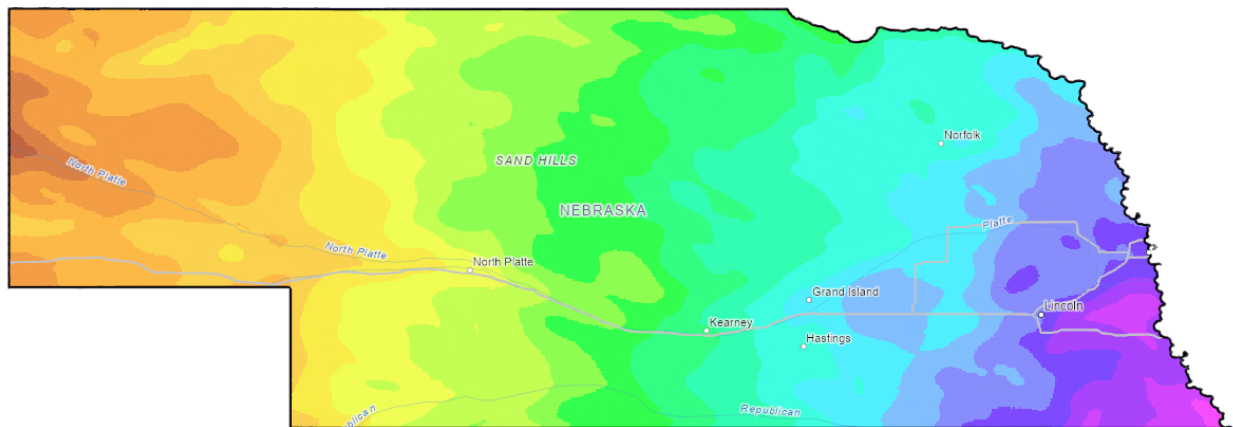


Annual Exceedance Probability Study for Nebraska Final Report

Prepared for:
Nebraska Department of Natural Resources, under subcontract to HDR



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Bill Kappel, President/Chief Meteorologist, Applied Weather Associates

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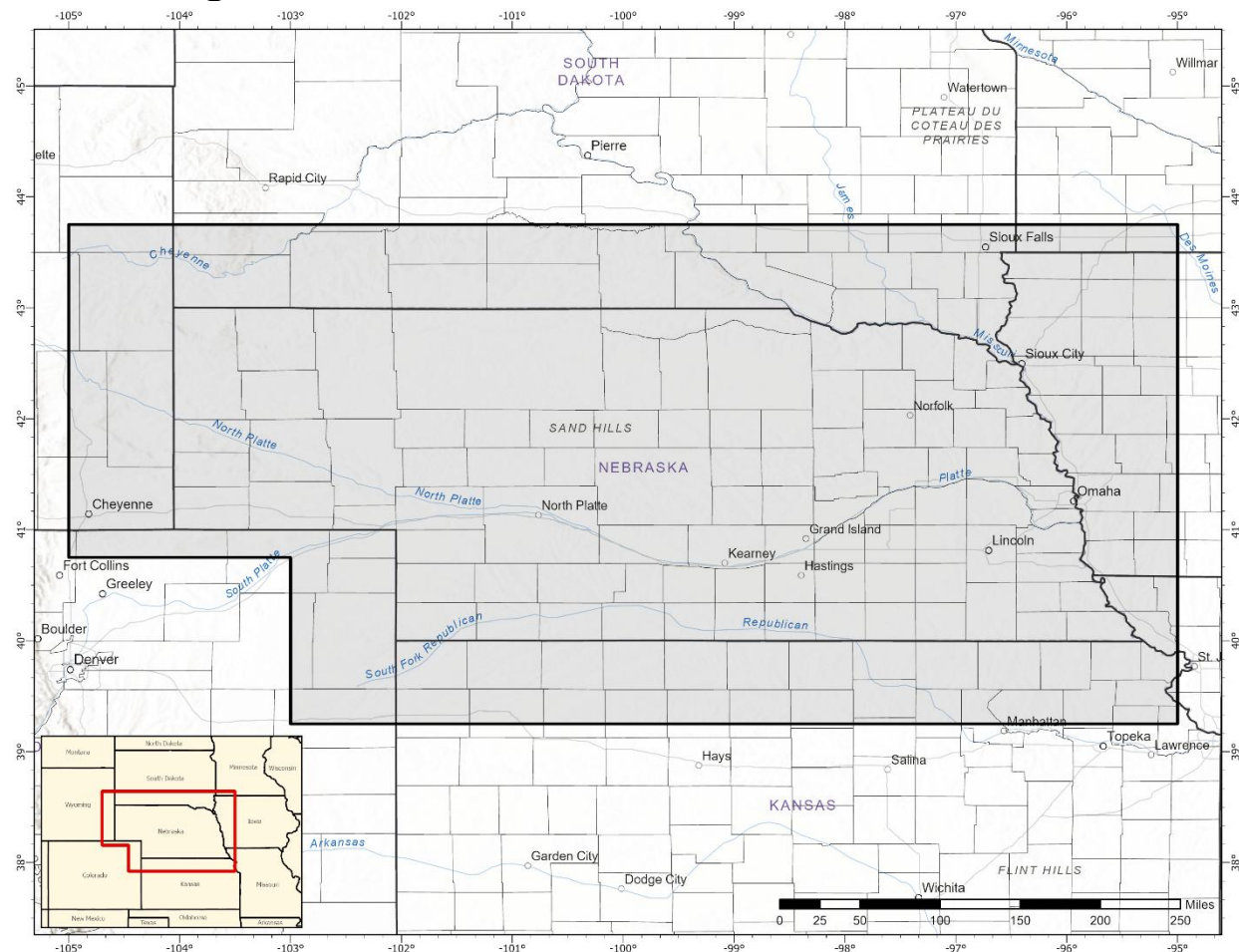


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Executive Summary

This report documents the methods and data utilized by Applied Weather Associates (AWA) to complete an in-depth study to assess precipitation frequency estimates and temporal precipitation distributions over the state of Nebraska and immediately surrounding regions. This is the same domain as covered by the Nebraska statewide Probable Maximum Precipitation (PMP) developed by AWA in 2008. This analysis targeted shifts in precipitation frequency and maximum rainfall events over 1-hour, 6-hour, 24-hour, and 72-hour durations and recurrence intervals from 10^{-1} to 10^{-10} to enhance understanding of potential impacts on water resources, infrastructure resilience, and planning which are affected by rainfall accumulation patterns and variability.

AWA analyzed precipitation-frequency relationships to derive the 1-hour, 6-hour, 24-hour, and 72-hour annual exceedance probability (AEP) based on annual maximum series (AMS) methods. The analysis was based on regional L-moments methodology. L-moment statistics tend to decrease the uncertainty of rainfall frequency estimates for more rare events and dampens the influence of outlier precipitation amounts from extreme storms (Hosking and Wallis, 1997). The basis of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites. Key steps in the regional precipitation-frequency analysis included: i) extraction and quality control (QC) of annual maximum data, ii) calculation of an areal reduction factor used to relate point precipitation to areal/basin precipitation, iii) determination of homogeneous regions, iv) calculation of goodness-of-fit measurements, v) calculation of regional frequency curves, vi) estimation of the at-site mean (scaling factor) at any location in a region, and vii) derivation of uncertainly bounds.

Examples of the results of the 1-hour, 6-hour 100-year, 24-hour 100-year, and 72-hour 100-year analysis are presented in Figure E.1 to Figure E.4. The updated analysis incorporates a significantly larger dataset both in the number of stations used and the period of record applied within the Nebraska region as compared to NOAA Atlas 14. This approach provides a better fit to the study data compared to NOAA Atlas 14 outputs. The use of cluster analysis and spatial modeling of L-moment statistics (MAM, Lcv, and Lsk) enables a more data-driven and flexible regionalization process. It adapts to localized precipitation patterns and variations in station density, resulting in more precise and representative frequency estimates. Additionally, the probability distributions were carefully selected based on their alignment with observed data, ensuring improved accuracy and reliability of the final frequency estimates.

The accuracy of precipitation frequency estimates becomes increasingly uncertain at extremely low AEPs (e.g., 1 in 10 million or 10^{-10}). AWA precipitation frequency development includes quantification of uncertainty; the amount of uncertainty increases as AEPs become rarer and represent our best statistical estimates. We acknowledge that the true estimate and error associated with such rare events is unknown and cannot be reliably quantified with current data and methods. Beyond the 10,000-year return period, estimates should be interpreted with caution, as they represent extrapolations far beyond the period of observational record (last 100-years). These results are best viewed as indicative, and we recommend revisiting and refining them as new data and methodologies become available.

The second component of this analysis was to evaluate precipitation temporal patterns for the 1-hour, 6-hour, 24-hour, and 72-hour durations that can be applied to the AEP gridded data. AWA utilized the Huff Curve Method, along with synthetic and controlling storm patterns used in the PMP development for the state of Nebraska. The Huff methodology is a widely used approach for representing the temporal distribution of rainfall within a storm event, particularly in the context of PMP and design storm studies. Developed by Huff (1967), the method is based on statistical analysis of numerous observed storm events to determine average temporal rainfall patterns. These curves provide a probabilistic, dimensionless representation of accumulated rainfall depth versus accumulated storm duration. Synthetic storm patterns were developed based on AWA's experience with regional storm types and durations. In addition, controlling storm patterns, those that represent the most critical PMP distributions for a given duration, were identified and included. In total, 26 temporal patterns were developed as part of this study (Figure E.5). Each of these were evaluated to determine the most critical, or 'recommended', pattern for each duration. The remaining applicable patterns were provided as 'alternative' distributions.

The third component of this analysis involved the development of a GIS-based AEP Tool to provide an interface to access the outputs for hydrologic analysis. This tool incorporates the 1-hour, 6-hour, 24-hour, and 72-hour AEP gridded datasets, corresponding Areal Reduction Factors (ARFs), and the 26 temporal rainfall patterns developed for this study. The tool enables users to efficiently compute point or basin-average precipitation frequency estimates, AEP of PMP, and generate temporal distribution outputs.

To accommodate different user needs and software environments, two independent GIS tools were developed:

- A web-based application, which provides point or basin-average precipitation frequency estimates via a standard web browser, without the need for ArcGIS software.
- A desktop GIS tool designed for use within the ArcGIS Pro environment, offering enhanced GIS analysis capabilities, including gridded computations.

Both tools use the same underlying datasets and computational algorithms to ensure consistency and reliability of results across platforms.

Nebraska Statewide Annual Exceedance Probability Study

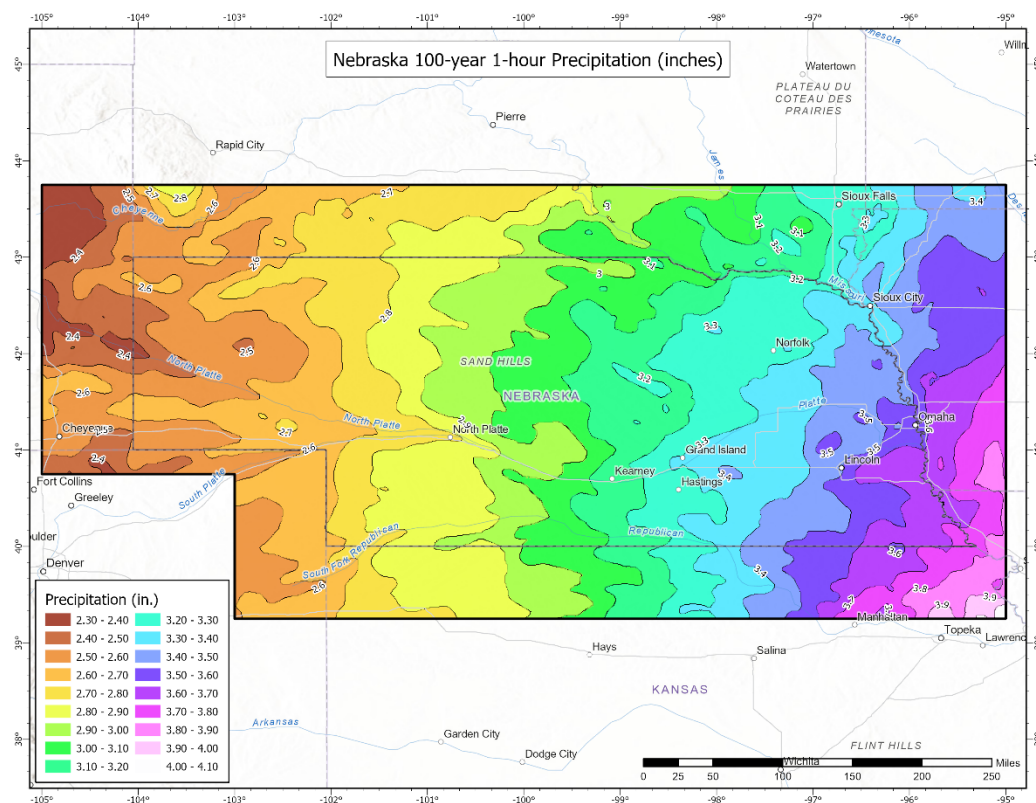


Figure E.1: Nebraska 1-hour 100-year frequency analysis

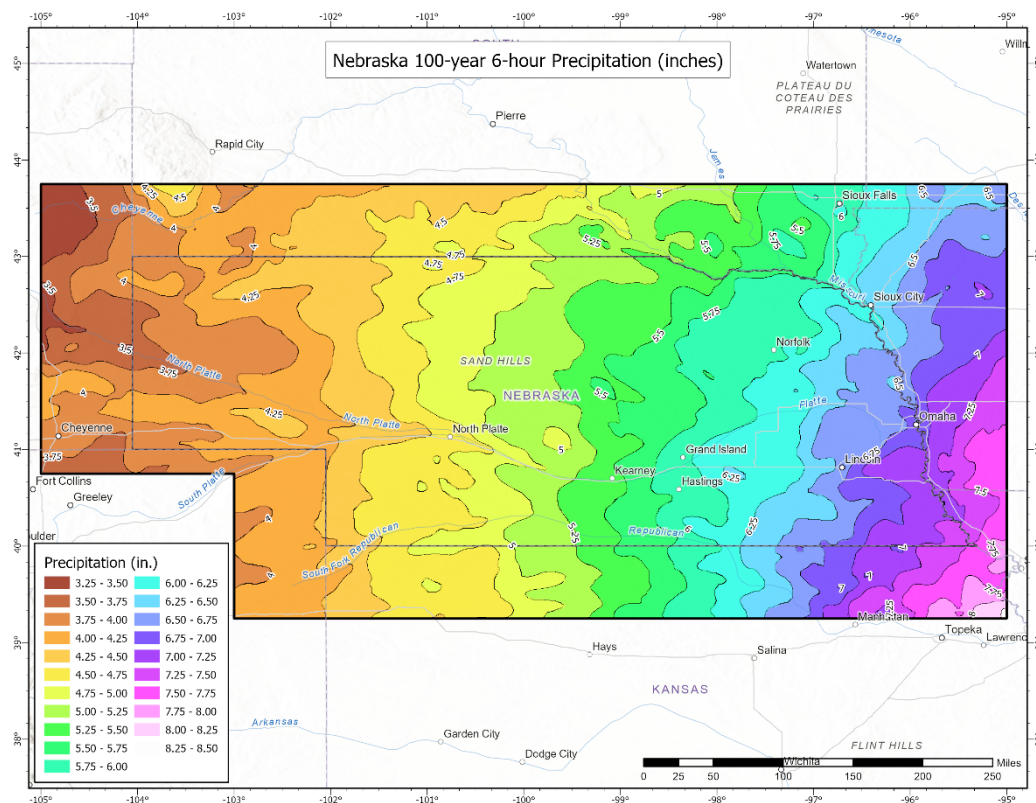


Figure E.2: Nebraska 6-hour 100-year frequency analysis



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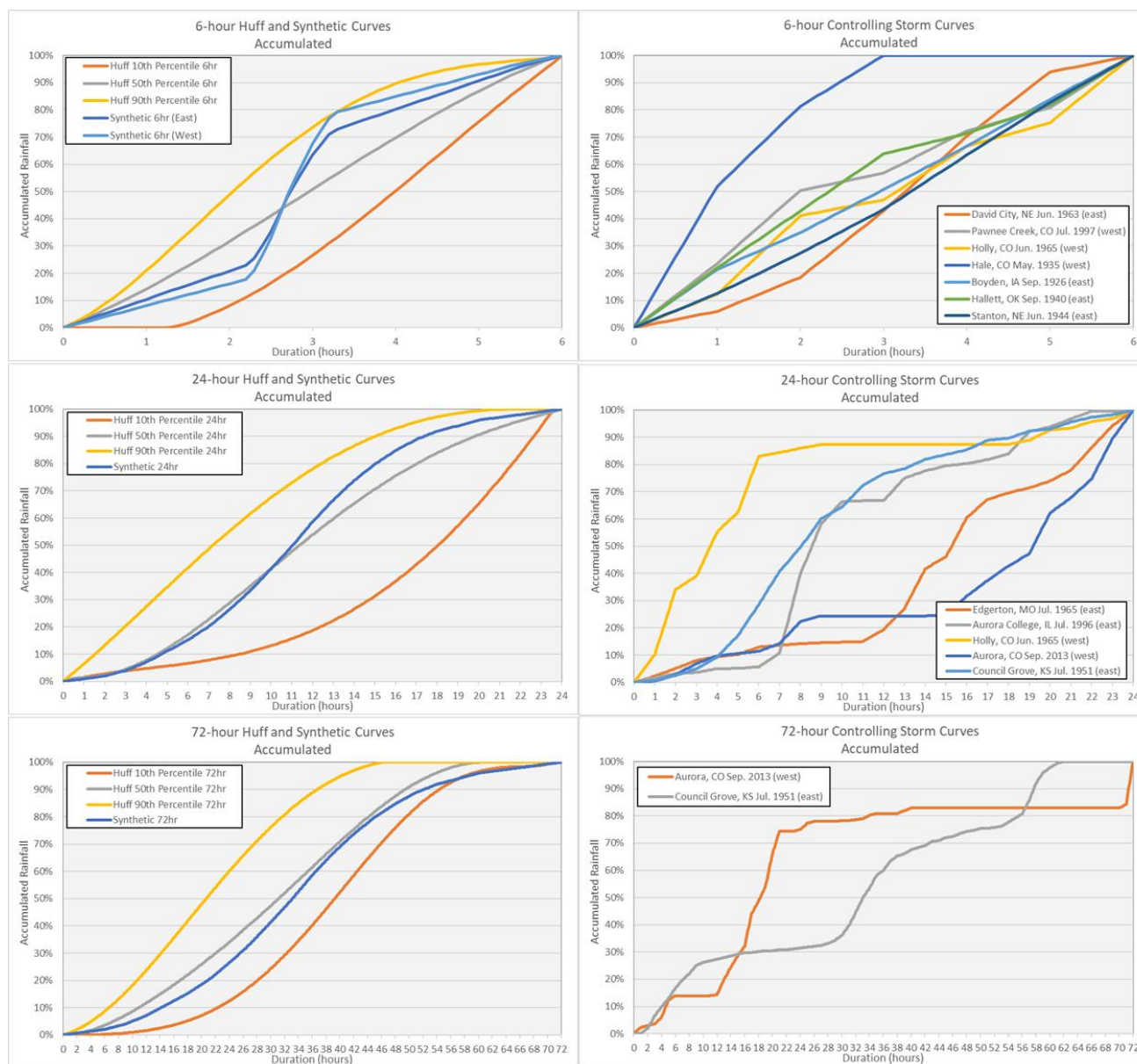


Figure E.5: Nebraska temporal patterns developed as part of this study for the 6-hour, 24-hour, and 72-hour durations

Glossary

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

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

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

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

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

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

Depth-Duration curve: Curve showing, for a given area size, the relation of maximum average depth of precipitation to duration periods within a storm or storms.
National Weather Service and records observations on a continuous basis.

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

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

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

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

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

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

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

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

Acronyms and Abbreviations

AEP	Annual Exceedance Probability
AMS	Annual Maximum Series
ARF	Areal Reduction Factor
ARI	Average Recurrence Interval
AWA	Applied Weather Associates
CDF	Cumulative Distribution Function
GEV	Generalized Extreme Value distribution
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GLO	Generalized Logistic distribution
GNO	Generalized Normal distribution
GPA	Generalized Pareto distribution
L-Cv	L-moment coefficient of L-variation
L-Kurtosis	L-moment ratio of kurtosis
L-Skewness	L-moment ratio of skewness
MAM	Mean Annual Maximum
MAP	Mean Annual Precipitation
NCDC	National Climate Data Center
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PE3	Pearson Type III distribution
PF	Precipitation-Frequency
POR	Period of Record
Ppt	Precipitation
PMP	Probable Maximum Precipitation
PRISM	Parameter-elevation Regressions on Independent Slopes Model
QC	Quality Control
RAWS	Remote Automated Weather Stations
RGC	Regional Growth Curve
SPAS	Storm Precipitation and Analysis System

1. Study Development Overview

This study provides Annual Exceedance Probability (AEP) depths and associated temporal patterns for the state of Nebraska. AEP were derived for the 1-hour, 6-hour, 24-hour, and 72-hour durations over the same analysis domain as the Probable Maximum Precipitation (PMP) study developed by Applied Weather Associates (AWA) in 2008 (Tomlinson et al., 2008). These produced probability estimates that extend to 10^{-10} and provide valuable information related to the probability of the deterministic PMP and many other risk-based processes.

A regional L moments process was applied to develop the AEP for the overall domain. Moments are a numerical description of the shape of a dataset, and two types of moments are frequently used for this purpose. The first is the more common product moments and the other is linear moments or L-moments. Both product moments and L-moments describe various shape properties of a dataset or model, the difference between the two methods is that product moments give equal weights to transformations of observations and L-moments give unequal weights to order statistics of observations based on the rank of the observation. Functionally, the difference is that L-moments give less weight to extreme observations. They are sometimes thought to be a more robust alternative to product moments, especially for higher-order moments (e.g., skew and kurtosis).

The regional frequency analysis approach applied in this study utilizes L-moment statistics instead of product moment statistics, which decreases the uncertainty of rainfall frequency estimates for more rare events and dampens the influence of outlier precipitation amounts from extreme storms (Hosking and Wallis, 1997). The basis of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites. Key steps in the regional precipitation-frequency analysis included: i) extraction and quality control (QC) of annual maximum data, ii) calculation of an areal reduction factor used to relate point precipitation to areal/basin precipitation, iii) determination of homogeneous regions, iv) calculation of goodness-of-fit measurements, v) calculation of regional frequency curves, vi) estimation of the at-site mean (scaling factor) at any location in a region, and vii) derivation of uncertainly bounds.

The analysis domain includes the entire state plus a buffer around the state (Figure 1.1), this is the same domain that is used in the 2008 PMP study. The portion of the buffer over Colorado south of 40.75° N is excluded as the topography of Colorado's Eastern Slope influences precipitation in this region.

Nebraska Statewide Annual Exceedance Probability Study

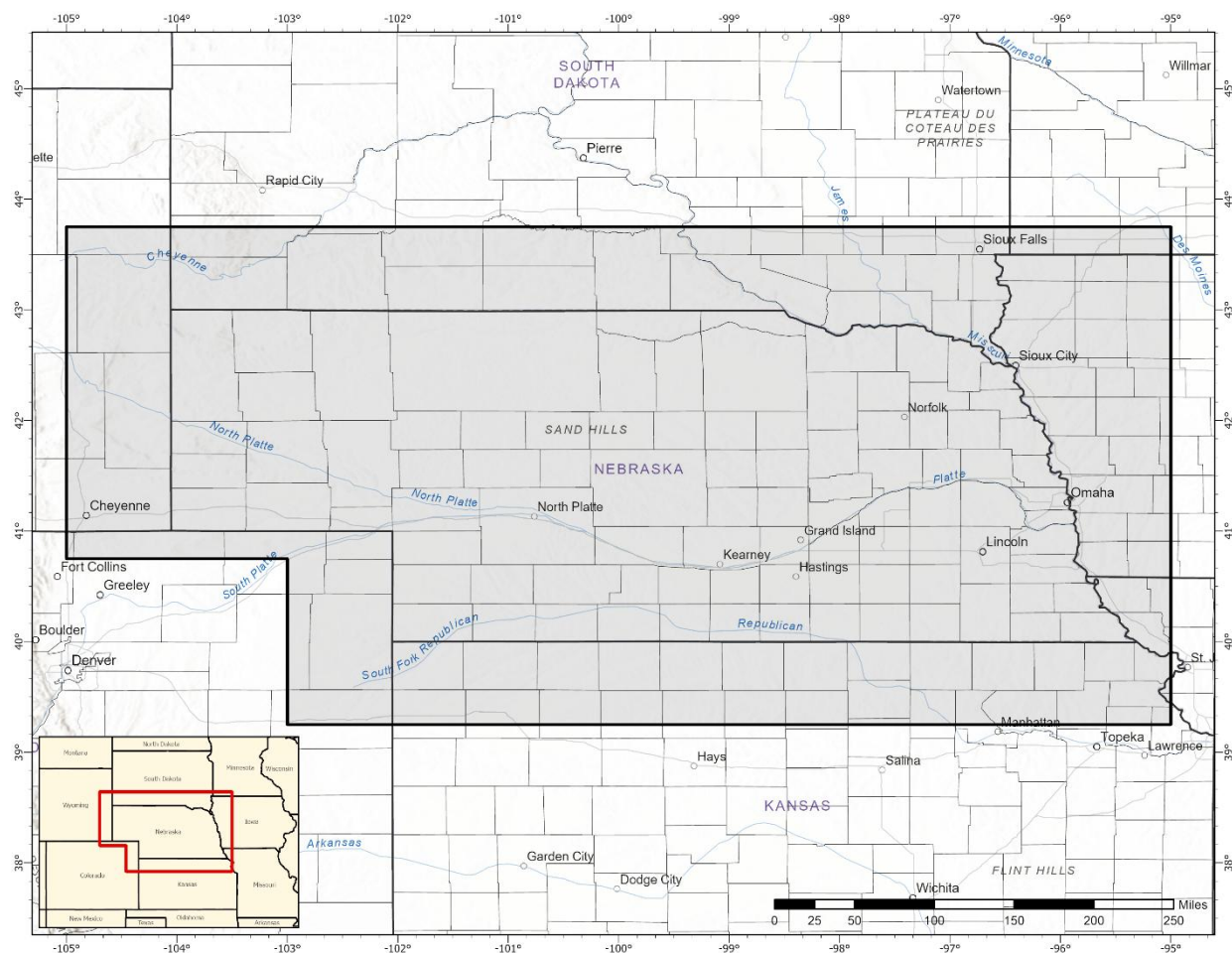


Figure 1.1: Annual Exceedance Probability study domain

2. Annual Exceedance Probability Analysis of PMP Depths

AWA analyzed precipitation-frequency relationships to derive the Annual Exceedance Probability (AEP) for the 6-, 24-, and 72-hour durations, covering the same statewide domain as the PMP depths developed in 2008 (Tomlinson et al., 2008). The development of AEP outputs was based on a regional L-moment analysis following the methods described by Hosking and Wallis (1997). This analysis was conducted using the R statistical software packages *lmom* and *lmomRFA*, both developed by Hosking (Hosking 2015a, 2015b).

2.1 Regional Frequency Analysis

A regional frequency analysis approach utilizes L-moment statistics instead of product moment statistics, which decreases the uncertainty of rainfall frequency estimates for more rare events and dampens the influence of outlier precipitation amounts from extreme storms (Hosking and Wallis, 1997). This analysis follows methodologies similar to those used in NOAA Atlas 14 Volume 6 (Perica et al., 2013), which was based on regional L-moment statistics and goodness-of-fit evaluations—an approach comparable to the one used in this analysis. For the upcoming NOAA Atlas 15 precipitation frequency update, the overall methodology is expected to resemble the structure of this study but will utilize maximum likelihood estimation (MLE) instead of L-moments, as MLE is more compatible with Bayesian modeling approaches used in climate to account for climate change (Perica et al., 2024). The basis of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites. A homogeneous region may be a geographic area delineated by meteorological climatologies or may be a collection of sites having similar characteristics pertinent to the phenomenon being investigated. The data and methods used are listed in the following sub-sections.

2.2 Precipitation Data and Annual Maximum Series Data

A search to identify individual stations in the region was conducted using precipitation data sources from official National Weather Service (NWS) stations, Remote Automated Weather Stations (RAWS), CoCoRaHS, and USGS stations. Each station's period of record (POR) was evaluated to determine which stations were appropriate for use in the final regional analysis. CoCoRaHS station data was extracted but utilized for AMS extraction due to limitations with consistent observations (time and duration) which would make it difficult to incorporate in the statistical analysis.

The term “annual maximum” refers to the single largest 1-, 6-, 24-, and 72-hour precipitation event being selected for each precipitation gauge for each year of record. Several procedures were required for assembly of the precipitation annual maximum series (AMS) dataset. The Partial Duration Series (PDS) includes all data points that exceed a predefined “threshold” within the entire time period. The threshold is chosen based on analysis of data and magnitudes, usually a certain percentile of the maximum values to identify significant extreme events. The AMS and PDS are two methods used for analyzing extreme events. AMS uses the single highest value from each year, while PDS considers all independent values above a certain threshold. PDS can capture more extreme events, especially in years with multiple significant events, whereas AMS might miss these if they do not exceed the annual maximum. The

differences between the values estimated using AMS and PDS methods decrease as the recurrence interval becomes more rare, meaning they tend to converge. The convergence occurs around 20- to 25-year return periods, both methods produce similar results for less frequent (more extreme events). The PDS yields higher values for a given frequency than AMS for more frequent events (e.g., 2-year, 5-year, 10-year return periods). Figure 2.1 displays an example for the PDS (red line and triangles) and AMS (blue line and circles) for the Expo Park station.

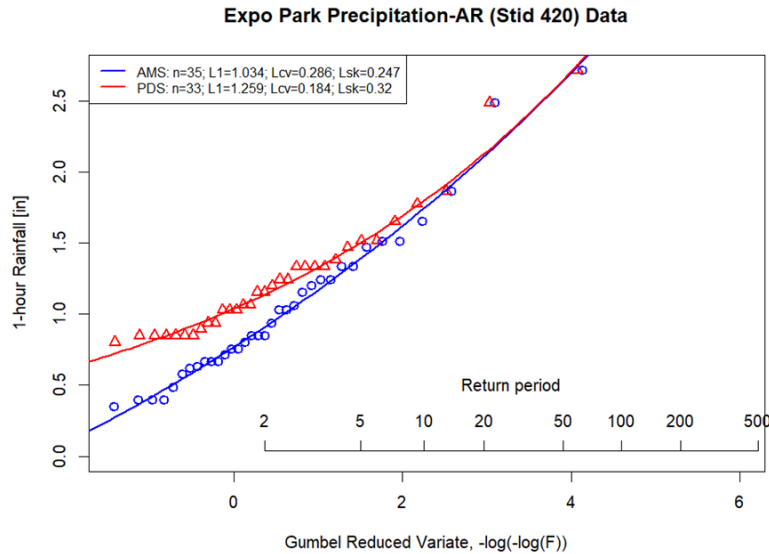


Figure 2.1: Example of differences in AMS and PDS frequency estimates

PDS precipitation frequency estimates can be calculated indirectly from Langbein's formula (Langbein, 1949) which transforms a PDS based average recurrence interval (ARI) to an AEP, using the equation $AEP = 1 - \exp(-1/ARI)$. Conversion factors for an AMS to PDS frequency is shown in Table 2.1. As part of this study, AWA extracted AMS and converted to PDS estimates based on Langbein's formula and the values presented in Table 2.1.

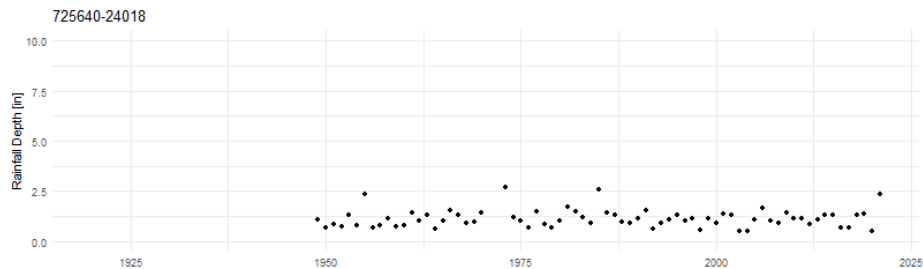
Table 2.1: Conversion factors to convert AMS to PDS frequency estimates.

ARI (Years)	AEP (PDS)	AEP (AMS)	Conversion to PDS
1	0.628	0.99	1.58
2	0.393	0.500	1.27
5	0.181	0.200	1.10
10	0.095	0.100	1.05
25	0.039	0.040	1.02
50	0.020	0.020	1.01
100	0.010	0.010	1.01
200	0.005	0.005	1.00

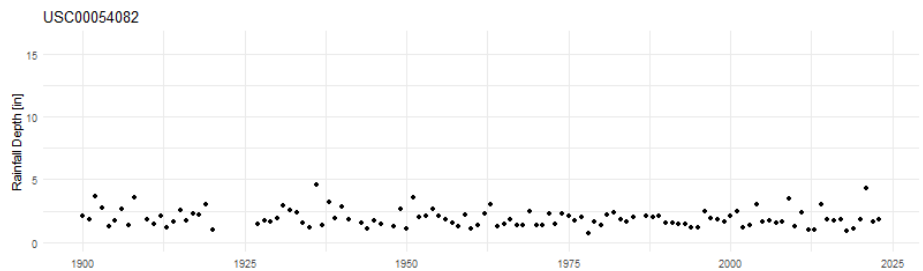
The extent of the study area and the stations used in the analysis after the completion of these procedures and all subsequent quality checks are shown in Figure 2.2. Regional L-moment statistics (Hosking and Wallis, 1997) were computed for the annual maximum data for stations used in the analysis. The Nebraska AMS data (1hr, 6hr, 24hr, and 72hr) were evaluated for climatic stationarity using the Mann-Kendall trend test. The results indicate that the assumption of a stationary climate is generally valid, as most stations did not exhibit statistically significant trends (Figure 2.3).

A total of 143 hourly stations were used in the analysis with an equivalent period of record of 2,647 accumulated station years. A total of 991 daily stations were used in the analysis with an equivalent period of record of 46,901 accumulated station years.

- Hourly Data Extraction** – Precipitation data from hourly gauges were applicable to the 1-, 6-, 24-, and 72-hour durations. Precipitation annual maxima for hourly gauges were identified for each year. In the case of the 1-hour, 6-hour, 24-hour, and 72-hour durations, a 1-hour, 6-hour, 24-hour, and 72-hour window was examined and precipitation for the given 1-hour, 6-hour, 24-hour, and 72-hour period were considered as a candidate annual maximum. An example of one station's 6-hour annual maximum series is shown below:



- Daily Data Extraction** – Precipitation data from daily gauges were applicable to the 24- and 72-hour durations. Precipitation annual maxima for daily gauges were identified for each year. In the case of the 24- and 72-hour duration, each 1- and 3-day window was examined and precipitation for the given 1- and 3-day period was considered as a candidate annual maximum. The 1-day and 3-day AMS are converted to a true 24-hour and 72-hour AMS by applying a fixed time constraint adjustment factor of 1.13 and 1.03. The fixed-time adjustment factors are discussed below in the Observational Period Adjustments section. An example of one station's 24-hour annual maximum series is shown below:



- **Identification of Duplicate Gauges** – “Duplicate” gauge is the term given to the situation where two or more gauges are either co-located at a given site or closely located and have overlapping years of record. Closely located gauges were considered to be gauges within about five miles of each other and within about a hundred feet of elevation. The AMS of candidate pairs were scrutinized for having duplicate data before determining which gauge to be excluded as a duplicate. Generally, the longer record was retained for analysis as appropriate. Duplicate gauges were marked and not considered in regional frequency analysis to avoid double-counting.
- **Maximum Series Screening** – Station data with less than 60% annual data coverage were conditionally rejected or accepted, meaning if a station were offline for more than 40% of the year, the corresponding year would be flagged and potentially excluded from the AMS. This quality control step helped ensure the robustness of the AMS used in frequency analysis.
- **Stationarity and serial independence** - NOAA Atlas 14 did not conduct formal statistical stationarity tests but acknowledged the importance of evaluating this assumption. In contrast, AWA applied the Mann-Kendall trend test to the annual maxima series (AMS) to assess whether the assumption of a stationary climate holds. For serial independence, Atlas 14 implicitly assumed that annual maxima are independent from year to year.
- **Observational Period Adjustments** – Precipitation annual maxima for continuous durations are desired for regional precipitation-frequency analysis. This can be visualized as having continuous precipitation measurements and sliding a window of time for the desired duration through the continuous data to determine the precipitation maximum for the climatic year. However, daily precipitation is reported on fixed time intervals and not on a continuous basis. For example, at a daily gauge where measurements are taken each day at 7 AM, it is easy to imagine situations where part of a continuous 24-hour precipitation event is reported on day 1 (the first calendar day) and the remainder on day 2 (the second calendar day) during a 24-hour period (called an observational day) that overlaps midnight. In this example, the maximum 1-day measurement underestimates the continuous 24-hour measurement, 3-day versus 72-hour measurements suffer the same issue, but with less underestimation, and 5-day versus 120-hour measurements suffer the same issue, also with less underestimation. Standard practice is to use an Observational Period Adjustment (Weiss, 1964; Young and McEnroe, 2003) to adjust the sample statistics for the mean and standard deviation from fixed interval measurements to be representative of continuous measurements. For these adjustments a value of 1.13 (Young and McEnroe, 2003) was applied to the 1-day observational period and a value of 1.01 was applied to the 6-hour observational period and a value of 1.03 was applied to the 72-hour observational period, these adjustments are similar to other frequency studies (Hershfield, 1961; Young and McEnroe, 2003; Bonin et al., 2011). The observational period adjustment was applied to sample at-site mean values for precipitation gauges and durations (Hosking and Wallis, 1997). No adjustments are needed for dimensionless sample L-Moment ratio statistics for L-Cv, L-Skewness and L-Kurtosis.

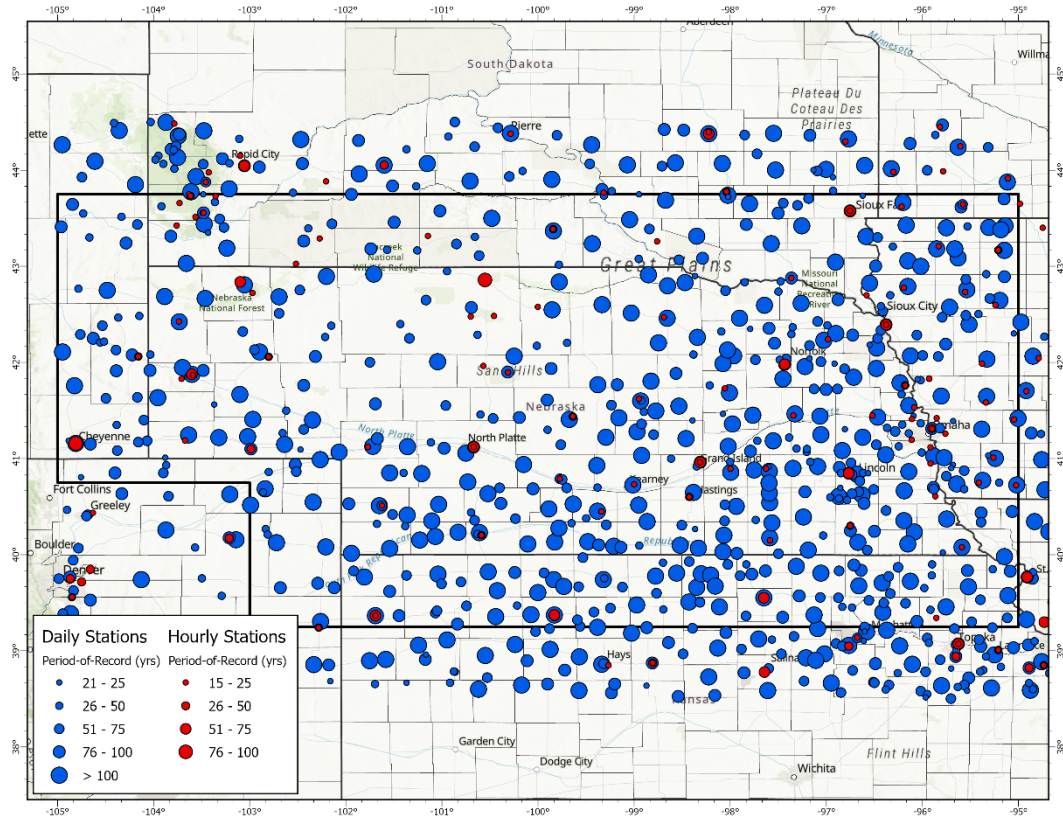


Figure 2.2: Locations of stations used for regional frequency analysis, red circles are hourly stations and blue circles are daily stations graduated by record length.

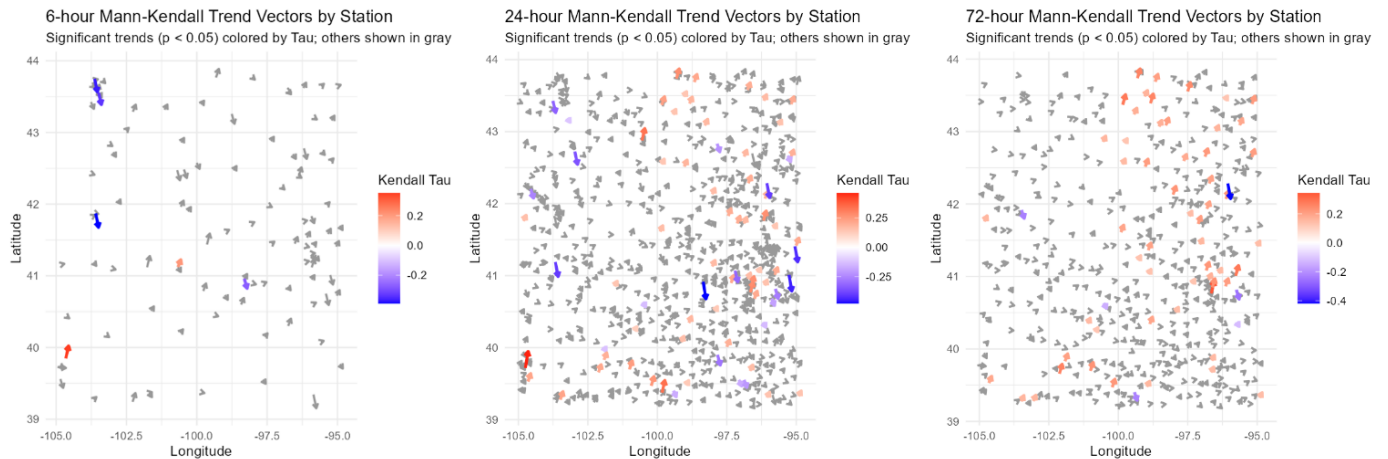


Figure 2.3: Mann-Kendall trend results testing the assumption of a stationary climate.

2.3 Regional L-moments

Key steps in the regional precipitation-frequency analysis included: i) extraction and quality control (QC) of annual maximum data, ii) calculation of an areal reduction factor used to relate point precipitation to areal/basin precipitation, iii) determination of homogeneous regions, iv) calculation of goodness-of-fit measurements, v) calculation of regional frequency curves, vi)

estimation of the at-site mean (scaling factor) at any location in a region, and vii) derivation of uncertainly bounds.

The definition of a homogeneous region is the condition that all sites can be described by one probability distribution having common distribution parameters after the site data are rescaled by their at-site mean (Hosking and Wallis, 1997; Schaefer et al., 2006). The at-site mean is calculated as the mean value of the AMS data. All sites within a homogeneous region have a common regional magnitude-frequency curve, termed as a regional growth curve, that becomes site-specific after scaling by the at-site mean of the data. Quantile estimates at a given site, i , are estimated by:

$$Q_i(F) = u_i q(F) \quad \text{Equation 1}$$

where $Q_i(F)$ is the at-site inverse Cumulative Distribution Function (CDF), u_i is the index flood, taken as the estimate of the at-site mean, and $q(F)$ is the regional growth curve, or regional inverse CDF. This method is often called an index-flood approach to regional frequency analyses (Hosking and Wallis, 1997). Regional L-moment statistics (Hosking and Wallis, 1997) were computed for the annual maximum data for stations in the basin of interest using R-statistical software packages lmom and lmomRFA developed by Hosking (Hosking, 2015a, and Hosking, 2015b). Figure 2.4 provides a graphical example of a regional growth curve that would be scaled to the at-site mean annual maximum (MAM) value (Equation 1).

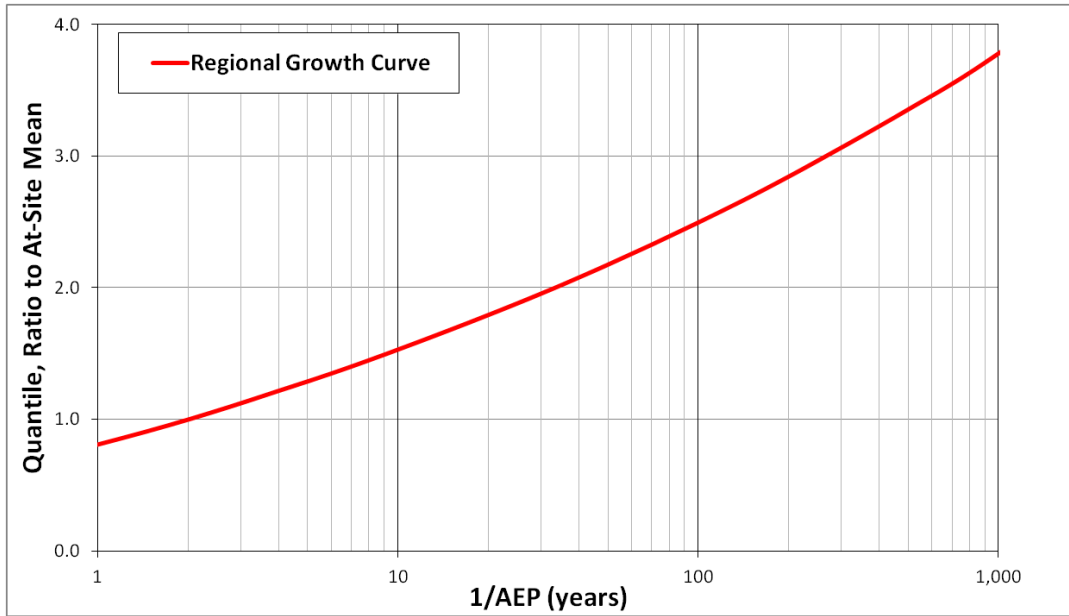


Figure 2.4: Example of regional growth curve

2.4 Areal Reduction Factor: Point to Areal Precipitation

AWA calculated storm centered areal reduction factors (ARFs) using a storm centered depth-area approach based on gridded hourly rainfall data from the Storm Precipitation Analysis System (SPAS) (Hultstrand and Kappel, 2017; Hultstrand et al., 2024). The storm centered ARF does not have a fixed area in which rain falls but changes dynamically with each storm event

(NOAA Atlas 2, 1973; Guo, 2012). Instead of the representative point being an average, the representative point is the center of the storm, defined as the point of maximum rainfall. Storm centered ARFs are calculated as the ratio of areal storm rainfall enclosed between isohyets equal to or greater than the isohyet value to the maximum point rainfall at the storm center. A storm centered ARF is calculated as:

$$ARF_{center} = \frac{\bar{R}_i}{R_{center}} \quad \text{Equation 2}$$

where $\bar{R}_i$ is the areal storm rainfall enclosed between isohyets equal to or greater than the isohyets, and R_{center} is the maximum point rainfall at the storm center.

The SPAS DAD program was used to derive 1-hour, 6-hour, 24-hour, and 72-hour depth-area values based on a set of SPAS storms analyzed and used as part of the PMP development. The point maximum (1-mi²) 1-, 6-, 24-, and 72-hour rainfall (within each SPAS DAD zone) was selected as the storm center. The maximum 6-, 24-, and 72-hour rainfall depth for standard area sizes (1-, 10-, 25-, 50-, 100-, 150-, 200-, 250-, 300-, 350-, 400-, 450-, 500-, 700-, 1000-, 2000-, and 5000-mi²) were calculated. The point maximum and maximum areal averages depths were used to calculate each event's specific ARFs. The ARFs for the basins were determined by linear interpolation using the two bounding area sizes. A three-parameter log-logistic function with an upper limit of 1 was used to estimate the average, maximum, and minimum ARF by area size following:

$$ARF_x = c + \frac{1-c}{1+\exp(b(\ln(x)-\ln(e)))} \quad \text{Equation 3}$$

where x is area size, and c , b , and e are fitting coefficients.

The ARF curves derived from each event in the short list were grouped by region—all regions, western, central, and eastern—to assess variability in ARF by storm duration and location (Figure 2.5). A comparison of the regional ARFs is presented in Figure 2.6. Based on this analysis, the final recommended ARFs were delineated by longitude, specifically east and west of -103.00°. Initial Regions 1 and 2 were combined to form the Eastern ARF region, while Region 3 was designated as the Western ARF region.

Figure 2.7 highlights the differences between these regions, with the Western region exhibiting a more pronounced decay in ARF values. This difference is attributed to variations in storm type, elevation, and moisture availability. The finalized ARFs are shown in Figure 2.8 and summarized in Tables 2.2 and 2.3.

For this study, average storm event ARFs were applied to convert point precipitation values to areal estimates for the 1-, 6-, 24-, and 72-hour durations. Several test basins within the Nebraska domain were evaluated (Figure 2.9). In smaller basins, the difference between point and areal values was minimal, as shown in Table 2.4. While this outcome was expected, the application of site-specific ARFs offers a more accurate representation of AEP across the region.

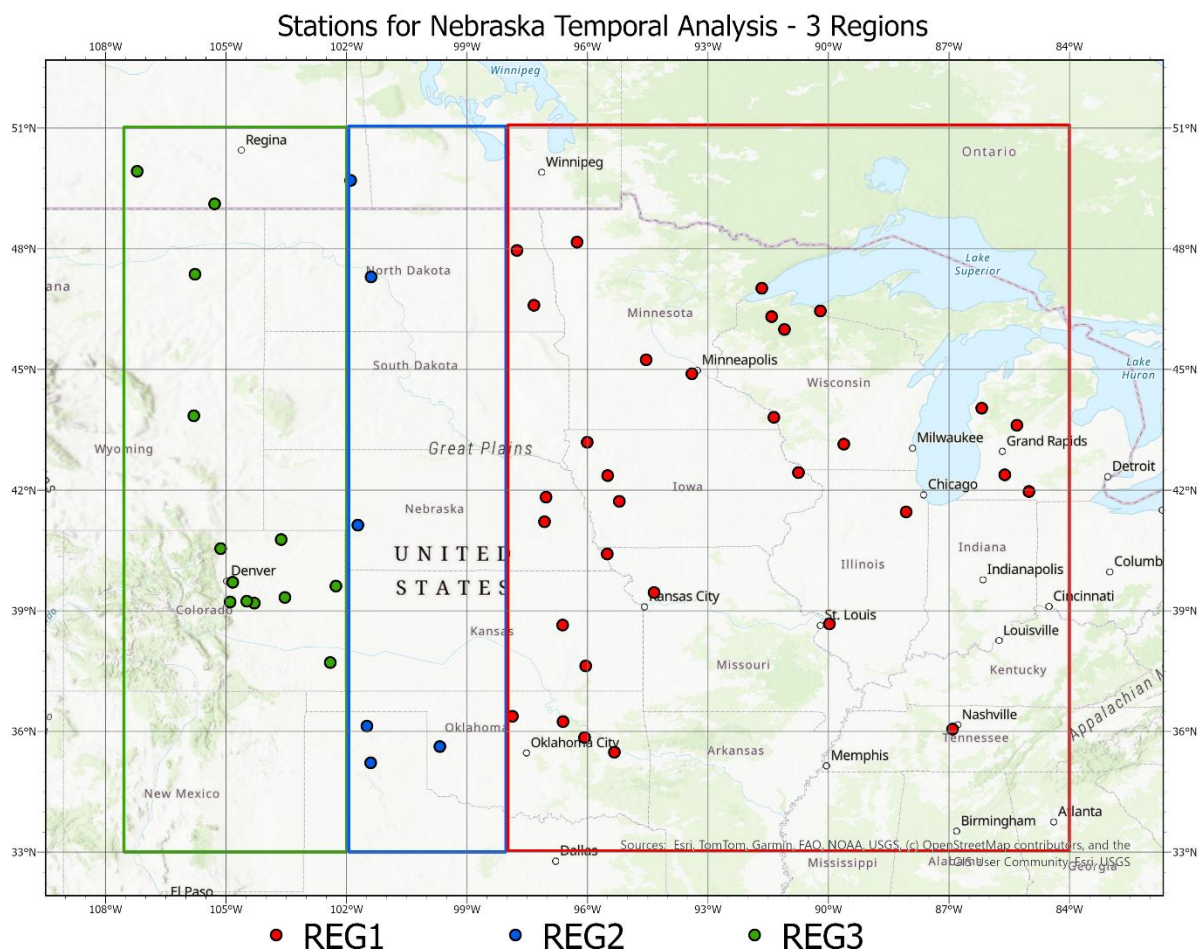


Figure 2.5: Three regions (west, central, and east) investigated for ARFs.

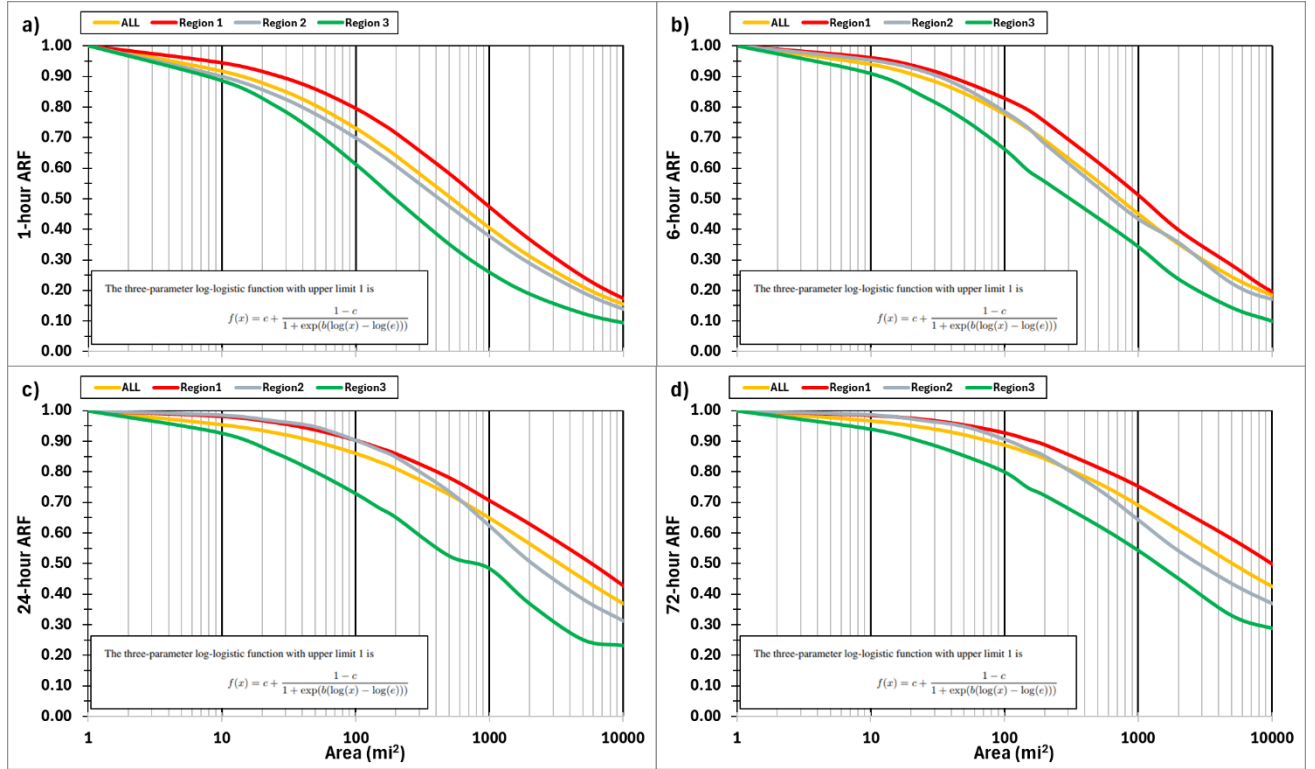


Figure 2.6: Initial comparison of ARFs by region.

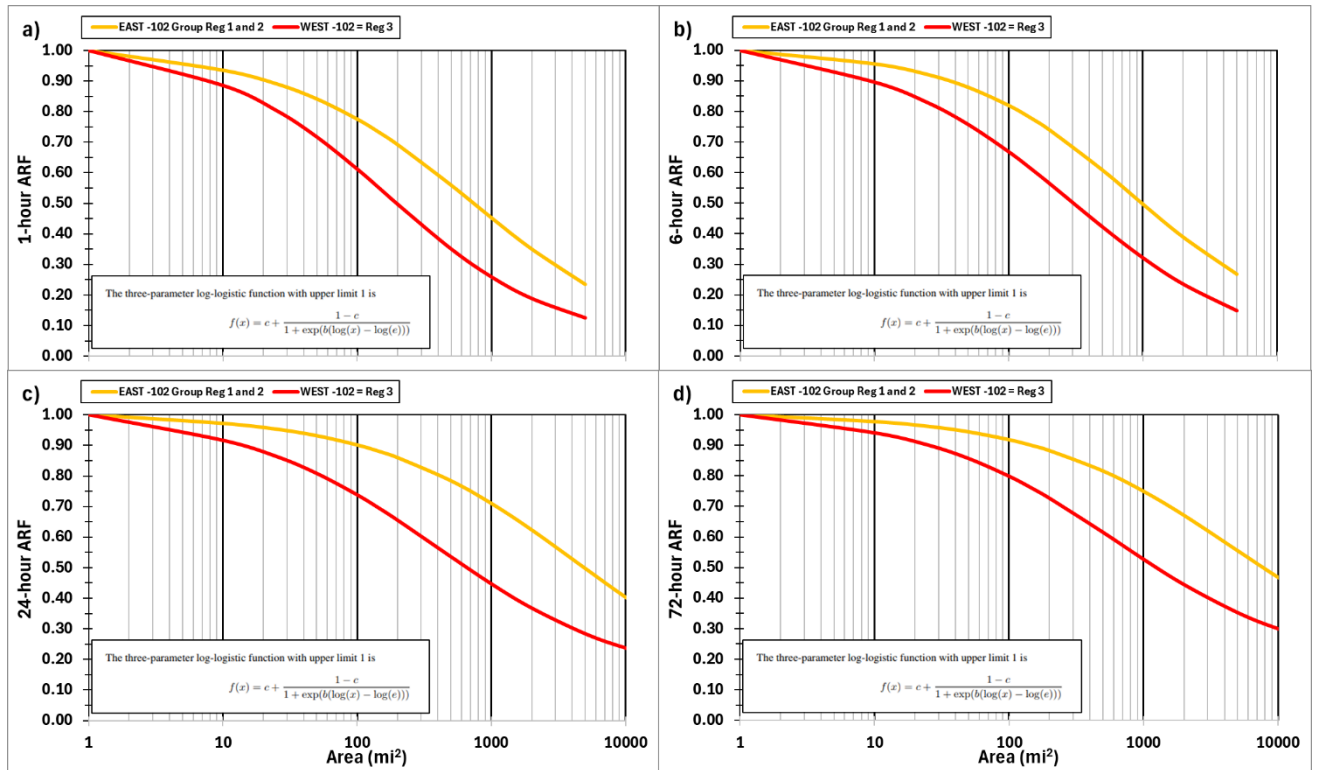


Figure 2.7: Difference in ARFs between regions, with the Western region (3) exhibiting a more pronounced decay in ARF values compared to Eastern region (1 and 2): a) 1-hour, b) 6-hour, c) 24-hour, and d) 72-hour

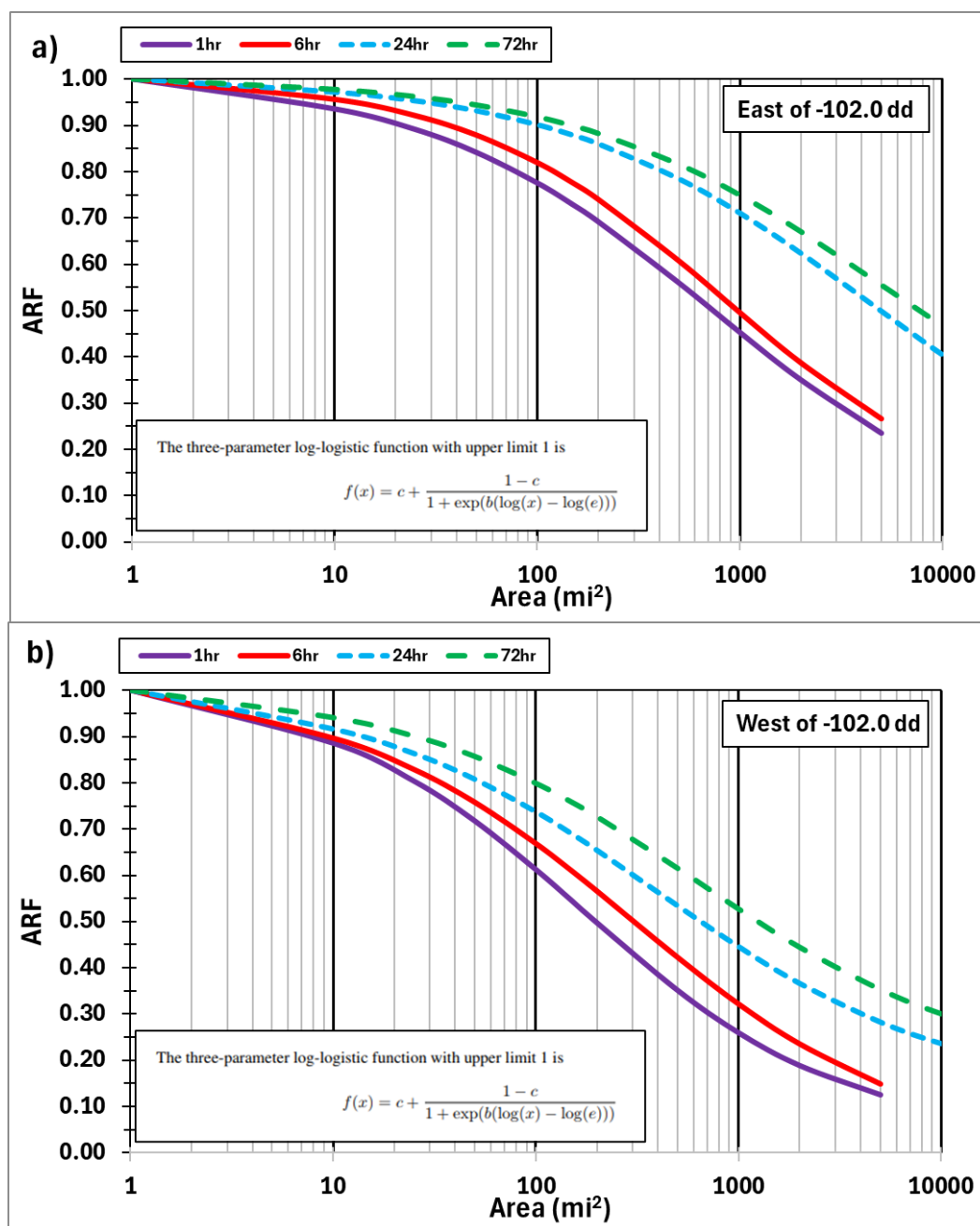


Figure 2.8: Final Nebraska 1-, 6-, 24-, and 72-hour ARF curves by region: a) east of -102.0 and b) west of -102.0.

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Table 2.1: Nebraska 1-, 6-, 24-, and 72-hour for transposition region 1 and 2 (east group)

EAST -102 Group Reg 1 and 2				
mi²	1hr	6hr	24hr	72hr
1	1.000	1.000	1.000	1.000
10	0.935	0.956	0.972	0.977
25	0.891	0.921	0.953	0.962
50	0.842	0.879	0.931	0.944
100	0.776	0.820	0.901	0.918
150	0.729	0.776	0.878	0.899
200	0.692	0.740	0.860	0.882
500	0.560	0.608	0.784	0.816
1000	0.453	0.496	0.710	0.749
2000	0.351	0.388	0.623	0.670
5000	0.235	0.267	0.498	0.555
10000			0.404	0.467
20000			0.318	0.388
50000			0.225	0.301

Table 2.3: Nebraska 1-, 6-, 24-, and 72-hour for transposition region 3 (west group)

WEST -102 = Reg 3				
mi²	1hr	6hr	24hr	72hr
1	1.000	1.000	1.000	1.000
10	0.886	0.896	0.916	0.941
25	0.804	0.829	0.863	0.901
50	0.717	0.758	0.808	0.857
100	0.612	0.669	0.737	0.799
150	0.545	0.610	0.690	0.758
200	0.497	0.566	0.655	0.727
500	0.351	0.423	0.535	0.615
1000	0.259	0.322	0.446	0.527
2000	0.188	0.236	0.367	0.444
5000	0.125	0.149	0.283	0.353
10000			0.236	0.300
20000			0.202	0.261
50000			0.172	0.226

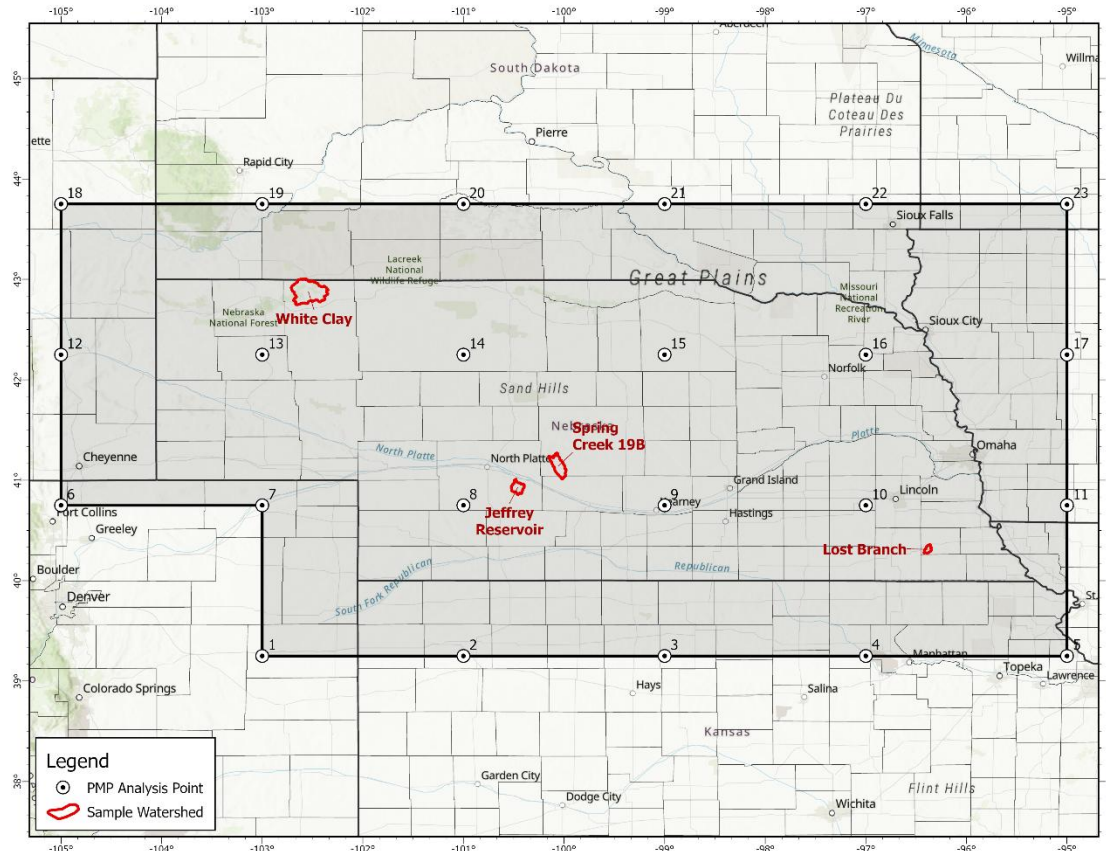


Figure 2.9: Test basin for application of 6-, 24-, and 72-hour ARF

Table 2.4: Basin specific ARF values used to convert point precipitation to areal precipitation

Basin	Area (sqmi)	1hr Storm ARF	6hr Storm ARF	24hr Storm ARF	72hr Storm ARF
Lost Branch	15	0.918	0.943	0.964	0.929
Jeffrey Reservoir	41	0.858	0.893	0.938	0.986
White Clay	220	0.481	0.551	0.642	0.848
Spring Creek 19	77	0.983	0.803	0.914	0.645

2.5 Homogenous Regions

The regional analysis approach is based on the concept that at-site data can be pooled within regions that are "homogeneous." In this context, homogeneous is taken to mean that probability distributions and their resultant frequency curves for at-site data are identical, except for a site-specific scaling factor, at all sites in a region. The at-site station mean MAM value is commonly used as the scaling factor in regional analyses. It was initially assumed that one homogeneous region was represented by all stations within close proximity to the basin location. This assumption is reasonable and justifiable to make for a small local region prior to performing heterogeneity measures. For the cluster analysis, regions based on 2, 3, 4, 5, 6, and 7 clustered regions, were performed to test and to identify the set of regions to group. An example of 24-hour cluster analysis is shown in Figure 2.10. Note, the 1-hour, 6-hour, 24-hour, and 72-hour

cluster analysis all showed three distinct and similar regions (Figure 2.11). For illustration purposes, the final 24-hour cluster analysis regions used are shown in Figure 2.12. The three regions identified in this study are different than the larger regional regions used in NOAA Atlas 15 (Perica et al., 2013) whereas this analysis is based on the Nebraska station specific data.

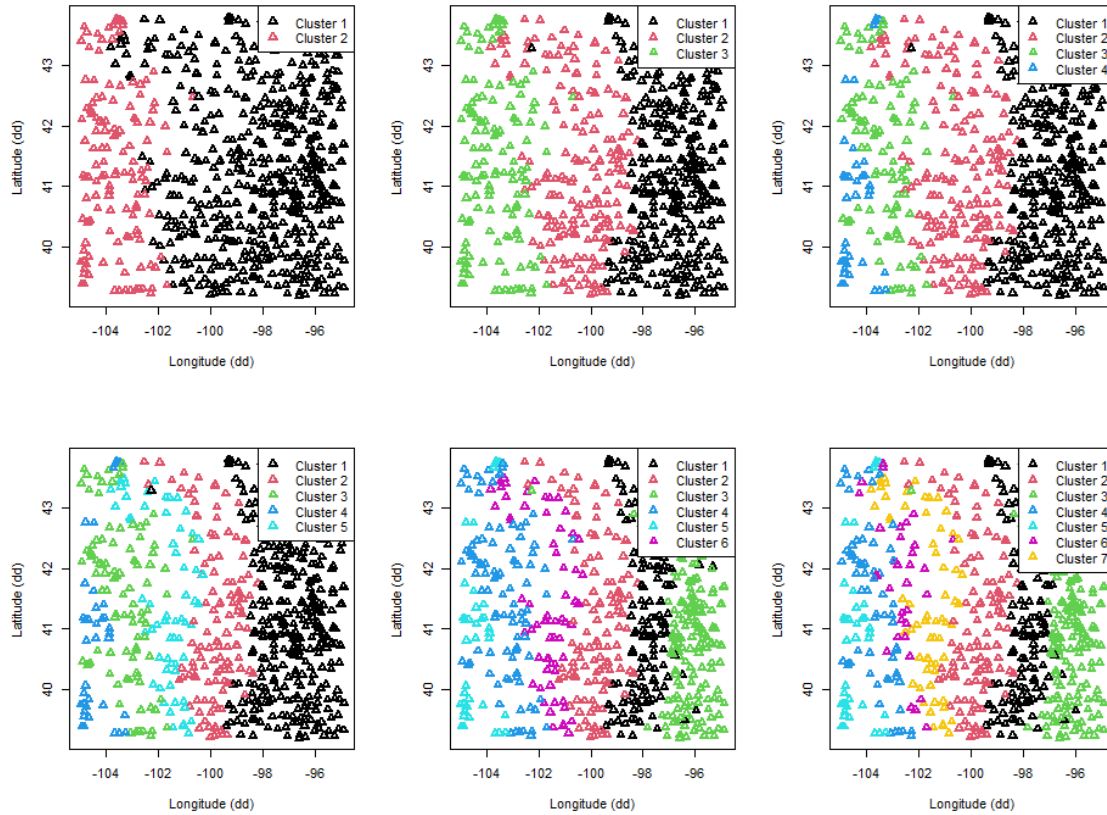


Figure 2.10: 24-hour cluster analysis investigated in the region

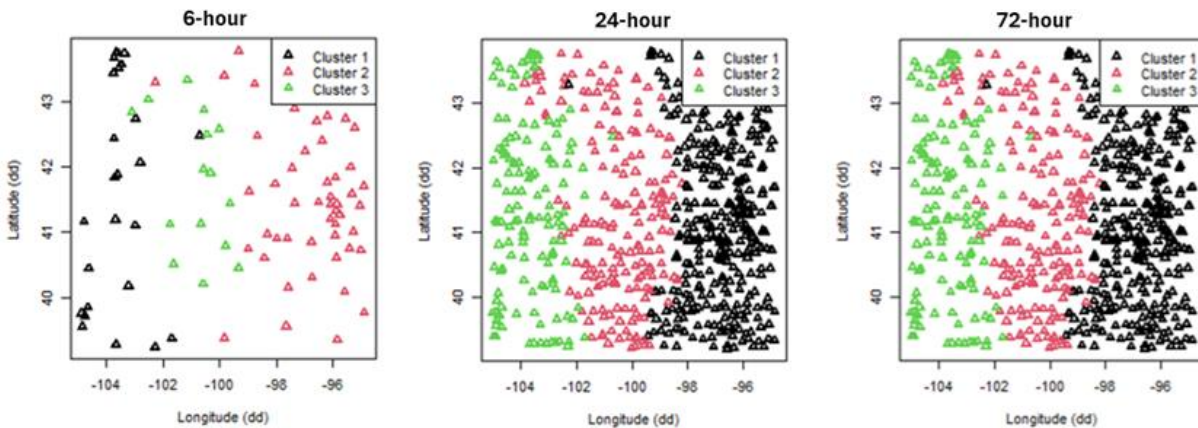


Figure 2.11: The 6-hour, 24-hour, and 72-hour cluster analysis all showed three distinct and similar regions.

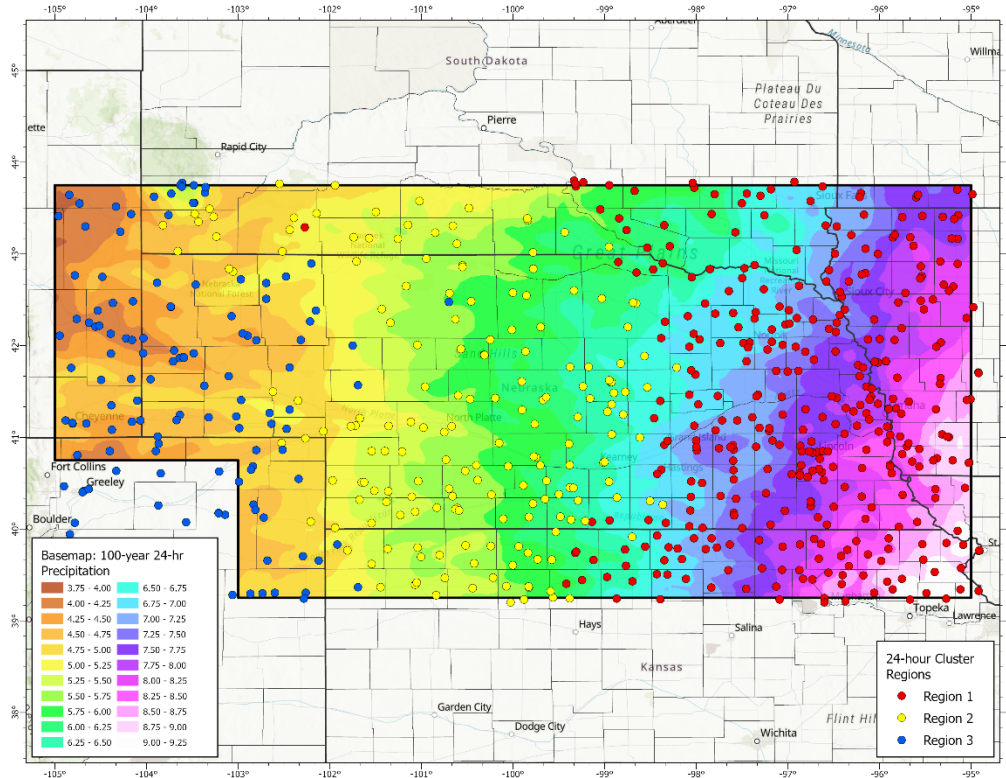


Figure 2.12: Final 24-hour cluster analysis based on three regions

Heterogeneity measures were computed for the annual maximum data for stations within the region. Hosking and Wallis (1997) developed heterogeneity measures to help indicate the level of heterogeneity or homogeneity in the L-moment ratios for a group of stations representing a sub-region. The statistics H1 and H2 denote the relative variability of observed L-Cv and L-Skewness respectively for stations within a sub-region. The H1 and H2 measures compare the observed variability to that which is expected from a large sample drawn from a homogeneous region based on the Kappa distribution. The 1-, 6- and 72-hour durations passed the homogeneity criteria ($H1 < 3$) while the 24-hour duration barely exceeded the homogeneity criteria ($H1 < 3$) but was still deemed homogeneous (Hosking and Wallis, 1997). Although Hosking and Wallis (1997) recommend homogenous regions screening of the H1 statistic to be less than three, numerous studies have claimed homogenous regions with H1 values to be larger than three. For example, England et al., (2014) deemed one basin in New Mexico to be homogeneous with an H1 value of 7.73. The heterogeneity tests and three parameter distributions that are statistically significant for the region are shown in Table 2.5.

Table 2.5: Heterogeneity statistics for the region

Duration	H1	H2	Distribution
1-hour			
Region 1	2.49	0.08	GEV, GNO
Region 2	2.11	0.86	GEV, GNO
Region 3	0.94	1.14	GEV, GNO, PEIII
6-hour			
Region 1	2.15	0.24	GEV, GNO, GLO
Region 2	1.71	0.46	GEV, GLO
Region 3	0.35	0.99	GEV, GNO, PEIII
24-hour			
Region 1	3.20	0.03	GEV
Region 2	1.22	0.37	GEV
Region 3	3.08	1.78	GEV
72-hour			
Region 1	1.22	0.53	GEV
Region 2	0.16	0.22	GEV
Region 3	2.55	0.27	GEV, GNO

2.6 Discordancy Test

Even among homogeneous regions, some stations may be considered grossly inconsistent from the region as a whole. Such stations are identified using a test, which resulted in a discordancy measure. The discordancy measure provided an important indicator of stations that should be moved to a different region and/or contained data errors in their AMS. However, by nature of the L-moment approach, an erroneous individual annual maximum at this early stage in the analysis will have a limited negative impact on the results. For the final set of stations utilized in this study, all passed the discordancy tests ($D < 3$) (Hosking and Wallis, 1997).

2.7 Identification of Probability Distribution

Regional L-moment statistics were computed for annual maximum data for each site at the homogenous region discussed above. In order to identify the best fit probability distribution, goodness of fit measures were evaluated for five three parameter distributions: generalized logistic (GLO), generalized extreme value (GEV), generalized normal (GNO), Pearson type III (PE3), and generalized Pareto (GPA). In addition, five two parameter distributions were evaluated: Linear (L), Gumbel (G), Normal (N), Uniform (U), and Exponential (E).

An L-Moment Ratio Diagram was prepared based on L-Skewness and L-Kurtosis pairs for the collection of stations in each homogenous region for each duration. Example L-Moment Ratio diagrams for Region 1 for all three durations are shown in Figure 2.13 to Figure 2.16.

Goodness-of-fit measures and the regional weighted-average L-Skewness and L-Kurtosis pairing were found to be very near the GEV and GLO distributions. As shown in Table 2.4, the AMS data indicated that the GEV distribution was the only statistically significant distribution for all three durations.

The GEV distribution was selected over the GNO for frequency estimates because: i) the GEV distribution was ranked statistically higher, ii) NOAA Atlas 14 precipitation frequency studies in the region use this distribution, iii) the GEV was identified in goodness-of-fit measures and used for frequency estimates in nearby AWA studies, and iv) using the same distribution among frequency studies ensures a direct comparison to more rare values of the frequency curve (Kappel et al., 2018; Kappel et al., 2023; Hultstrand et al., 2025). The GEV is a general mathematical form that incorporates Gumbel's Extreme Value (EV) type I, II, and III; Hultstrand et al., 2024 distributions for maxima. The parameters of the GEV distribution are the ξ (location), α (scale), and k (shape). The Gumbel EV type I distribution is obtained when $k = 0$. For $k > 0$, the distribution has finite upper bound at $\xi + \alpha/k$ and corresponds to the EV type III distribution for maxima that are bounded above. For $k < 0$, this corresponds to the Gumbel EV type II distribution.

Regional growth curves were created for the homogenous region based on the best statistically fit GEV distribution and quantiles for eighteen return periods (1, 2, 5, 10, 25, 50, 100, 200, 500, 1,000, 5,000, 10,000, 100,000, 1,000,000, 10,000,000, 100,000,000, 1,000,000,000, and 10,000,000,000 years) were calculated for the 6-, 24-, and 72-hour durations.

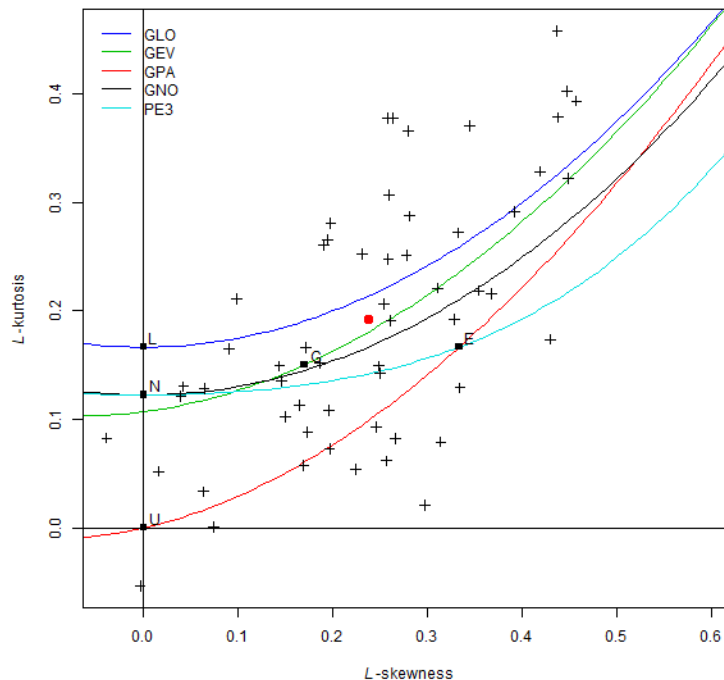


Figure 2.13: 1-hour L-moment ratio diagram used in the regional analysis for Region 2

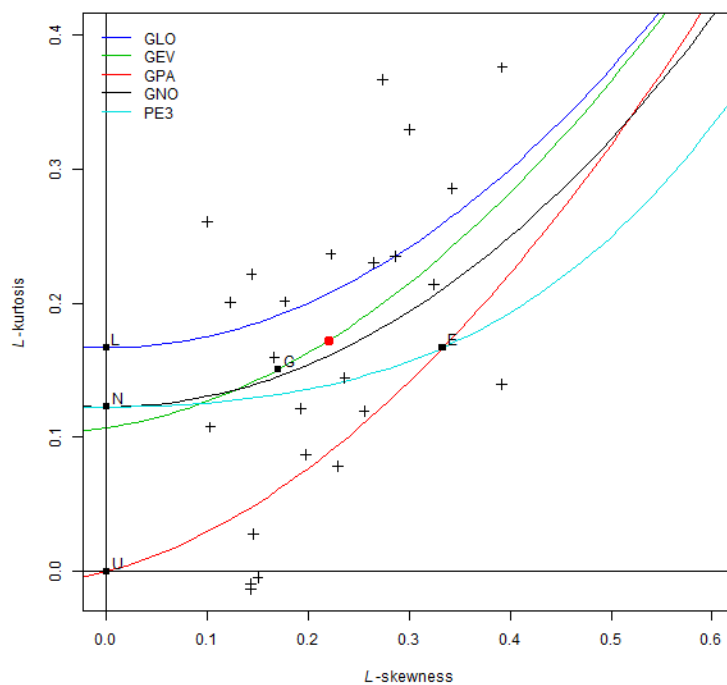


Figure 2.14: 6-hour L-moment ratio diagram used in the regional analysis for Region 1

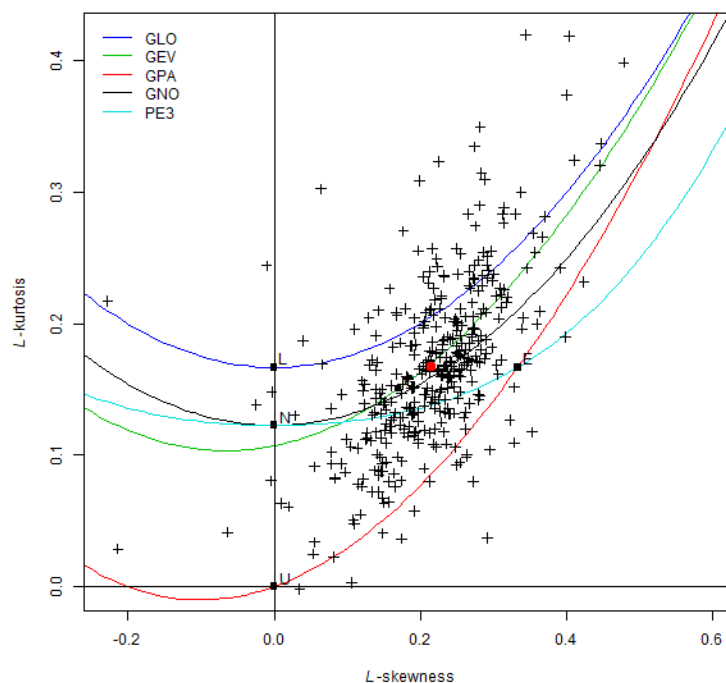


Figure 2.15: 24-hour L-moment ratio diagram used in the regional analysis for Region 1

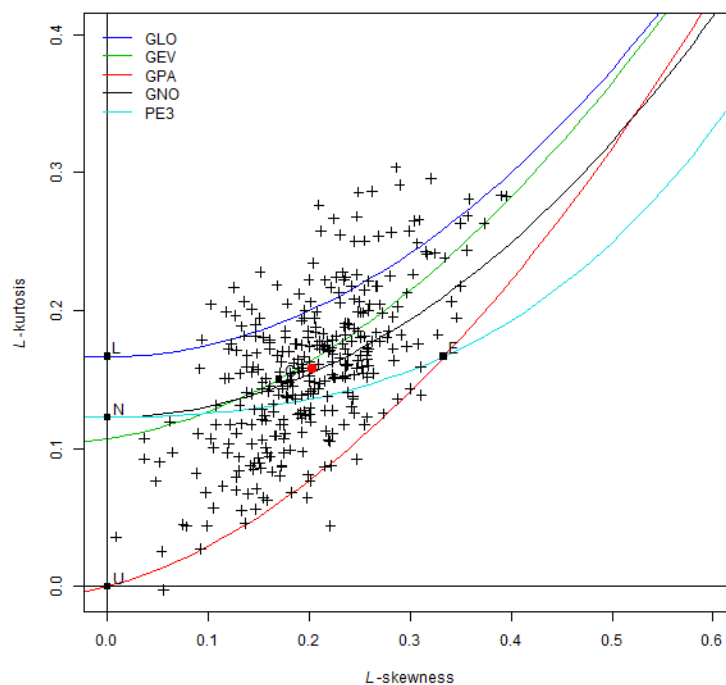


Figure 2.16: 72-hour L-moment ratio diagram used in the regional analysis for Region 1

2.8 Derivation of Uncertainty Bounds

The uncertainty analysis for deriving the frequency curve and uncertainty bounds were conducted as follows. The frequency distributions at the site were randomly permuted, and data were simulated from the selected frequency distribution. The procedure is described in Hosking and Wallis (1997) and Hosking (2015b), except that the permutation of frequency distributions is a later modification, intended to give more realistic sets of simulated data (Hosking, 2015b). From each permutation, the sample mean values and estimates of the quantiles of the regional growth curve for non-exceedance probabilities are saved. From the simulated values, for each quantile specified the relative root mean square error (relative RMSE) is computed as in Hosking and Wallis (1997). The error bounds are sample quantiles of the ratio of the estimated regional growth curve to the true at-site growth curve or of the ratio of the estimated to the true quantiles at individual sites (Hosking, 2015b).

2.9 Spatial Mapping of At-Site Scaling Factor

The at-site L-moment statistics, including the MAM, Lcv, and Lsk, were mapped to develop precipitation frequency grids. As shown in Figure 2.1, station density is highest in the eastern part of the state and decreases toward the interior and western regions. Despite these differences, all three regions contain stations with sufficiently long records. Therefore, variations in station density and record length are expected to have a limited impact on the spatial interpolation and overall accuracy of the results across the study area from east to west.. Typically, explanatory variables and associated predictor equations are used to map at-site MAM using existing continuous gridded variables. Explanatory variables considered included climatic and location indices such as PRISM mean annual precipitation (Daly et al., 1997), Latitude, Longitude, and Elevation. Spatial mapping of at-site MAM, Lcv, and Lsk involved a three-step process:

1. Determine a predictor equation that describes the regional behavior of the at-site means across the study area.
2. Compute a best-estimate of the at-site mean at a given station using a weighted average of the regionally-predicted at-site mean (step 1 above) and the sample at-site.
3. Adjust the resulting at-site statistics to account for spatial coherence of the error residuals (observed-predicted values) in a given locality.

At-site MAM, Lcv, and Lsk have been well-predicted by climate indicators such as PRISM precipitation. Review of the behavior of at-site means like this allowed for the development of regression relationships for the prediction of at-site means for spatial mapping. Best estimates of the station statistics were obtained using an Empirical Bayes Approach (Kuczera, 1982) as a weighted average of the values predicted from the regression relationship and the sample value of the station at-site MAM (Step 2 above). Greater weight was given to the sample value of the at-site mean as the record length at a station increased. Residuals were defined as the difference between the weighted-average at-site mean and the regression-predicted at-site mean. Adjustments were then made to the predicted estimates of the at-site means to account for coherence in the spatial distribution of residuals, where the residuals in some geographic areas were not random, but rather systematically over-estimated or under-estimated the at-site mean relative to the regression prediction (Step 3 above); this was done by interpolating standardized residuals and summing the residual grid with the at-site mean grid

developed in Step 1. Generalized Additive Model (GAM) methods were also investigated for the ability to capture non-linear interactions (Hastie and Tibshirani, 1987; López-Moreno and Nogués-Bravo, 2005). GAMs are non-parametric extensions of linear model regressions that apply non-parametric smoothing functions to each predictor and additively calculate the component response.

The final mapped values of the at-site MAMs for the study area are compared to the observed sample values to achieve reduction in the predictive error for the mapped values of the at-site means. This is a result of accounting for both regional information (regional predictive equation), local information (station at-site mean) and accounting for the spatial coherence of residuals. The final (mapped) values of the at-site MAM are thought to be the best-estimates achievable from the collection of regional and at-site information. Figures 2.17 -2.20 depict the final mapped MAM values of the 1-, 6-, 24-, and 72-hour at-site MAM.

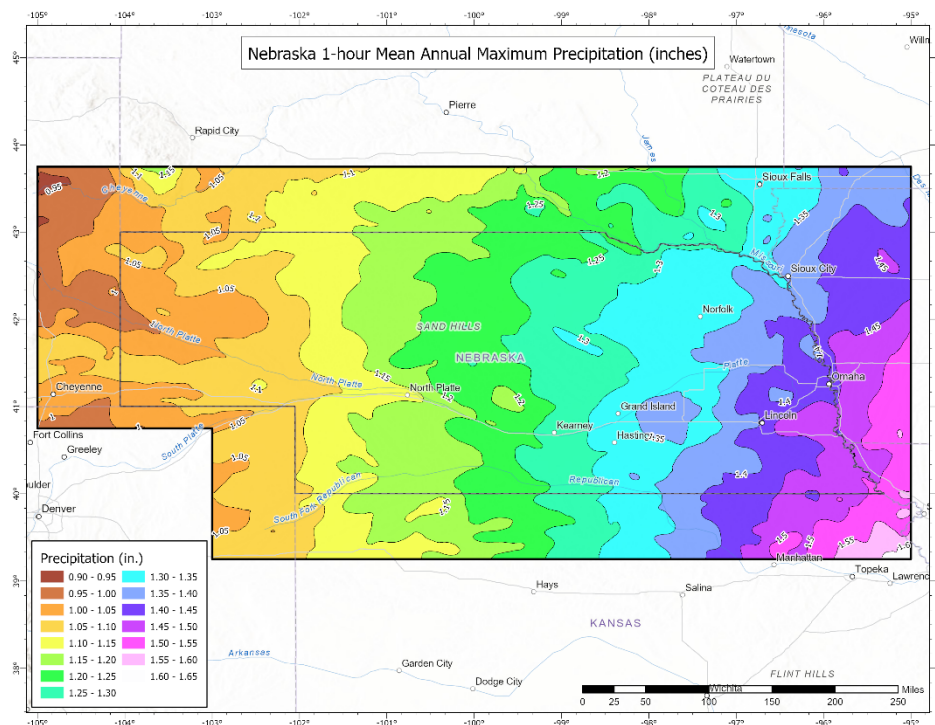


Figure 2.17: Spatially mapped at-site MAM values for 1-hour duration

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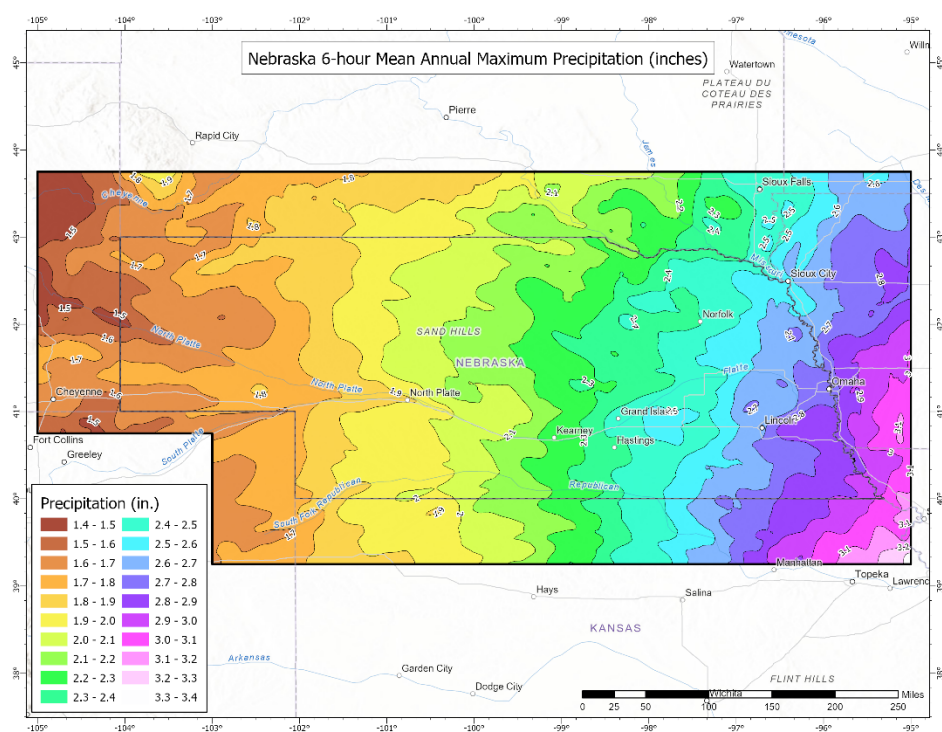


Figure 2.18: Spatially mapped at-site MAM values for 6-hour duration

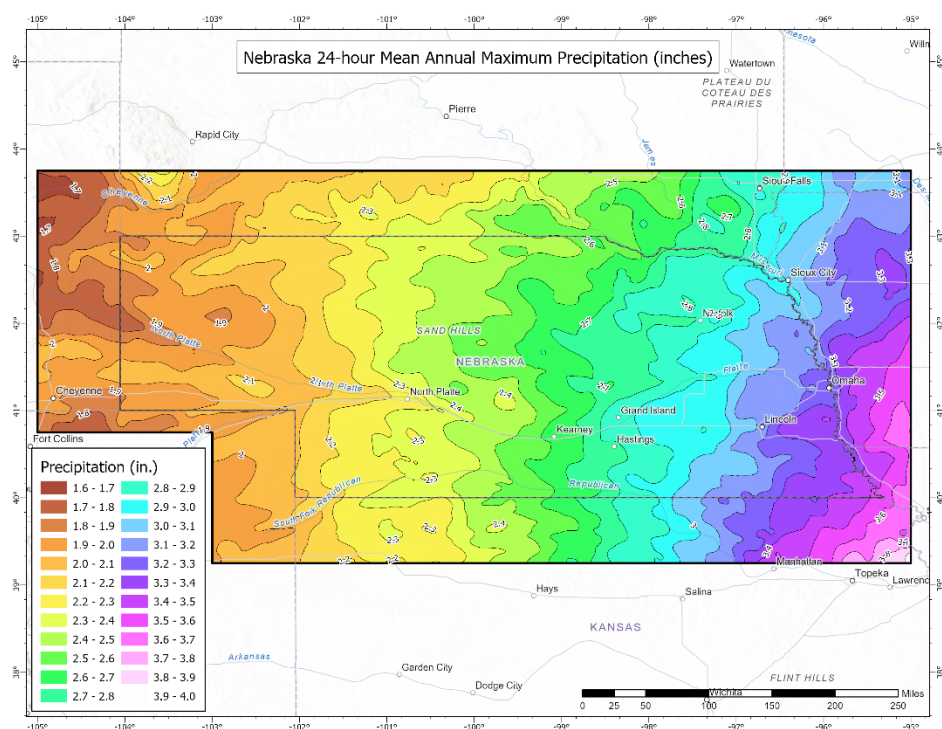


Figure 2.19: Spatially mapped at-site MAM values for 24-hour duration

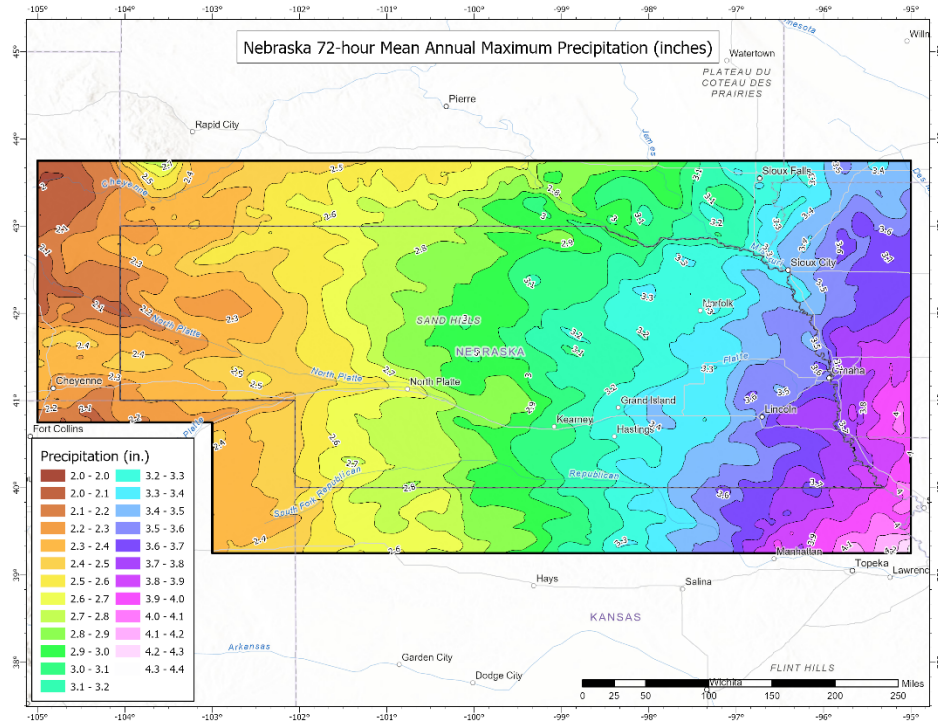


Figure 2.20: Spatially mapped at-site MAM values for 72-hour duration

2.10 Gridded Precipitation Frequency Estimates

The gridded datasets for the at-site MAM statistics described in the above sections were then used to scale the GEV distribution regional curve for each duration on a grid-cell by grid-cell basis. This allowed spatial mapping of precipitation-frequency estimates for selected recurrence intervals for the durations of 1-hour, 6-hour, 24-hour, and 72-hour. Eighteen average recurrence interval (ARI) grids per duration were prepared from this information for point precipitation maxima for 1, 2, 5, 10, 25, 50, 100, 200, 500, 1,000, 5,000, 10,000, 100,000, 1,000,000, 10,000,000, 100,000,000, 1,000,000,000, and 10,000,000,000 years. Final 1-, 6-, 24-, and 72-hour 100-year ARI are shown in Figure 2.21 to Figure 2.24. Point frequency grids were converted to basin average precipitation using the site-specific ARF discussed above.

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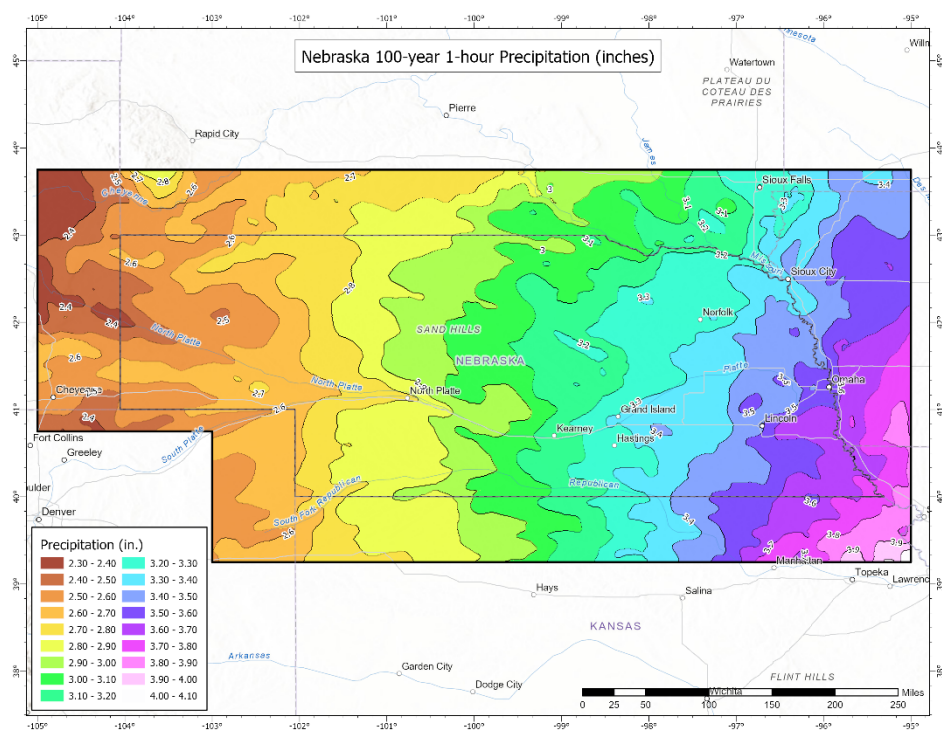


Figure 2.21: Spatially mapped 1-hour 100-year precipitation

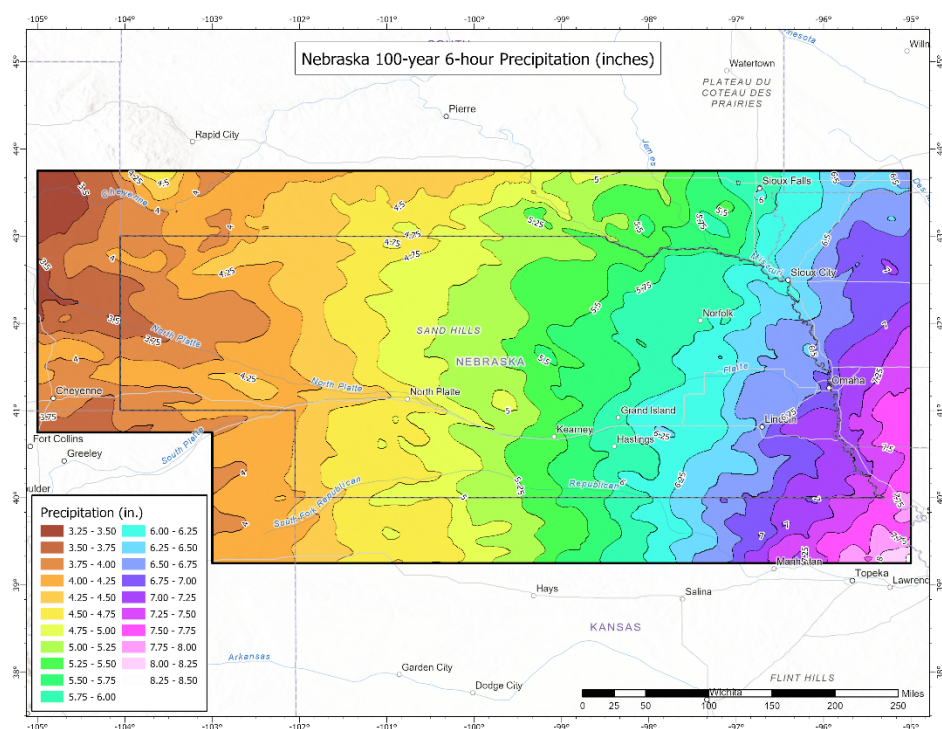


Figure 2.22: Spatially mapped 6-hour 100-year precipitation

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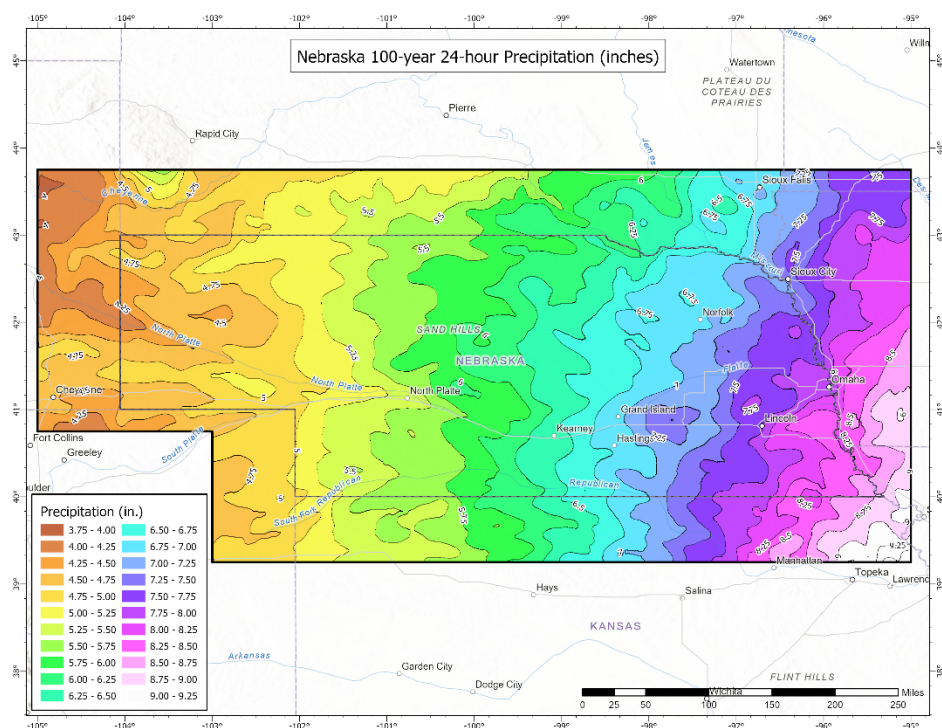


Figure 2.20: Spatially mapped 24-hour 100-year precipitation

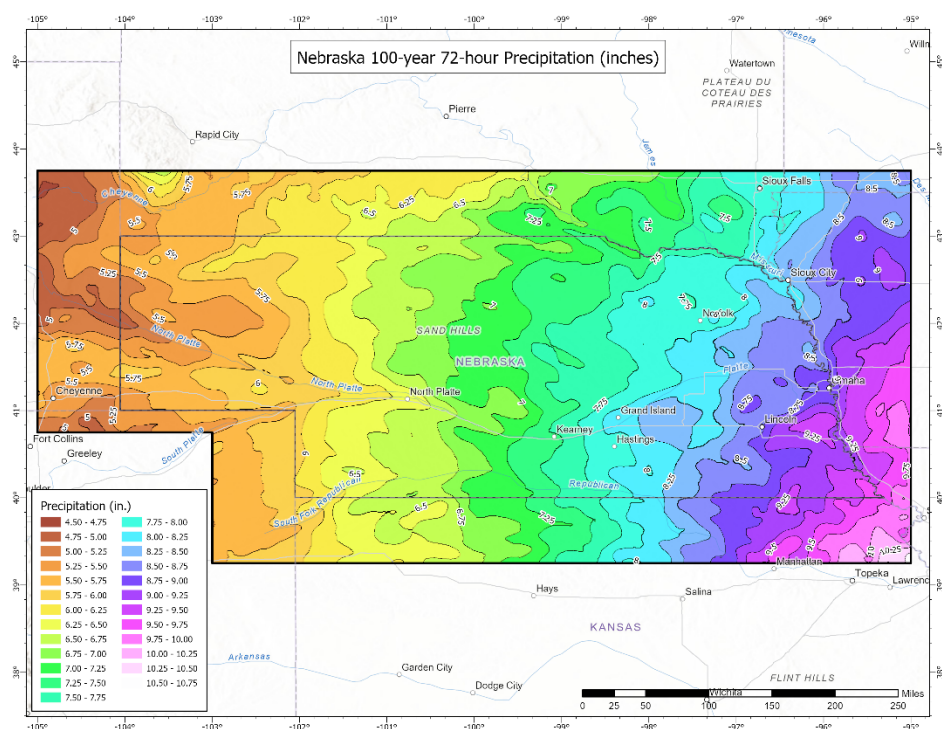


Figure 2.21: Spatially mapped 72-hour 100-year precipitation

2.11 Annual Exceedance Probability of PMP

As part of this study, four test basins were selected to quantify the 1-hour, 6-hour, and 24-hour deterministic PMP (Tomlinson et al., 2008) (Figure 2.7; Table 2.6). AEP grids for the 1-hour, 6-hour, and 24-hour durations were used to extract 1-mi² gridded AEP data. Basin-average point AEP values were calculated, converted to basin-average precipitation using the developed ARFs, and then used to estimate the average AEP corresponding to PMP.

The resulting 1-hour, 6-hour, and 24-hour basin-average AEP values for the four test basins are provided in Tables 2.7 through 2.10 and illustrated in Figures 2.24 through 2.27. The estimated AEPs of PMP for these basins range from 10^{-6} to 10^{-9} , representing appropriately rare events consistent with PMP expectations. For temporal pattern guidance, the information developed in this study and discussed in Section 3 should be applied.

Table 2.6: Basin specific ARF values used to convert point precipitation to areal precipitation for comparison to areal PMP estimates

Basin	Area (sqmi)	6-hour PMP	24-hour PMP	1hr Storm	6hr Storm	24hr Storm
				ARF	ARF	ARF
Lost Branch	15	20.1"	23.9"	0.918	0.943	0.964
Jeffrey Reservoir	41	17.6"	20.6"	0.858	0.893	0.938
White Clay	220	12.1"	16.3"	0.481	0.551	0.642
Spring Creek 19	77	16.3"	19.3"	0.803	0.844	0.914

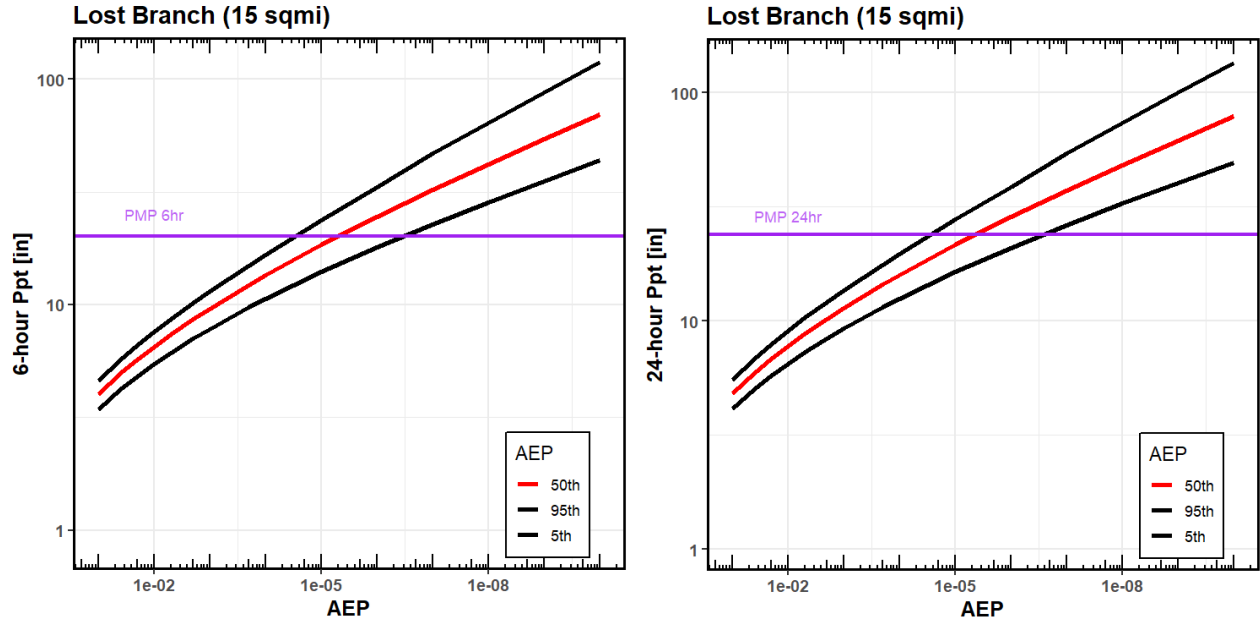


Figure 2.22: Lost Branch regional L-moment frequency curve (red line) and uncertainty bounds (black line) with basin average PMP (purple line) for the 6- and 24-hour durations

Table 2.7: Lost Branch basin average AEP for 1-hour, 6-hour and 24-hour used to estimate the AEP of PMP

Lost Branch (15 mi ²)		1-hour			6-hour			24-hour		
ARI	AEP	50%	5%	95%	50%	5%	95%	50%	5%	95%
1	9.9 ⁻¹	0.8	0.7	1.0	1.6	1.4	1.9	2.0	1.6	2.3
2	5.0 ⁻¹	1.5	1.3	1.8	3.0	2.6	3.5	3.6	3.1	4.2
5	2.0 ⁻¹	1.8	1.6	2.1	3.7	3.1	4.2	4.4	3.8	5.1
10	1.0 ⁻¹	2.1	1.8	2.4	4.2	3.6	4.8	5.1	4.3	5.8
25	4.0 ⁻²	2.5	2.1	2.9	5.0	4.3	5.8	6.0	5.1	6.9
50	2.0 ⁻²	2.9	2.4	3.3	5.8	4.9	6.7	6.9	5.8	8.0
100	1.0 ⁻²	3.3	2.7	3.8	6.5	5.5	7.6	7.8	6.5	9.1
200	5.0 ⁻³	3.7	3.1	4.3	7.4	6.1	8.7	8.8	7.3	10.4
500	2.0 ⁻³	4.3	3.5	5.1	8.6	7.0	10.2	10.2	8.4	12.1
1,000	1.0 ⁻³	4.8	3.9	5.7	9.6	7.8	11.5	11.4	9.3	13.6
5,000	2.0 ⁻⁴	6.0	4.8	7.3	12.2	9.7	14.8	14.5	11.5	17.6
10,000	1.0 ⁻⁴	6.6	5.2	8.2	13.5	10.6	16.6	15.9	12.5	19.6
100,000	1.0 ⁻⁵	9.0	6.8	11.6	18.4	14.0	23.7	21.6	16.4	27.8
1,000,000	1.0 ⁻⁶	11.9	8.7	16.1	24.5	18.0	33.2	28.6	20.9	38.7
10,000,000	1.0 ⁻⁷	15.5	11.0	22.5	32.2	22.8	46.7	37.3	26.4	54.1
100,000,000	1.0 ⁻⁸	20.0	13.6	30.6	41.9	28.5	64.2	48.2	32.8	73.8
1,000,000,000	1.0 ⁻⁹	25.6	16.7	41.5	54.1	35.3	87.6	61.8	40.4	100.0
10,000,000,000	1.0 ⁻¹⁰	32.6	20.5	55.9	69.5	43.6	119.1	78.7	49.4	135.0

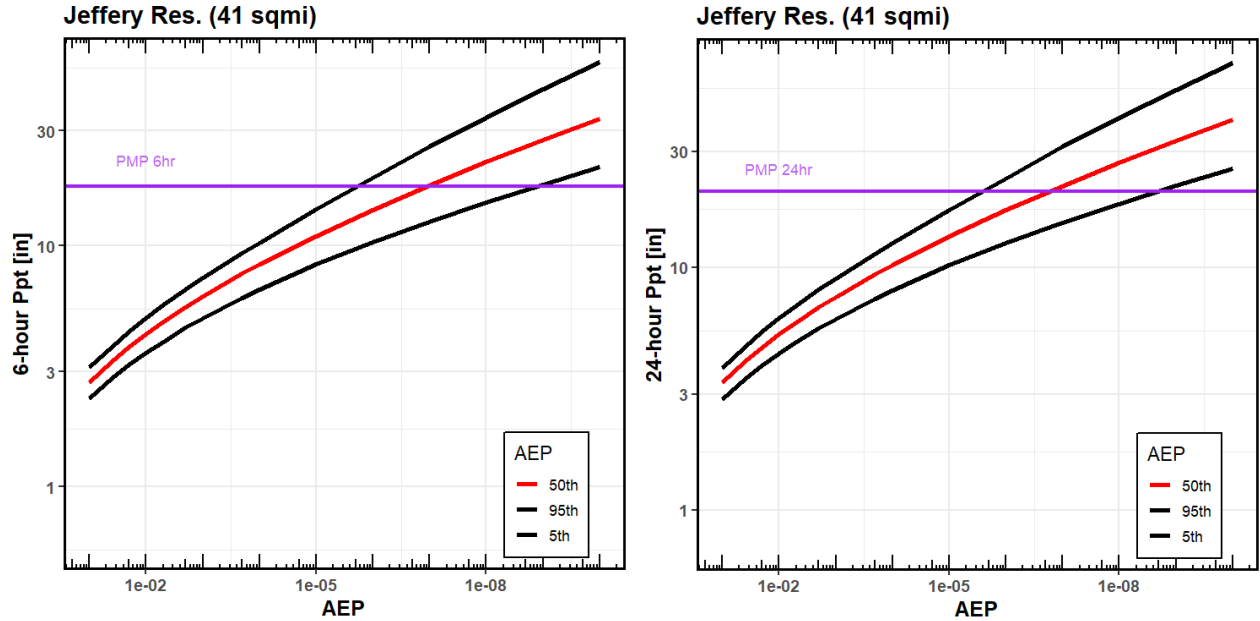


Figure 2.23: Jeffery Res regional L-moment frequency curve (red line) and uncertainty bounds (black line) with basin average PMP (purple line) for the 6- and 24-hour durations

Table 2.8: Jeffery Res basin average AEP for 1-hour, 6-hour and 24-hour used to estimate the AEP of PMP

Jeffrey Res. (41 mi ²)		1-hour			6-hour			24-hour		
ARI	AEP	50%	5%	95%	50%	5%	95%	50%	5%	95%
1	9.9 ⁻¹	0.6	0.5	0.7	1.1	0.9	1.3	1.3	1.1	1.6
2	5.0 ⁻¹	1.2	1.0	1.4	2.1	1.8	2.4	2.6	2.2	3.0
5	2.0 ⁻¹	1.4	1.2	1.6	2.5	2.1	2.9	3.1	2.6	3.6
10	1.0 ⁻¹	1.6	1.4	1.9	2.9	2.4	3.3	3.5	3.0	4.0
25	4.0 ⁻²	1.9	1.6	2.2	3.4	2.9	3.9	4.2	3.5	4.8
50	2.0 ⁻²	2.2	1.9	2.5	3.8	3.2	4.4	4.7	4.0	5.5
100	1.0 ⁻²	2.5	2.1	2.9	4.3	3.6	5.0	5.3	4.4	6.2
200	5.0 ⁻³	2.8	2.3	3.3	4.8	4.0	5.7	5.9	4.9	7.0
500	2.0 ⁻³	3.2	2.6	3.8	5.6	4.6	6.6	6.8	5.6	8.1
1,000	1.0 ⁻³	3.5	2.9	4.2	6.2	5.0	7.4	7.5	6.1	9.0
5,000	2.0 ⁻⁴	4.4	3.5	5.3	7.7	6.1	9.3	9.4	7.4	11.4
10,000	1.0 ⁻⁴	4.8	3.8	5.9	8.4	6.6	10.3	10.2	8.0	12.6
100,000	1.0 ⁻⁵	6.3	4.8	8.1	11.0	8.4	14.2	13.4	10.2	17.3
1,000,000	1.0 ⁻⁶	8.0	5.9	10.8	14.1	10.3	19.1	17.2	12.6	23.2
10,000,000	1.0 ⁻⁷	10.1	7.1	14.6	17.8	12.6	25.9	21.6	15.3	31.4
100,000,000	1.0 ⁻⁸	12.5	8.5	19.2	22.2	15.1	34.0	26.9	18.3	41.2
1,000,000,000	1.0 ⁻⁹	15.4	10.1	24.9	27.5	18.0	44.5	33.2	21.7	53.7
10,000,000,000	1.0 ⁻¹⁰	18.8	11.8	32.3	33.8	21.2	57.9	40.6	25.5	69.6

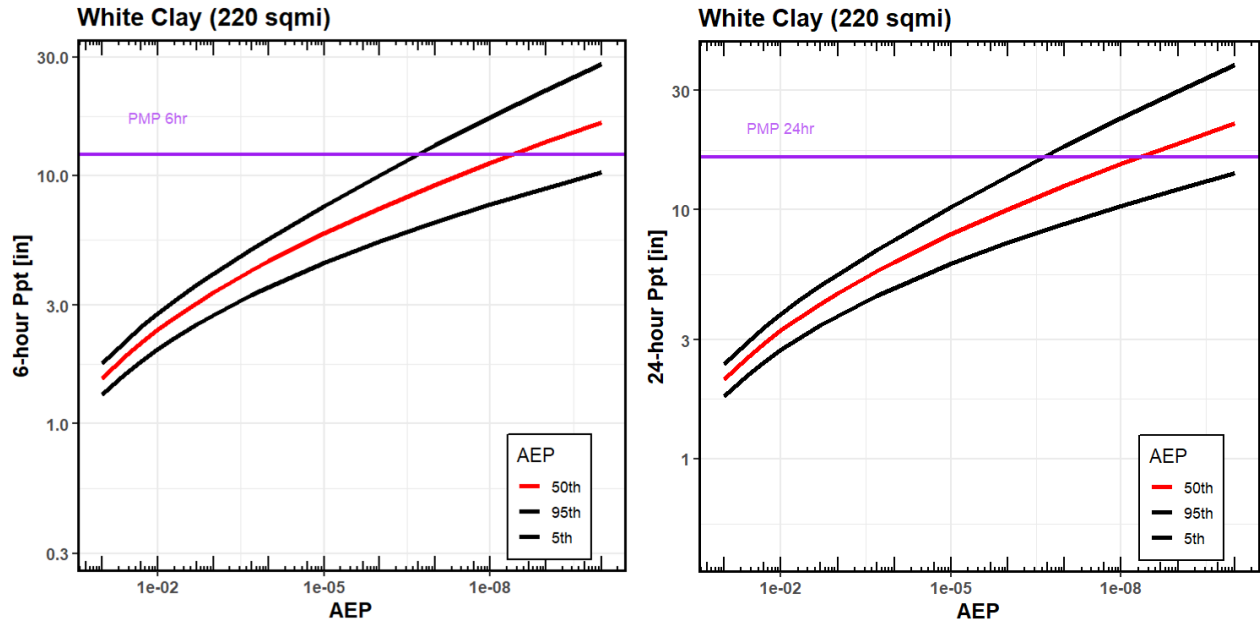


Figure 2.24: White Clay regional L-moment frequency curve (red line) and uncertainty bounds (black line) with basin average PMP (purple line) for the 6- and 24-hour durations

Table 2.9: White Clay basin average AEP for 1-hour, 6-hour and 24-hour used to estimate the AEP of PMP

White Clay (220 mi ²)		1-hour			6-hour			24-hour		
ARI	AEP	50%	5%	95%	50%	5%	95%	50%	5%	95%
1	9.9 ⁻¹	0.3	0.3	0.4	0.6	0.5	0.7	0.8	0.7	1.0
2	5.0 ⁻¹	0.6	0.5	0.7	1.2	1.0	1.3	1.6	1.4	1.8
5	2.0 ⁻¹	0.8	0.6	0.9	1.4	1.2	1.6	1.9	1.7	2.2
10	1.0 ⁻¹	0.9	0.7	1.0	1.6	1.4	1.8	2.2	1.9	2.5
25	4.0 ⁻²	1.0	0.9	1.2	1.9	1.6	2.2	2.6	2.2	3.0
50	2.0 ⁻²	1.2	1.0	1.3	2.1	1.8	2.5	2.9	2.5	3.4
100	1.0 ⁻²	1.3	1.1	1.5	2.4	2.0	2.8	3.3	2.7	3.8
200	5.0 ⁻³	1.4	1.2	1.7	2.7	2.2	3.1	3.7	3.0	4.3
500	2.0 ⁻³	1.7	1.4	2.0	3.1	2.5	3.6	4.2	3.4	5.0
1,000	1.0 ⁻³	1.8	1.5	2.2	3.4	2.7	4.0	4.6	3.7	5.5
5,000	2.0 ⁻⁴	2.3	1.8	2.7	4.1	3.3	5.0	5.7	4.5	6.9
10,000	1.0 ⁻⁴	2.5	1.9	3.0	4.5	3.5	5.6	6.1	4.8	7.6
100,000	1.0 ⁻⁵	3.2	2.4	4.1	5.8	4.4	7.5	7.9	6.0	10.2
1,000,000	1.0 ⁻⁶	4.0	2.9	5.4	7.4	5.4	10.0	10.0	7.3	13.6
10,000,000	1.0 ⁻⁷	5.0	3.5	7.2	9.2	6.5	13.3	12.4	8.8	18.0
100,000,000	1.0 ⁻⁸	6.1	4.1	9.3	11.2	7.6	17.2	15.2	10.3	23.3
1,000,000,000	1.0 ⁻⁹	7.4	4.8	11.9	13.6	8.9	22.0	18.5	12.1	29.9
10,000,000,000	1.0 ⁻¹⁰	8.8	5.5	15.1	16.4	10.3	28.1	22.2	13.9	38.1

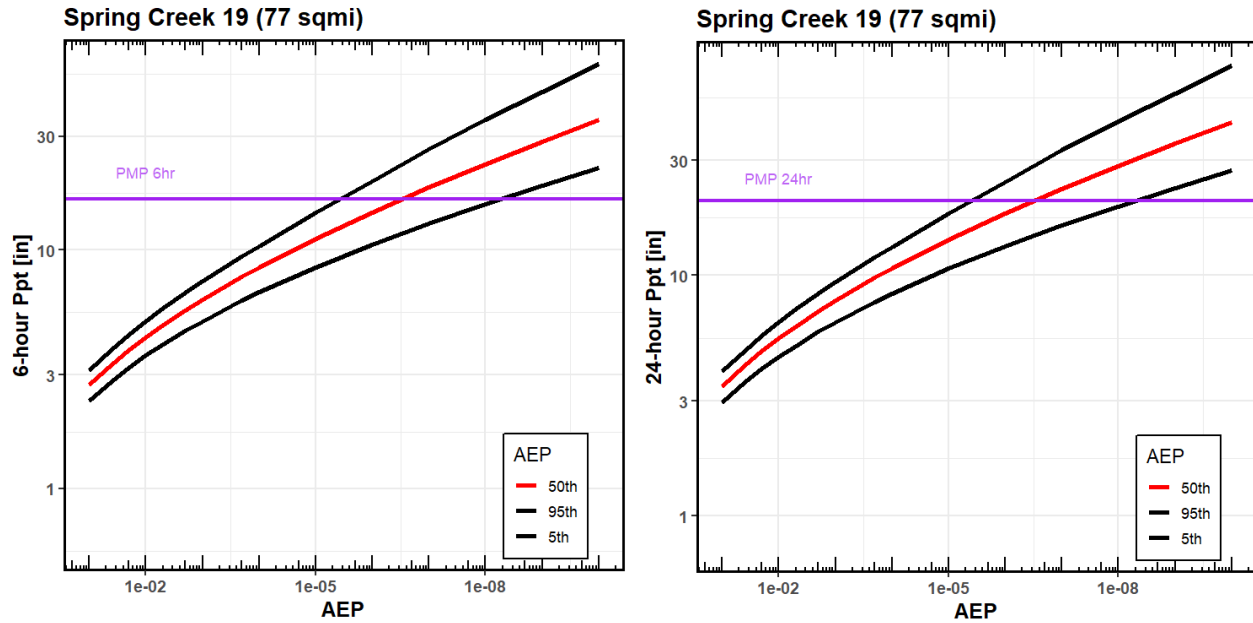


Figure 2.25: Spring Creek regional L-moment frequency curve (red line) and uncertainty bounds (black line) with basin average PMP (purple line) for the 6- and 24-hour durations

Table 2.10: Spring Creek basin average AEP for 1-hour, 6-hour and 24-hour used to estimate the AEP of PMP

Spring Creek 19 (77 mi ²)		1-hour			6-hour			24-hour		
ARI	AEP	50%	5%	95%	50%	5%	95%	50%	5%	95%
1	9.9 ⁻¹	0.6	0.5	0.7	1.1	0.9	1.3	1.4	1.2	1.6
2	5.0 ⁻¹	1.1	1.0	1.3	2.1	1.8	2.4	2.6	2.2	3.0
5	2.0 ⁻¹	1.4	1.2	1.6	2.5	2.1	2.9	3.2	2.7	3.7
10	1.0 ⁻¹	1.6	1.4	1.8	2.8	2.4	3.3	3.6	3.1	4.2
25	4.0 ⁻²	1.9	1.6	2.2	3.4	2.9	3.9	4.3	3.7	4.9
50	2.0 ⁻²	2.1	1.8	2.5	3.8	3.2	4.5	4.9	4.1	5.6
100	1.0 ⁻²	2.4	2.0	2.8	4.3	3.6	5.1	5.5	4.6	6.4
200	5.0 ⁻³	2.7	2.2	3.2	4.9	4.0	5.7	6.2	5.1	7.2
500	2.0 ⁻³	3.1	2.6	3.7	5.6	4.6	6.6	7.1	5.8	8.4
1,000	1.0 ⁻³	3.4	2.8	4.1	6.2	5.0	7.4	7.8	6.4	9.4
5,000	2.0 ⁻⁴	4.3	3.4	5.2	7.7	6.1	9.4	9.7	7.8	11.8
10,000	1.0 ⁻⁴	4.7	3.7	5.8	8.4	6.7	10.4	10.6	8.4	13.1
100,000	1.0 ⁻⁵	6.2	4.7	7.9	11.1	8.5	14.4	14.0	10.7	18.0
1,000,000	1.0 ⁻⁶	7.9	5.8	10.7	14.4	10.6	19.5	18.0	13.2	24.4
10,000,000	1.0 ⁻⁷	10.0	7.1	14.5	18.3	12.9	26.5	22.8	16.1	33.0
100,000,000	1.0 ⁻⁸	12.5	8.5	19.2	22.9	15.6	35.1	28.4	19.3	43.5
1,000,000,000	1.0 ⁻⁹	15.5	10.1	25.1	28.5	18.6	46.1	35.2	23.0	57.0
10,000,000,000	1.0 ⁻¹⁰	19.0	11.9	32.6	35.2	22.1	60.3	43.3	27.2	74.2

2.12 Comparison to NOAA PF Estimates

This analysis follows methods similar to those used in NOAA Atlas 14 Vol. 6 (Perica et al., 2013). NOAA Atlas 14 was based on regional L-moments and goodness-of-fit measures, akin to the Nebraska analysis. The updated Nebraska frequency analysis incorporates a significantly larger dataset, including an additional 14 years of observations (2010–2024). The AWA study utilized 143 hourly stations and 991 daily stations, with approximate station record lengths of 2,647 and 46,901 accumulated station years, respectively. In comparison, NOAA Atlas 14 used 35 hourly stations and 369 daily stations within Nebraska, with approximate station record lengths of 1,232 and 27,392 accumulated station years. A key difference between this analysis and Atlas 14 is the handling of annual maxima data, sometimes NOAA Atlas 14 included or excluded different AMS years. While incorporating Atlas 14’s AMS data could help extend the historical record, notable inconsistencies limit its direct integration. For example:

- **Bonny Dam 2 NE, CO (2001):** Atlas 14 rejected a larger 24-hour event (4.26” on 7/15) in favor of a smaller one (1.57” on 5/5) without a clear quality control reason.
- **Agate 3 E, NE:** Atlas 14 excluded several years (1903, 1946, etc.) that this analysis retained, though both sources align on other years. This is a result of screening for the station record percent complete by year.

These discrepancies highlight differences in data selection criteria and emphasize the tradeoffs in integrating Atlas 14 AMS directly. As part of this study, AWA conducted high-level quality control to remove erroneous outliers from the AMS using an approximate 500-year precipitation threshold by duration.

The updated Nebraska analysis applied cluster analysis methods to develop homogeneous regions, ensuring that stations with similar precipitation characteristics were grouped together based on spatial and statistical patterns. This approach enhances regional frequency analysis by reducing variability within each cluster and improving the robustness of estimated precipitation frequency values. In contrast, NOAA Atlas 14 utilized a methodology which relies on predefined regional boundaries and statistical homogeneity tests without explicitly clustering stations based on shared precipitation behavior. The cluster analysis method and spatial modelling of MAM, Lcv, and Lsk used in this study allows for a more data-driven and flexible regionalization process, adapting to localized precipitation trends and station density variations, ultimately leading to more precise and representative frequency estimates.

To illustrate differences between the AWA and NOAA Atlas 14 analyses, we conducted a spatial comparison of precipitation estimates for the 100-year return period at 1-hour, 6-hour, 24-hour, and 72-hour durations (Figure 2.28 and Figure 2.29). This comparison highlights regional variations in estimated precipitation magnitudes, with the most significant differences are observed in the 6-hour western half of the state. This comparison highlights a more variable change across the state with larger values in the western half of the state and lower values in the eastern portions in our new analysis.

In this region, the AWA analysis indicates an increase in precipitation magnitudes compared to NOAA Atlas 14. These differences are primarily attributed to the incorporation of a significantly larger and more recent dataset, improved statistical methodologies, and refined regionalization techniques. The inclusion of 14 additional years of data (2010–2024) captures

additional extreme precipitation events that were not represented in NOAA Atlas 14, leading to higher frequency estimates. Furthermore, the use of cluster analysis for regionalization, rather than the star methodology, allows for more precise grouping of stations with similar precipitation characteristics, reducing statistical bias and improving the accuracy of precipitation frequency estimates.

Regarding the NOAA Atlas 15 precipitation frequency update, the general methodology will be similar to this analysis. However, instead of L-moment statistics, it will rely on maximum likelihood estimation (MLE). Direct comparisons to NOAA Atlas 15 remain challenging, as its overall methodology is still under evaluation (Perica et al., 2024). Additionally, NOAA Atlas 15 is designed to cover the entire contiguous United States (CONUS), whereas this study focuses on region- and site-specific analyses, necessitating different methodological approaches.

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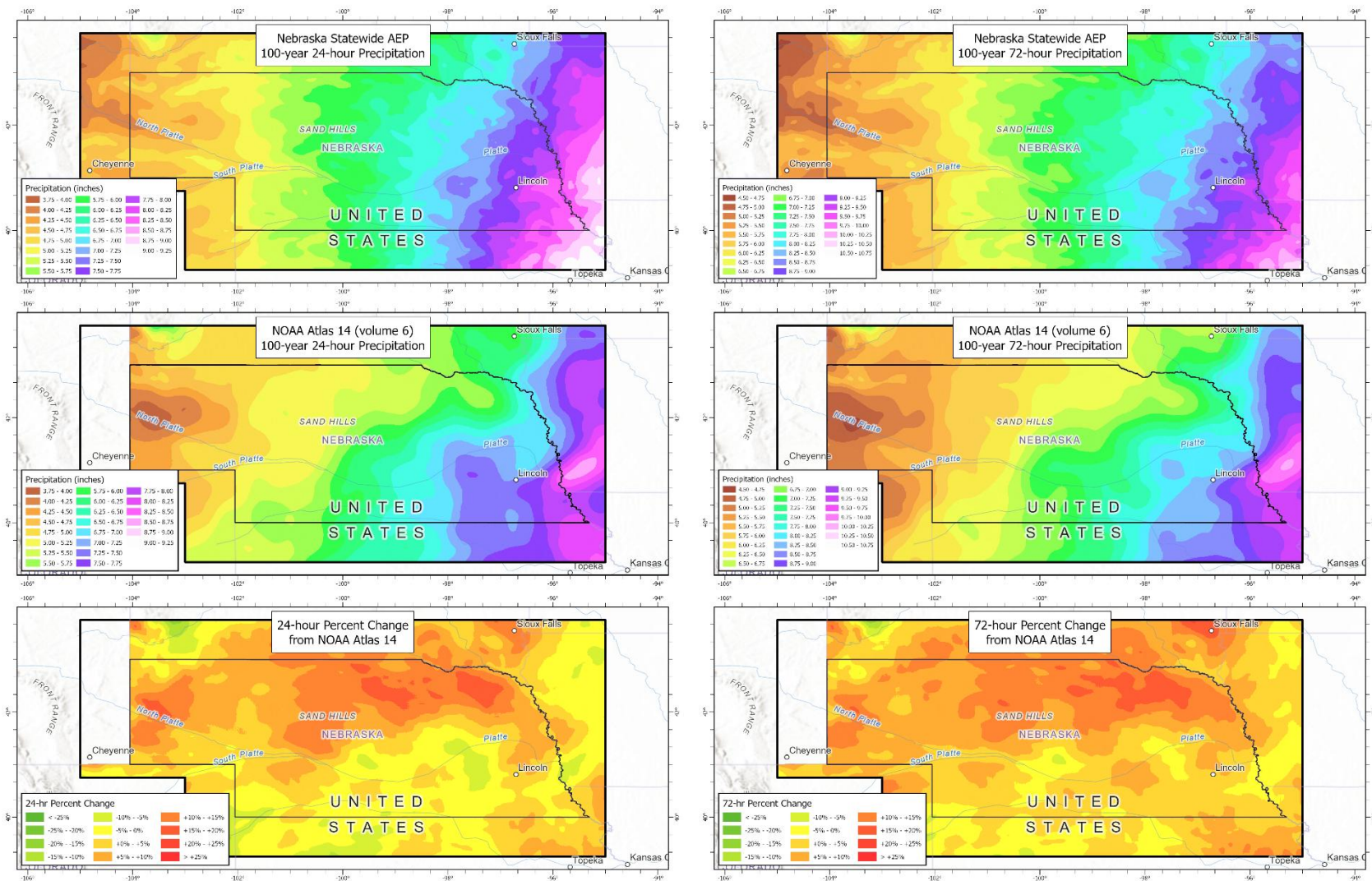


Figure 2.26: Spatial comparison of precipitation estimates for the 100-year return period at 24-hour (left column) and 72-hour (right column) durations. Top row displays the updated Nebraska 100-year precipitation estimates, the middle row shows the NOAA Atlas 14 100-year estimates, and the bottom row illustrates the difference.

Nebraska Statewide Annual Exceedance Probability Study

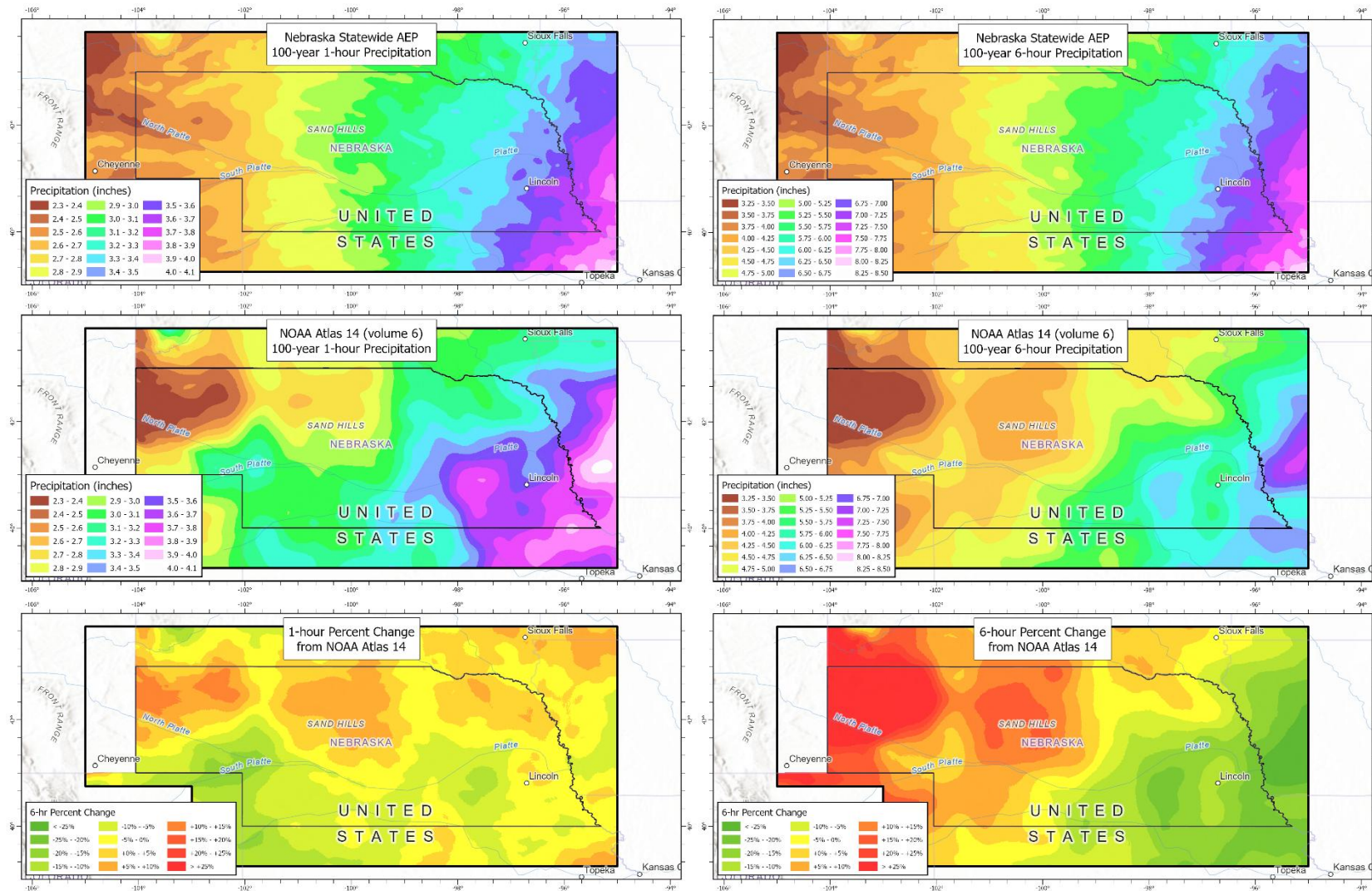


Figure 2.27: Spatial comparison of precipitation estimates for the 100-year return period, 1-hour duration (left column) and 6-hour duration (right column). Top row displays the updated Nebraska 100-year precipitation estimates, the middle row the NOAA Atlas 14 100-year estimates, and the bottom row the differences.

3. Temporal Distributions for Use in Runoff Modeling

Temporal distribution patterns were developed to reflect the rainfall accumulation characteristics applicable to AEP precipitation for Nebraska. Storm temporal patterns were developed by storm duration (6-hour, 24-hour, and 72-hour), application of controlling storm patterns, and through frequency analysis following Huff curve methods (Huff, 1967) applied in NOAA Atlas 14 (e.g., Bonnin et al., 2006 and Perica et al., 2013). The updated Nebraska temporal patterns are to be used in place of the HMR 52 (Hansen et al., 1982) alternating block pattern and/or the critically stacked pattern (Cudworth, 1989).

For the 1-hour temporal distribution, AWA evaluated 5-minute incremental rainfall accumulation patterns derived from SPAS-NEXRAD data (Hultstrand and Kappel, 2017) to identify representative storm events suitable for developing site-specific sub-hourly accumulation guidance. The SPAS-NEXRAD 5-minute data were used to compute ratios of the maximum 5-, 10-, 15-, 20-, 25, 30-, and 45-minute rainfall accumulations relative to the maximum 1-hour rainfall accumulation. This approach follows methodologies described in the Colorado–New Mexico Extreme Storms Study (Kappel et al., 2018) and the North Dakota PMP Study (Kappel et al., 2021). The resulting 1-hour temporal distribution ratios recommended for disaggregating 1-hour AEP rainfall are provided in Appendix G.

For each storm duration, several types of temporal patterns were developed for application to the Nebraska precipitation frequency estimates. These included the 10th percentile, 50th percentile, 90th percentile Huff curves; synthetic curves; and PMP controlling storms distributions. The development of each of these patterns is detailed below.

3.1 Huff Curve Development

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

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

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

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

- 50th curve - the 50th curve indicates that 50% of the corresponding SPAS storms had distributions that fell above and below the 50th curve (mid-loaded)
- 10th curve - the 10th curve indicates that 10% of the corresponding SPAS storms had distributions that fell below and to the right of the 10th curve (back-loaded)

The raw data results are presented below (Figure 3.1 to Figure 3.3); the final curves selected for use were smoothed using non-linear regression and data were provided at 5-minute (local storms) and 15-minute (general, hybrid, tropical) time steps from the non-linear regression equation (data were extracted from the non-linear equation). Some of the Huff curves result in accumulated precipitation at time zero, this is a result of front-loaded storms that generate a significant portion of their precipitation in the first hour, the analysis that was performed on hourly data, and the interpolation method that did not force the curve to zero. The final set of Huff curves were set to zero at time zero.

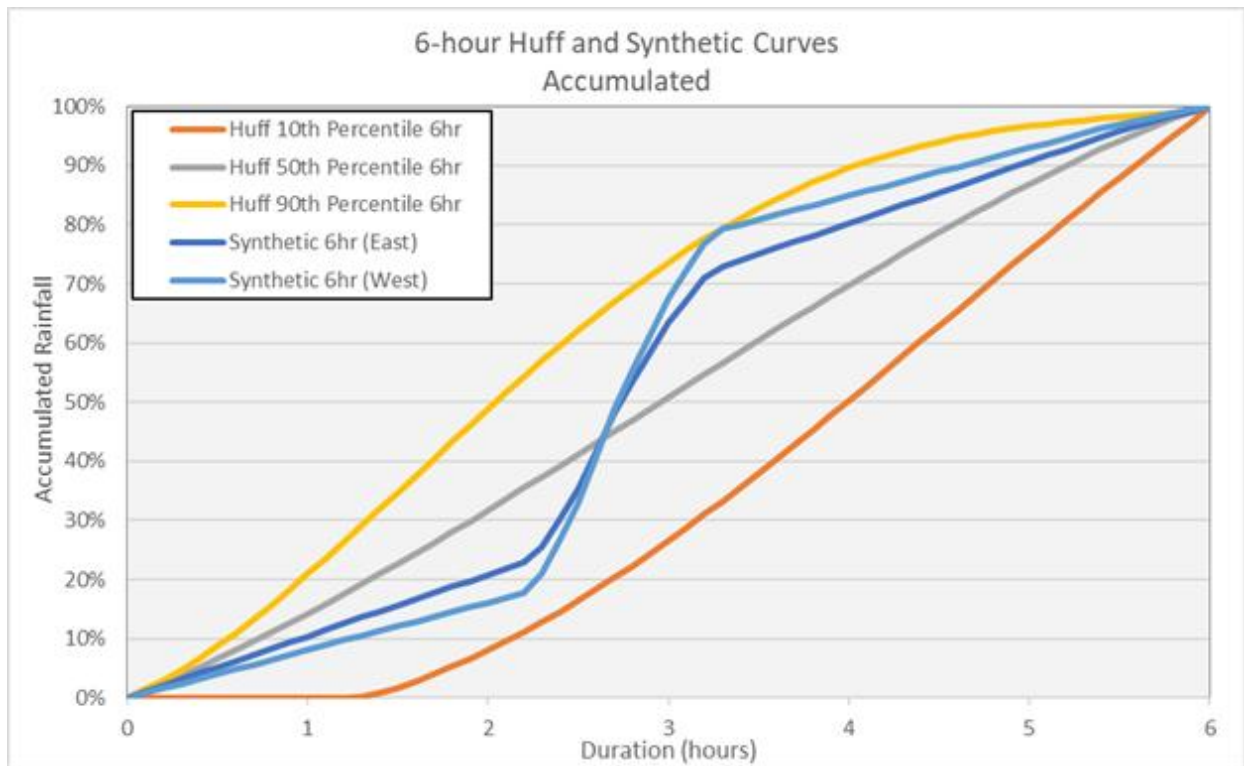


Figure 3.1: Accumulated rainfall patterns for the 10th-, 50th-, 90th-percentile, and Synthetic 6-hour curves

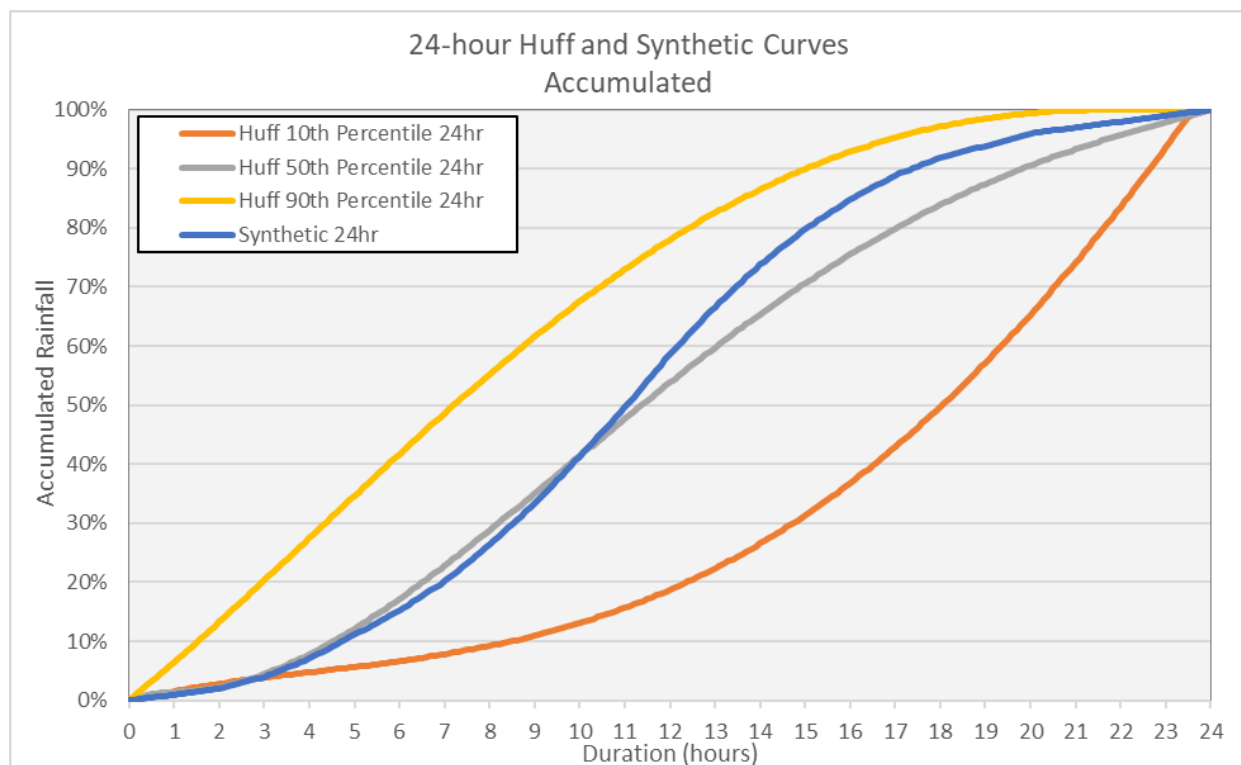


Figure 3.2: Accumulated rainfall patterns for the 10th-, 50th-, 90th-percentile, and Synthetic 24-hour curves

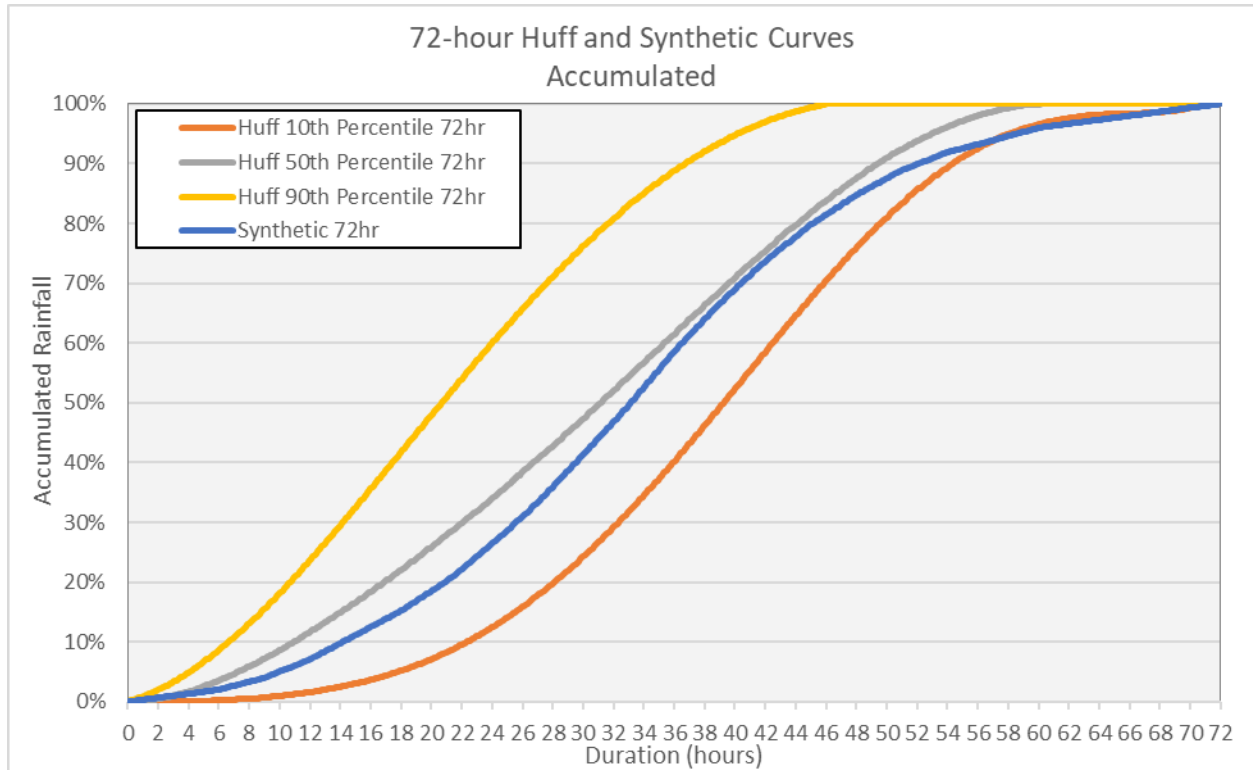


Figure 3.3: Accumulated rainfall patterns for the 10th-, 50th-, 90th-percentile, and Synthetic 72-hour curves

3.2 Synthetic Curve Development

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

3.2.1 Standardized Timing Distribution by Storm Type

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

3.2.2 Temporal Analysis Parameters Evaluated

SPP - Significant Precipitation Period when the majority of the rainfall occurred

R - Accumulated rainfall at the storm center during the SPP

R_n - Normalized R

T - Time when R occurred

T_s - Time when 50% accumulation occurs, value is set to zero. Negative time values precede the time to 50% rainfall, and positive values follow

T_{50} - Time when $R_n = 0.5$

3.2.3 Procedures used to Calculate Parameters

Below are the steps utilized to investigate the rainfall accumulation patterns from each storm used in the PMP development. Each of these were applied to the SPAS analyzed mass curves by storm type.

1. Determine the SPP. Inspect each storm's rainfall data for "inconsequential" rainfall at either the beginning and/or the end of the records. Remove these "tails" from calculations. Generally, AWA used a criterion of less than 0.1 inches/hour intensity to eliminate non-intense periods. No internal rainfall data were deleted.
2. Recalculate the accumulated rainfall records for R. This yields the SPP.
3. Plot the SPAS rainfall and R mass curves and inspect for reasonableness.
4. Normalize the R record by dividing all values by the total R to produce R_n for each hour, R_n ranges from 0.0 to 1.0.
5. Determine T50 using the time when $R_n = 0.5$.
6. Calculate T_s by subtracting T50 from each value of T. Negative time values precede the time to 50% rainfall, and positive values follow.
7. Determine maximum 24-hour and maximum 6-hour precipitation, convert accumulations into a ratio of the cumulative rainfall to the total accumulated rainfall for that duration.
8. Visually inspect resulting data to determine a best fit of the curves. This includes both the intensity (steepness) of accumulation and whether most of the accumulations are exhibiting a front, middle, or back loaded accumulation.

Graphs were prepared of a) R vs T, b) R_n vs T, c) R_n vs T_s , and d) maximum point precipitation for, Local (6-hour), General (24-hour and 72-hour) and Hybrid (24-hour and 72-hour) storm events. Evaluations of the resulting rainfall accumulation curves individually and in relation to each other were completed by visually inspecting the data. From these investigations, a rainfall accumulation pattern that represented a significant majority of the patterns with a steep intensity was utilized as the synthetic pattern. This process is subjective. The objective is to produce a synthetic pattern that captures the majority of the worst-case runoff scenarios for most basins and represents a physically possible temporal accumulation pattern. However, it is not possible for a single synthetic curve to capture all of the worst-case runoff scenarios for all basins.

The 6-hour synthetic pattern was scaled so that the largest 1-hour period of precipitation within the 6-hour distribution would not exceed the 1-hour AEP after the distribution is applied to the 6-hour AEP. A separate version of the 6-hour synthetic pattern was developed for the east (of 102°W) and the west (of 102°W) portions of the study to provide a closer fit to the 1-hour AEP.

3.2.4 Examples of Temporal Pattern Analyses from Adjacent Studies

Following the procedures and description from the previous section, results are presented as three graphs. The graphs are a) R vs T, b) R_n vs T, and c) R_n vs T_s for local, general, tropical, and hybrid storm types. Figure 3.4 to Figure 3.12 show these graphs for SPAS PMP type storm events west of the Appalachian Mountains and east of the Rocky Mountains which are relevant to this study.

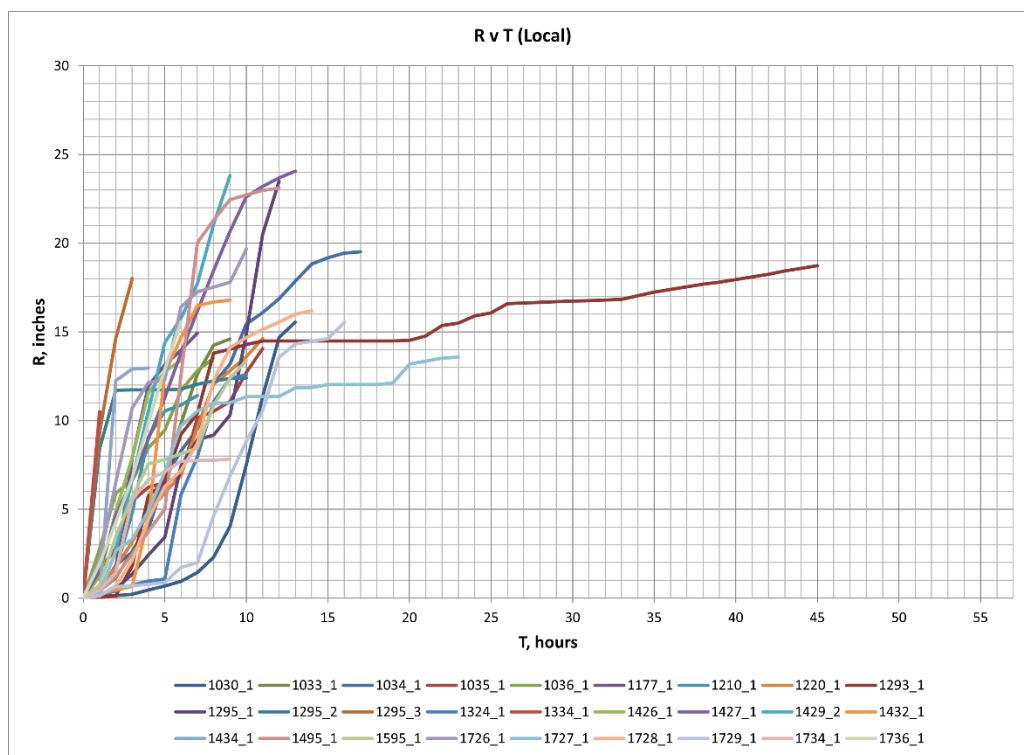


Figure 3.4: SPAS Rainfall (R) versus time (T) for local type storms

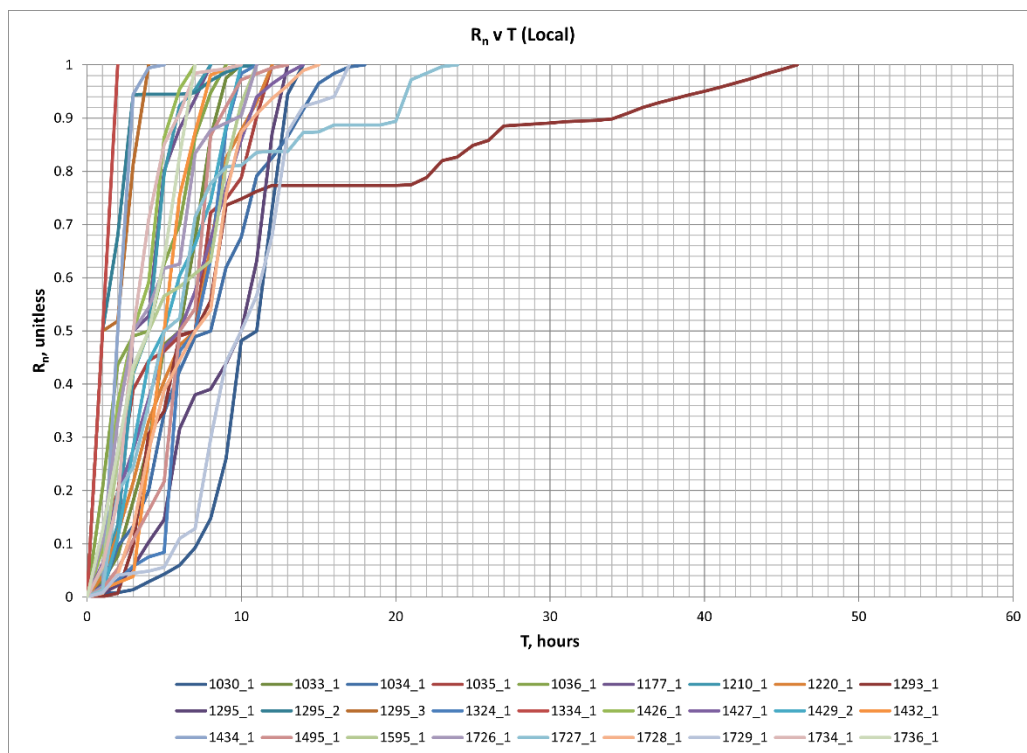


Figure 3.5: Normalized R (R_n) versus time (T) for local type storms

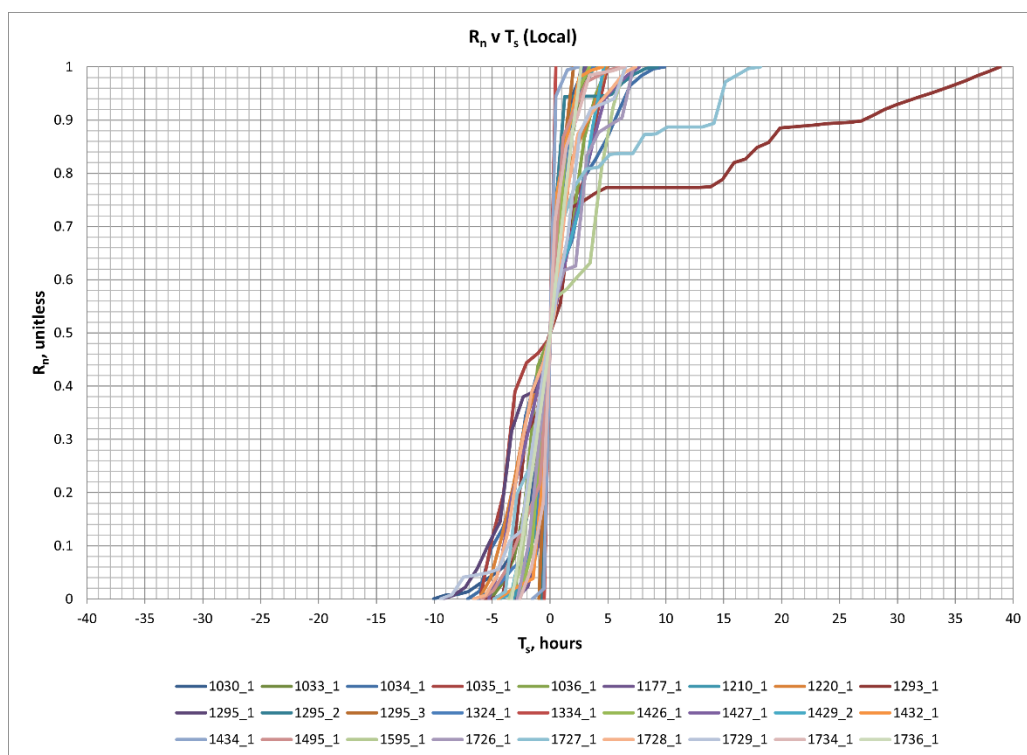


Figure 3.6: Normalized R (R_n) versus shifted time (T_s) for local type storms

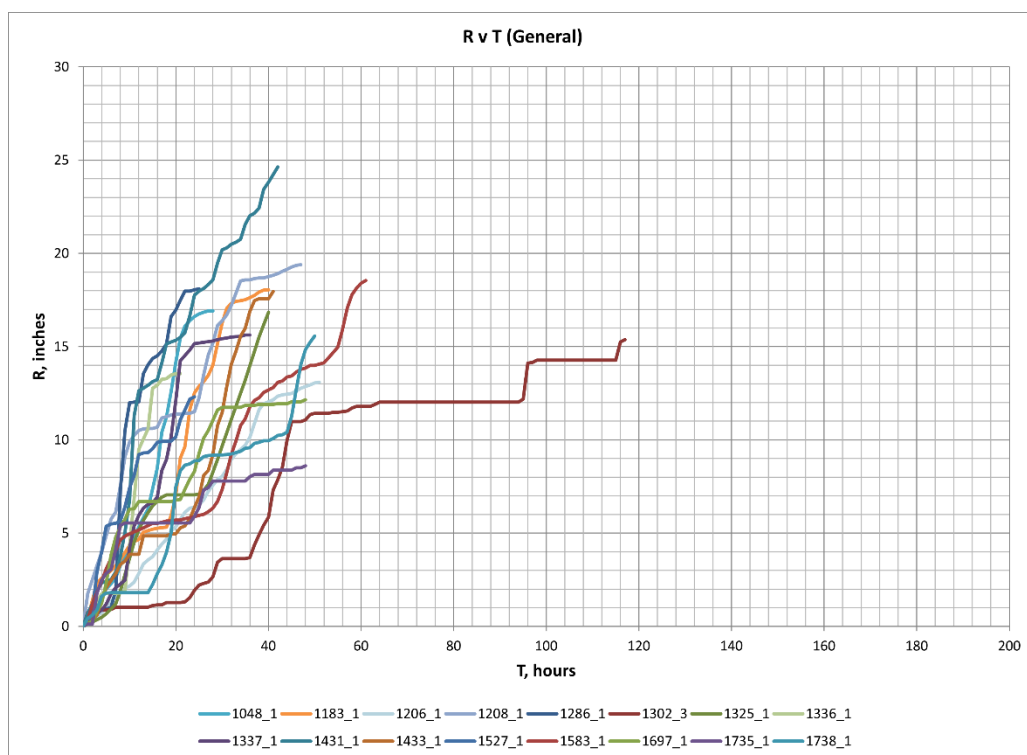


Figure 3.7: SPAS Rainfall (R) versus time (T) for general type storms

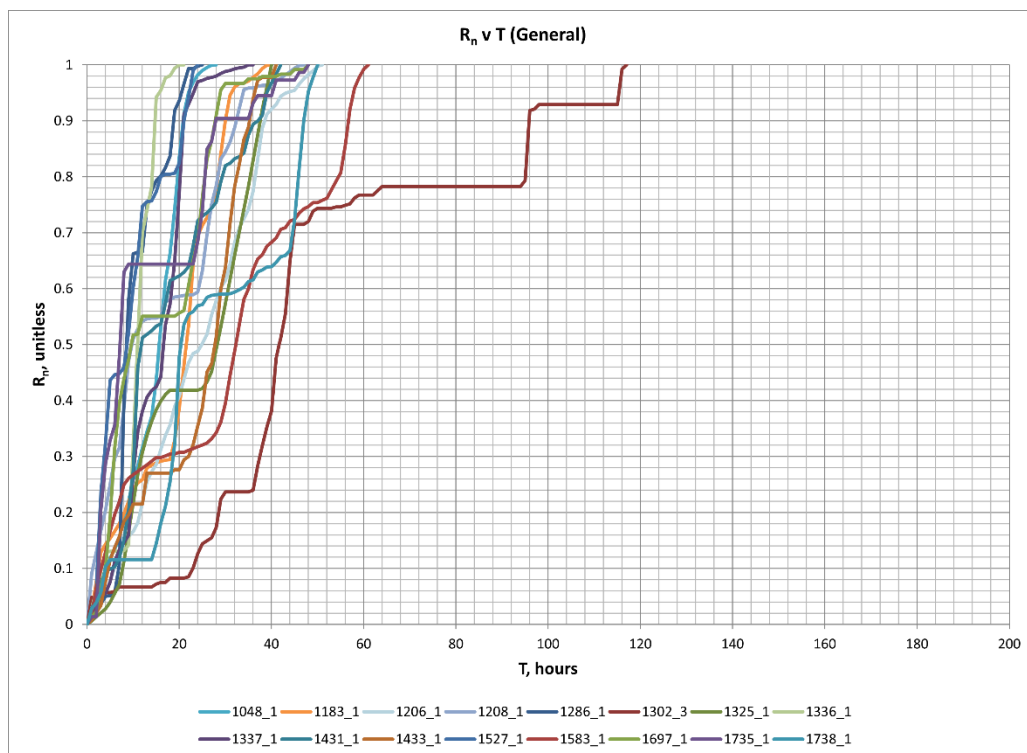


Figure 3.8: Normalized R (R_n) versus time (T) for general type storms

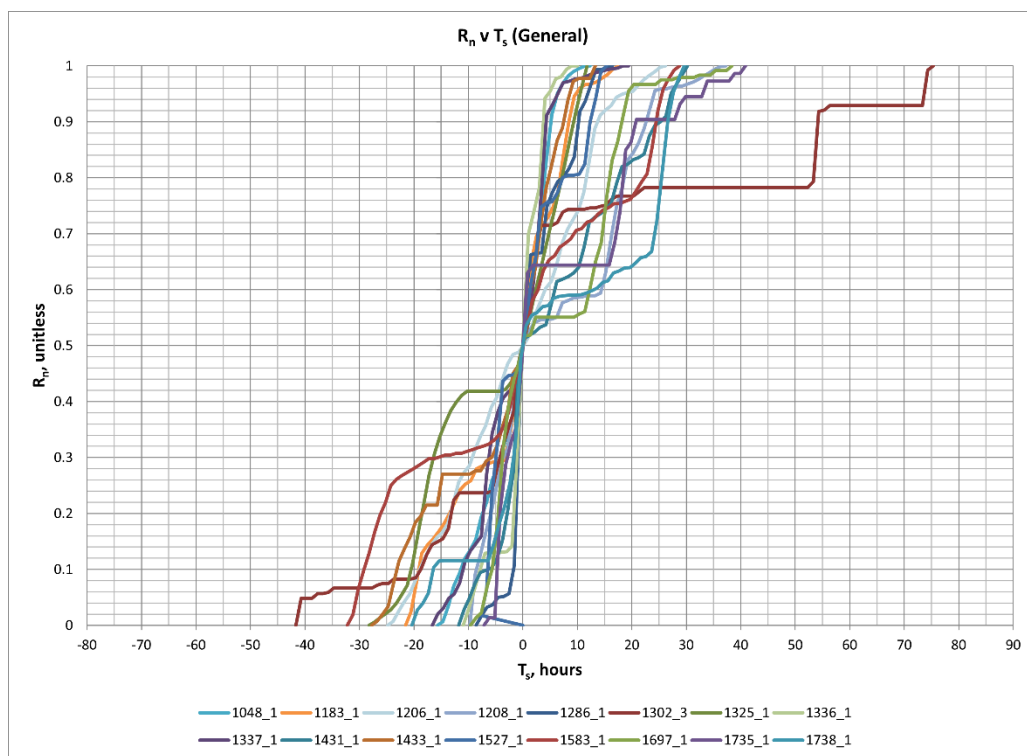


Figure 3.9: Normalized R (R_n) versus shifted time (T_s) for general type storms

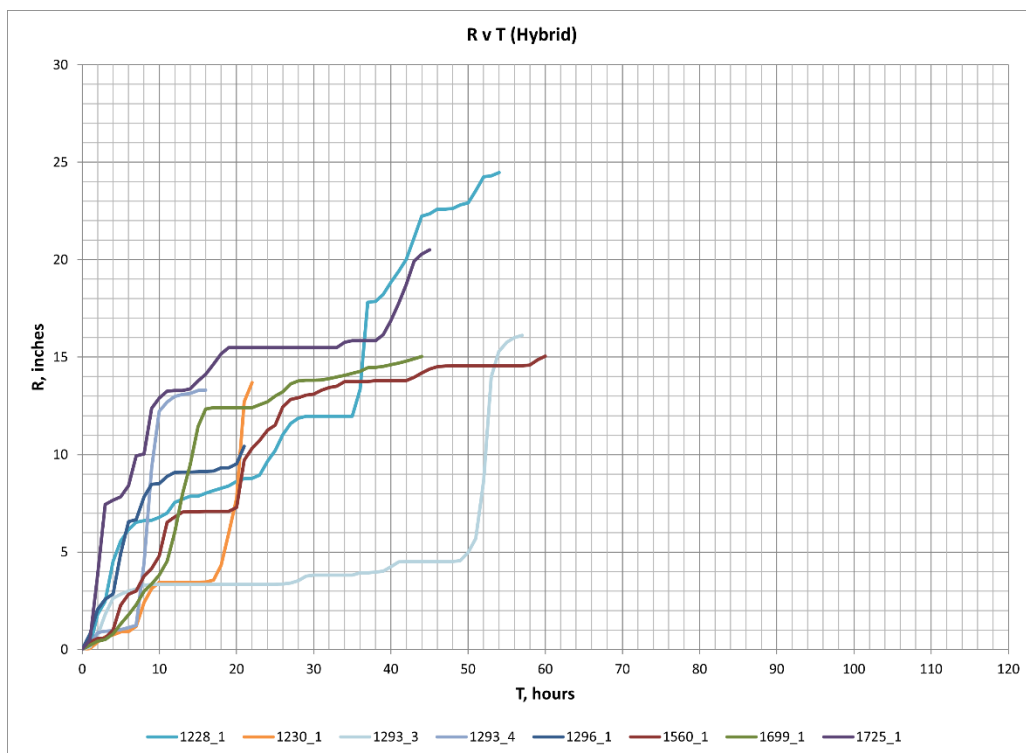


Figure 3.10: SPAS Rainfall (R) versus time (T) for hybrid type storms

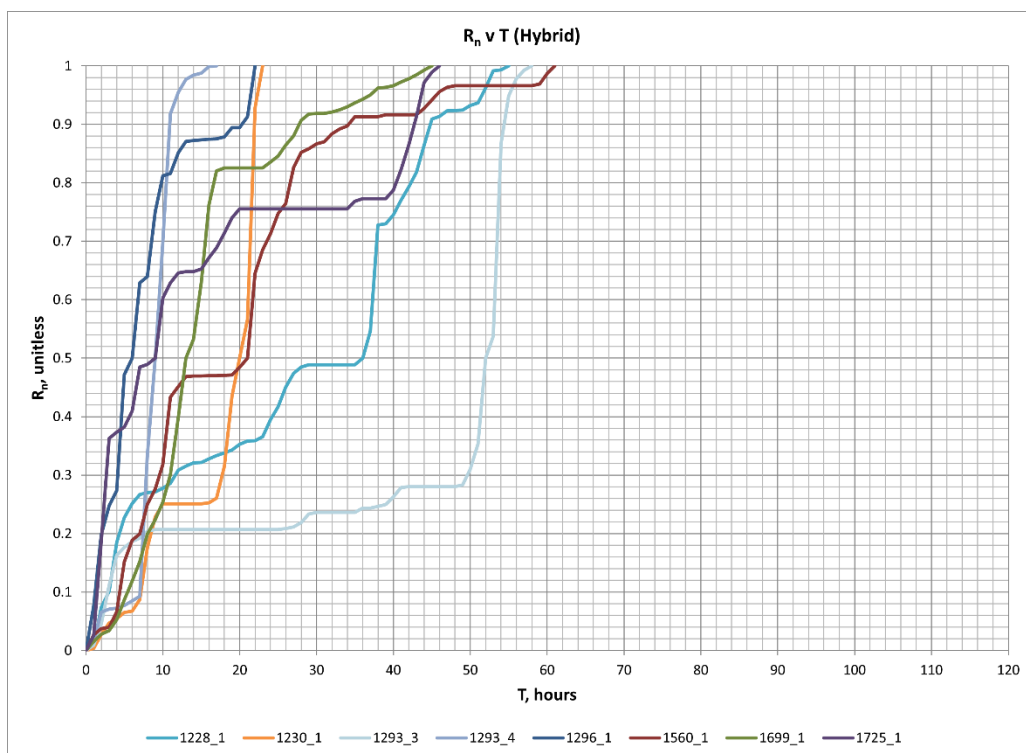


Figure 3.11: Normalized R (R_n) versus time (T) for hybrid type storms

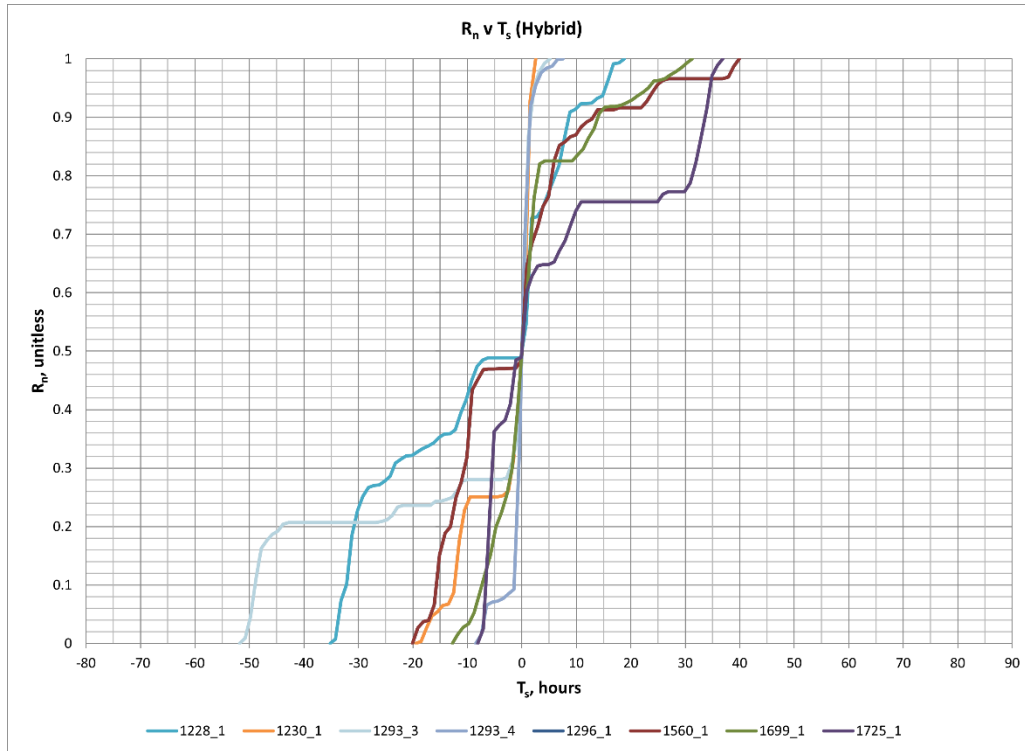


Figure 3.12: Normalized R (R_n) versus shifted time (T_s) for hybrid type storms

3.3 Controlling Storm Curve Development

In addition to the more generalized Huff and Synthetic temporal patterns, distributions derived from Nebraska PMP-controlling storm events were also developed. The 6-hour, 24-hour, and 72-hour PMP from the Nebraska Statewide PMP Study (Tomlinson et al., 2008), were determined. Additionally, more recent PMP studies in the region that have controlling storms considered transposable to the Nebraska AEP domain were also evaluated (Kappel et al., 2015; Kappel et al., 2016; Kappel et al., 2018; Kappel et al., 2019). From these controlling storms, a list was compiled of events of SPAS-analyzed mass curves which were determined to have good confidence in temporal accuracy and appropriate for AEP precipitation temporal distributions. Table 3.1 provides the list of storms utilized to develop the controlling storm temporal distributions.

The storms were divided into regions according to their transposition limits. The ‘east’ region storms, aligning with the ARF region 1 & 2 group, are storms transposable to the eastern portion of the analysis domain (east of 102°W). The ‘west’ region storms, aligning with the ARF region 3, are storms transposable to the western portion of the analysis domain (west of 102°W). The controlling storm temporal patterns are applied with the AEP GIS tools (Section 4) based on the point or basin centroid location.

Table 3.1: PMP-controlling events used for controlling storm temporal distributions

SPAS ID	NAME	Storm Center Latitude	Storm Center Longitude	Total Storm Precip (in.)	Region	Duration
SPAS_1286_1	Aurora College, IL Jul. 1996	41.458	-88.070	18.13	East	6hr/24hr
SPAS_1583_1	Council Grove, KS Jul. 1951	38.646	-96.621	18.56	East	6hr/24hr/72hr
SPAS_1030_1	David City, NE Jun. 1963	41.213	-97.071	15.98	East	6hr/24hr
SPAS_1183_1	Edgerton, MO Jul. 1965	40.413	-95.513	20.76	East	24hr/72hr
SPAS_1429_2	Hallett, OK Sep. 1940	36.246	-96.613	24.00	East	6hr
SPAS_1736_1	Stanton, NE Jun. 1944	41.821	-97.029	17.49	East	6hr
SPAS_1427_1	Boyden, IA Sep. 1926	43.196	-95.996	24.22	East	6hr/24hr
SPAS_1036_1	Pawnee Creek, CO Jul. 1997	40.775	-103.625	13.58	West	6hr
SPAS_1295_3	Hale, CO May. 1935	39.613	-102.263	18.00	West	6hr
SPAS_1293_1	Holly, CO Jun. 1965	37.713	-102.404	19.18	West	6hr
SPAS_1302_3	Aurora, CO Sep. 2013	39.670	-104.850	16.62	West	24hr/72hr

To extract the controlling storm temporal distribution patterns, the hourly rainfall incremental depths were extracted from the mass curves for the largest consecutive period of rainfall over the analysis duration at the SPAS-analyzed storm center. The extracted hourly precipitation time series were normalized to non-dimensional incremental and accumulated rainfall factors. These hourly factors were then converted to 15-minute timesteps by linearly interpolating between each hourly data point. The accumulated precipitation controlling storm temporal curves are plotted for the 6-hour duration (**Error! Reference source not found.**), 24-hour duration (**Error! Reference source not found.**), and 72-hour duration (**Error! Reference source not found.**).

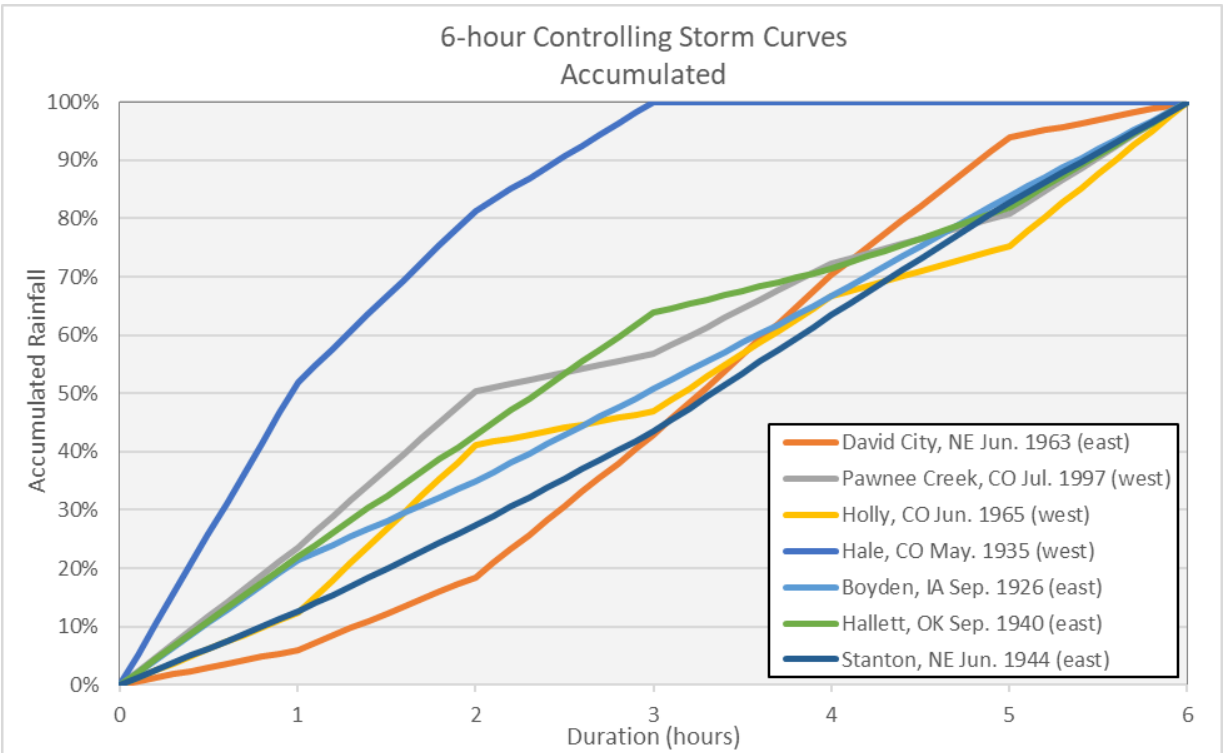


Figure 3.13: Accumulated rainfall patterns for the controlling storm 6-hour curves

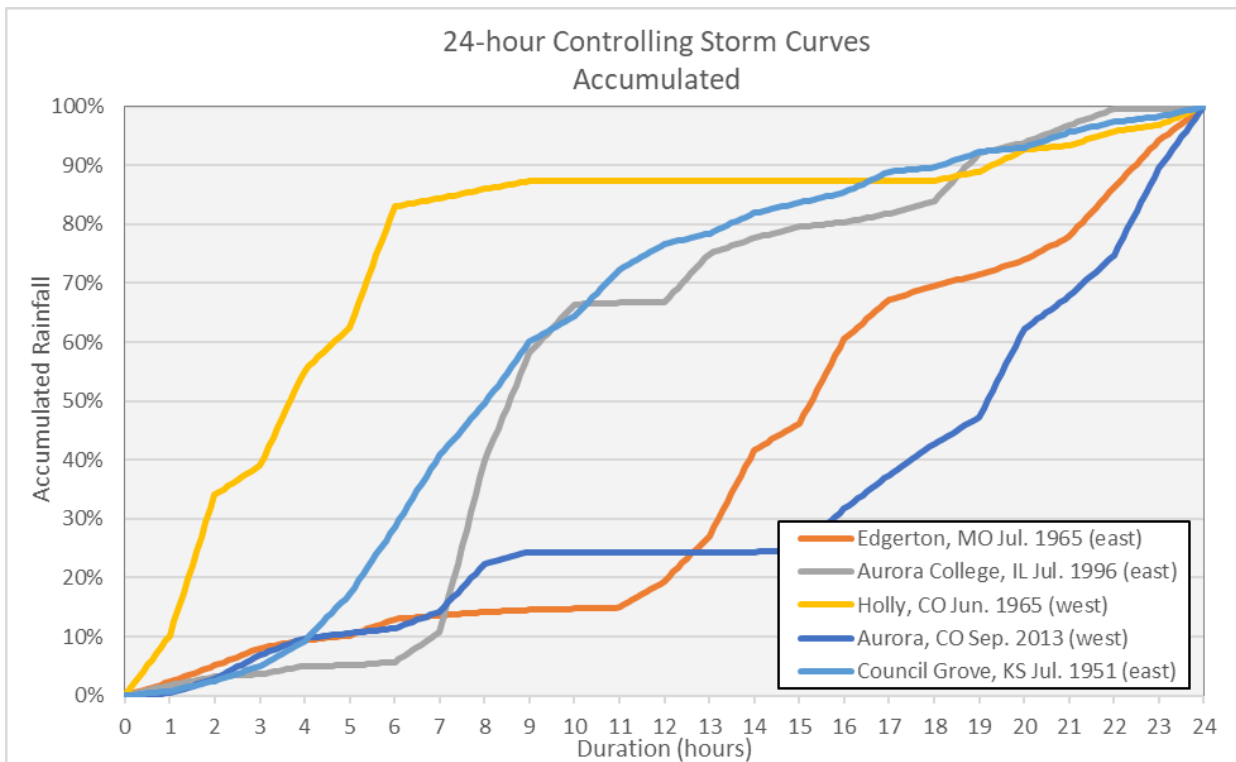


Figure 3.14: Accumulated rainfall patterns for the controlling storm 24-hour curves

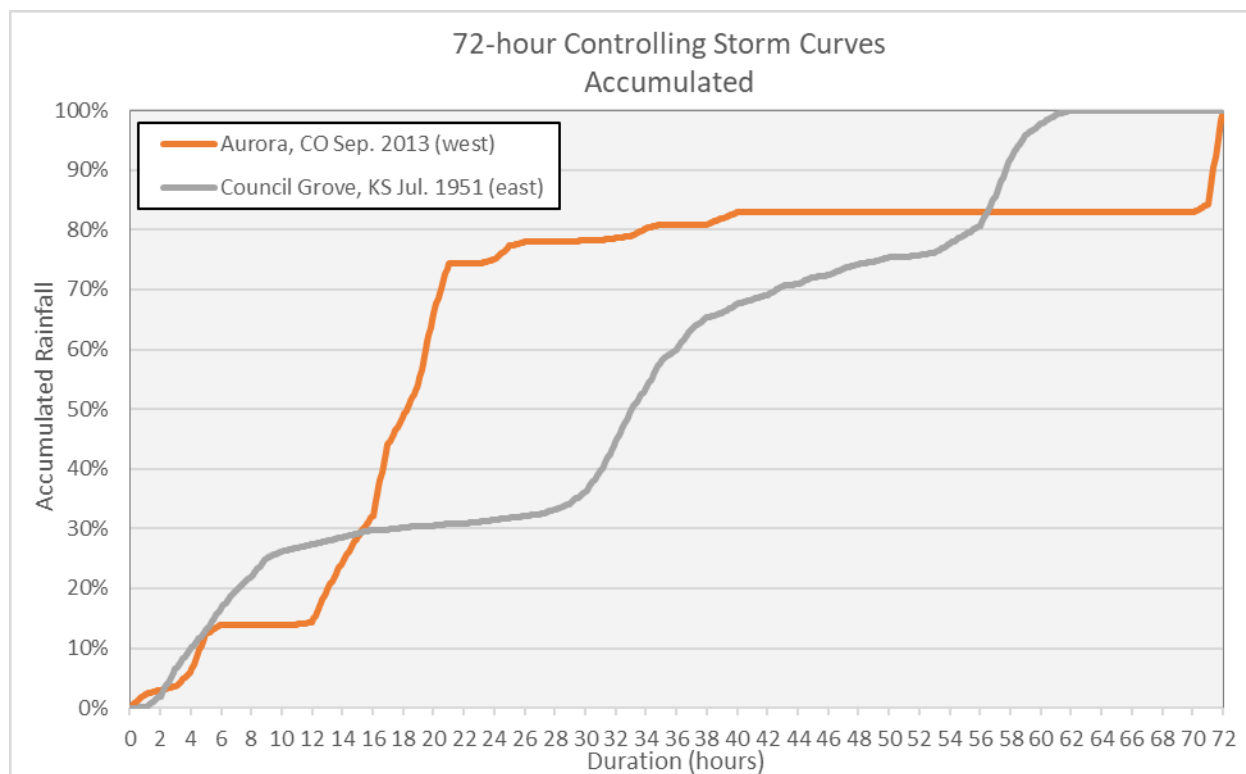


Figure 3.15: Accumulated rainfall patterns for the controlling storm 72-hour curves

3.4 Temporal Distribution Application

For each duration, a ‘recommended’ distribution is identified to provide the user with single distribution recommended for hydrologic analysis. This pattern is estimated to be the most critical reasonable distribution associated with the given duration and location. The recommended temporal distribution for each duration/basin location is provided in Table 3.1. Additionally, several ‘alternative’ patterns are also provided and considered applicable for hydrologic analysis. The AEP GIS tools, as discussed in Section 4, provide the recommended and alternative temporal distributions as output.

Table 3.2 Recommended temporal distribution for each duration

Duration/Location	Distribution
6-hour East:	Synthetic 6hr (East)
6-hour West:	Synthetic 6hr (West)
24-hour East:	Aurora College, IL Jul. 1996
24-hour West:	Holly, CO Jun. 1965
72-hour East:	Council Grove, KS Jul. 1951
72-hour West:	Aurora, CO Sep. 2013

4. Web Application and ArcGIS Pro Tool

GIS-based tools were developed to provide users with the ability to efficiently calculate point or basin average precipitation frequency estimates, AEP of PMP, and temporal distribution outputs. Two independent GIS tools were developed to allow users an option based on analysis needs and software availability. The web-based application allows the user to obtain point or basin average precipitation frequency information from a web browser without ArcGIS software. The desktop GIS tool allows users to obtain the same information from within the ArcGIS Pro environment which allows for additional GIS analysis capabilities including gridded analysis. Both tools utilize the same source datasets and calculation algorithms ensuring output consistency.

The tool accepts a polygon layer (representing a drainage basin) or point layer (representing a discrete location) as input. The precipitation frequency estimates are extracted over the basin (or point) layer and the gridded average is calculated and tabulated. A spatial resolution of 90 arc-seconds is used for gridded calculations. The basin area is calculated and the appropriate ARF is calculated based on the basin centroid location. The ARF is applied to the precipitation frequency estimates. The 5% and 95% confidence intervals are calculated and tabulated. If PMP depths were provided, the tool calculates the AEP of PMP by interpolating the recurrence interval of PMP from the precipitation frequency series. AEP of PMP can be calculated for the 6-, 24-, and 72-hour durations. AEP of PMP is not available for the 1-hour duration as 1-hour PMP was not available. The tool then applies the appropriate temporal distributions for each analysis duration (6-, 24-, and 72-hours) to the AEP of the user's choice. Finally, the tool provides the AEP output tables and plots.

4.1 Web Application

The Nebraska Precipitation AEP Web Application is a web application developed by AWA and hosted on the AWA GIS Portal. The application allows users to upload a GIS file (in Shapefile, CSV, KML, GeoJSON, or GPX format) representing a drainage basin or point location. Alternatively, the user can 'draw' a point or area on the map to use as the analysis input. The user then populates the AEP tool with the basin (or point) layer, and optionally the basin (or point) PMP depths (for the 6-, 24-, and 72-hour durations), and the AEP to use for temporal distribution (Figure 4.1).

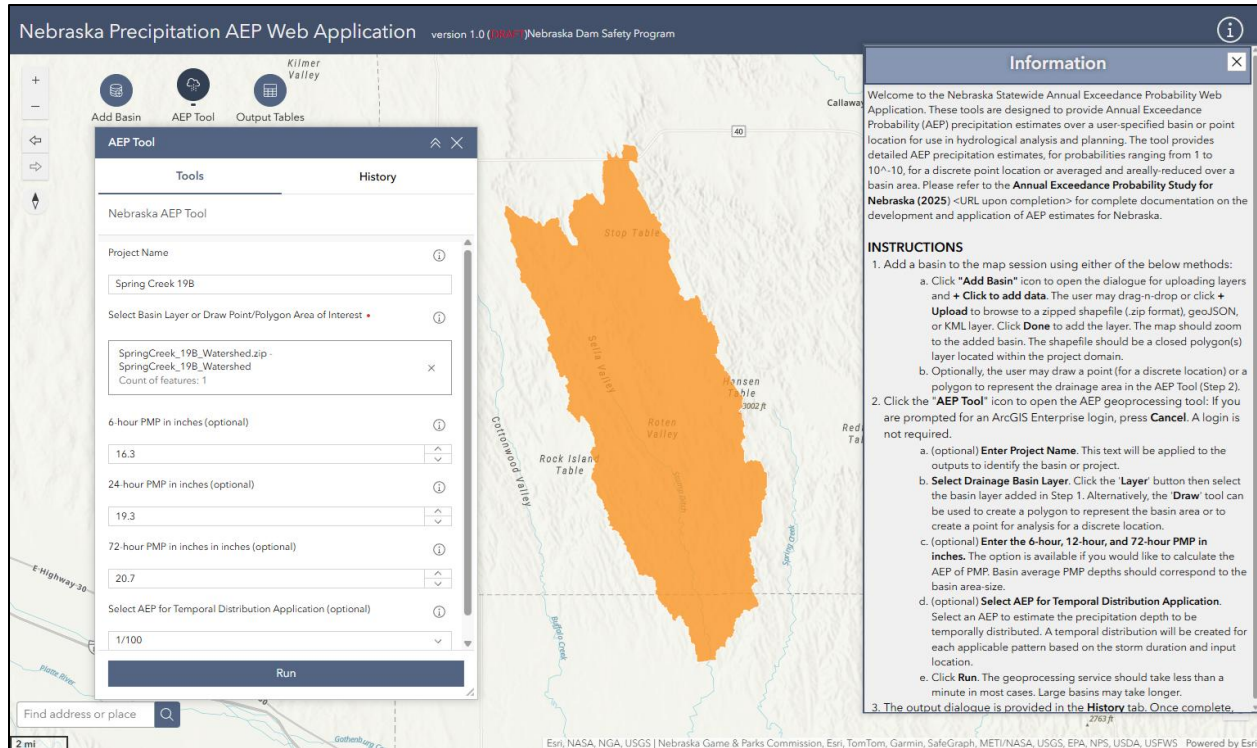


Figure 4.1: Nebraska Precipitation AEP Web Application

After running the tool, the application provides the user with a dialogue (Figure 4.2) of output messages, output AEP tables which can be viewed in the application, an Excel file download link which includes all output tables (basin average or point precipitation frequency and temporal distributed precipitation), and plot images of the basin (or point) precipitation frequency estimates with AEP of PMP (if PMP was provided), and applicable temporal distributions. Example output precipitation vs AEP plots for the Spring Creek 19B basin are provided for the 6-hour duration (Figure 4.3), 24-hour duration (Figure 4.4), and 72-hour duration (Figure 4.5).

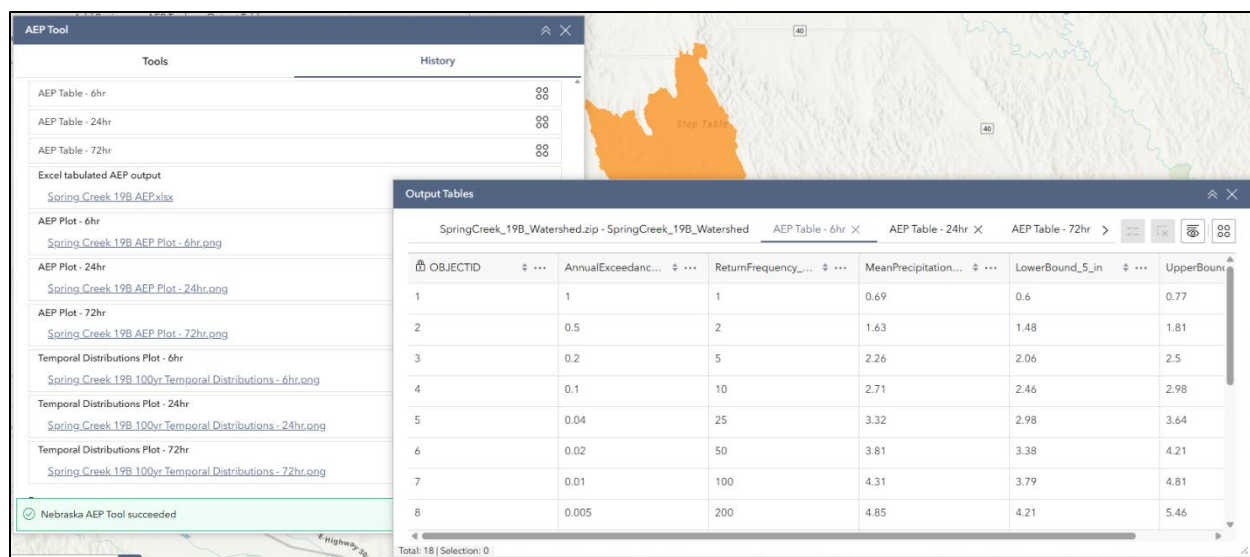


Figure 4.2: Example of the web application output dialogue

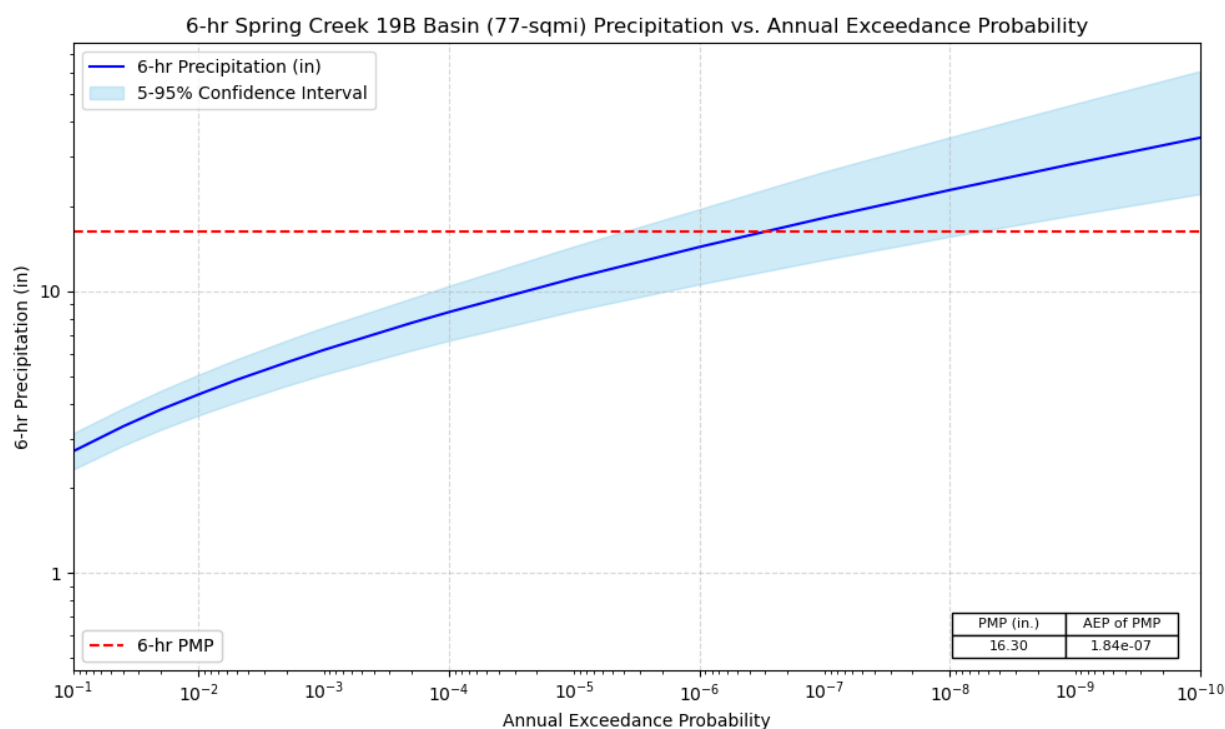


Figure 4.3: Sample output plot of the 6-hour basin average precipitation vs AEP

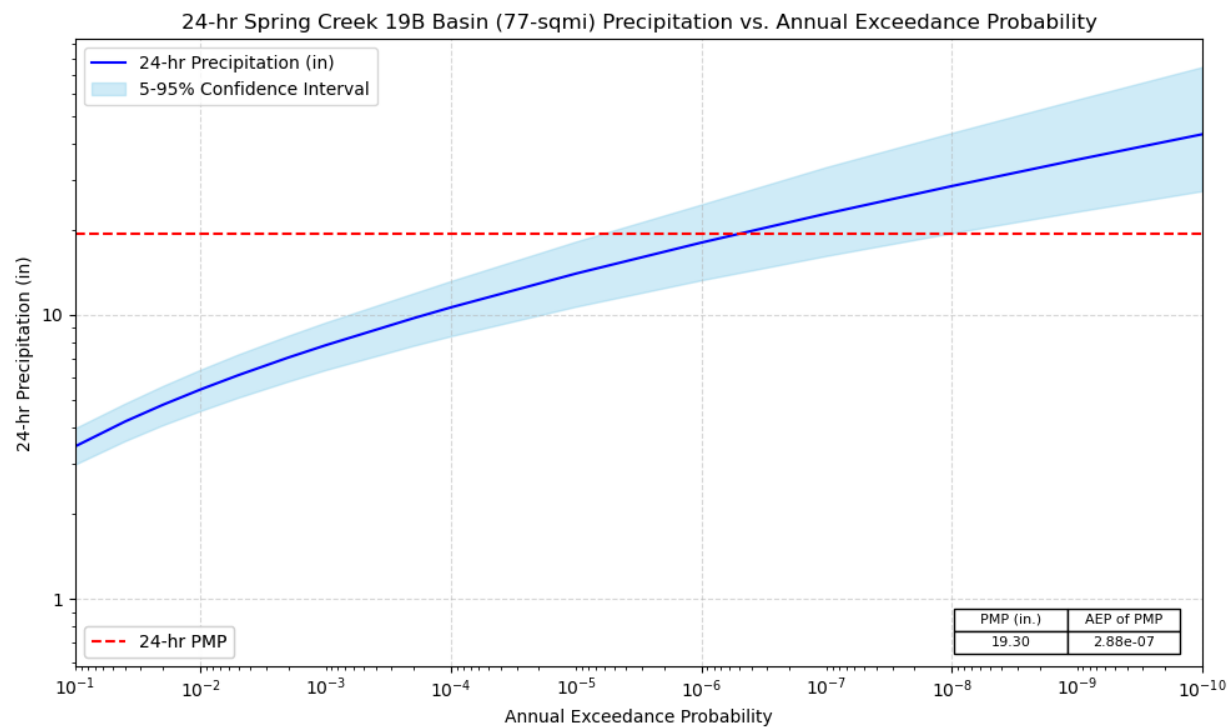


Figure 4.4: Sample output plot of the 24-hour basin average precipitation vs AEP

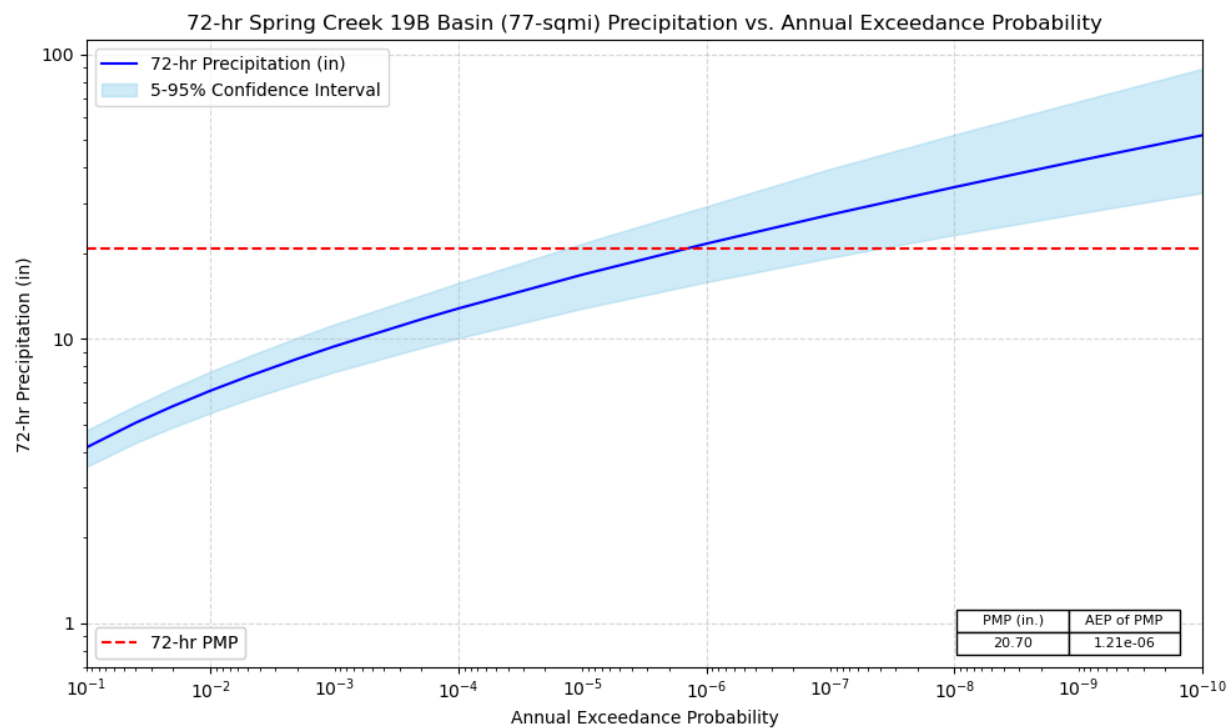


Figure 4.5: Sample output plot of the 72-hour basin average precipitation vs AEP

4.2 Desktop GIS Tool

An ArcGIS Pro desktop GIS tool was developed and provided with this study. The tool is a Python Script Tool and requires ArcGIS Pro software with a Basic license level. No additional extensions are required. The tool was developed and tested on ArcGIS Pro version 3.5.

The desktop GIS tool is accessed from an ArcGIS Pro project by navigating to the local folder containing the tool and opening the Nebraska_AEP_Tools.tbx toolbox to access the script tool. The tool has the same input dialogue as the web application and provides the same output, with the exceptions of the added parameter to provide a folder path for output files and the option to ‘Extract AEP GRIDs over basin’. If this option is selected, the tool will clip each precipitation frequency GRID to the basin, apply the ARI, and output the GRID (in ESRI Geodatabase Raster format) to a geodatabase in the output folder, along with the standard outputs.

The screenshot shows the 'Nebraska AEP Tool' dialog box within the 'Geoprocessing' pane of ArcGIS Pro. The 'Parameters' tab is active. The 'Project Name' is 'Spring Creek 19B'. The 'Select Basin Layer or Draw Point/Polygon Area of Interest' dropdown is set to 'SpringCreek_19B_Watershed'. The 'Output Folder Location' is 'Temporal Distribution'. The 'Calculate AEP of PMP?' checkbox is checked. The '6-hour PMP in inches' is 16.3, '24-hour PMP in inches' is 19.3, and '72-hour PMP in inches' is 20.7. The 'Select AEP for Temporal Distribution Application (optional)' dropdown is set to '1/100'. The 'Extract AEP GRIDs over basin?' checkbox is checked. A 'Run' button is at the bottom right.

Parameter	Value
Project Name	Spring Creek 19B
Select Basin Layer or Draw Point/Polygon Area of Interest	SpringCreek_19B_Watershed
Output Folder Location	Temporal Distribution
Calculate AEP of PMP?	☒
6-hour PMP in inches	16.3
24-hour PMP in inches	19.3
72-hour PMP in inches	20.7
Select AEP for Temporal Distribution Application (optional)	1/100
Extract AEP GRIDs over basin?	☒

Figure 4.6: Desktop GIS tool input dialogue window

5. References

- Bonnin, G., D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, 2006: NOAA *Atlas 14 Volume 2, Precipitation-Frequency Atlas of the United States, Delaware, District of Columbia, Illinois, Indiana, Kentucky, North Carolina, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia*. NOAA, National Weather Service, Silver Spring, MD.
- Cudworth, A.G., 1989: Flood Hydrology Manual, Water Resources Technical Publication, United States Dept, of the Interior, United States Bureau of Reclamation, Denver office, 243pp.
- Daly, C., Taylor, G., and W. Gibson, 1997: The PRISM Approach to Mapping Precipitation and Temperature, 10th Conf. on Applied Climatology, Reno, NV, Amer. Meteor. Soc., 10-12.
- England, J. F., Julien, P. Y., & Velleux, M. L., 2014: Physically-based extreme flood frequency with stochastic storm transposition and paleoflood data on large watersheds. *Journal of Hydrology*, 510, 228–245.
- Guo, J.C.Y., 2012: Storm Centering Approach for Flood Predictions from Large Watersheds, *Journal of Hydrologic Engineering*.
- Hansen, E.M., L.C. Schreiner and J.F. Miller, 1982: Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian. Hydrometeorological Report No. 52, U.S. Department of Commerce, Washington, D.C., 168 pp.
- Hastie T, R. Tibshirani, 1987. Generalised additive model: Some applications, *Journal of the American Statisticians Association*, 82: 371–386
- Hershfield, D.M., 1961: *Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years*. Weather Bureau Technical Paper No. 40, U.S. Weather Bureau, Washington, D.C., 115 pp.
- Hosking, J.R.M, 2015a. L-moments. R package, version 2.5. URL: <http://CRAN.R-project.org/package=lmom>.
- Hosking, J.R.M, 2015b. Regional frequency analysis using L-moments. R package, version 3.0-1. URL: <http://CRAN.R-project.org/package=lmomRFA>.
- Hosking, J.R.M. and J.R. Wallis, 1997: “Regional Frequency Analysis, An Approach Based on L-Moments,” Cambridge University Press, 224 pp.
- Huff, F.A., 1967: Time Distribution of Rainfall in Heavy Storms, Water Resources Research.
- Hultstrand, D.M., and Kappel, W.D., 2017: The Storm Precipitation Analysis System (SPAS) Report. Nuclear Regulatory Commission (NRC) Inspection Report No 99901474/2016-201, Enercon Services, Inc., 95pp
- Hultstrand, D.M., S.R. Fassnacht, J.D. Stednick, and K. Suzuki, 2024: The Best Precipitation Estimates for a Hydrologic Model by Combining Gauge and Radar Data. *Geoöko*, XLV(1-4), 5-34.
- Hultstrand, D.M., Kappel, W.D., Steinhilber, K., Venticinque, M., 2025: Precipitation Frequency and Climate Change Analysis for the Mile High Flood District.
- Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., Parzybok, T.W, and E.M. Tomlinson, December 2014: Statewide Probable Maximum Precipitation (PMP) Study for Wyoming.

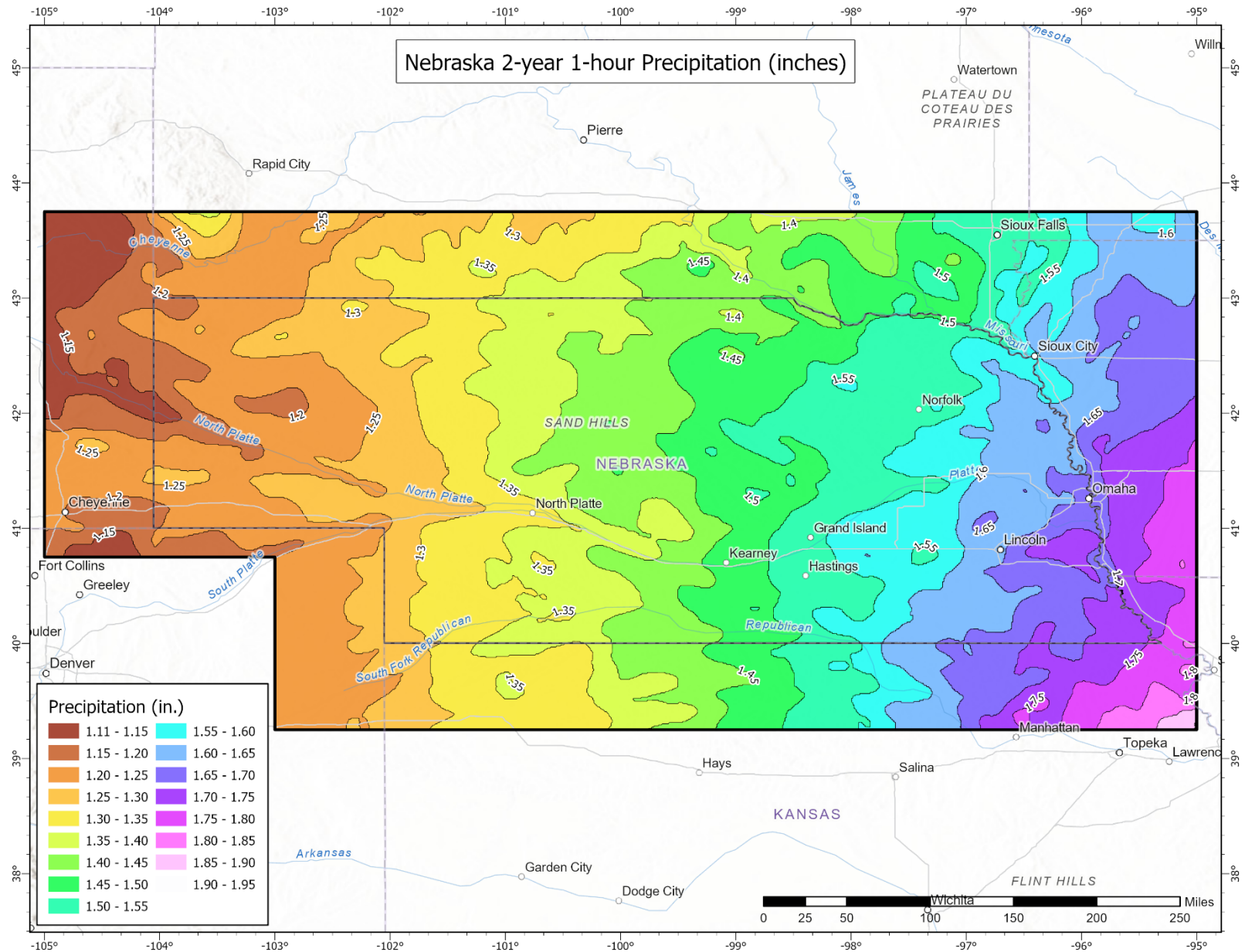
- Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., and McGlone, D., December 2015: Application of Temporal Patterns of PMP for Dam Design in Wyoming. Prepared for the Wyoming State Engineer's Office.
- Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., Rodel, J.T., McGlone, D., Parzybok, T.W., and B. Lawrence, September 2016: Statewide Probable Maximum Precipitation for Texas. Prepared for the Texas Commission of Environmental Quality.
- Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., and B. Lawrence, August 2018: Regional Probable Maximum Precipitation for the States of Colorado and New Mexico. Prepared for the Colorado Division of Water Resources and the New Mexico State Engineers Office.
- Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., Rodel, J., and B. Lawrence, August 2019: Regional Probable Maximum Precipitation for the states of Oklahoma, Arkansas, Louisiana, and Mississippi. Prepared for the Oklahoma Water Resources Board, Arkansas Dept. of Natural Resources, Louisiana Dept. of Transportation & Development, Mississippi Dept. of Environmental Quality.
- Kappel, W.D., Hultstrand, D.M., Rodel, J.T., Muhlestein, G.A., and Steinhilber, K., June 2021: Statewide Probable Maximum Precipitation for North Dakota. Prepared for the North Dakota State Water Commission.
- Kappel, W.D., Hultstrand, D.M., Rodel, J.T., Muhlestein, G.A., Venticinque, M, Cheke, D., and Steinhilber, K., July 2023: Statewide Probable Maximum Precipitation for New Jersey. Prepared for the New Jersey Dept. of Environmental Protection Dam Safety.
- Langbein, W. B., 1949. Annual Floods and the Partial-Duration Flood Series. Transactions American Geophysical Union 30, 879-881.
- López-Moreno J.I., D. Nogués-Bravo, 2005. A generalized additive model for the spatial distribution of snowpack in the Spanish Pyrenees, Hydrological Processes, 19, 3167–3176. <https://doi.org/10.1002/hyp.5840>
- Natural Resources Conservation Service (NRCS), Conservation Engineering Division. (2005, July). Earth Dams and Reservoirs, TR-60.
- Perica, S., Martin, D., Pavlovic, S., Roy, I., St. Laurent, M., Trypaluk, C., Unruh, D., Yetka, M., Bonnin, G., 2013: *NOAA Atlas 14 Volume 8 Version 2.0, Precipitation-Frequency Atlas of the United States, Midwestern States*. Tech. Rep., NOAA National Weather Service, Silver Spring, MD. <http://hdsc.nws.noaa.gov/hdsc/pfds/>
- Perica, S., J. Hanrahan, M. Lago, K. Kunkel, and D. Martin, 2024: Atlas 15 Pilot Technical Report. NOAA. National Weather Service, Office of Water Prediction, Silver Spring, MD.
- PRISM Mapping Methodology, <http://www.ocs.oregonstate.edu/prism/index.phtml> Schaefer, M.G., B.L. Barker, G.H. Taylor and J.R. Wallis, 2006: *Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Eastern Washington*. Publication prepared for Washington State Department of Transportation, MGS Engineering Consultants. Tomlinson, E.M., Kappel W.D., Parzybok, T.W., Hultstrand, D., Muhlestein, G., and P. Sutter, December 2008: Statewide Probable Maximum Precipitation (PMP) Study for the state of Nebraska, Prepared for Nebraska Dam Safety, Omaha, Nebraska.
- Weiss, L.L., 1964: Ratio of True to Fixed Interval Maximum Rainfall, Journal Hydraulics, ASCE, 90(HY1), pp77-82.

- World Meteorological Organization, 1986: Manual for Estimation of Probable Maximum Precipitation, Operational Hydrology Report No 1, 2nd Edition, WMO, Geneva, 269 pp.
- World Meteorological Organization, 2009: Manual for Estimation of Probable Maximum Precipitation, Operational Hydrology Report No 1045, WMO, Geneva, 259 pp.
- Young, B.C and B.M. McEnroe, 2003: Sampling Adjustment Factors for Rainfall Recorded at Fixed Time Intervals. Journal of Hydrologic Engineering, Vol8 (5).

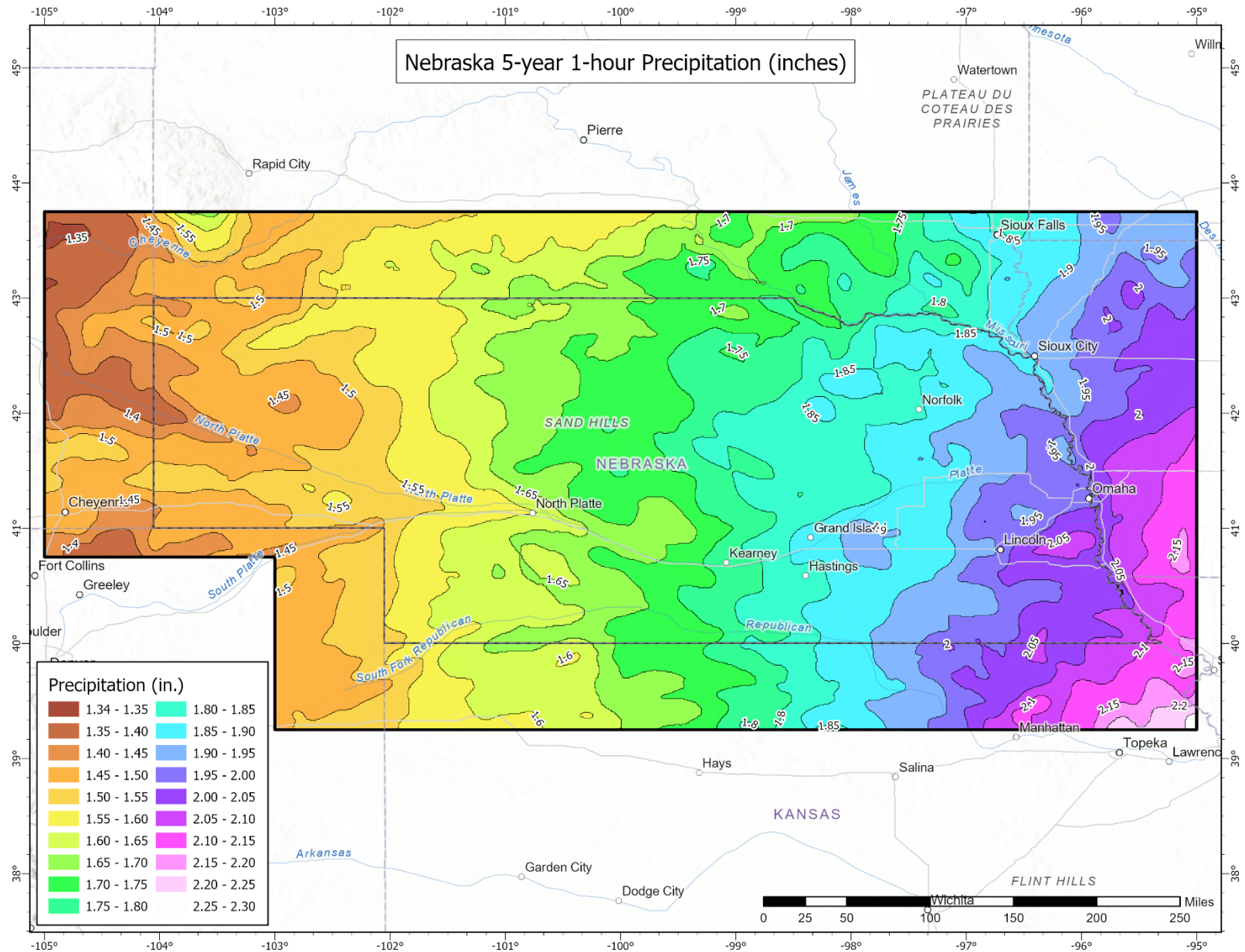
Appendix A

Precipitation Frequency Map Images

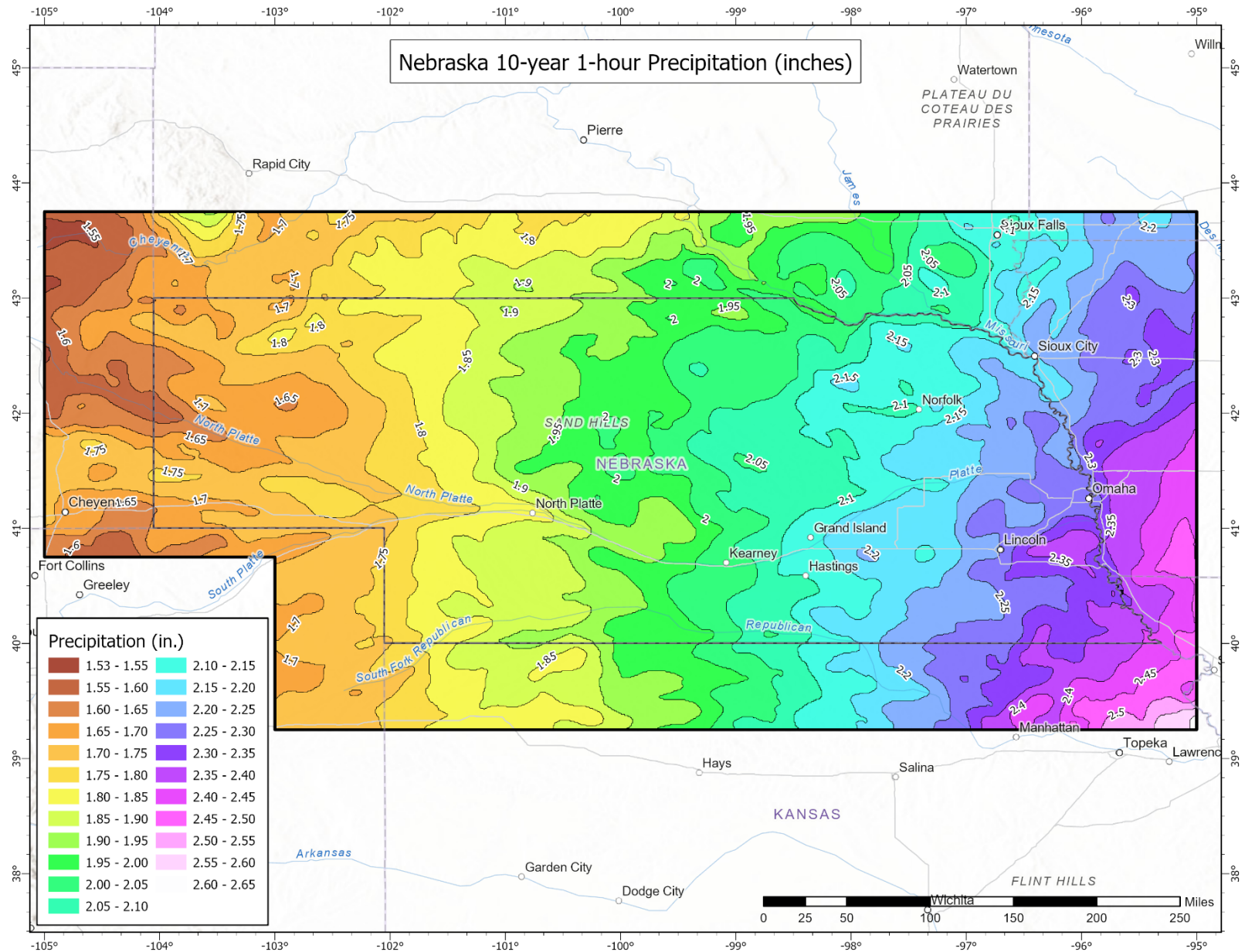
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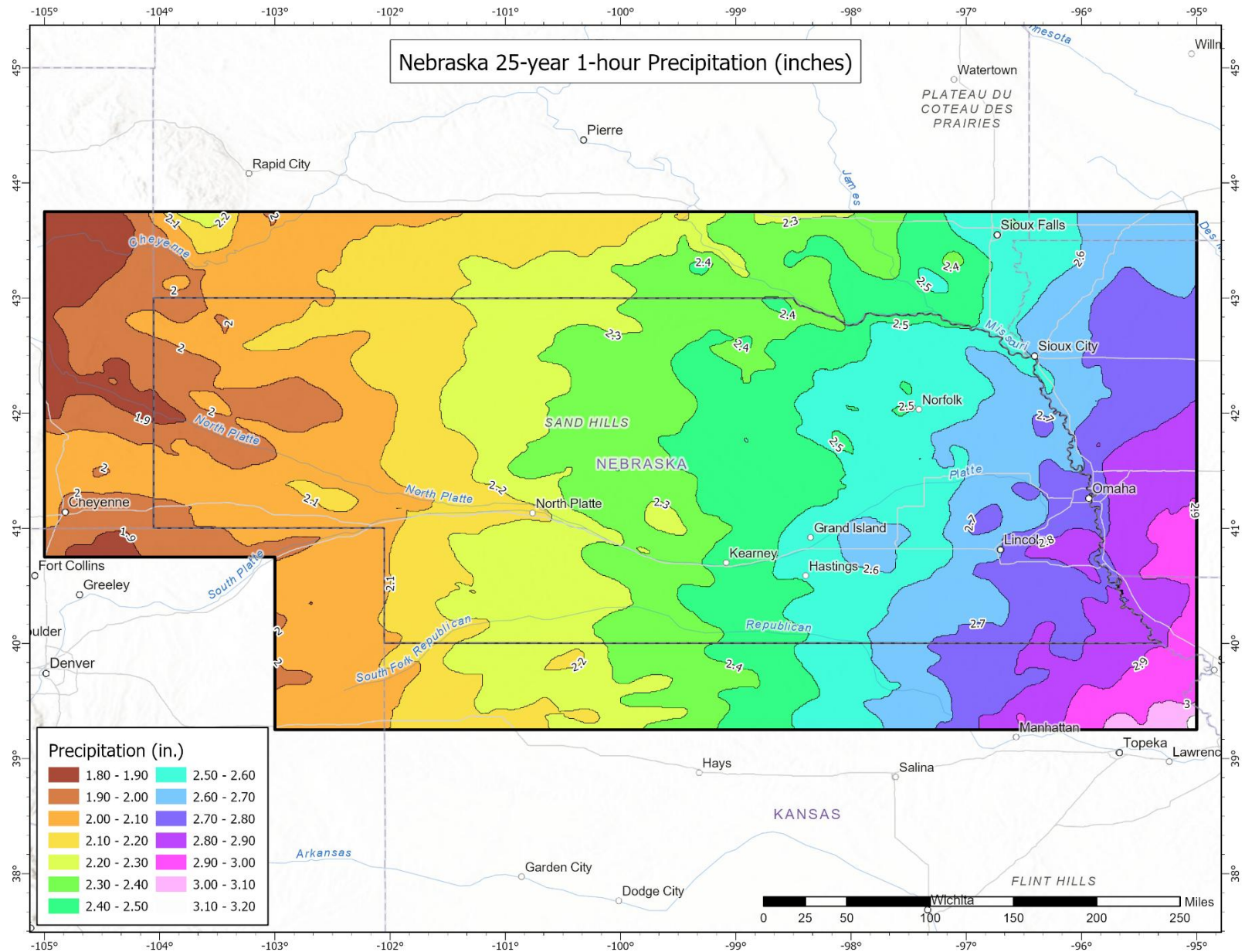
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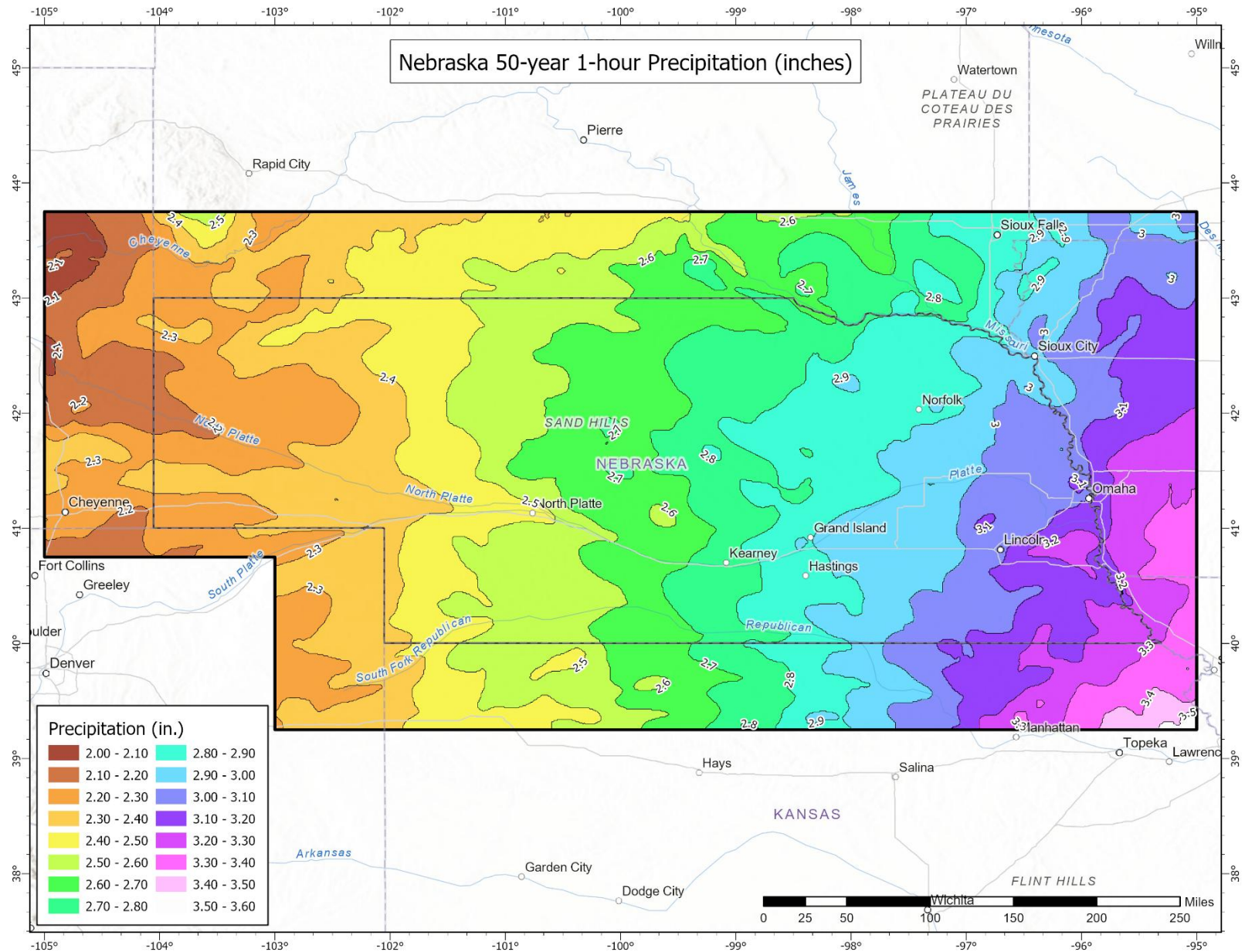
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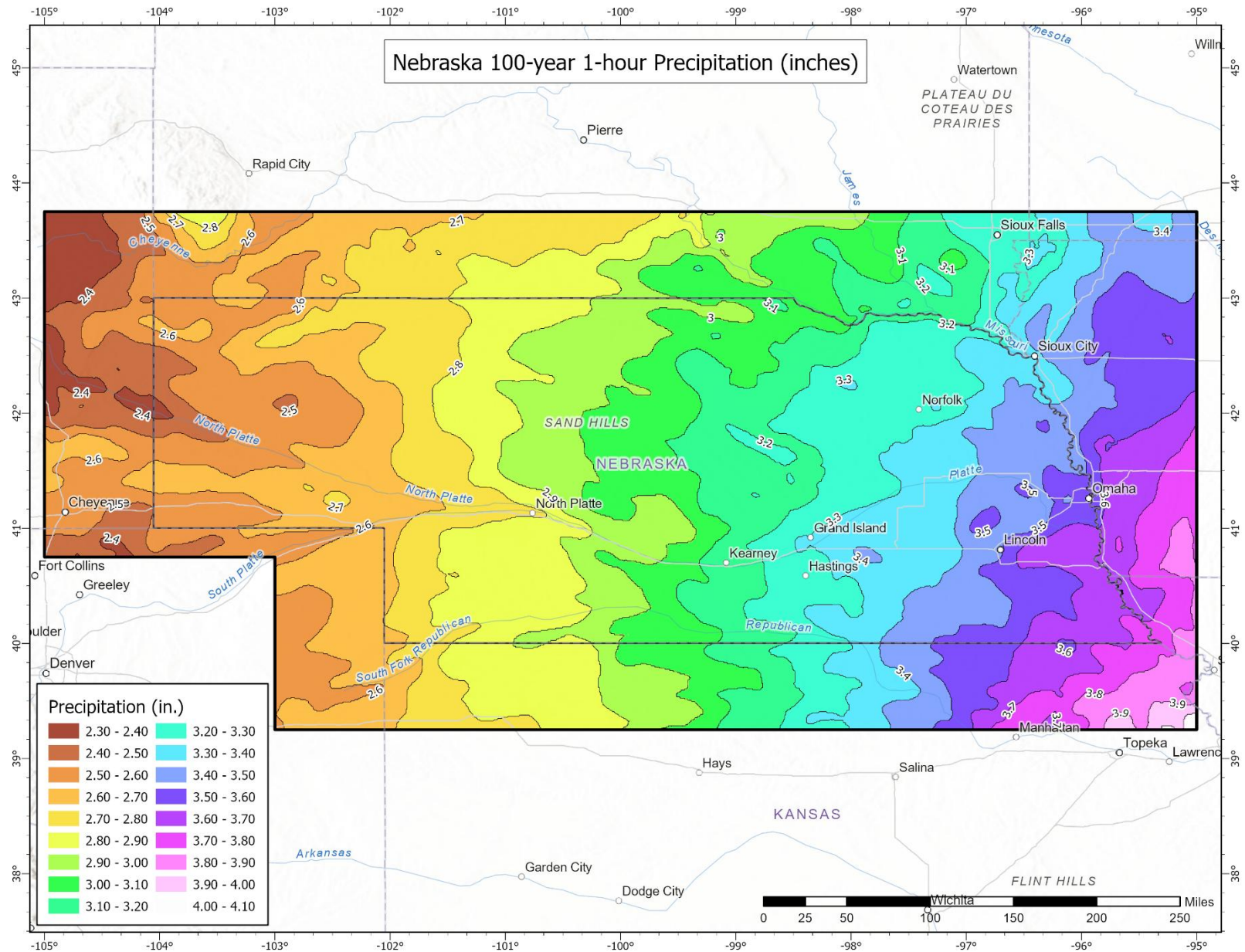
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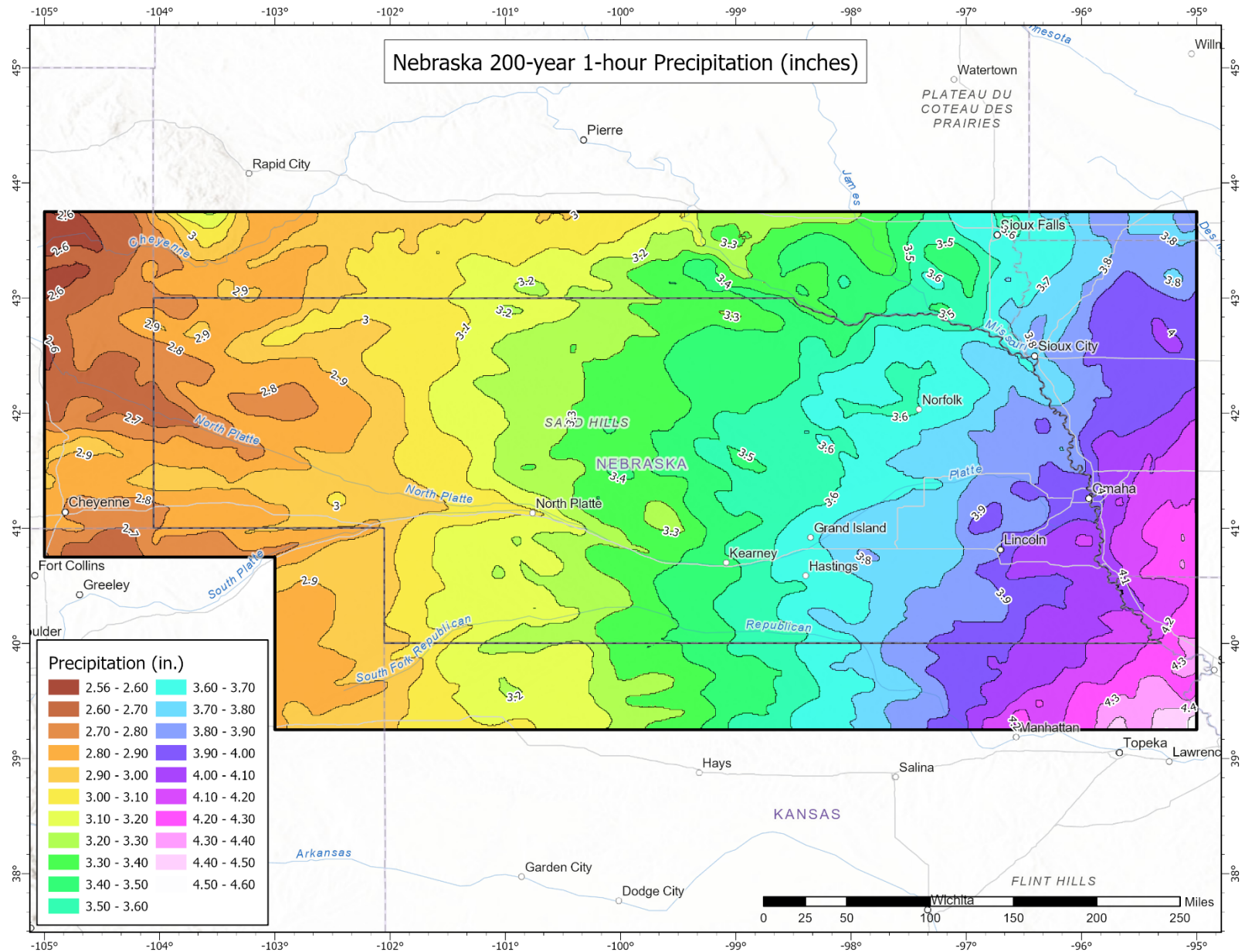
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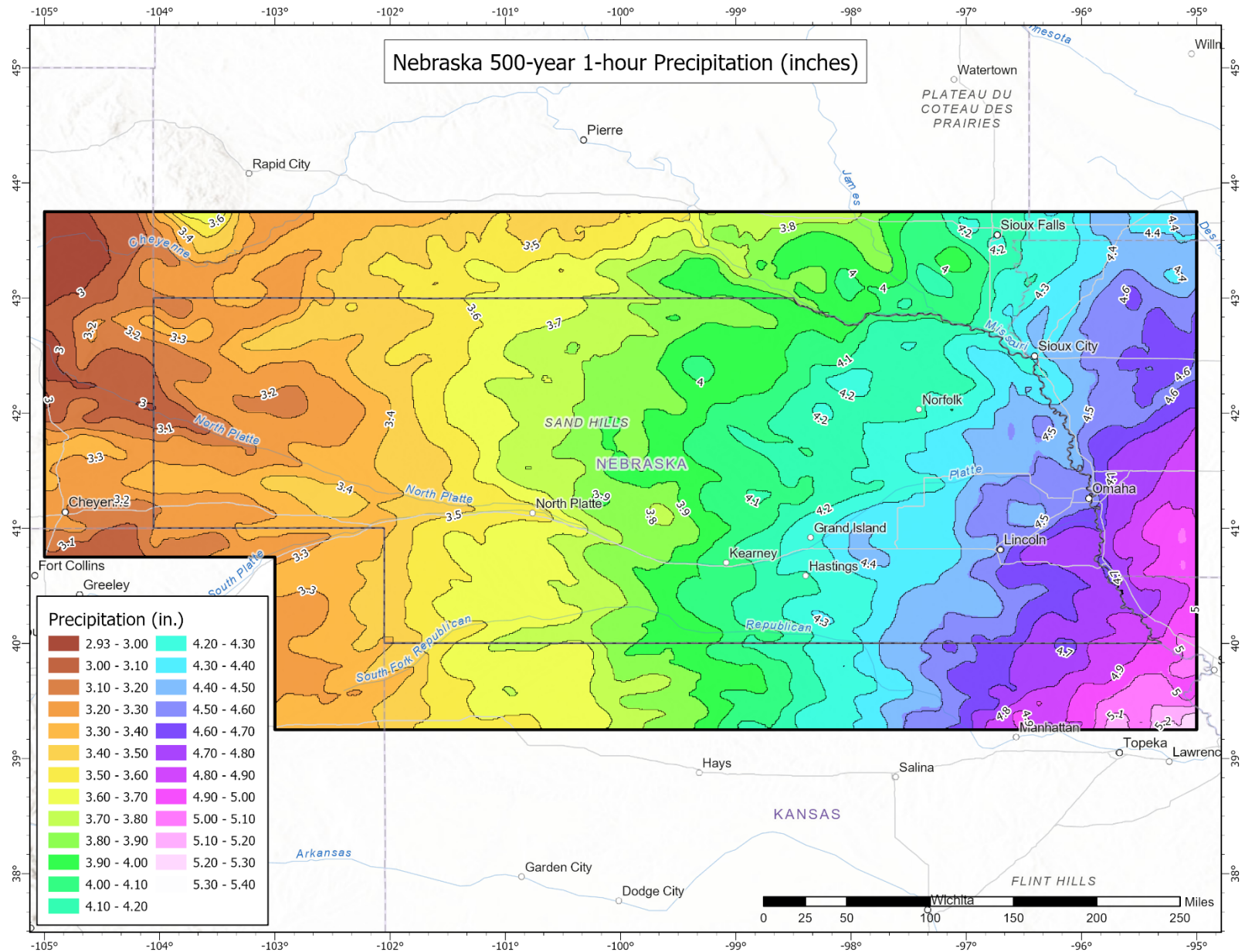
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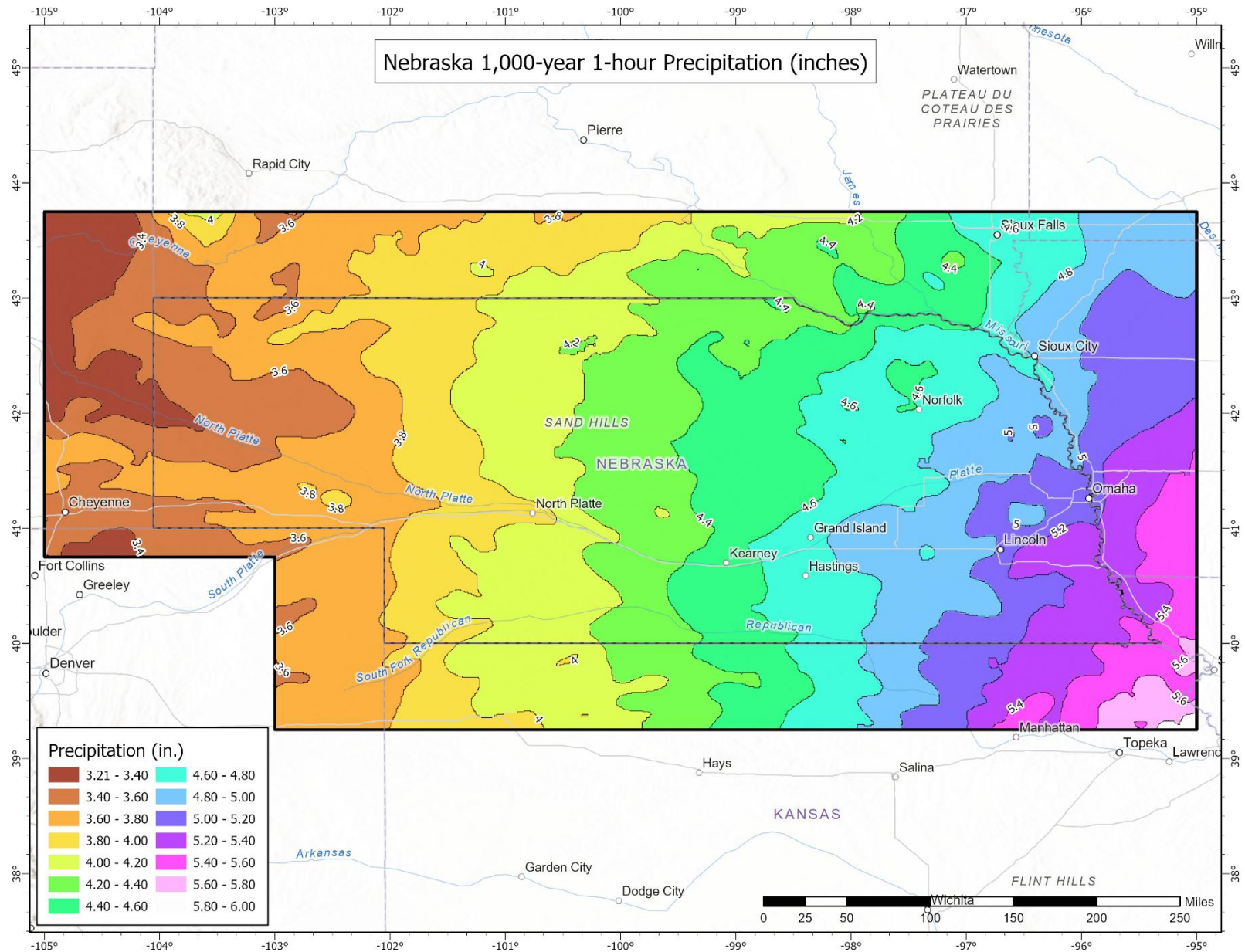
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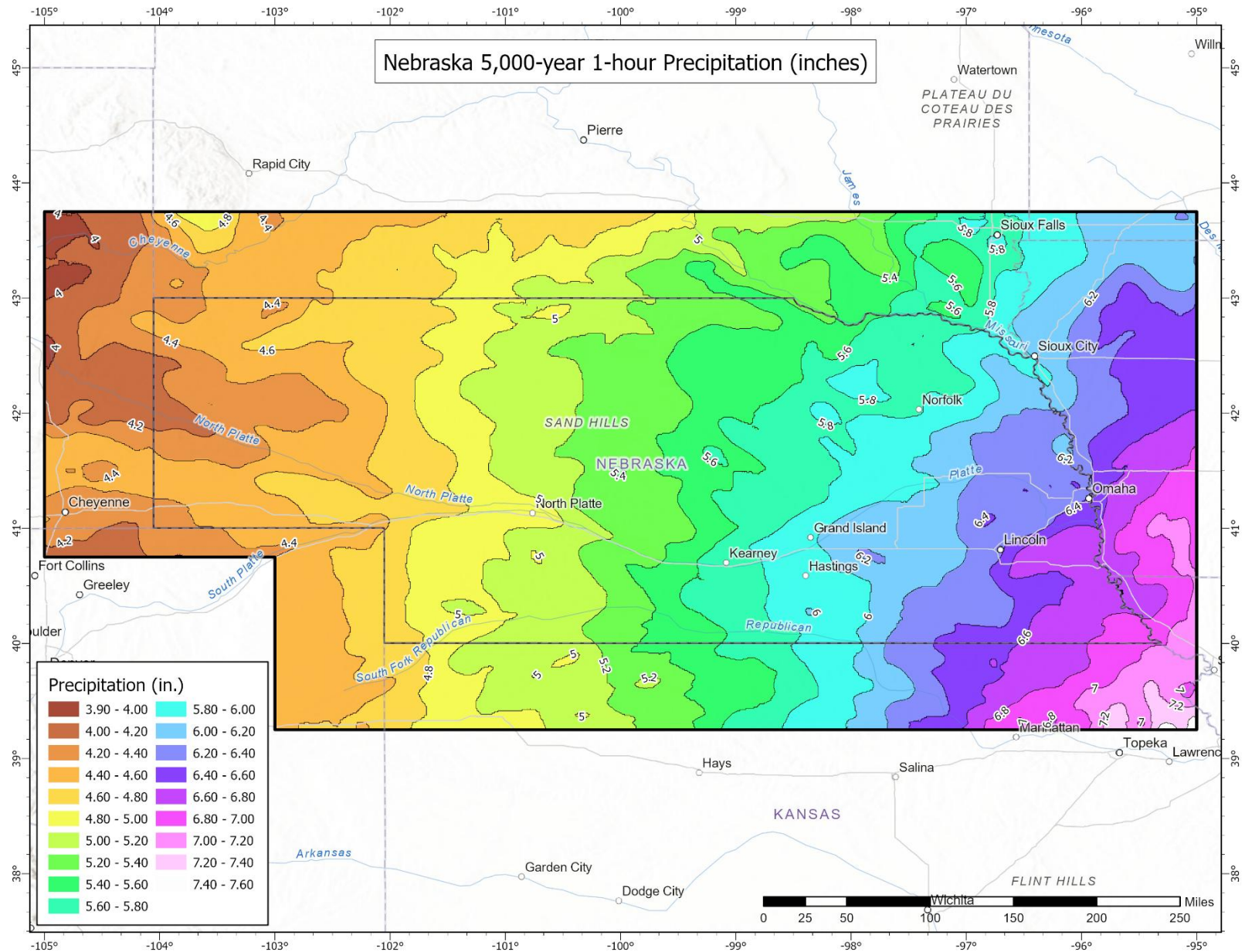
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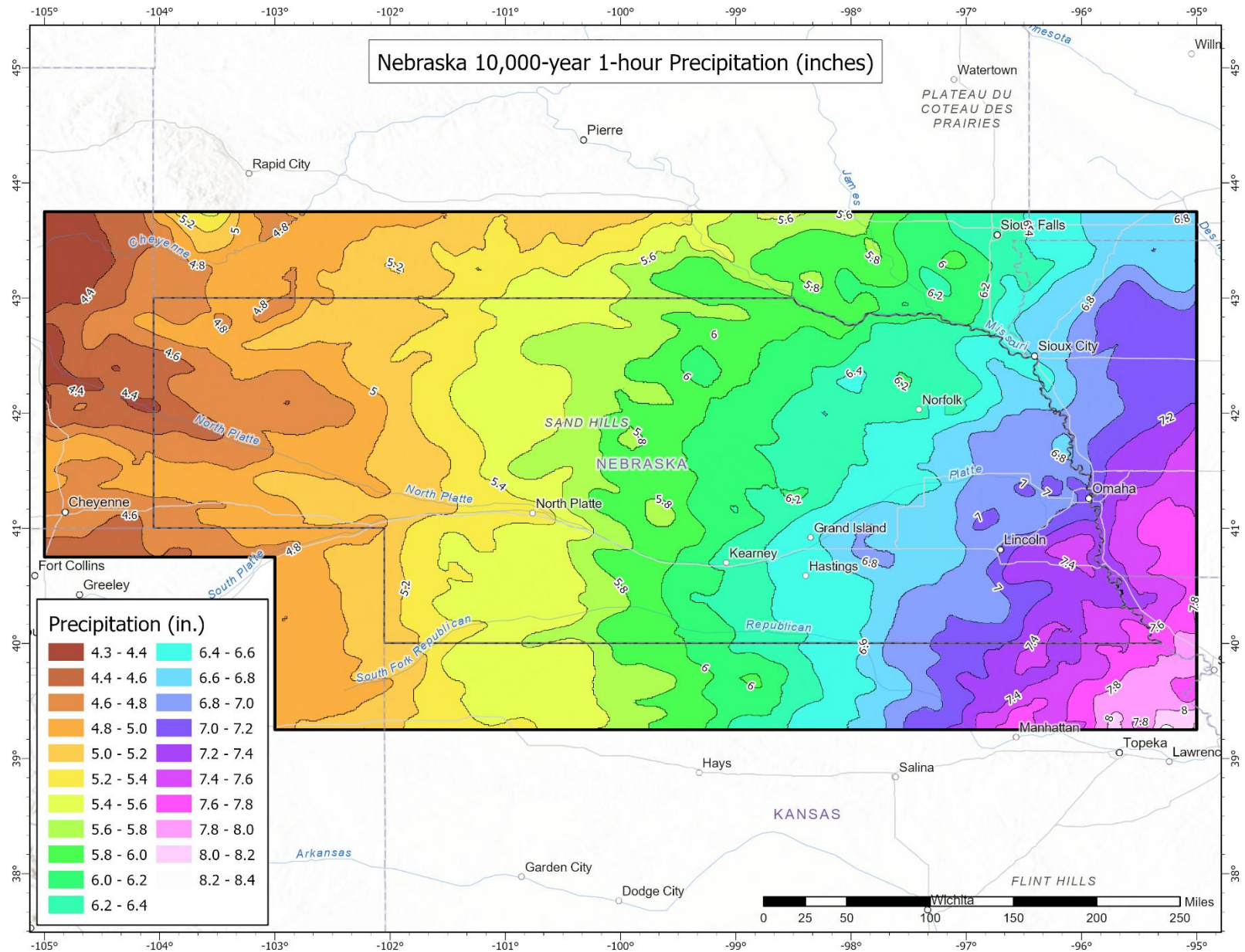
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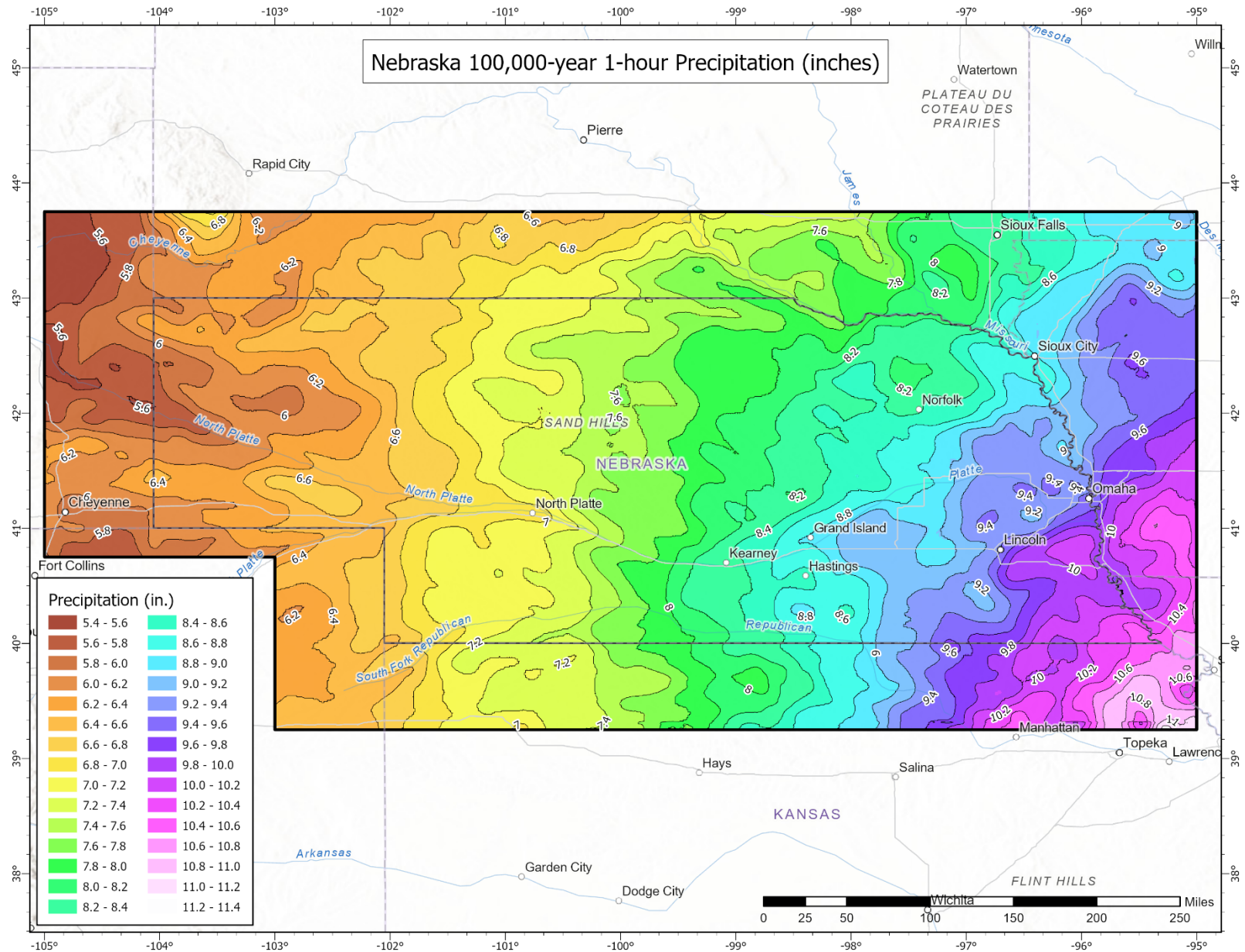
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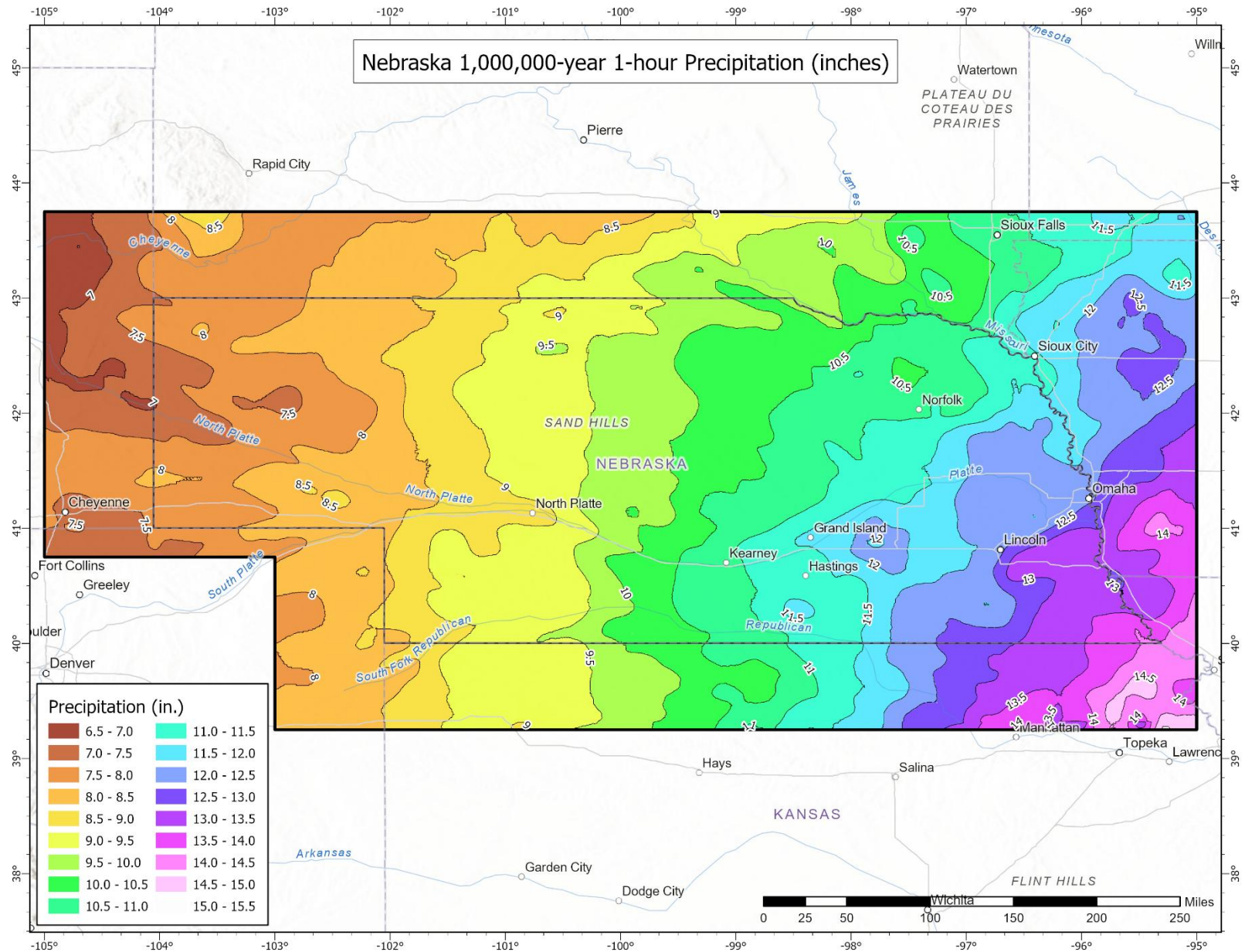
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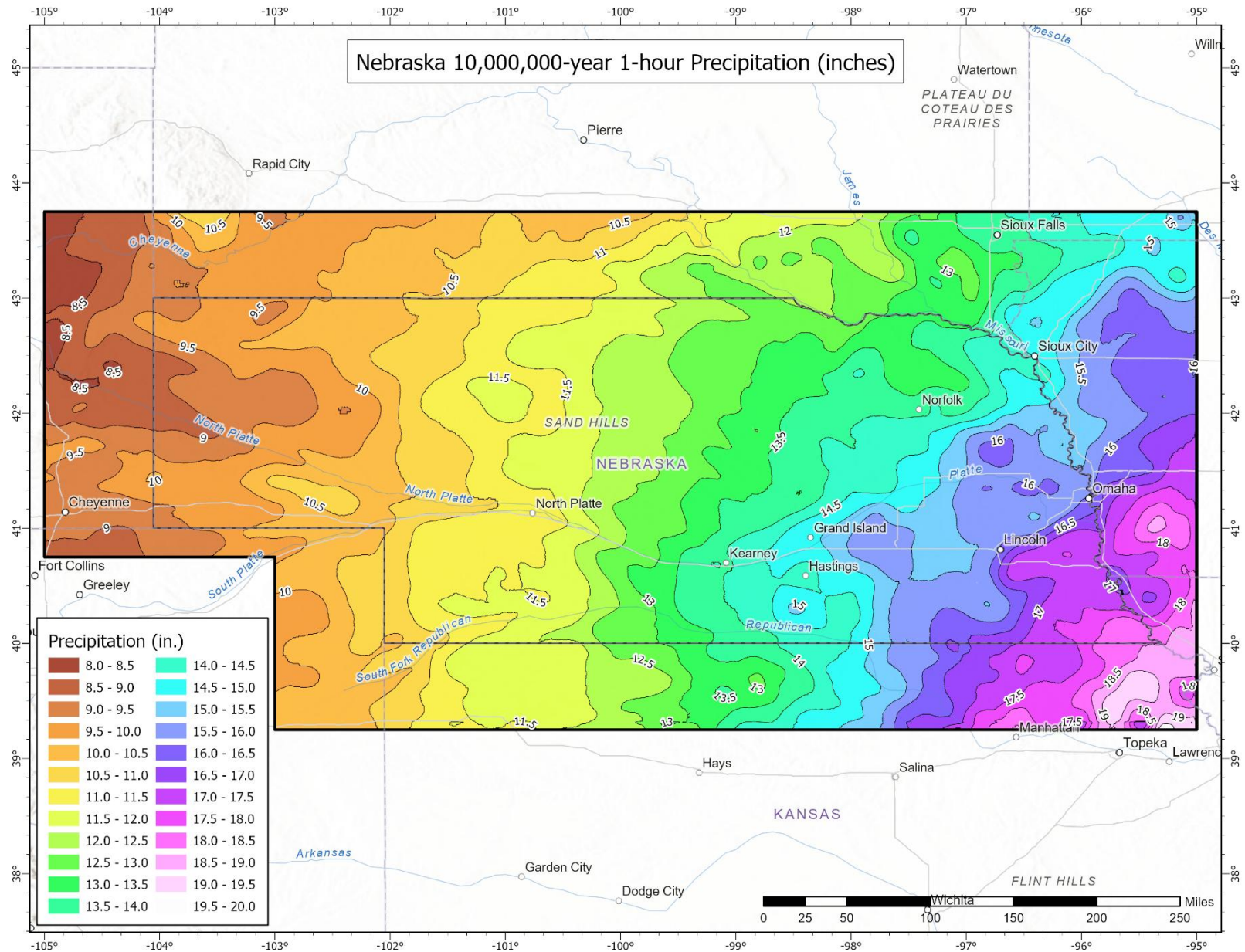
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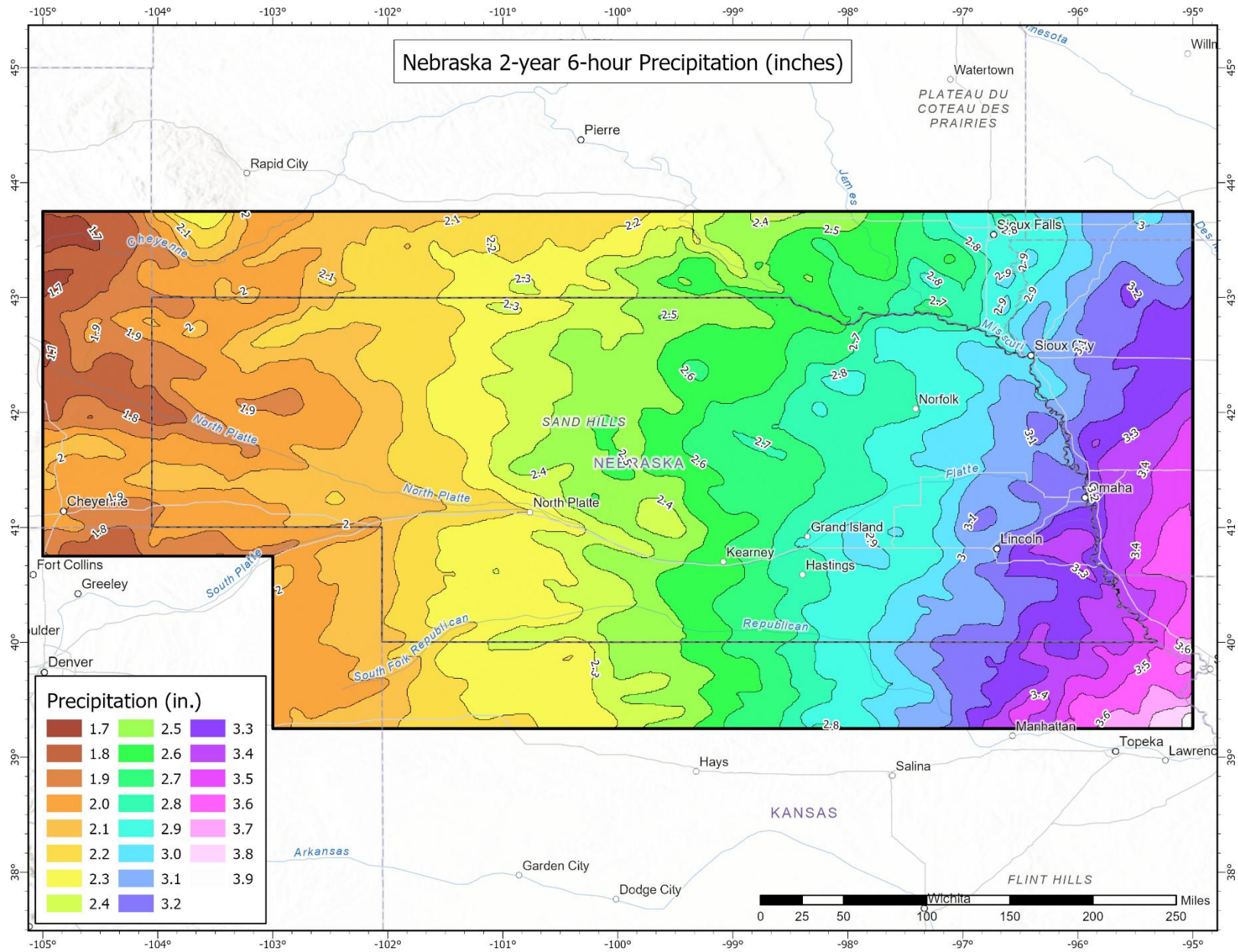
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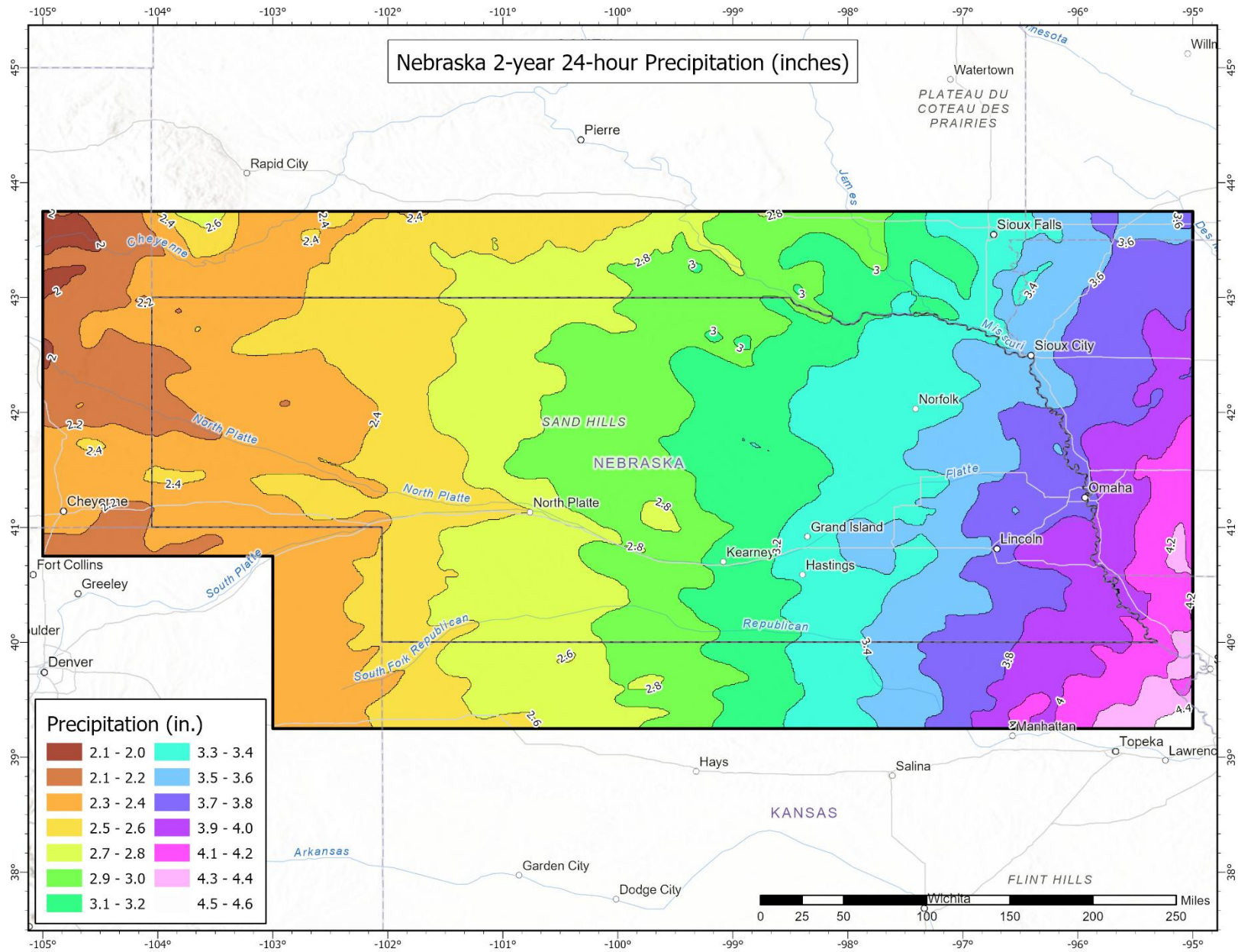
Nebraska Statewide Annual Exceedance Probability Study



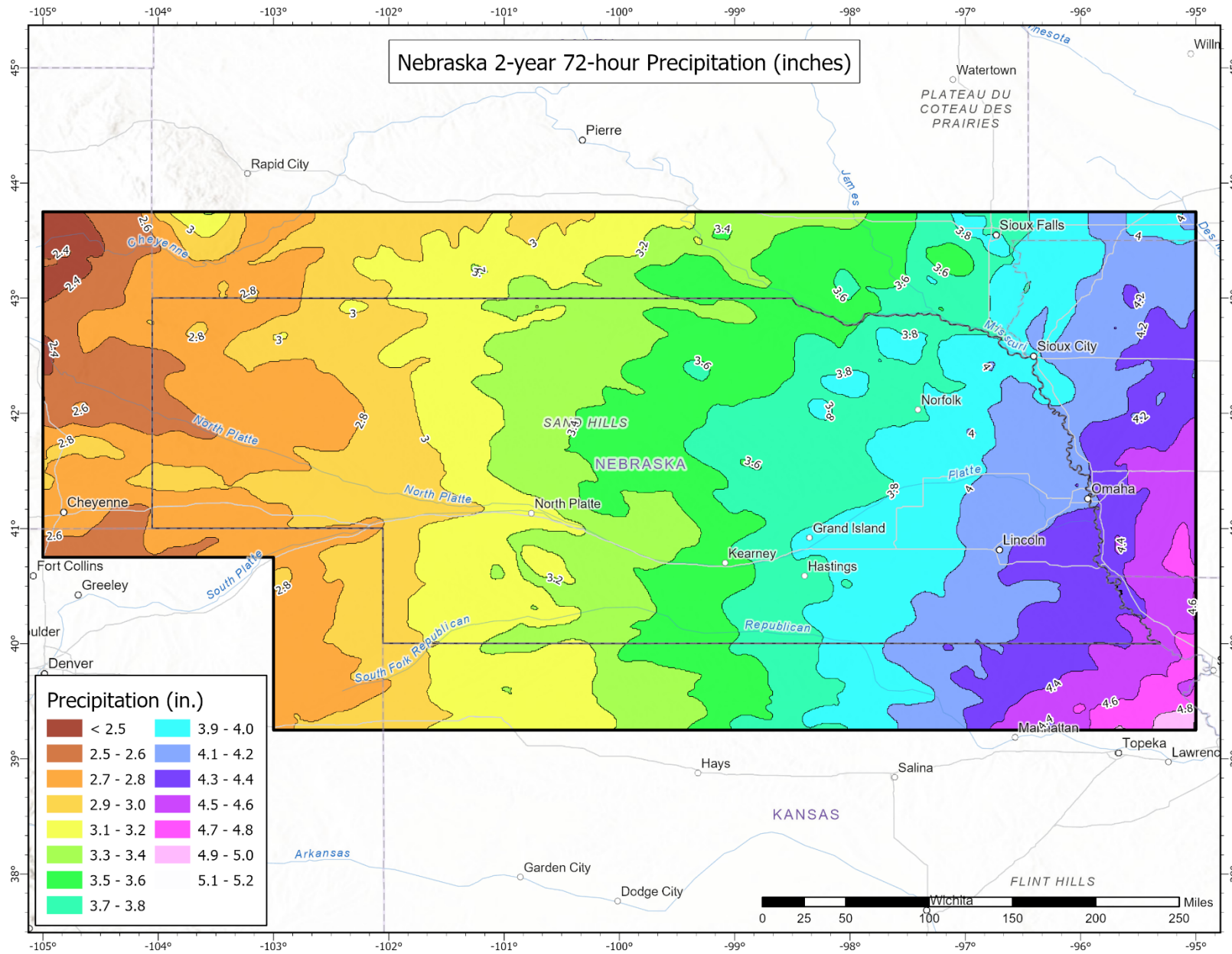
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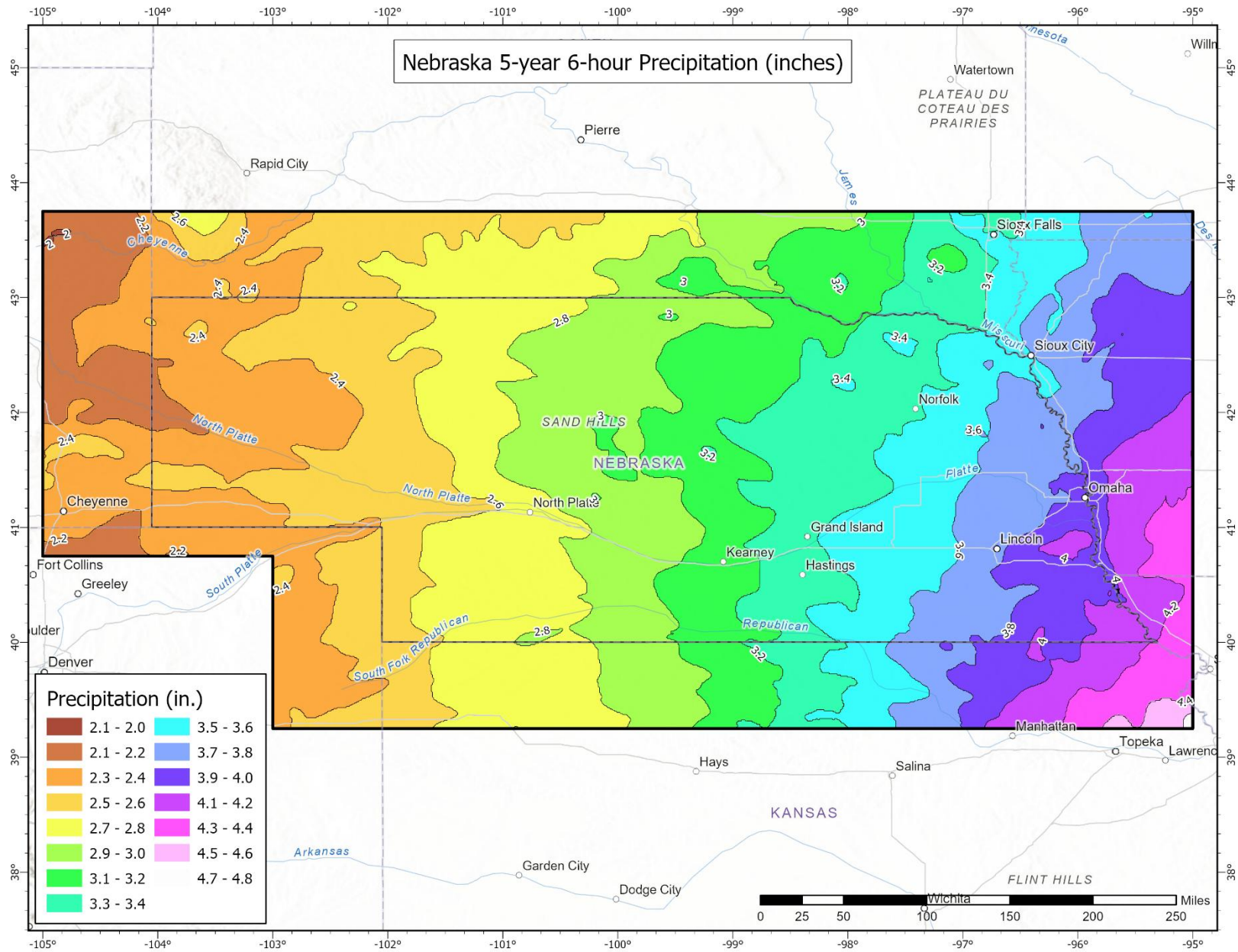
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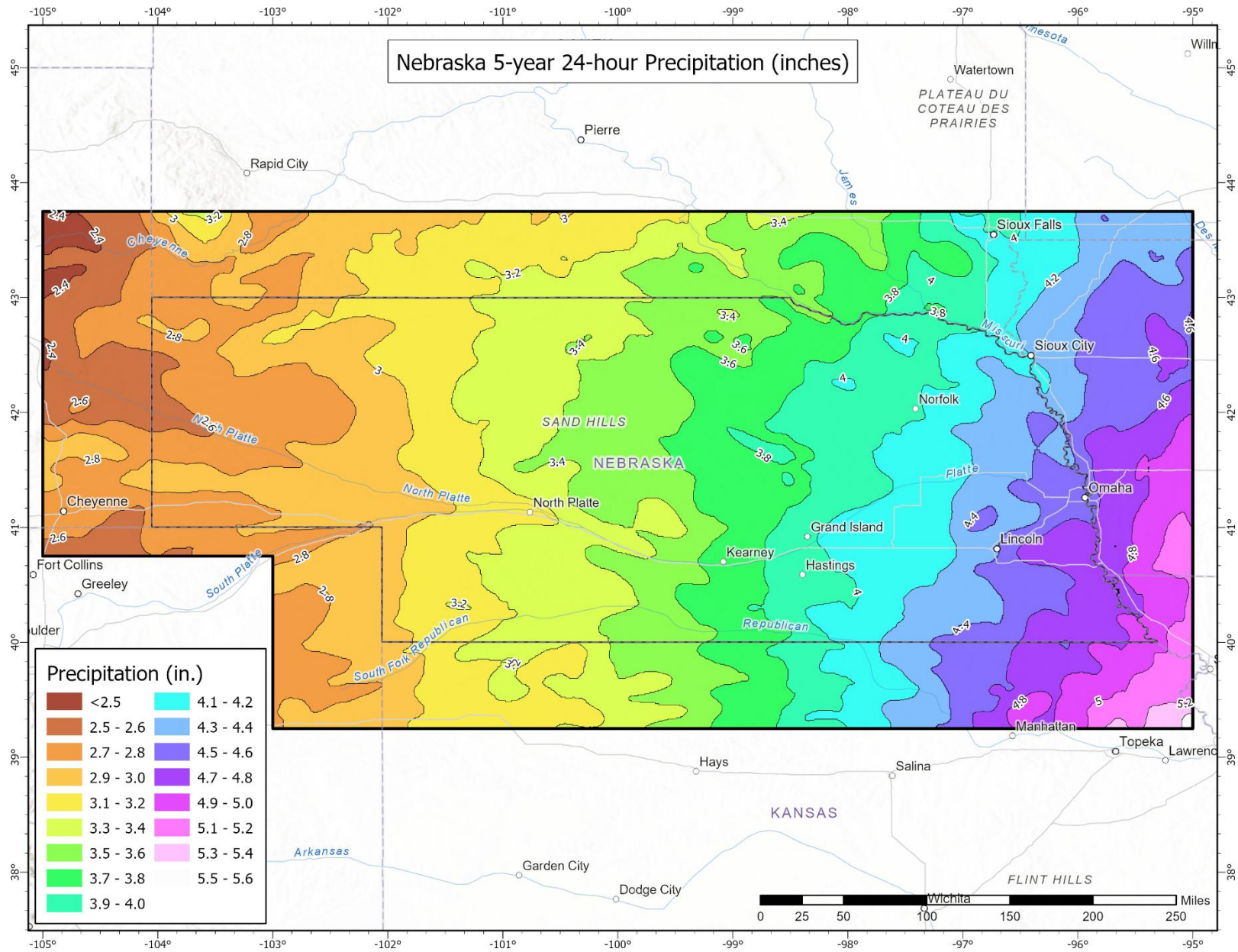
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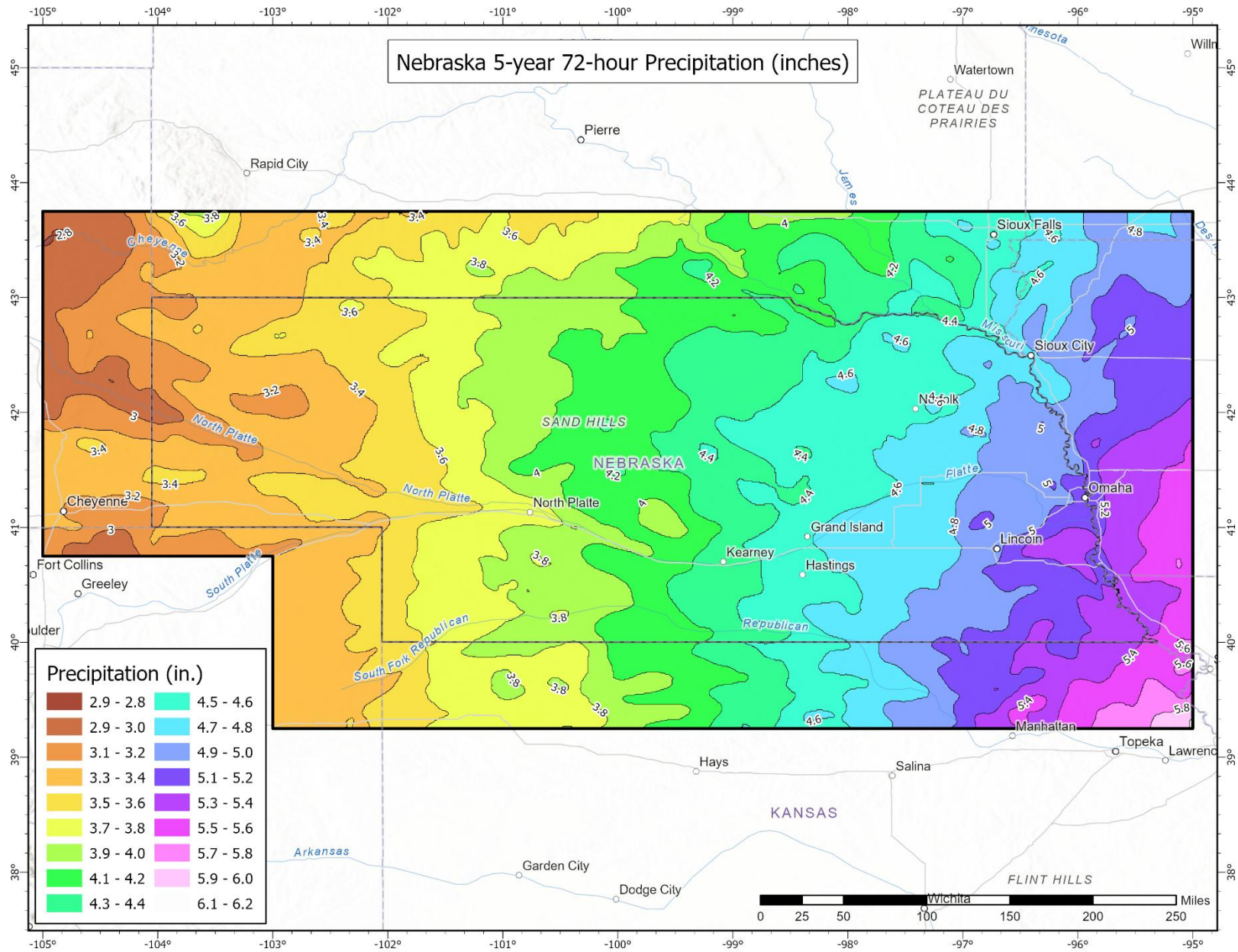
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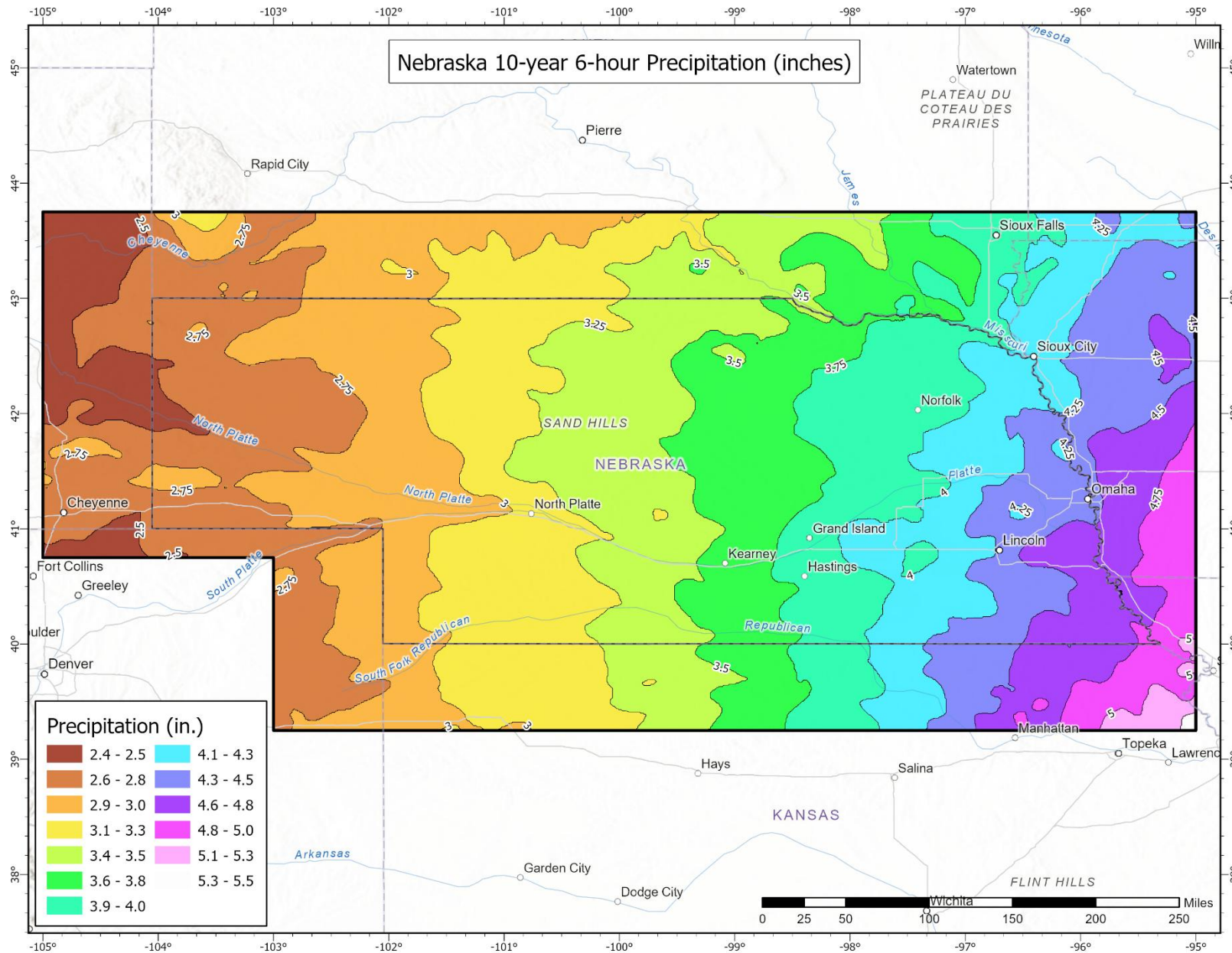
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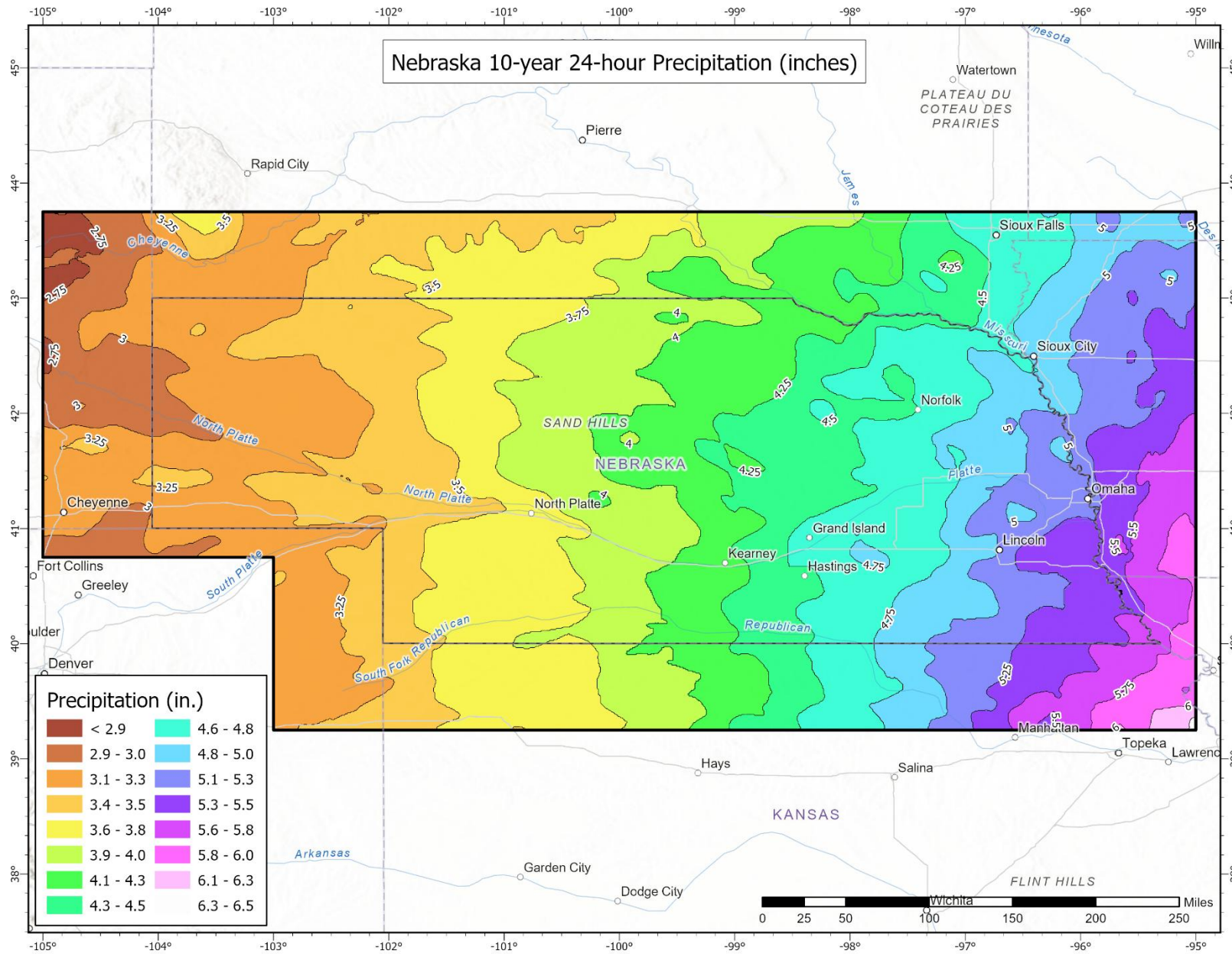
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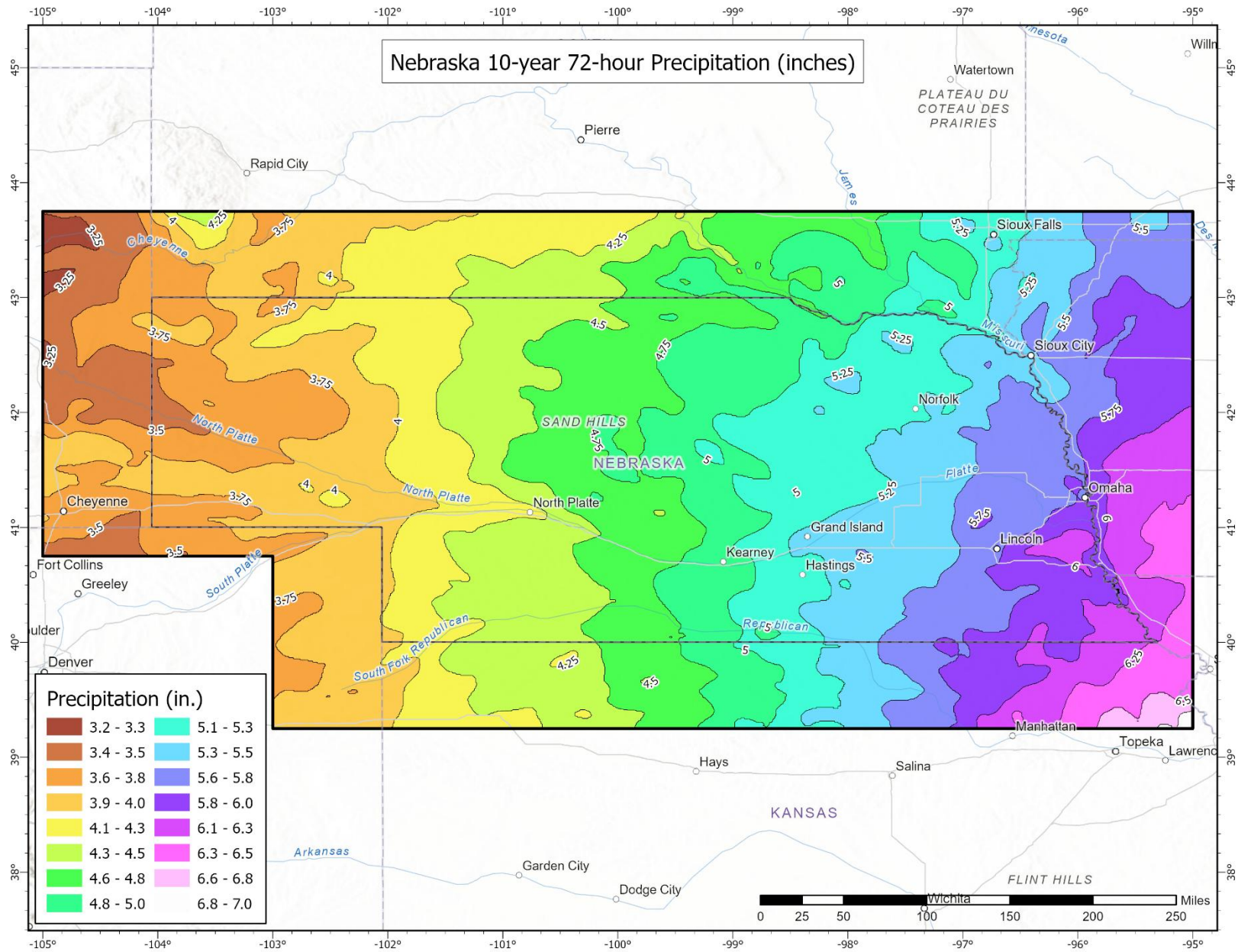
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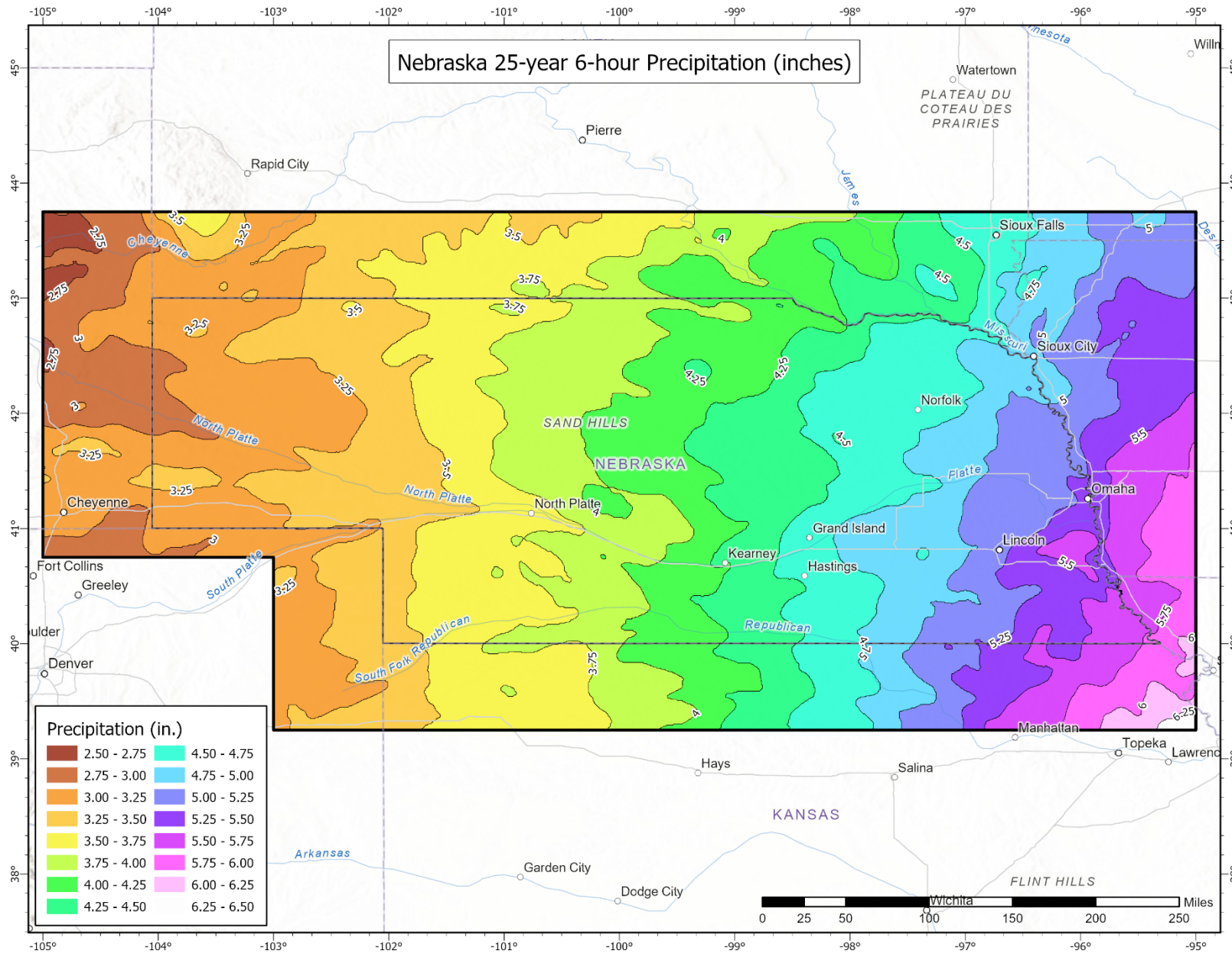
Nebraska Statewide Annual Exceedance Probability Study



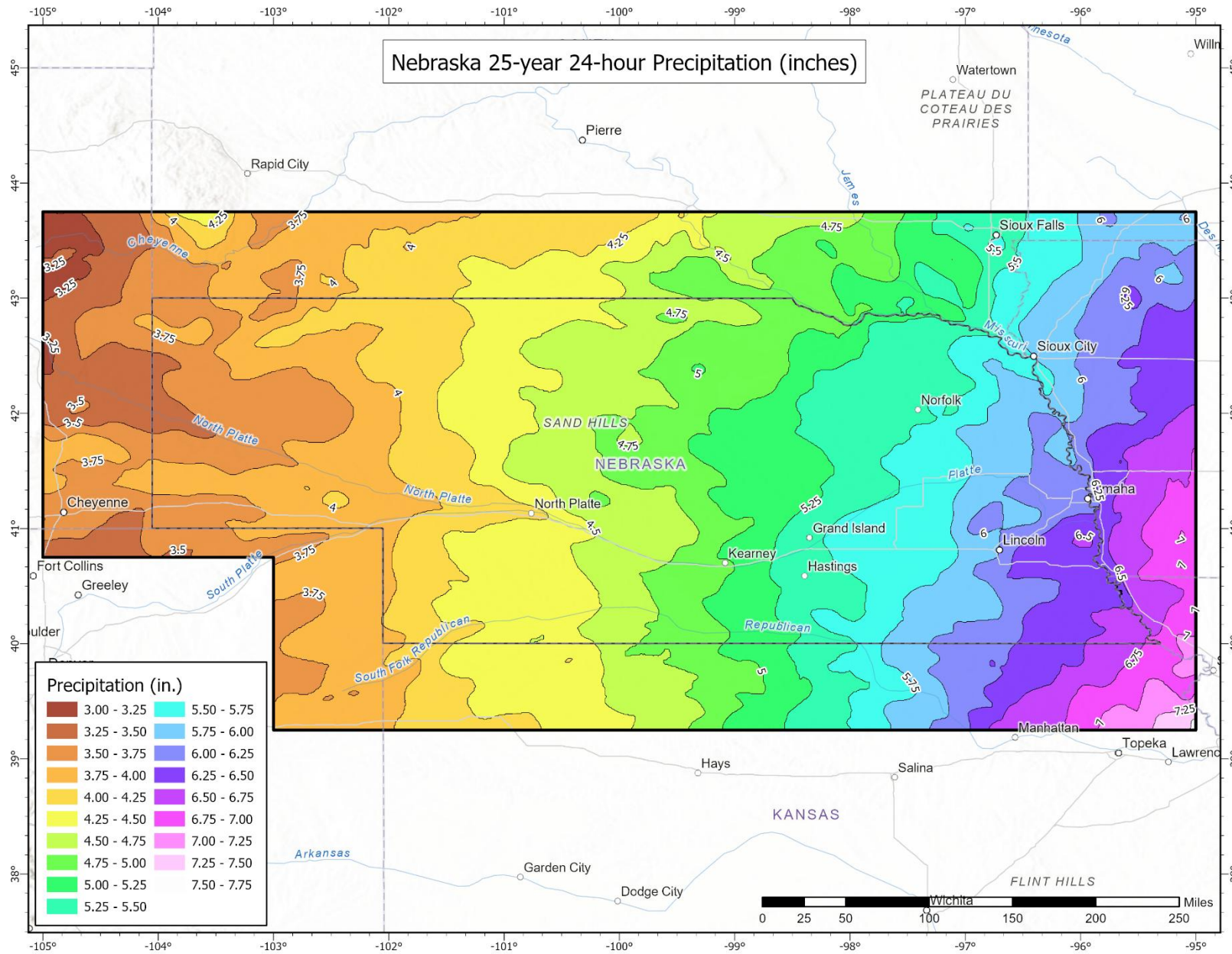
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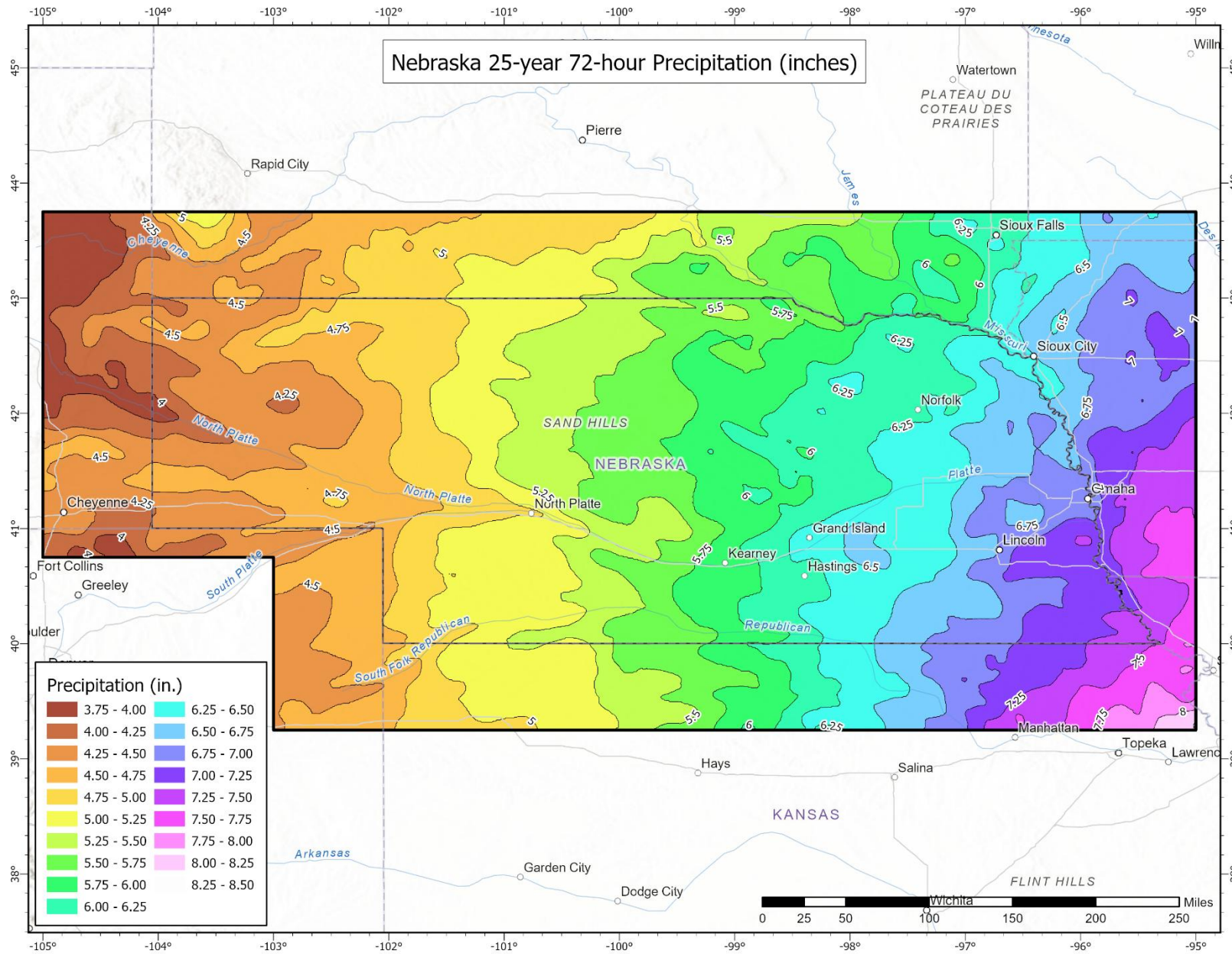
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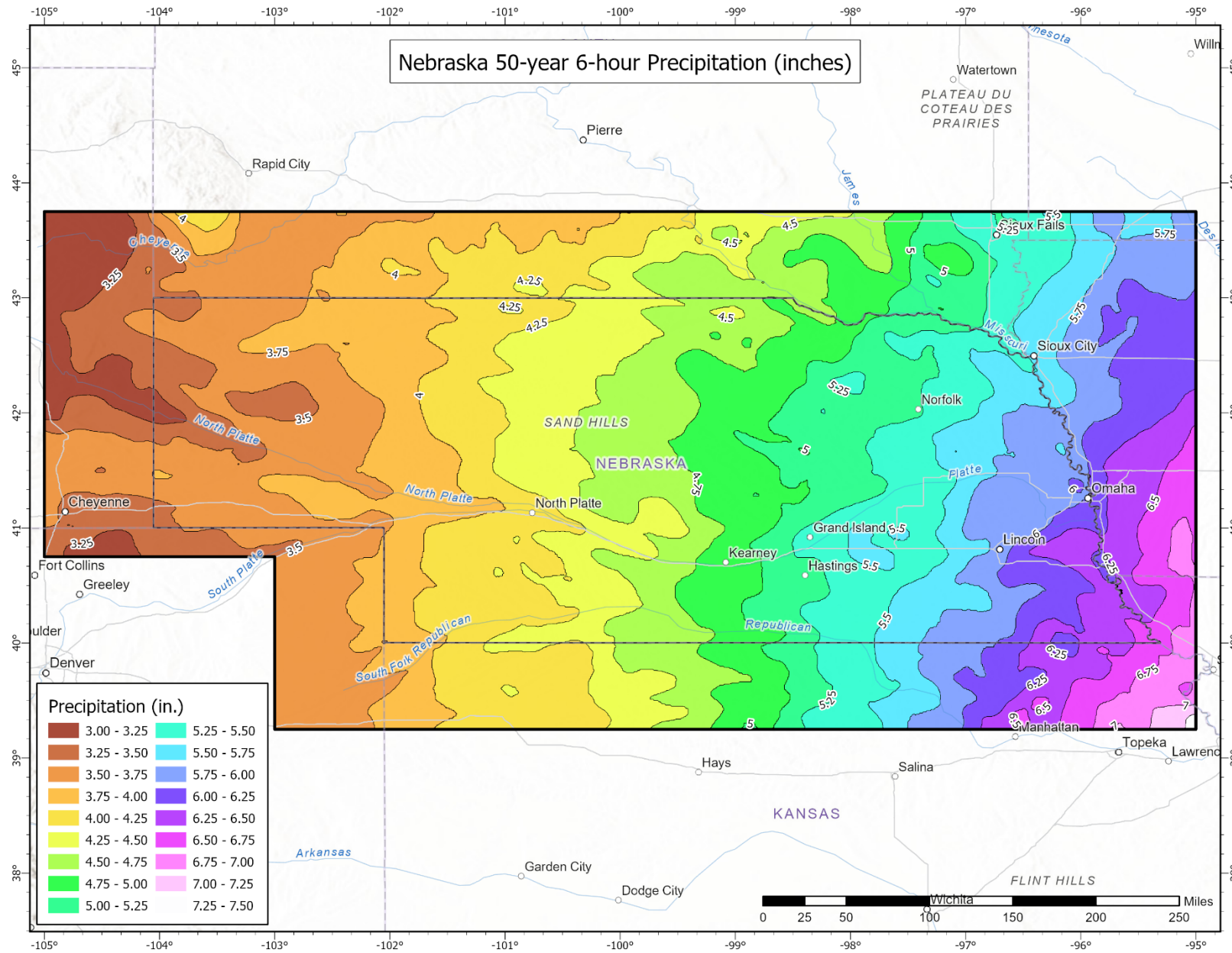
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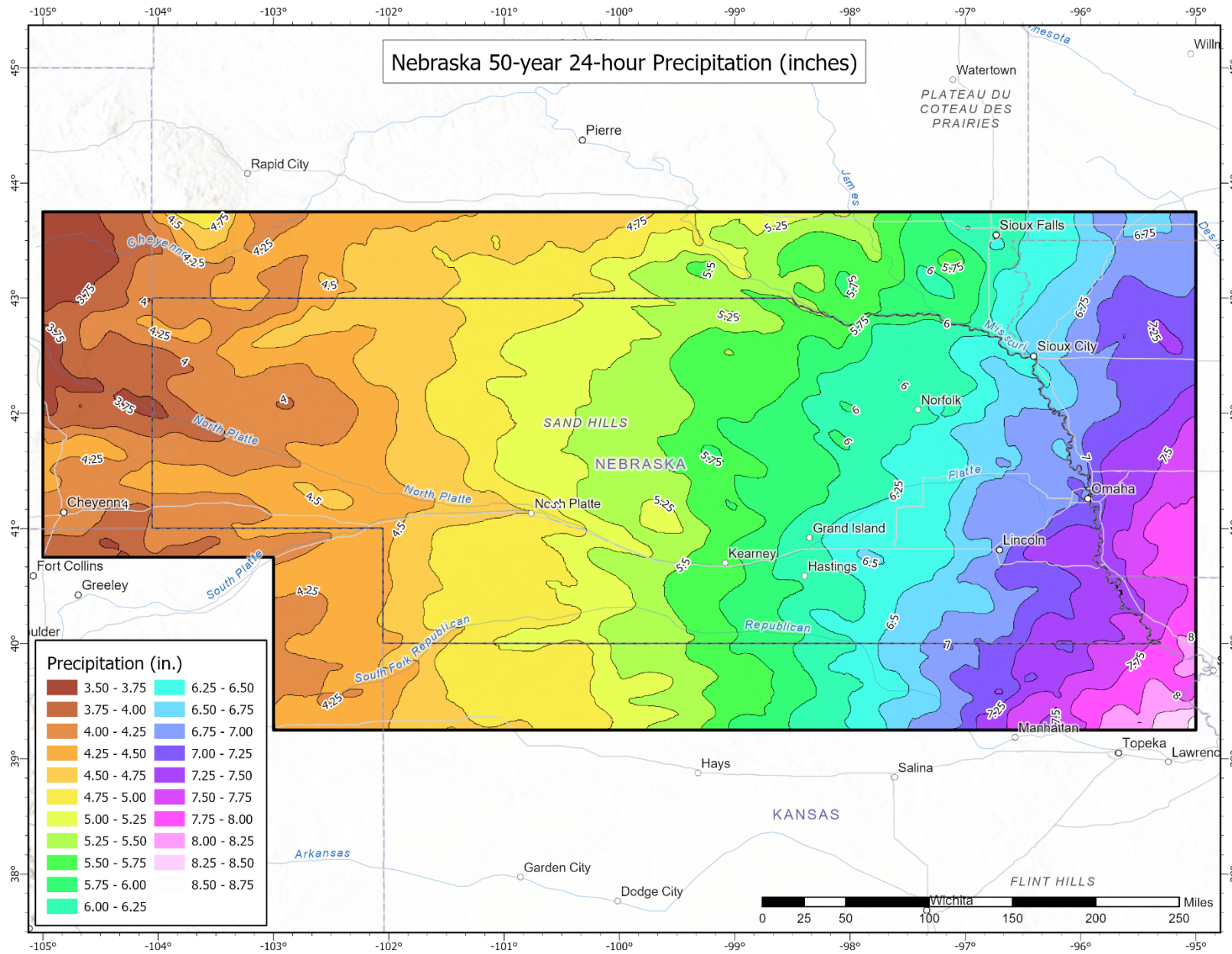
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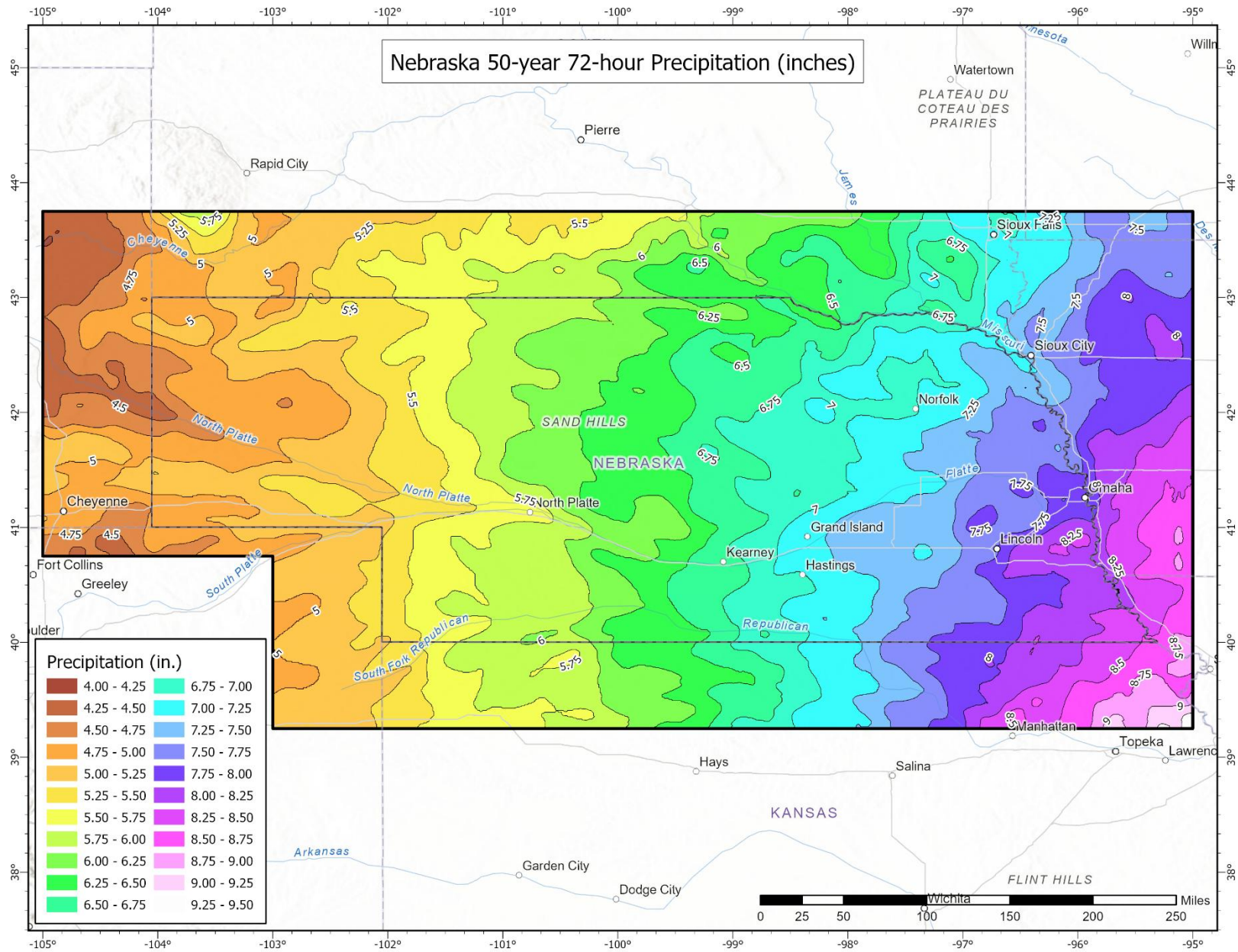
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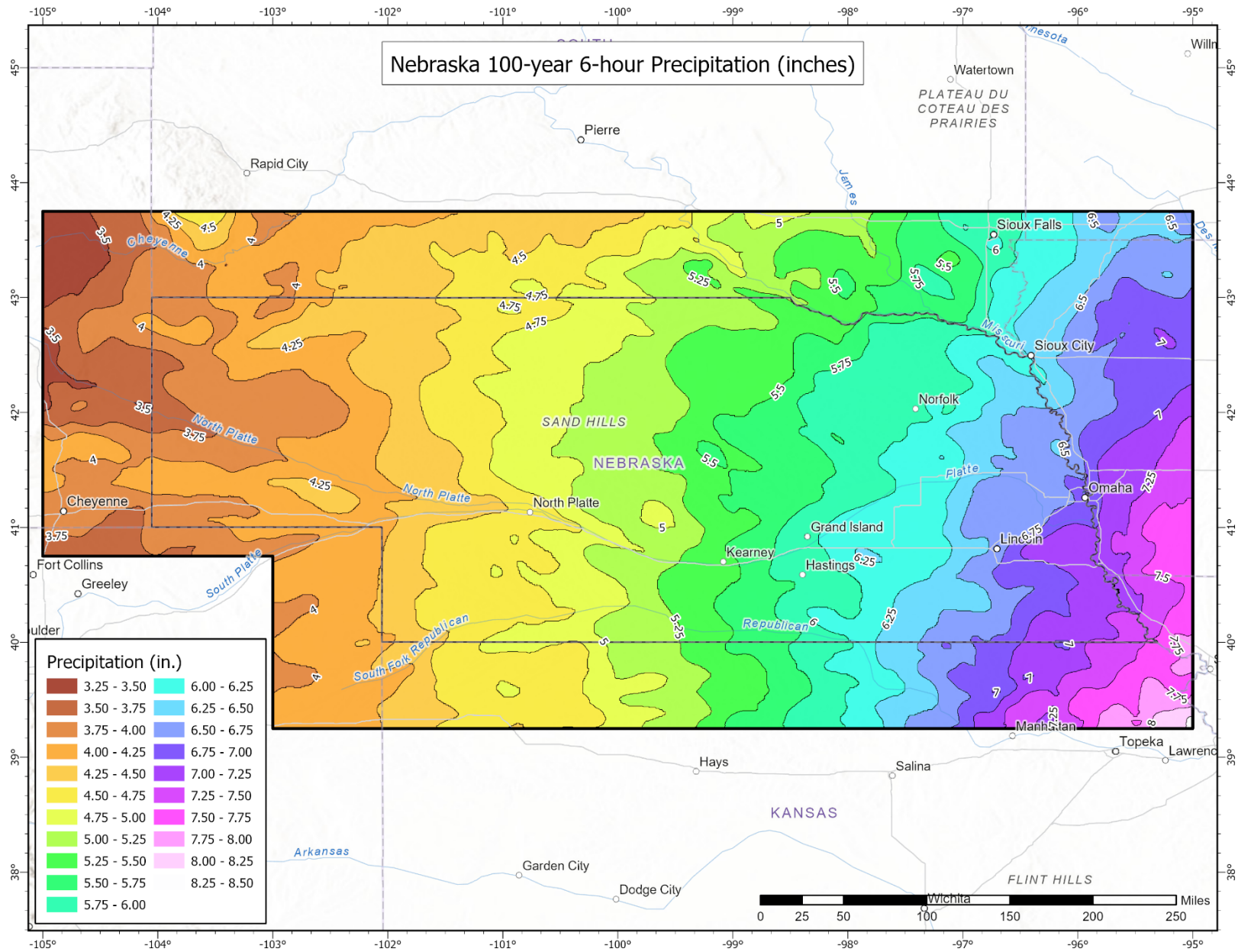
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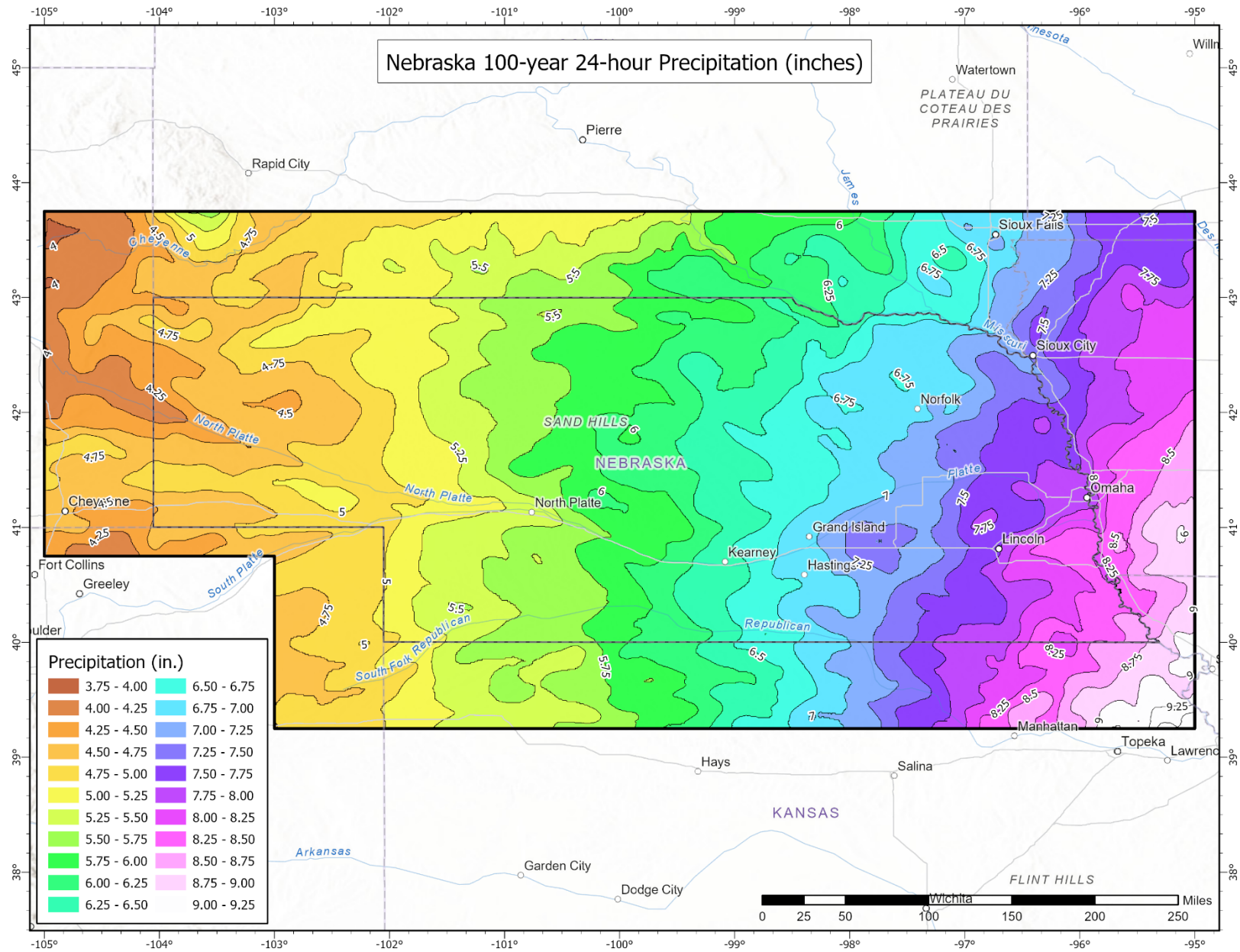
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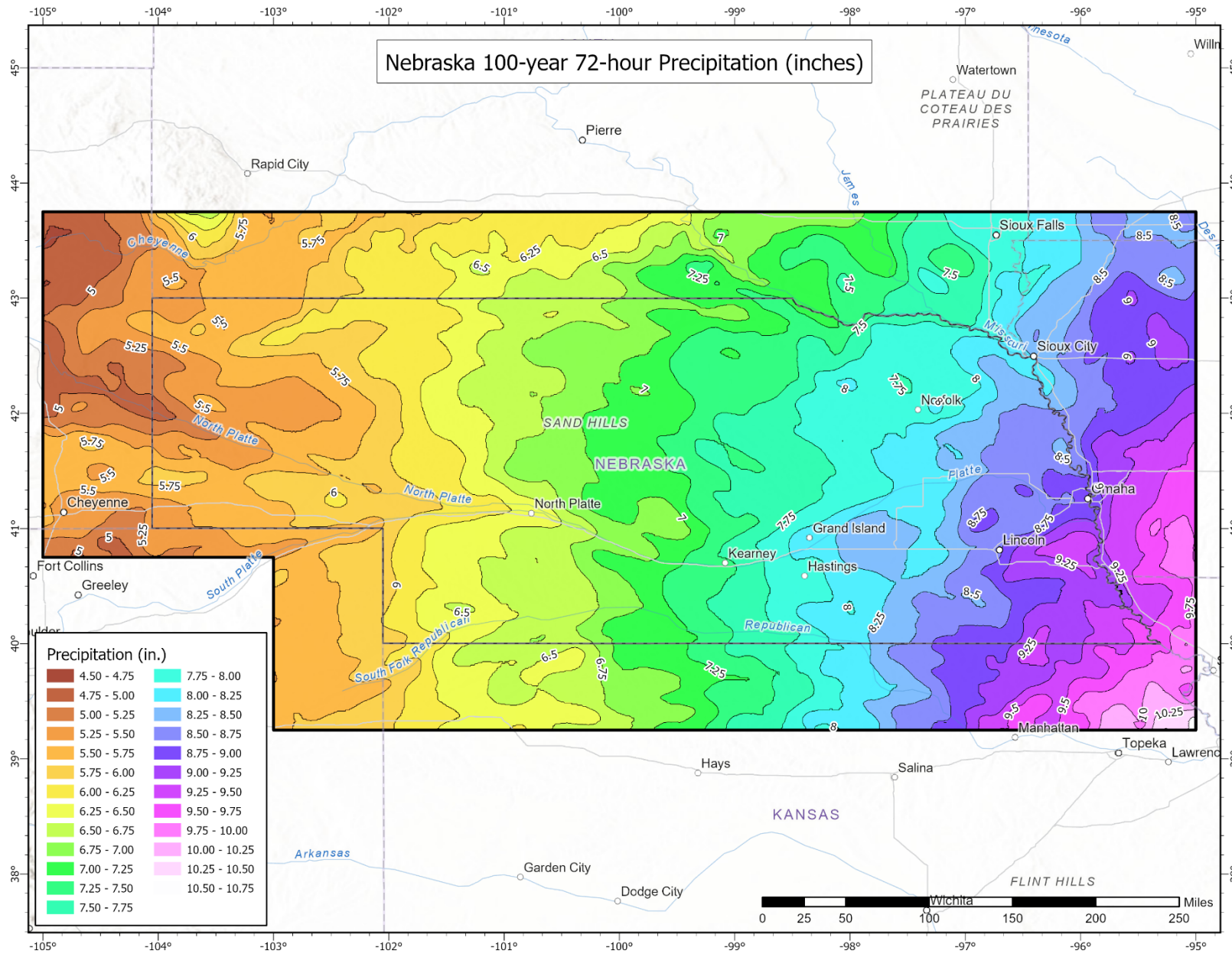
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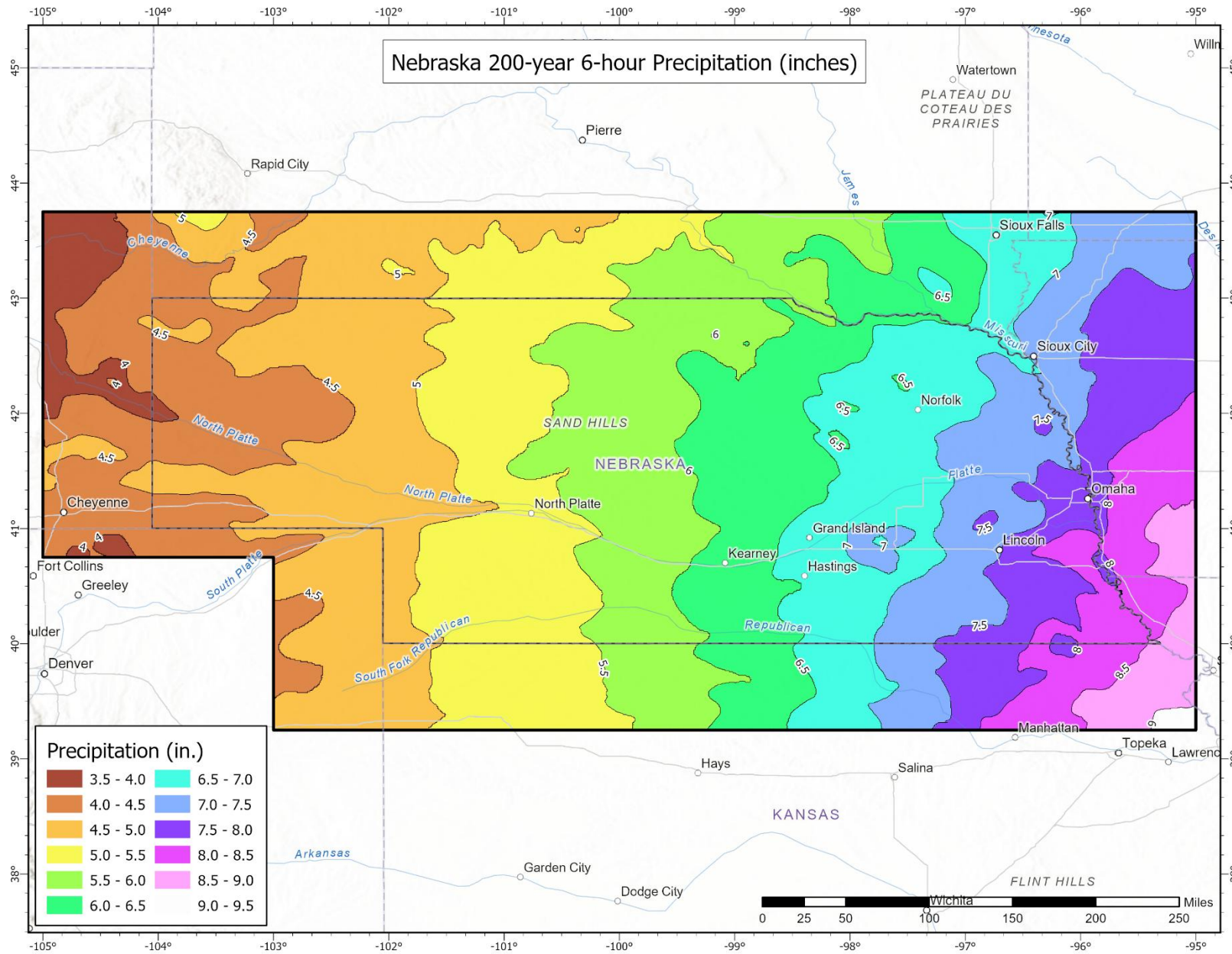
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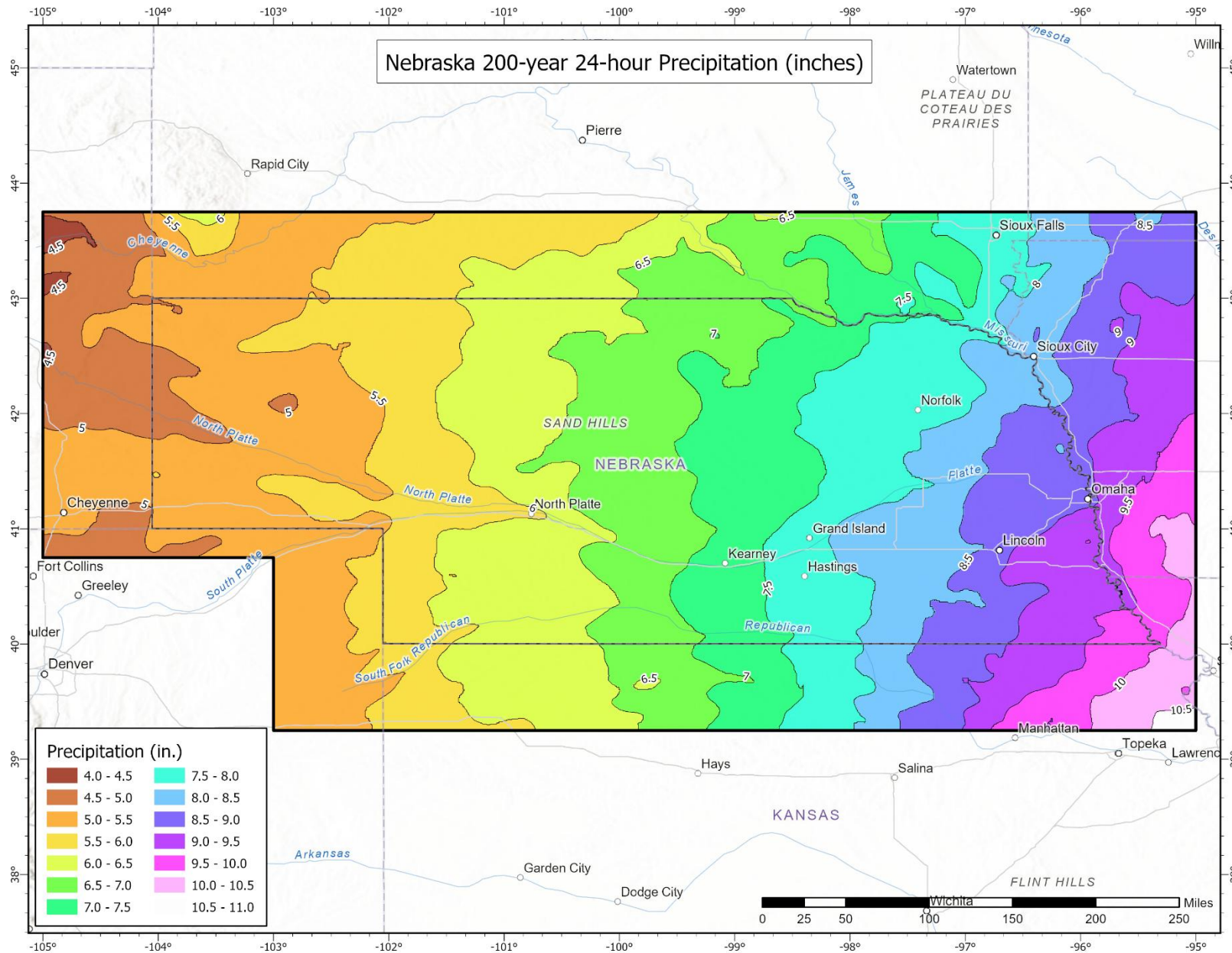
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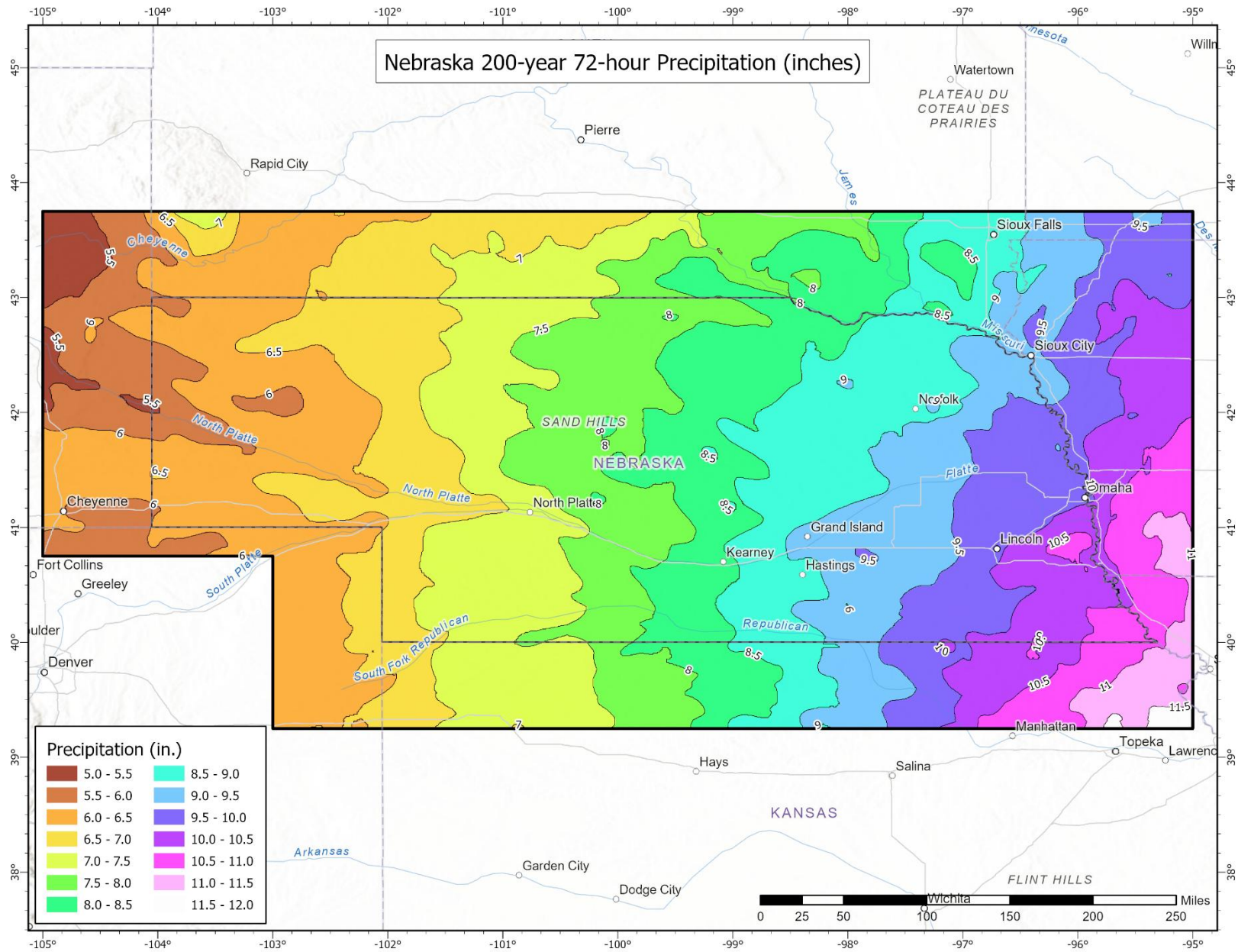
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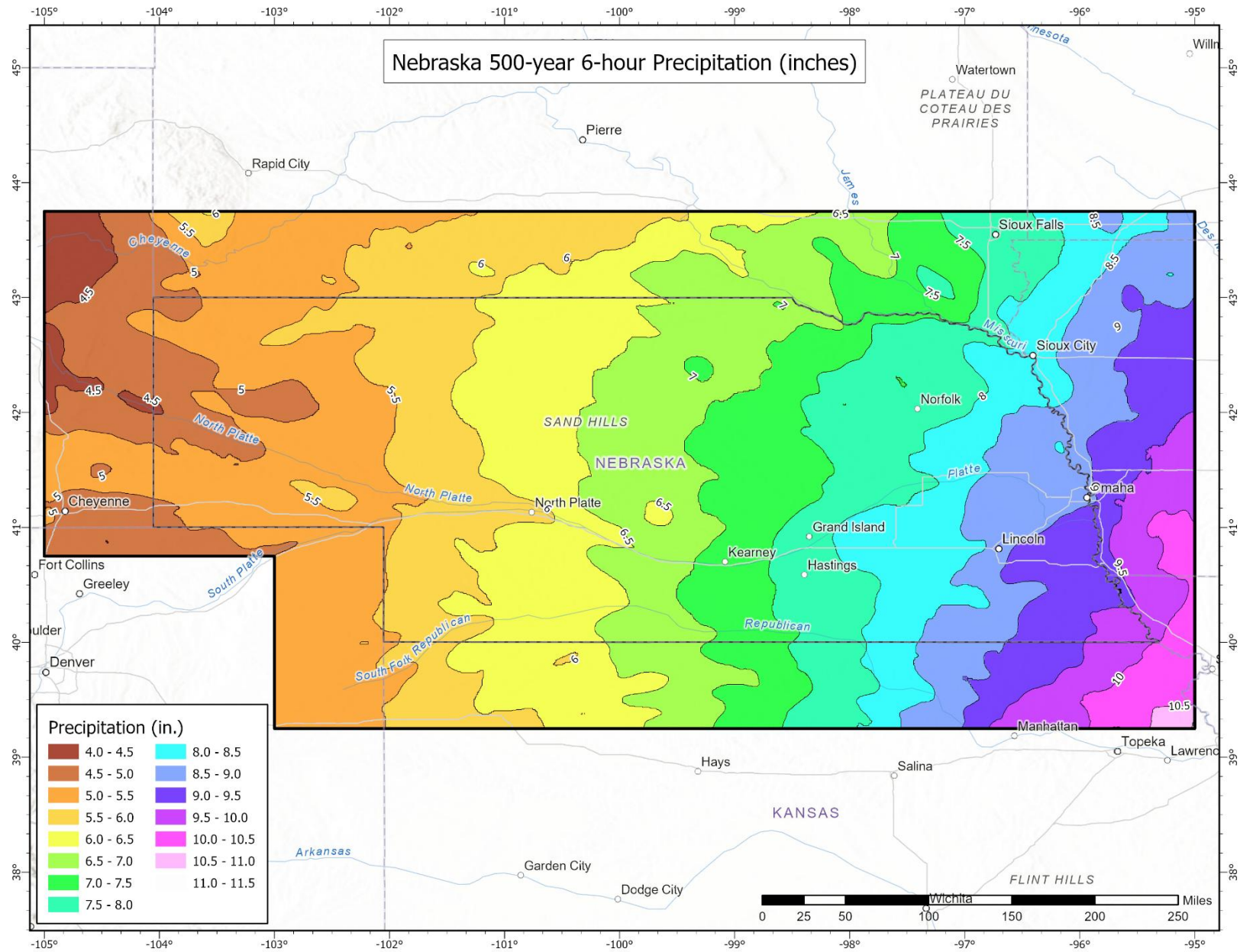
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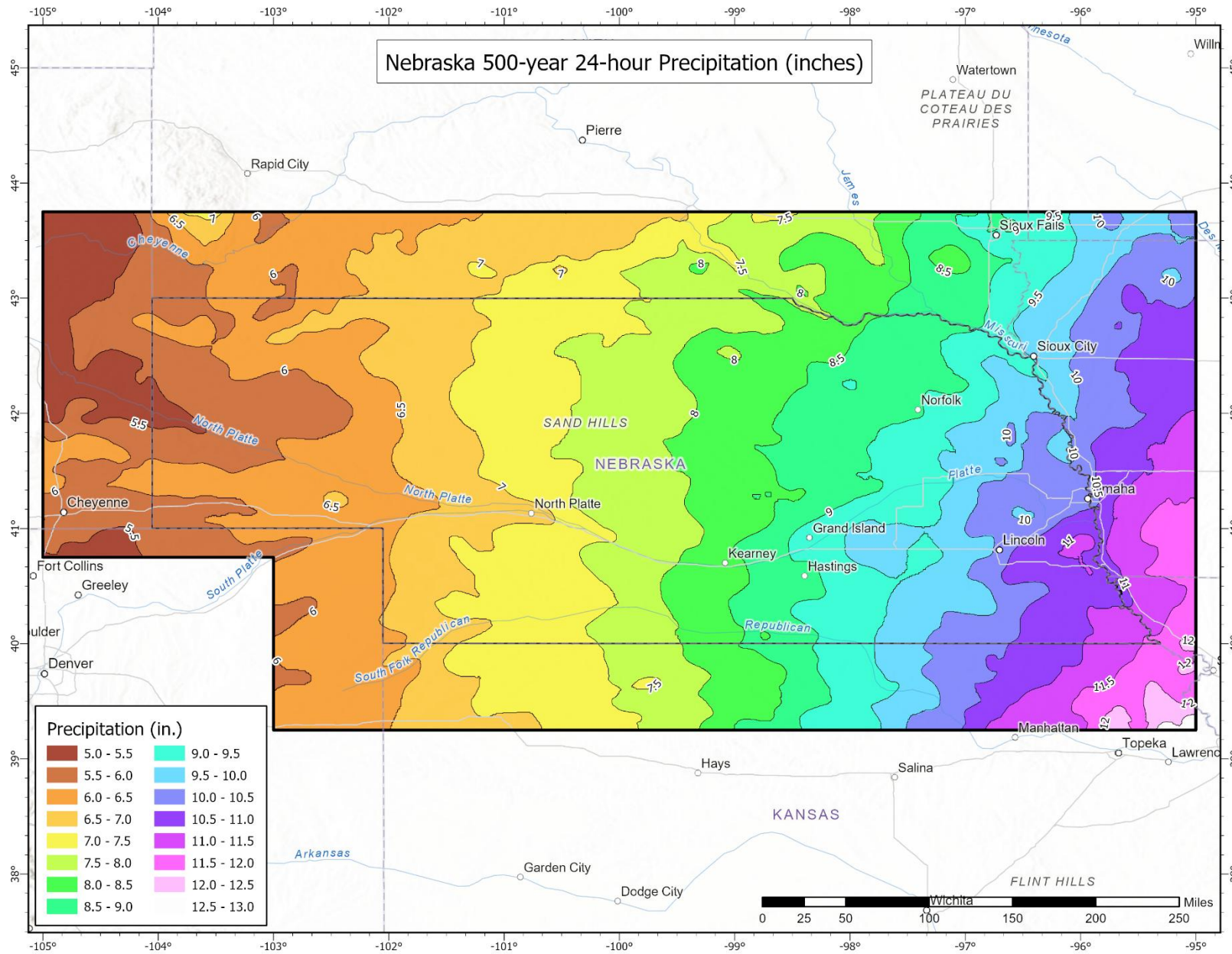
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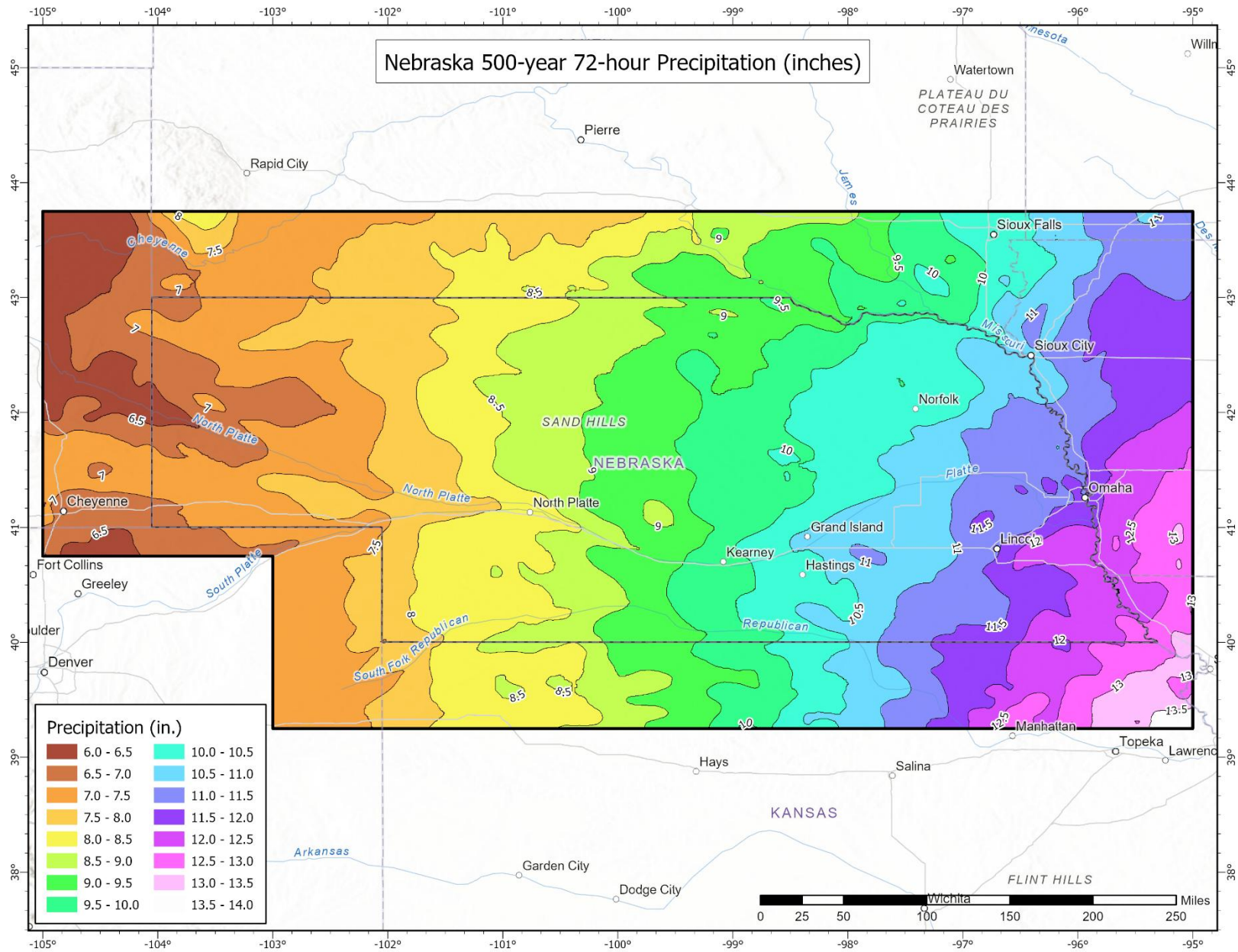
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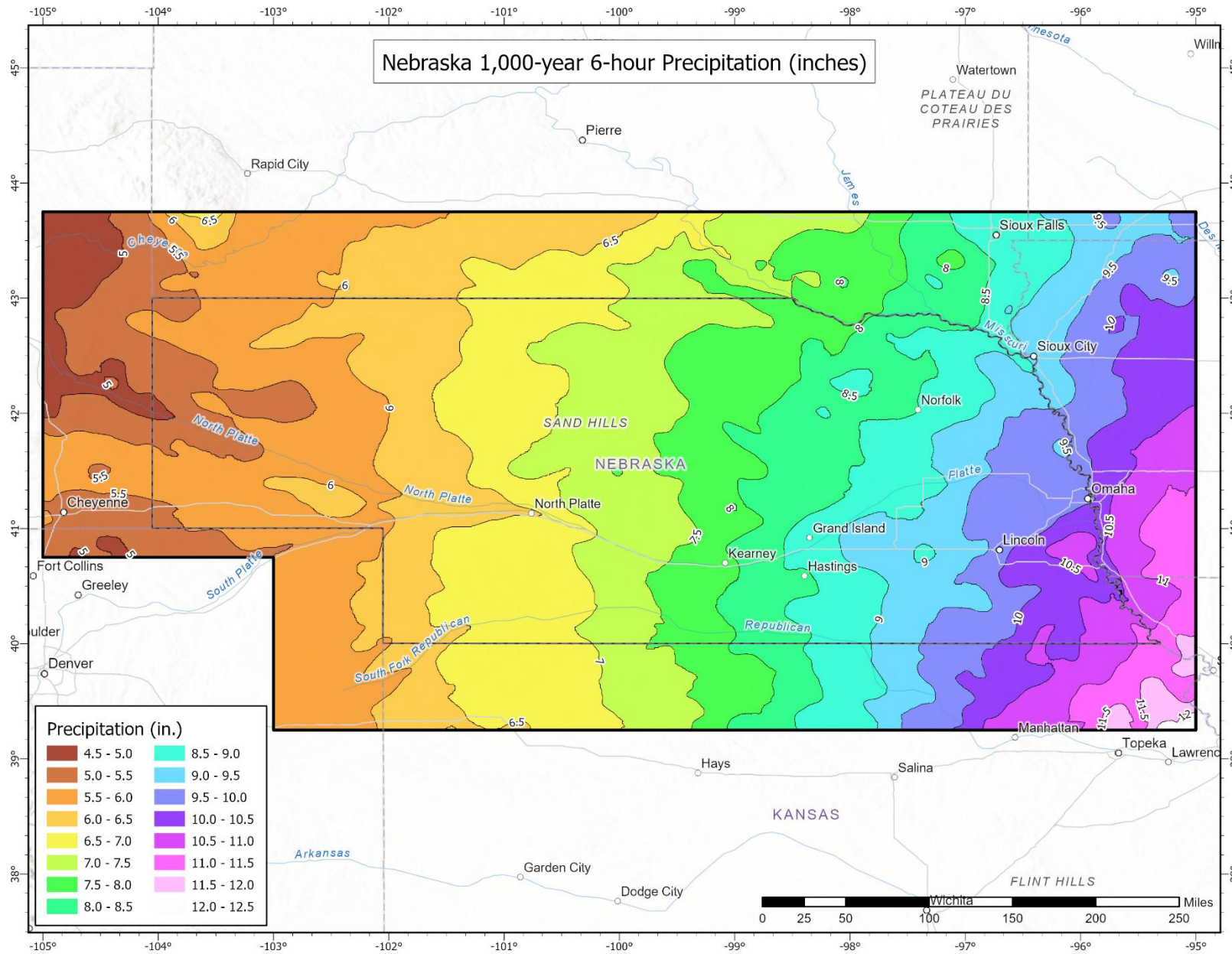
Nebraska Statewide Annual Exceedance Probability Study



Nebraska Statewide Annual Exceedance Probability Study



Nebraska Statewide Annual Exceedance Probability Study



Nebraska 1,000-year 24-hour Precipitation (inches)

This map displays the 1,000-year 24-hour precipitation isohyets for Nebraska. The precipitation levels are categorized into 16 ranges, each represented by a specific color. The map shows a clear trend of increasing precipitation from west to east, with the lowest values (5.5-6.0 inches) in the western part of the state and the highest values (14.0-14.5 inches) in the eastern part. Major geographical features like the Sand Hills, North Platte, and South Platte are labeled. The map also includes latitude and longitude coordinates, a scale bar in miles, and names of major cities and neighboring states.

Precipitation (in.)

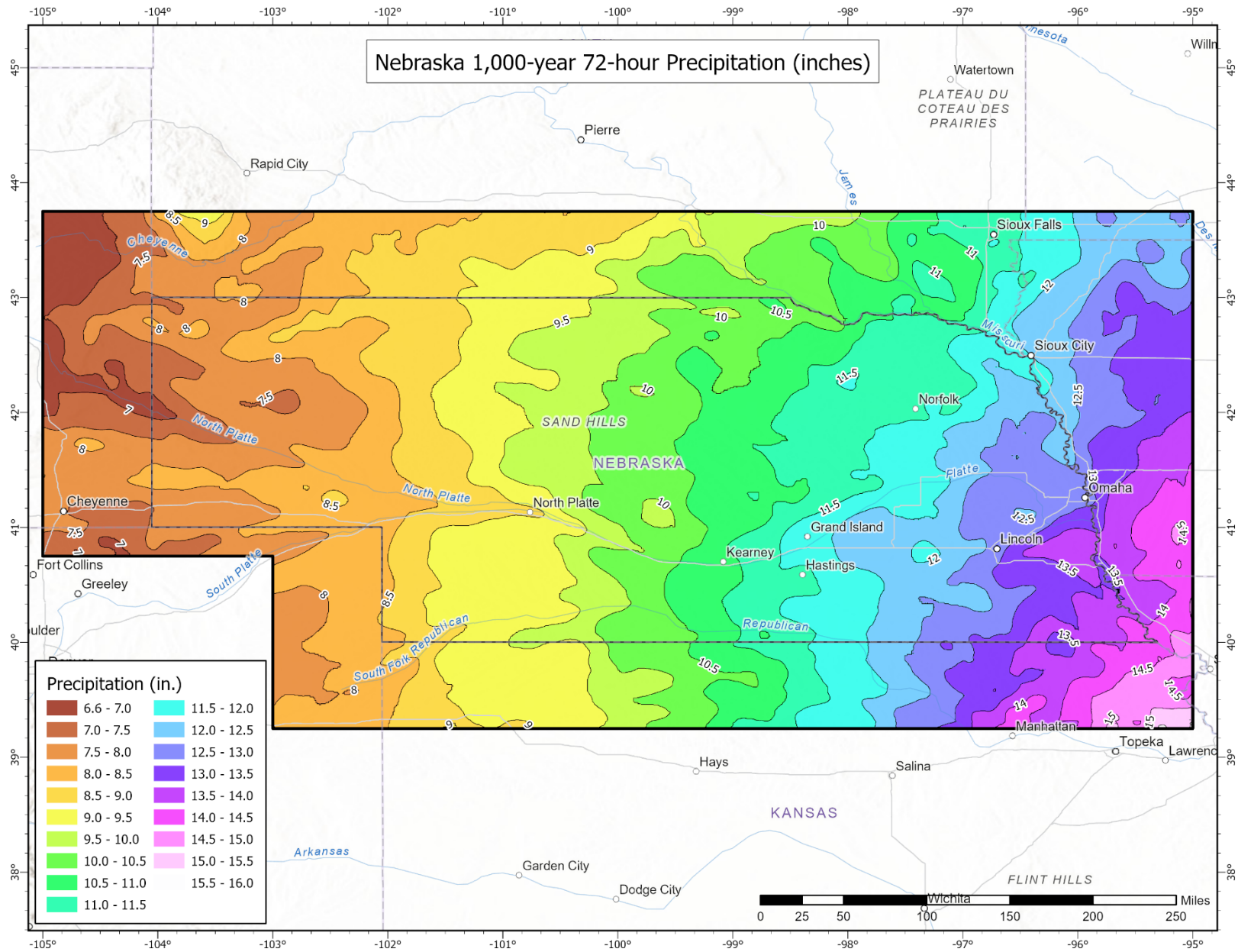
5.5 - 6.0	10.0 - 10.5
6.0 - 6.5	10.5 - 11.0
6.5 - 7.0	11.0 - 11.5
7.0 - 7.5	11.5 - 12.0
7.5 - 8.0	12.0 - 12.5
8.0 - 8.5	12.5 - 13.0
8.5 - 9.0	13.0 - 13.5
9.0 - 9.5	13.5 - 14.0
9.5 - 10.0	14.0 - 14.5

Map Labels:

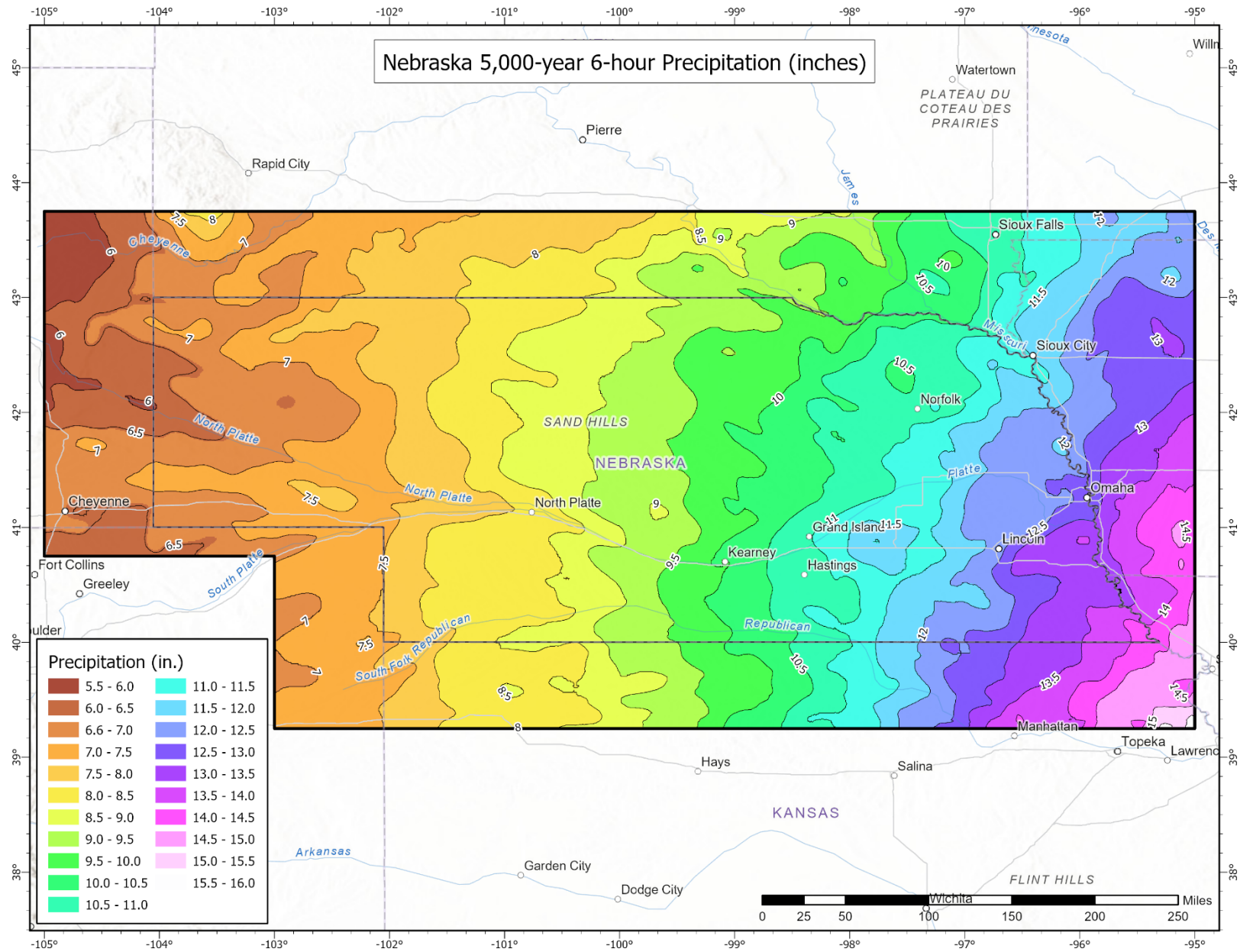
- Nebraska:** SAND HILLS, NEBRASKA
- Neighboring States:** WYOMING, KANSAS, MISSOURI, IOWA, NEBRASKA
- Cities:** Cheyenne, Fort Collins, Greeley, Denver, Rapid City, Pierre, Watertown, Sioux Falls, Sioux City, Omaha, Lincoln, Manhattan, Topeka, Lawrence, Dodge City, Garden City, Hays, Salina, Wichita
- Water Bodies:** North Platte, South Platte, Republican, Platte, James, Missouri, Arkansas, Flint Hills

Scale: 0 to 250 Miles

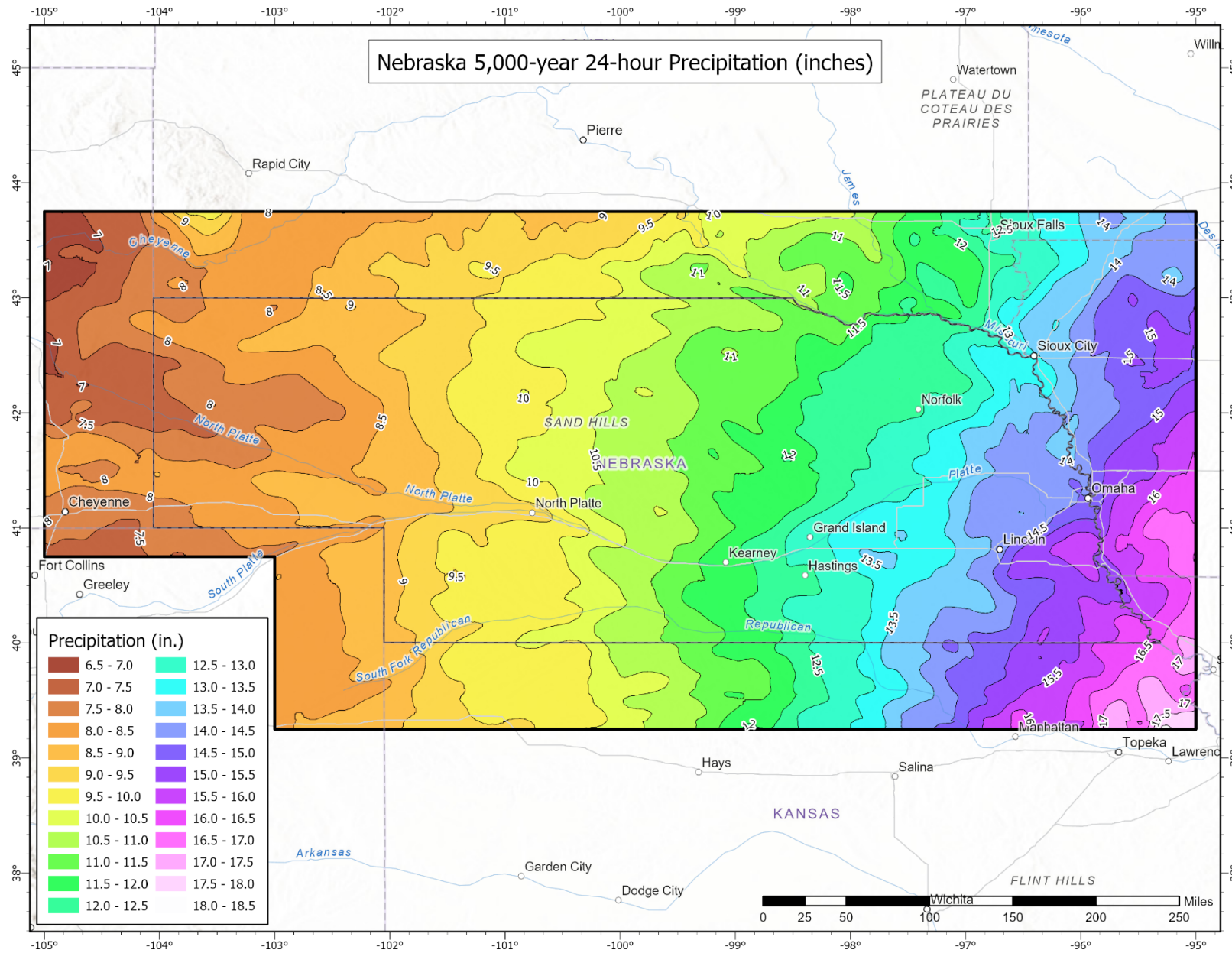
Nebraska Statewide Annual Exceedance Probability Study



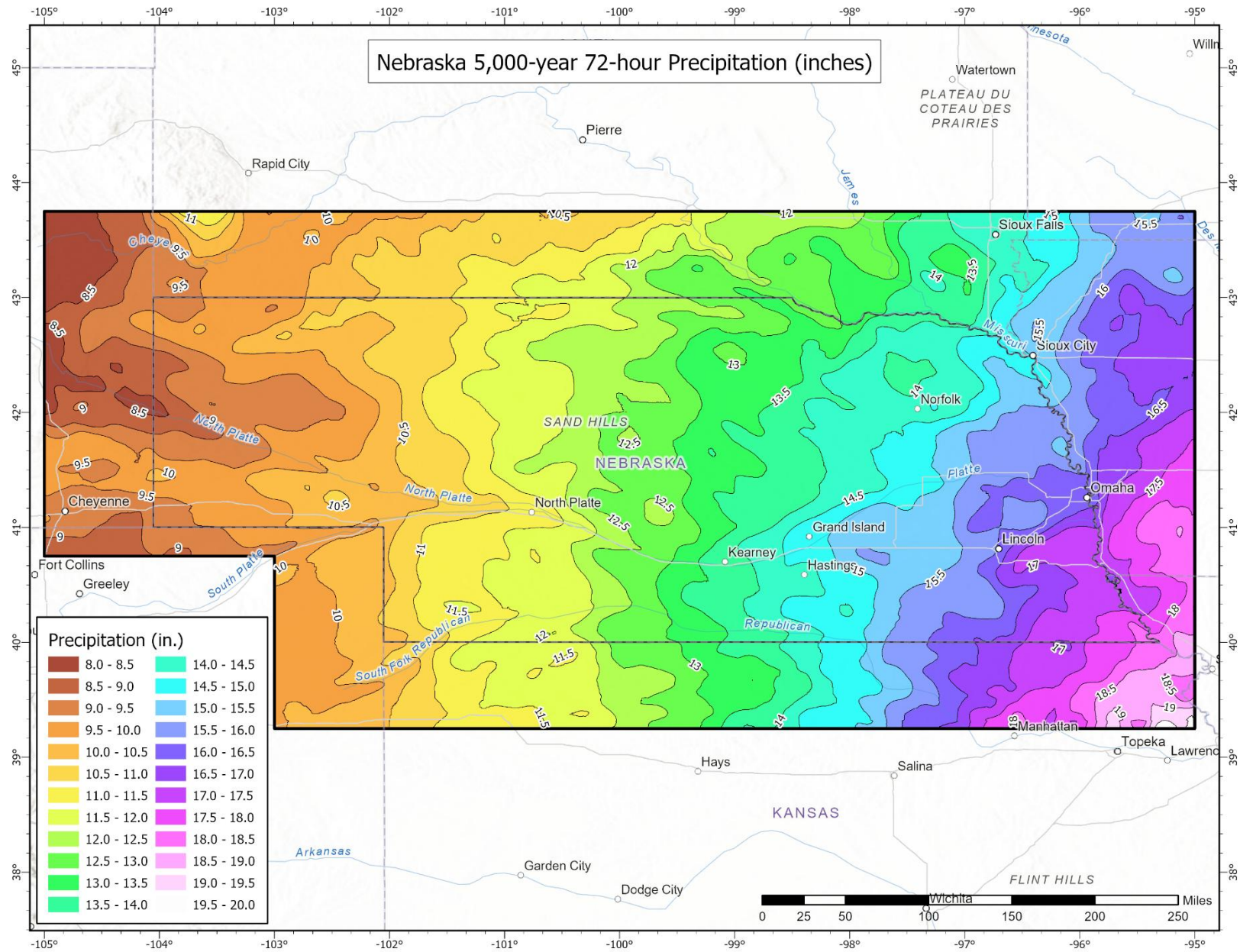
Nebraska Statewide Annual Exceedance Probability Study



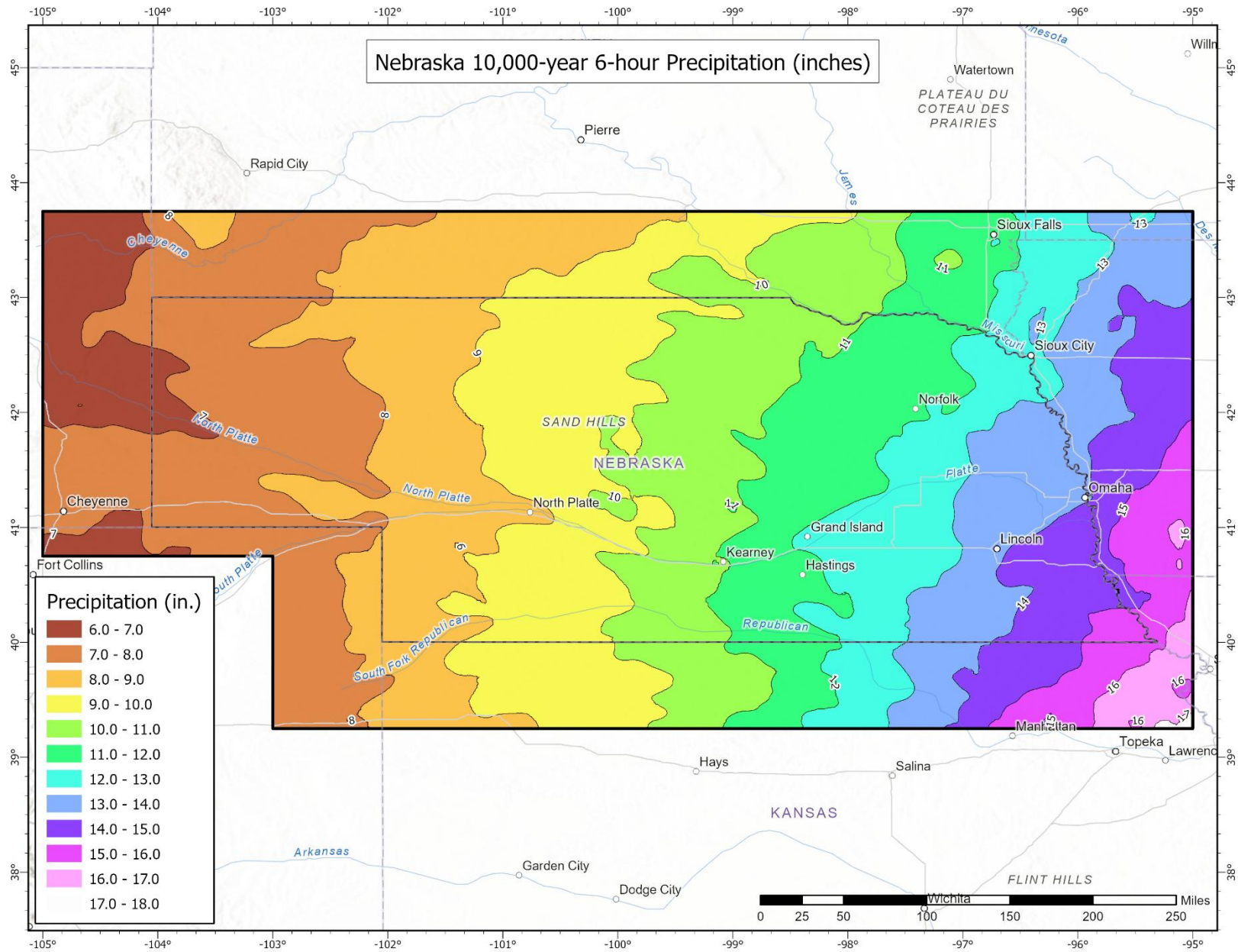
Nebraska Statewide Annual Exceedance Probability Study



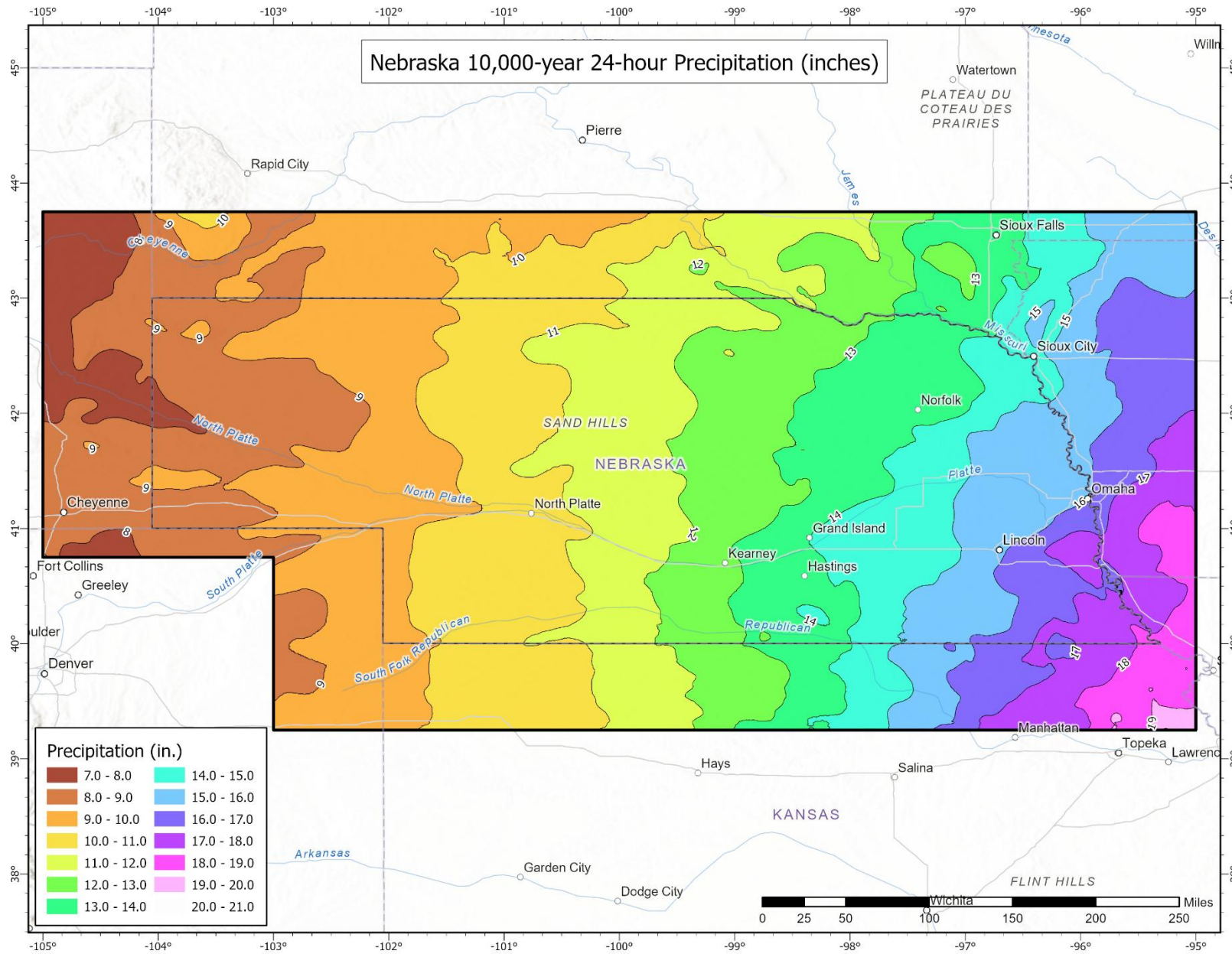
Nebraska Statewide Annual Exceedance Probability Study



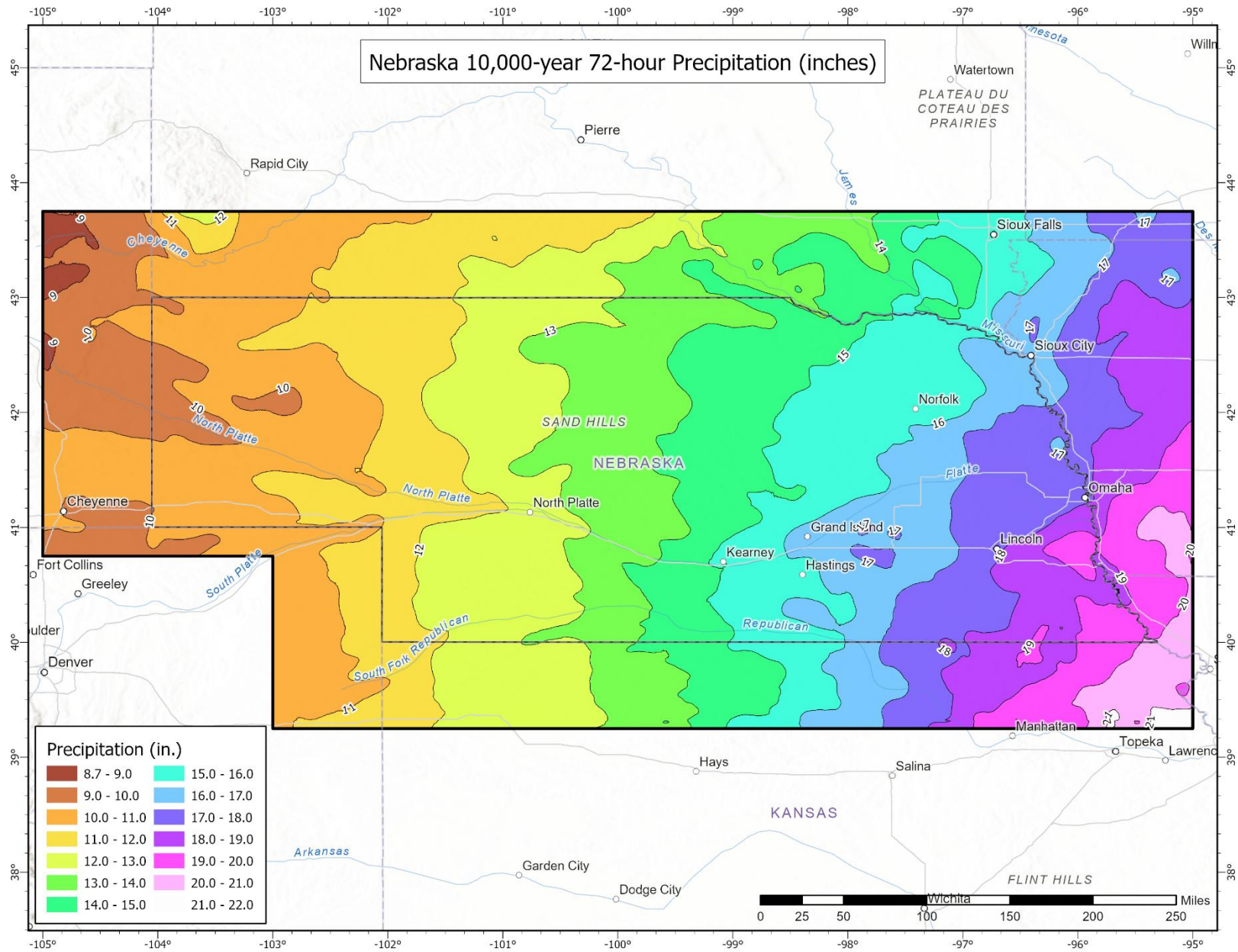
Nebraska Statewide Annual Exceedance Probability Study



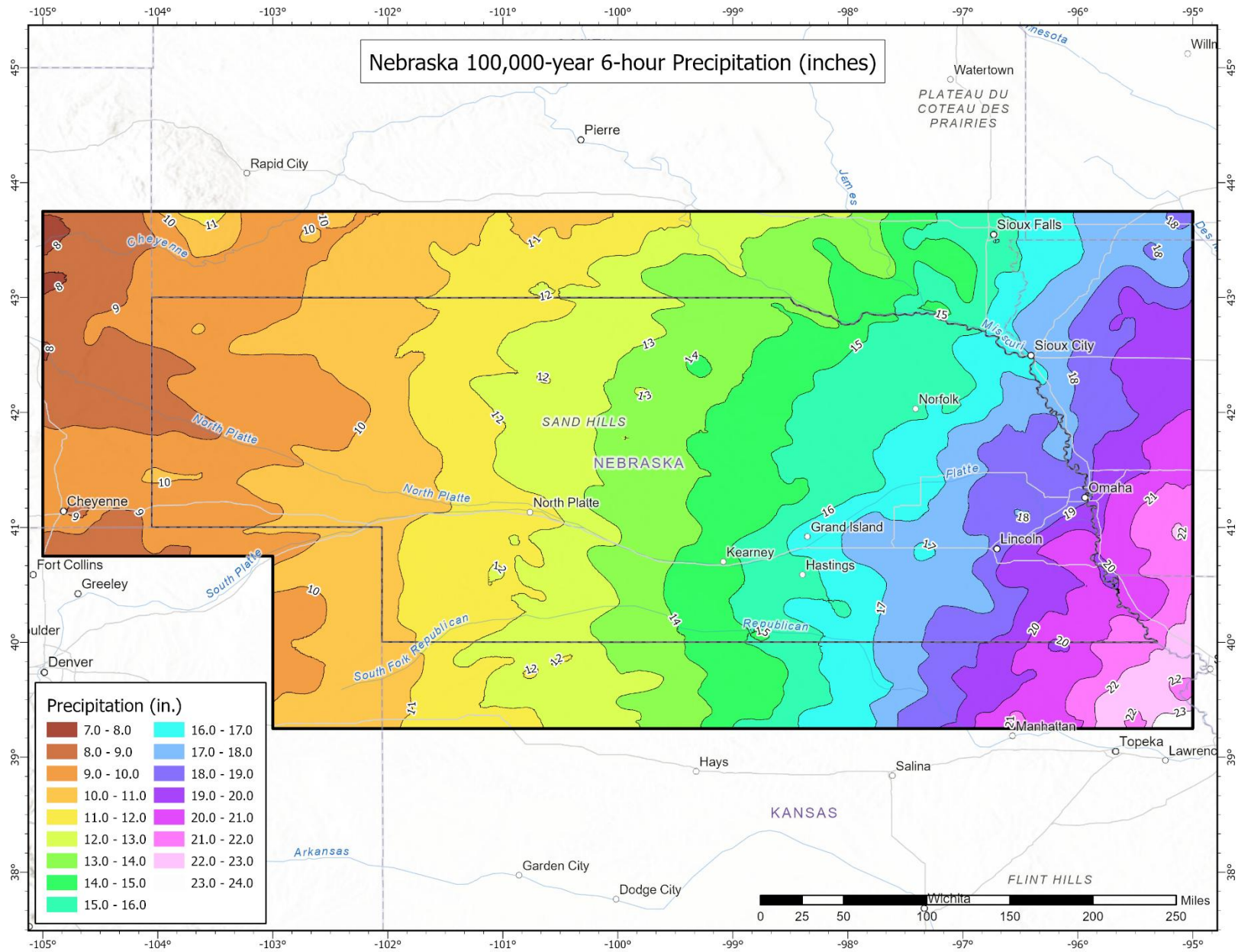
Nebraska Statewide Annual Exceedance Probability Study



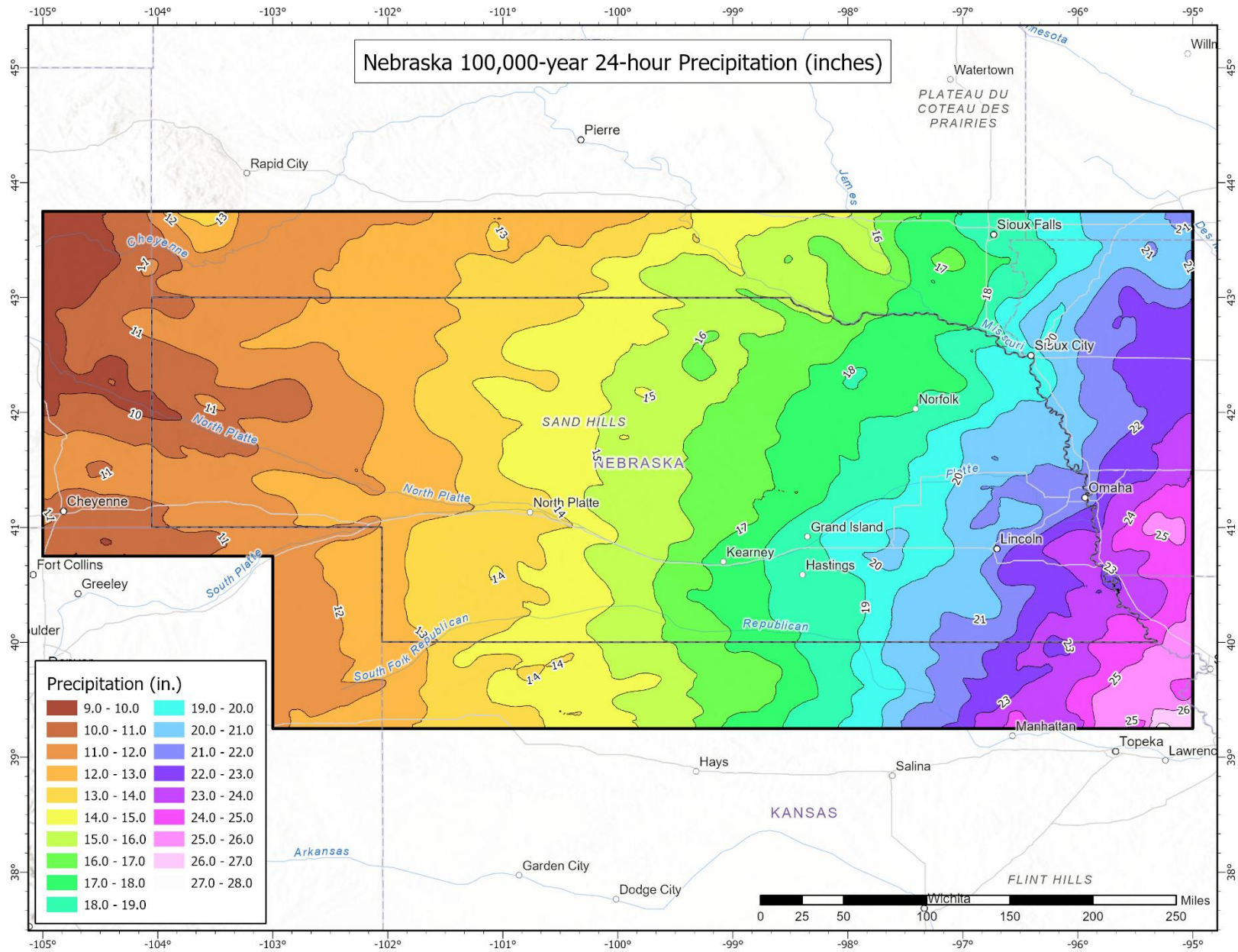
Nebraska Statewide Annual Exceedance Probability Study



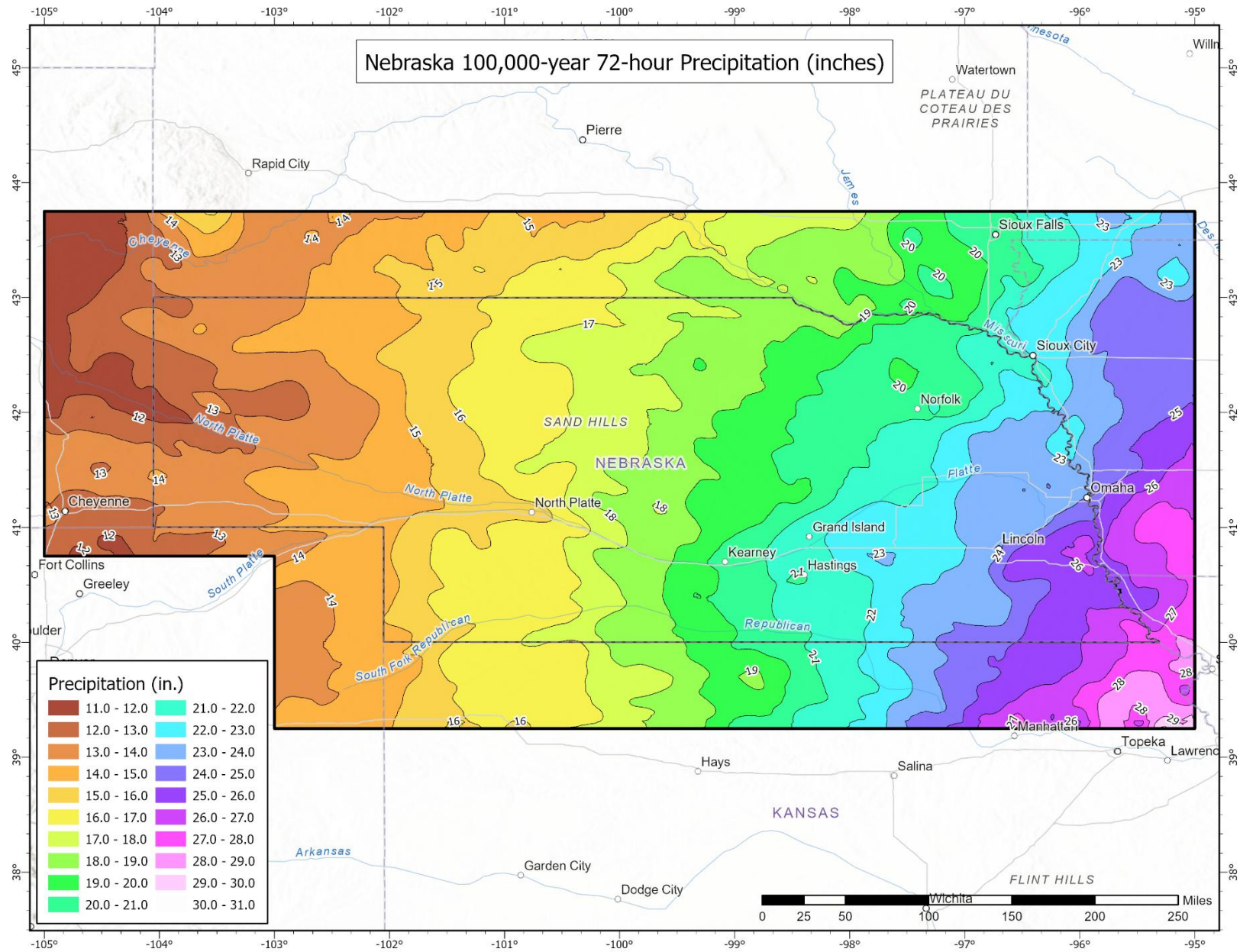
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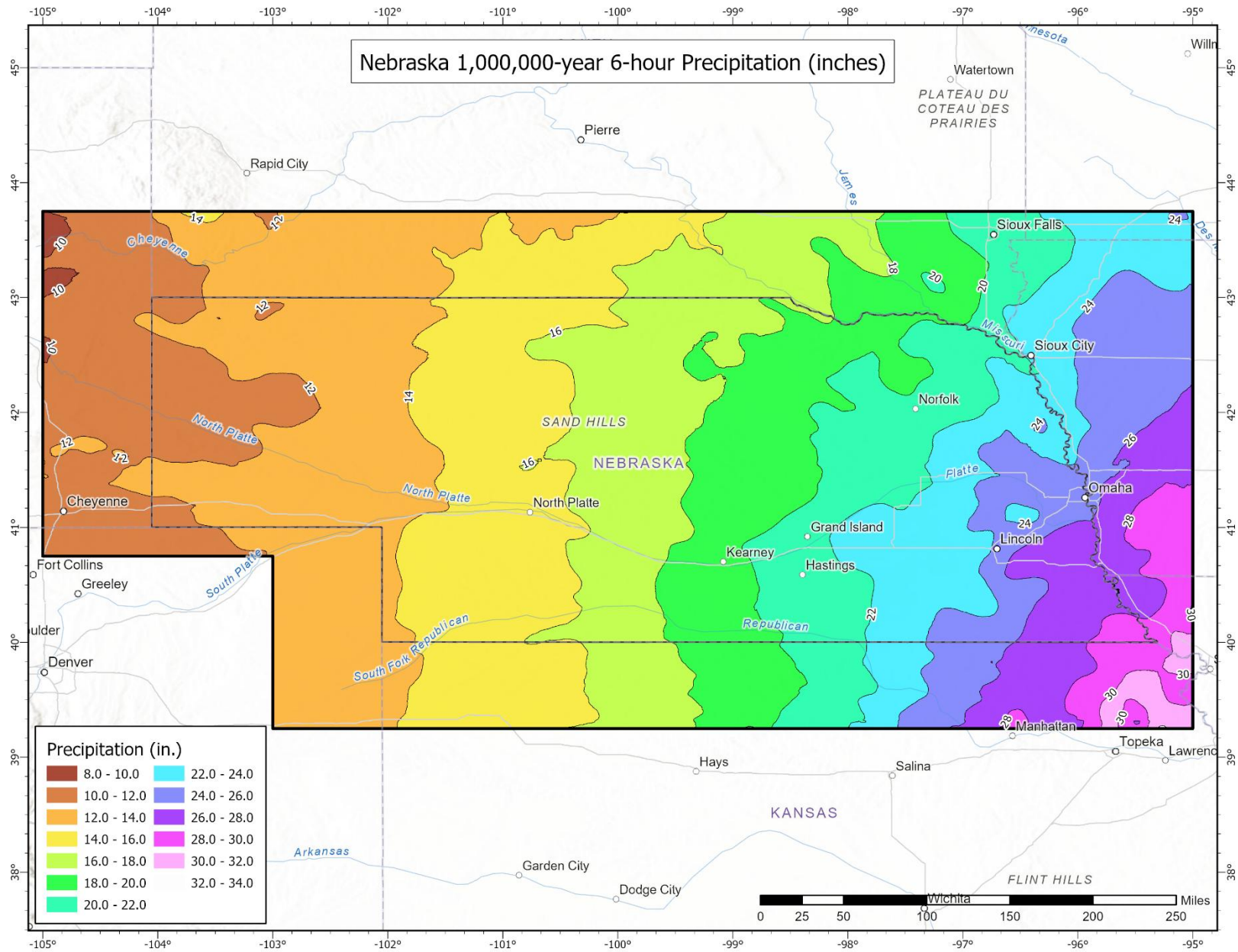
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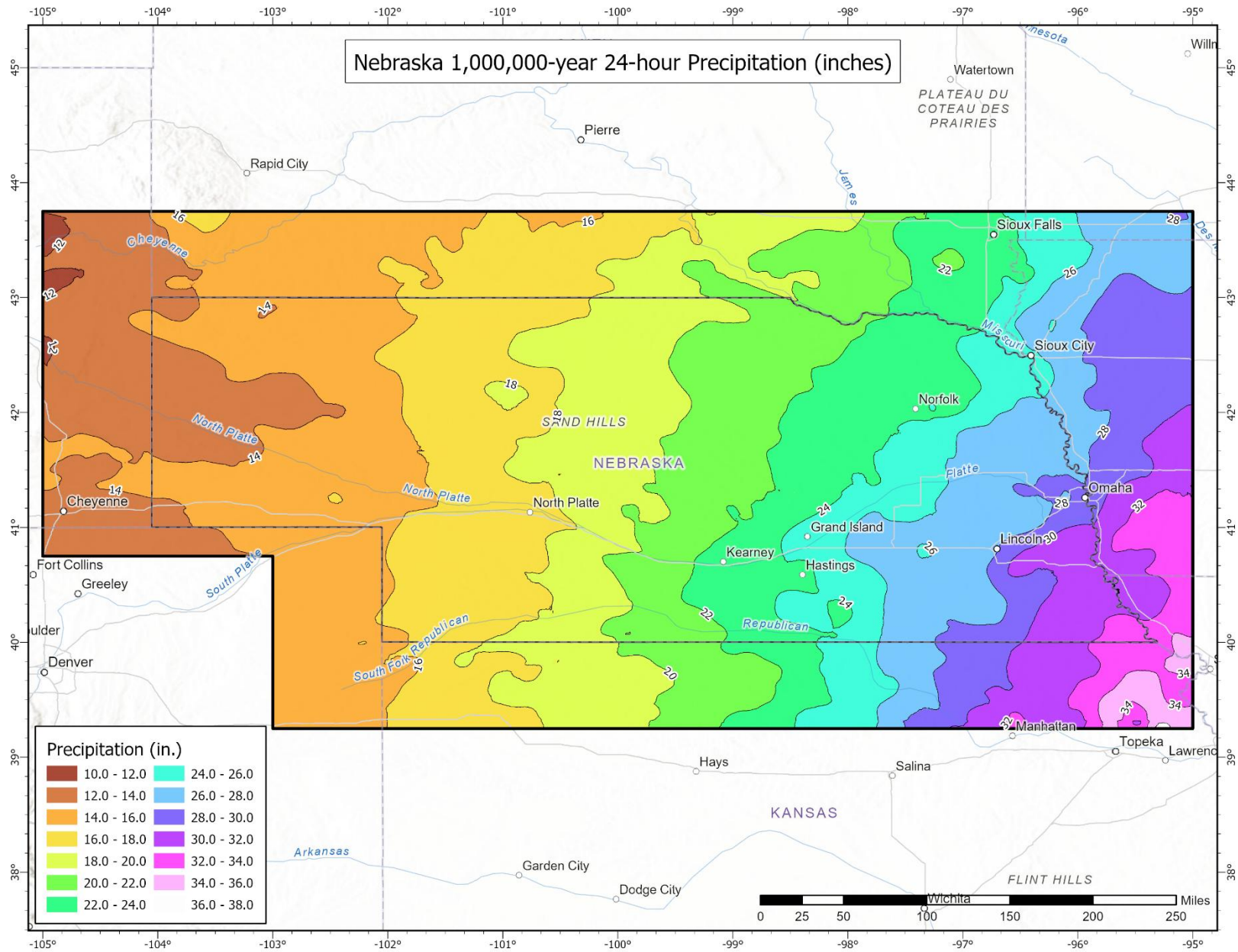
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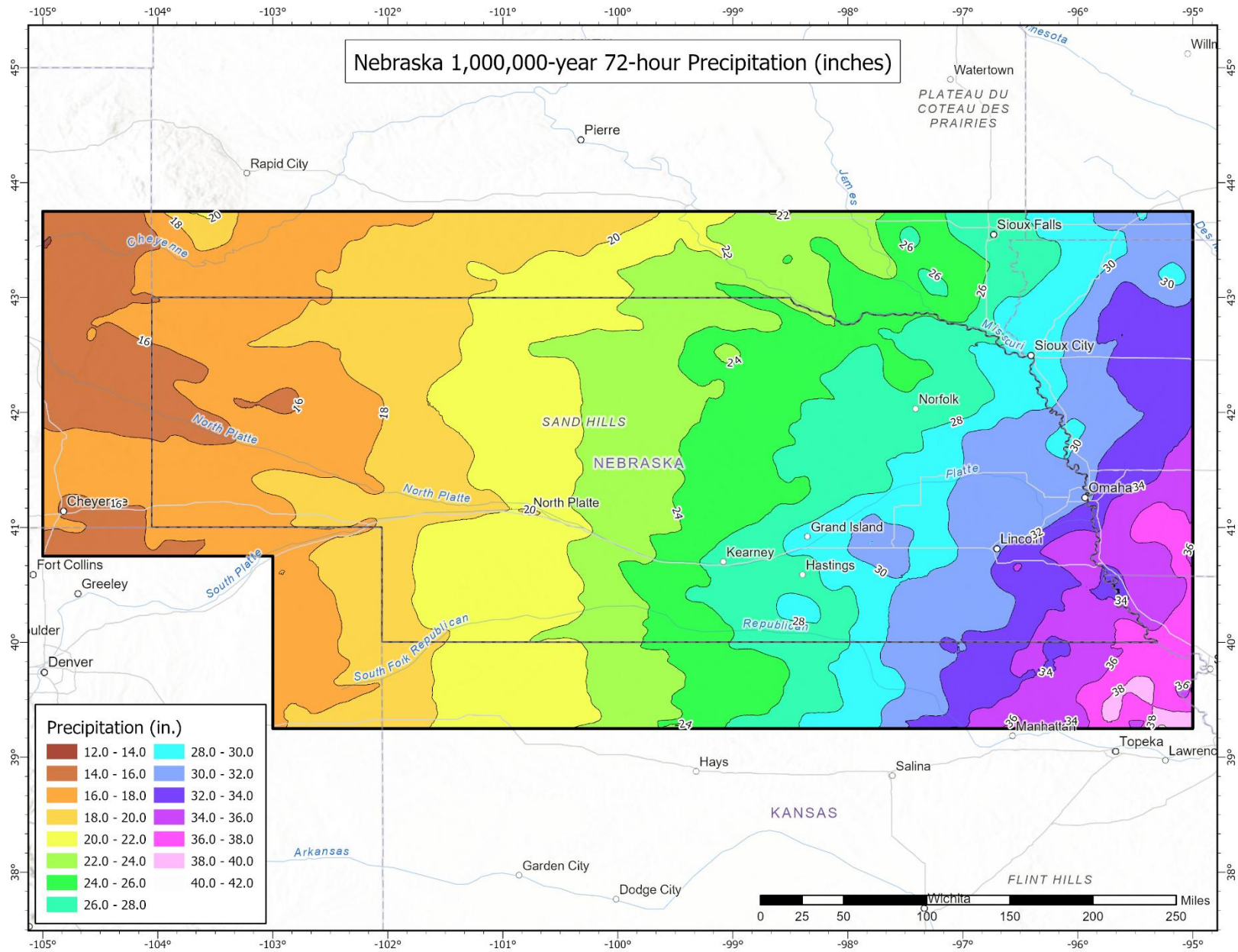
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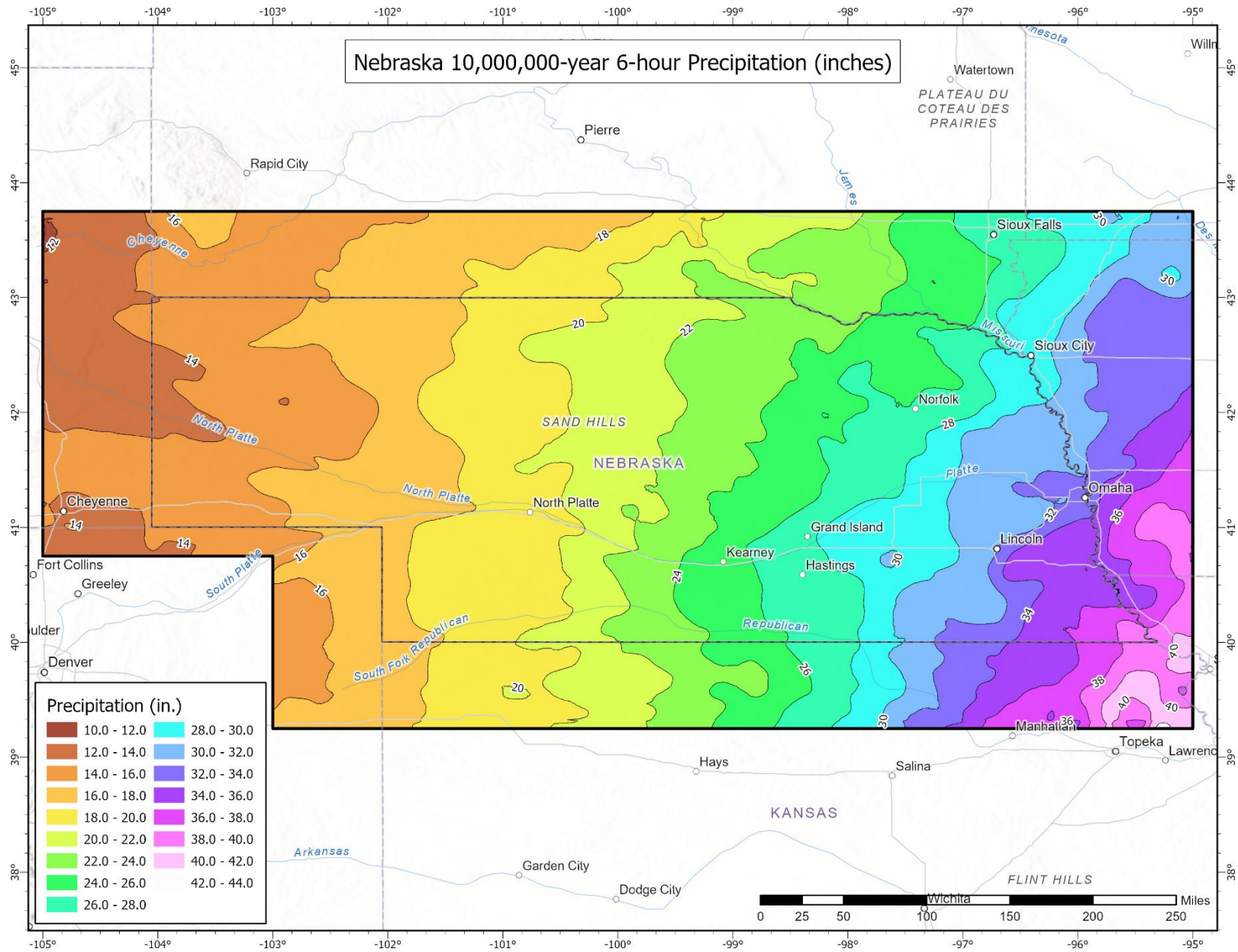
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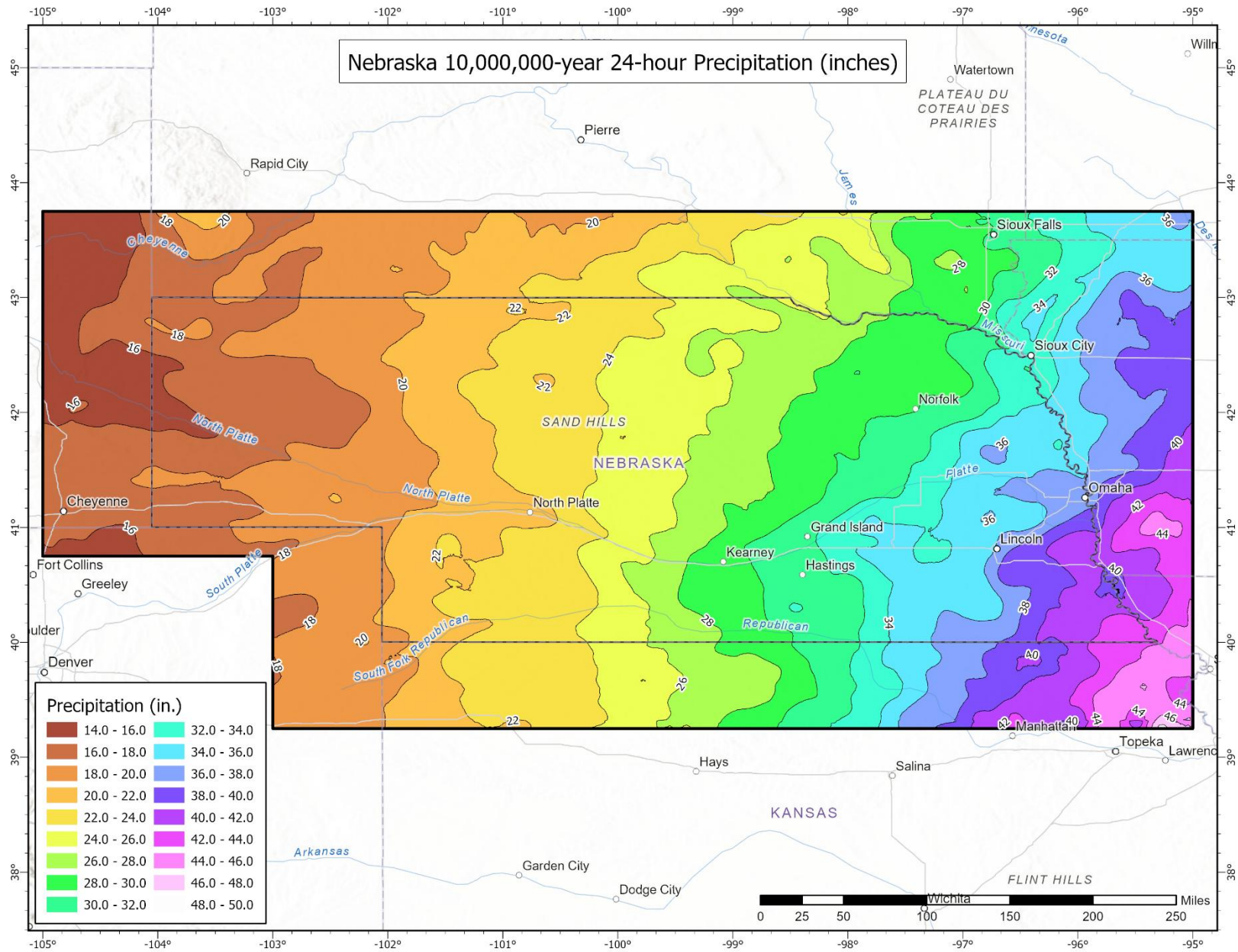
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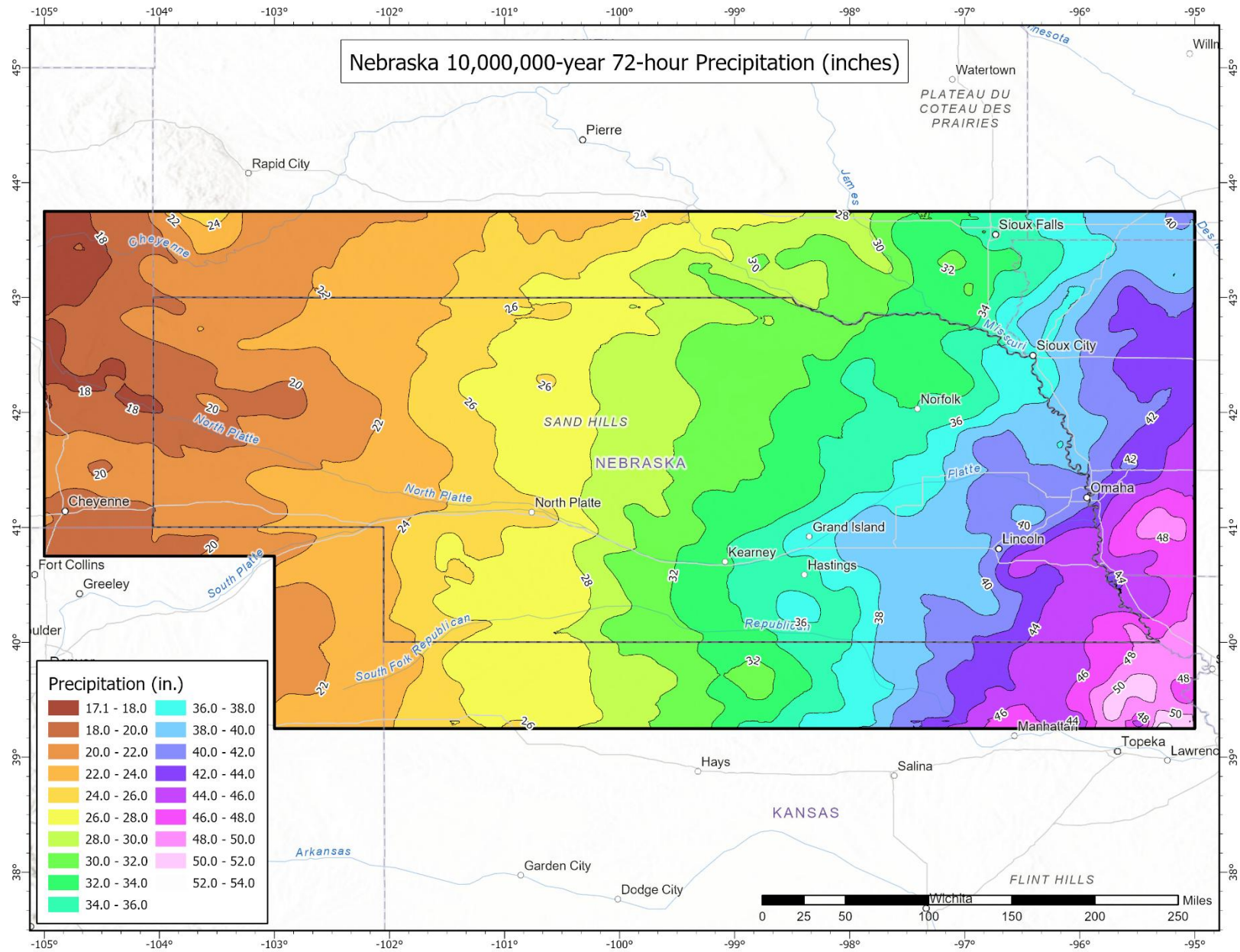
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Nebraska Statewide Annual Exceedance Probability Study



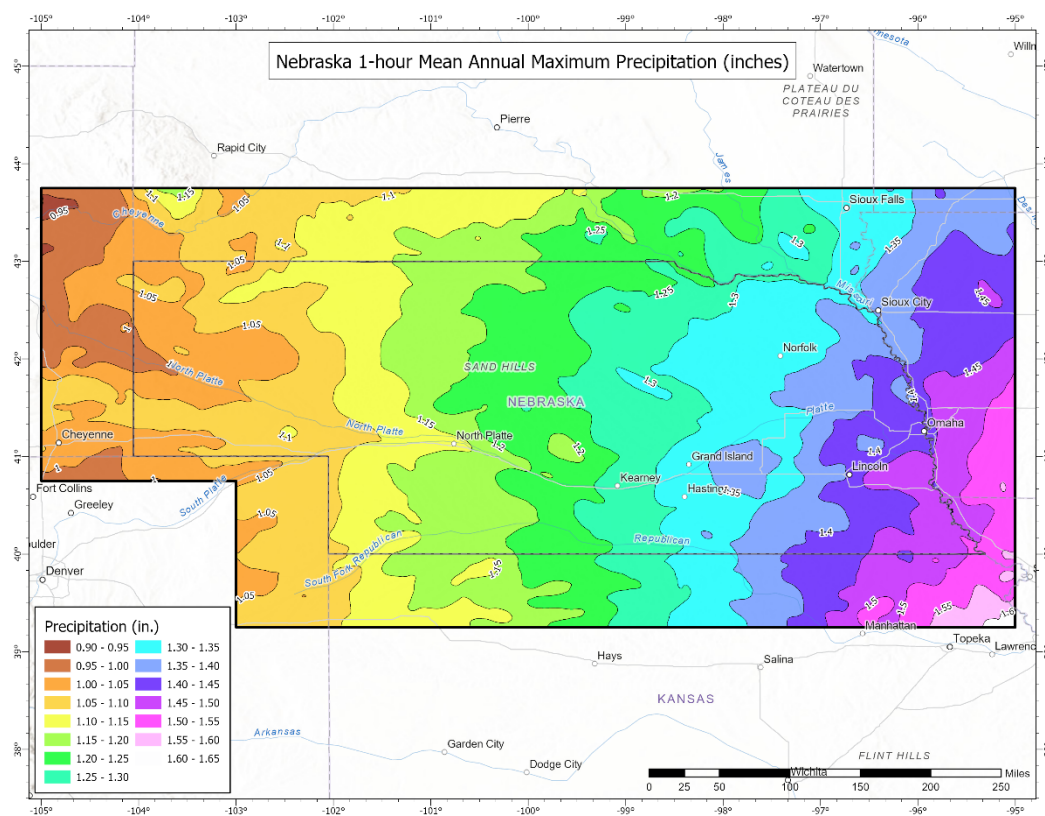
Nebraska Statewide Annual Exceedance Probability Study



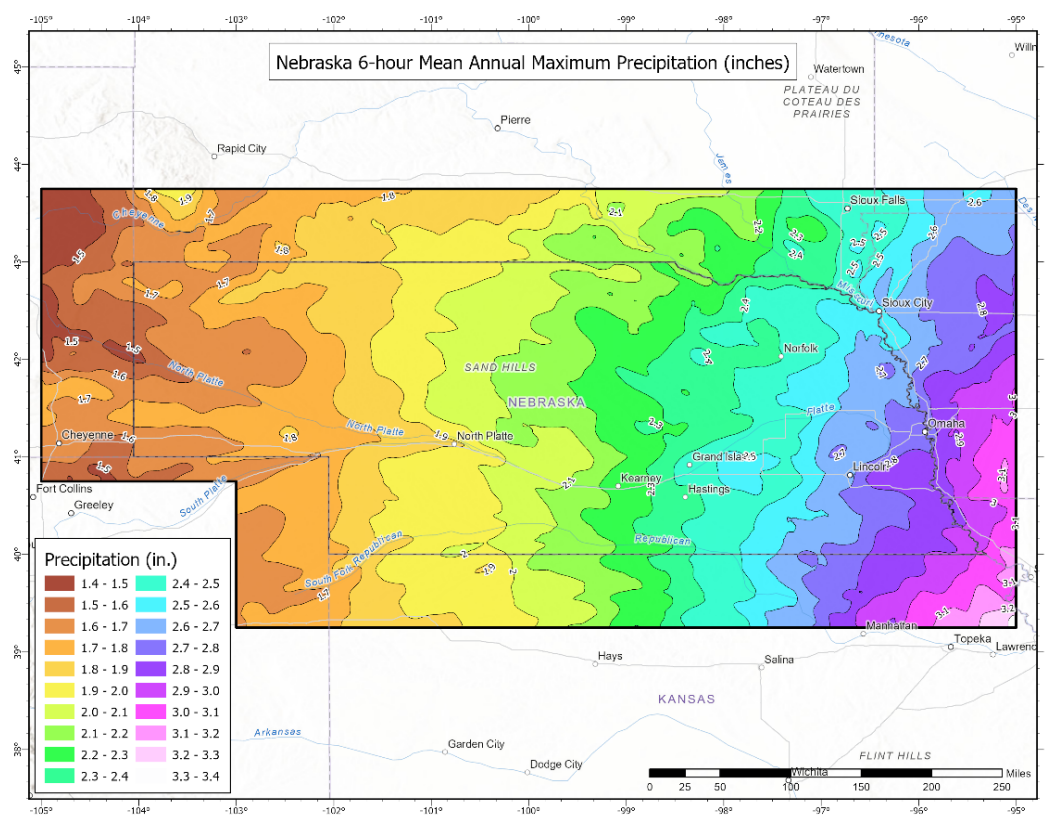
Appendix B

Additional Map Images

Nebraska Statewide Annual Exceedance Probability Study

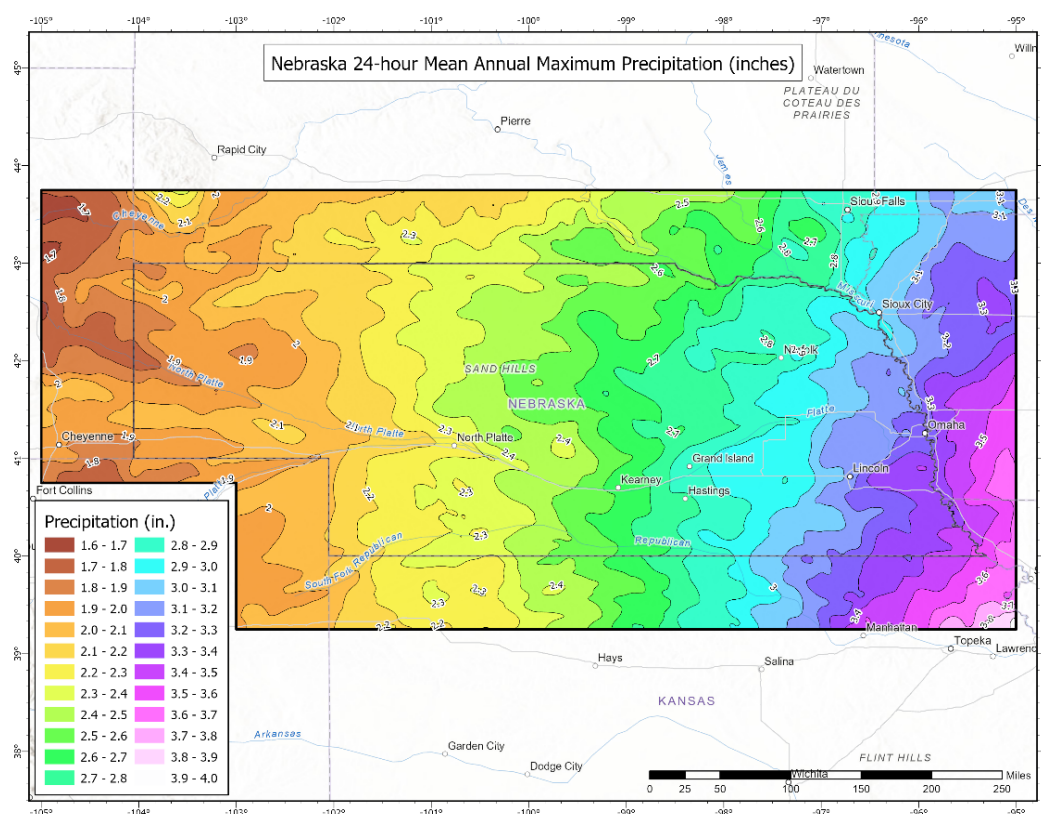


Appendix B.1: 1-hour Mean Annual Maximum Precipitation

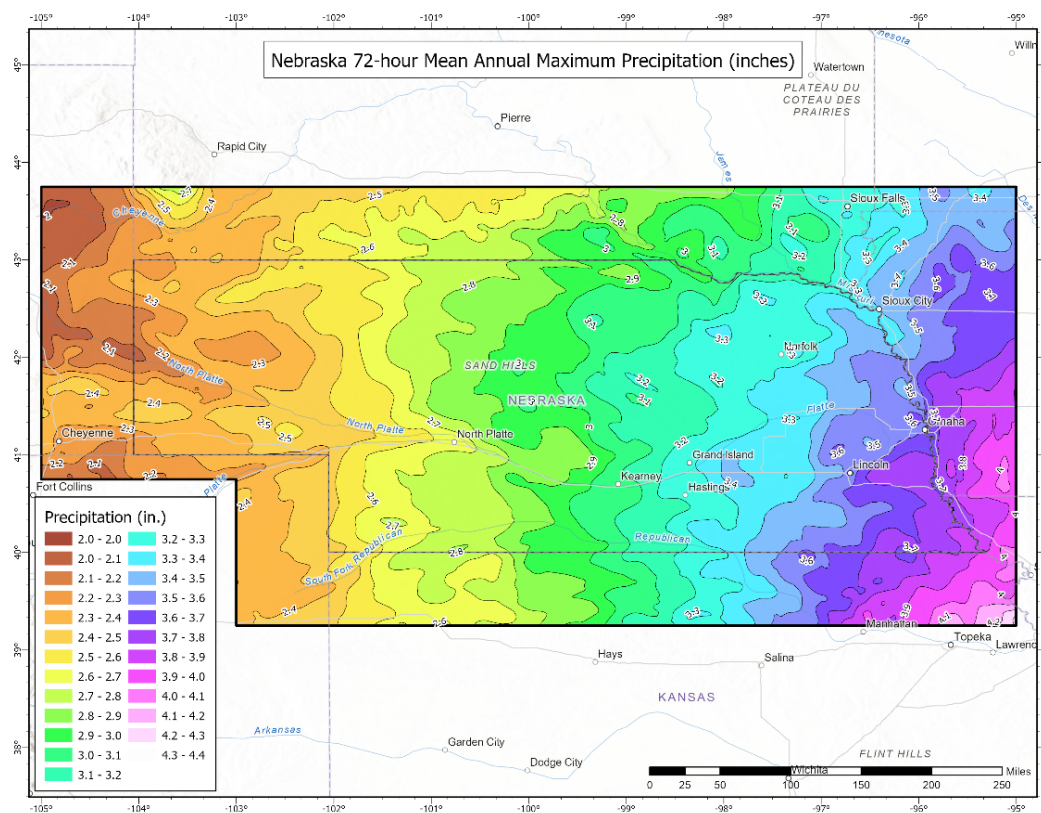


Appendix B.2: 6-hour Mean Annual Maximum Precipitation

Nebraska Statewide Annual Exceedance Probability Study

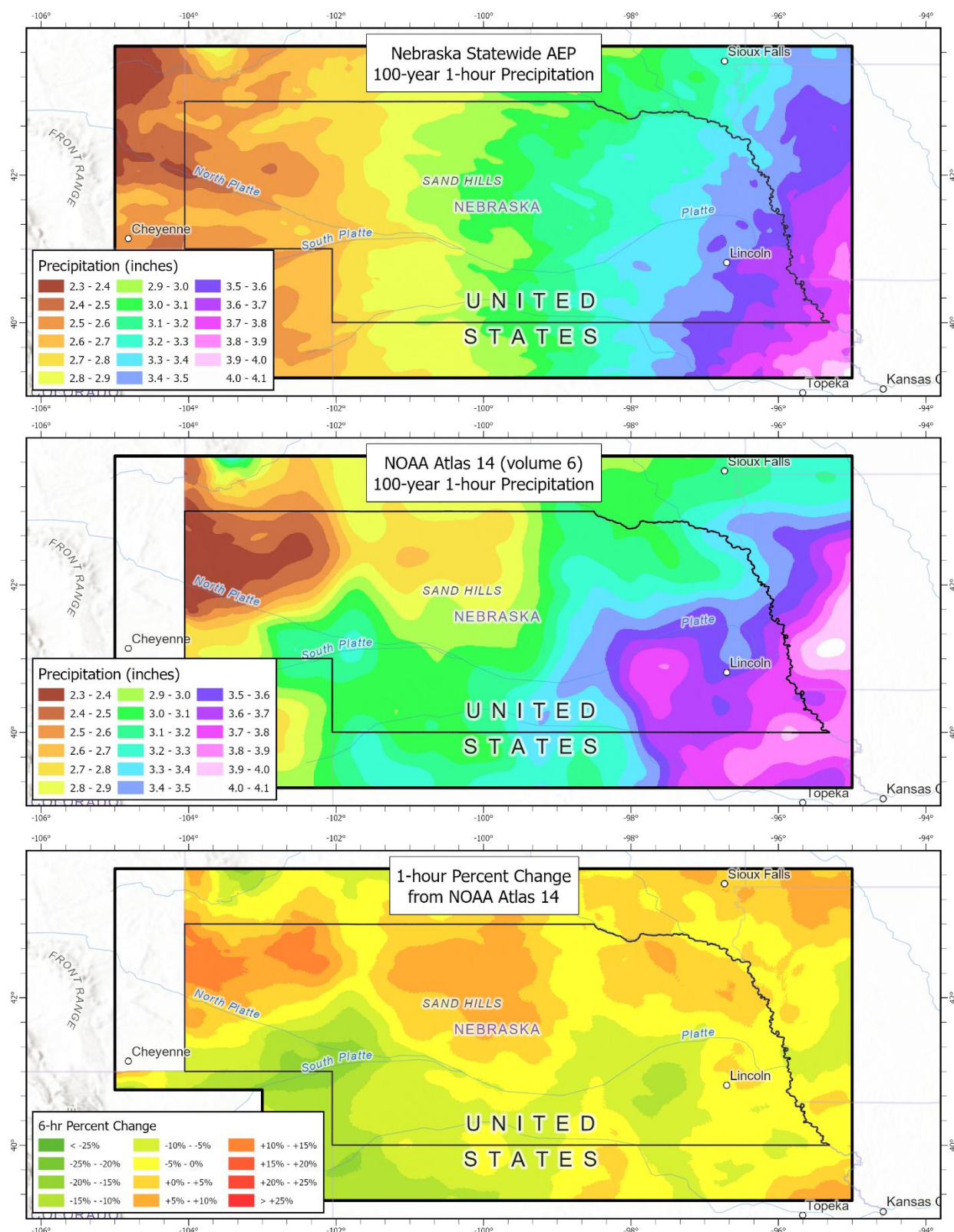


Appendix B.3: 24-hour Mean Annual Maximum Precipitation



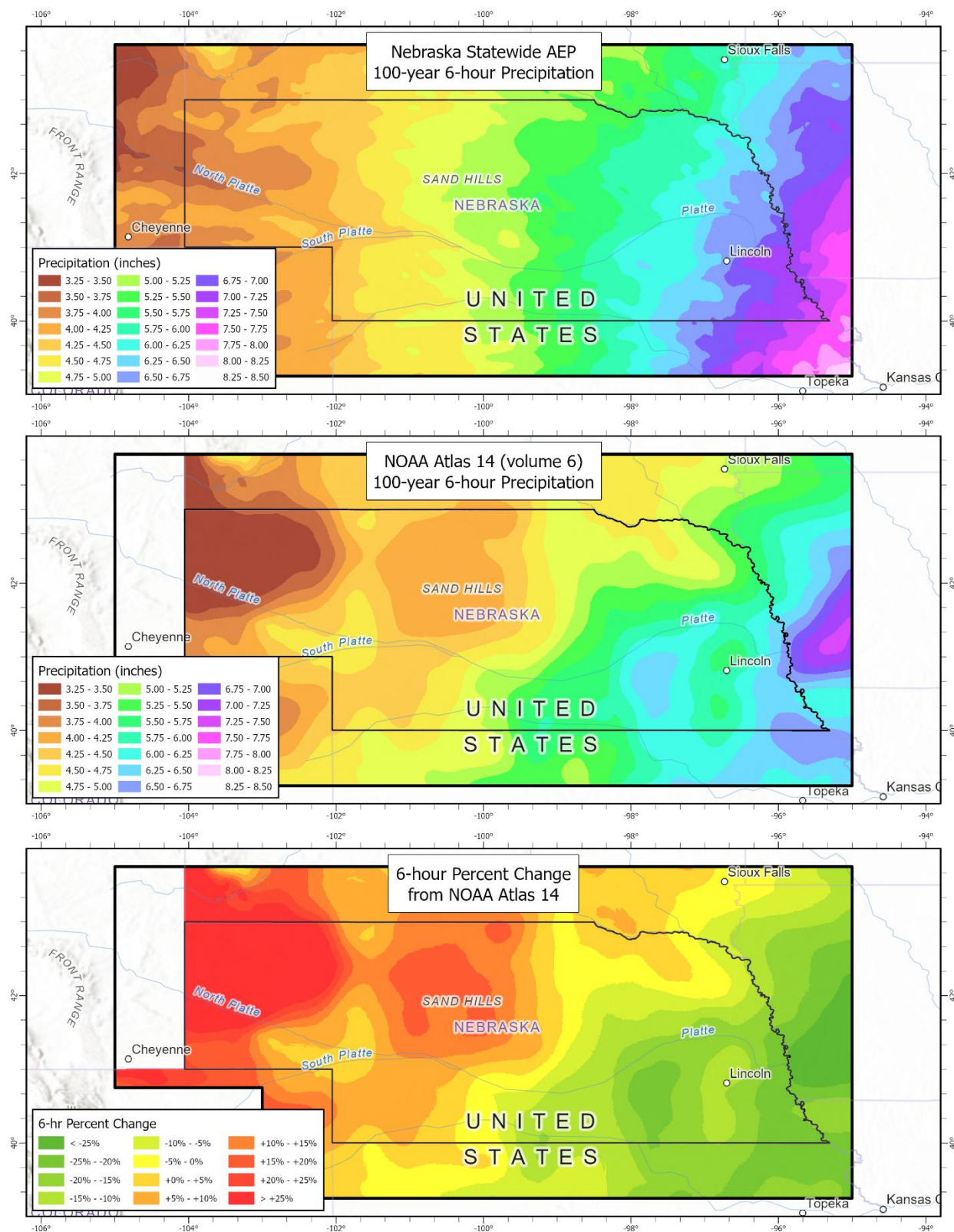
Appendix B.4: 72-hour Mean Annual Maximum Precipitation

Nebraska Statewide Annual Exceedance Probability Study



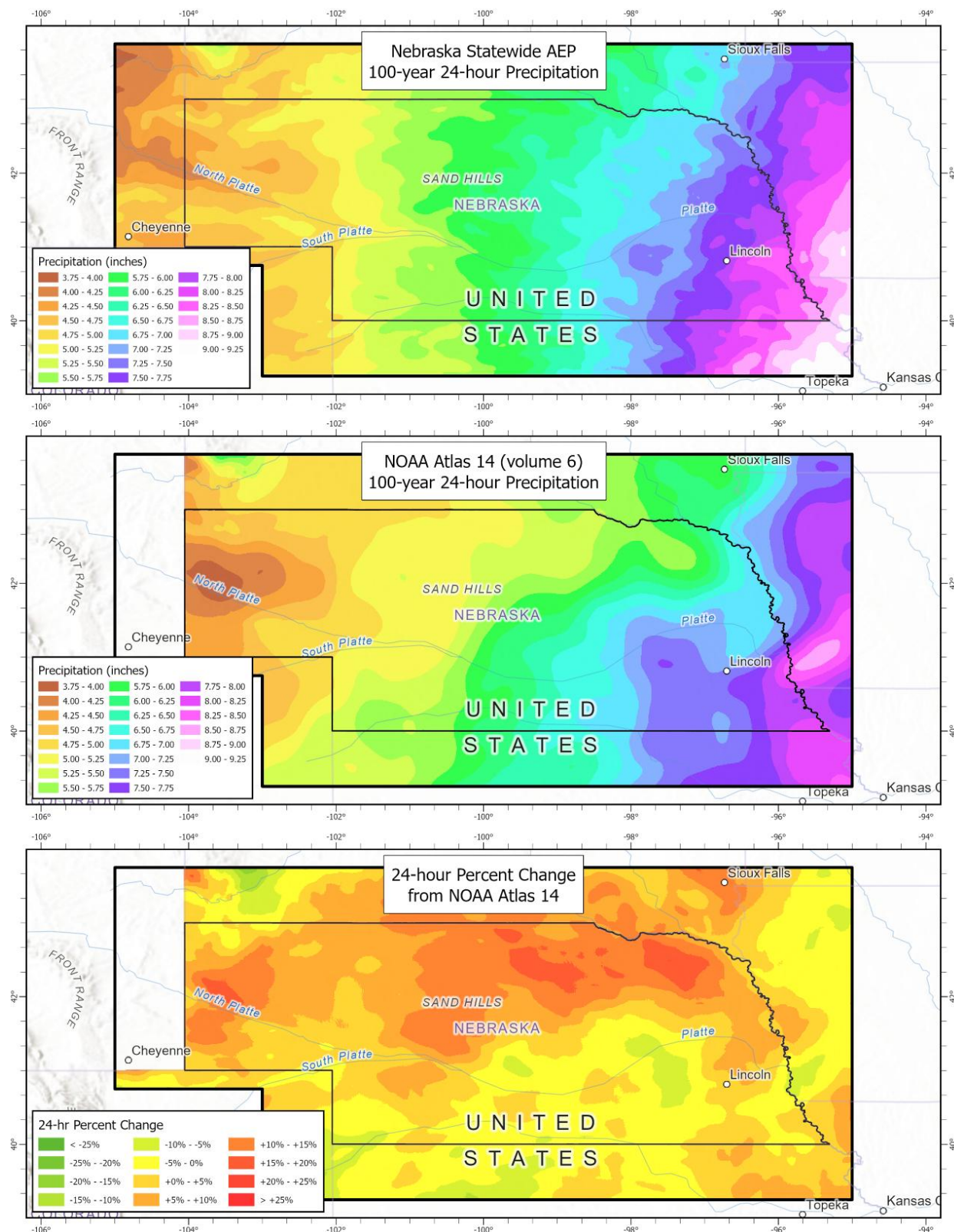
Appendix B.5: 1-hour 100-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



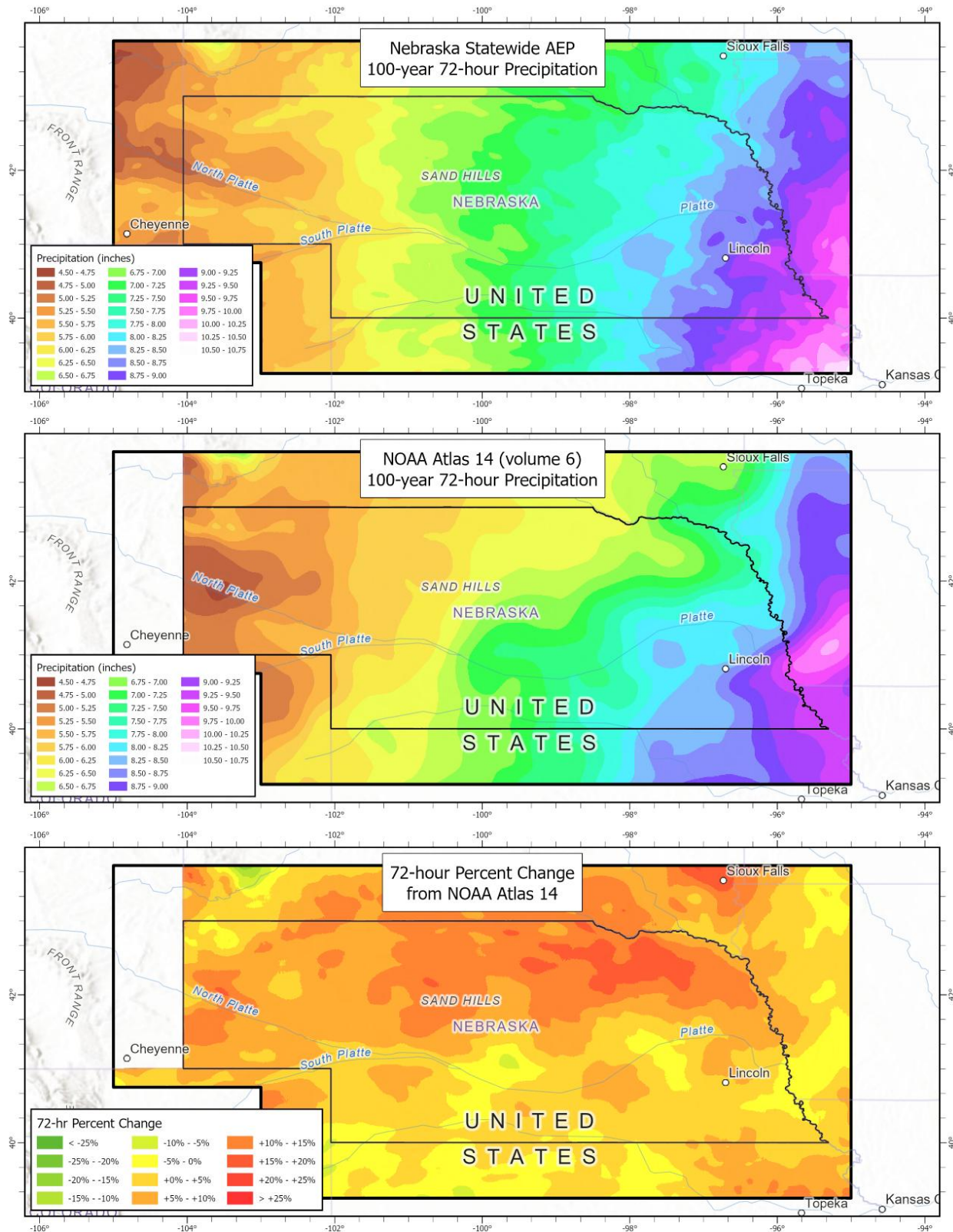
Appendix B.6: 6-hour 100-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



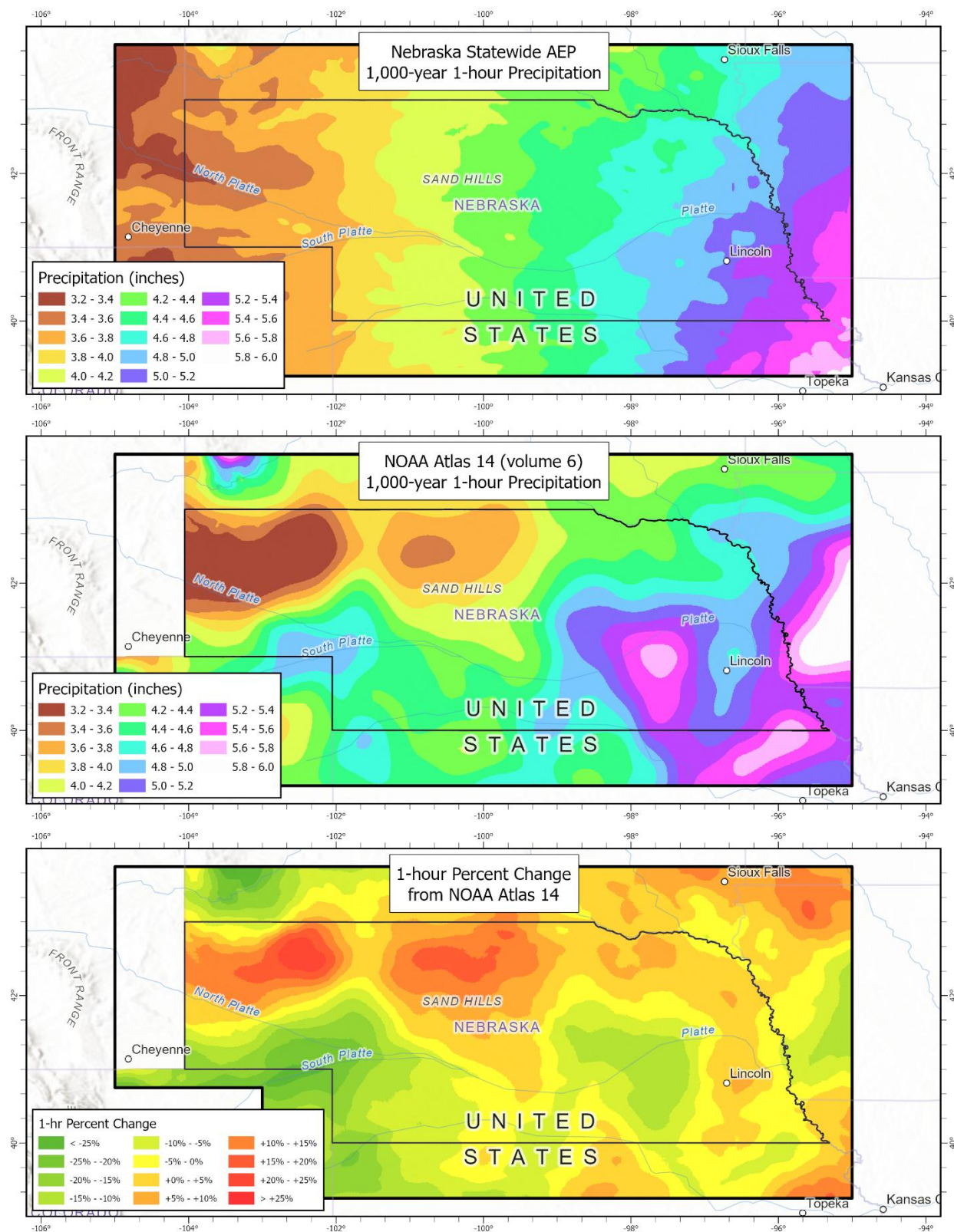
Appendix B.7: 24-hour 100-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



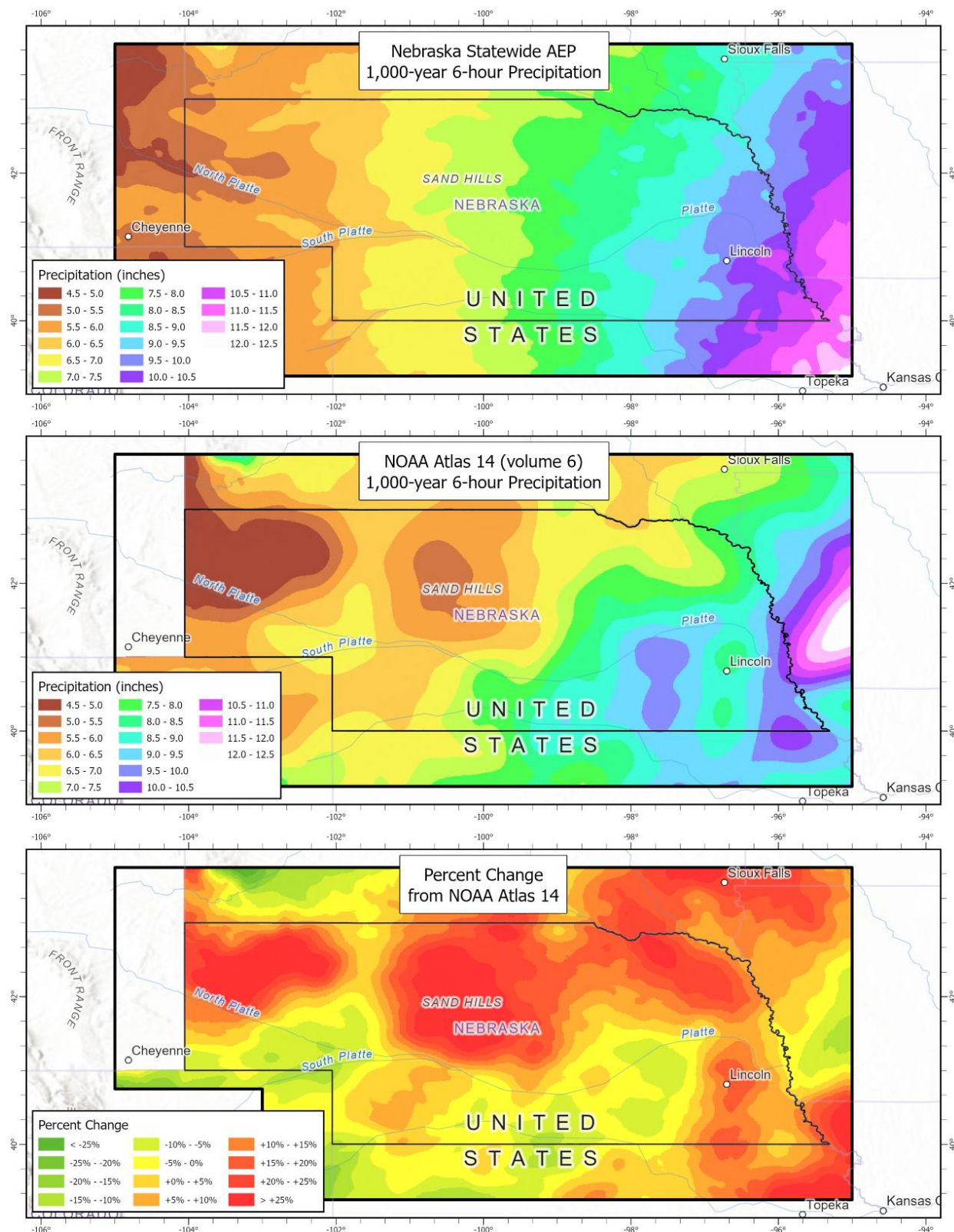
Appendix B.8: 72-hour 100-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



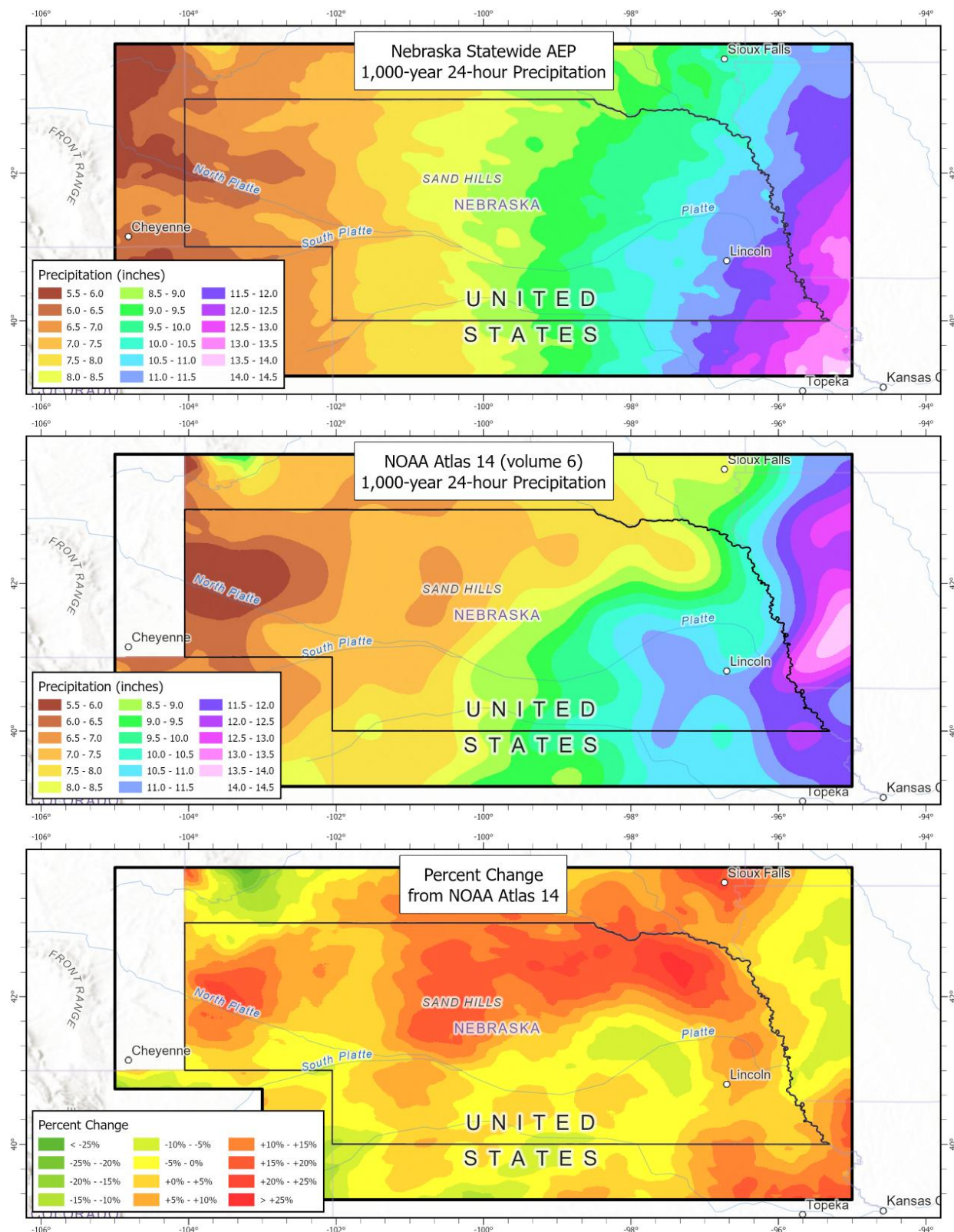
Appendix B.9: 1-hour 1000-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



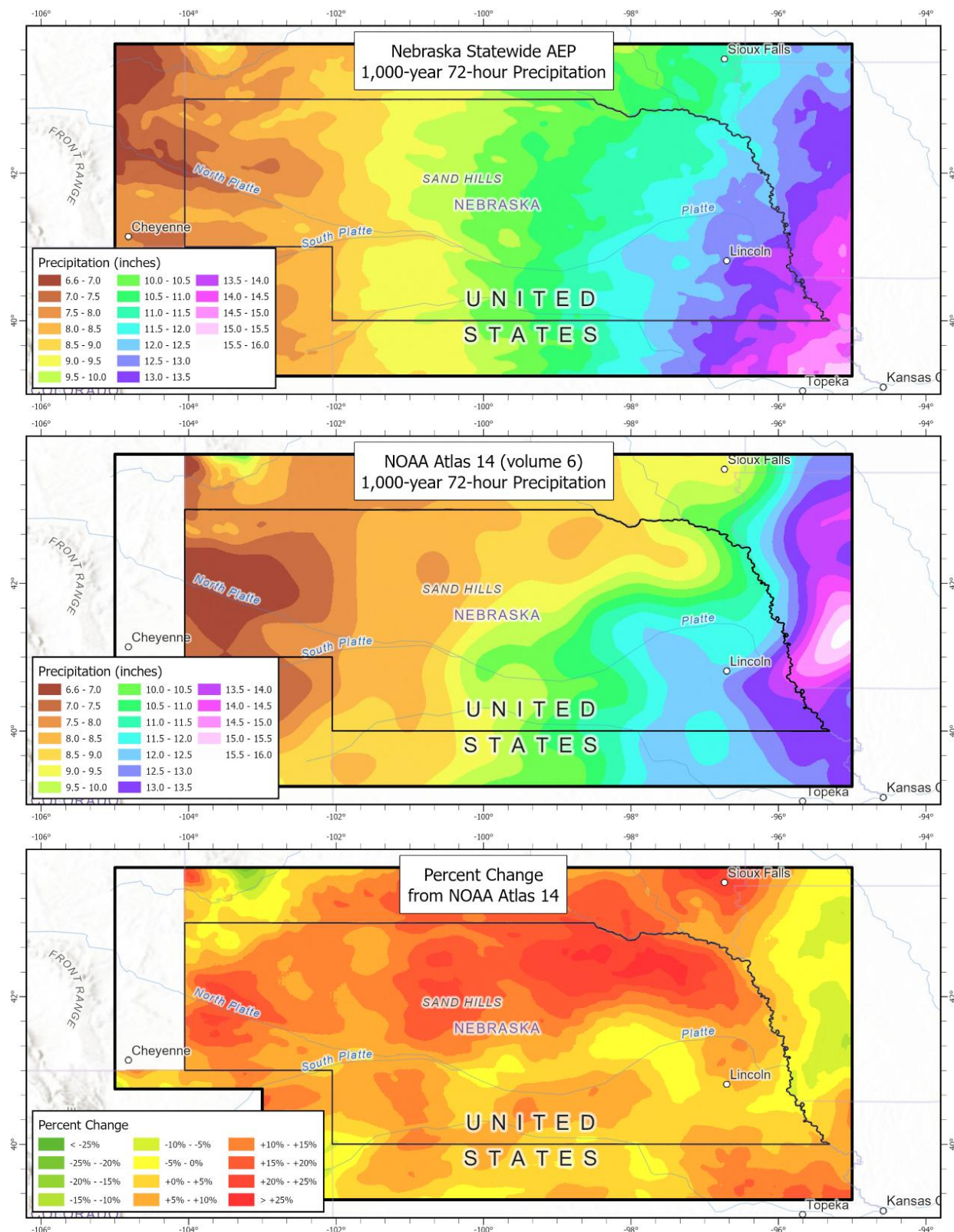
Appendix B.10: 6-hour 1000-year precipitation comparison

Nebraska Statewide Annual Exceedance Probability Study



Appendix B.11: 24-hour 1000-year precipitation comparison

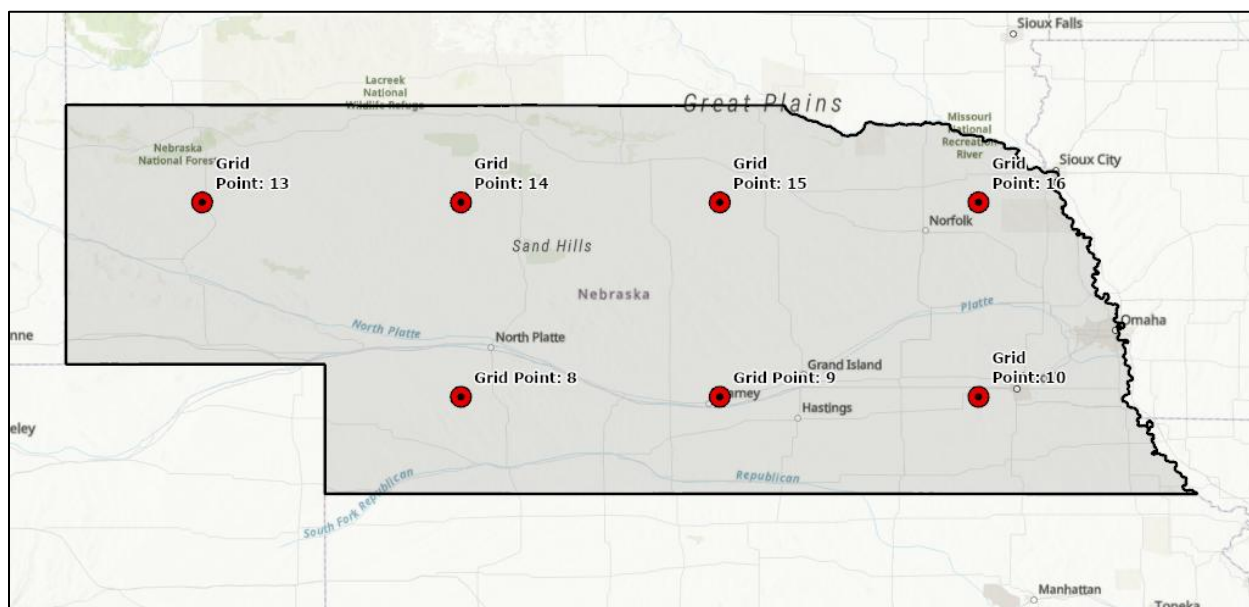
Nebraska Statewide Annual Exceedance Probability Study



Appendix B.12: 72-hour 1000-year precipitation comparison

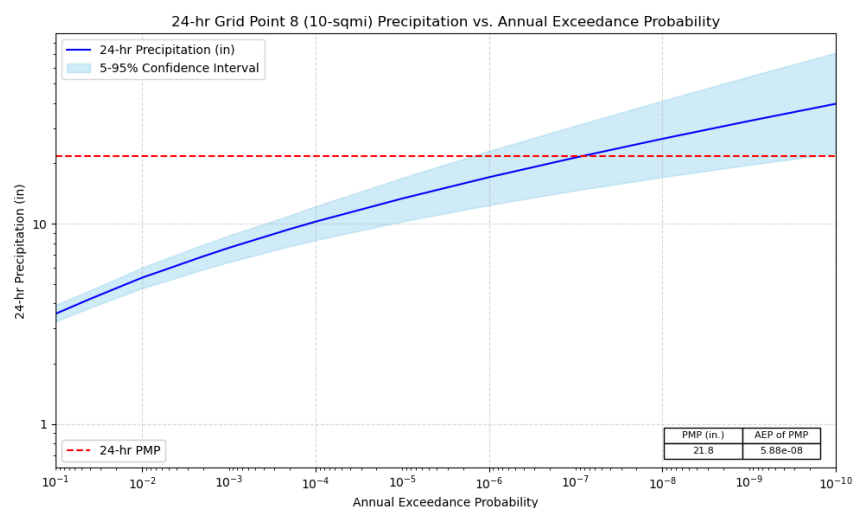
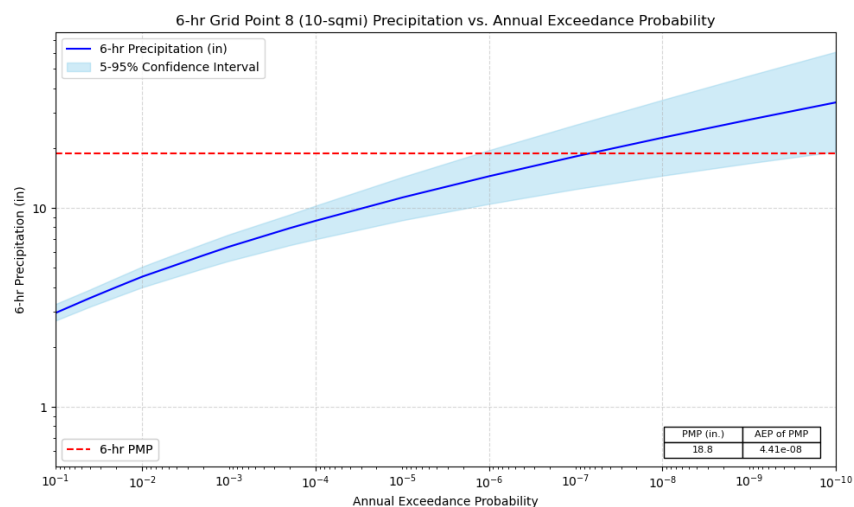
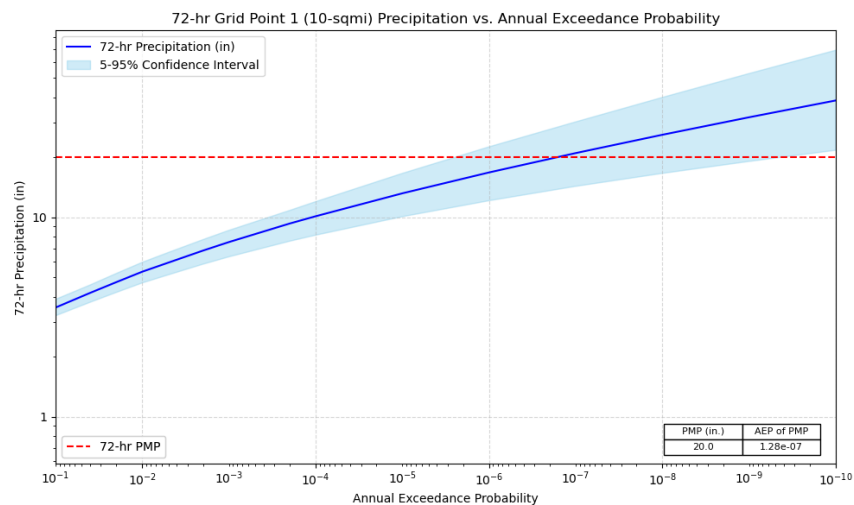
Appendix C

AEP Plots at PMP Grid Points



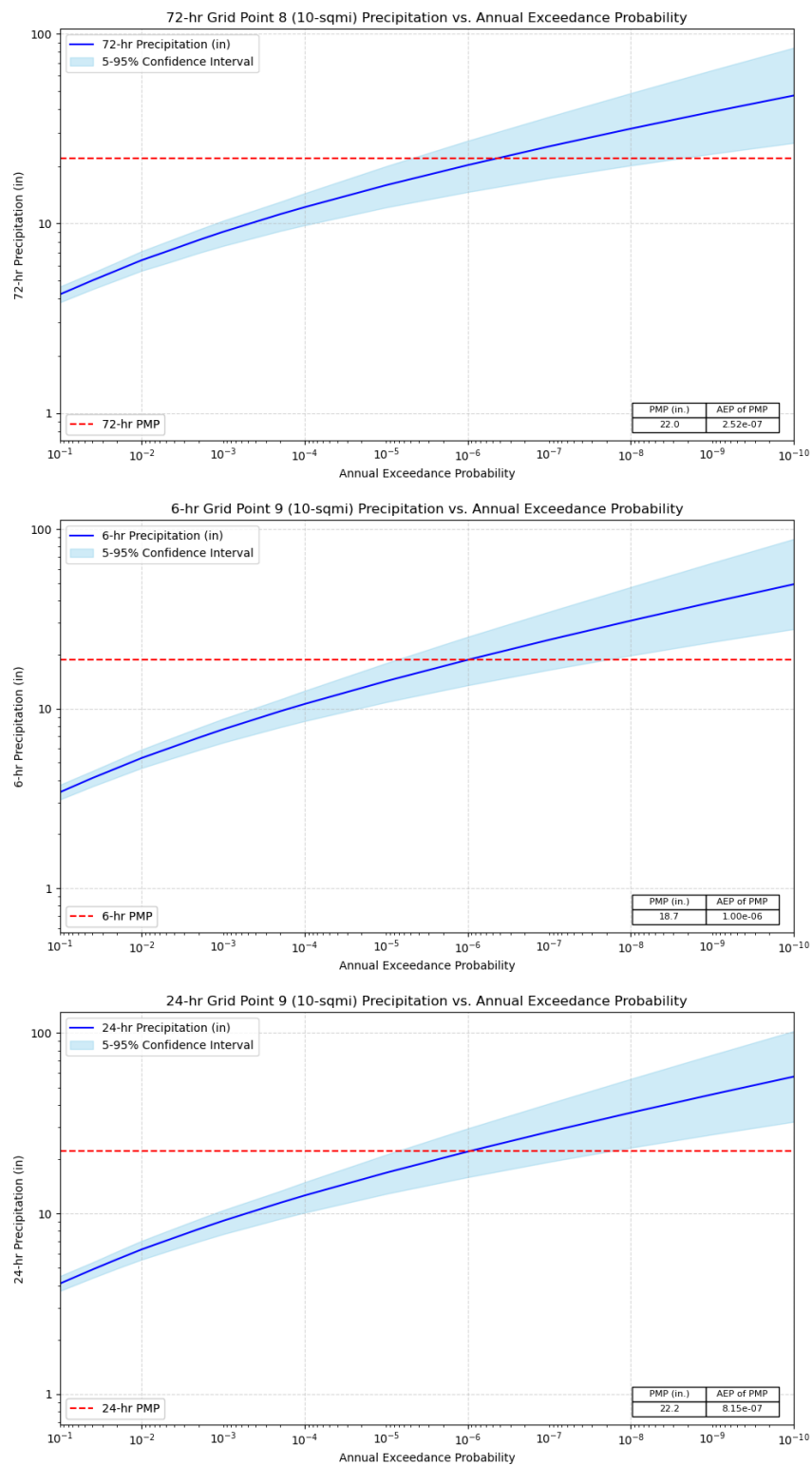
Appendix C.1 PMP analysis points used for sample AEP plots

Nebraska Statewide Annual Exceedance Probability Study



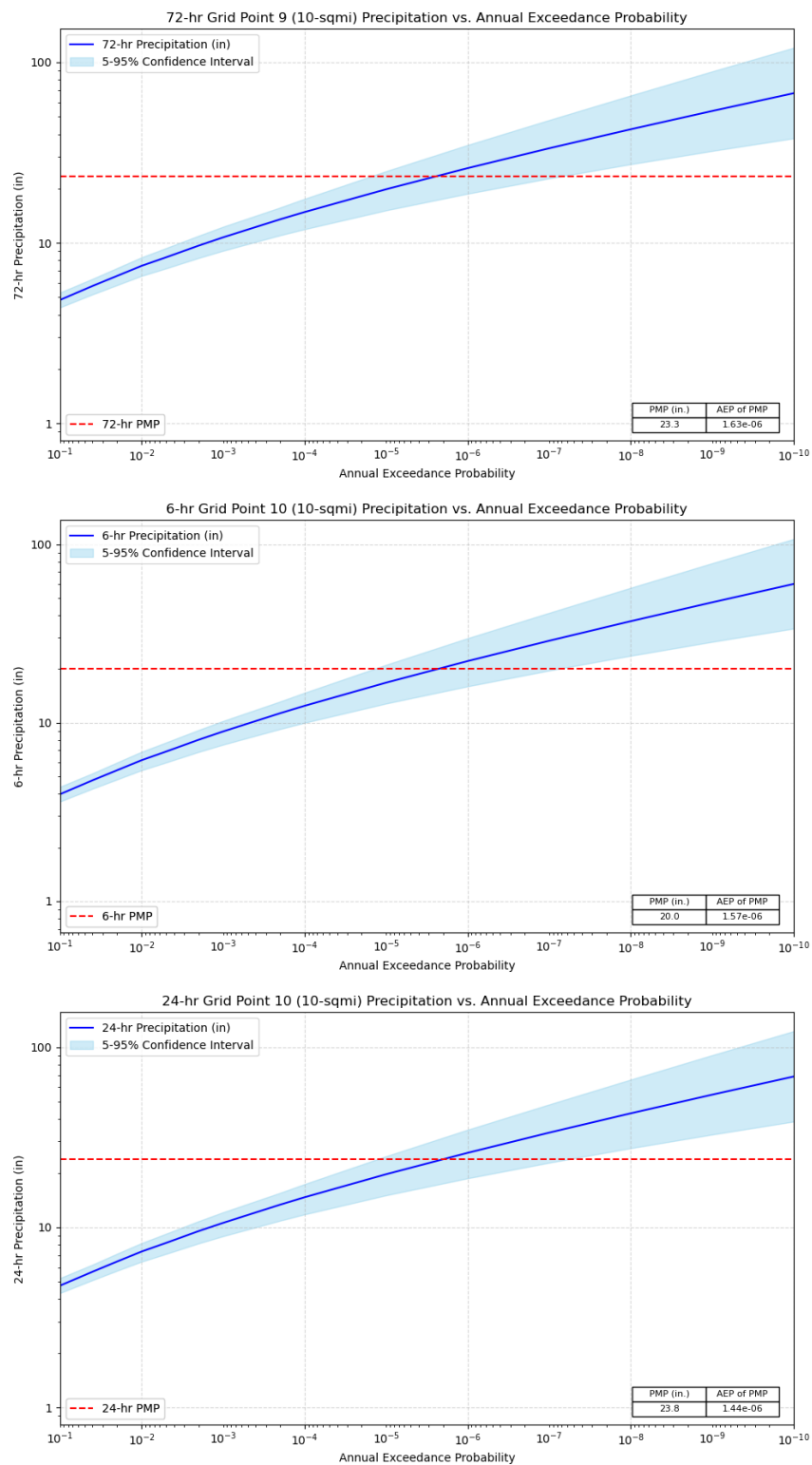
Appendix C.2 Grid Point #8 AEP Plots

Nebraska Statewide Annual Exceedance Probability Study



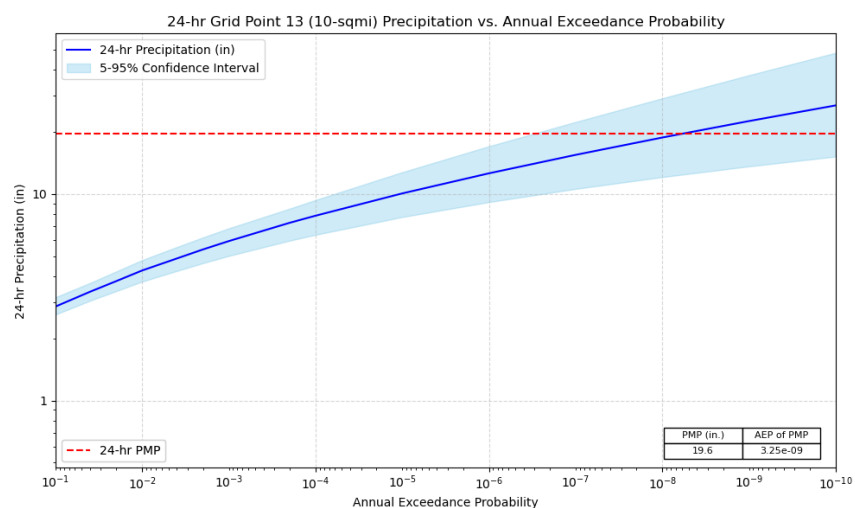
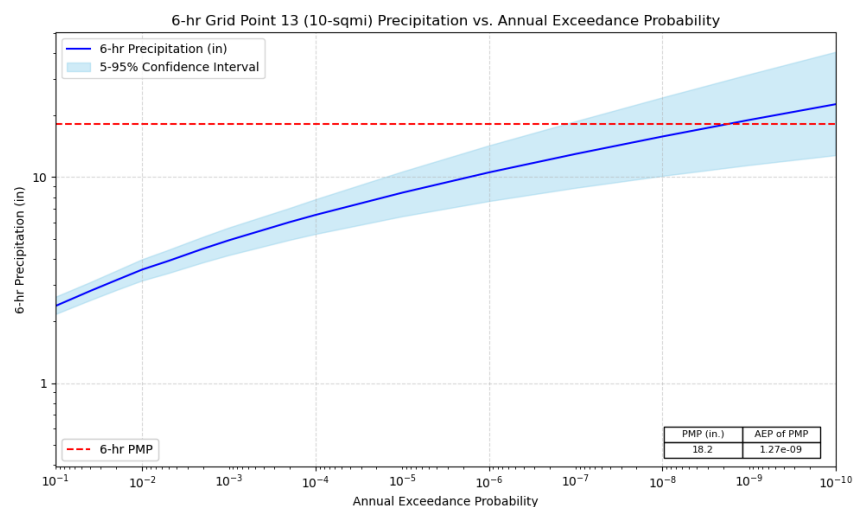
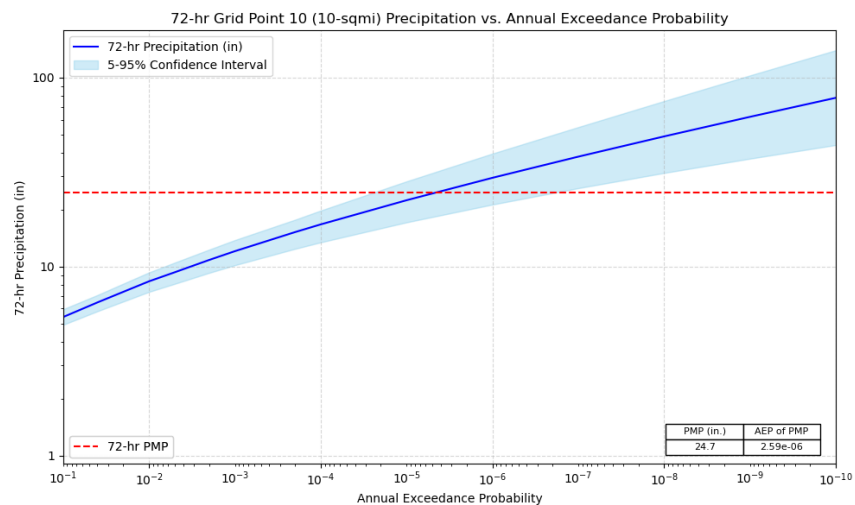
Appendix C.3 Grid Point #9 AEP Plots

Nebraska Statewide Annual Exceedance Probability Study



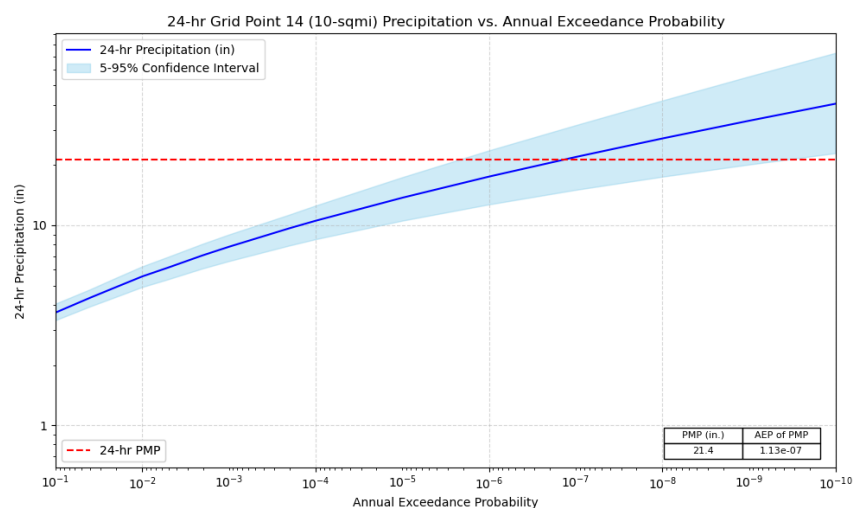
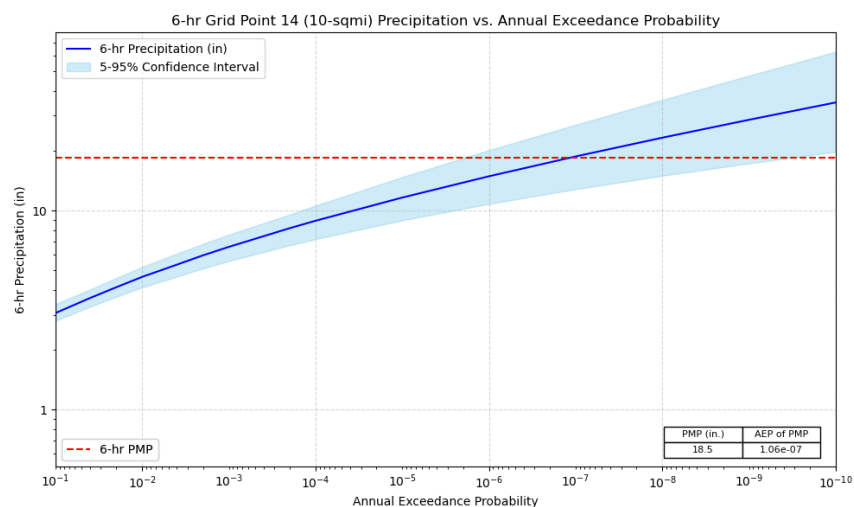
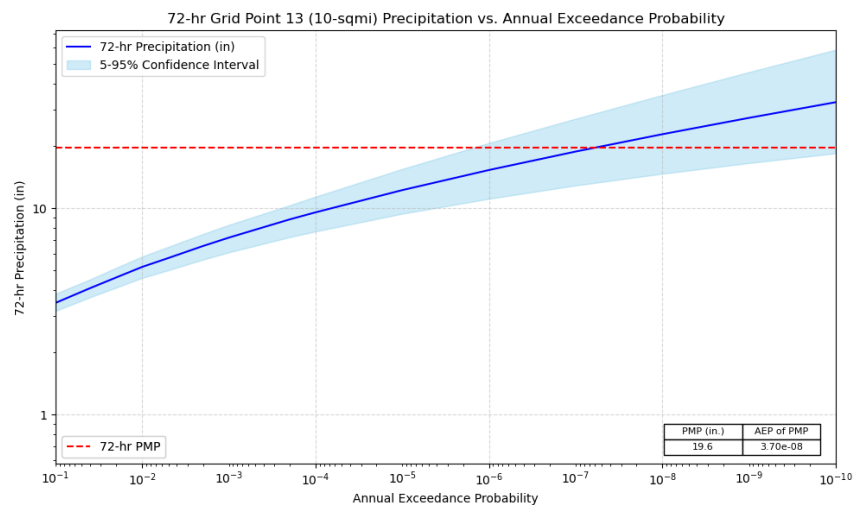
Appendix C.4 Grid Point #10 AEP Plots

Nebraska Statewide Annual Exceedance Probability Study



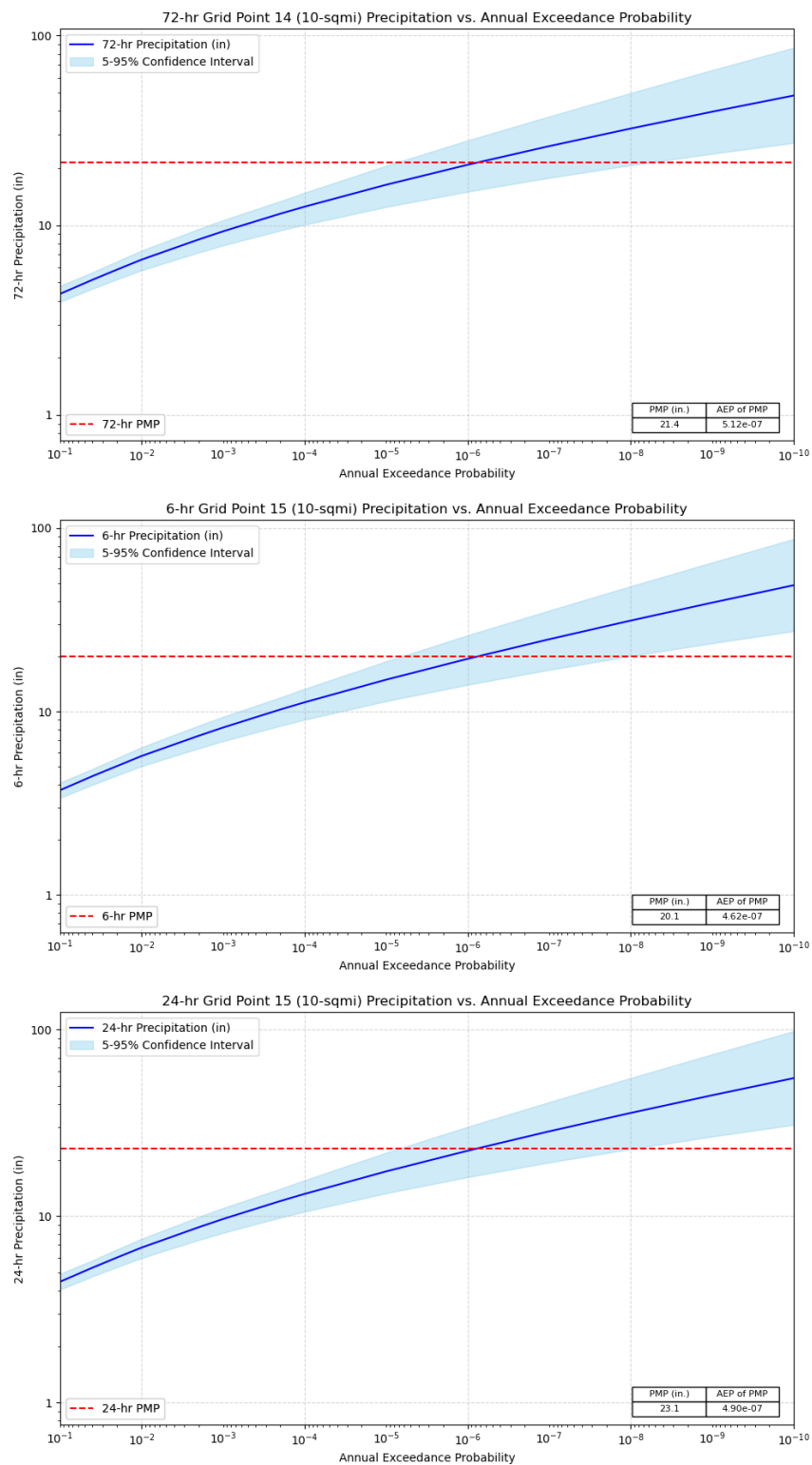
Appendix C.5 Grid Point #13 AEP Plots

Nebraska Statewide Annual Exceedance Probability Study



Appendix C.6 Grid Point #14 AEP Plots

Nebraska Statewide Annual Exceedance Probability Study



Appendix C.7 Grid Point #15 AEP Plots

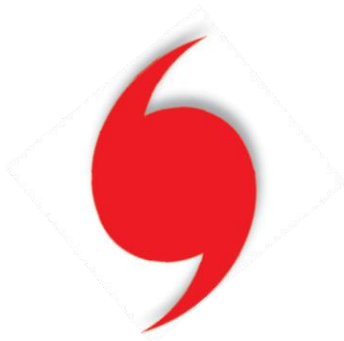
Appendix D

Precipitation Frequency Final Presentation

(Digital Appendix)

Appendix E

Independent Review Memo



**Barry Keim
Keim Consulting LLC
161 Metairie Lawn Drive
Metairie, LA 70001**

e-mail: barrykeim007@gmail.com
225-328-0749 (c)

Final Reviewer Report on the Annual Exceedance Probability Study for Nebraska

August 14, 2025

Matt McConville, PE (NE)
NE/IA Dams, Levees, and Civil Works Business Class Lead
Associate Vice President
HDR
1917 S. 67th Street
Omaha, NE 68106-2973

Dear Mr. McConville:

This letter serves as my official acceptance of the precipitation frequency analysis conducted by Applied Weather Associates for Nebraska. I was charged with reviewing and assessing each phase of AWA's statewide precipitation frequency study while providing oversight, as necessary, to confirm the study methods were consistent with accepted theories and procedures. I read the final report and made a series of comments to better elucidate the methods and findings. Overall, the methods used in this report are consistent with state-of-the-art precipitation frequency analyses. In particular, the methods used here are largely in accord with NOAA Atlas 14.

The basic foundation of the AWA analysis relies on annual maximum rainfall series, which include the largest storm from every year of some duration (i.e., 1-hour, 24-hour, or 72-hour). These storm data are then fit to the Generalized Extreme Value (GEV) Distribution for each station using a regional L-moments approach that pools data from nearby similar stations. This is precisely how NOAA Atlas 14 was developed, but I note that NOAA 15 will not use the L-moment regional approach, but rather the regional Maximum Likelihood Estimation (MLE) parameterization approach that better addresses a non-stationary climate.

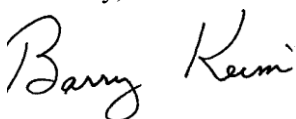
While I understand that the intended use of this analysis is to utilize very rare return periods at return frequencies greater than 100-years, or even 1000-years. I do take issue with estimating return frequencies of 100,000,000 years or 10,000,000,000 years. The best estimates of earth's age is 4,600,000,000 years and the range of climates that is assumed to have occurred over this time frame is beyond our comprehension. Over earth's history, it is assumed that there were times when the climate did not resemble our modern climate and was likely not suitable for human survival due a very different atmospheric

chemistry and temperature profile. Because of this, I want to temper the confidence in rainfall estimates for these extremely rare return periods, especially since they are based on the delivery rainfall for a period of about a century at best, and they are based on the specific climate of the past century, and not of the period of time reflected in the return period. This is particularly valid for really rare events.

Another item of concern is related to use of the annual maximum series (AMS) data rather than implementing use of partial duration series (PDS) data. The difference between the two is that an AMS takes the single largest rainfall event of n-duration for every calendar year. In the end, an AMS series has as many rainfall events as there are years of available data. With a PDS, we would extract as many events of n-duration as there are years of data, but storms included in the PDS would not be constrained to one every calendar year, but rather we would extract the largest events any time during the period of record, with the number of events being equal to the number of the years in the record. In other words, some calendar years could have 2, 3, or even 4 events (or more) included in a PDS, while many other years would have no events at all contributing to the PDS. This method ensures that the largest events over a period of record are captured. In an AMS, some years with multiple heavy rainfall events, the second and third largest events in those years could be larger than the largest annual event in other years. The end result of using AMS data is that the lower return periods, in particular, the 2-year, 5-year, and 10-year rain totals, are underestimated because smaller rainfall totals (low end AMS storms that are smaller in magnitude than second and third largest storms in storm-active years) make up that end of the probability distribution. Most studies actually implement use of AMS data in precipitation frequency analysis due to its ease of use. However, the final data are typically converted to a "PDS equivalent" at the back end of the statistical processing. For example, David Hershfield's Technical Paper No. 40 utilized AMS data but made conversions to make them equivalent to PDS. On average, a 2-year return period rainfall total derived from an AMS is only 88 percent of that derived from a PDS. Similarly, a 5-year return period rainfall total derived from an AMS is 96 percent of that of a PDS. While a 10-year AMS is 99 percent of a PDS. The conversion from AMS data to PDS data is a very simple conversion factor and it yields more accurate rainfall amounts for these lower end return frequencies, which are important in certain drainage designs. Note that this similar conversion is done in NOAA Atlas 14. As a result, I strongly urge users to ensure that this conversion is implemented.

In conclusion, I read the report and provided my insight, but it should be noted that I acted in an advisory capacity only. Specifically, I performed no calculations myself nor did I check any of the calculations made by AWA. It was my expectation that AWA utilized adequate quality assurance and control procedures to provide assurance that the calculations were performed accurately and without error. As such, I do not make any warranty, express or implied, regarding use of any information or method shown in this precipitation frequency study for Nebraska or assume any future liability regarding use of any information or method contained therein. These results are applicable to Nebraska only and should not be used in other states.

Sincerely,



Barry Keim,
Principal Keim
Consulting LLC

AWA Response to Review Comment:

The independent reviewer's main concern regarding the use of AMS versus PDS time series analysis was addressed by applying Langbein's formula (Langbein, 1949), which allows an AMS estimate to be transformed into a PDS estimate. The reviewer noted that more frequent events (<25-year return periods) may be underestimated, since the differences between AMS- and PDS-based estimates are greater for shorter return periods. However, these differences diminish as the recurrence interval increases, and the two methods converge around the 20- to 25-year return period. Beyond this point, both approaches yield similar results for less frequent (more extreme) events. The Langbein conversion factors used in this analysis are provided in Table E.1.

Table E.3: Conversion factors to convert AMS to PDS frequency estimates.

ARI (Years)	AEP (PDS)	AEP (AMS)	Conversion to PDS
2	0.393	0.500	1.27
5	0.181	0.200	1.10
10	0.095	0.100	1.05
25	0.039	0.040	1.02
50	0.020	0.020	1.01
100	0.010	0.010	1.01
200	0.005	0.005	1.00

Appendix F

Digital Appendix

1. Precipitation Frequency Map Images
2. Additional Map Images
3. AEP Plots for PMP Grid Points
4. Precipitation Frequency Presentation
5. AEP Desktop GIS Tool and Gridded Datasets
6. Temporal Distributions

Appendix G

1-hour Temporal Distribution

The 1-hour temporal distribution ratios recommended for disaggregating 1-hour AEP rainfall are provided in Table G1 and shown in Figure G1.

Table G1: 1-hour temporal distribution ratios

Time		Incremental	Accumulation
(min)	(hr)	(fraction)	(fraction)
0	0.00	0.000	0.000
5	0.08	0.147	0.147
10	0.17	0.129	0.276
15	0.25	0.113	0.389
20	0.33	0.099	0.488
25	0.42	0.087	0.575
30	0.50	0.077	0.652
35	0.58	0.069	0.721
40	0.67	0.062	0.783
45	0.75	0.057	0.840
50	0.83	0.054	0.894
55	0.92	0.053	0.947
60	1.00	0.053	1.000

Figure G1: 1-hour temporal distribution ratios

