e. assume that for the given 1000-mb dew point value, the atmosphere holds the maximum amount of moisture possible. The ratio of the precipitable water associated with the maximum 1000mb dew point to the precipitable water associated with the 1000-mb storm representative dew point is the maximization factor.

For example, consider the following case:

1000mb storm representative dew point:	72^oF
1000mb maximum dew point:	76^oF
Precipitable water associated with a 1000mb dew point of 72^oF:	2.47 inches
Precipitable water associated with a 1000mb dew point of 76^oF:	2.99 inches

Maximization factor: $PW(76^oF)/PW(72^oF)$ = 2.99 "/2.47" = 1.21

For transpositioning, the storm inflow vector (determined by connecting the storm representative dew point location with the location of maximum rainfall) is moved to the basin location being studied. The new location of the upwind end of the vector is determined. The maximum dew point associated with that location is then selected using the same maximum dew point climatology map used for in-place maximization. The transpositioning factor is the ratio of the precipitable water associated with the maximum 1000mb dew point value at the transpositioned location to the precipitable water associated with the maximum 1000mb dew point for the storm representative dew point location.

An example is provided.

1000mb maximum dew point at the storm representative dew point location:	76^oF
1000mb maximum dew point at the transpositioned location:	74^oF
Precipitable water associated with a 1000mb dew point of 76^oF:	2.99 in
Precipitable water associated with a 1000mb dew point of 74^oF:	2.73 in

Transposition factor: $PW(74^oF)/PW(76^oF)$ = 2.73 "/2.99" = 0.91

Appendix E

Procedure for Deriving PMP Values from Storm Depth-Area-Duration (DAD) Analyses

Although PMP rainfall amounts are theoretical values, there currently is no theoretical method for determining the values. The accepted procedure for determining PMP values begins with the largest identified historic observed rainfall amounts and applies the following procedures:

1. Increase the rainfall amounts to some maximized value (in-place maximization),
2. Adjust the "maximized" rainfall amounts to the potential situation where the historic storm occurs over the basin being studied (transposition),
3. Adjust the "maximized transpositioned" rainfall amounts for elevation changes or intervening topographic barriers which could potentially affect the storm moisture and subsequently the rainfall amounts for the "maximized transpositioned" storm (barrier adjustment).

The procedure begins with the Depth-Area-Duration (DAD) analysis from the largest of the identified storms that have occurred over regions that are climatologically and topographically similar to the area being studied. Identification of the largest rainfall events is relatively straight forward and is accomplished by identifying the largest station rainfall amounts and correlating the dates among adjacent stations to identify the areal extent of the heavy rainfall and the storm period. The DAD for each storm is computed using isohyetal analyses for each hour during the storm and determining the largest rainfall totals for each duration of interest over each area size of interest. HMR 51 uses temporal periods of 6, 12, 24, 48 and 72 hours. Standard area sizes of 10, 200, 1000, 5000, 10000 and 20000 square miles area used. Other durations and area sizes can also be used in the DAD analysis as desired. For this study, the 100-square mile and 500-sqaure mile area sizes are added to better define small areas and help in smoothing and enveloping.

The US Army Corps of Engineers, the Bureau of Reclamation and the National Weather Service have performed storm studies and produced DADs for many storms. This study reviewed additional weather station data to identify extreme rainfall storms that had not been identified and studied previously. The new storms identified primarily occurred since the publication of HMR 51 but additional storms that occurred prior to HMR 51 publication were also identified. DADs that had been previously developed are used in this report. Newly identified storms are analyzed in this study and DADs are developed for these storms. These DADs quantify the rainfall associated with each storm event, providing the largest rainfall amounts for each of the durations and area sizes used in this study.

Identification of storms that can be transpositioned to one or more of the grid points is largely based on subjective judgments. For a storm to be transpositionable, it should have occurred over a region that is climatologically and topographically similar to the basin being studied. Storms generally should not be transpositioned across significant topographic features or into different climate regions (WMO 1986). The largest rainfall events identified in the storm search generally occurred over locations in the Great Plains.

These storms did not have significant topographic features between the location of maximum rainfall and the moisture source for the storm. Therefore, it is assumed that the same moisture sources and dynamics that produced these events could have produced a similar storm over some point within Nebraska. Use of these storms in general provides larger rainfall amounts at each particular grid point location than would have occurred if only rainfall events that occurred in a smaller search domain had been used. However, it is our professional judgment that storms that have occurred within our storm search domain (see Figure 4.1) could have occurred over one or more of the grid points (with the exception of the Rocky Mountain region). Comparisons with the NWS transposition limits for some of the storms used in HMR 51 showed that the NWS transposition limits were much more constrained than the limits used in this study. Hence, transpositioning of these storms should be considered a conservative procedure in the development of site-specific PMP values at any locations within Nebraska.

Maximization of the storm DADs involves use of dew point temperatures associated with the air mass that provided the moisture for the production of rainfall by the storm dynamics. To determine the storm dew point, winds coming into the storm in the lower portion of the atmosphere (surface to about 5,000 feet above sea level) are evaluated. The direction of the wind provides the direction to the region from which the air mass came and the speed provides the rate at which the air mass was transported into the storm. The procedure is to go upwind along the inflow wind direction until a position is found where no rain is occurring and there are weather stations that report dew point temperatures. Using this location, an inflow vector (direction and distance) is determined. The weather station dew point data are used to determine the dew point temperature for the storm. This dew point value is used together with the maximum dew point value to compute the in place maximization factor for the storm.

The maximum dew point represents the greatest amount of atmospheric moisture that potentially could have been available to the storm. Using maximum dew point climatology, the maximum dew point is determined for the same location as was selected for the storm dew point. Precipitable water associated with each of these dew point values is used to determine the in-place maximization factor. This procedure assumes that the storm dynamics of the largest historic storms are very close to being as efficient as is physically possible and are representative of a PMP storm. The assumption is also made that if additional atmospheric moisture had been available to the storm, the storm rainfall would have increased by a ratio directly proportional to the increase in atmospheric moisture. Hence, once a dew point associated with the storm air mass is determined, the moisture in the actual storm air mass, referred to as the "in-place" storm precipitable water (storm PW), can be quantified. The moisture in an air mass with the maximum dew point for the same location, referred to as maximum precipitable water (maximum PW) can also be quantified. The ratio of maximum PW to storm PW is the in-place maximization factor.

The equation for this computation is as follows:

In-place maximization factor = (in-place maximum PW)/(in-place storm PW)

Unless the actual storm occurred within the boundaries of the basin under investigation, a transpositioning procedure is followed to adjust the maximized storm DAD for "moving" the storm to the study basin, i.e. determine the potential maximum rainfall that would be produced had the same storm occurred over the study basin. The storm inflow vector is moved to the study basin location and the location of the upwind end of the vector (the end away from the basin) is determined. Using that location and the maximum dew point climatology, a transpositioned maximum dew point value is selected. The precipitable water values associated with the in-place maximum dew point and the transpositioned maximum dew point are used to compute the transposition factor.

The equation for this computation is as follows:

Transposition factor = (transpositioned maximum PW)/(in-place maximum PW)

For this study, all computations associated with historic storms are computed at the 1000-mb level (approximately sea level). The elevation of the location where the largest rainfall was observed is used as the storm elevation. An adjustment is applied to the storm moisture to account for the elevation of the storm above sea level. For example, if the maximum rainfall occurred at an elevation of 500 feet, the total atmospheric moisture (500 to 30,000 feet) is increased by the amount of moisture between sea level and 500 feet. The adjustment factor uses precipitable water contained in the moisture maximized atmosphere above the storm elevation, i.e., the moisture contained in the entire depth of the moisture maximized atmosphere, minus the moisture contained in the moisture maximized atmosphere below the storm elevation. For Nebraska, there were no upwind barriers that had to be accounted for. An adjustment was made to account for the storm's elevation (either higher or lower than a particular grid point) and the amount of PW that would be available, more if the elevation was lower and less if the elevation was higher. This elevation adjustment factor is determined by computing the ratio of precipitable water in the moisture maximized atmosphere above the elevation to the precipitable water in the entire depth of the moisture maximized atmosphere.

The equations for this computation are as follows:
In place maximization factor =

(storm representative maximum dew point PW – in place storm elevation maximum PW)/(storm representative dew point PW – in place storm elevation representative dew point PW)

Transpositioned/elevation to basin factor =
(transpositioned maximum dew point PW – basin elevation maximum PW)/(storm representative maximum dew point PW – in place storm elevation representative dew point PW)
Barrier adjustment factor (always 1.00 for Nebraska because there are no upwind barriers) =

(transpositioned maximum dew point PW – basin elevation maximum dew point PW)/(transpositioned maximum dew point PW – basin elevation maximum dew point PW)

Multiplication of these terms leads to a simplified computation where all the required adjustments are combined in a single equation.

Total adjustment factor =

(in-place max factor) X (transpositioned/elevation to basin factor) X (barrier adjustment factor)

The total adjustment factor modifies the storm DAD by a factor using two computed values:

1) The maximum atmospheric moisture available to a historic storm if it were to occur over the study basin. This air mass is assumed to contain the maximum amount of atmospheric moisture for the basin location and elevation.
2) The atmospheric moisture available for the historic storm at the location and elevation where it occurred.

The total adjustment factor is applied as a linear multiplier for all rainfall amounts in the storm DAD.

As an example, the DAD from the Ogallala, NE 2002 storm center associated with the flood that collapsed I-80 is transpositioned, maximized, and elevation adjusted to Nebraska. The following are values for the parameters used in computing the adjustments:

Storm representative dew point:	74.5° F
In-place maximum dew point:	81.5° F
Transpositioned maximum dew point:	82.0° F
Storm elevation:	3428'
Grid Point 2 elevations:	3117’

Total atmospheric precipitable water for 74.5° F:	2.79"
Total atmospheric precipitable water for 81.5° F:	3.84"
Adjustment for storm elevation, 1000mb to 3428' at 74.5°F:	0.775"
Adjustment for storm elevation, 1000mb to 3428' at 81.5°F:	0.99"
Total atmospheric precipitable water for 82.0° F:	3.92"
Adjustment for grid point elevation, 1000mb to 3100' at 82.0°F:	0.90"

Adjustment for grid point elevation, 1000mb to 3100' at 82.0°F: 0.90"

Total adjustment factor =

(in-place max factor) X (transpositioned/elevation to basin factor) X (barrier adjustment factor)

= ((3.84" - 0.99") / (2.79" - 0.775")) X ((3.92" - 0.41") / (3.84" - 0.99")) X ((3.92" - 0.90") / (3.92" - 0.90")) = (1.41) X (1.06) X (1.00)

= 1.50

To explicitly show how each adjustment factor (in-place maximization, transposition and barrier adjustment) affects the total adjustment, separate computation are provided.

<u>In-place maximization factor</u>

Storm representative dew point:	74.5° F
In-place maximum dew point:	81.5° F
Storm atmospheric precipitable water for 74.5° F:	2.79"
Maximum atmospheric precipitable water for 81.5° F:	3.84"

In-place maximization factor =

(storm representative maximum dew point PW – in place storm elevation maximum PW)/(storm representative dew point PW – in place storm elevation maximum dew point PW)

= (3.84"- 0.99) / (2.79" - 0.775")

= 2.85" / 2.015"

= 1.41

<u>Transposition factor</u>

In-place maximum dew point	81.5° F
Transpositioned maximum dew point	82.0° F
Maximum atmospheric precipitable water for 81.5° F:	3.84"
Maximum atmospheric precipitable water for 83.0° F:	3.92"

Transposition factor =

(transpositioned maximum dew point PW – basin elevation maximum dew point PW)/(storm representative maximum dew point PW – in place storm elevation maximum dew point PW)

= (3.92"- 0.90) / (3.84" - 0.99")

= 3.02" / 2.85"

= 1.06

<u>Storm elevation/barrier adjustment factor</u>

Transpostioned maximum dew point:	82.0° F
Grid Point 2 elevation:	3117'
Storm atmospheric precipitable water for 82.0° F:	3.92"
Adjustment for basin elevation, 82.0° F, 1000mb to 3100':	0.90"

Storm elevation adjustment factor =

(transpositioned maximum dew point PW – basin elevation maximum dew point PW)/(transpositioned maximum dew point PW – basin elevation maximum PW)

= (3.92"- 0.90) / (3.92" - 0.90")

= 3.02" / 3.02"

= 1.06

Total adjustment factor = (In-Place maximization) X (Transposition) X (Barrier Adjustment/Storm elevation)

= 1.41 X 1.06 X 1.00

= 1.50

This is the same total adjustment computed earlier (within round-off error) using the single equation to compute the total adjustment factor.

Since these procedures involve linear multiplication, computer software spread sheets can be used to incorporate the storm DAD and apply the factors to compute the transpositioned maximized barrier adjusted DAD. In this study, this procedure is applied for each storm transpositioned to the basin using Excel macros.

Once the total adjustment factors are applied to all of the storms being considered, rainfall amounts from largest storms are plotted on a log-linear plot with rainfall depth plotted on the linear scale and area size plotted on the log scale. Appendix E contains examples of these plots from Grid Point 10. A separate graph is constructed for each duration period, e.g. 6-hour, 12-hour, etc. The graphs provide curves of the transpositioned maximized adjusted storm rainfall amounts for all area sizes. These depth area curves represent the maximum rainfall potential based on standard procedure modifications of the largest observed historic storms in the region surrounding the basin. An enveloping curve is drawn using the largest rainfall values. All of the plotted rainfall amounts either lie on the enveloping curve or below it. The exception is in the case where there is reason to suspect that a value is larger than is reasonable and that rainfall value may be undercut, i.e. the envelop curve should be drawn beneath the value. Undercutting should rarely be done and each case needs to be justified. No undercutting was done in this study at any grid point. In general, the enveloping curve should provide a smooth transition among the maximum rainfall values for various area sizes. This process of enveloping depth-area plots provides continuity in space for the rainfall amounts among various area sizes.

After enveloping curves are completed for each of the duration periods, depth-duration curves are plotted on a linear-linear graph, with duration on one axis and depth on the other. Since there is only a single curve for each area size from the enveloped depth-area plots, all of depth-area curves can be plotted as a family of curves on a single graph. Enveloping curves are drawn for each area size. The enveloping curve should provide a smooth transition among the maximum rainfall values for various durations.

This procedure of enveloping depth-duration plots provides continuity in time for the rainfall amounts among various durations.

The final envelopment curves provide the maximum rainfall amounts that represent PMP values for each particular grid point. Rainfall amounts for each area size and each duration are taken from the curves and used to construct the PMP DAD table.

Appendix F

Short Storm List Storm Analysis

See Separate Binding

Appendix G

Storm Precipitation Analysis System (SPAS) Description

Introduction

The Weather Bureau (currently the National Weather Service, or NWS) and the Corps of Engineers routinely performed detailed storm rainfall analyses until the 1950s. Since then, only a few selected storms have been analyzed. Using digital precipitation data now available, storm rainfall analysis procedures and software have been developed to provide detailed rainfall analyses using Geographical Information Systems (GIS). Hourly high spatial resolution rainfall analyses are produced to quantify the spatial and temporal distribution of storm rainfall over watersheds. Furthermore, the availability of NEXRAD (Next Generation Radar) data has allowed SPAS to better account for the spatial and temporal variability of storm precipitation for events occurring since the early 1990s.

Applied Weather Associates, LLC and Metstat, Inc have teamed to develop a rainfall analysis procedure for analyzing rainfall associated with extreme storms. The Storm Precipitation Analysis System (SPAS) applies the same basic approach used by the Weather Bureau and the Corps of Engineers, thereby achieving a level of consistency between the newly analyzed storms and the historic storms previously analyzed. However, more recent (i.e. post 1990) storms can be analyzed using NEXRAD data and a slightly different approach. The SPAS algorithms are a suite of UNIX-based programs that utilize the Geographic Resources Analysis Support System (GRASS) GIS engine to evaluate the spatial, temporal and depth-area characteristics of precipitation events. (1) For pre-NEXRAD storms, SPAS uses a spatial approach for allocating precipitation at the daily reporting stations into hourly rainfall values, thus creating high resolution precipitation maps for each hour of the rainfall event. Likewise, for post-NEXRAD storms SPAS utilizes the spatial and temporal information from radar data.

SPAS has been rigorously tested, both with a theoretical storm where the rainfall rates and spatial distribution are known exactly and with historic storms that have been previously analyzed by the Weather Bureau.

SPAS analyses have been completed for several recent extreme rainfall storms (Figure G.1). Results are presented from two Weather Bureau analyzed storms (Westfield, MA 1955 and Ritter, IA 1953), as well as Hurricane Floyd 1999. The SPAS analysis results compared very well with the theoretical storm rainfall amounts and timing. The SPAS storm-centered depth-area-duration (DAD) analysis results were within 5% of the Weather Bureau results for Westfield 1955 and Ritter 1953 for most area sizes and durations. SPAS DADs for Hurricane Floyd have been used in a FERC approved site-specific PMP study in New York and several subsequent site-specific PMP studies and storm analyses. The SPAS analysis results are continually being incorporated into updated technology applications for PMP and PMF analyses.

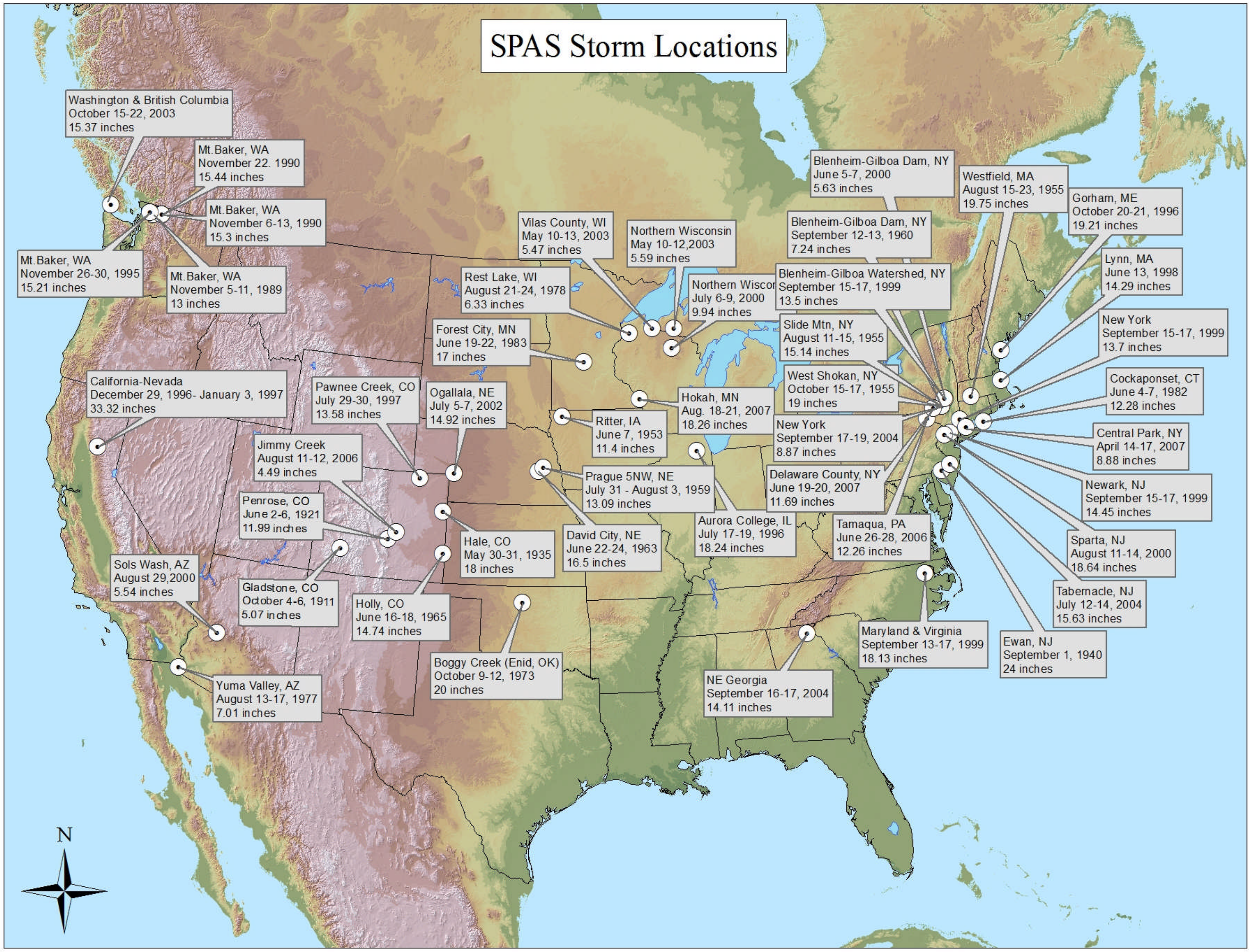


Figure G.1 SPAS storm analysis locations through July of 2008

Background

The Weather Bureau and Corps of Engineers produced many storm studies for extreme rainfall events that occurred during the first half of the last century. The DADs from these studies were used to compare rainfall events and were used in Hydrometeorological Reports (HMRs) to determine PMP rainfall amounts. Objective procedures were used in these analyses augmented with subjective judgment by well qualified Hydrometeorologists. The SPAS analysis procedures incorporate many of the earlier procedures while providing updated techniques along with GIS and NEXRAD to improve the quality and speed of the analyses.

With SPAS, storms analyses (including storm-centered DADs and mass curves) can be efficiently completed much more quickly and with more detail than historic analyses. In the past, a detailed analysis of a storm's precipitation required a great deal of manual labor, hence making it time consuming and prone to human errors. SPAS is a largely automated system, yet it provides flexibility and several enhancements over the old storm analysis procedure. In the past, it was time and cost prohibitive to produce hourly precipitation maps, therefore assumptions had to be made in the computations of the DAD results. SPAS, however, does not have to make as many assumptions since it has the ability to mimic and resolve the storm's precipitation much better through the use of NEXRAD data and GIS algorithms. Table G.1 compares the procedures used historically by the Weather Bureau and SPAS.

Table G.1. Comparison between the Weather Bureau storm analysis method and SPAS.

Topic	Weather Bureau	SPAS
Timing of daily stations	Mimics the hourly distribution of the nearest hourly station	Uses several representative hourly stations in an inverse distance weighting scheme
Pseudo data	Did not use	Various options for use
Base map options	100-year 24-hour or nothing	Multiple base map options
DAD calculations based on six hour duration analyses	The total storm, hand-analyzed isohyetal map	Based on hourly GIS-created precipitation grids
Automation	None	Largely automated

Storm Depth-Area-Duration (DAD) Analyses for New Storms

For newly identified extreme rainfall events without published depth-area-duration (DAD) analyses, DADs needed to be computed. The Storm Precipitation Analysis System (SPAS) was used to compute DADs for these storms.

There are two main steps in a DAD analysis: 1) The creation of high-resolution hourly precipitation grids and 2) the computation of depth-area rainfall amounts for various durations. The reliability of the results from step 2) depends on the accuracy of step 1). Historically the process has been very labor intensive. SPAS utilizes Geographic Information Systems (GIS) concepts to create more spatially-oriented and accurate results in a more efficient manner (step 1). Furthermore, the availability of NEXRAD (NEXt Generation RADar) data allows SPAS to better account for the spatial and temporal variability of storm precipitation for events occurring since the early 1990s. Prior to NEXRAD, the National Weather Service (NWS) developed and used a method based on the research of several scientists. Because this process has been the standard for many years and holds merit, the DAD analysis process developed for this study attempts to mimic it as much as possible. See Appendix G for a full description of SPAS. By adopting this approach, some level of consistency between the newly analyzed storms and the hundreds of storms already analyzed can be achieved. Comparisons between the NWS DAD results and those computed using the new method for two storms (Westfield, MA 1955 and Ritter, IA 1953) indicated very similar results.

Data Collection

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

The daily database is comprised of data from National Climatic Data Center (NCDC) TD-3206 (pre 1948) and TD-3200 (generally 1948 through present). The hourly database is comprised of data from NCDC TD-3240. The daily supplemental database is largely comprised of data from "bucket surveys," local rain gauge networks (e.g. ALERT, USGS, etc.) and daily gauges with accumulated data.

The various types of stations include:

1. Hourly complete

2. Hourly stations with reliable temporal precipitation data, but the magnitude is questionable in relation to co-located daily gauge
3. Daily complete
   Daily stations with complete data and known observation times
4. Daily supplemental
   Daily stations without known observation times

As part of the daily data extraction process, the time of observation – as indicted in NCDC TD-3200/3206 – is used. However, experience has indicated that the times in TD3200/3206 are not updated very frequently and are not reliable. Additional efforts are taken to ensure the observation times are accurate. Hardcopy reports of "Climatological Data," scanned observational forms and/or station metadata forms have proven to be valuable and accurate resources for observation times. Furthermore, erroneous observation times and dates are identified in the mass-curve procedure and can be corrected at that point in the analysis procedure. For stations with an observation time that is undetermined, it is assumed to have an accurate storm total precipitation and is converted to a daily supplemental using the full tabulated time period of record as the observational period.

Mass Curves

The most complete rainfall observational dataset available is compiled for each storm. To obtain temporal resolution to the nearest hour in the final DAD results, it is necessary to distribute the daily precipitation observations (at daily stations) into hourly bins. This process has traditionally been accomplished by anchoring each of the daily stations to a single hourly timer station. However, this may introduce biases and may not correctly represent hourly precipitation at locations between hourly stations. A preferred approach is to anchor the daily station to some set of the nearest hourly stations. This is accomplished using a spatially based approach that is called the spatially based mass curve (SMC) process. Steps involved in the SMC process are described below:

1. Evaluate and quality control (QC) hourly station data using synoptic maps, nearby stations, orographic effects, station history and other documentation on the storm. Resolve any problems with the hourly data as well as manually distributing accumulated hourly values. At this point in the process, pseudo (hourly) stations can be added to represent rainfall timing in topographically complex locations, areas with limited hourly data, and to capture the temporal variations of the precipitation. This is done by distributing the precipitation by hand at a co-located daily station or by creating a completely new pseudo station. In either case, the pseudo station is flagged with a "P" so the software knows only to use it for timing and not its actual precipitation. A true hourly station is flagged "H" while daily and supplemental stations are flagged "D" and "S" respectively. If a daily station is used to create a pseudo station, the pseudo station is used in all of the subsequent mass-curve related products (i.e. grids and maps). This procedure is similar to the NWS approach. Like in the NWS procedure, care must be taken

to ensure hourly stations represent important physical and meteorological characteristics before being incorporated into the process. In general, use of pseudo data is kept to a minimum. In fact, pseudo stations were not needed and thus not used in the DAD analyses for the Nebraska study but are described here since they are potentially a part of the SPAS procedure. The importance of insuring the reliability of every hourly station can not be over emphasized. Since the entire SMC process is based on them, it is important to collect as many accurate and representative hourly stations as possible. All of the final hourly stations, including pseudos, are included in the master GIS hourly rainfall file.

2. Using the master GIS hourly file, actual hourly precipitation values are converted into percentages that are the actual individual hourly precipitation values divided by the total tabulated hourly precipitation for that station. The percentages are not a function of the core precipitation period (CPP), but rather a percentage based on the storm precipitation period (SPP). An hourly percent of total storm rainfall value is computed for the location of the daily reporting station for each hour of the storm. Adjustments are made to account for any differences in accumulated daily rainfall amounts between the sum of hourly rainfall values and the daily amounts reported at the daily reporting station. A GIS-ready x-y file is then constructed for each hour that contains the latitude, longitude and percent of precipitation for a particular hour. Using GIS (GRASS 6.2), an inverse-distance-weighting (IDW) interpolation technique is applied to each of the files. The result is a continuous grid with percentage values for the entire domain, keeping the grid cells on which the hourly station resides faithful to the observed/actual percentage. Because the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation has skill in determining the percentages between stations, especially since the percentages are somewhat independent of the precipitation magnitude. The end result is a grid file for each hour that represents the percentage of the SPP precipitation that fell during that hour.

3. At this point another quality control procedure has been designed for the SMC process. Since the SMC process is spatially oriented, a tool was designed that allows the analyst to use a point-and-click interface to evaluate the hourly percentile maps. This is an effective way to immediately detect temporal and spatial problems with the hourly-based percentiles. Any problems identified are resolved and the process to this point is re-run.

4. After the hourly maps of percentages are generated and QC'd for the entire SPP, a program is executed that converts the daily station data into incremental hourly data. The timing at each of the daily stations is based on (1) the daily station observation and (2) the interpolated grid-cell hourly percentage of total storm precipitation. To make the daily accumulated mass curve data faithful to the daily observations (at daily stations), it is necessary to adjust the hourly percentages such that they add up to 100% and therefore account for 100% of the daily observed precipitation. To accomplish this, an adjustment factor is applied to

each of the hourly values with greater than zero inches of precipitation.

5. A similar program is run that converts the supplemental daily stations (i.e. those stations with unknown or uneven observational periods and/or accumulated values) into incremental hourly data. In cases where the hourly grids/maps do not indicate any precipitation falling during the daily stations' observational period but the daily station reported precipitation, the daily total precipitation is evenly distributed throughout the hours that make up the observational period. This is the same procedure traditionally used by the NWS method in these cases. Another possible problem at this point is the situation where the observational period at the daily station extends before or beyond that of the hourly data. The software is sensitive to this and forces an exit, then prompts the analyst with suggested changes to the raw data.

6. Similar to the NWS method, exhaustive quality control measures are taken at this point. The SMC procedure groups each station (regardless of type) and some number (user specified) of nearest stations (regardless of type) into a single file. These files are subsequently imported into graphing software (or a spreadsheet) for graphing and evaluation. Unusual characteristics in the mass curve are investigated and the station data corrected, if necessary. Once the final mass curve results are complete, the database is ready to create hourly precipitation maps.

Hourly or Sub-hourly Precipitation Maps

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

NEXRAD mode

Radar has been in use by meteorologists since the 1960's to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the equation (1) below:

(1) $Z = aR^b$

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

The National Weather Service (NWS) uses this relationship to estimate rainfall through the use of their network of Doppler radars (NEXRAD) located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ is the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and DND, and differing air mass characteristics across the United States (Dickens 2003). The DSD and DND are determined by a complex interaction of microphysical processes in a cloud. They fluctuate hourly, daily, seasonally, regionally, and even within the same cloud. Other factors that affect radar rainfall computations include occultation or blockage of the radar beam due to terrain features and range effects that are the result of the radar beam passing through the cloud at elevations too high in the cloud to observe the main precipitation portion of the cloud.

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

The methodology that is used to estimate the rainfall is described below.

1. Surface rainfall observations measured within the project area are obtained from multiple sources for the rainfall event. A Geographic Information System (GIS) layer containing the locations of these rainfall observations (Figure G.2) is created using GIS software.

2. NEXRAD Level II data is obtained from the National Climatic Data Center (NCDC). Level II Base Reflectivity data, 0.50-degree beam angle (lowest beam angle), 124 km range, data resolution of 1 degree x 1.0 km (polar coordinates) and 0.50 dBZ data bin resolution is extracted from the Level II dataset (Figure G.3).

3. The polar coordinate base reflectivity data (Z) is converted into Cartesian coordinate ESRI ASCII GIS files and combined with the rainfall observations GIS layer. The grid cells within the GIS grid have a resolution of approximately 1.00 km^2. A SPAS program is used to determine base reflectivity values (Z) over each grid cell, within the project area, for each base reflectivity time step.

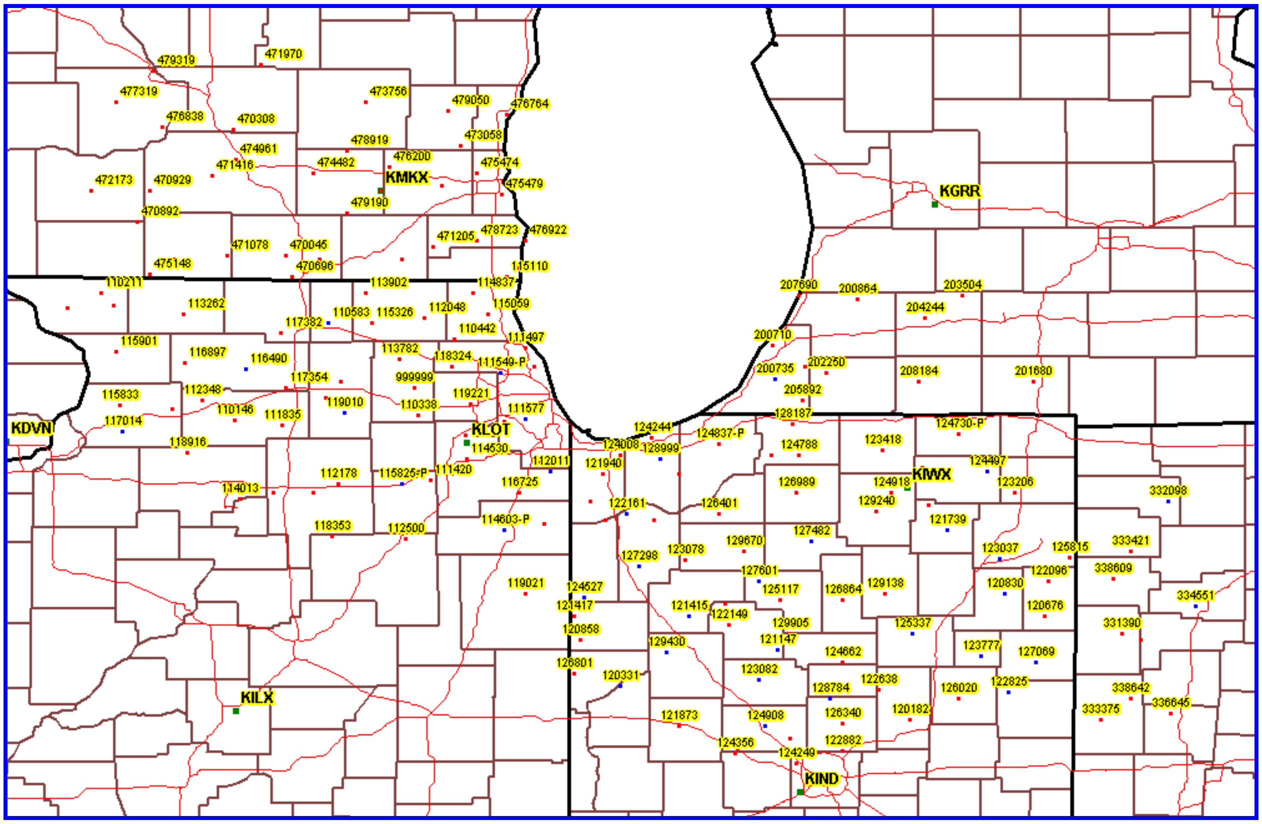


Figure G.2 Example rainfall calculation project area with rain gauge locations

4. A range correction scheme developed by the United States Bureau of Reclamation is applied to each grid cell.

   The range correction factor (CF) used was: (1.04607 - 0.0029590) (r + 0.0000506) r^2

   where r is the range (distance in km) from the radar (Hartzell and Super, 2000). The correction is applied to grid cells that are greater than 35 km beyond the radar site. The range correction corrects for rainfall underestimation due to the radar beam passing through an elevation too high in the cloud to observe the main precipitation portion of the cloud.

A procedure is used to calculate a “best-fit” Z-R algorithm for the project area. A “best-fit” Z-R algorithm is calculated on an hourly basis by using the least squares methodology.

Least squares is a mathematical optimization technique which, when given a series of observed data values, finds a function which closely approximates the data (a "best fit"). It attempts to minimize the sum of the squares of the differences between points generated by the function and corresponding points in the data.

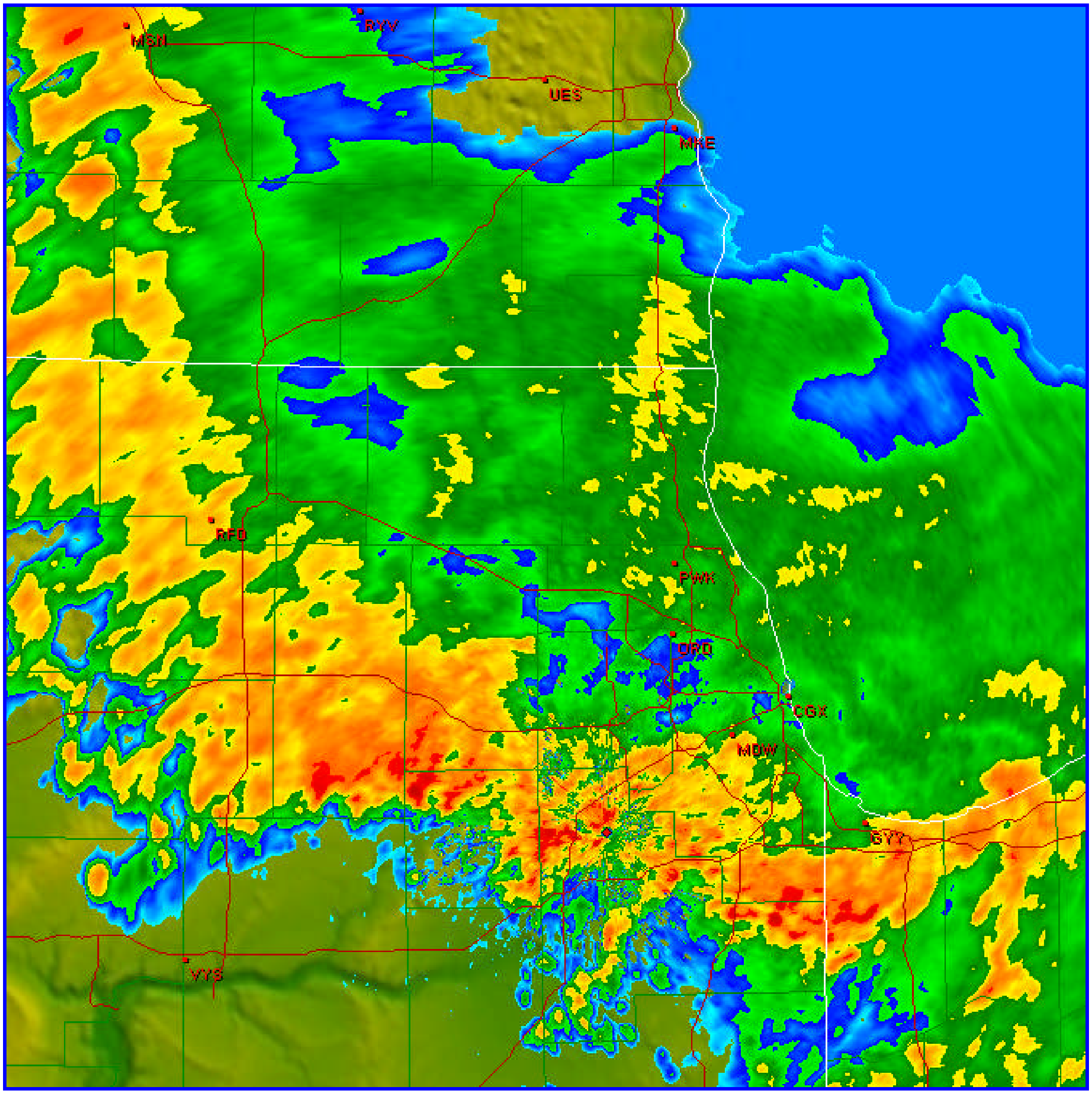


Figure G.3 Doppler radar Level II base reflectivity image

The calculated hourly "best-fit" Z-R algorithm is used to compute radar derived hourly rainfall depths for each hourly rain gauge location.

By comparing radar calculated rainfall (Rcalc) depths to observed point rainfall depths at the rainfall observation sites and calculating a ratio (Rcalc/Robs), it is determined how close a fit exists between the estimated rainfall depths and the observed point rainfall depths. This procedure yields areas where ratios are above 1.0 and areas where ratios are below 1.0. These differences in ratios can be partially contributed to convective rainfall and hail. This results in vastly different DSD and DND being observed by the radar beams during each radar scan, producing some variability between the radar derived rainfall and the observed rainfall depths. Other issues that contribute are discussed in the next section.

Issues are sometimes encountered in the radar-rainfall calculation process that can contribute to a less than perfect correlation between radar rainfall depth calculations and rainfall depth observations at the rainfall observation sites. These issues include the following:

1. Area average radar-rainfall depth estimates versus observed point rainfall depths: A rain gauge observation represents a much smaller area than the area sampled by the radar. The area that the radar is sampling is approximately $1km^2$. The radar data provides the average reflectivity (Z) within the area being sampled. This average reflectivity is used to convert Z to Rcalc for the sample area. This radar derived rainfall value is compared to a point rainfall depth measured by a rain gauge located within the radar sample area. This area vs point issue contributes to correlations greater than or less than 1.0 within the project area.

2. Rain gauge catch: Precipitation gauges, shielded and unshielded, inherently underestimate total precipitation due to local airflow, wind undercatch, wetting, and evaporation. The wind undercatch errors are usually around 5% but can be as large as 40% in high winds (Mather 1974). In addition, tipping buckets miss a small amount of rainfall during each tip of the bucket due to the bucket travel and tip time. As rainfall intensities increase, the volumetric loss of rainfall due to tipping tends to increase. At rainfall intensities greater than 152 mm per hour, 1 mm tipping buckets will under report rainfall in the range of 0-5% depending on how the gauge was calibrated (Duchon 2001). Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies.

3. Radar Calibration: NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a problem with the calibration and precipitation estimates could be significantly in error. The calibration test is supposed to maintain a reflectivity precision of 1 dBZ. A 1 dBZ error results in an error of 17% in Rcalc, using the default Z-R relationship Z=3001.4. Higher calibration errors will result in higher Rcalc errors. However, by performing correlations each hour, the calibration issue is minimized.

4. Attenuation: Attenuation is the reduction in power of the radar beams energy as it travels from the antenna to the target and back and is caused by the absorption

and the scattering of power from the beam by precipitation. Attenuation can result in errors in Z as large as 1 dBZ especially when the radar beam is sampling a large area of heavy precipitation, as was the case for this rainfall event.

5. Range effects: The curvature of the Earth and standard refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar bean not sampling the main precipitation portion of the cloud. A correction scheme is used for this issue.

6. Radar Beam Occultation/Ground Clutter: Radar occultation (beam blockage) results when to the radar beam's energy intersects terrain features. The result is an increase in radar reflectivity values that can result in higher then normal rainfall estimates.

Using GIS the radar reflectivity grids are converted into rainfall depths using Z-R equations. The equations were unique to defined "sectors" which exhibited similar DSD, reflectivity (Z) values and observed rainfall. After several iterations to account for changes in the sector boundaries, a final "radar reconstruction" (Rcalc) is completed for each radar site being utilized in the process.

If more than one radar site is being utilized the 5 or 6-minute rainfall grids from each radar site are mosaiced together to produce a seamless grid of precipitation for the storm domain. The complete grid is smoothed to remove extraneous noise. Additionally, the radar domain boundaries are subjected to additional smoothing to ensure a smooth spatial transition from one radar domain to the next and across sector boundaries. The mosaiced grids are then summed into hourly or sub-hourly intervals.

SPAS mode-non NEXRAD

The standard SPAS mode requires a full listing of all the actual hourly precipitation values, as well as the newly created estimated hourly data from daily and daily supplemental stations (pseudo stations are not included). This is done by creating an hourly file that contains the newly created hourly mass curve precipitation data (from the daily and supplemental stations) and the "true" hourly mass curve precipitation (not percent). The option of incorporating base maps was not used in this study. If not using a base map, the individual hourly precipitation values are simply plotted and interpolated to a raster with an IDW interpolation routine in a GIS. For the Nebraska study, no base maps were used.

Gridded Rainfall Quality Control

At this point, additional QC checks are completed on the resulting hourly or sub-hourly precipitation maps/grids for the SPP. Among the tools, is a point-and-click graphical user interface used to evaluate the hourly precipitation grids. However, by this point error detection becomes much more difficult since the maps contain more data points and the data has been through several QC screening processes already. The total cumulative precipitation (or any combination of hours) and/or maximum 1-hour grids can be viewed to find gross errors. The end result is individual hourly or sub-hourly precipitation grids for the entire SPP.

Depth-Area-Duration (DAD) Program

The DAD extension of SPAS runs from within a GRASS 6.2 GIS environment and utilizes many of the built-in functions for calculation of area sizes and average depths. The following is the general outline of the procedure:

1. Given a duration (e.g. x-hours) and cumulative precipitation, sum up the appropriate hourly or sub-hourly precipitation grids to obtain an x-hour total precipitation grid starting with the first x-hour moving window.

2. Determine x-hour precipitation total and its associated areal coverage. Store these values. Repeat for various lower rainfall thresholds. Store the average rainfall depths and area sizes
   a. Determine if the x-hour window includes the last hour of the CPP, if it does not move the x-hour window forward one hour and return to step 1.

3. The result is a table of depth of precipitation and associated area sizes for each x-hour window location. Summarize the results by moving through each of the area sizes and choosing the maximum precipitation amount. A log-linear plot of these values provides the depth-area curve for the x-hour duration.

4. Based on the log-linear plot of the rainfall depth-area curve for the x-hour duration, determine rainfall amounts for the standard area sizes for the final DAD table. Store these values as the rainfall amounts for the standard sizes for the x-duration period.
   a. Determine if the x-hour duration period is the longest duration period being analyzed, if it is not, analyze the next longest duration period and return to step 1.

5. Construct the final DAD table with the stored rainfall values for each standard area for each duration period.

Test Cases

To check the accuracy of the DAD software, three test cases were evaluated.

"Pyramidville" Storm

The first test was that of a theoretical storm with a pyramid shaped isohyetal pattern. This case was called the Pyramidville storm. It contained 361 hourly stations, each occupying a single grid cell. The configuration of the Pyramidville storm (see Figure 5.3) allowed for uncomplicated and accurate calculation of the analytical depth-area truth independent of the DAD software. The main motivation of this case was to verify that the DAD software was properly computing the area sizes and average depths.

1. Storm center: 39°N 104°W
2. Duration: 10-hours
3. Maximum grid cell precipitation: 1.00" (see Figure G.4)
4. Grid cell resolution: 0.06 sq.-miles (361 total cells)
5. Total storm size: 23.11 sq-miles
6. Distribution of precipitation:
   - Hour 1: Storm drops 0.10" at center (area 0.06 sq-miles)
   - Hour 2: Storm drops 0.10" over center grid cell AND over one cell width around hour 1 center
   - Hours 3-10:
     1. Storm drops 0.10" per hour at previously wet area, plus one cell width around previously wet area
     2. Area analyzed at every 0.10"
     3. Analysis resolution:
        15-sec (~.25 sq-miles)

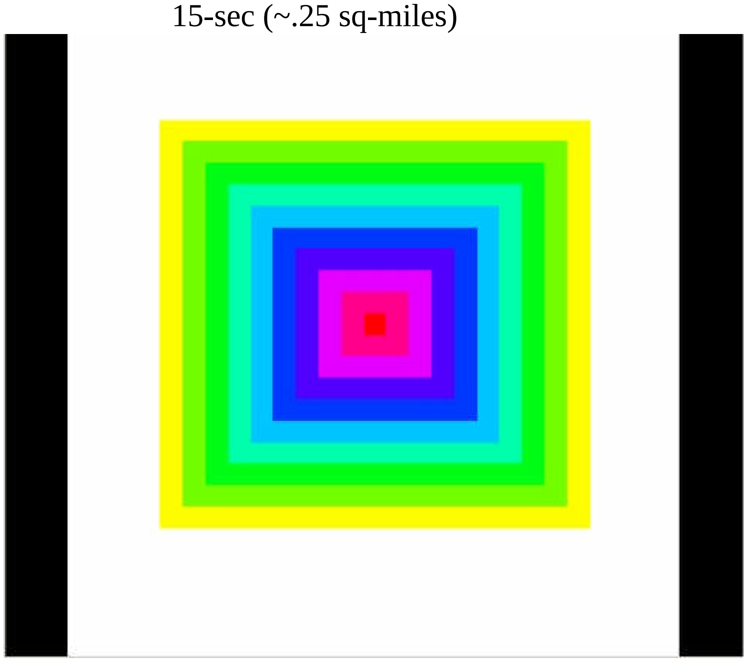


Figure G.4 "Pyramidville" Total precipitation. Center = 1.00", Outside edge = 0.10"

The analytical truth was calculated independent of the DAD software, and then compared to the DAD output. The DAD software results were equal to the truth, thus demonstrating that the depth-area estimates were properly calculated (Figure G.5).

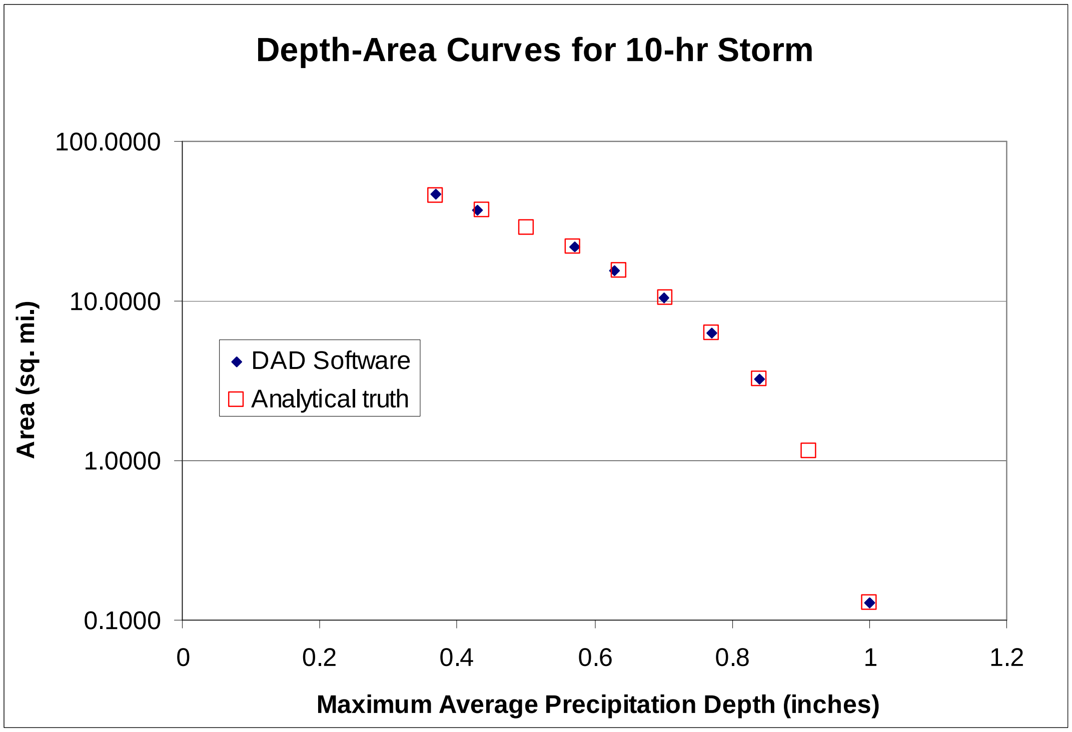


Figure G.5 10-hour depth-area results for "Pyramidville"; truth vs. output from DAD software

The Pyramidville storm was then changed such that the mass curve and spatial interpolation methods would be stressed. Test cases included:

- Two-centers, each center with 361 hourly stations
- A single center with 36 hourly stations, 0 daily stations
- A single center with 3 hourly stations and 33 daily stations

As expected, results began shifting from the 'truth,' but minimally and within the expected uncertainty.

Ritter, Iowa Storm, June 7, 1953

Ritter, Iowa was chosen as a test case for a number of reasons. The NWS had completed a storm analysis, with available DAD values for comparison. The storm occurred over relatively flat terrain so orographics was not an issue. An extensive "bucket survey" provided a great number of additional observations from this event. Of the hundreds of additional reports, about 30 of the most accurate reports were included in the DAD analysis.

The DAD software results are very similar to the NWS DAD values (Table G.2).

Table G.2 The percent difference [(AWA-NWS)/NWS] between the AWA depth-area results and those published by the NWS for the 1953 Ritter, Iowa storm

% Difference

	Duration (hours)				
Area (sq.mi.)		6	12	24	total
10		-15%	-7%	2%	2%
100		-7%	-6%	1%	1%
200		2%	0%	9%	9%
1000		-6%	-7%	4%	4%
5000		-13%	-8%	2%	2%
10000		-14%	-6%	0%	0%

Westfield, Massachusetts Storm, August 8, 1955

Westfield, Massachusetts was also chosen as a test case for a number of reasons. It is a probable maximum precipitation (PMP) driver for the northeastern United States. Also, the Westfield storm was analyzed by the NWS and the DAD values are available for comparison. Although this case proved to be more challenging than any of the others, the final results are very similar to those published by the NWS (Table G.3).

Table G.3 The percent difference [(AWA-NWS)/NWS] between the AWA depth-area results and those published by the NWS for the 1955 Westfield, Massachusetts storm.

% Difference

	Duration (hours)							
Area (sq. mi.)		6	12	24	36	48	60	total
10		2%	3%	0%	1%	-1%	0%	2%
100		-5%	2%	4%	-2%	-6%	-4%	-3%
200		-6%	1%	1%	-4%	-7%	-5%	-5%
1000		-4%	-2%	1%	-6%	-7%	-6%	-3%
5000		3%	2%	-3%	-3%	-5%	-5%	0%
10000		4%	9%	-5%	-4%	-7%	-5%	1%
20000		7%	12%	-6%	-3%	-4%	-3%	3%

The principle components of SPAS are: storm search, data extraction, quality control (QC), conversion of daily precipitation data into estimated hourly data, hourly and total storm precipitation grids/maps and a complete storm-centered DAD analysis.

Data

Storm Search

A storm search is the first step in a SPAS run. A total storm map is created with readily available rainfall data to estimate the areal extent of the storm. Based on the initial storm map, a user-defined domain is established as the SPAS study area, typically a latitude-longitude box. The study area and storm dates are entered into software that extracts and formats all of the available hourly and daily precipitation data. For example, Hurricane Floyd produced heavy rain over many regions of the Atlantic seaboard. One of the SPAS analyses selected the rainfall center over northern New Jersey. The state of New Jersey along with portions of surrounding states was analyzed. Additionally, for a NEXRAD-based analysis's radar sites are identified and the NEXRAD Level II is obtained from the National Climatic Data Center (NCDC). Level II Base Reflectivity data, 0.50-degree beam angle (lowest beam angle), 124 km range, data resolution of 1 degree x 1.0 km (polar coordinates) and 0.50 dBZ data bin resolution is extracted from the Level II dataset. In order to make the NEXRAD data compatible with SPAS, it is re-projected from its native polar coordinate system to a Cartesian coordinate system. Thereafter, the grids are converted into ESRI ASCII GIS files. The grid cells within the GIS grid have a resolution of approximately 1.00 km^2.

Precipitation Data

SPAS has the ability to utilize a variety of different types of data in order to achieve the highest spatial and temporal resolution possible. The majority of data is obtained from digital archives provided by NCDC. These datasets represent official precipitation information and therefore provide the most critical precipitation input to SPAS. However, supplemental data from other sources can also be used to better resolve the storm's characteristics.

Hourly data

Precipitation data that is reported every hour comes from a variety of sources. The base hourly data is from the NCDC dataset TD-3240, U.S. Control Cooperative Hourly Precipitation. This dataset provided hourly data sufficient for the Hurricane Floyd analysis. However, other hourly precipitation gauge data from Automated Local Evaluation in Real Time (ALERT) networks, Remote Automated Weather Stations (RAWS) stations, NWS's Automated Surface Observing Systems (ASOS), municipal networks, etc. can also been used.

Quality control (QC) is an ongoing exercise in SPAS. The first QC takes place after the hourly data has been collected. The hourly station data is evaluated based on knowledge acquired from weather maps, nearby stations, known orographic effects, station history and other documentation on the storm. Any hourly data errors are resolved.

Observed hourly data governs the temporal characteristics of the storm and is also used in the radar calibration (for NEXRAD-based SPAS runs), so every attempt is made to restore incomplete or accumulated hourly data records. This is done using the same knowledge used to QC the data. Based on professional judgment and the level of restoration required, the restored hourly stations are flagged either as pseudo-hourly stations or as supplemental hourly stations. Supplemental hourly stations will be treated in SPAS just like a complete hourly station. Pseudo-hourly stations, on the other hand, are only utilized for timing considerations. Pseudo-hourly stations allow the SPAS meteorologist to add data to the analysis to better resolve physical and meteorological processes that would otherwise be ignored in a strict model. Creating pseudo hourly data is accomplished by manually distributing precipitation at a daily station into hourly estimates. This distribution is determined from nearby hourly stations and information from other sources such as radar or local storm reports. The Hurricane Floyd analysis did not require any pseudo-hourly stations since the precipitation and terrain were both relatively uniform. However, several hourly stations were flagged supplemental.

Daily data

Daily precipitation data representing a 24-hour accumulation, are more abundant than hourly precipitation data, and thus provide valuable spatial detail. Daily data are available from a number of sources, but the base data are from the NCDC datasets TD-3200, U.S. Cooperative Summary of Day, and TD-3206 U.S., Cooperative Summary of the Day – pre 1948. Additional supporting daily data is often obtained from other sources such as municipal networks, etc. In fact, for our Floyd analysis we obtained over 100 supplemental daily observations, taken by volunteer observers who belong to one or more of several networks across New Jersey, from the New Jersey State Climatologist Office.

An initial QC screening of the daily data is conducted at this point. The daily data are summed into storm totals and mapped to spatially identify gross errors. Also, the daily data are subjected to a threshold check that identifies all of the daily precipitation values that equal or exceed some threshold. The threshold is usually objectively based on the depth of precipitation for a 50- or 100-year reoccurrence interval available from the current precipitation frequency atlases. For our Hurricane Floyd analysis, we used 7.50 inches, the average 100-year 24-hour precipitation in New Jersey from Technical Paper 40.

Once an initial QC pass is completed on all of the available data, SPAS begins its analysis of the hourly data in order to convert the daily data into estimated hourly amounts.

Methodology

Among one of most significant strengths of SPAS is its ability to convert daily measured precipitation into hourly precipitation – known as timing - utilizing several nearby hourly stations. In the past, timing of daily measured data was accomplished by associating each daily station with a nearby hourly station and distributing the daily precipitation exactly the same as that hourly station. SPAS, however, uses several hourly stations to time each of the daily stations, thereby allowing the hourly precipitation distribution to be unique at each daily station. If NEXRAD data is available, then it is also used for timing.

Hourly Percentile Grids

The hourly data serve as the basis for timing the daily stations. The first step involved with this transformation is converting each of the hourly precipitation depths into a percent of the total storm precipitation. The hourly percentages from each station are then plotted and spatially distributed for each hour of the storm. The percentages are spatially distributed to a uniform grid by applying an inverse-distance-weighting (IDW) algorithm, an exact interpolator where the grid cell values at stations are equal to the station value. Because the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation carries skill in predicting the percentages between hourly stations, especially since the percentages are largely independent of the precipitation magnitude. For instance, an orographic flow over a mountain range will deposit more precipitation on the windward side and less on the lee side; however the timing of the precipitation across the mountain range will generally be the same. The end result is a grid for each hour of the storm, each representing the percentage of precipitation that fell during that hour (see Figure G.6.)

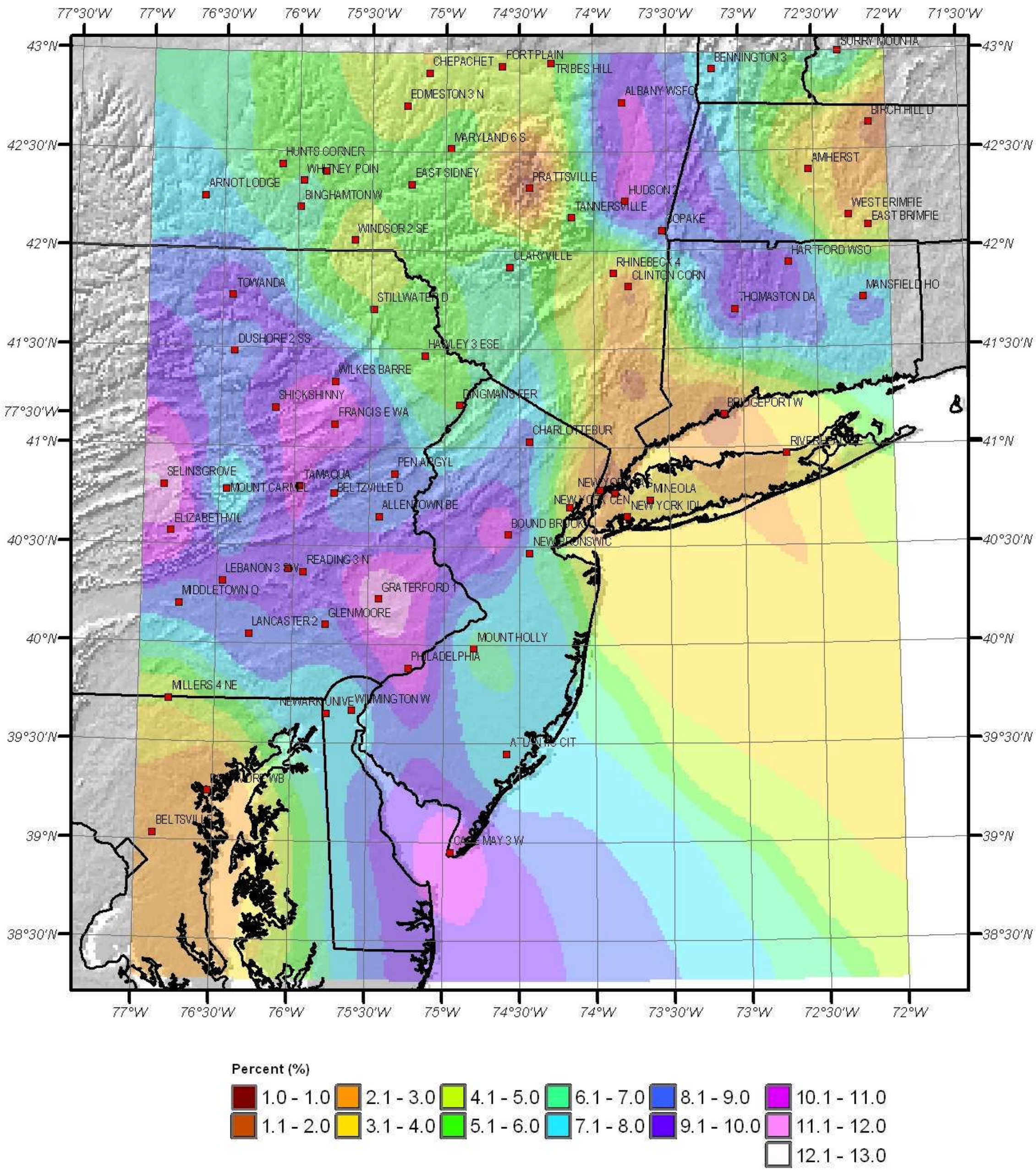


Figure G.6 An example of a percent of total precipitation map for a single hour during hurricane Floyd. Each symbolized station represents an hourly station.

At this point, a point-and-click QC interface in a GIS is used to evaluate the hourly percentile grids. This has proven to be an effective way to immediately detect temporal and spatial problems with the hourly station data. After all problems have been resolved, the process is then re-run to this point.

Timing of Daily Data

After the hourly percentile grids are finalized, they are used to create simulated hourly data for daily station data. The observation time and coordinates of the daily station are used to extract the appropriate percentile values from the appropriate hourly percentile grids and stored. In order to make the daily-accumulated hourly data faithful to the daily observations it is necessary to adjust the hourly percentages such that they add up to 100% and therefore account for 100% of the daily observed precipitation. To accomplish this, an adjustment factor is applied to each of the hourly values by multiplying the daily station observational day precipitation by the ratio of the actual hourly percentage to the sum of percentages for that observational day. The daily precipitation amounts are then multiplied by the adjusted percentile values, resulting in a series of hourly precipitation estimates for the daily station (see Figure G.7).

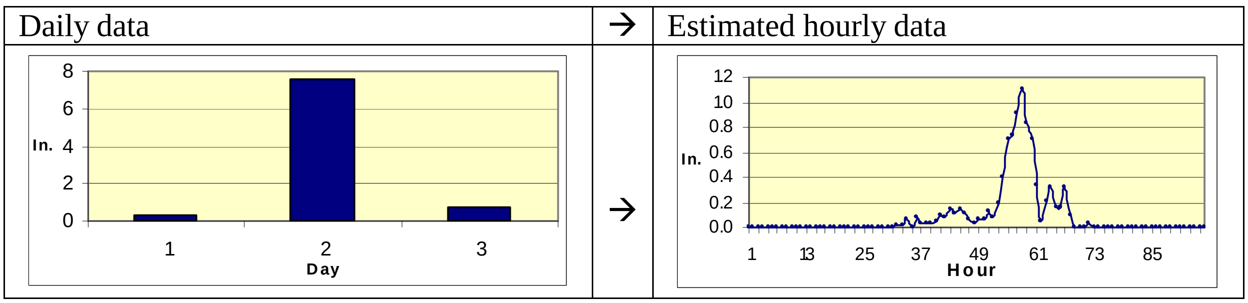


Figure G.7 An illustration of how SPAS converts three days of daily precipitation into estimated hourly amounts.

A similar procedure is used to convert the supplemental and pseudo daily data (i.e. those stations with uneven observational periods and/or accumulated values) into hourly precipitation estimates. Since these stations do not always have a complete precipitation record for the entire storm period, their missing hours of precipitation are in filled with spatially interpolated estimates later in the SPAS process.

Once the daily data has been converted into hourly estimates, exhaustive and very effective QC measures are taken. Plots of the incrementally accumulated precipitation data (known as mass curves) are created for each daily station and then combined into a single plot with other nearby stations for evaluation. The most common QC issue detected at this stage is related to the observation time of the daily station. A suspect observation time will cause a shift in the distribution of precipitation in comparison to the other nearby stations. Any suspect observation times are corrected when possible. Otherwise, the station is converted to a supplemental station with the observational period set to the bounds of the storm period, hence making it not necessary to know the daily stations' observation time(s). Once any and all timing issues are resolved, SPAS is re-run.

Output

SPAS generates a number of products to aid in hydrologic modeling, Probable Maximum Precipitation (PMP) applications and other hydrologic studies. The SPAS output includes:

1. High resolution (user defined, but typically 30-seconds or about 0.5 miles) hourly precipitation grids and ArcView Shapefiles.
2. Mass curves for all of the stations (see Figure G.8)
3. A complete storm-centered DAD table and summary, including station density. (See Figure G.9 and G.10)
4. A complete station list.
5. Color cartographic total storm precipitation map (see Figure G.11)

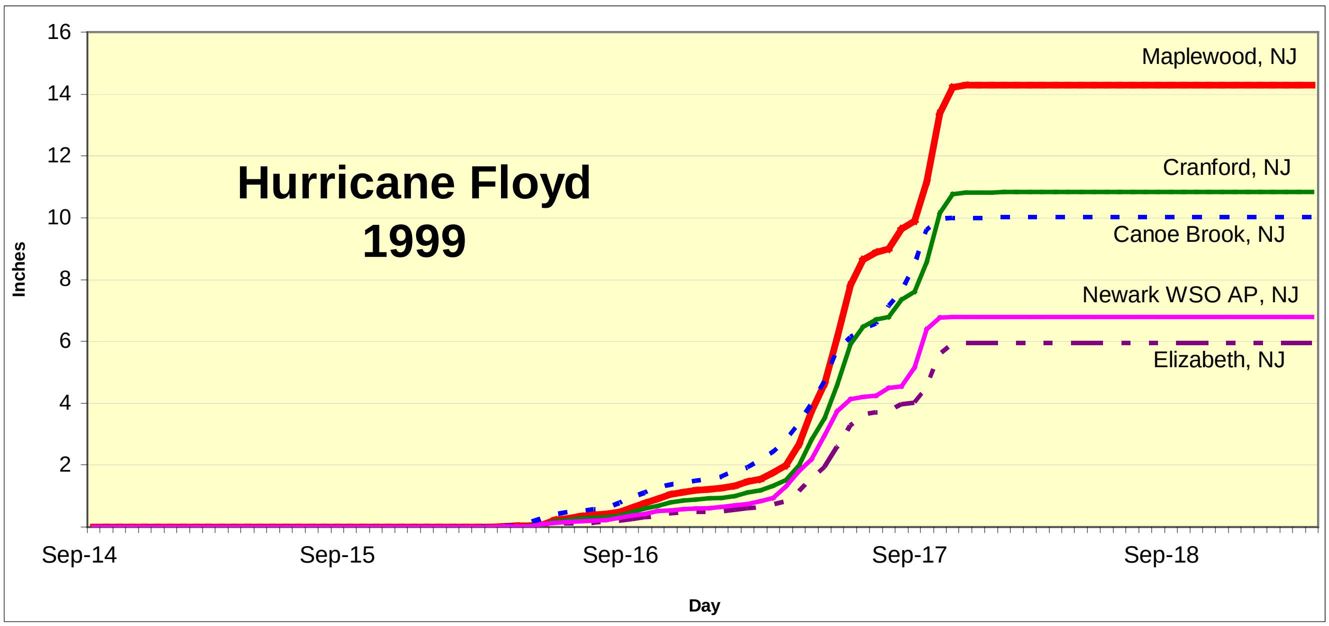


Figure G.8 Storm center mass curve for precipitation associated with Hurricane Floyd (September 14-18, 1999) in New Jersey.

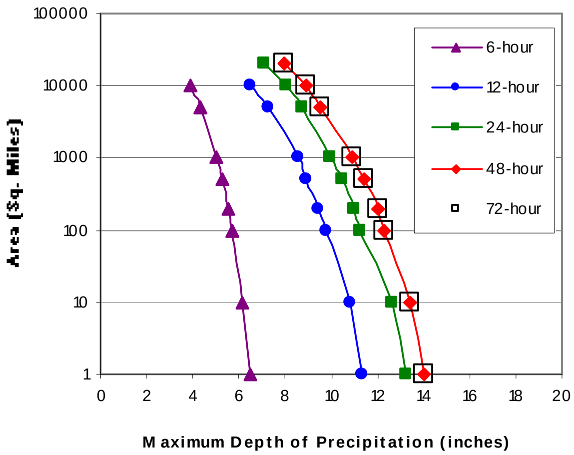


Figure G.9 Storm-centered DAD graph associated with the New Jersey rainfall from hurricane Floyd (September 14-18, 1999).

Area	Duration (hours)				
(Sq. mi.)	6	12	24	48	72
1	6.5	11.3	13.2	14.0	14.0
10	6.1	10.9	12.7	13.4	13.4
100	5.7	9.8	11.3	12.3	12.3
200	5.6	9.5	11.0	12.0	12.0
500	5.3	9.0	10.5	11.4	11.4
1000	5.1	8.6	10.0	10.9	10.9
5000	4.4	7.3	8.8	9.5	9.5
10000	3.9	6.5	8.0	8.9	8.9
20000	3.3	5.6	7.1	8.0	8.0

Figure G.10 Storm-centered DAD table for the New Jersey rainfall from hurricane Floyd (September 14-18, 1999).

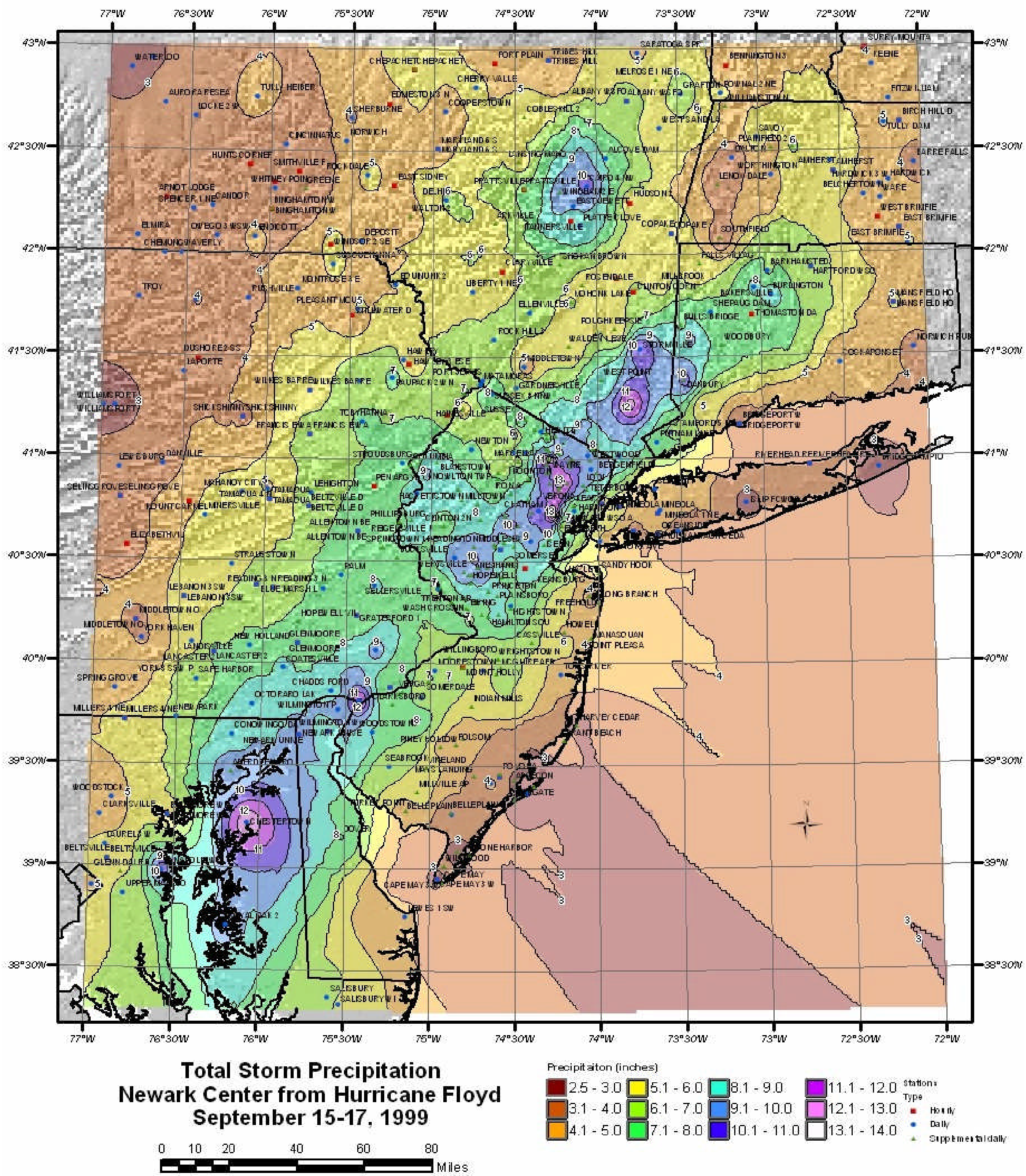


Figure G.11 Total storm (Hurricane Floyd) precipitation map for the New Jersey region during the period September 14-18, 1999 developed using SPAS.

Summary

SPAS is based on the sound foundation of the storm analysis procedure used by the Weather Bureau, thereby providing consistency between storms already analyzed and those being analyzed today. However, SPAS has the ability to compute more precise and perhaps more accurate results by using a more sophisticated timing algorithm, a variety of base maps, a wider variety of data and fewer assumptions. Although largely automated, SPAS has been designed to be flexible such that it can be utilized for any storm situation. SPAS produces reproducible results and uses less subjectivity than previous storm analysis studies.

There is an extremely large backlog of extreme rainfall storm analyses that should be completed. With rare exception, extreme rainfall storms that have occurred in the last 50 years have not been analyzed. Without storm DADs, comparison of rainfall amounts from extreme rainfall storms for various area sizes and durations is not possible. The storm databases in most of the current HMRs are significantly out of date. For example, the most recent storm used in HMR 51 occurred in 1972. Using SPAS, this backlog in storm analyses can be addressed. Equally important, storm analyses can be provided in near real-time, utilizing rainfall observations that are not included in official archives and providing emergency managers with some measure of how extreme the storm rainfall amounts over various area sizes and for various durations were compared to other storms, to published return frequency values and to published PMP values.

Appendix H

Depth-Area (DA) Estimator Program Development and Description

The DA Estimator program is a Perl program used to *estimate* the depth-area characteristics of a defined storm event based on point rainfall observations and the corresponding longitude/latitude of the observations. The DA Estimator only estimates the total storm rainfall area sizes and it is only a tool to evaluate storms, therefore it does not give precise analysis results.

The program prompts a user for: storm center (lon/lat), begin date, number of storm days and the maximum allowable distance a station can be from the center to be included in the analysis and a storm center precipitation amount. The software is flexible enough to include a storm center that is not represented in the regular daily data set on our servers. For instance, the Gorham, October 1996 storm has a center at a non-COOP site. A gross QC check prevents precipitation amounts in the analysis from exceeding the storm center (user defined) depth. The software is also flexible enough to account for user defined precipitation thresholds by which area calculations are made.

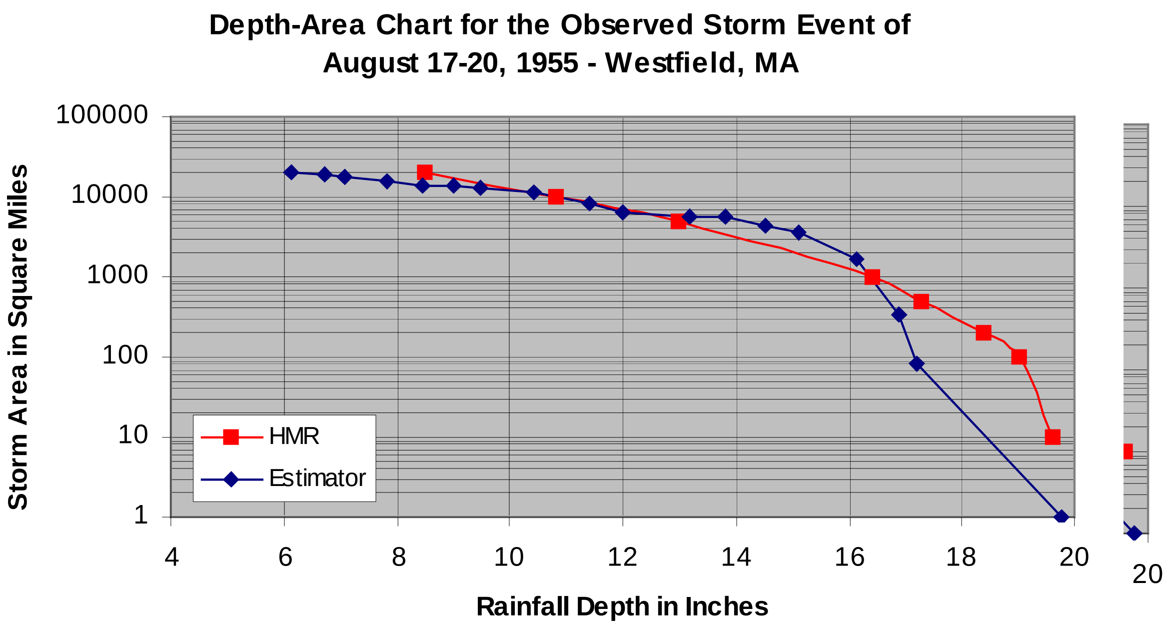
The DA Estimator iterates through the user-defined precipitation thresholds. For each threshold, the software screens the database for observed values greater than or equal to the threshold (e.g. 10"). The average precipitation from this subset of observations becomes the average precipitation depth. The latitude longitude bounds of these observations serve as the basis for computing the corresponding area size. Occasionally, the software will output a duplicate area size and average precipitation value. This occurs when the next higher precipitation threshold doesn't eliminate any stations. Therefore the area and depth statistics are being computed from the same set of stations. As a post-process, these are eliminated to prevent anomalies in the corresponding graphs.

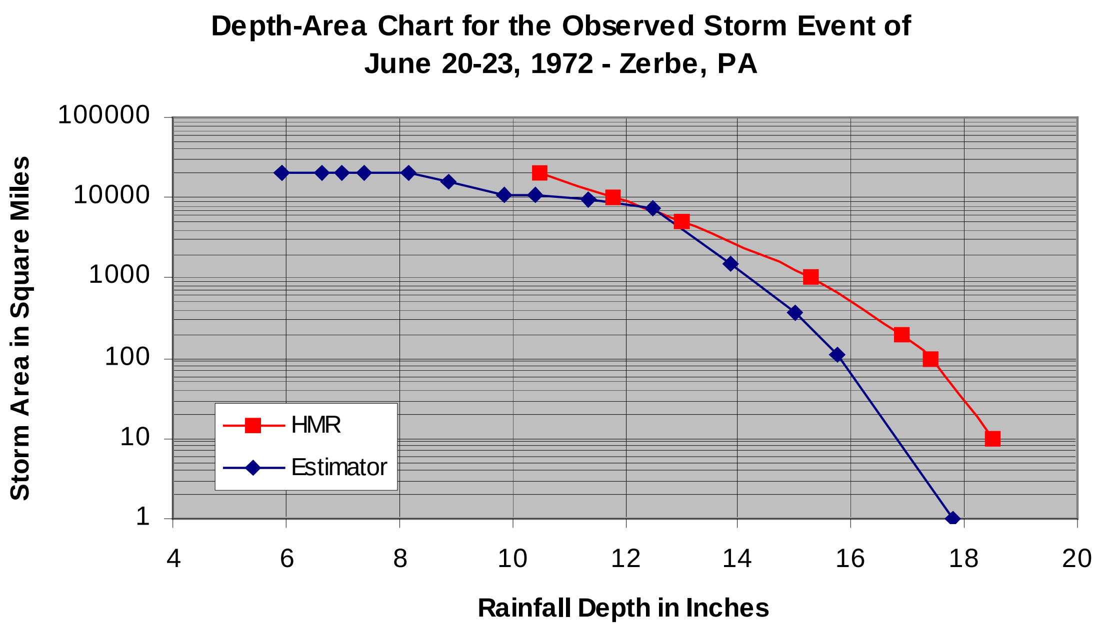
Several comparisons have been made between the DA estimator and either HMR or SPAS DA results. The DA estimator results do a decent job at describing the general depth-area characteristics of the storm, and SPAS define the rainfall at mid-sized areas much more accurately.

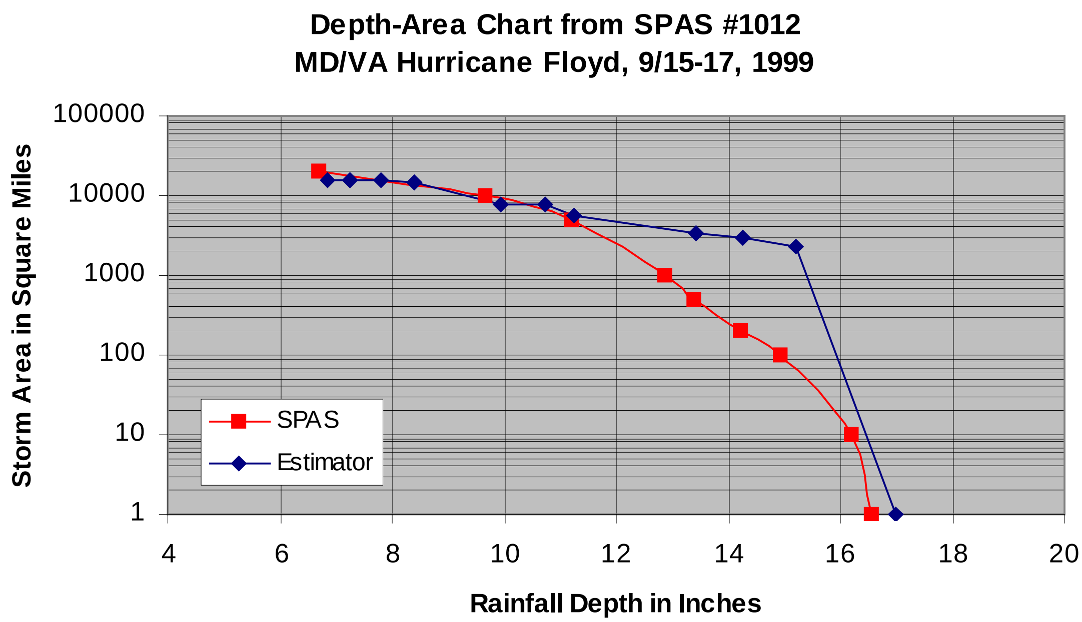
For 1-day (24 hour) DA results, the software selects the greatest 1-day total during a 3-day (user-defined period) in order to avoid observation time biases. At this time the software does not apply a 1-day to 72-hour conversion factor, but this concept will be considered as part of future software enhancements.

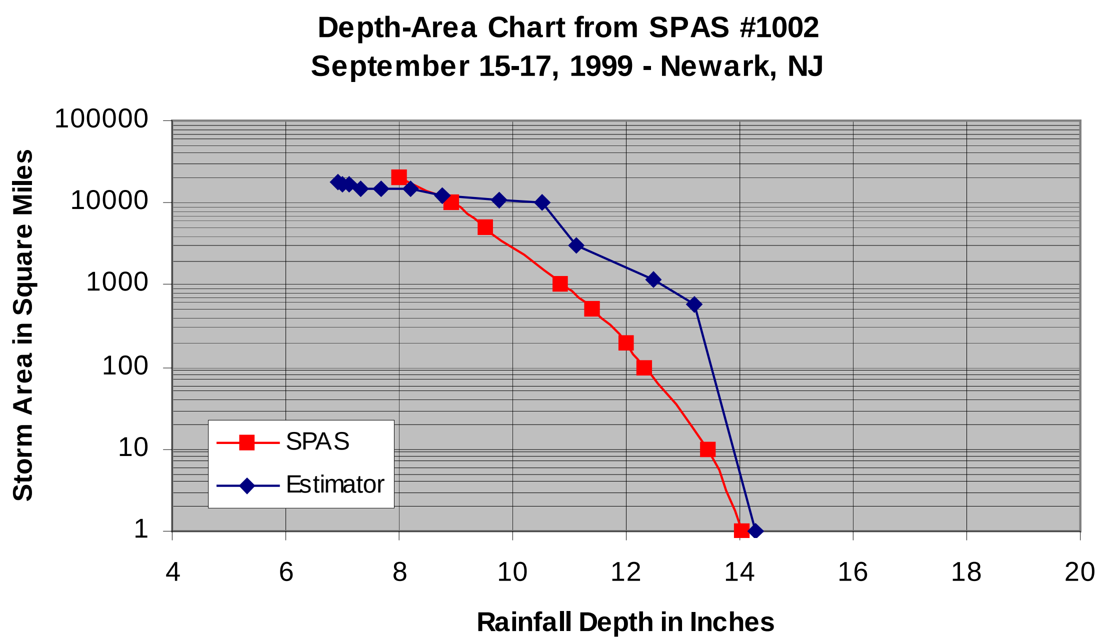
The following slides depict a comparison between known DA values from previously analyzed storms from HMR 51 and AWA SPAS runs and the results for the same storms as derived from the DA estimator program. Note that the 72 hour DA estimator is based on 3 days worth of observations, so depending on observation time and storm occurrence time, it may not be the highest 72 hour storm total. While the HMR/SPAS totals are the highest 72 hour totals, this explains some of the differences in the output between the DA estimator and the HMR/SPAS values.

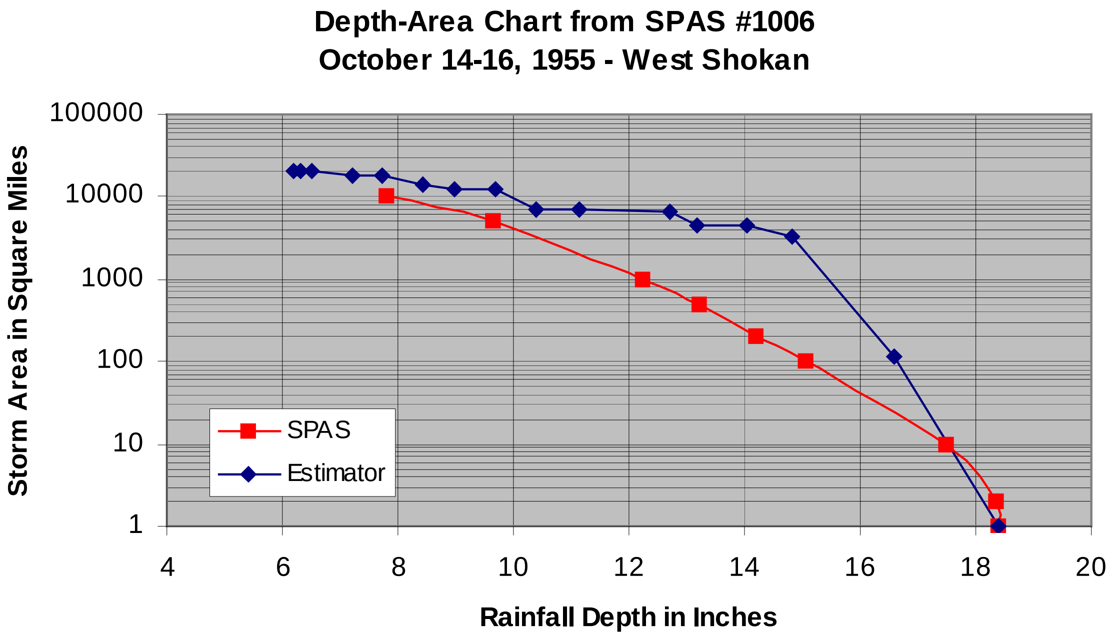
The figures below represent comparison of the DA Estimator results vs. published DA data from selected HMR 51 storms.






Depth-Area Chart from SPAS #1012
MD/VA Hurricane Floyd, 9/15-17, 1999
Storm Area in Square Miles
100000
10000
1000
100
10
1
4
6
8
10
12
14
16
18
20
Rainfall Depth in Inches
SPAS
Estimator


Depth-Area Chart from SPAS #1002
September 15-17, 1999 - Newark, NJ
Storm Area in Square Miles
100000
10000
1000
100
10
1
4
6
8
10
12
14
16
18
20
Rainfall Depth in Inches
SPAS
Estimator


Depth-Area Chart from SPAS #1006
October 14-16, 1955 - West Shokan
Storm Area in Square Miles
100000
10000
1000
100
10
1
4
6
8
10
12
14
16
18
20
Rainfall Depth in Inches
SPAS
Estimator

Appendix I

Storm Transpositioning within the HMR 51 Gentle Upslope Region

AWA investigated the transpositioning of storms for the Nebraska statewide PMP study during the Wanahoo site-specific PMP study. In particular, the topic was being evaluated is the transpositioning or the application of the elevation adjustment to all area sizes for eastward and westward transpositioning of storms.

The general procedure used in HMR 51 is to not make elevation adjustments when transpositioning storms from their in-place location to other locations within their transposition limits. The one exception to this procedure is when transpositioning storms within the "Gentle Upslope Region". Figure I.1 (Figure 3 of HMR 51) shows the gentle upslope region on a map of the US and discussed storm transpositioning in this region in Section 2.4.5 of that report.

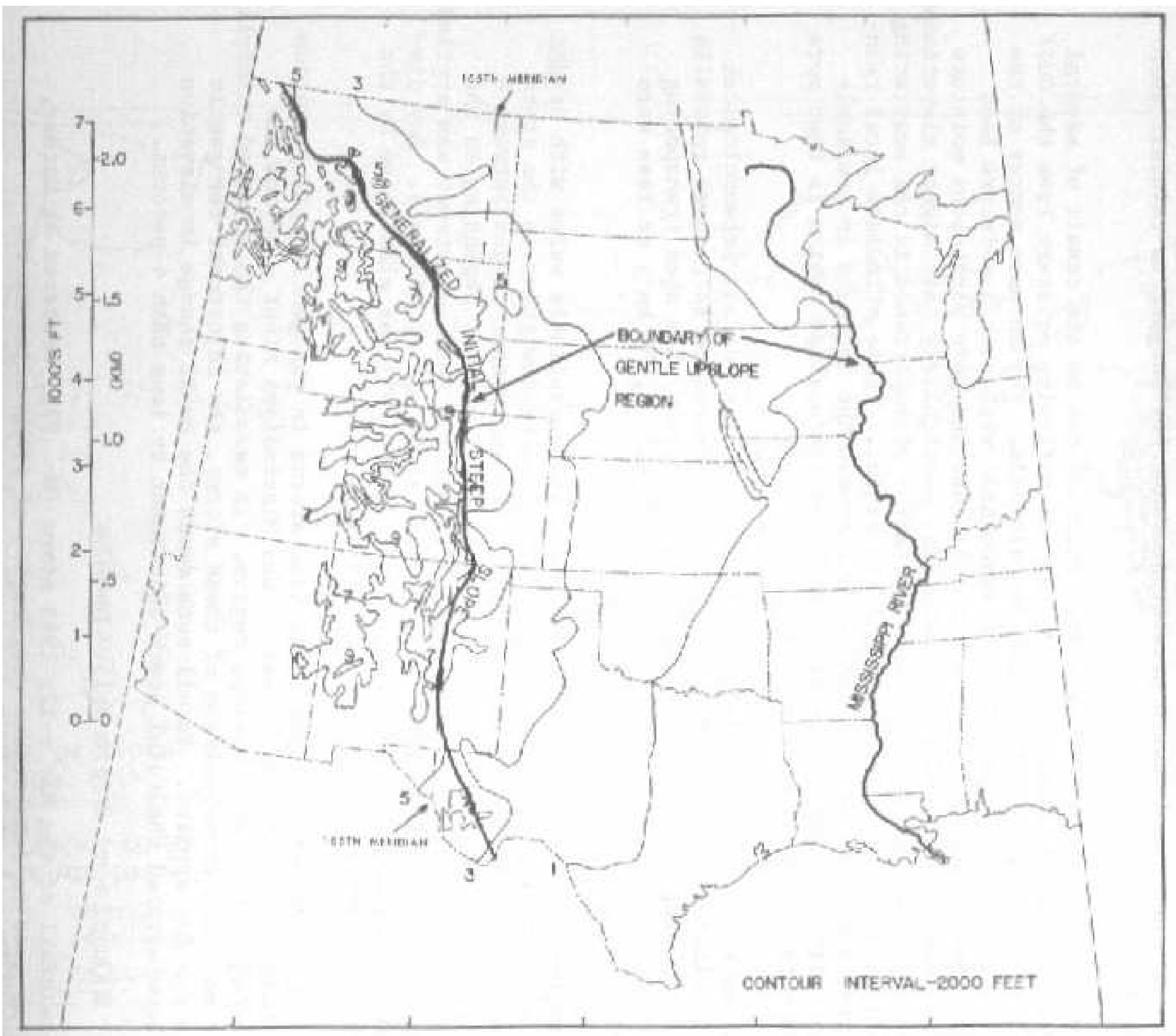


Figure I.1 The Gentle Upslope Region Identified in HMR 51, Figure 3

Important guidelines to storm transposition in HMR 51 that affect storms within and surrounding Nebraska are:

2.4.2 c. In regions of large elevation differences, transpositions were restricted to a narrow elevation band (usually within 1000 ft of the elevation of the storm)

2.4.2 e. Westward transposition limits of storms located in Central United States were related to elevation. This varied from storm-to-storm but in most cases the 3000- or 4000-ft contour.

2.4.6 This report did not apply an elevation adjustment when transposing storms within limited differences in elevation. However, in the gently rising terrain west of the Mississippi River to the generalized initial steep slopes in the western portion of the study region (fig 3) patterns of tentative PMP were not consistent with the patterns in the guidance material. The guidance material indicated a greater decrease in areal rainfall towards the west in the gentle upslope region….

Stratification of the rainfall by area size showed a decided trend toward greater decrease for large-area rainfall than for small….

With the evidence from rainfall data of various kinds and meteorological analyses within the gentle upslope region, we decreased large-area rainfalls when transposing to higher elevations and increased them when transposing to lower elevations. Storm depths for 1,000 mi^2 or less were not adjusted….

Any discontinuity introduced in PMP at 1,000 mi^2 was eliminated by the various consistency checks.

There are a number of major large-area storms in the gentle upslope region with limits of transposition east of the Mississippi River – beyond the boundaries of the gentle upslope region. In calculating the adjusted rainfall for the eastward transposition of these storms, the adjustment for gentle upslope was not applied.

What was explicitly done when transpositioning storms within the gentle upslope region i.e. how the elevation adjustments were computed and applied, and what consistency checks were used to modify storm data in HMR 51 is not known. However, the authors did recognize and tried to address what they described as a "decided trend toward greater decreases for large-area rainfall than for small" as storms were transpositioned towards the west. The discussion in HMR 51 also indicates that rainfall values were increased when transposing to lower elevations but only for area sizes larger than 1,000 mi^2. The approach taken to-date in the Nebraska PMP studies is 1) to use large transposition limits for all storms and 2) to apply the elevation adjustment for all area sizes and all durations throughout the gentle upslope region (which is more conservative than HMR 51). This approach does not address the "decided trend toward greater decreases for large-area rainfall than for small" identified in HMR 51.

A site-specific PMP study was completed in 2003 by Applied Weather Associates for the Cherry Creek drainage basin south of Denver, Colorado. The issue of differences in the spatial distribution of rainfall between eastern Colorado storms and Midwestern storms was also identified in that study. In particular, the same storm rainfall spatial distribution issue was identified and a conclusion consistent with the HMR 51 discussions was reached. That study concluded that although the storms in eastern Colorado and Midwestern storms have some similar characteristics, storms from the Midwestern states should not be transpositioned into Colorado because of significant differences in spatial rainfall distributions. Figure I.2 shows one of the plots developed in that study showing significant differences between Colorado storms and the 29 storms used in HMR 52 to develop the within storm rainfall distribution curves. Hence, the Cherry Creek study used only Colorado storms in its PMP analysis.

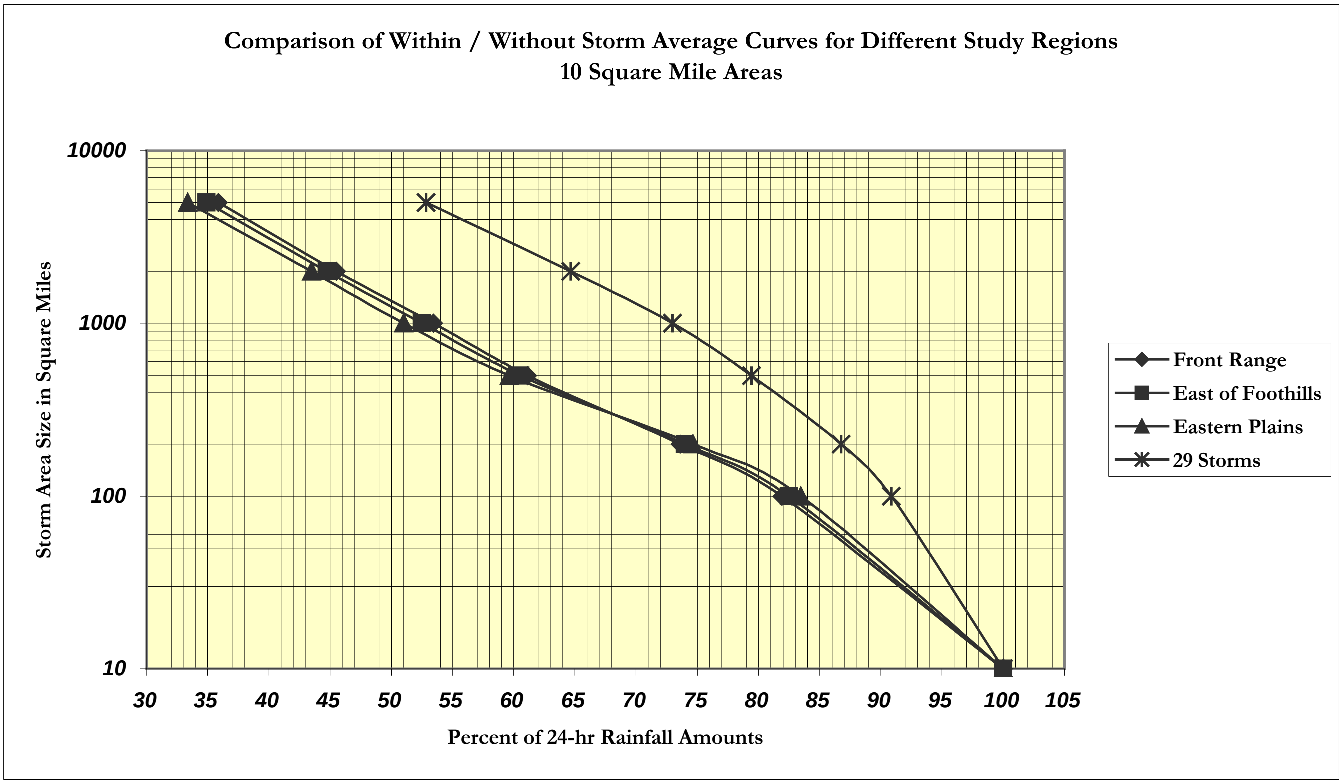


Figure I.2 Comparison of the Within Storm Rainfall for Colorado Storms with the 29 Storms used to Develop the Within Storm rainfall Curves in HMR 52

Both the site-specific Cherry Creek PMP study and HMR 51 recognized differences between High Plains storms and lower elevation Central Plains storms. However, the approaches taken to address these differences in storm transpositioning procedures varied. Since the Cherry Creek drainage is located at the western edge of the High Plains in Colorado, the site-specific Cherry Creek PMP study used only Colorado storms in the PMP analysis procedure i.e. used only storms with similar spatial rainfall distributions.

The approach taken in HMR 51 was to constrain the transposition limits of storms, often within regions with elevation that differs from the in-place storm elevation by 1,000 feet or less (HMR 51, Section 2.4.2.c). Westward transposition limits of storms located in the central United States were related to elevation. This varied from storm to storm but in most cases the 3,000- or 4,000- contours were used (HMR 51, Section 2.4.2.e). For transpositioning within these limits, the spatial distribution of storm rainfall was modified as storms were transpositioned to locations with differing elevations (HMR 51, Section 2.4.5). Discontinuities introduced by this modification were eliminated by "various consistency checks" (HMR 51, Section 2.4.5). Smoothing appears to be the primary tool used in applying the consistency checks (HMR 51, Section 3.3).

This procedure is unique to HMR 51 and has not been used in any other HMR or site-specific or regional PMP studies. Storms are transpositioned to regions where storms with similar characteristics have occurred. When adjustments are applied during the transpositioning process (moisture, elevation and/or barrier adjustments), the adjustments are applied at all durations and all area sizes. To selectively apply these adjustments warps the storms' temporal and/or spatial rainfall pattern, thereby creating a storm with different characteristics at the transpositioned location than it had at its in-place location.

AWA has plotted the rainfall distributions for the most significant High Plains storms and the most significant central and eastern Nebraska storms used in the PMP studies (Figure I.3-I.14). The High Plains storms included Ogallala, Pawnee Creek and Hale (AWA SPAS analysis). The central and eastern Nebraska storms include David City, Greeley and Stanton. These plots show the ratios of the rainfall for various area sizes compared to the rainfall at standard area sizes for the 6-hour and 24-hour duration periods.

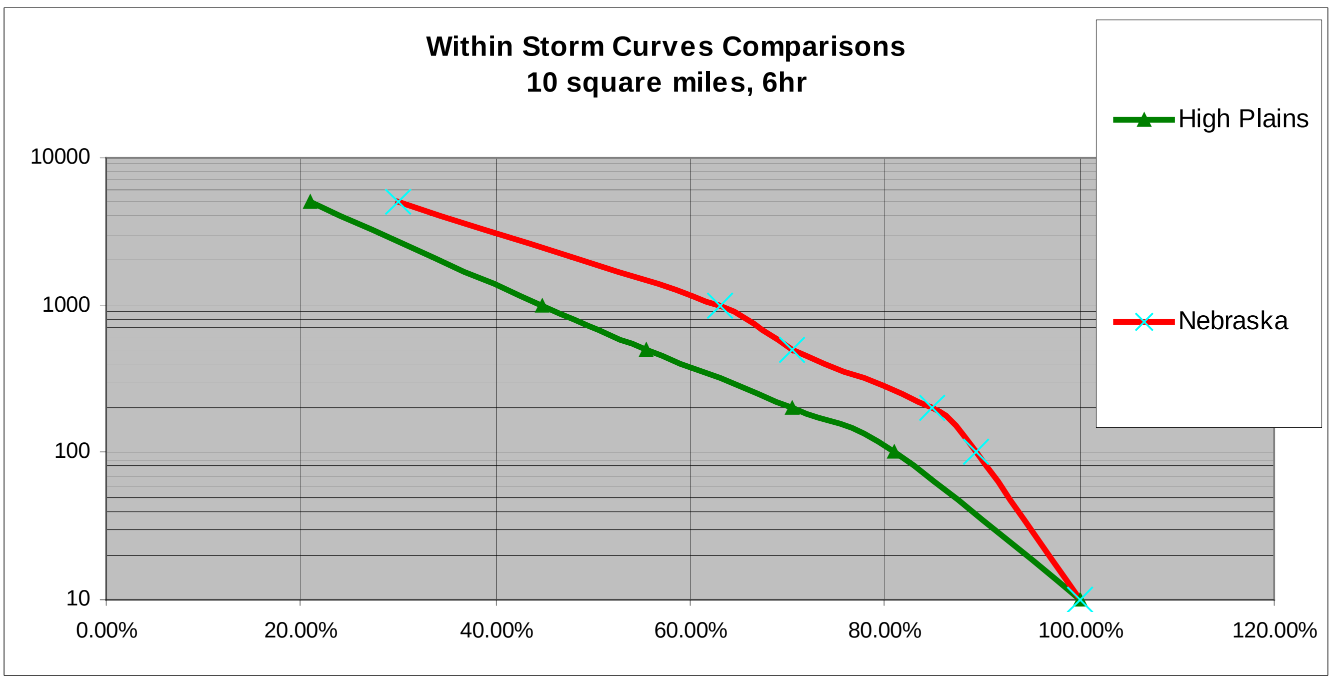


Figure I.3 Within Storm Comparisons to 10 Square Mile Area Size for the 6-hour Duration

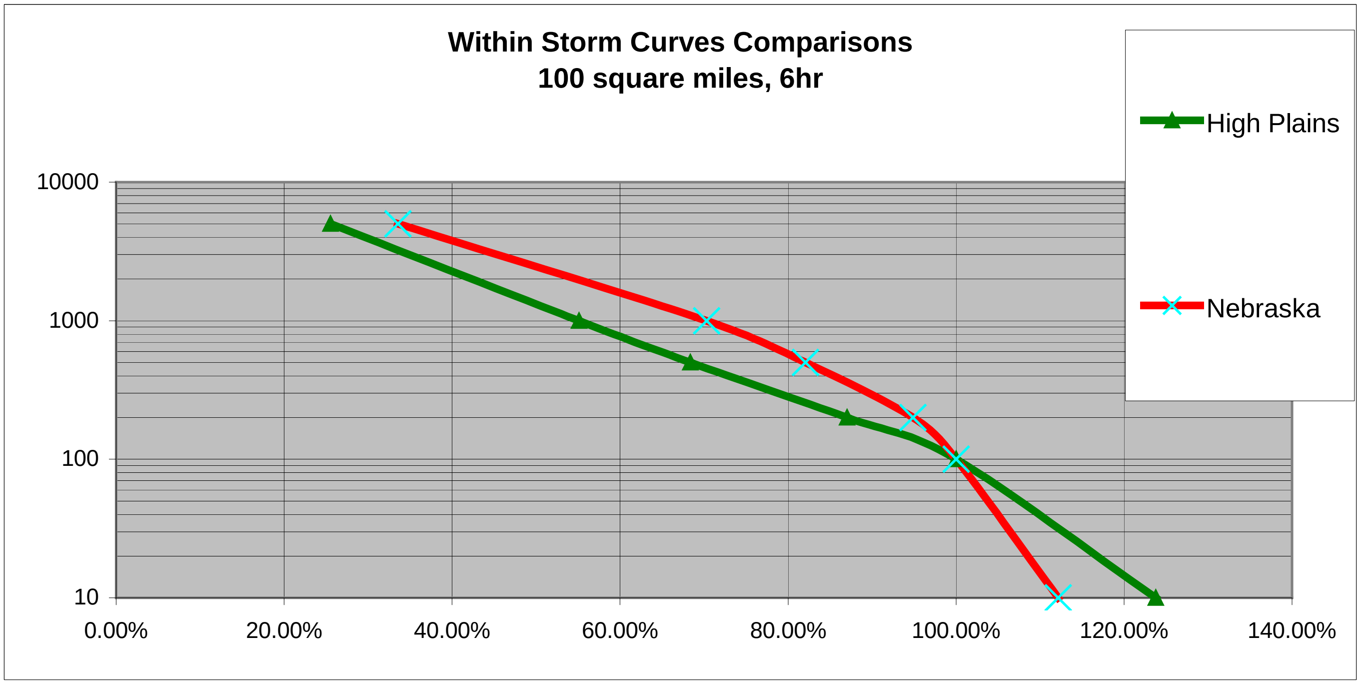


Figure I.4 Within Storm Comparisons to 100 Square Mile Area Size for the 6-hour Duration

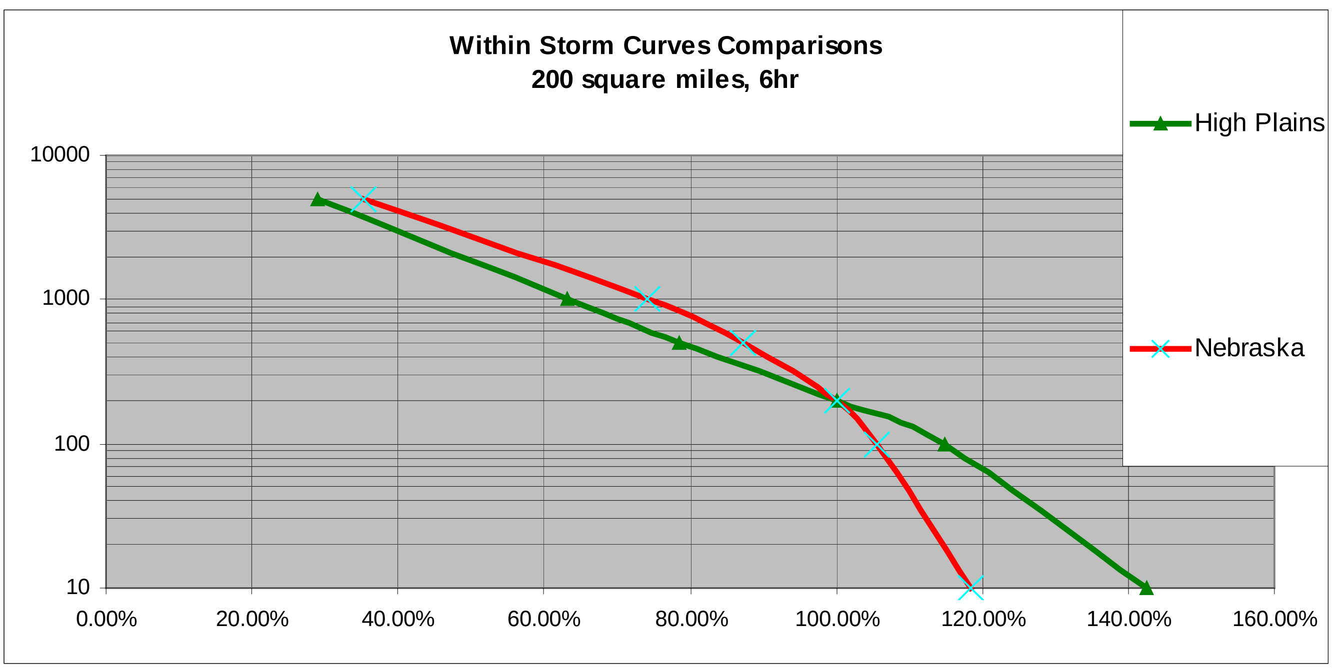


Figure I.5 Within Storm Comparisons to 200 Square Mile Area Size for the 6-hour Duration

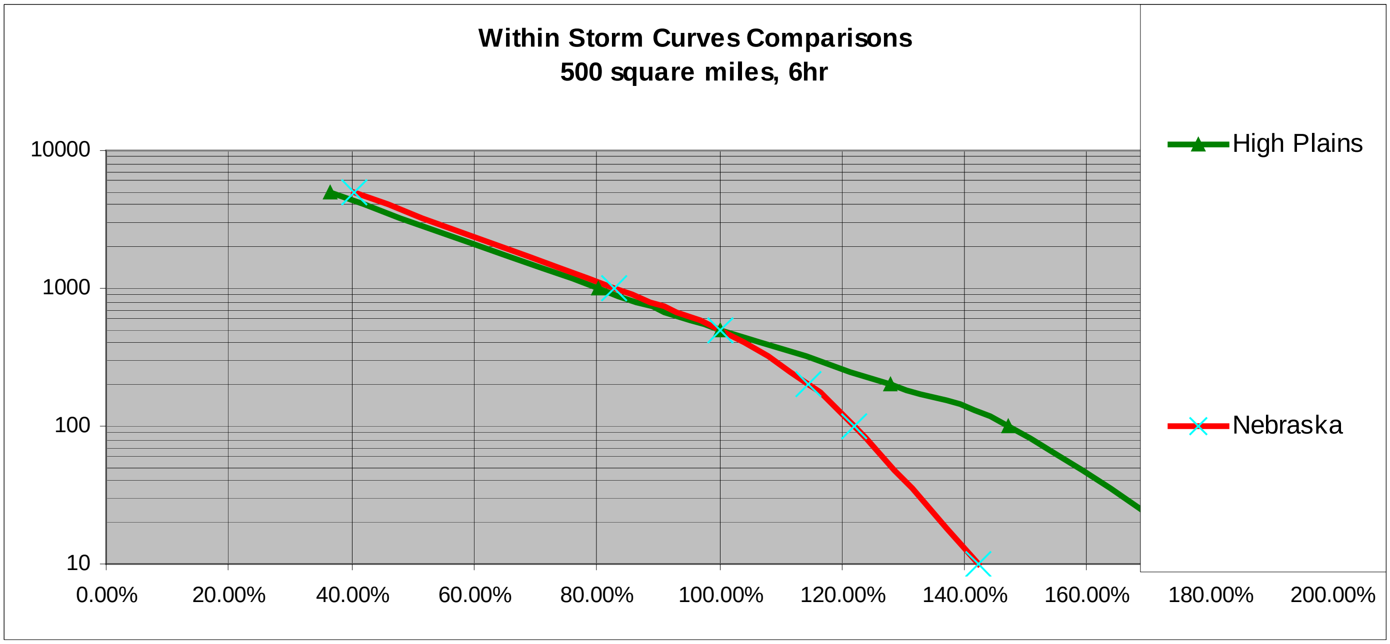


Figure I.6 Within Storm Comparisons to 500 Square Mile Area Size for the 6-hour Duration

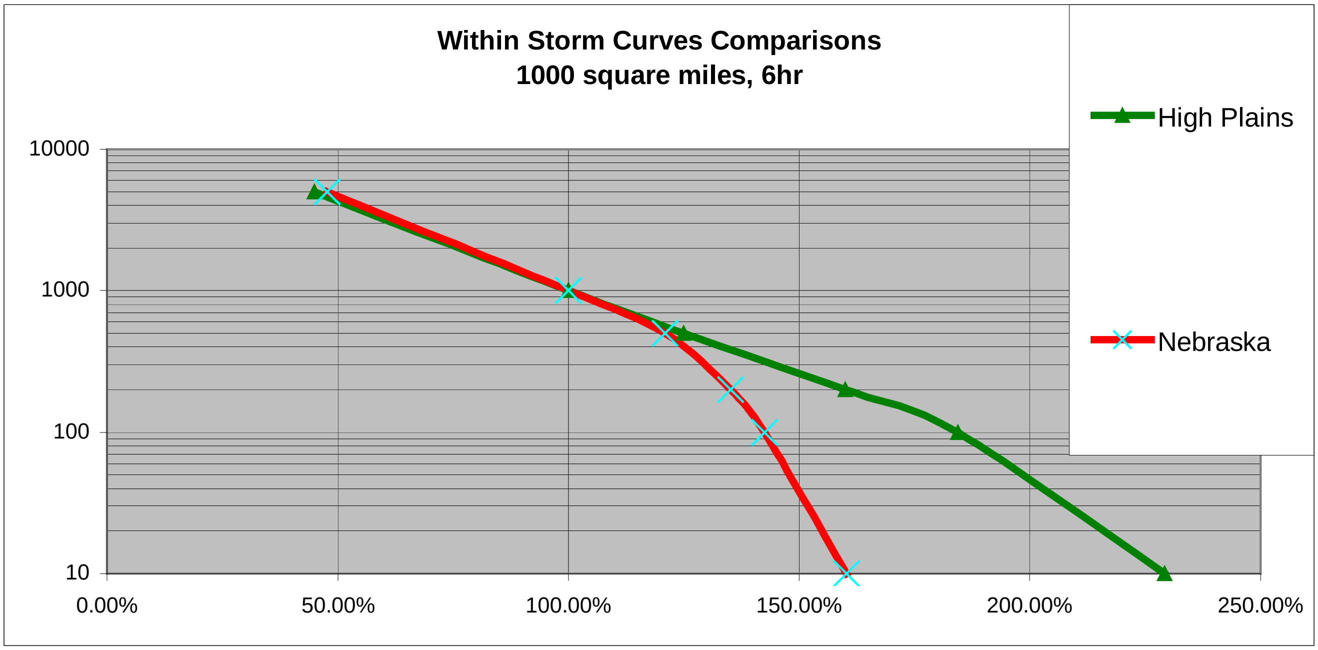


Figure I.7 Within Storm Comparisons to 1000 Square Mile Area Size for the 6-hour Duration

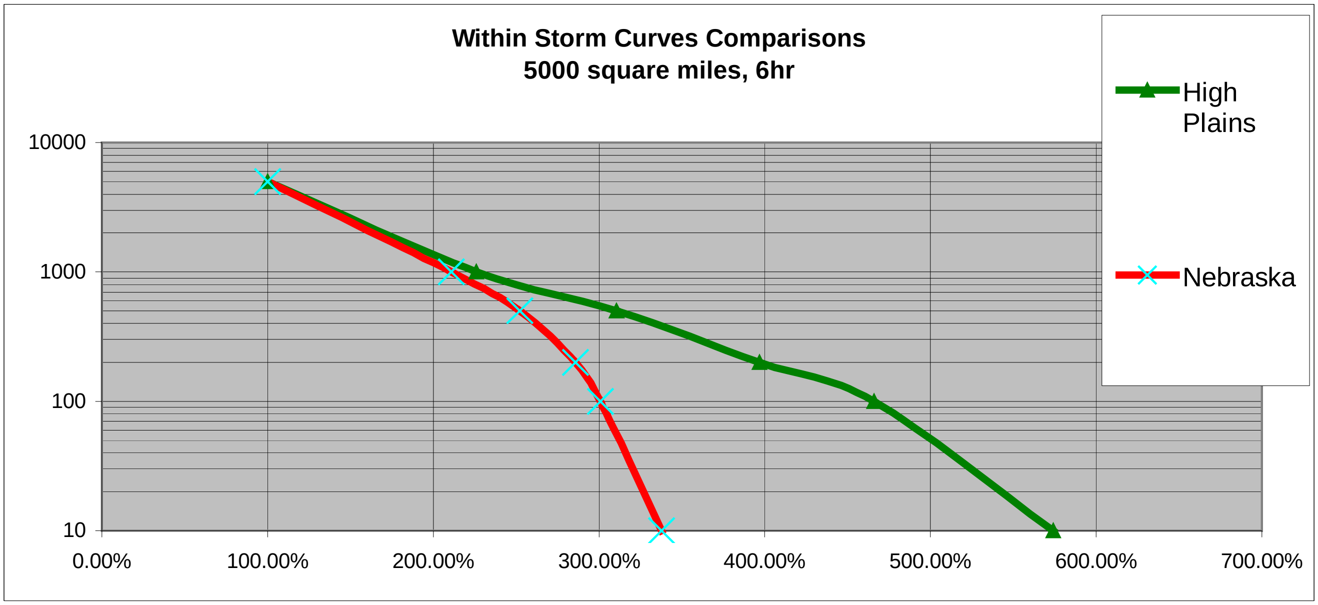


Figure I.8 Within Storm Comparisons to 5000 Square Mile Area Size for the 6-hour Duration

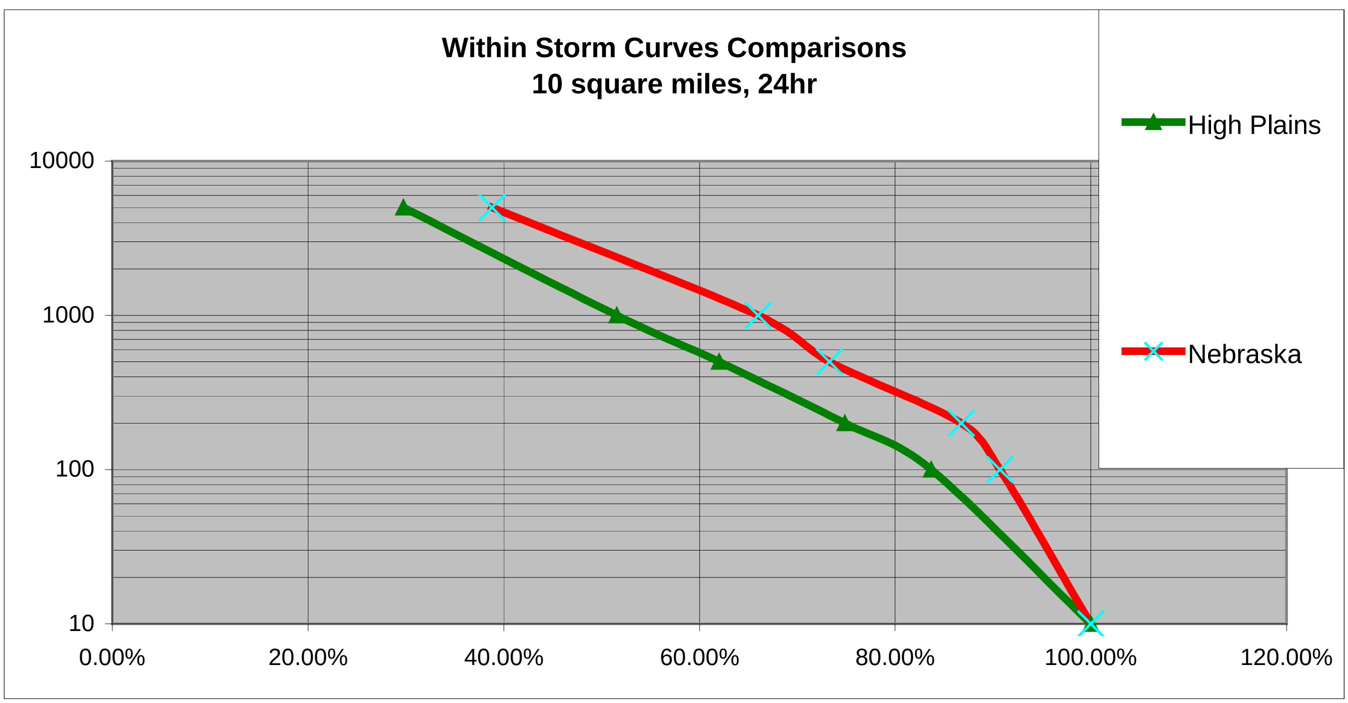


Figure I.9 Within Storm Comparisons to 10 Square Mile Area Size for the 24-hour Duration

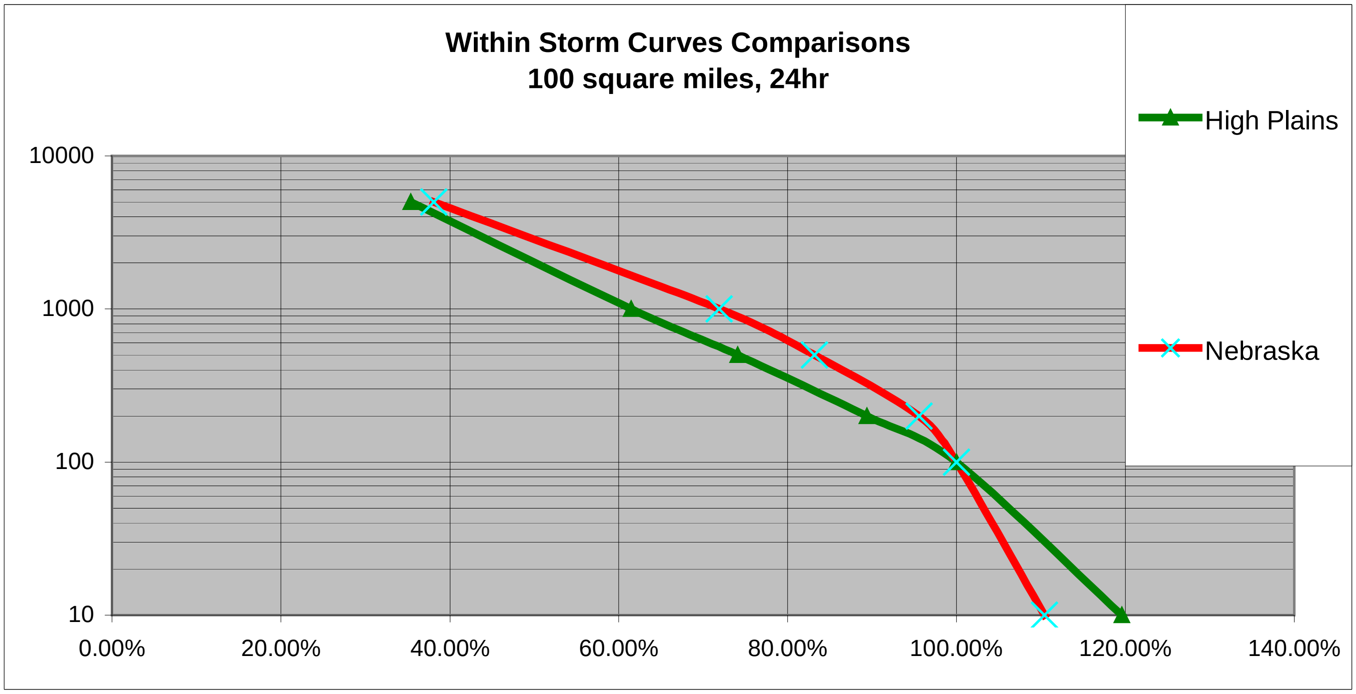


Figure I.10 Within Storm Comparisons to 100 Square Mile Area Size for the 24-hour Duration

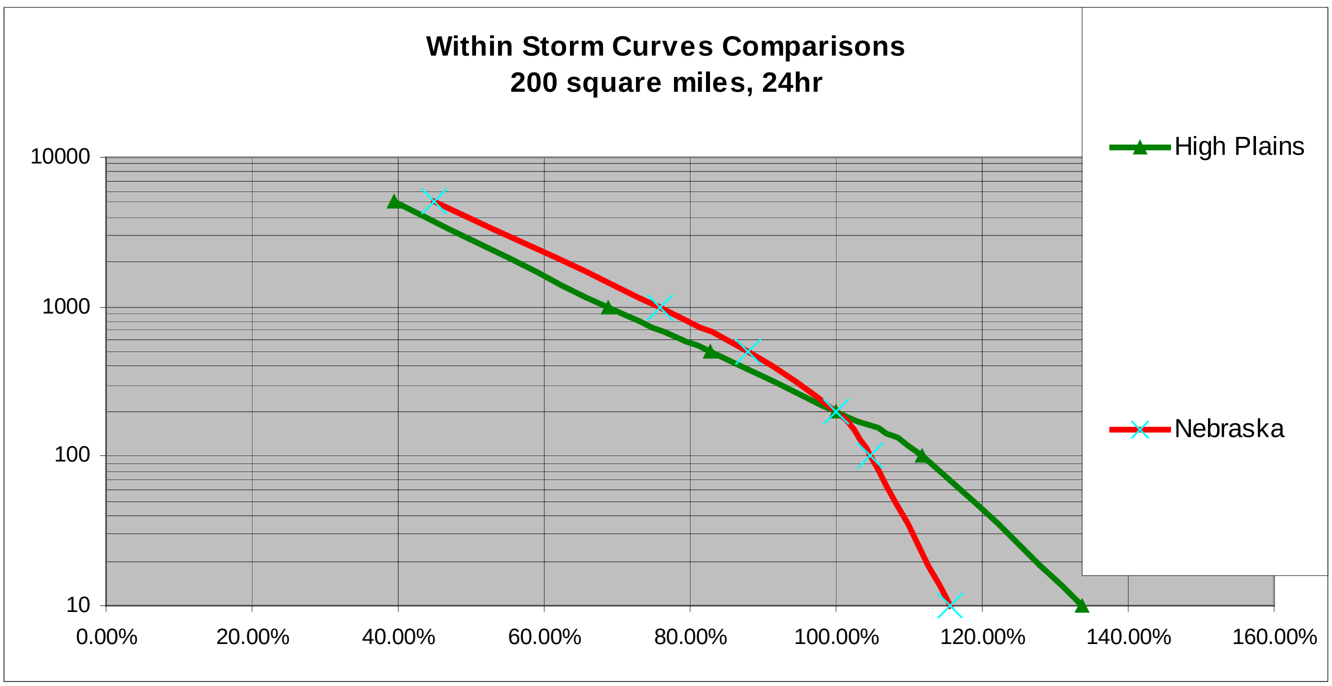


Figure I.11 Within Storm Comparisons to 200 Square Mile Area Size for the 24-hour Duration

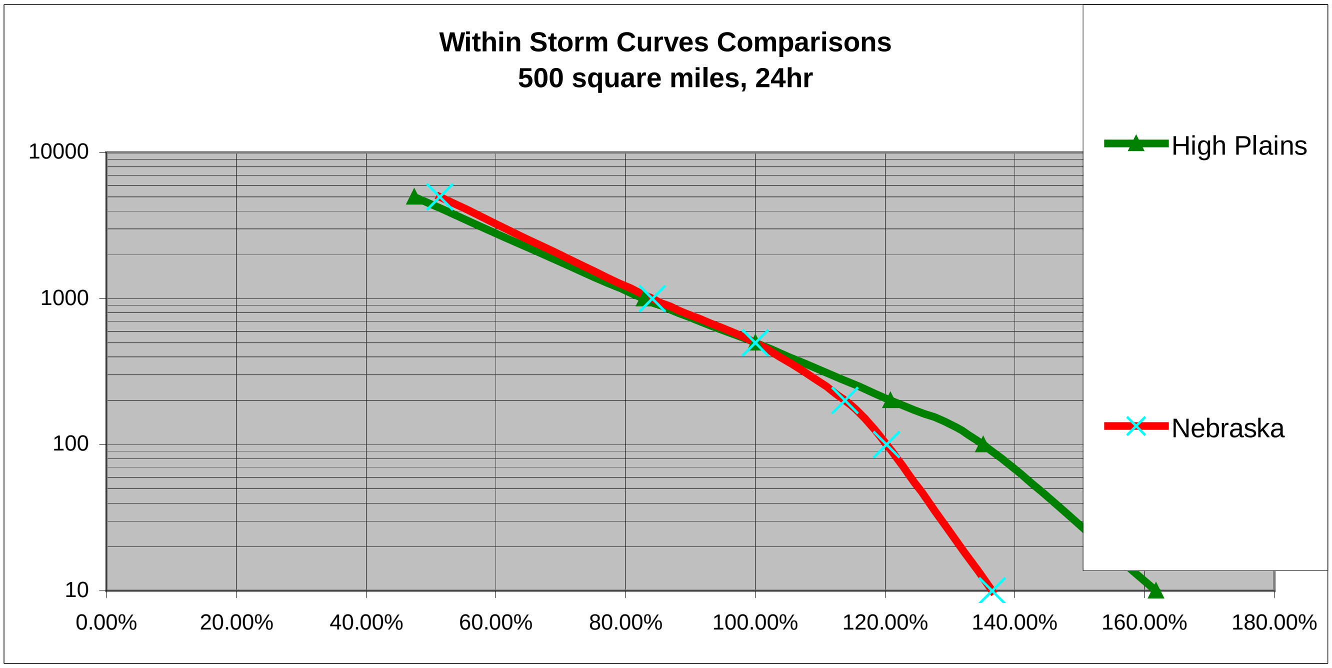


Figure I.12 Within Storm Comparisons to 500 Square Mile Area Size for the 24-hour Duration

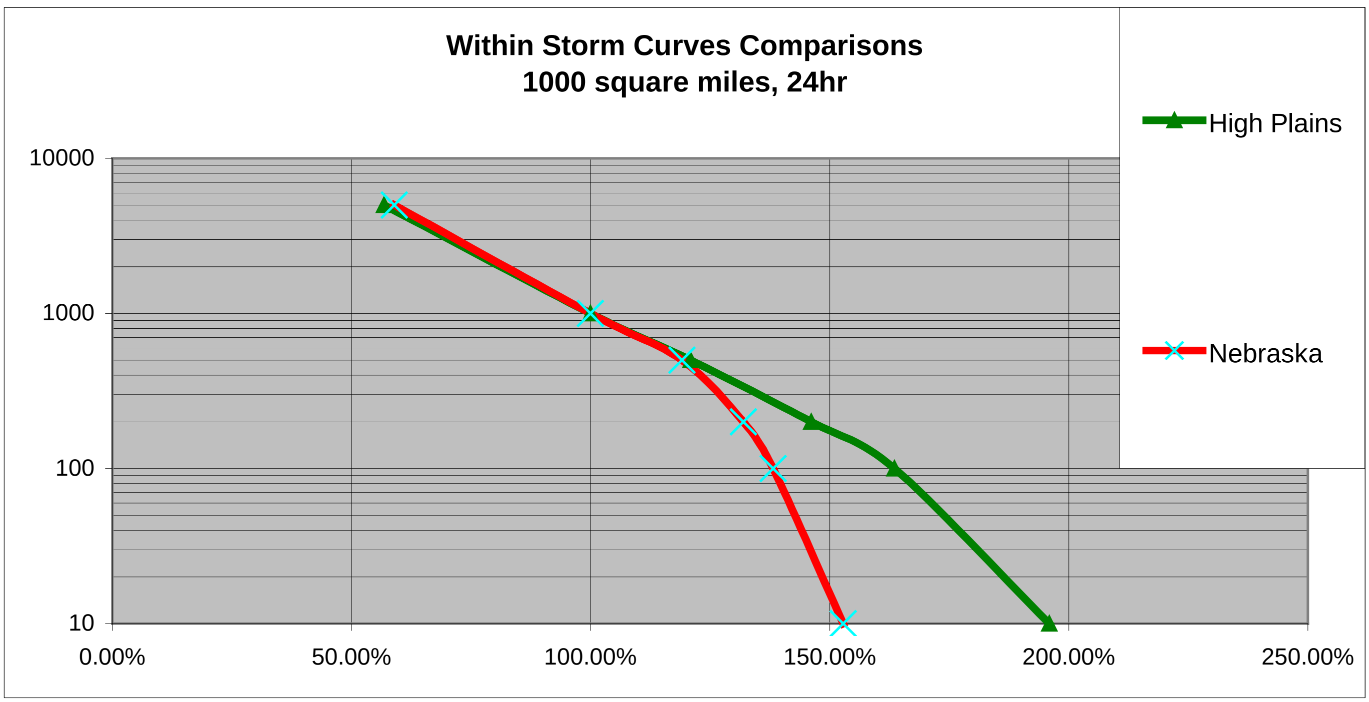


Figure I.13 Within Storm Comparisons to 1000 Square Mile Area Size for the 24-hour Duration

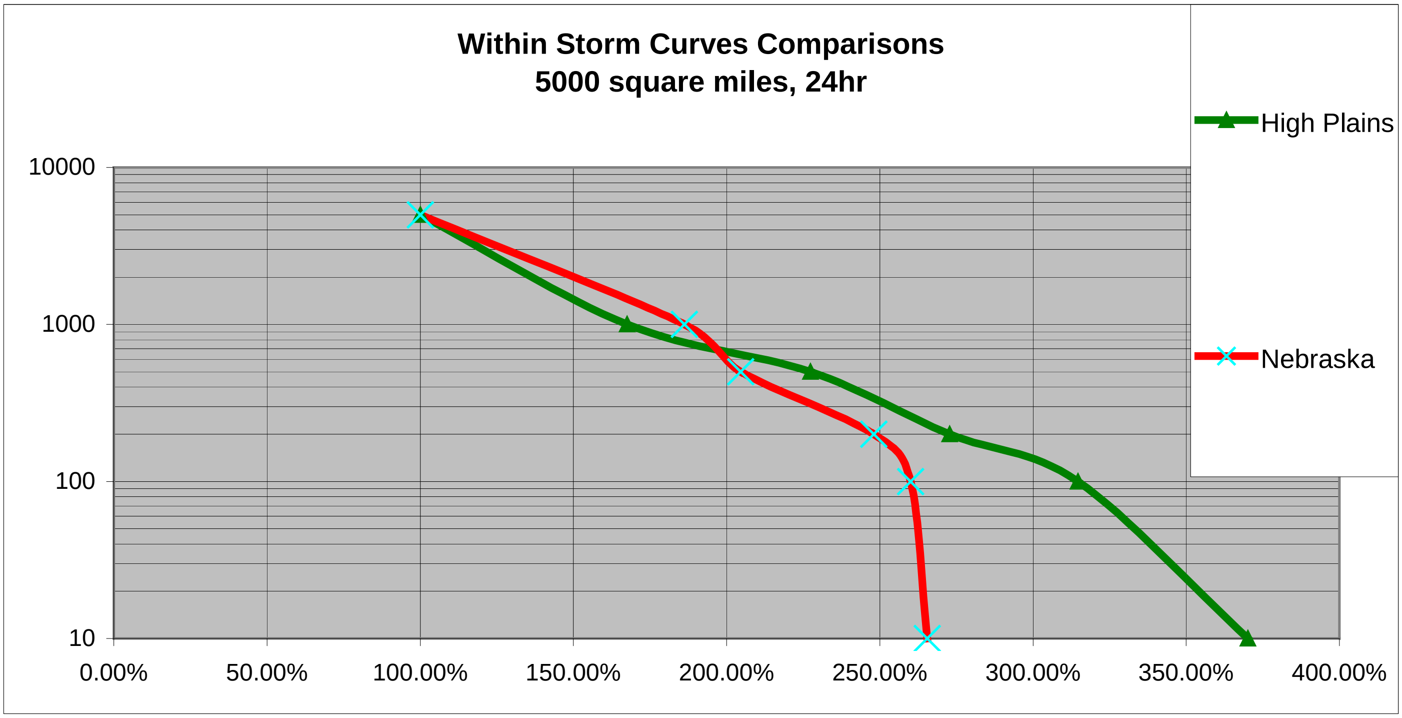


Figure I.14 Within Storm Comparisons to 5000 Square Mile Area Size for the 24-hour Duration

Figures I.3 through I.14 show differences between the spatial rainfall distributions of High Plains storms, and central and eastern Nebraska storms. The most dramatic differences appear for short durations and small area size comparisons (e.g. 10 square mile, 6-hour). For larger sizes the differences are less significant (e.g. 500 square miles, 24-hour).

Given these differences in spatial rainfall distributions, the issue of how to develop an appropriate storm transposition procedure becomes paramount. A procedure like the one used in the Cherry Creek site-specific PMP study is not reasonable since eastern Colorado storms are appropriate for western Nebraska transpositioning. A procedure similar to the one used in HMR 51 distorts a storm's spatial rainfall distribution into one that is not consistent with the storm's original characteristics. The WMO Manual for Estimation of PMP states that the within storm curves for a region should be patterned after actual storms that have occurred over the region and reflect actual storm rainfall distributions (WMO Manual, Section 2.13.6).

The WMO manual also discusses the importance of having an adequate storm sample for the development of PMP for a region (WMO Manual, Section 2.13.1). In general, if only a few storms are available for a region, transposition limits are extended to consider additional storms. The Nebraska statewide PMP study has a very large selection of storms for use in developing PMP values. Therefore, it is reasonable to ensure that all storms used for a region are as appropriate as possible since an inadequate storm database is not a problem for this study. To constrain storm transpositioning limits to areas that have observed storms with the same characteristics is not only reasonable but prudent.

Based on the above discussions, AWA revisited the storm transposition procedure for the Wanahoo site-specific PMP study. The NWS storm transposition limits discussed in HMR 51 have been reviewed in light of the above discussions. The transpositioning procedure should ensure an adequate storm database for each region while insuring to the maximum extent possible that storms are not transpositioned beyond appropriate limits.

As a result of this analysis, AWA constrained transpositioning to within +/-1,000 feet of the storm's in-place elevation and continued to use this limitation for the Nebraska statewide PMP study. This procedure constrains High Plains storms to approximately the western half of Nebraska while allowing lower elevation storms to influence PMP values over eastern and central Nebraska. This procedure, although not completely consistent with the NWS transposition limits will maintain some consistency with NWS limits that appear to have been used in HMR 51 while maintaining the integrity of the within storm rainfall distributions of individual storms.