SIMPLIFIED SPT PERFORMANCE-BASED ASSESSMENT OF LIQUEFACTION AND EFFECTS: *TASKS 5 AND 6 (YEAR 1)*

Prepared For:

Utah Department of Transportation
Research Division

Submitted By:

Brigham Young University
Department of Civil and Environmental Engineering

Authored By:

Kevin W. Franke
Levi T. Ekstrom
Kristin J. Ulmer

**Year 1, Quarter 2 Update Report for the TPF-5(296) Technical Advisory Committee
September 2014**

RESEARCH
UDOT udot.utah.gov
Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

ACKNOWLEDGMENTS

The authors acknowledge the Utah, Idaho, Montana, Alaska, South Carolina, and Connecticut Departments of Transportation for funding this research for pooled fund study TPF-5(296). The views and opinions presented in this report represent those of its authors, and may not represent those of the state agencies funding this research.

TECHNICAL REPORT ABSTRACT

1. Report No. NA	2. Government Accession No. NA	3. Recipient's Catalog No. NA
4. Title and Subtitle SIMPLIFIED SPT PERFORMANCE-BASED ASSESSMENT OF LIQUEFACTION AND EFFECTS: *TASKS 5 AND 6 (YEAR 1)*		5. Report Date September 2014 6. Performing Organization Code NA
7. Author(s) Kevin W. Franke, Levi T. Ekstrom, Kristin J. Ulmer		8. Performing Organization Report No. NA
9. Performing Organization Name and Address Brigham Young University Department of Civil and Environmental Engineering 368 Clyde Building Provo-UT 84602-4009		10. Work Unit No. 4206515D 11. Contract or Grant No. 148753
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Year 1, Quarter 2 TAC Update June - August 2014 14. Sponsoring Agency Code PIC No. UT13.407
15. Supplementary Notes Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

The purpose of the research being performed is to provide the benefit of the full performance-based probabilistic earthquake hazard analysis, without requiring special software, training, and experience. To do this, simplified models of liquefaction triggering and lateral spread displacements that approximate the results of the full probabilistic analysis were developed in the Year 1 Quarter 1 report. These simplified methods require liquefaction parameter maps. This report describes the process of creating these parameter maps, addressing the Year 1 portion of Tasks 5 and 6 of the TPF-5(296) research contract.

To create proper parameter maps, it was necessary to define a set of rules for optimum grid spacing which would keep the error due to interpolation within a reasonable amount. As shown in this report, such a set of rules was derived. Assuming that these rules are followed, the grid spacings should result in a 5% or less difference between an interpolated value and the value that would have been produced if a full analysis were performed at that location. The set of grid spacing rules were used in creating the grid of points used for map making.

Using the set of rules developed in the grid spacing study, a set of points was determined for each state to be used in analysis. A full performance-based analysis was performed at each point for three return periods (475, 1033, and 2475 years) yielding three different values for each return period: standard penetration test (SPT) blow count required to resist liquefaction (Nreq), percent cyclic stress ratio (CSR%), and the log of lateral spread displacement (logDH). The values at each point were used to create a surface raster file in ArcMap using Kriging-style interpolation. This raster was then used to create contour maps for each parameter in each state. These contour maps can be re-formatted as desired from the raster file in ArcMap. Sample contour maps created by the research team can be found in the Appendix of this report.

17. Key Words Lateral Spread Displacements, Liquefaction Triggering, Performance-based Engineering, Reference Maps, Simplified Models, Seismic Hazards		18. Distribution Statement Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal NA
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 103	22. Price NA	

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

UNIT CONVERSION FACTORS

Units used in this report and not conforming to the UDOT standard unit of measurement (U.S. Customary system) are given below with their U.S. Customary equivalents:

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

EDP	Engineering Demand Parameter
FHWA	Federal Highway Administration
GMPE	Ground Motion Predictive Equation
IM	Intensity Measure
PBEE	Performance-Based Earthquake Engineering
PSHA	Probabilistic Seismic Hazard Analysis
UDOT	Utah Department of Transportation

LIST OF TERMS

Liquefaction Triggering Terms

a_{max}	peak ground surface acceleration
CRR	cyclic resistance ratio
$CRR_{PL=50\%}$	median *CRR* (*CRR* corresponding to a probability of liquefaction of 50%)
CSR	cyclic stress ratio
CSR%	cyclic stress ratio expressed as a percent (i.e. *CSR**100%)
CSR^{ref}	uniform hazard estimate of *CSR* associated with the reference soil profile
CSR^{site}	site-specific uniform hazard estimate of *CSR*
ΔCSR_{σ}	correction factor for vertical stress
ΔCSR_{Fpga}	correction factor for soil amplification
ΔCSR_{rd}	correction factor for shear stress reduction
ΔCSR_{MSF}	correction factor for magnitude scaling factor
$\Delta CSR_{K\sigma}$	correction factor for overburden pressure
ΔCSR	difference between CSR^{site} and CSR^{ref} values
FC	fines content (%)
FS_L	factor of safety against liquefaction triggering
FS_L^{site}	site-specific uniform hazard estimate of FS_L
F_{PGA}	soil amplification factor
K_{σ}	overburden correction factor (Idriss and Boulanger model)
MSF	magnitude scaling factor
M_w	mean moment magnitude
N	SPT blow count (uncorrected)
$(N_1)_{60}$	SPT resistance corrected to 60% efficiency and 1 atm pressure
$(N_1)_{60,cs}$	clean sand-equivalent SPT corrected to 60% efficiency and 1 atm pressure
N_{req}	SPT resistance required to resist or prevent liquefaction
N_{req}^{ref}	uniform hazard estimate of N_{req} associated with the reference soil profile
N_{req}^{site}	site-specific uniform hazard estimate of N_{req}
ΔN_L	difference between N_{site} and N_{req} values
P_a	atmospheric pressure (1 atm, 101.3 kPa, 0.2116 psf)
PGA	peak ground acceleration
P_L	probability of liquefaction
r_d	shear stress reduction coefficient
SPT	Standard Penetration Test
$V_{s,12}$	average shear wave velocity in upper 12 m (39.37 ft) of soil profile
z	depth to middle of soil profile layer
γ	unit weight of soil (i.e. pcf, kN/m^3, etc.)
σ_{ε}	error term for either model + parametric uncertainty or parametric uncertainty

σ_T	error term for both model and parametric uncertainty
σ_v	total vertical stress in the soil
σ'_v	effective vertical stress in the soil
Λ_{FS_L*}	mean annual rate of not exceeding some given value of FS_L
λ_{Nreq*}	mean annual rate of exceeding some given value of N_{req}
τ_{cyc}	equivalent uniform cyclic shear stress
Φ	standard normal cumulative distribution function

Lateral Spread Displacement Terms

D_H	median computed permanent lateral spread displacement (m)
R	closest horizontal distance from the site to the source (km)
M	earthquake moment magnitude
W	free-face ratio (%)
S	ground slope (%)
T_{15}	cumulative thickness (in upper 20 m) of all saturated soil layers with corrected SPT blowcounts (i.e., $(N_1)_{60}$) less than 15 blows/foot (m)
F_{15}	average fines content of the soil comprising T_{15} (%)
$D50_{15}$	average mean grain size of the soil comprising T_{15} (mm)
$\mathscr{L}$	Loading Parameter
$\mathscr{S}$	Site Parameter
$\mathscr{D}$	transformed (e.g. log, ln, square root) lateral spread displacement
ε	uncertainty term (used in lateral spread displacement model)
$\left[\log D_H\right]^{site}$	logarithm of the lateral spread displacement adjusted for site-specific conditions
$\left[\log D_H\right]^{ref}$	logarithm of the lateral spread displacement corresponding to the reference site
ΔD_H	adjustment factor for lateral spread displacement
D_H^{site}	site-specific hazard-targeted lateral spread displacement

EXECUTIVE SUMMARY

The purpose of the research being performed is to provide the benefit of the full performance-based probabilistic earthquake hazard analysis, without requiring special software, training, and experience. To do this, simplified models of liquefaction triggering and lateral spread displacements that approximate the results of the full probabilistic analysis were developed and validated in the Year 1 Quarter 1 update report. These simplified methods are designed to require only a few calculations programmed into a spreadsheet and a provided liquefaction parameter map. This report describes how to create these parameter maps, specifically addressing the Year 1 portion of Tasks 5 and 6 of the TPF-5(296) research contract.

Creating a contour map based on an infinite number of analyzed points is not possible for the scope of this research project. Therefore, it was necessary to define a finite number of points to analyze. Interpolation was then used to evaluate the values in between the points selected for analysis. Using a finite number of points introduces the possibility for error based on interpolation between these points. Thus it was necessary to define a set of rules for proper grid spacing which would keep the error due to interpolation within a reasonable amount. As shown in this report, such a set of rules was derived. Assuming that these rules are followed, the grid spacings should result in a 5% or less difference between an interpolated value and the value that would have been produced if a full analysis were performed at that location. The set of grid spacing rules were used in creating the grid of points used for map making.

Using the set of rules developed in the grid spacing study, a set of points was determined for each state to be used in analysis. A full performance-based analysis was performed at each point for three return periods (475, 1033, and 2475 years) yielding three different values for each return period: standard penetration test (SPT) blow count required to resist liquefaction (N_{req}), percent cyclic stress ratio ($CSR\%$), and the log of lateral spread displacement ($\log D_H$). These values were calculated based on the reference soil profile introduced in the Year 1 Quarter 1 update report, not based on site-specific soil characteristics. The values at each point were used to create a surface raster file in ArcMap using Kriging-style interpolation. This raster was then used to create contour maps for each parameter in each state. These contour maps can be re-formatted as desired from the raster file in ArcMap. Sample contour maps created by the research team can be found in the Appendix of this report.

1.0 INTRODUCTION

1.1 Problem Statement

An important aspect of the simplified performance-based liquefaction initiation and lateral spread displacement models is the use of parameter and hazard maps. These maps are developed using a reference soil profile and require an analysis of a grid of points covering the desired area. The results of the analysis are then interpolated into a complete contour map providing the reference value. This quarterly report provides the methodology and process in developing these maps.

1.2 Objectives

The objective of this report is develop an optimum grid spacing for the development of the parameter and hazard maps as well as to create these maps and the GIS files associated with them, addressing Tasks 5 and 6 of the TPF-5(296) research contract.

1.3 Scope

The tasks to be performed in this research will be: perform the grid spacing evaluation, generate the grid of points needed for the analysis for each state, perform the performance-based analysis for the grid points, and create the parameter and hazard maps.

1.4 Outline of Report

The research conducted for this report will contain the following:

- Introduction
- Evaluation of Grid Spacing
- Development of Maps
- Conclusions
- Appendices

2.0 EVALUATION OF GRID SPACING

2.1 Overview

Because biases due to spacing of grid points in gridded seismic hazard analyses are known to exist, the grid spacing study will evaluate the potential for bias to occur due to grid spacing effects in a gridded probabilistic liquefaction and lateral spread hazard assessment. Because the states involved in this study comprise areas of varying seismicity levels, evaluations will be performed in each of the states to assess the optimum grid spacing for development of liquefaction and lateral spread parameter maps in future tasks.

The grid spacing assessment was performed by comparing interpolated results from a simple 4-point grid placed in various parts of the country with site-specific results. The difference between the interpolated and site-specific results was quantified. By minimizing these computed differences, the optimum grid spacing for the liquefaction parameter maps in each state was obtained.

Note that this grid spacing study does not provide estimates of accuracy between the simplified performance-based method and the full performance-based method. The measurements of error calculated in this grid spacing study reflect only the error involved in interpolation between grid points.

2.2 Performance-based Liquefaction Triggering Evaluation

This section will describe the methods used to derive a correlation between optimum grid spacing and *PGA* for simplified performance-based liquefaction triggering evaluation. The purpose of this correlation was to provide a simple, readily-available, well-defined set of rules for proper grid spacing across the states of interest. This set of rules is necessary because it is impractical to perform an infinite number of full performance-based analyses to create the liquefaction contour maps. It was necessary to determine a finite number of points to analyze. The set of rules created in this grid spacing study was used to define the optimum number of points which would be feasible to analyze in the amount of time given and would yield an acceptable amount of error due to interpolation between analyzed points.

2.2.1 Methodology for Preliminary Study

The preliminary grid spacing study first focused on four cities in areas of varying seismicity: Berkeley, California; Salt Lake City, Utah; Butte, Montana; and Clemson, South Carolina with *PGA* values as shown in Table 2.1. Though Berkeley is not located in one of the funding states for this research, it was used as an extreme in the range of *PGA* values. The more rigorous grid spacing study to follow incorporates a higher number of cities within the funding states. This preliminary study was used to decide whether *PGA* had an effect on optimum grid spacing.

Table 2.1 Cities Used in Preliminary Grid Spacing Study

City	Anchor Point		*PGA* (g) (T_R = 2475 years)
	Latitude	Longitude	
Berkeley, CA	37.872	-122.273	1.1340
Salt Lake City, UT	40.755	-111.898	0.6478
Butte, MT	46.003	-112.533	0.1785
Clemson, SC	34.683	-82.837	0.1439

Using a square grid (like the one shown in Figure 2.1) with the city's anchor point as the center of the square, several grid spacings were tested. This preliminary testing process included grid spacings of 1, 2, 4, 8, 16, 25, 35, and 50 km (0.62, 1.24, 2.49, 4.97, 9.94, 15.5, 21.7 and 31.1 mi). Then a full performance-based liquefaction analysis was performed at each corner point and the center anchor point to solve for Standard Penetration Test (SPT) blowcount (clean-sand equivalent and corrected to 1 atm pressure and 60% hammer efficiency) required to resist liquefaction (i.e. N_{req}) and percent cyclic stress ratio (i.e. *CSR*%) at three return periods (475, 1033, and 2475 years). This process was repeated for each city in the preliminary study.

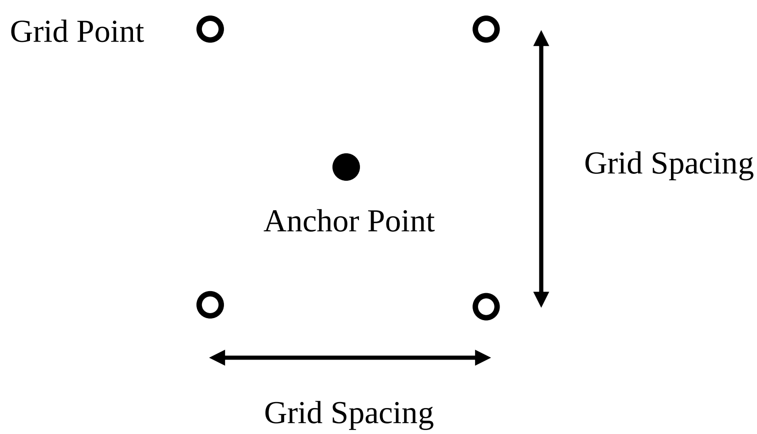


Figure 2.1 Layout of grid points centered on city's anchor point.

An estimate of the liquefaction hazard at the center point (i.e. the interpolated value of either N^{ref}_{req} or CSR^{ref} %) was calculated using the four corner points. This interpolated value was then compared to the actual value of the center point as calculated using a full performance-based liquefaction analysis. The difference between the interpolated value and the true value at the center is called the error term. The error terms were normalized to the actual values at the anchor points by calculating the percent error term as follows:

$$PercentError = \frac{|\,InterpolatedValue - ActualValue\,|}{ActualValue} \times 100\% \tag{1}$$

The maximum percent error (i.e. the maximum percent error across all return periods for a given anchor point) became the deciding parameter in selecting optimum grid spacing for a given location. The relationship between maximum percent error and grid spacing was analyzed for each city and is discussed in the following section.

2.2.2 Results of Preliminary Study

The relationship between maximum percent error and grid spacing was analyzed for each city and is displayed in Figure 2.2, Figure 2.3, Figure 2.4, and Figure 2.5. As can be seen in these figures, the relationship between maximum percent error and grid spacing is different for each city. Berkeley had the highest *PGA* value (1.1340g) out of the cities used in this preliminary study and required the smallest grid spacing (approximately 5 km or 3.107 mi) to restrict the maximum percent error to 5%. On the other hand, the maximum percent error for Clemson, which had the lowest *PGA* value (0.1439g), never exceeded 1% even with 50km (31.07 mi) grid spacing. Based on these graphs, it appears that seismicity (or *PGA*) has an impact on optimum grid spacing.

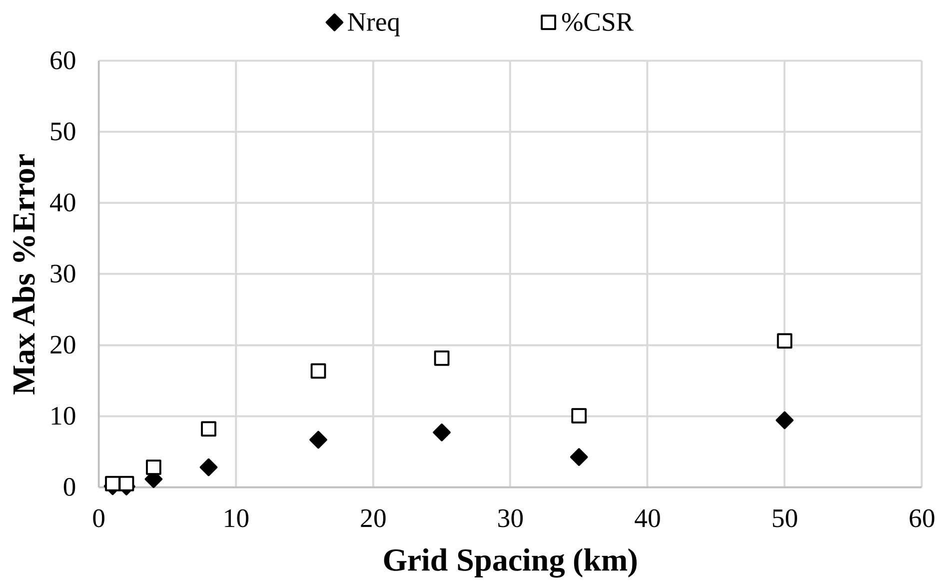


Figure 2.2 Variation of maximum absolute percent error with increasing distance between grid points (Berkeley, CA).

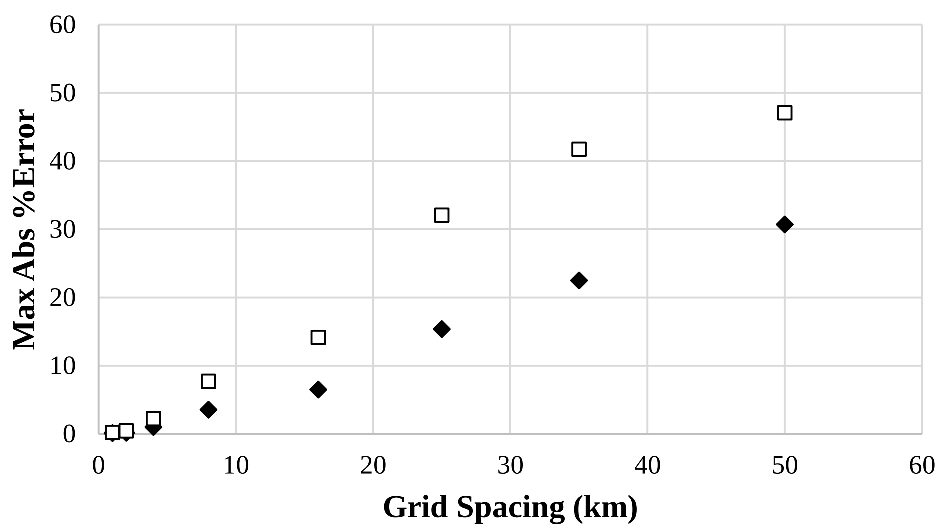


Figure 2.3 Variation of maximum absolute percent error with increasing distance between grid points (Salt Lake City, UT).

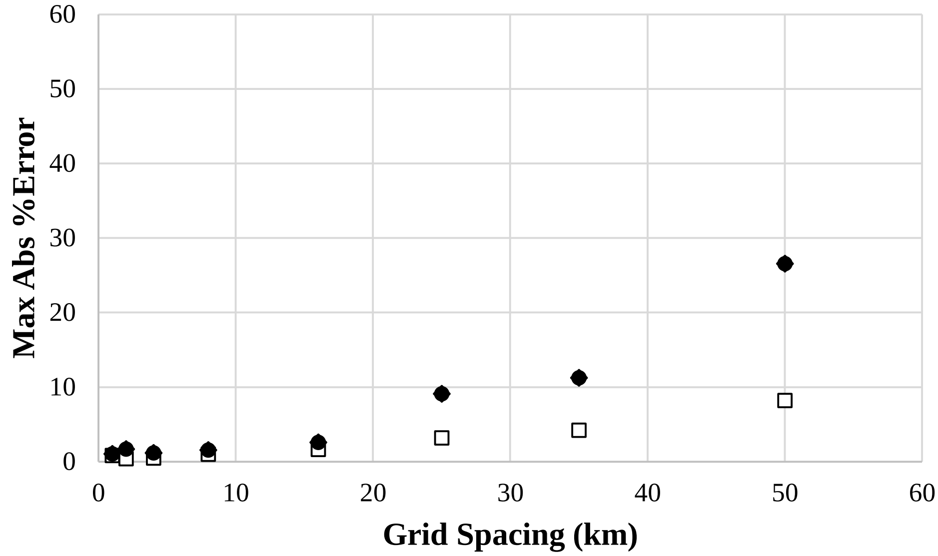


Figure 2.4 Variation of maximum absolute percent error with increasing distance between grid points (Butte, MT).

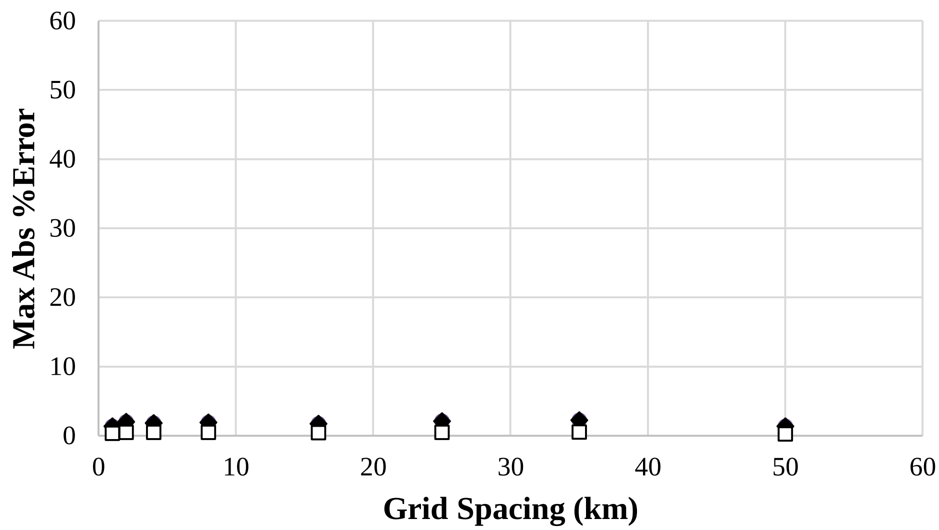


Figure 2.5 Variation of maximum absolute percent error with increasing distance between grid points (Clemson, SC).

2.2.3 Methodology for Grid Spacing Study

Based on the data from the preliminary study, it was hypothesized that *PGA* was a major factor in the relationship between grid spacing and maximum percent error. Specifically, it was hypothesized that as *PGA* increases, the optimum grid spacing decreases. To estimate the effect of *PGA* on optimum grid spacing, a similar study was conducted focusing on 21 cities from a wide range of *PGA* values (Figure 2.6).

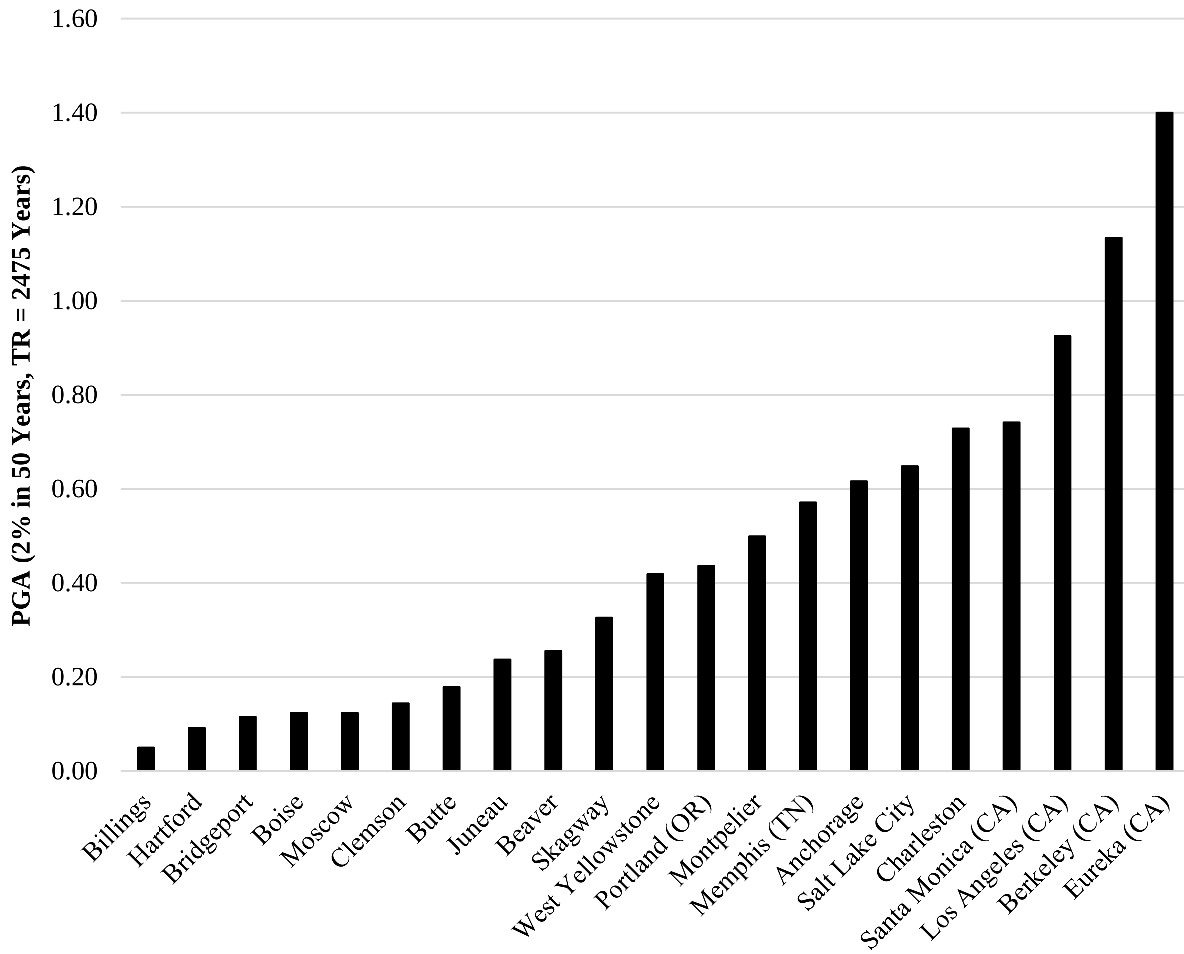


Figure 2.6 Range of *PGA* values for cities included in final grid spacing study.

The desired outcome of the final grid spacing study was to create a correlation between *PGA* and optimum grid spacing in km. An equation for the best-fit trend line alone would not be sufficient, because defining grid points to use in an analysis does not work well with non-integer values for grid spacing and constantly changing distances between points. Therefore, it was necessary to divide the different cities into *PGA* "bins" or defined ranges of values. These bins were determined using the USGS 2008 *PGA* hazard map (T_r = 2475 years) as shown in Figure 2.7. The *PGA* hazard map was chosen because it was clear and readily available as a well-documented definition of which areas in the country had significantly different seismicity levels compared to other areas' seismicity levels. The objective of this study was to determine the optimum grid spacing for each color bin.

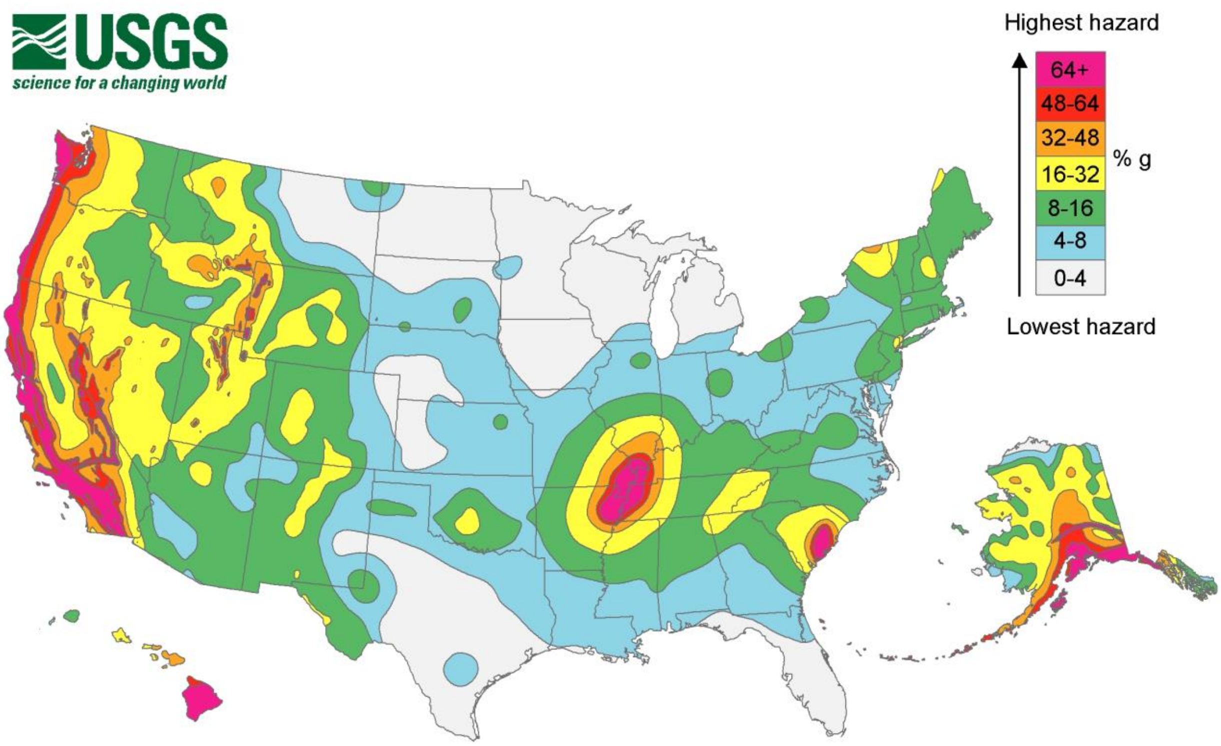


Figure 2.7 USGS 2008 *PGA* hazard map (T_r = 2475 years).

As in the preliminary study, a full performance-based analysis was performed at the anchor point of each city and at the corners of the grid surrounding the anchor point. This was repeated for multiple grid spacings until the percent error was within a reasonable amount. It was determined that "optimum grid spacing" would be defined as the smallest grid spacing (i.e shortest distance between grid points) which yielded a maximum percent error of 5% across all return periods based on *CSR*%. This definition is used because when the maximum percent error based on *CSR*% is limited to 5%, the interpolated value of N_{req} is within 1.5 blow counts of the actual value calculated at the anchor point, as shown in Figure 2.8. This seemed to be a reasonable amount of error, considering the inherent error in obtaining SPT blow counts during soil exploration at a site. If the definition of optimum grid spacing was defined as the smallest grid spacing which yielded a maximum difference of 1.5 blow counts, then the values of percent error based on *CSR*% may be unacceptably high. For example, as shown in Figure 2.8, if the maximum difference in N_{req} is 1.5 blow counts, the percent error in *CSR*% could be as high as 22.5%, which could cause substantial inaccuracies. Thus the definition of optimum grid spacing was defined based on *CSR*% and not N_{req}.

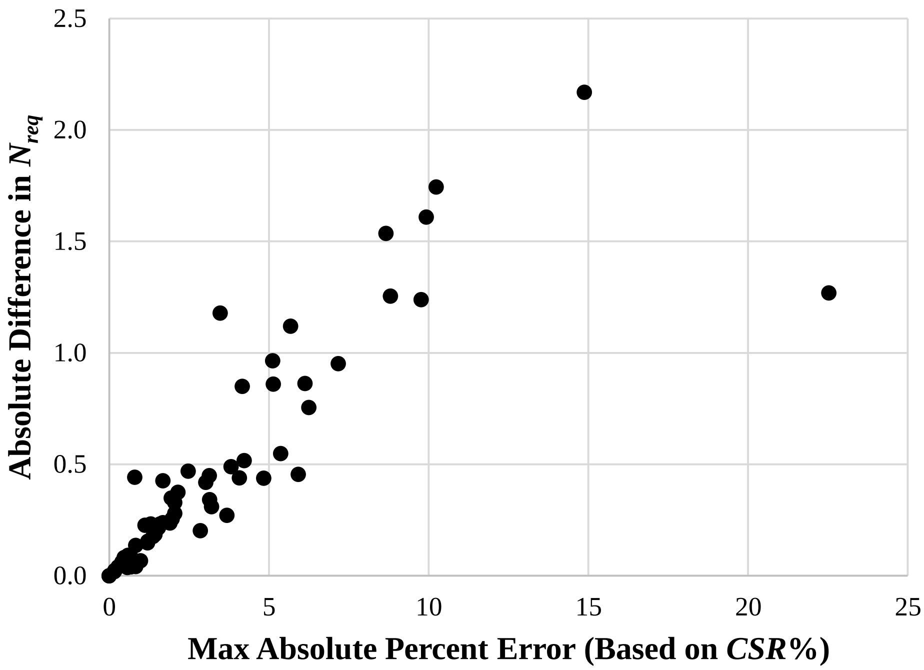


Figure 2.8 Comparison of difference in N_{req} to max absolute percent error based on *CSR*%.

Optimum grid spacing was determined using a plot of maximum percent error vs grid spacing in km. Unique plots were created for each city to determine the optimum grid spacing. Sample plots are provided in Figure 2.9, Figure 2.10, and Figure 2.11. Some cities' data followed a linear trend line while others followed a polynomial trend line. In each case, a reasonable best-fit line was used to determine optimum grid spacing. Some of the cities selected for this study did not reach a maximum percent error of 5%, even when the grid spacing was increased to 50 km (31.07 mi) or more. To avoid extrapolation, such cities (Hartford, CT, *PGA* = 0.0915; Bridgeport, CT, *PGA* = 0.1149; Clemson, SC, *PGA* = 0.1439; Anchorage, AK, *PGA* = 0.6161) were excluded from the final correlation between *PGA* and optimum grid spacing. A description of the final correlation between *PGA* and optimum grid spacing is included in the following section.

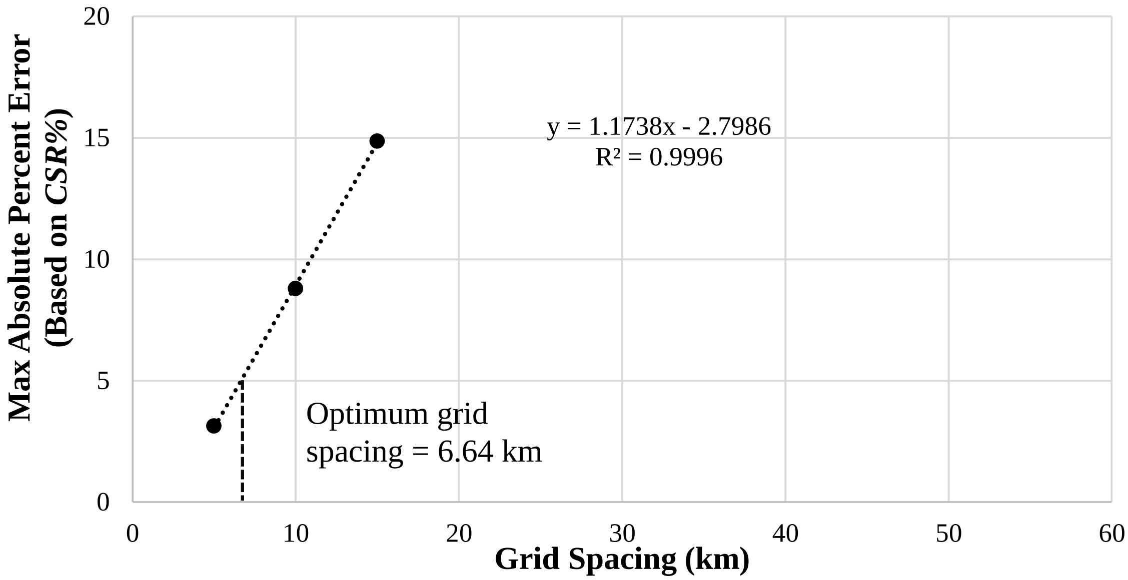


Figure 2.9 Variation of maximum percent error (based on *CSR*%) with increasing distance between grid points for Eureka, CA. (Pink zone, *PGA* = 1.4004)

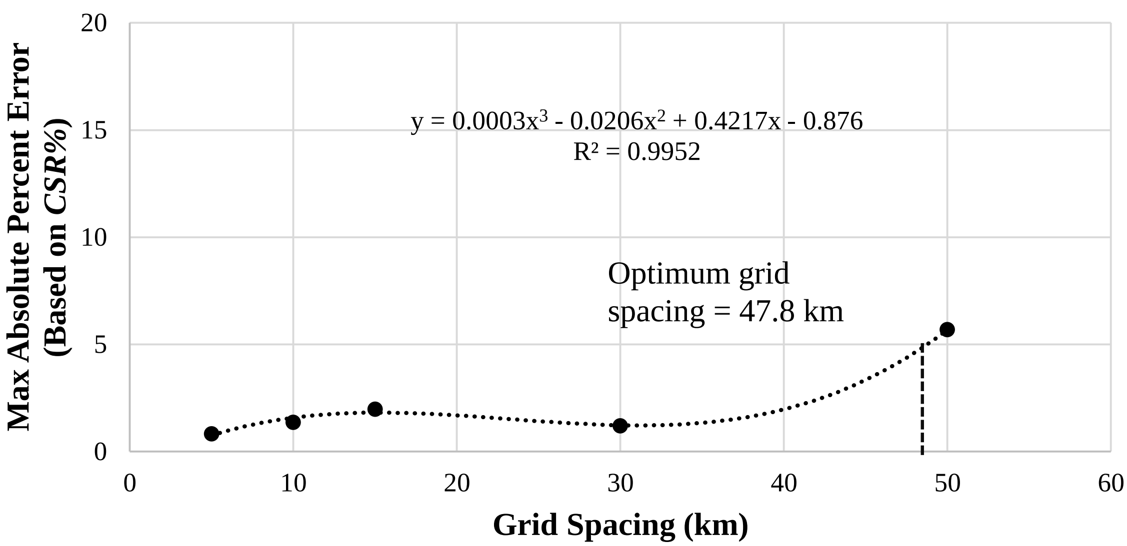


Figure 2.10 Variation of maximum percent error (based on *CSR*%) with increasing distance between grid points for West Yellowstone, MT. (Orange zone, *PGA* = 0.4187)

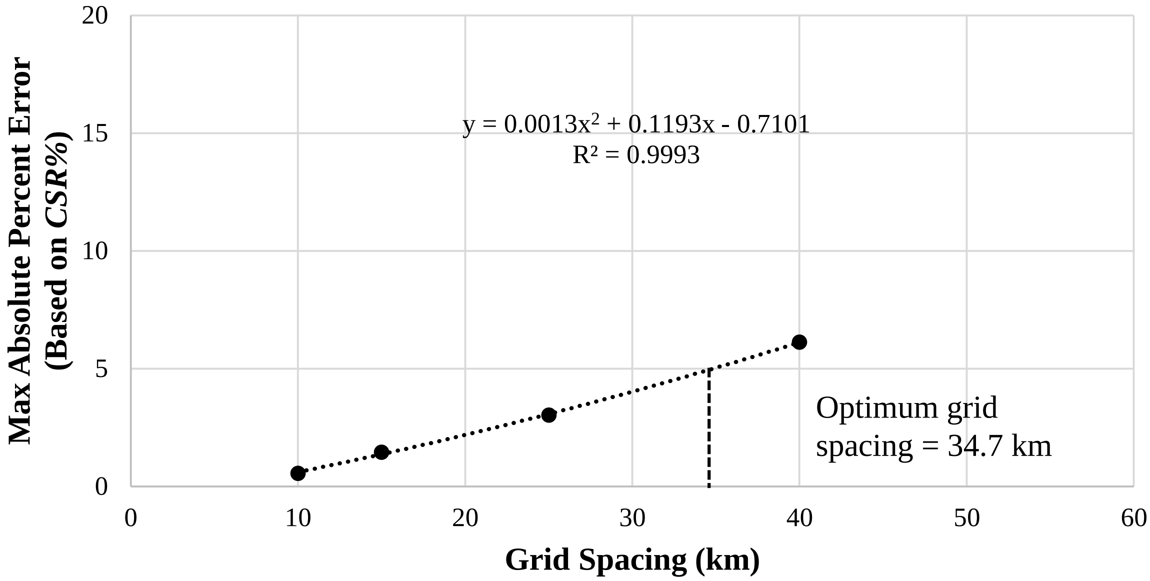


Figure 2.11 Variation of maximum percent error (based on *CSR*%) with increasing distance between grid points for Boise, ID. (Green zone, *PGA* = 0.1232)

2.2.4 *PGA* Correlation

As described in the previous section, optimum grid spacing was determined for each city included in the study that reached at least a maximum percent error of 5% based on *CSR*% (not N_{req}). Optimum grid spacing was then plotted against *PGA* as shown in Figure 2.12. The vertical dashed lines indicate the boundaries between *PGA* bins as defined in the USGS 2008 *PGA* hazard map. The general trend of the points (R^2 = 0.628) supports the hypothesis that as *PGA* increases the optimum grid spacing decreases. A hand-drawn lower bound was used to determine the optimum grid spacing based on *PGA*. The lower bound line was chosen as a conservative estimate of optimum grid spacing.

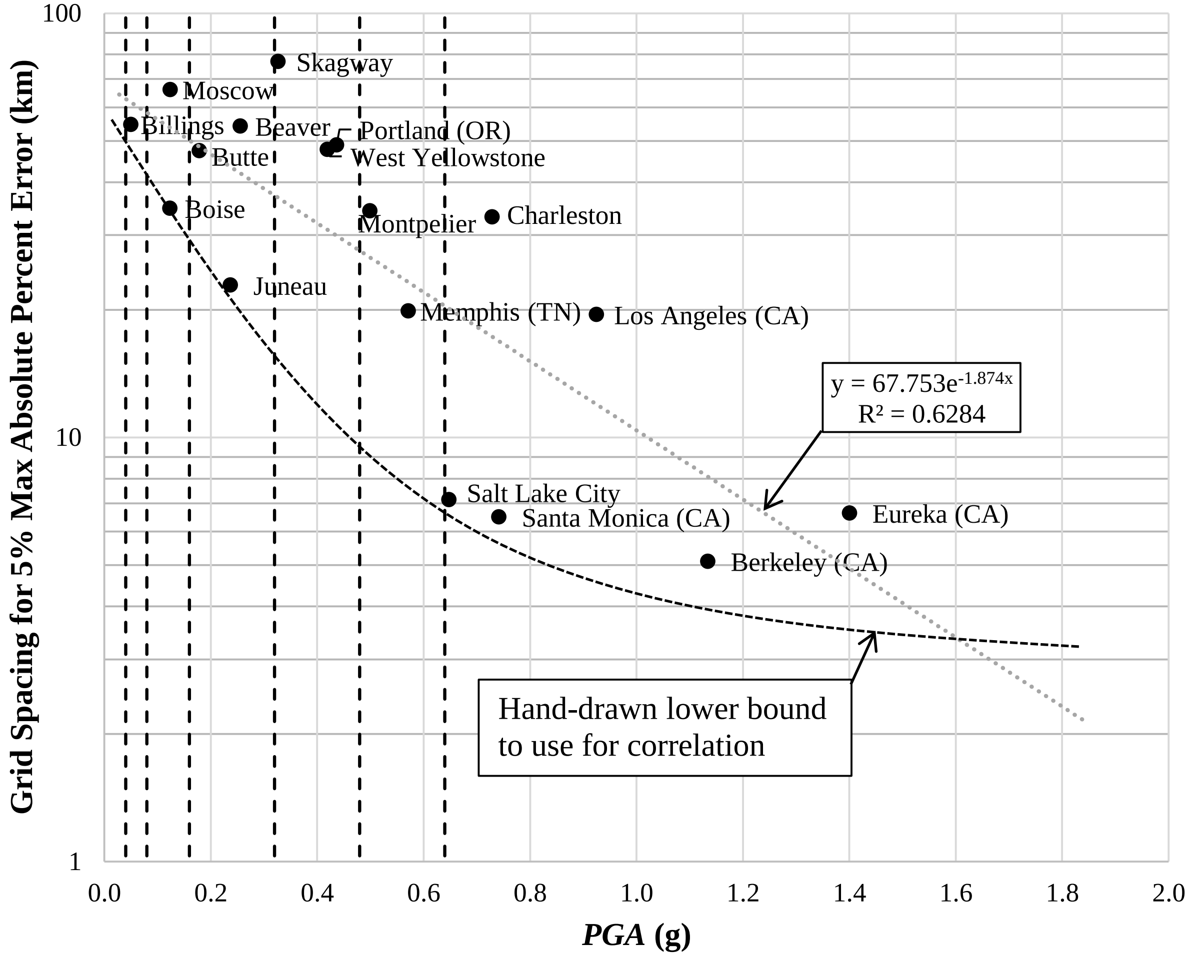


Figure 2.12 Correlation between *PGA* and optimum grid spacing to achieve 5% maximum absolute percent error (based on *CSR*%).

The hand-drawn lower bound shown in Figure 2.12 was used to determine the set of rules for selecting grid spacing in the mapping procedure. Within each *PGA* bin, a lower-bound value for optimum grid spacing was selected. The set of rules includes one optimum grid spacing distance for each *PGA* bin included in the study. Table 2.2 summarizes this set of rules.

Table 2.2 Proposed Set of Rules to Determine Optimum Grid Spacing within a *PGA* Range

PGA	Color	Spacing (km)	Spacing (mi)
0 - 0.04	Gray	50	31.1
0.04 - 0.08	Blue	50	31.1
0.08 - 0.16	Green	30	18.6
0.16 - 0.32	Yellow	20	12.4
0.32 - 0.48	Orange	12	7.5
0.48 - 0.64	Red	8	5.0
0.64+	Pink	4	2.5

In summary, the correlation determined in this study provided a set of rules to use when creating liquefaction loading maps for *CSR*% and liquefaction parameter maps for N_{req}.

2.3 Empirical Lateral Spread Displacement Model

This section will describe the methods used to derive the optimum grid spacing to ensure accuracy of interpolated points determined by the simplified performance-based lateral spread displacement evaluation. To ensure accuracy of the maps, interpolation between grid points must result in values reasonably close to the results of an actual analysis at the same location. It was determined that if the interpolated result was within 5% of an actual analysis at that site, then the result was acceptable.

2.3.1 Methodology for Grid Spacing Study

The methodology used to derive the optimum grid spacing for the simplified lateral spread displacement model began with the selection of three cities in each state that represent three different levels of seismic hazard (with the exception of Connecticut which had essentially uniform hazard across the state). Using the USGS 1996 and 2008 deaggregation websites the PGA at each site was determined for the 2475 year return period. The hazard level at each site as well as the hazard range for each state was found based on the same representation seen in the USGS 2008 PGA hazard map for the 2475 year return period. This map and the subdivision of hazard level can be seen in Figure 2.7, and a table listing each city with its corresponding *PGA* and hazard zone can be seen in Table 2.3.

Table 2.3 Grid Spacing Analysis Sites and *PGA*

State	Site	*PGA*	Hazard Zone
Alaska	Anchorage	0.618	Red
	Fairbanks	0.414	Orange
	Juneau	0.237	Yellow
Connecticut	Hartford	0.093	Green
	Norwich	0.086	Green
	Danbury	0.121	Green
Idaho	Salmon	0.375	Orange
	Boise	0.136	Green
	Pocatello	0.199	Yellow
Montana	Butte	0.179	Yellow
	Glendive	0.028	Grey
	Billings	0.050	Blue
South Carolina	Charleston	0.733	Pink
	Greenville	0.142	Green
	Columbia	0.225	Yellow
Utah	Salt Lake City	0.665	Pink
	Moab	0.087	Green
	Cedar City	0.285	Yellow

To assess the grid spacing, the reference lateral spread displacement, D_H^{ref}, was found at each city and then four locations surrounding the city at a set grid spacing. Using the city as an anchor point, the four points were selected equidistant from the center creating a square. The grid spacing is then the length of the sides of the square. This arrangement can be seen in Figure 2.1. Using the four surrounding points, a value was interpolated at the center of the points and then compared to the actual value found at the site. This process was repeated for several grid spacings and the % error was calculated. An example of this process can be seen for the city of Charleston, South Carolina at a grid spacing of 15 km (9.32 mi) in Table 2.4.

Table 2.4 Grid Spacing Interpolation Example Calculation for Charleston, South Carolina (32.783, -79.933) at 15 km (9.32 mi) grid spacing.

Grid Spacing - 15 km (9.32 mi)		
Latitude	Longitude	D_H^{ref} (m)
32.850	-80.000	0.829
32.716	-80.000	0.522
32.850	-79.866	0.479
32.716	-79.866	0.333
Interpolated D_H^{ref} (m)		**0.541**
Actual D_H^{ref} (m)		**0.513**
Error (%)		**5.41%**

This process was repeated for each city in the analysis at grid spacings of 5, 10, 15, 20, 25, 30, 40, and 50 km (3.1, 6.21, 9.32, 12.4, 15.5, 18.6, 24.9, and 31.1 mi). The grid spacing, where the error is 5% or less, was then plotted against *PGA* to get an idea of how the grid spacing differs from site to site. This plot can be seen in Figure 2.13.

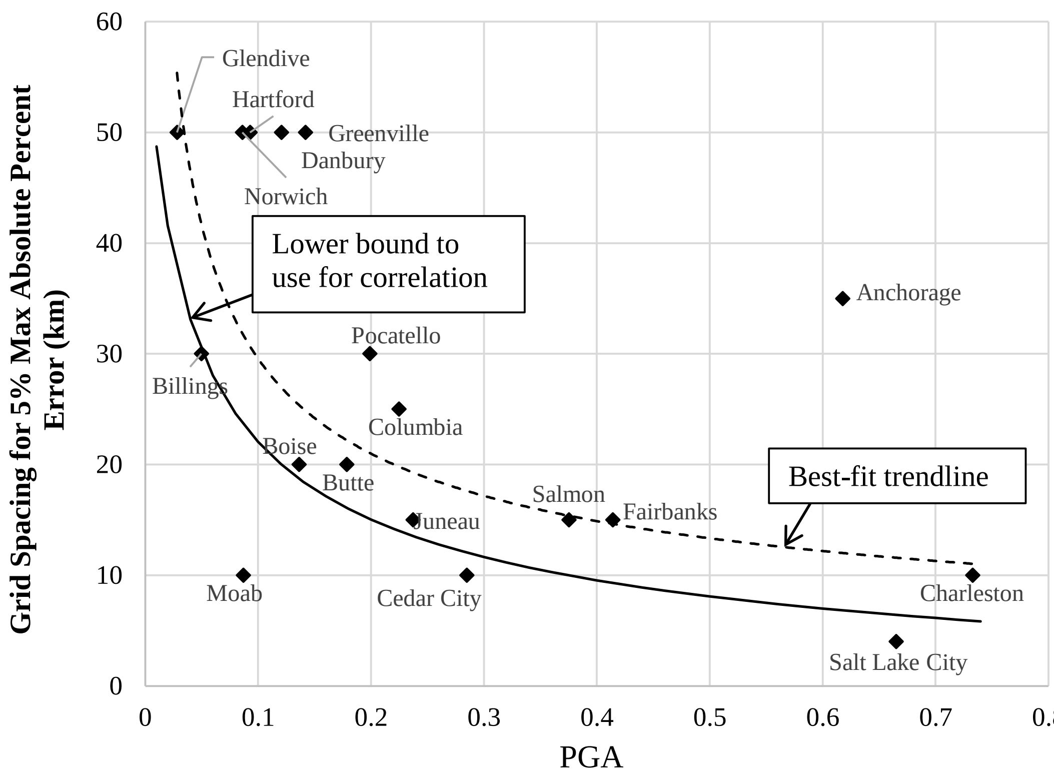


Figure 2.13 Grid spacing based on 5% error plotted against PGA for all sites.

As can be seen in this plot, there is significant scatter of the results. The seismic loading of each location can be very different, so the way that the lateral spread analysis attenuates could be influenced heavily by this. In order to address this uncertainty, a line was fit to the data (dashed line) than a lower bound (solid line) was drawn to represent the minimum grid spacing. This lower envelope was used for all locations, with the exception of Utah and Alaska. Utah was found to require a much finer grid spacing overall and so a specific grid spacing was created to account for this. Alaska was given a slightly coarser grid spacing for two reasons: the first was due to the analysis showing Alaska being overall higher on this plot, and second that Alaska has significantly more surface area than the rest of the states and required more analysis than the rest of the states combined. These proposed grid spacings can be seen in Table 2.5.

Table 2.5 Proposed Grid Spacing for Analysis Based on *PGA* Zone

PGA	Color	General (km)	Utah (km)	Alaska (km)
0 - 0.04	Gray	40	25	45
0.04 - 0.08	Blue	30	20	35
0.08 - 0.16	Green	20	15	25
0.16 - 0.32	Yellow	15	12	20
0.32 - 0.48	Orange	12	10	15
0.48 - 0.64	Red	8	7	10
0.64+	Pink	5	4	8

2.4 Summary

Based on the analysis outlined here, the grid spacing necessary to maintain accuracy in the interpolated results was found. The grid spacings should result on average 5% difference between an interpolated value and the result if an analysis were performed at the same site. These grid spacings will be very important in creating the grid of points that will be used in the analysis.

3.0 MAP DEVELOPMENT

3.1 Overview

Now that the optimum grid spacing between points has been determined, the grid points used in the analysis need to be determined, then those points need to be analyzed and the hazard parameters calculated. Once the analysis has been conducted for each grid, than those points will be used to create the liquefaction and lateral spread parameter maps for the target return periods.

This process required the use of several specialized software programs. To create the grid spacing and the maps the Graphical Information System (GIS) software ArcMap, developed by ESRI Incorporated, was used extensively. To perform the simplified liquefaction initiation analysis the software PBLiquefy, developed in house at BYU by Franke et al. (2014), was utilized. To perform the simplified lateral spread displacement analysis, the program EZ-FRISK created by Risk Engineering (2013) was used.

3.2 Creating the Grid Points

The process was started by dividing each state into sections based on the USGS 2008 *PGA* hazard map. This was done using GIS shapefiles downloaded from the USGS website representing the 2008 hazard map. Each *PGA* hazard zone was assigned a grid spacing based on the suggested grid spacing from the previous section. Then using ArcMap, a grid of points with latitude and longitude, was generated for each hazard zone at the specified grid spacing. All the zones were then combined into one general grid for the state.

Additionally, the representatives for each state involved in the research was asked to provide any areas which they felt constituted an “Area of Concern” (AOC). These areas were anywhere that a reduction in grid spacing was thought necessary to provide a more refined hazard surface. Each AOC was then accounted for by modifying the general grid spacing rules to reduce grid spacing in each AOC. This was accomplished differently for the two methods used in this report. For the liquefaction initiation method each AOC was elevated by two hazard levels and the grid spacing for that area was based off the higher hazard. For example, if the AOC was in the “green” section of the hazard map the grid spacing in the AOC would be reduced to that of the “orange” level. The lateral spread displacement model increased all AOC to the “red” level and used that reduced grid spacing for each example. An example of the subdivision and the overall grid of points for Utah can be seen in Figure 3.1.

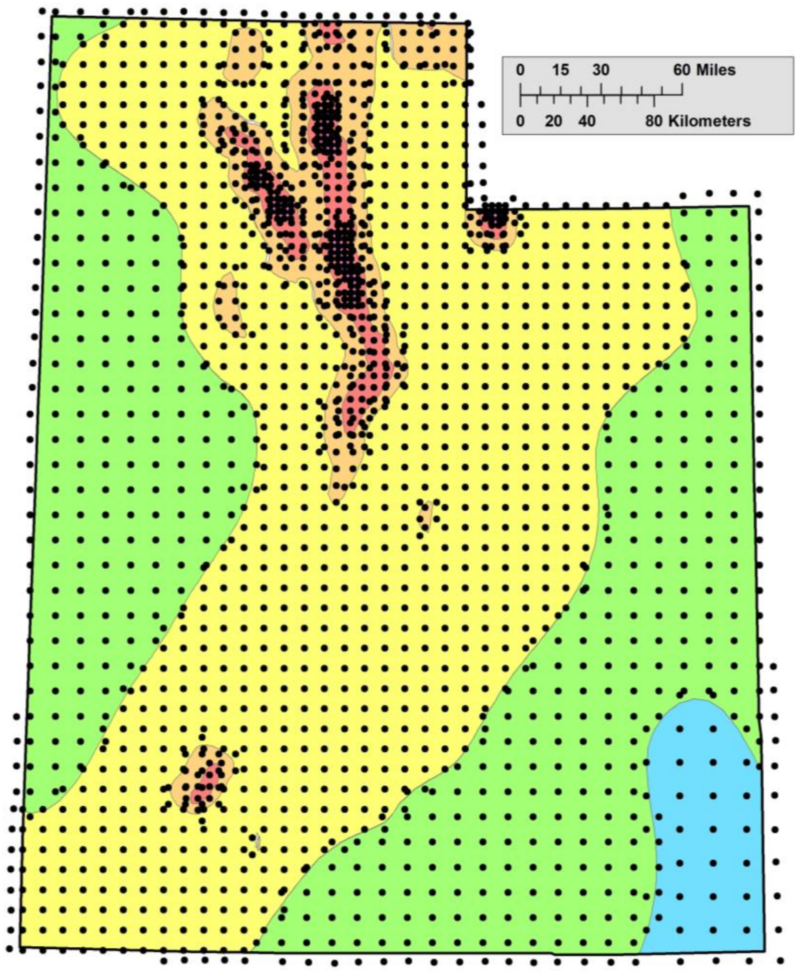


Figure 3.1 Grid points for Utah combined with USGS 2008 PGA hazard map.

3.3 Analysis of the Grid Points

Once the grid points were developed for all the states, the location of each of the points was evaluated for liquefaction and lateral spread hazard using the reference soil profiles discussed in the previous report. Each point was analyzed for the 475, 1033, and 2475 year return periods. Once all of the points for a particular state were successfully run, the results were compiled and then imported back into ArcMap to begin the process of making the parameter maps.

3.3.1 Analysis of the Liquefaction Initiation Model Grid Points

The grid points used in the liquefaction initiation method were analyzed using the USGS 2008 deaggregations for Connecticut, Idaho, Montana, South Carolina, and Utah while the USGS 1996 deaggregations were used for Alaska. The process utilized the ability of PBLiquefy to run multiple sites sequentially.

3.3.2 Analysis of the Lateral Spread Displacement Model Grid Points

Analyzing the grid points in EZ-FRISK requires that a seismic source model be used. To analyze the points in Connecticut, Idaho, Montana, South Carolina, and Utah the USGS 2008 seismic source model. For Alaska, the USGS 1998 gridded source model and the USGS 2002 seismic source models were used to analyze the grid points. Only area sources and faults were considered within 300 km of each site, with the exception of subduction zone sources which were considered within 500 km.

3.4 Creation of the Maps

Once the analyzed grid points were imported back into ArcMap the points needed to be turned into a contour map. This was done by converting the individual points into a surface raster using the Kriging tool. This tool interpolates between each point and makes a surface with a value at every point. In order to ensure that the contours of each state run all the way to the border, the state shape is buffered slightly. The Kriging raster is created based on this buffered shape. Once the Kriging raster is made, the raster surface needs to be converted into a contour.

To make the contour from the Kriging, first the spacing of the contours needs to be determined. It is important that the contour spacing be fine enough that the detail of the map can be read, but far enough apart that the contours can be read. The spacing will vary from map to map based on this process. An example of a Kriging raster and contour for the state of Utah can be seen in Figure 3.2.

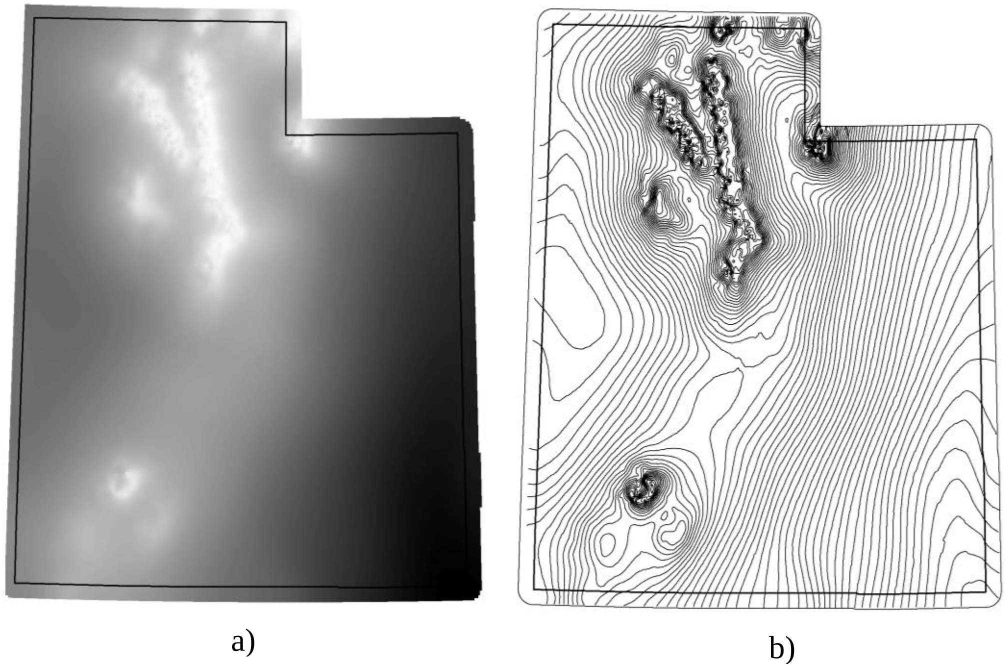


Figure 3.2 a) Kriging raster and b) contours for Utah (T_r = 2475 yrs).

Once the proper contour spacing is determined for each map, the contour is labeled and clipped to fit the state shapefile. Then a basemap and reference features are added to provide more detail about the topography to the parameter maps. An example of a completed liquefaction parameter map of N_{req} can be seen in Figure 3.3.

Each model has different parameters represented by the contours on the map. The liquefaction initiation model has two different parameters and therefore two different maps. The first parameter is the reference value of *CSR*% as calculated using the Boulanger and Idriss (2014) model. *CSR* is usually given as a decimal but was changed to a percent to make reading the maps easier. The second parameter is the reference value for N_{req} as calculated using the Cetin et al. (2004) model and is given in units of SPT blowcounts. The lateral spread parameter map shows the reference value of displacement, D_H^{ref} as calculated using the Youd et al. (2002) model, and is given in units of Log (meters). Careful attention needs to be given to the labeling of each map to ensure that map has the correct parameter and that the reference value used in the later steps of the simplified method are accurately read from the contours.

For this report, maps of *CSR*%, N_{req}, and D_H^{ref} were made for each state at the 475, 1033, and 2475 year return periods with the exception of Connecticut. At the 475 and 1033 year return periods for *CSR*% and the 475 year return period for N_{req}, the maps for Connecticut show no variation in those values and have uniform hazard (N_{req} = 1, *CSR*% = 4.65%) across the state. Consequently, those maps were not included. Additionally, maps for the cities of Anchorage, AK; Boise, ID; Butte, MT; Charleston, SC; and Salt Lake City, UT were created. These maps can be viewed in the Appendix: liquefaction parameter maps in Appendix A and lateral spread hazard maps in Appendix B. The contours were adjusted for each map to make reading it as user friendly as possible.

These maps were provided to show the potential types of parameter maps that can be created. Using the Kriging rasters that will be provided at the culmination of this research, each state can create maps of any area in their state and determine the contour spacing and scale.

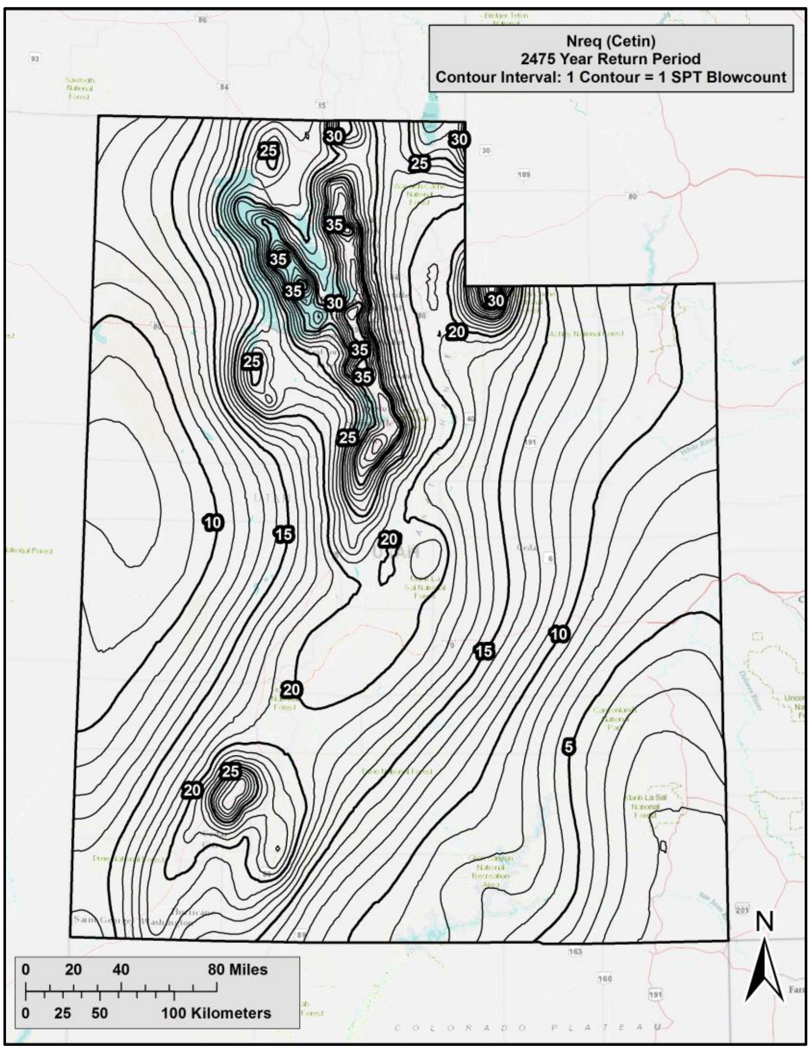


Figure 3.3 N_{req} for Utah (T_r = 2475 years).

3.5 Summary

To create the parameter and hazard maps, the state is subdivided into zones and a grid spacing for each zone is assigned. A grid of points is generated in ArcMap based on this grid spacing. Then the points are analyzed using the specified performance-based analytical software (PBLiquefy, EZ-FRISK). These points are then imported into ArcMap and converted to a Kriging raster that is then used to create a contour of the reference parameter. Sample maps for the states participating in this research study can be seen in the Appendix.

4.0 CONCLUSIONS

4.1 Summary

The purpose of the research being performed is to provide the benefit of the full performance-based probabilistic earthquake hazard analysis, without requiring special software, training, and experience. To do this, simplified models of liquefaction triggering and lateral spread displacements were developed in the Year 1 Quarter 1 update report that approximate the results of the full probabilistic analysis. These simplified methods require liquefaction parameter maps. This quarterly report addresses proper grid spacing of the points used for analysis and the process of creating parameter maps.

4.2 Findings

4.2.1 Evaluation of Grid Spacing

To create maps appropriate for the simplified performance-based procedures used in this research, it was necessary to define a set of rules for proper grid spacing which would keep error due to interpolation within a reasonable amount. As shown in this report, such a set of rules was derived. Assuming that these rules are followed, the grid spacings should result in a 5% or less difference between an interpolated value and the value that would have been produced if a full analysis were performed at that location. The appropriate set of grid spacing rules for each model type (i.e. liquefaction triggering or lateral spread displacement) were used in creating the grid of points used for map making.

4.2.2 Map Development

Using the set of rules developed in the grid spacing study, a set of points was determined for each state to be used in analysis. A full performance-based analysis was performed at each point for three return periods (475, 1033, and 2475 years) yielding three different values for each return period: standard penetration test (SPT) blow count required to resist liquefaction (N_{req}), percent cyclic stress ratio (CSR%), and the log of lateral spread displacement ($\log D_H$). These values were calculated based on the reference soil profile introduced in the Year 1 Quarter 1 update report, not based on site-specific soil characteristics. The values at each point were used to create a surface raster file in ArcMap using Kriging-style interpolation. This raster was then used to create contour maps for each parameter in each state. These contour maps can be re-formatted as desired from the raster file in ArcMap. Sample contour maps created by the research team can be found in the Appendix of this report.

4.3 Limitations and Challenges

These liquefaction parameter maps do not include site-specific soil information. Instead, these maps are based on a reference soil profile (introduced in the Year 1 Quarter 1 update report) and as such provide *reference* values to be inserted into the simplified performance-based procedure derived in the Year 1 Quarter 1 update report. These specific maps created for this report should not be used in any other way. Also, the values on these parameter maps should not be viewed as the actual hazard at a given site. Again, these are reference values which do not include site-specific soil characteristics.

As these maps are used, keep in mind the limitations of the liquefaction evaluation models used to calculate the reference values. Please refer to the proper liquefaction evaluation models (Boulanger and Idriss, 2014 and 2012; Cetin et al., 2004; Youd et al., 2002) for detailed descriptions of these models' limitations. The reference values displayed on these maps may incorporate input parameters which are outside the appropriate range for these models. These limitations should be carefully considered before accepting the results of this simplified procedure.

The reference values displayed on these parameter maps were calculated based on data from available seismic models. For liquefaction triggering, the USGS deaggregations were used while for lateral spread displacement, the seismic models available in EZ-FRISK were used. Therefore, the results displayed on these parameter maps are only as accurate as the seismic models used to create them. Any inaccuracies which may exist in these models may affect the accuracy of the simplified methods developed as part of this research.

REFERENCES

Bartlett, S.F., and Youd, T.L. (1995). Empirical prediction of liquefaction-induced lateral spread. *J. Geotech. Eng.*, 121(4), 316-329.

Boulanger, R. W., and Idriss, I. M. (2012). Probabilistic standard penetration test-based liquefaction-triggering procedure. *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000700, 1185–1195.

Boulanger, R. W., and Idriss, I. M. (2014). CPT and SPT based liquefaction triggering procedures. *Rep. UCD/CGM-14/01*, Dept. of Civil and Environmental Engineering, Univ. of California–Davis, Davis, CA.

Cetin, K. O., et al. (2004). Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. *J. Geotech. Geoenviron. Eng*., 10.1061/(ASCE)1090-0241(2004)130:12(1314), 1314–1340.

Franke, K.W., Wright, A.D., and Hatch, C.K. (2014). PBLiquefY: A new analysis tool for the performance-based evaluation of liquefaction triggering. Proceedings, 10th National Conference on Earthquake Engineering, Paper No. 87, EERI, Oakland, CA.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S. (2008). Documentation for the 2008 Update of the United States National Seismic Hazard Maps. Open-File Report 2008–1128, United States Geological Survey, Denver, CO: available at website: http://pubs.usgs.gov/of/2008/1128/.

Risk Engineering. (2013). EZ-FRISK, ver. 7.60. Boulder, Colorado.

USGS. (2008). "USGS 2008 interactive deaggregation." https://geohazards.usgs.gov/deaggint/2008/ (March 26, 2014).

USGS. (2008). "2008 Seismic Hazard Map (PGA, 2% in 50 years)" http://earthquake.usgs.gov/hazards/products/graphic2pct50.jpg (Sept 2, 2014).

USGS. (1996). "1996 Interactive Deaggregation." http://eqint.cr.usgs.gov/deaggint/1996/index.php (Sept 2, 2014).

Youd, T.L., Hansen, C.M., and Bartlett, S.F. (2002). Revised multilinear regression equations for prediction of lateral spread displacement. *J. Geotech. Geoenviron. Eng.*, ASCE. 128(12), 1007-1017.

APPENDIX A: Liquefaction Parameter Maps

a) Alaska

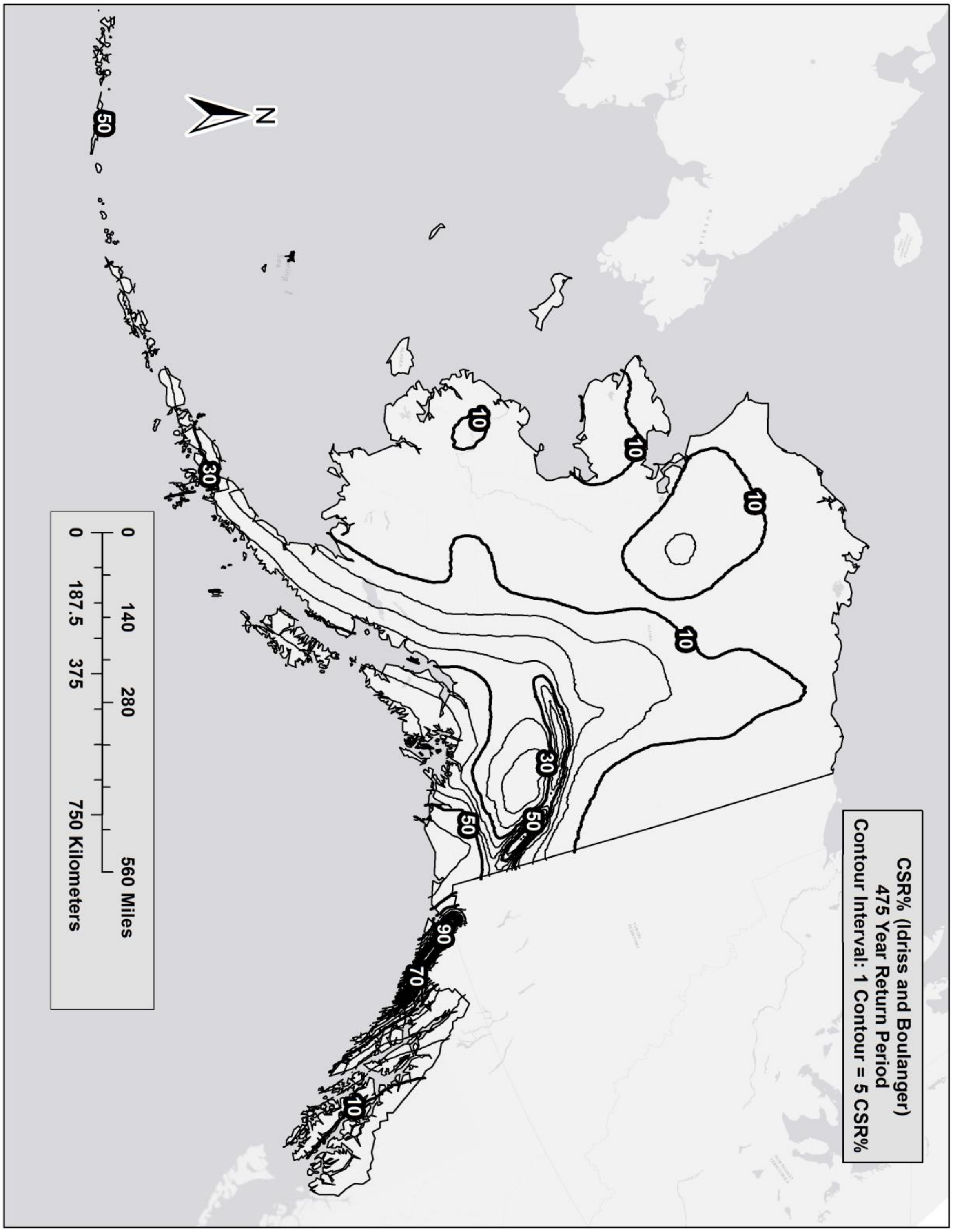


Figure A.1 – CSR% for Alaska (T_R = 475 years)

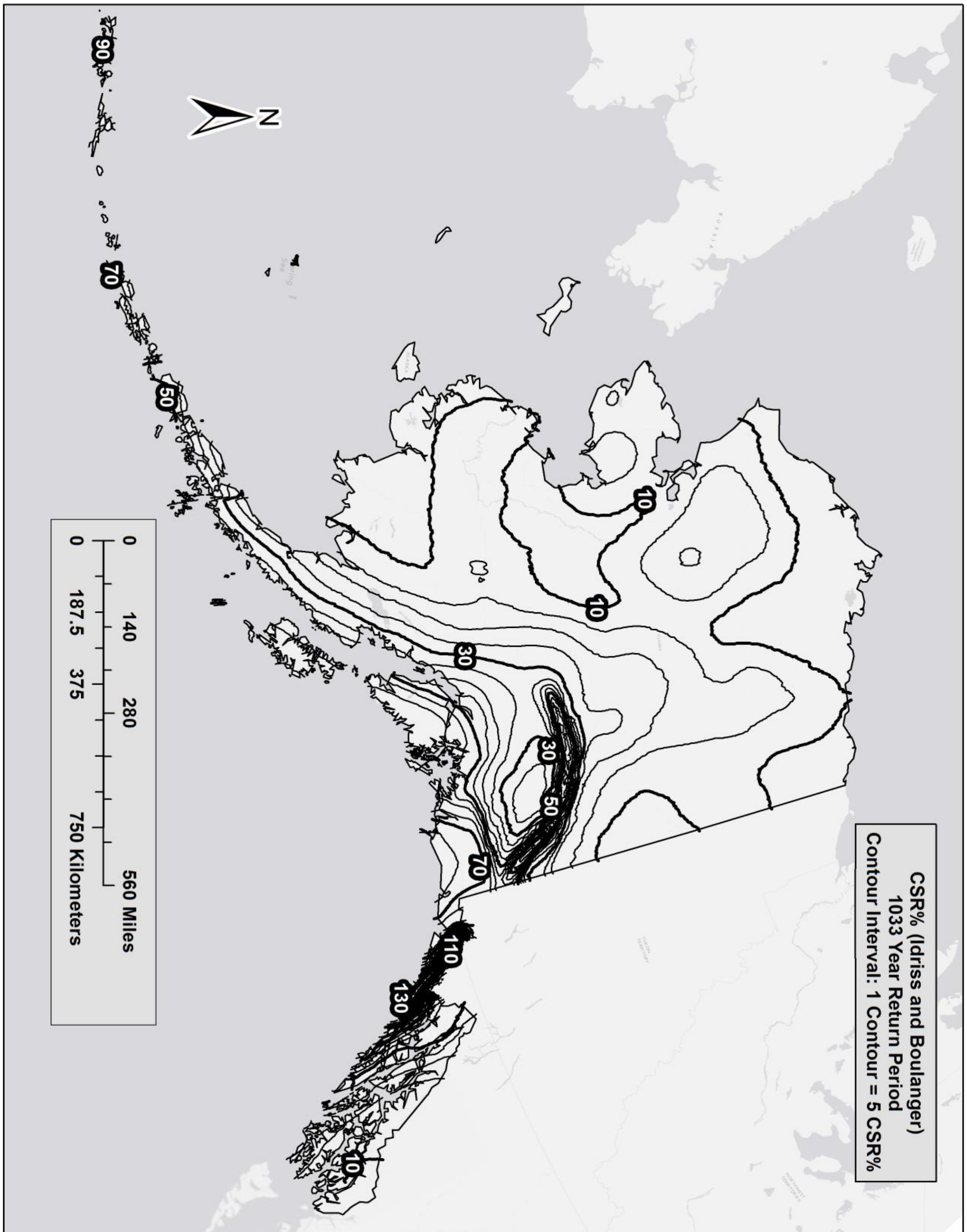


Figure A.2 – CSR% for Alaska (T_R = 1033 years)

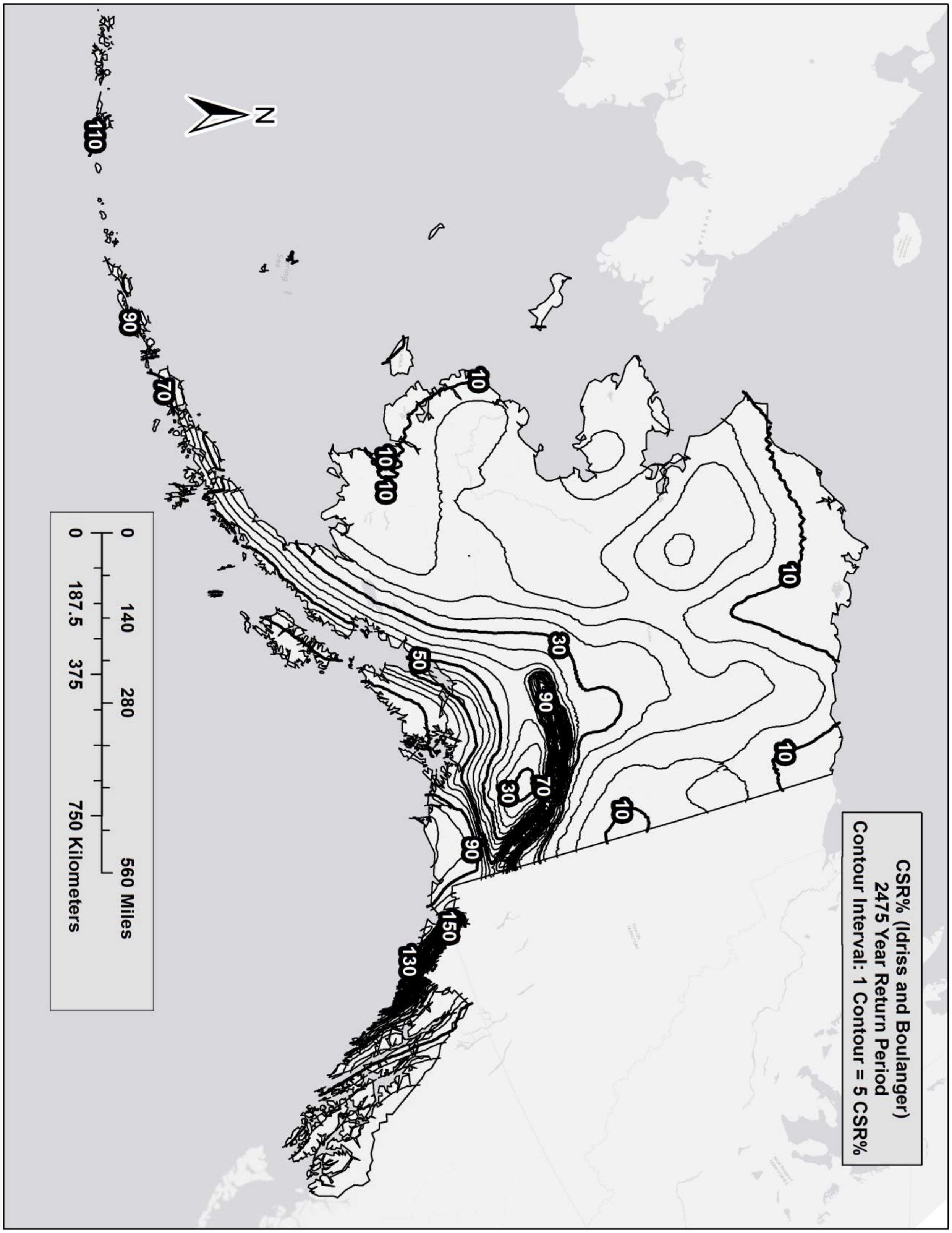


Figure A.3 – CSR% for Alaska (T_R = 2475 years)

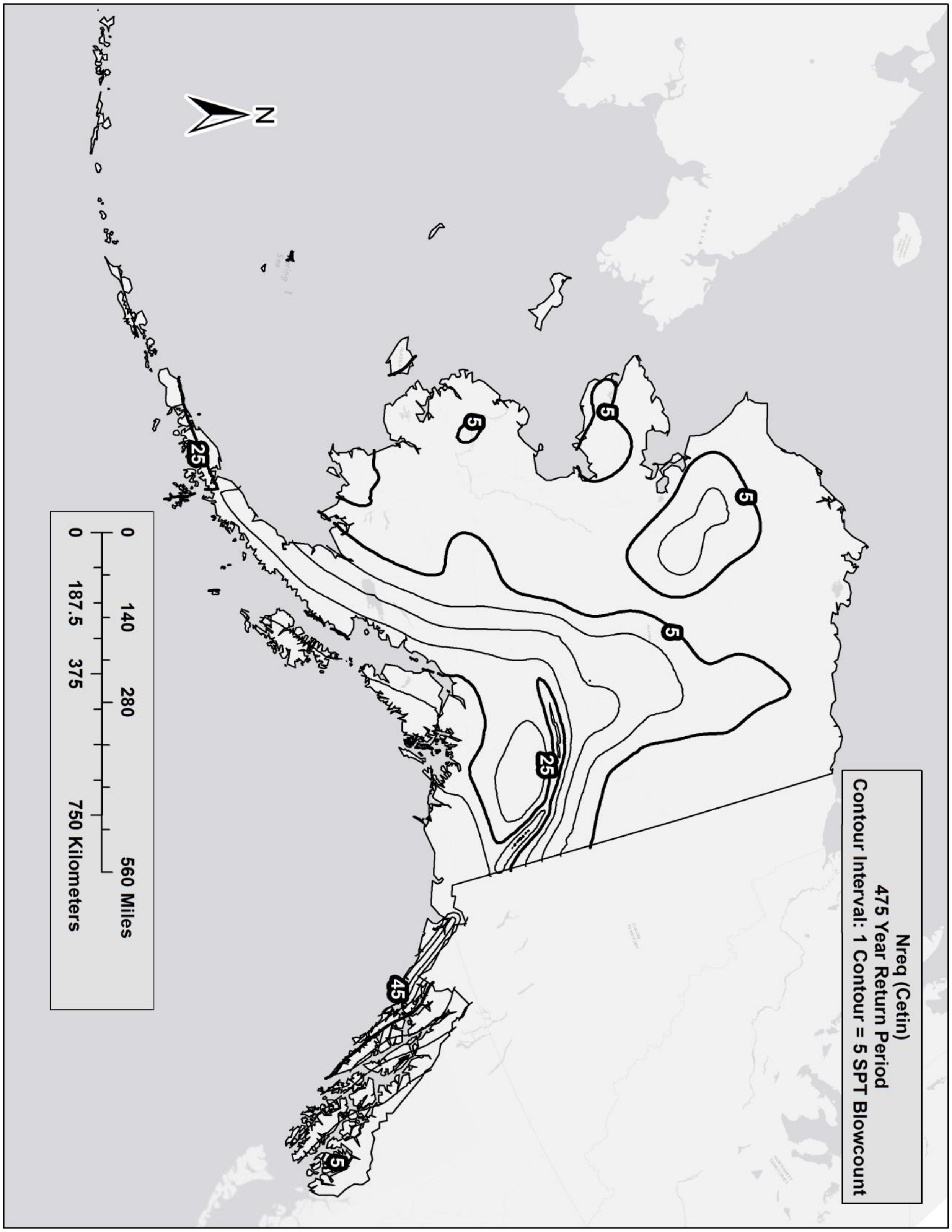


Figure A.4 – N_{req} for Alaska (T_R = 475 years)

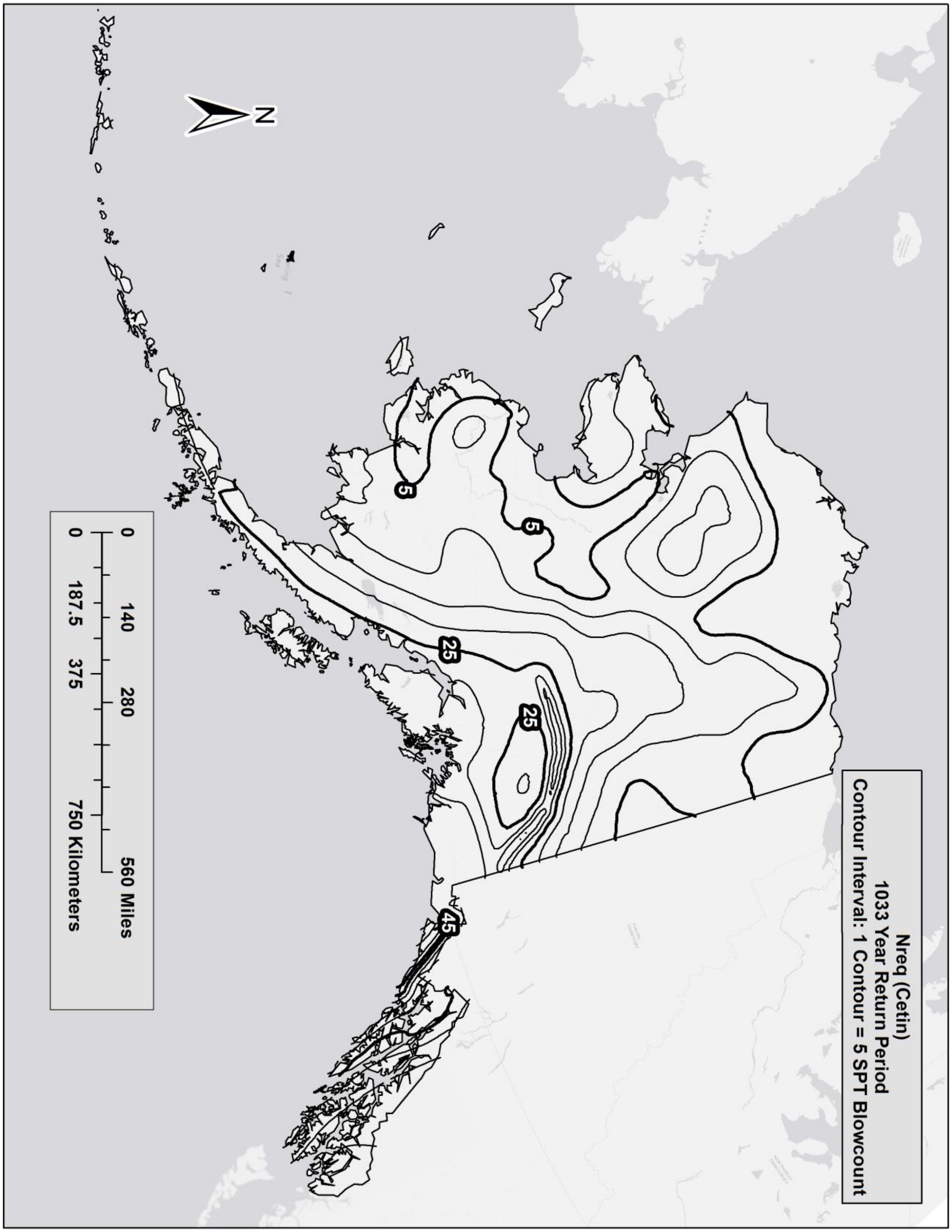


Figure A.5 – N_{req} for Alaska (T_R = 1033 years)

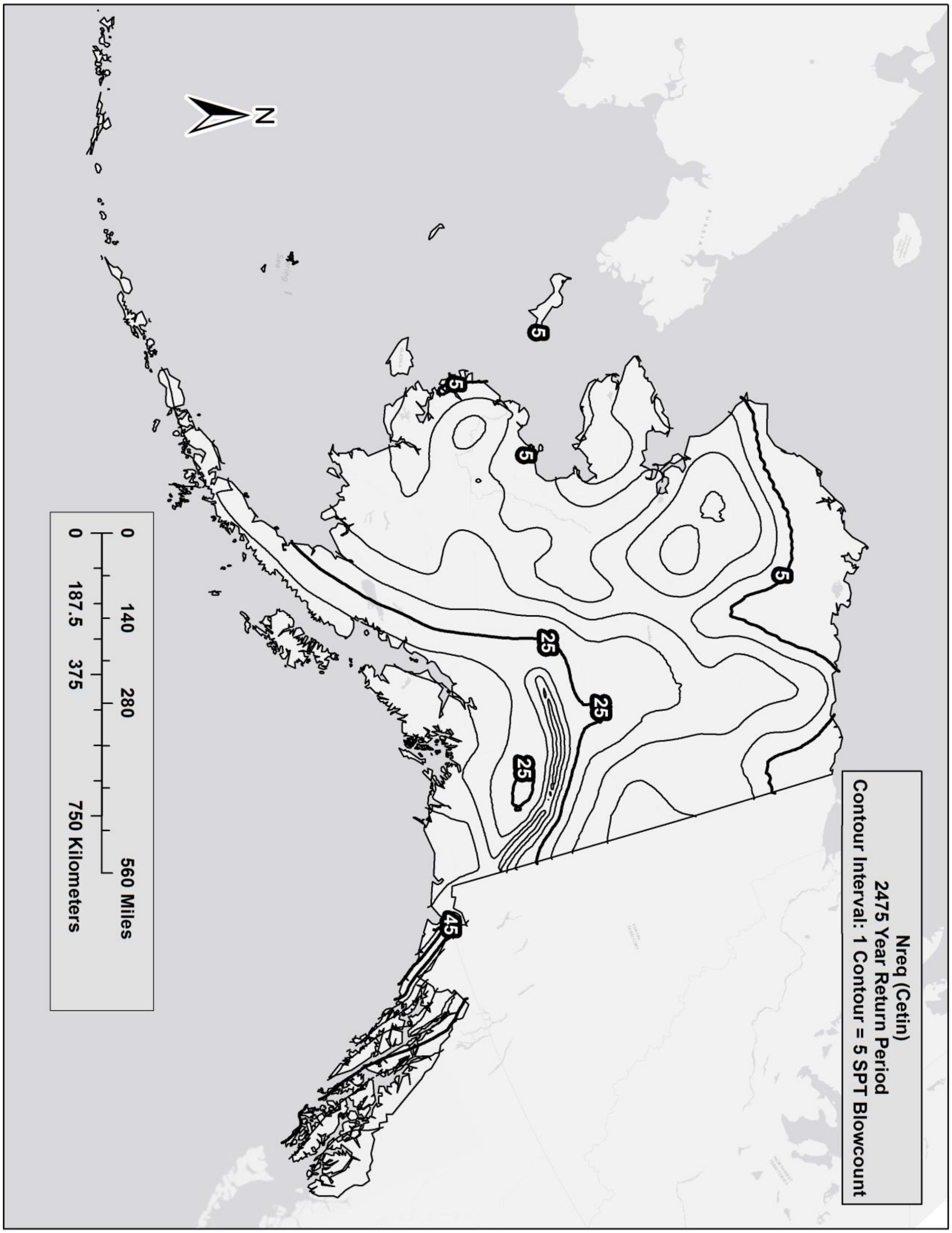


Figure A.6 – N_{req} for Alaska (T_R = 2475 years)

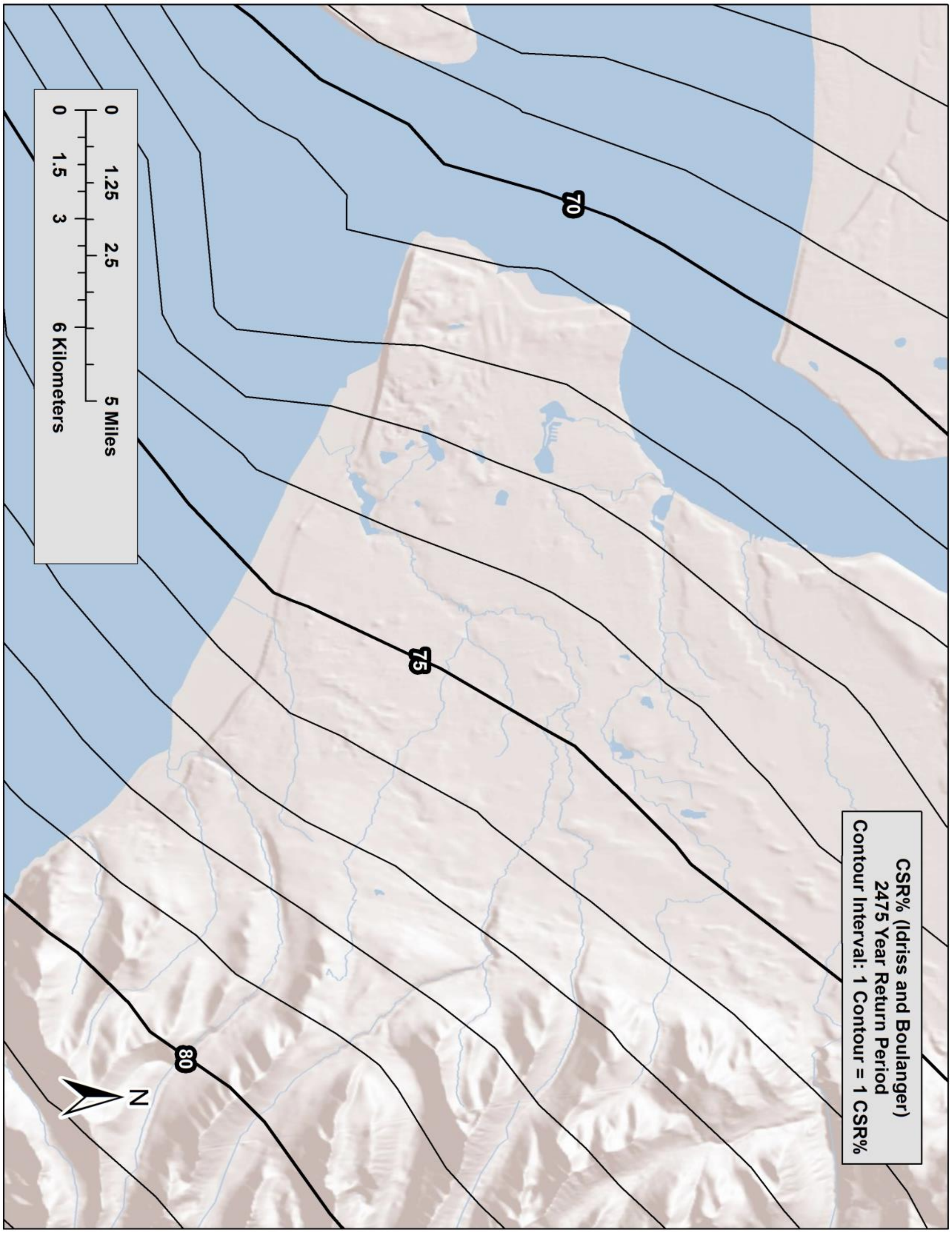


Figure A.7 – CSR% for Anchorage, AK (T_R = 2475 years)

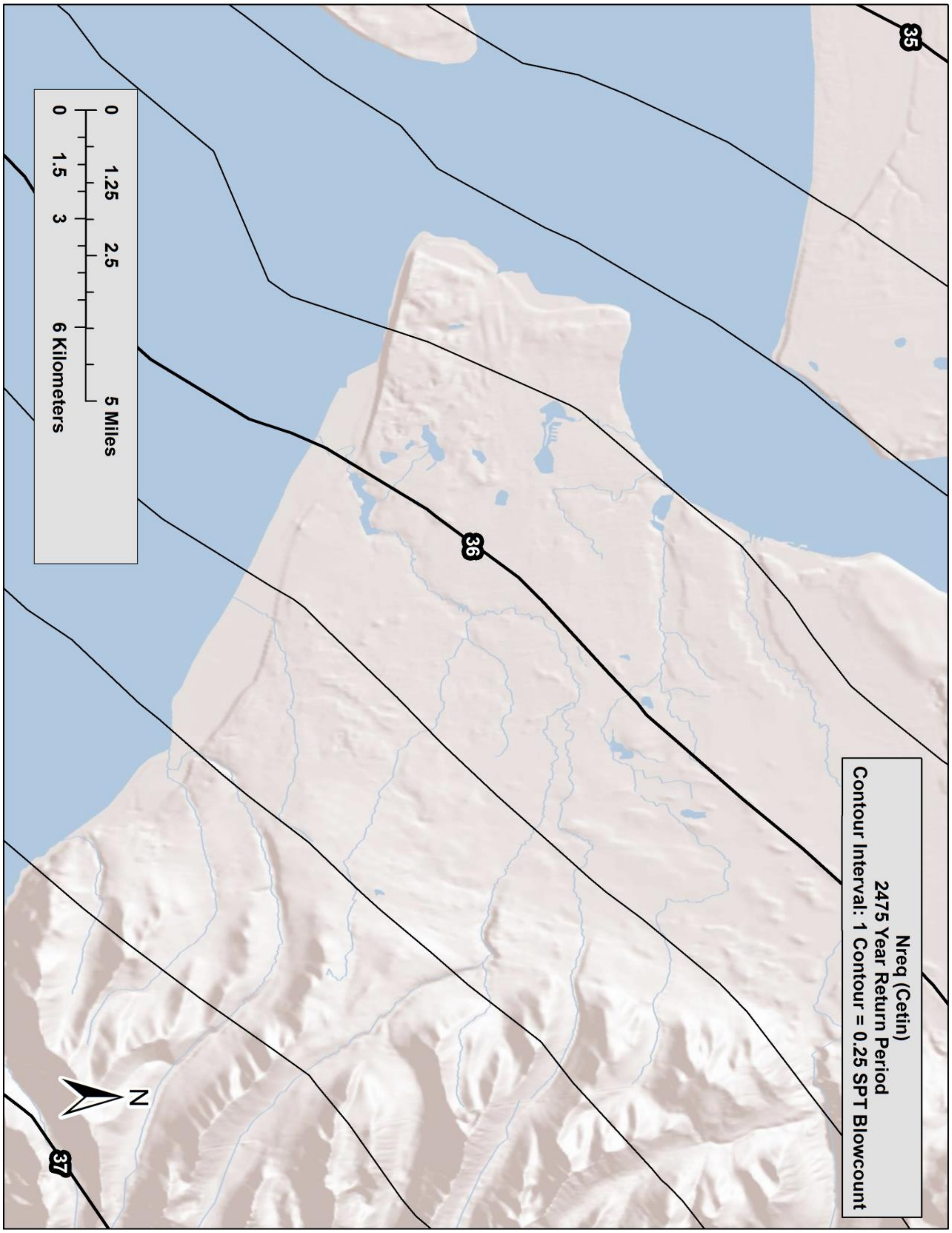


Figure A.8 – N_{req} for Anchorage,AK (T_R = 2475 years)

b) Connecticut

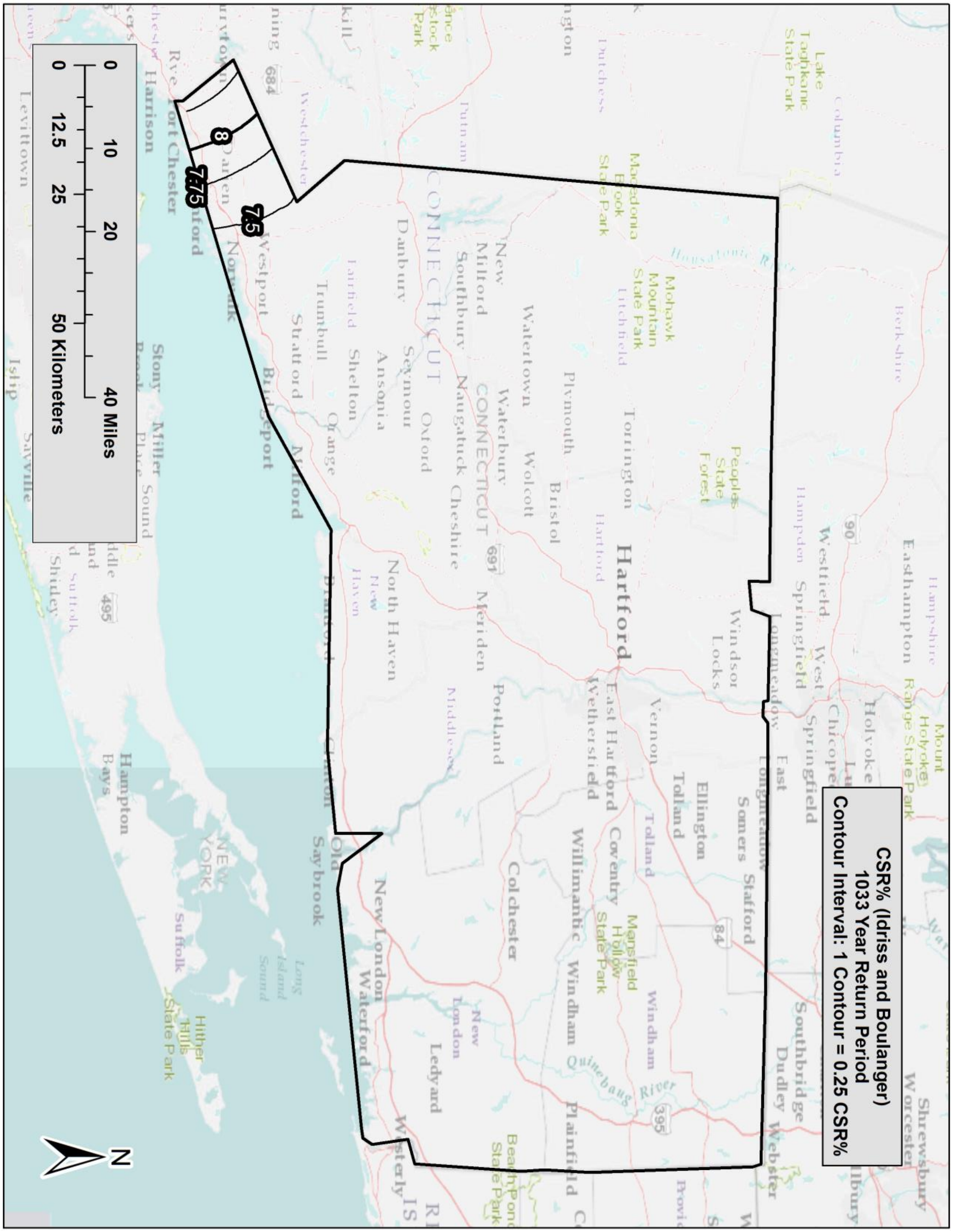


Figure A.1 – CSR% for Connecticut (T_R = 1033 years)

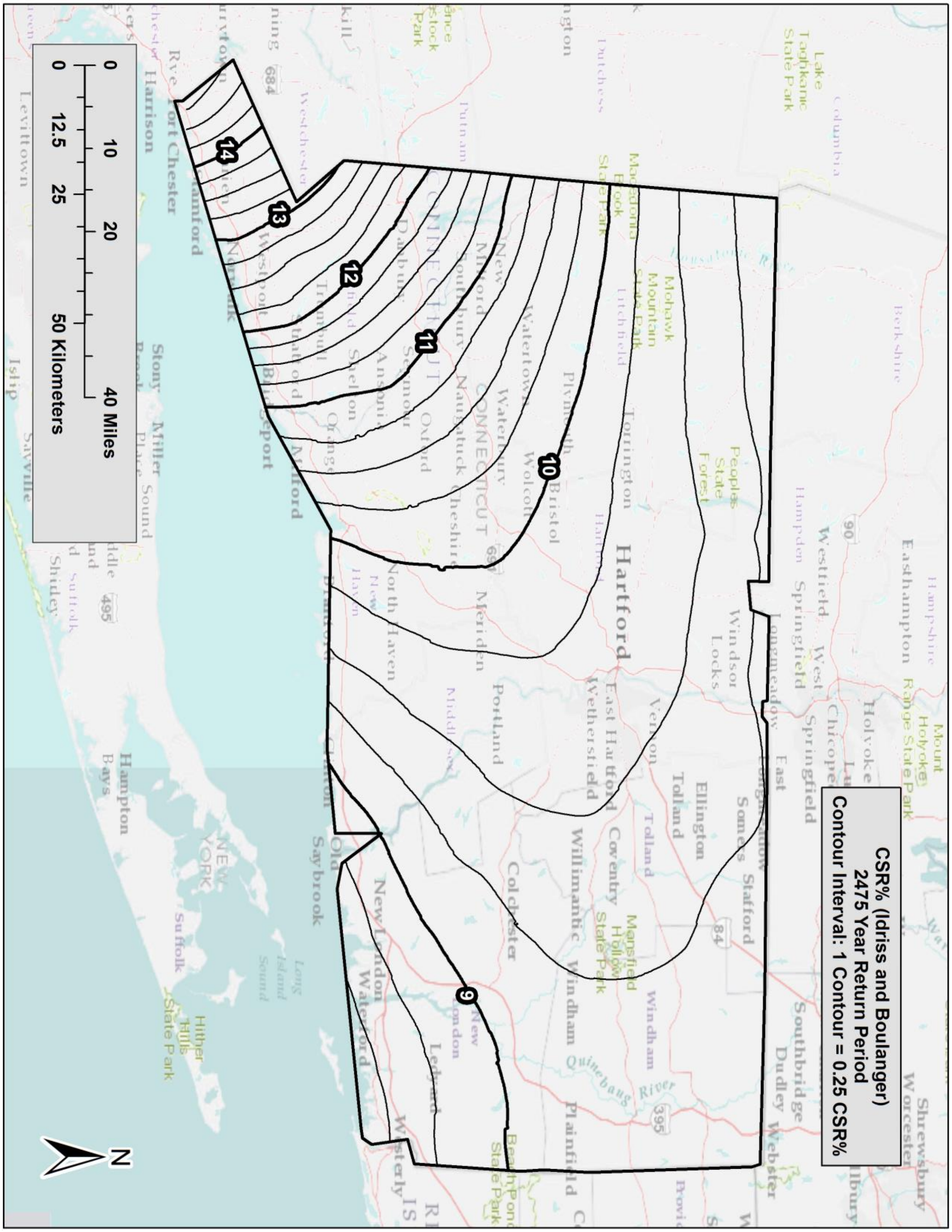


Figure A.2 – CSR% for Connecticut (T_R = 2475 years)

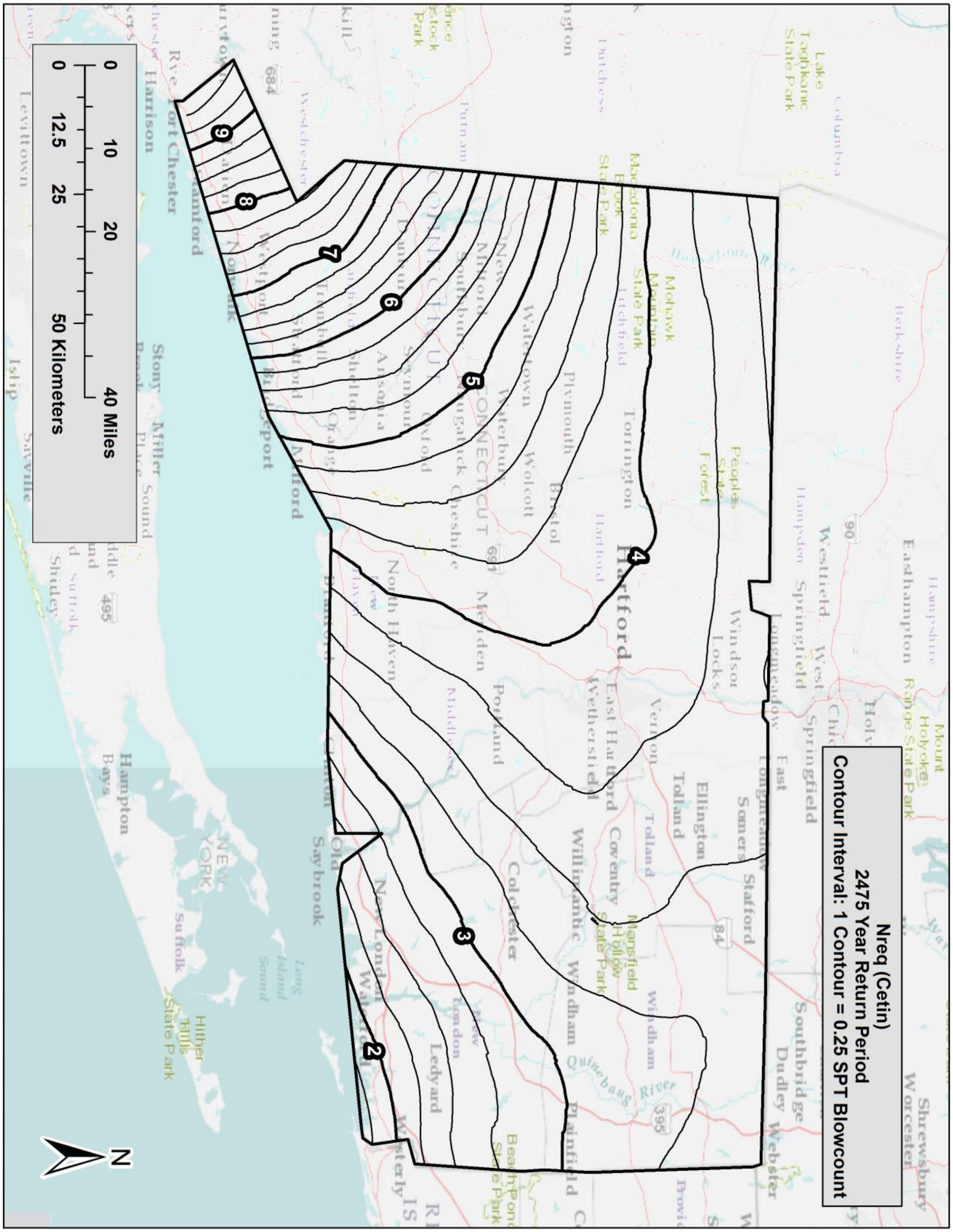


Figure A.3 – N_{req} for Connecticut (T_R = 2475 years)

c) Idaho

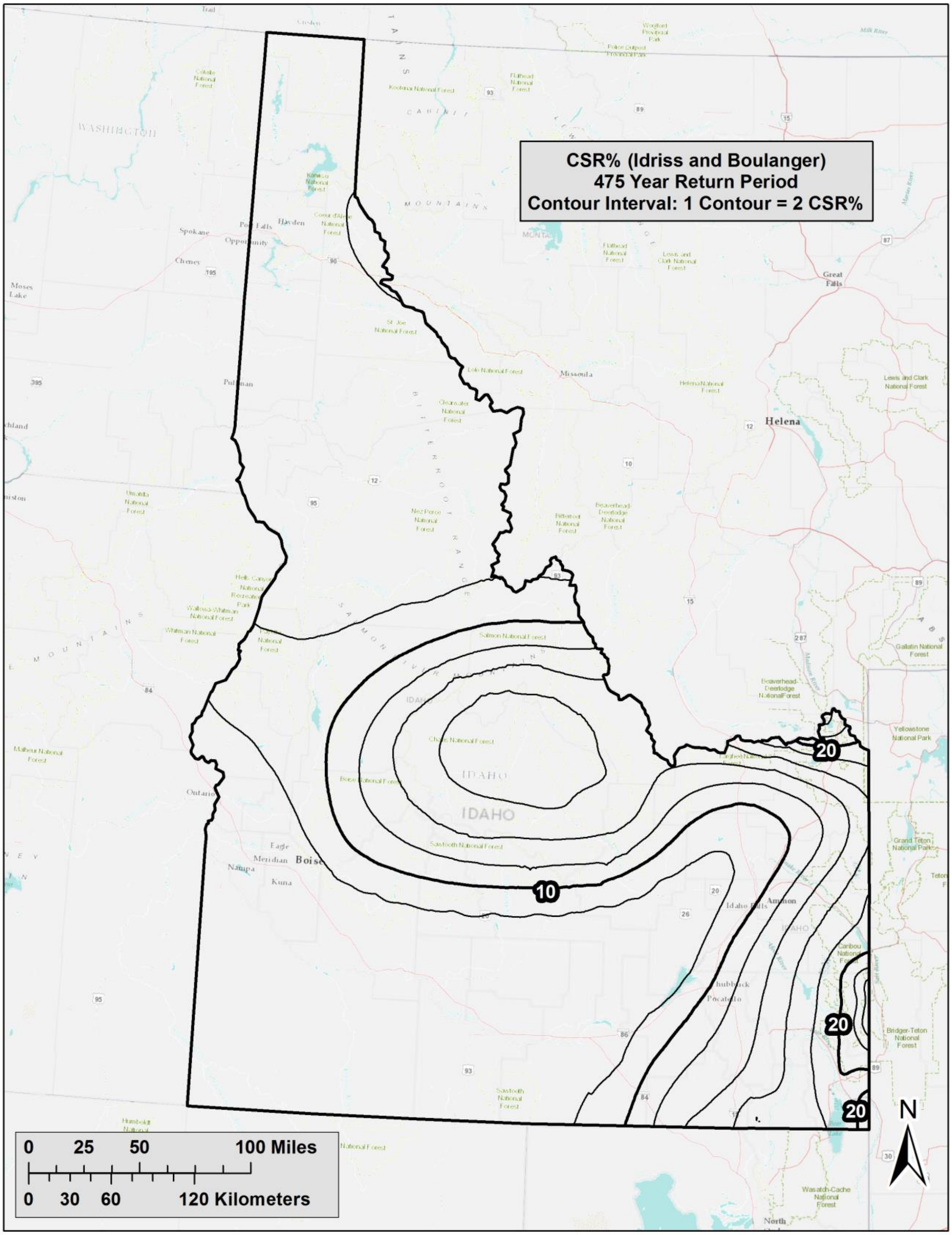


Figure A.4 – CSR% for Idaho (T_R = 475 years)

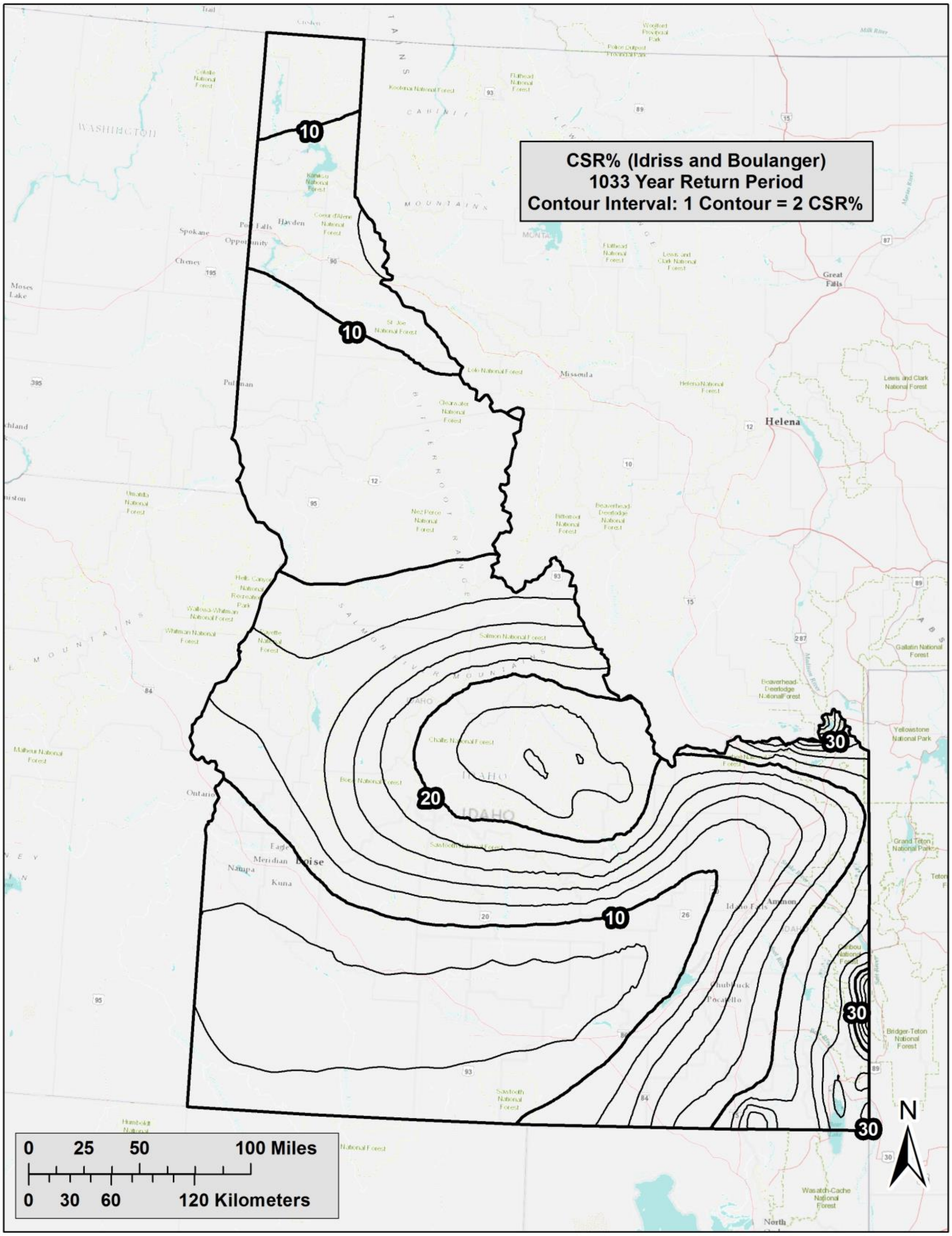


Figure A.5 – CSR% for Idaho (T_R = 1033 years)

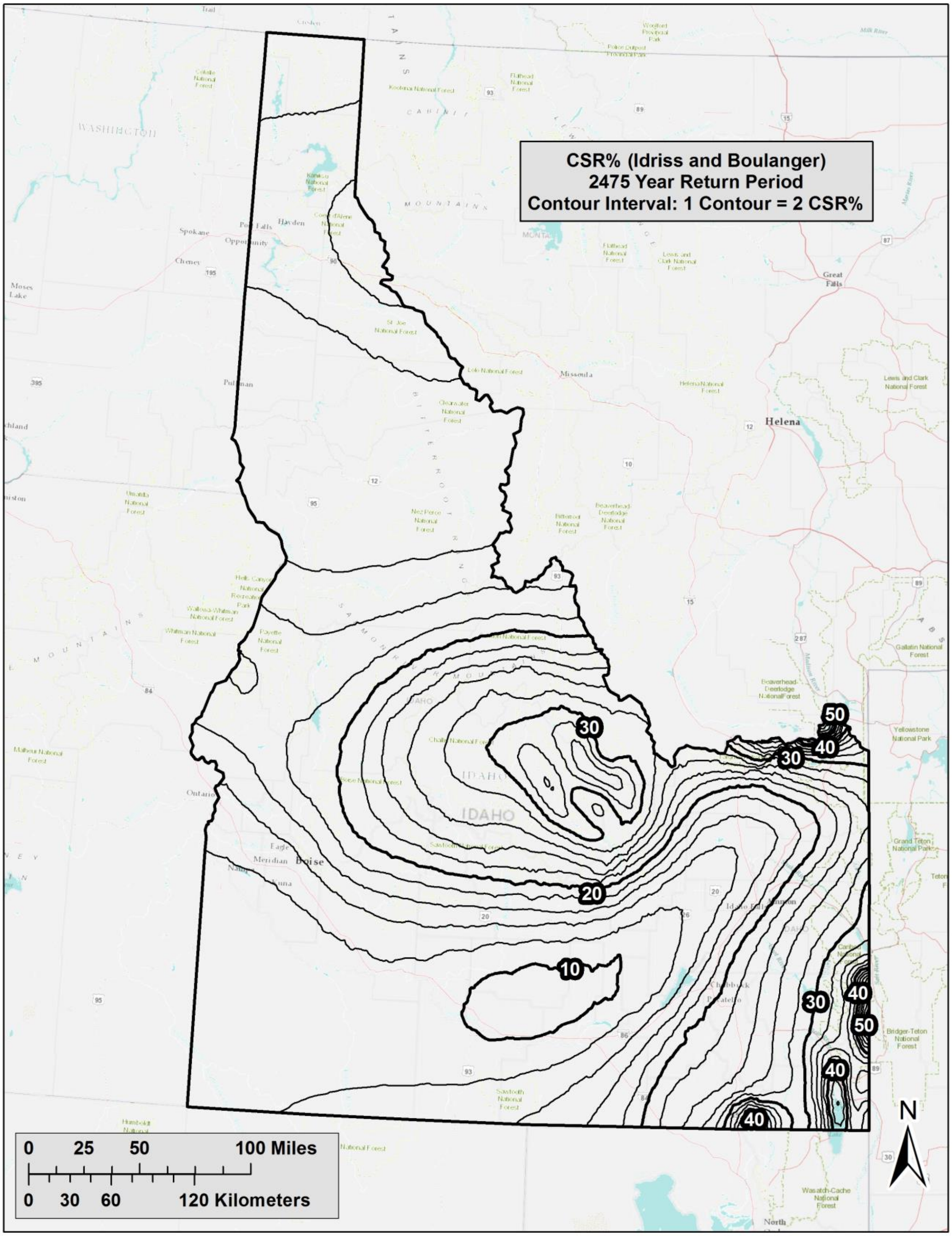


Figure A.6 – CSR% for Idaho (T_R = 2475 years)

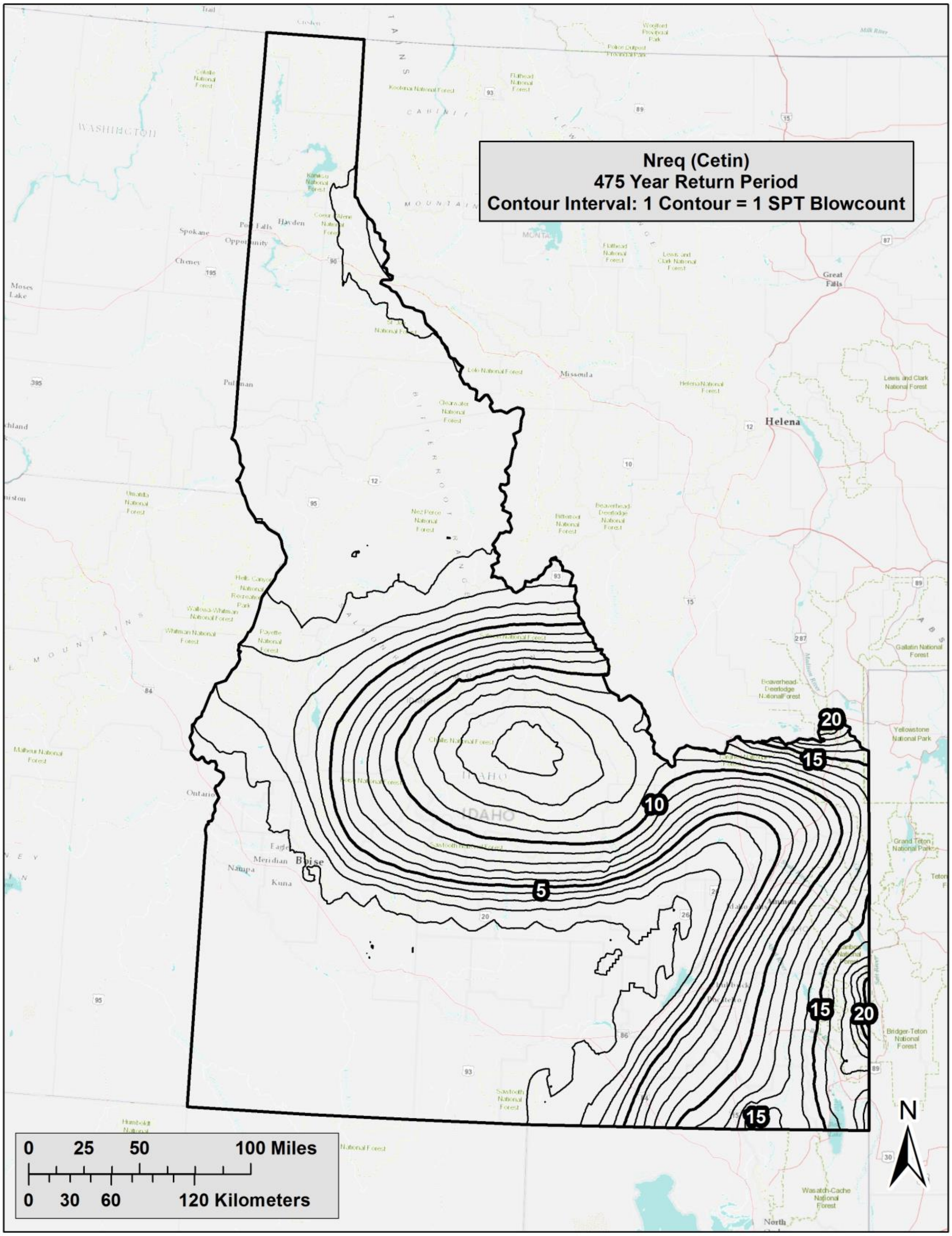


Figure A.7 – N_{req} for Idaho (T_R = 475 years)

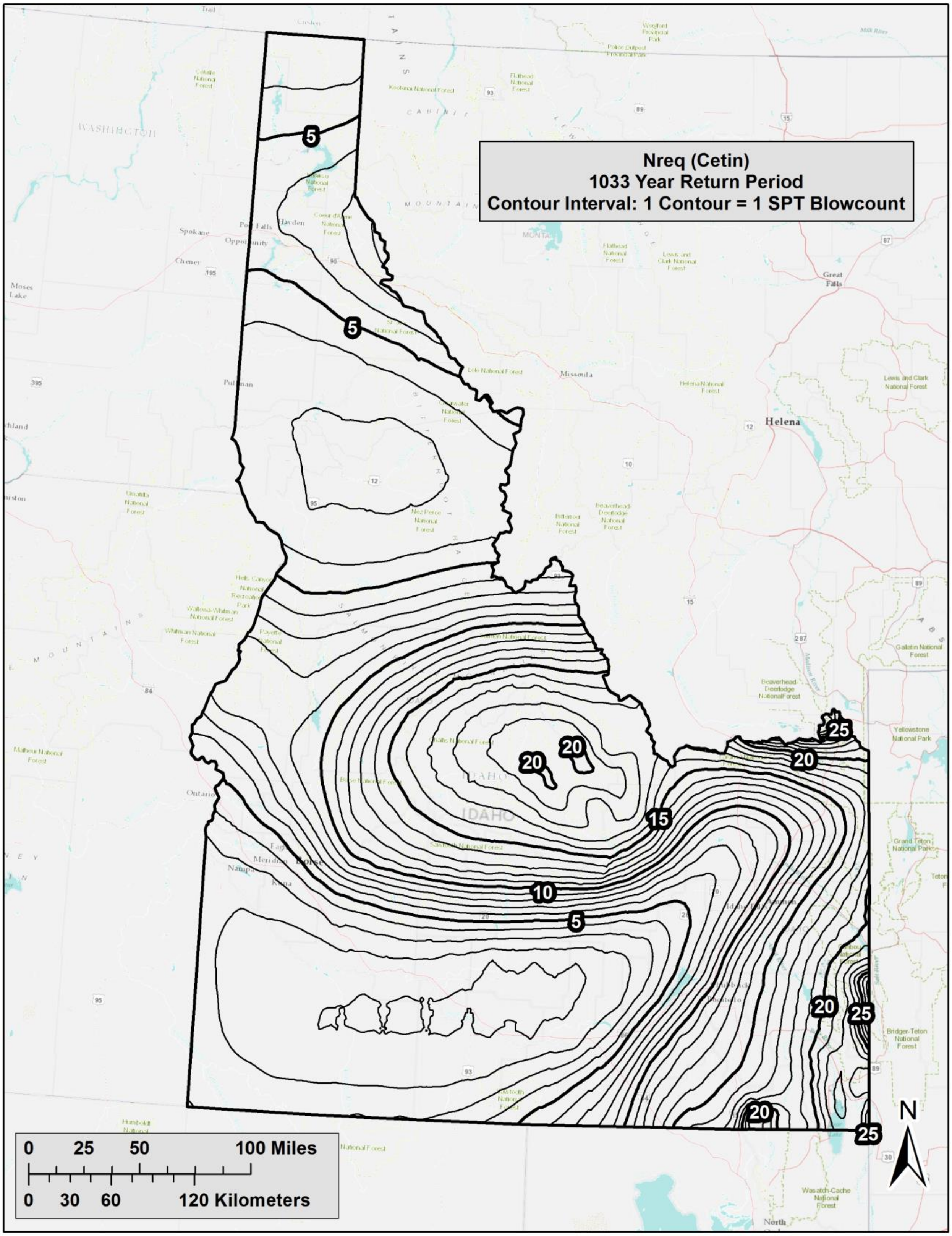


Figure A.8 – N_{req} for Idaho (T_R = 1033 years)

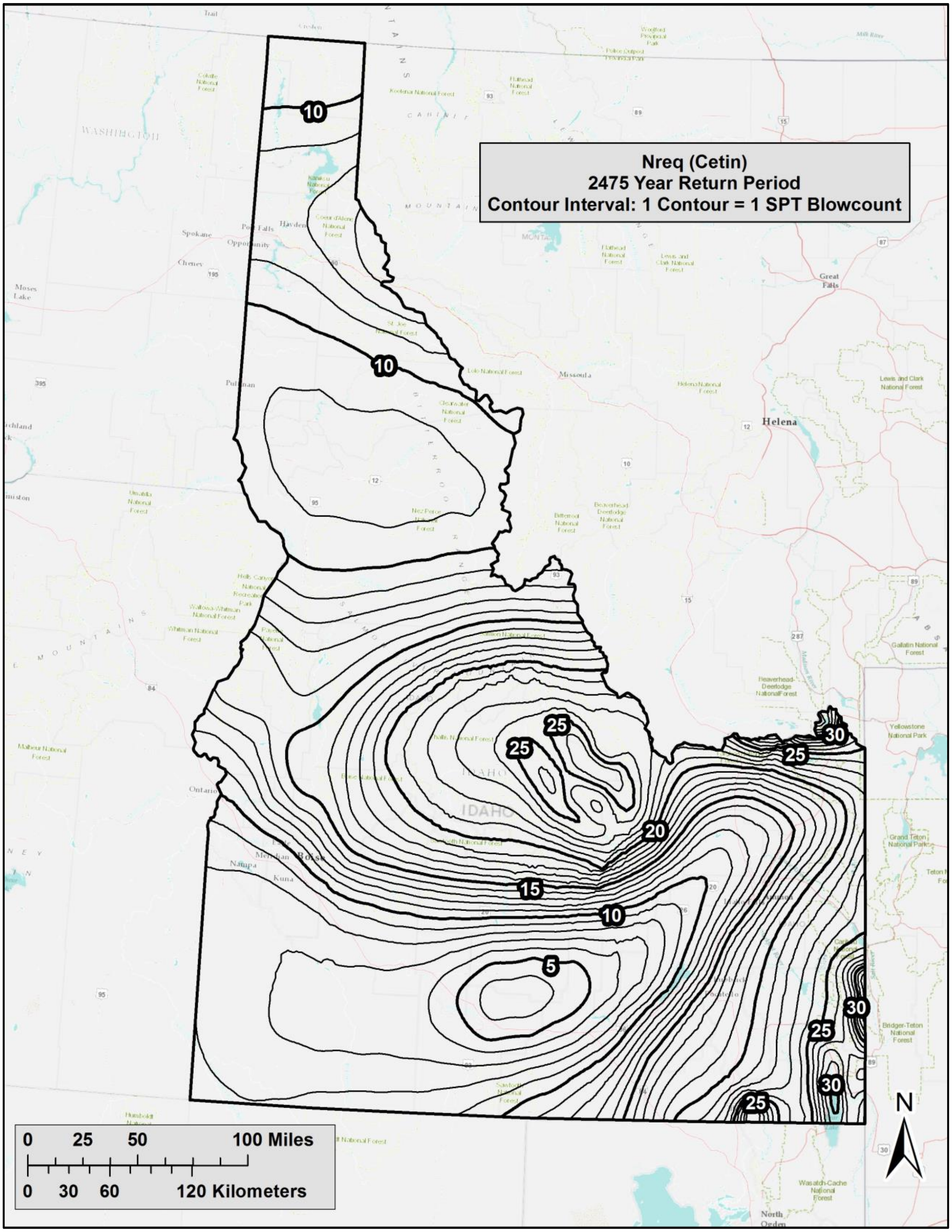


Figure A.9 – N_{req} for Idaho (T_R = 2475 years)

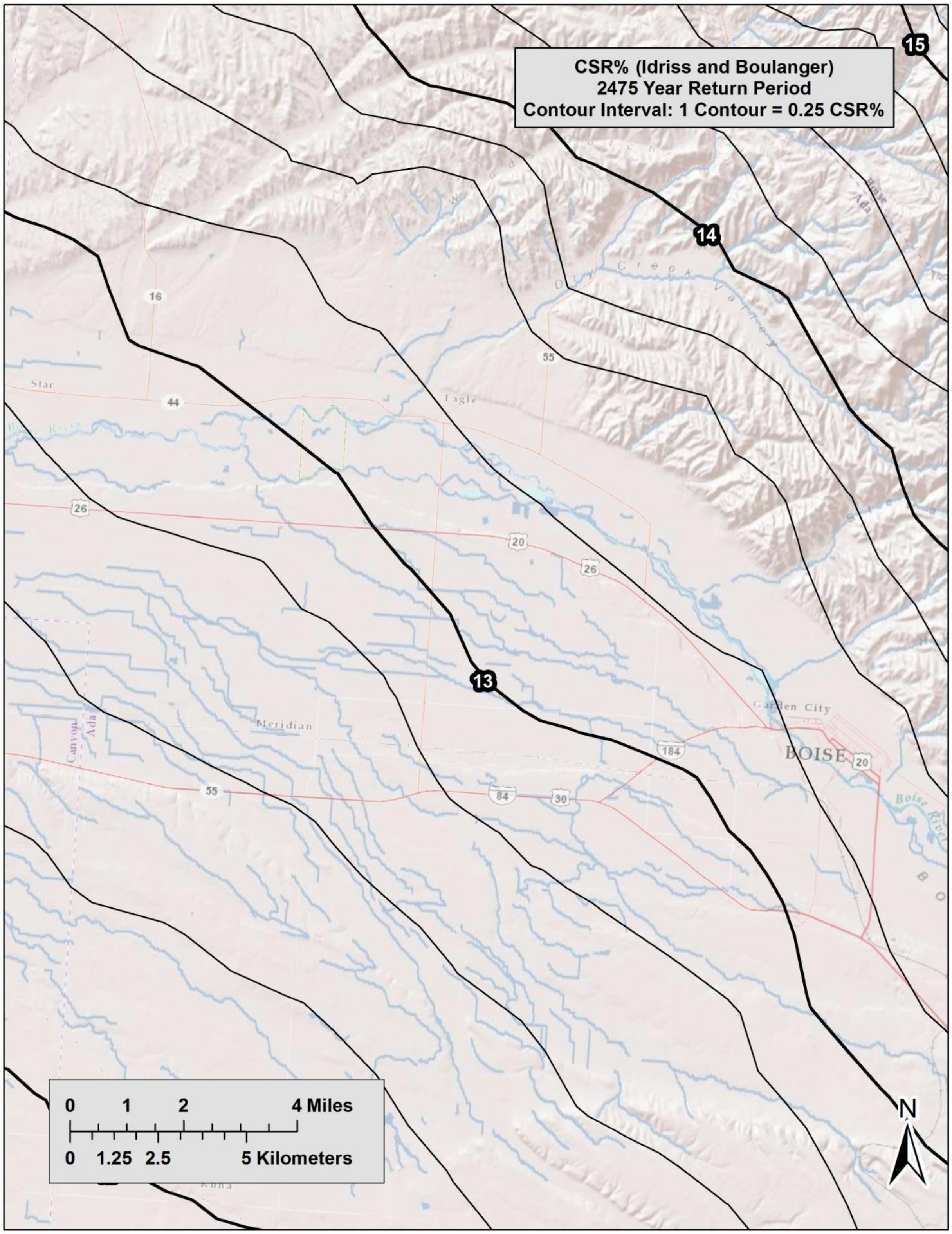


Figure A.10 – CSR% for Boise, ID (T_R = 2475 years)

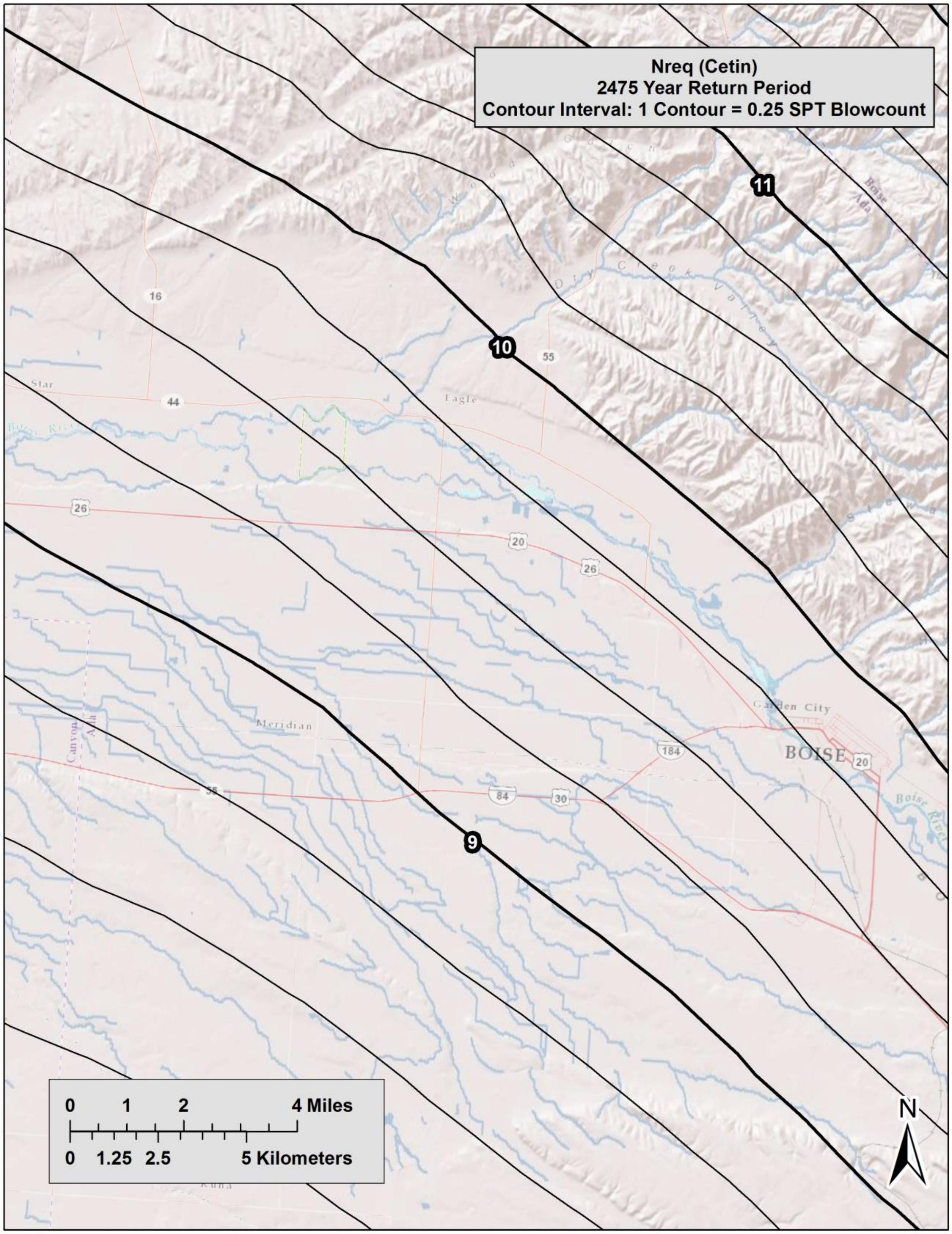


Figure A.11 – N_{req} for Boise, ID (T_R = 2475 years)

d) Montana

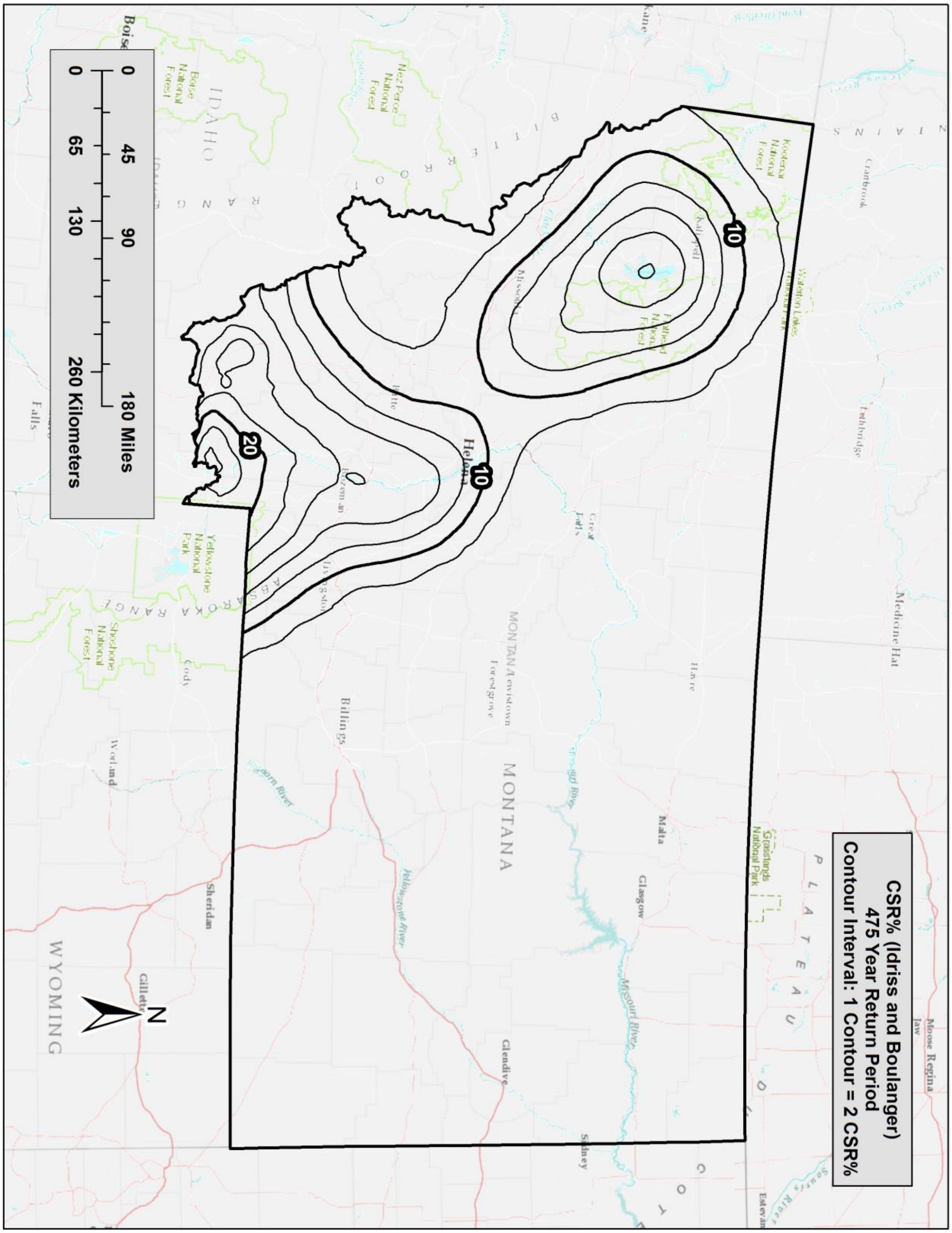


Figure A.12 – CSR% for Montana (T_R = 475 years)

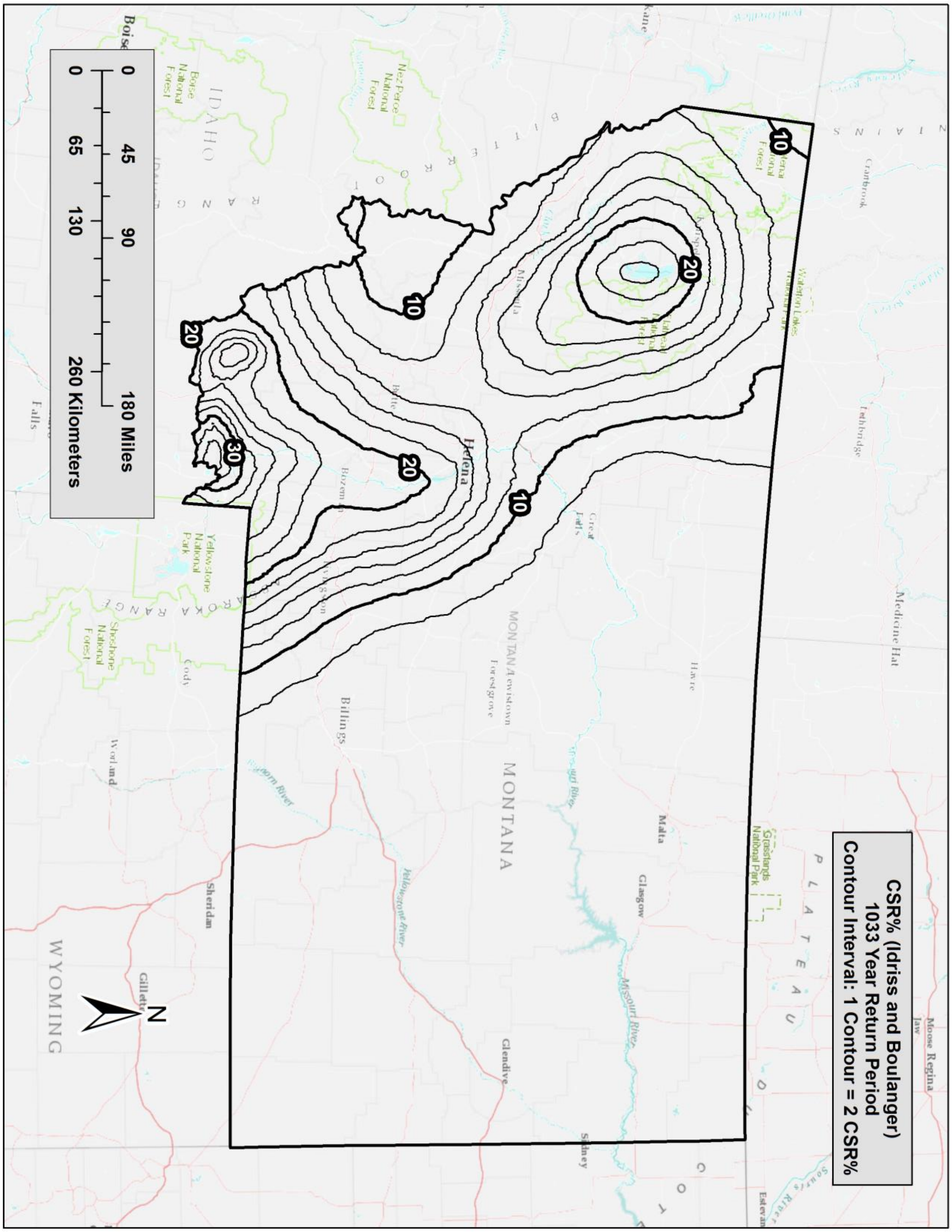


Figure A.13 – CSR% for Montana (T_R = 1033 years)

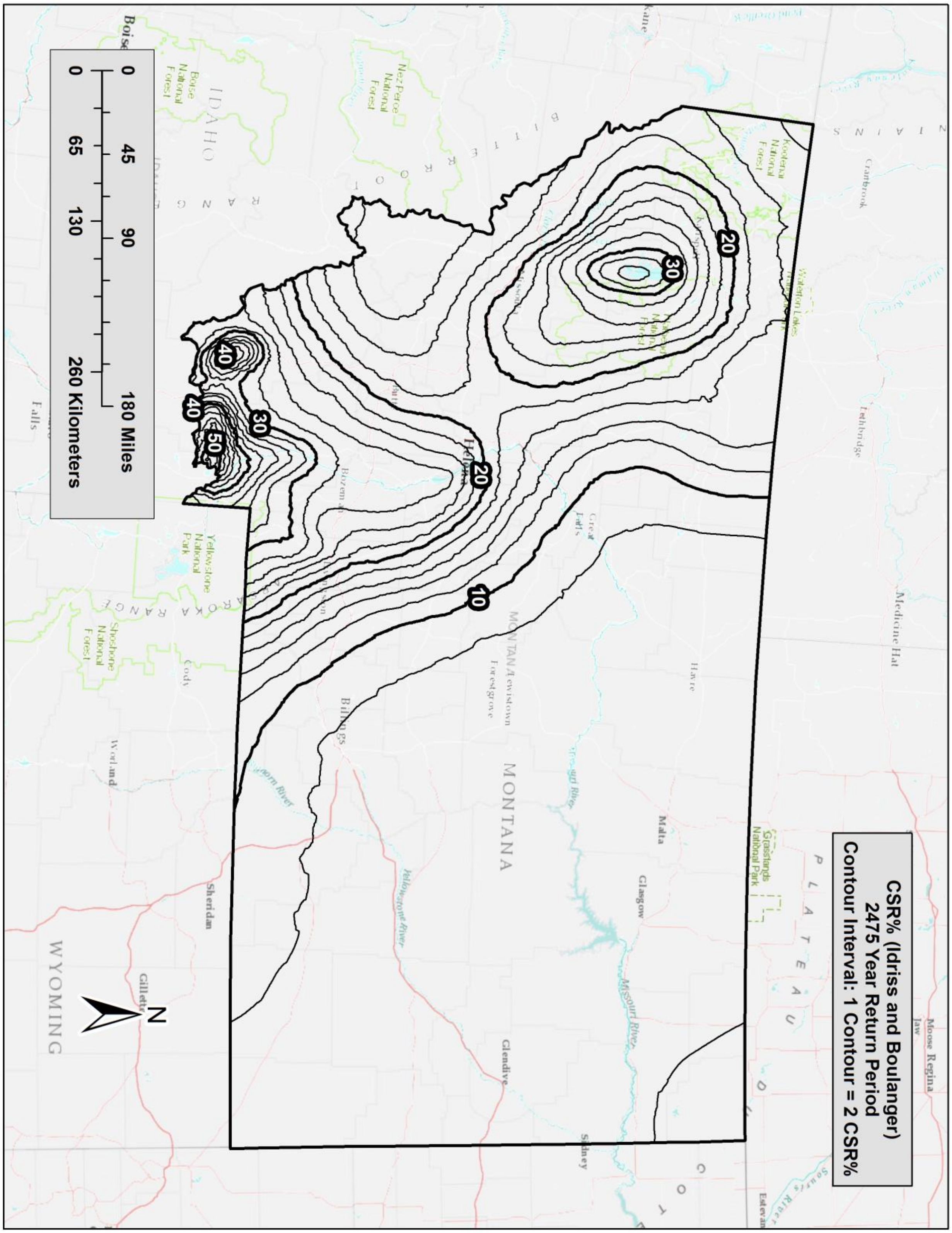


Figure A.14 – CSR% for Montana (T_R = 2475 years)

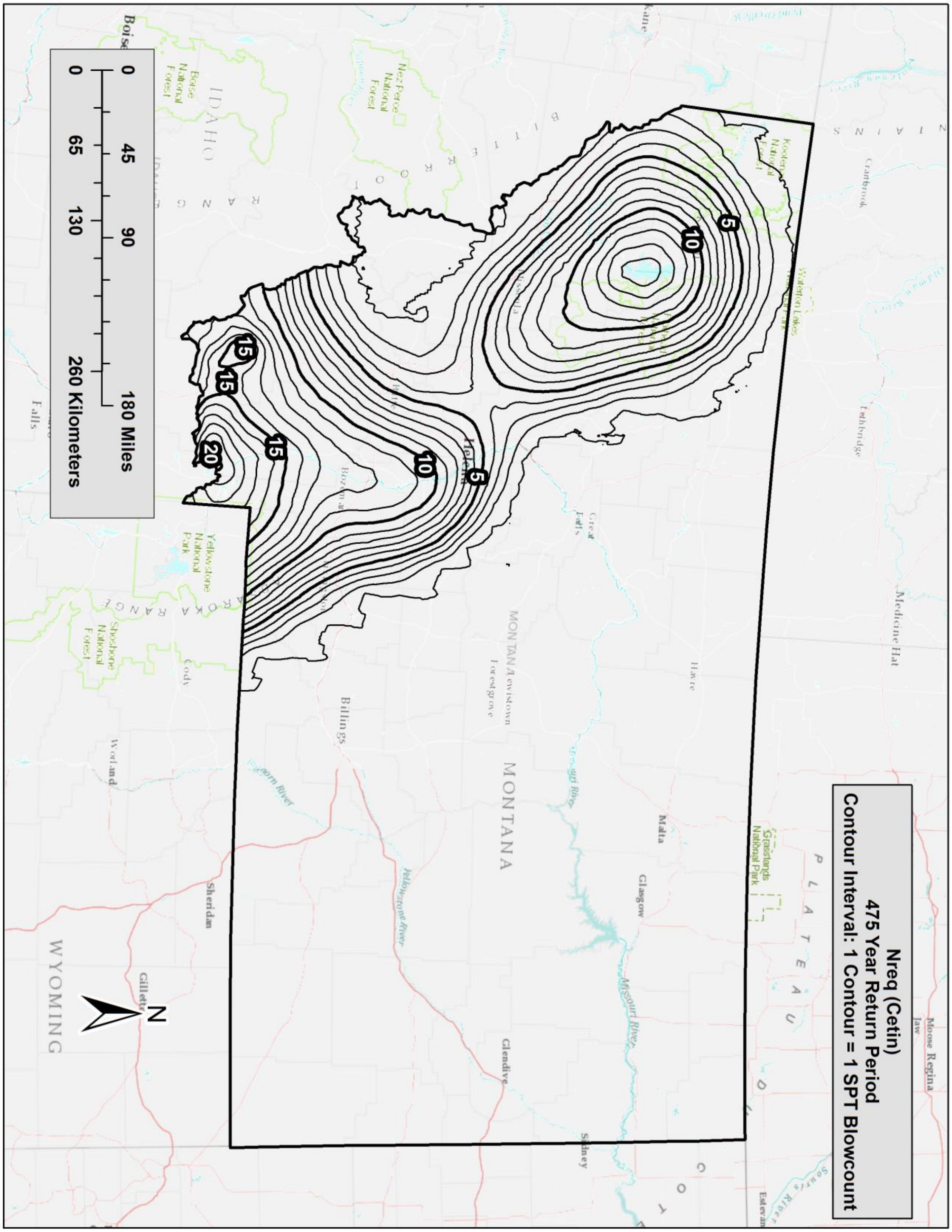


Figure A.15 – N_{req} for Montana (T_R = 475 years)

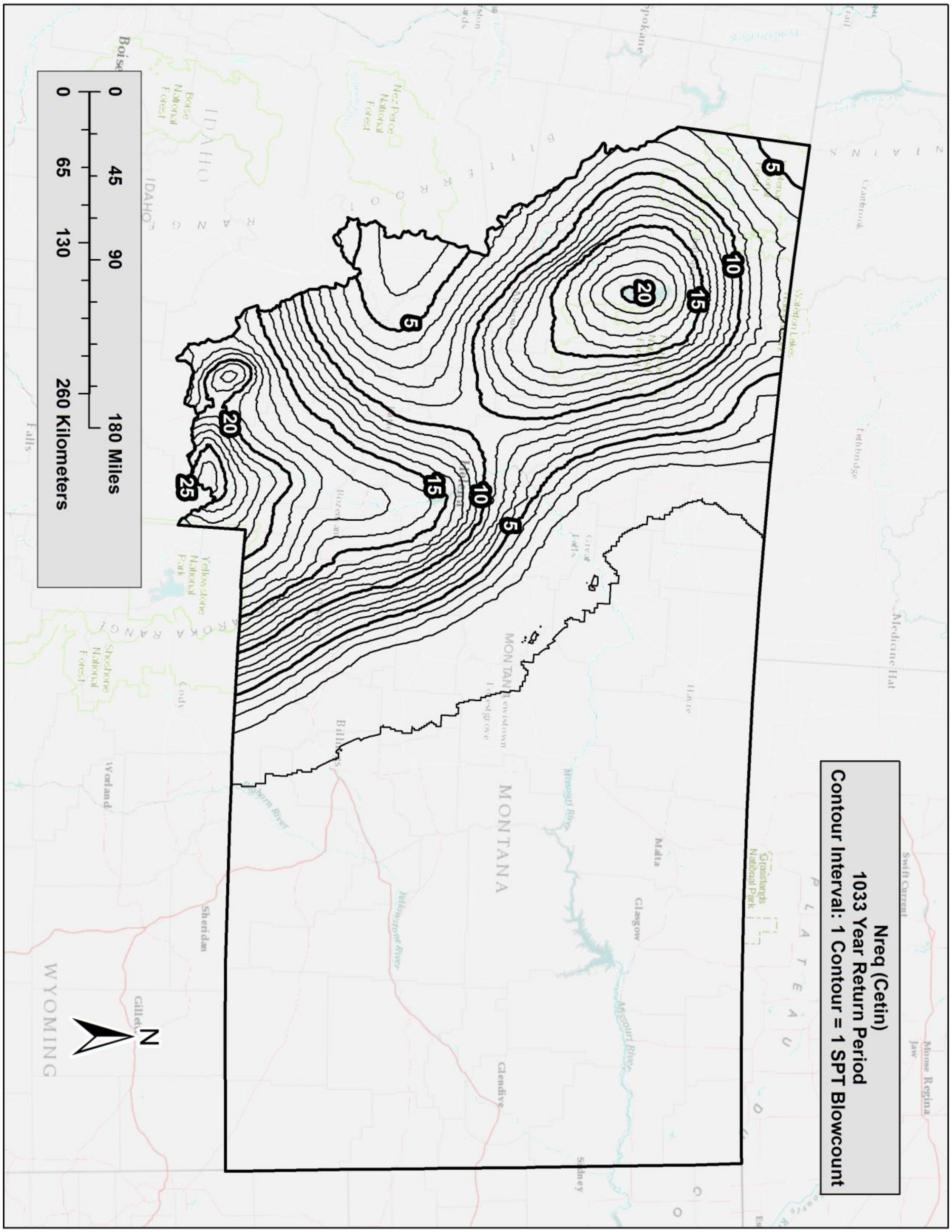


Figure A.16 – N_{req} for Montana (T_R = 1033 years)

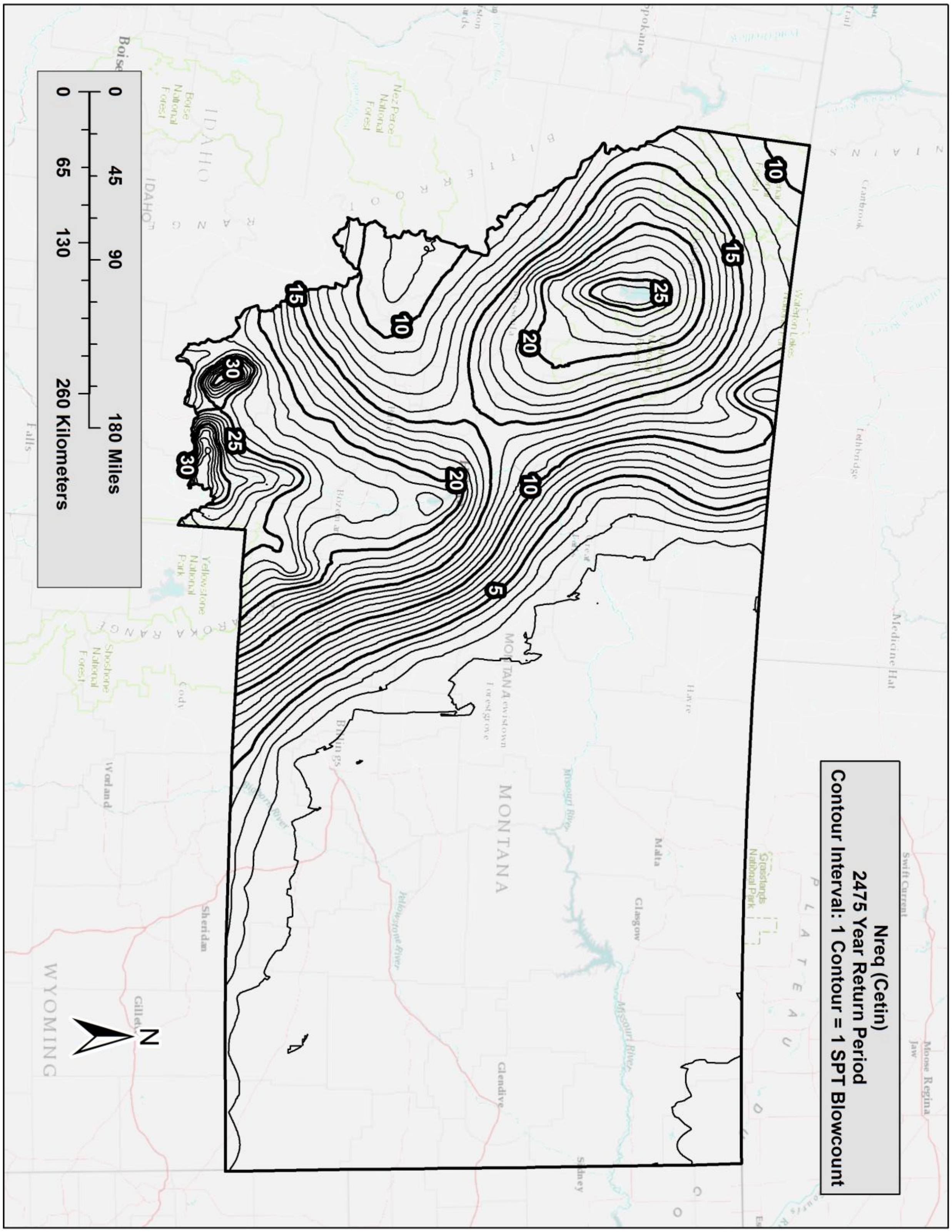


Figure A.17 – N_{req} for Montana (T_R = 2475 years)

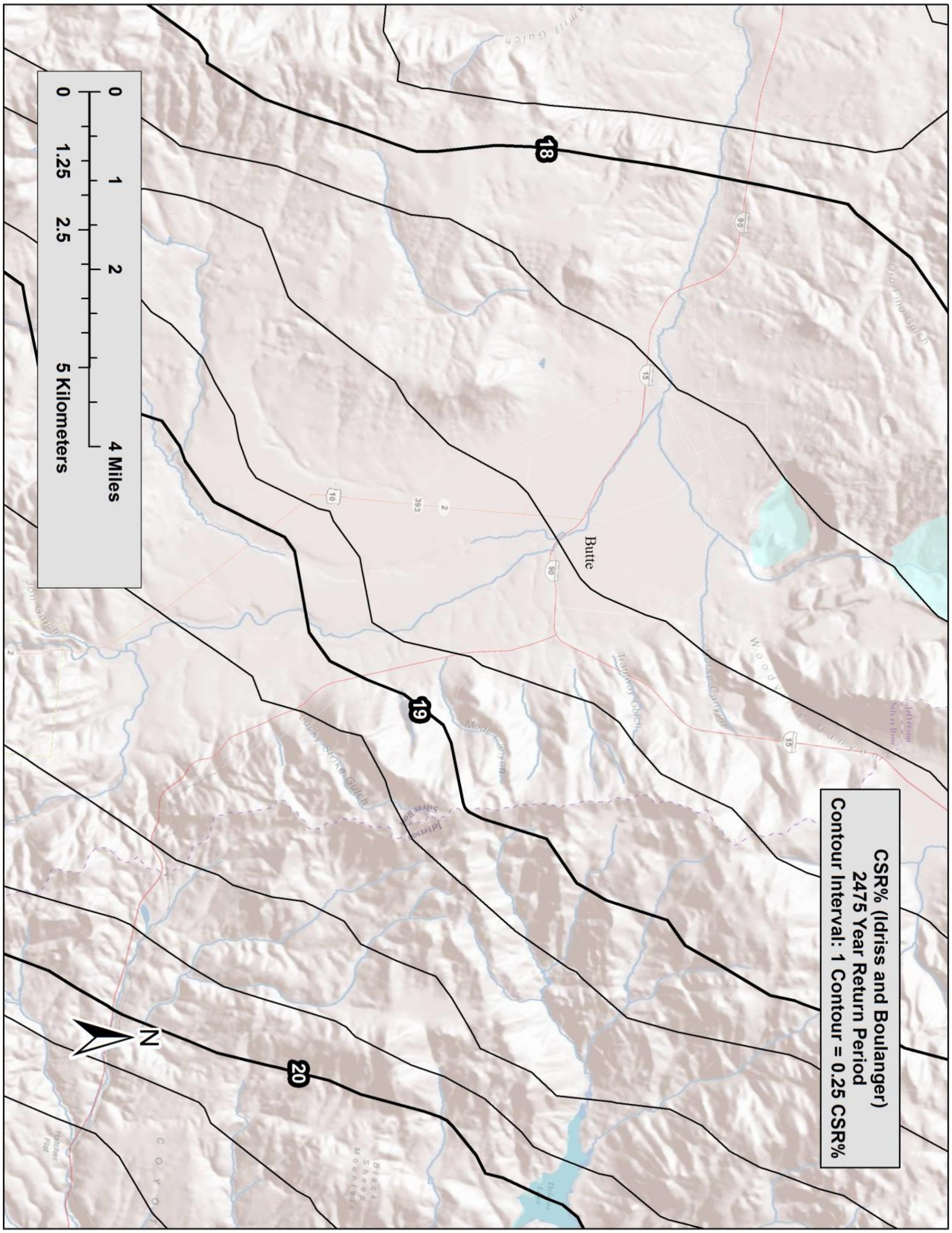


Figure A.18 – CSR% for Butte, MT (T_R = 2475 years)

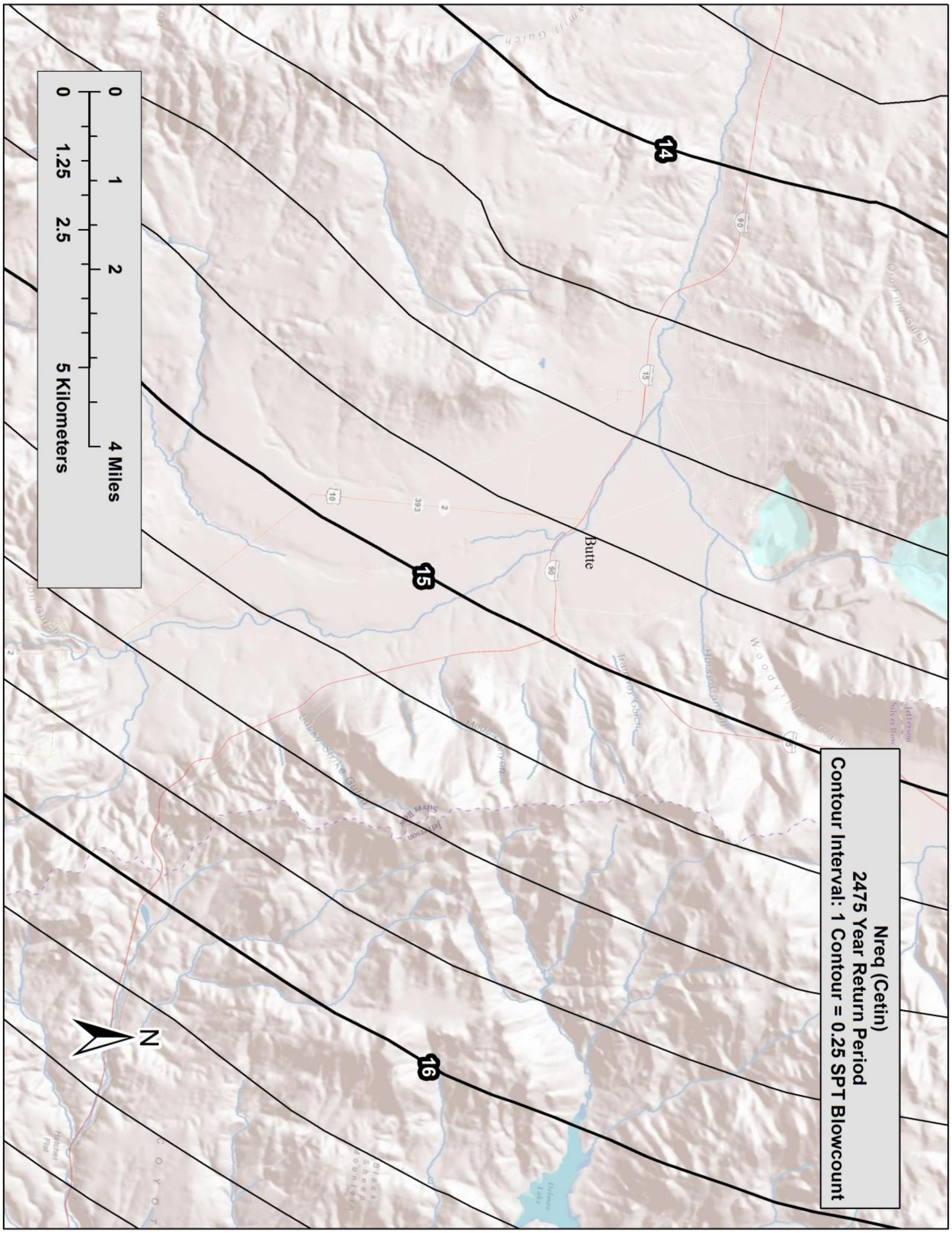


Figure A.19 – N_{req} for Butte, MT (T_R = 2475 years)

f) South Carolina

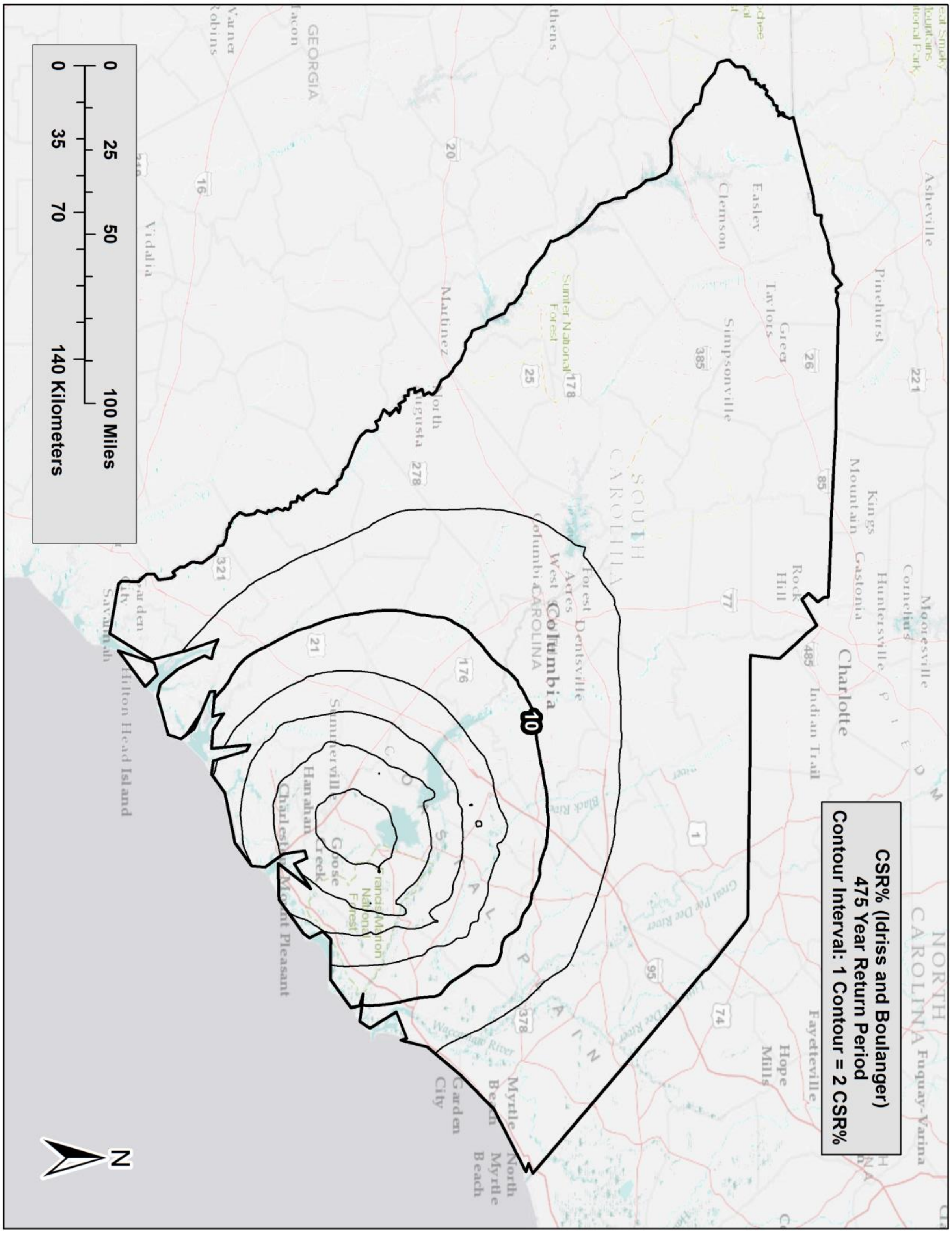


Figure A.20 – CSR% for South Carolina (T_R = 475 years)

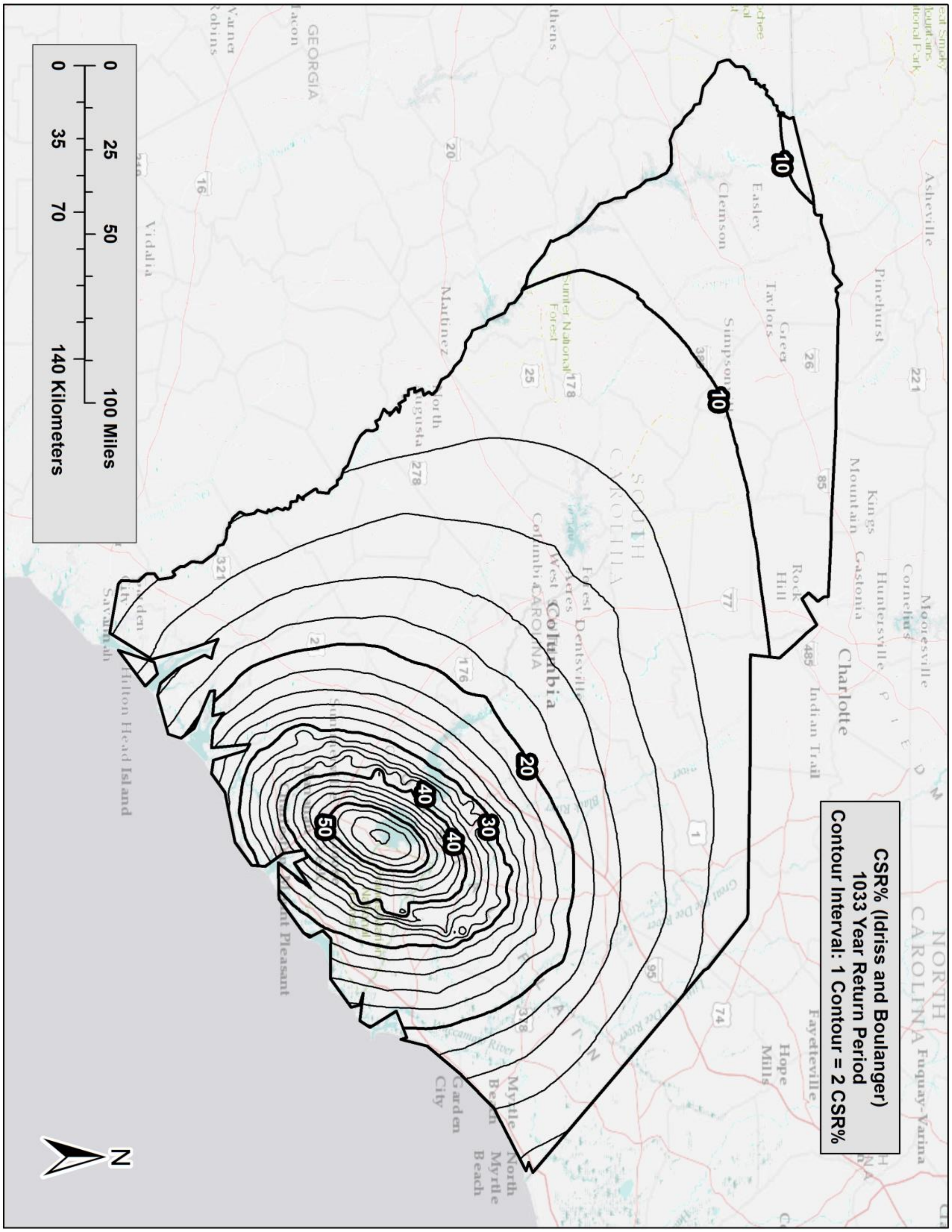


Figure A.21 – CSR% for South Carolina (T_R = 1033 years)

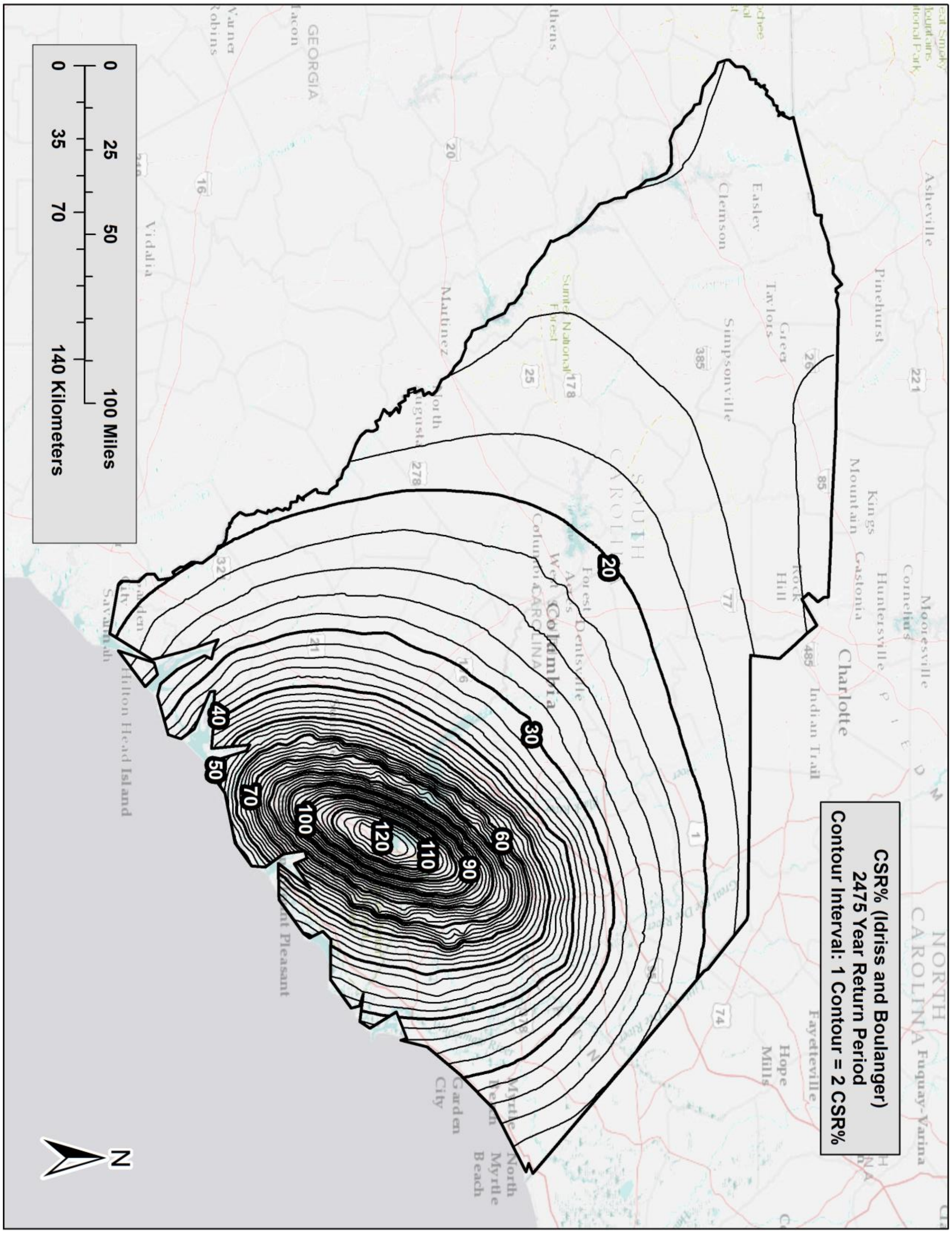


Figure A.22 – CSR% for South Carolina (T_R = 2475 years)

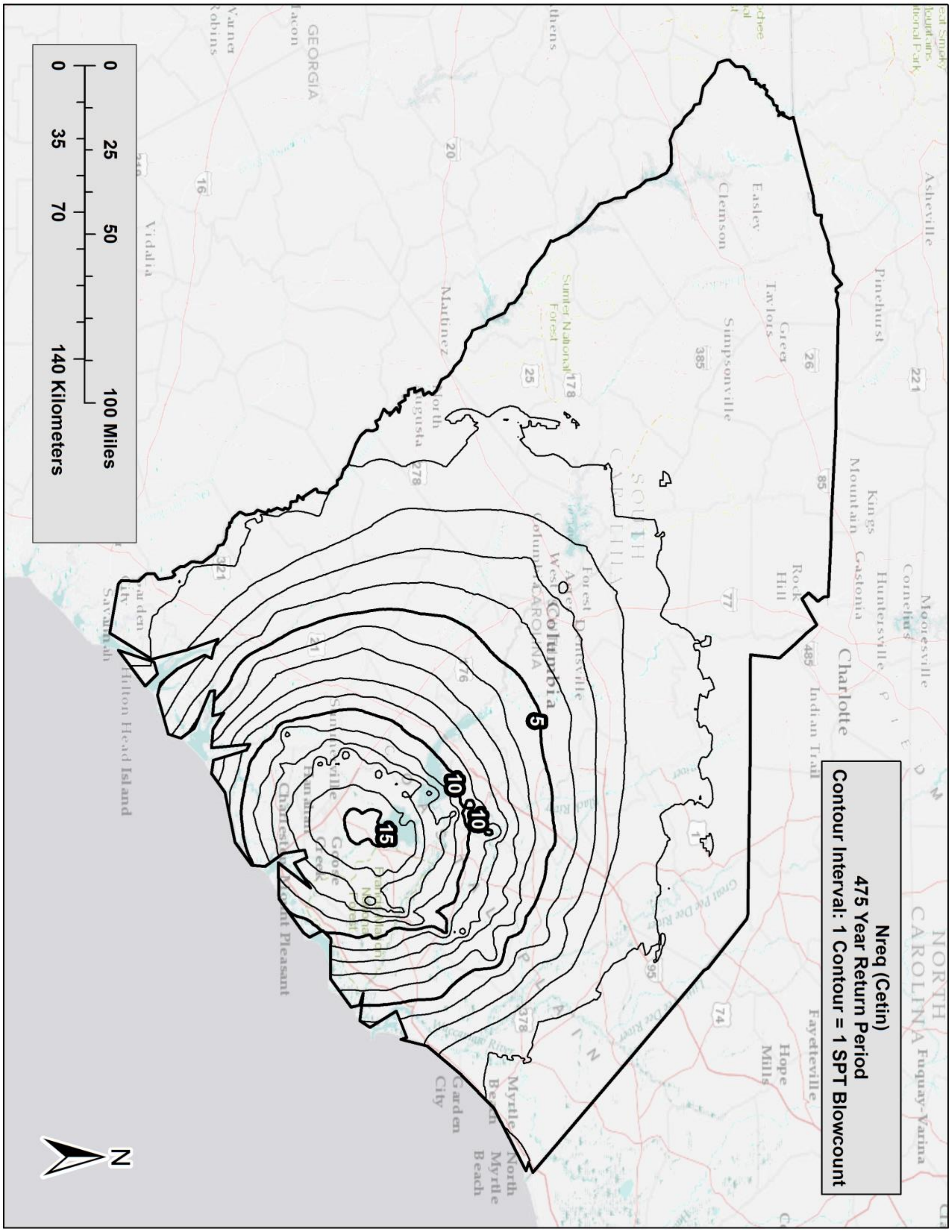


Figure A.23 – N_{req} for South Carolina (T_R = 475 years)

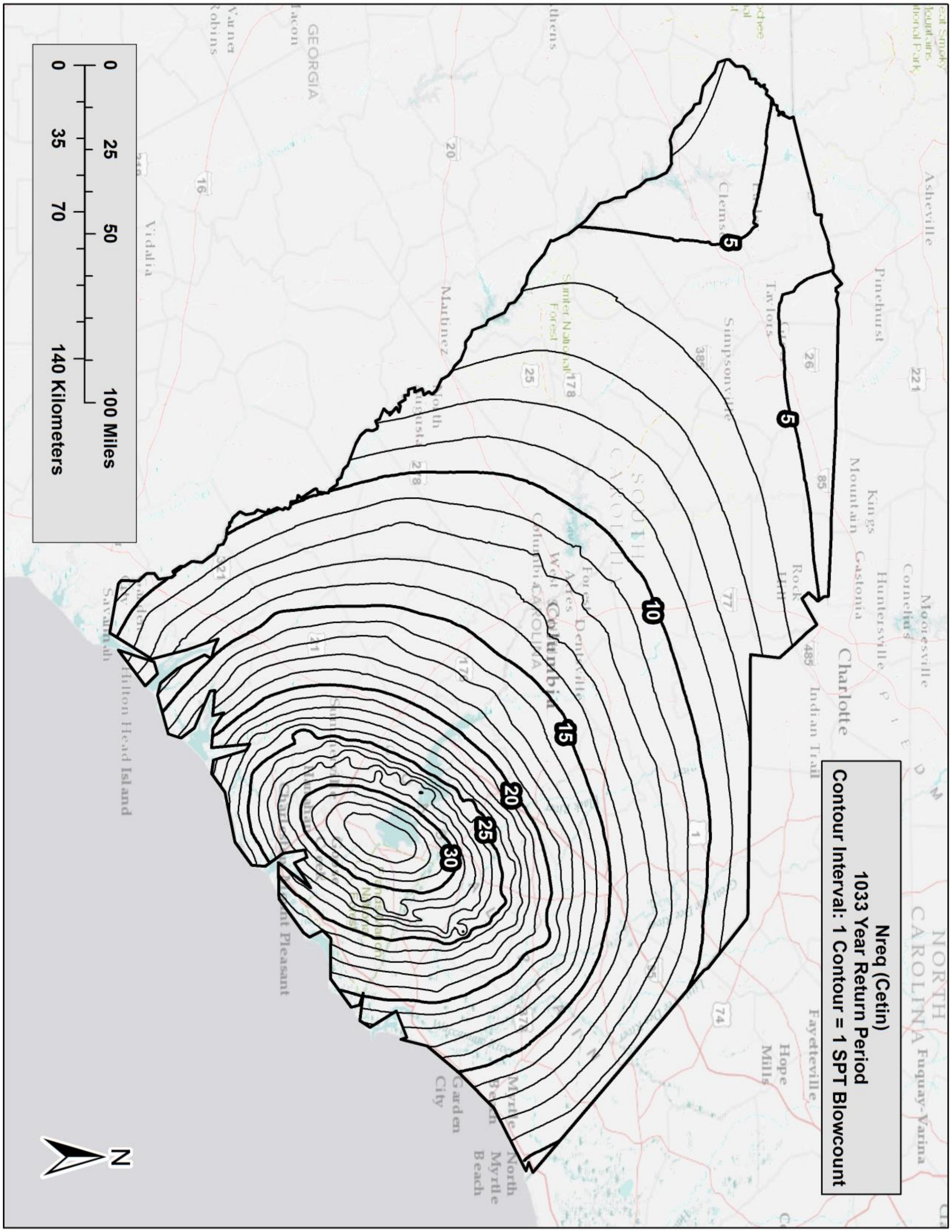


Figure A.24 – N_{req} for South Carolina (T_R = 1033 years)

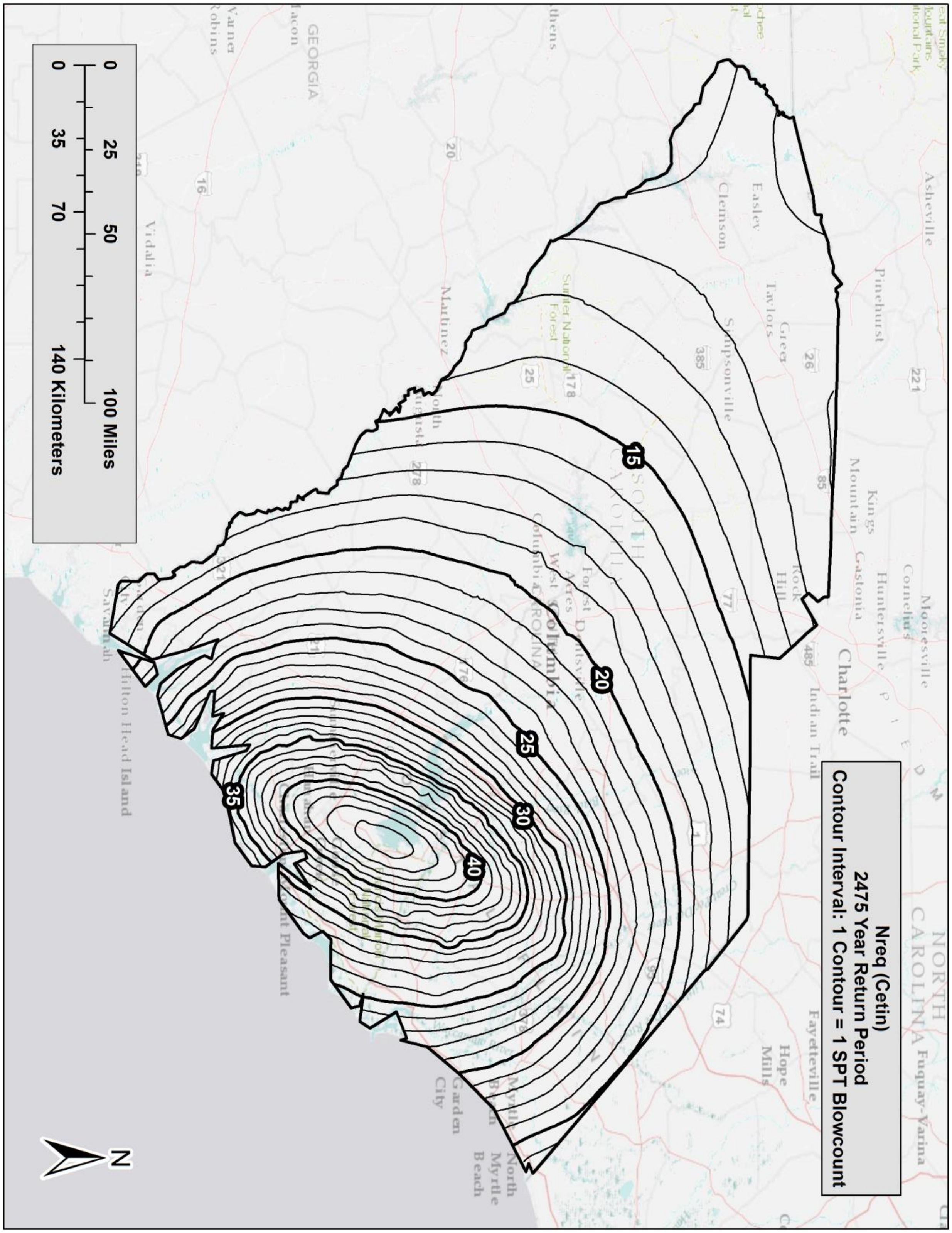


Figure A.25 – N_{req} for South Carolina (T_R = 2475 years)

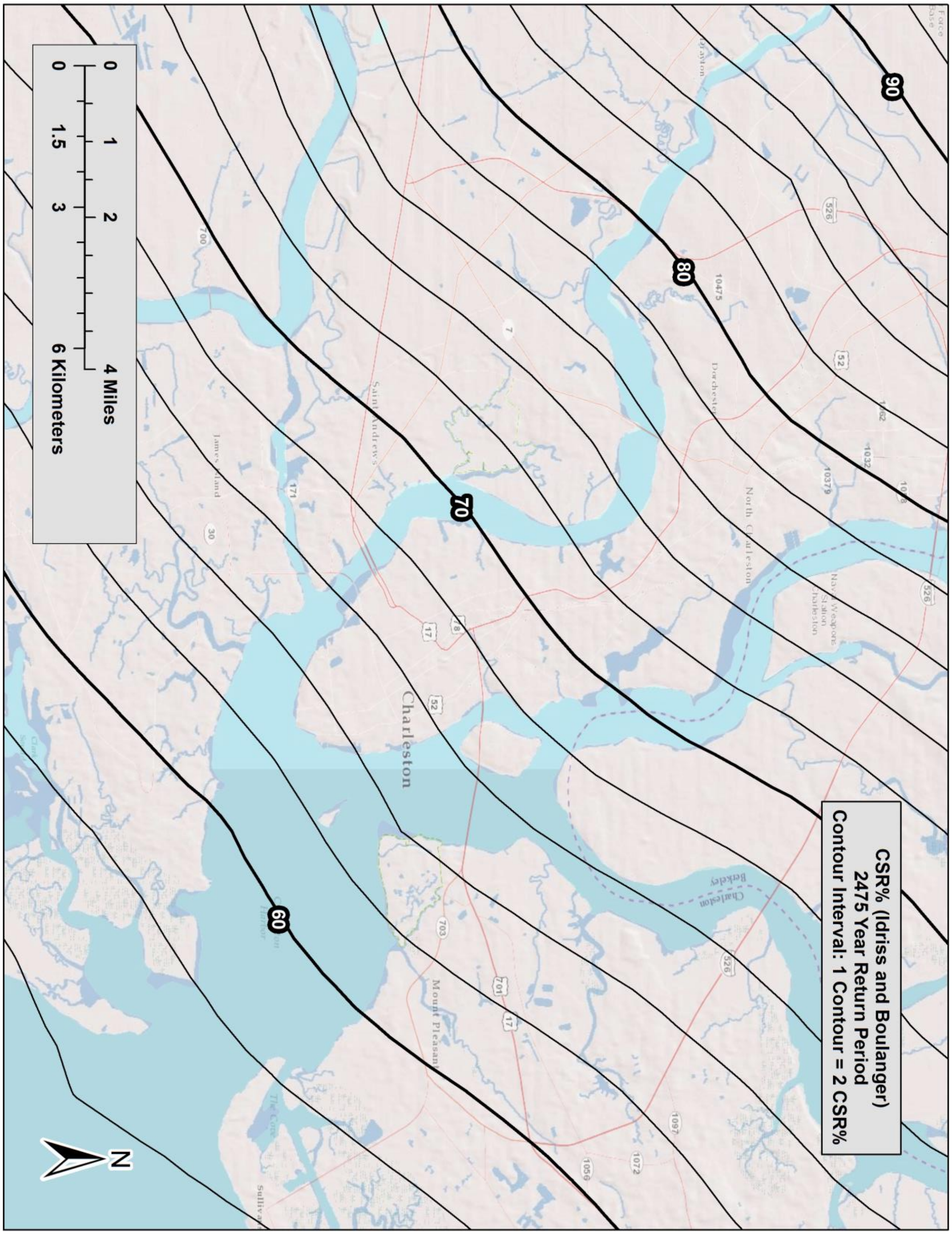


Figure A.26 – CSR% for Charleston, SC (T_R = 2475 years)

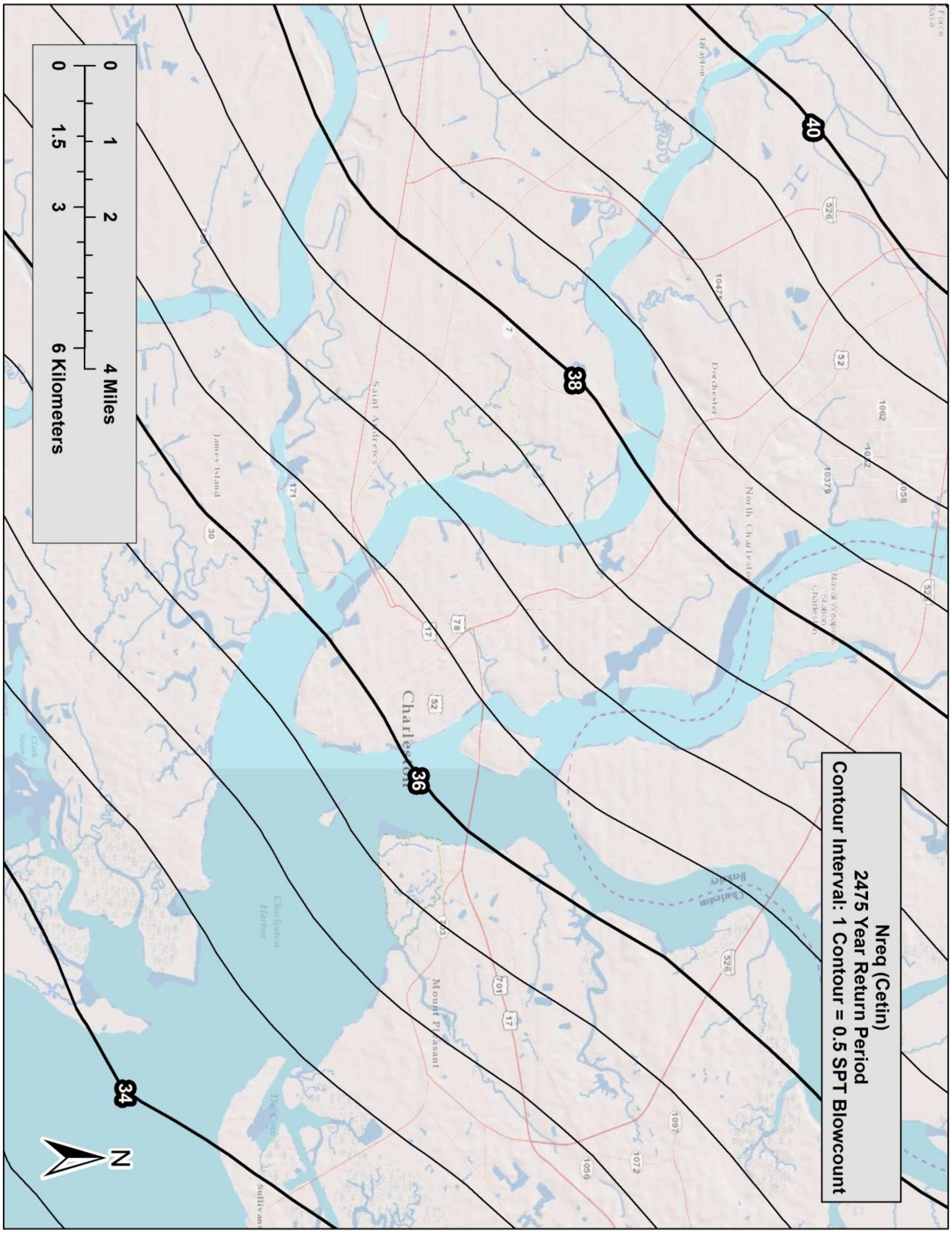


Figure A.27 – N_{req} for Charleston, SC (T_R = 2475 years)

h) Utah

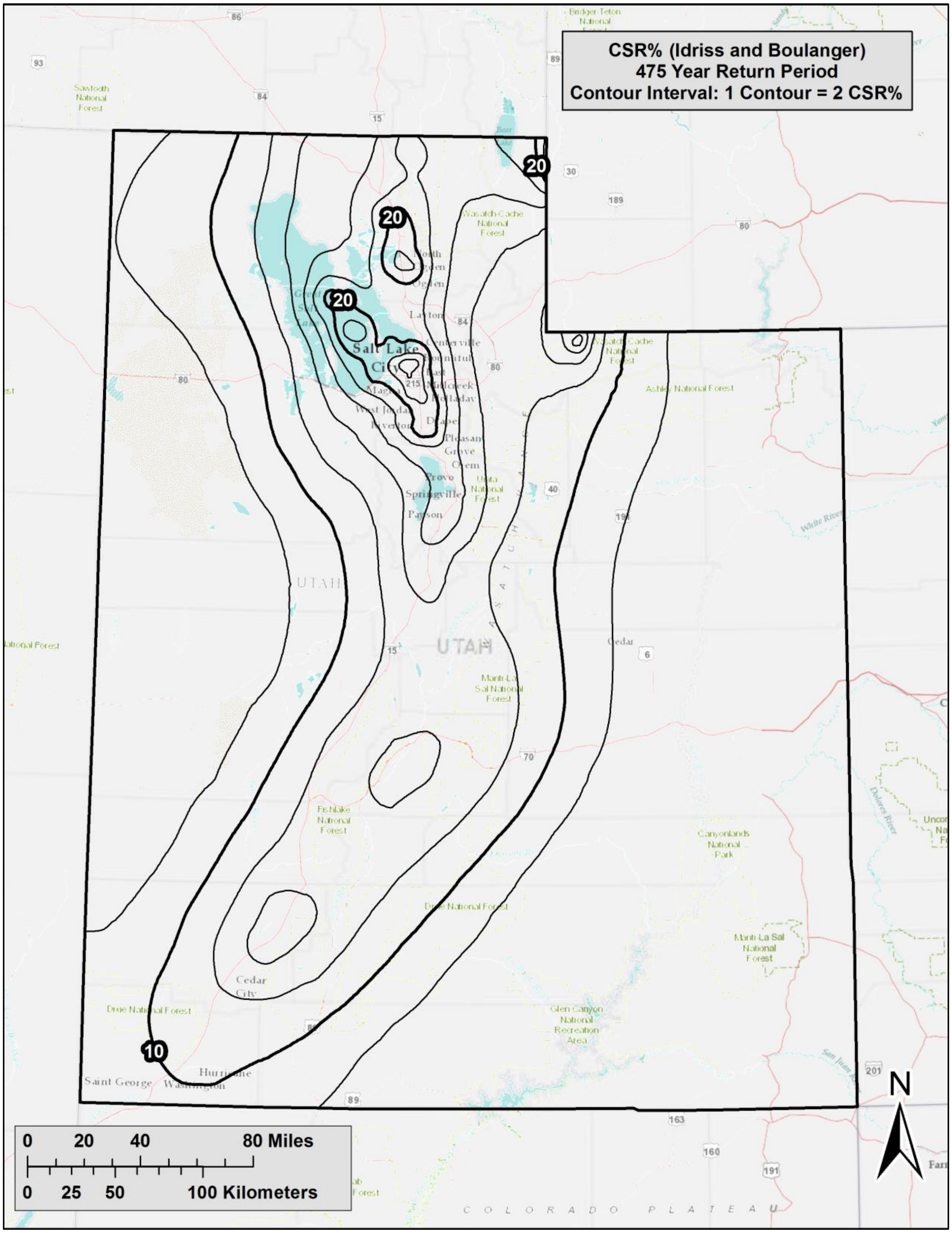


Figure A.28 – CSR% Utah (T_R = 475 years)

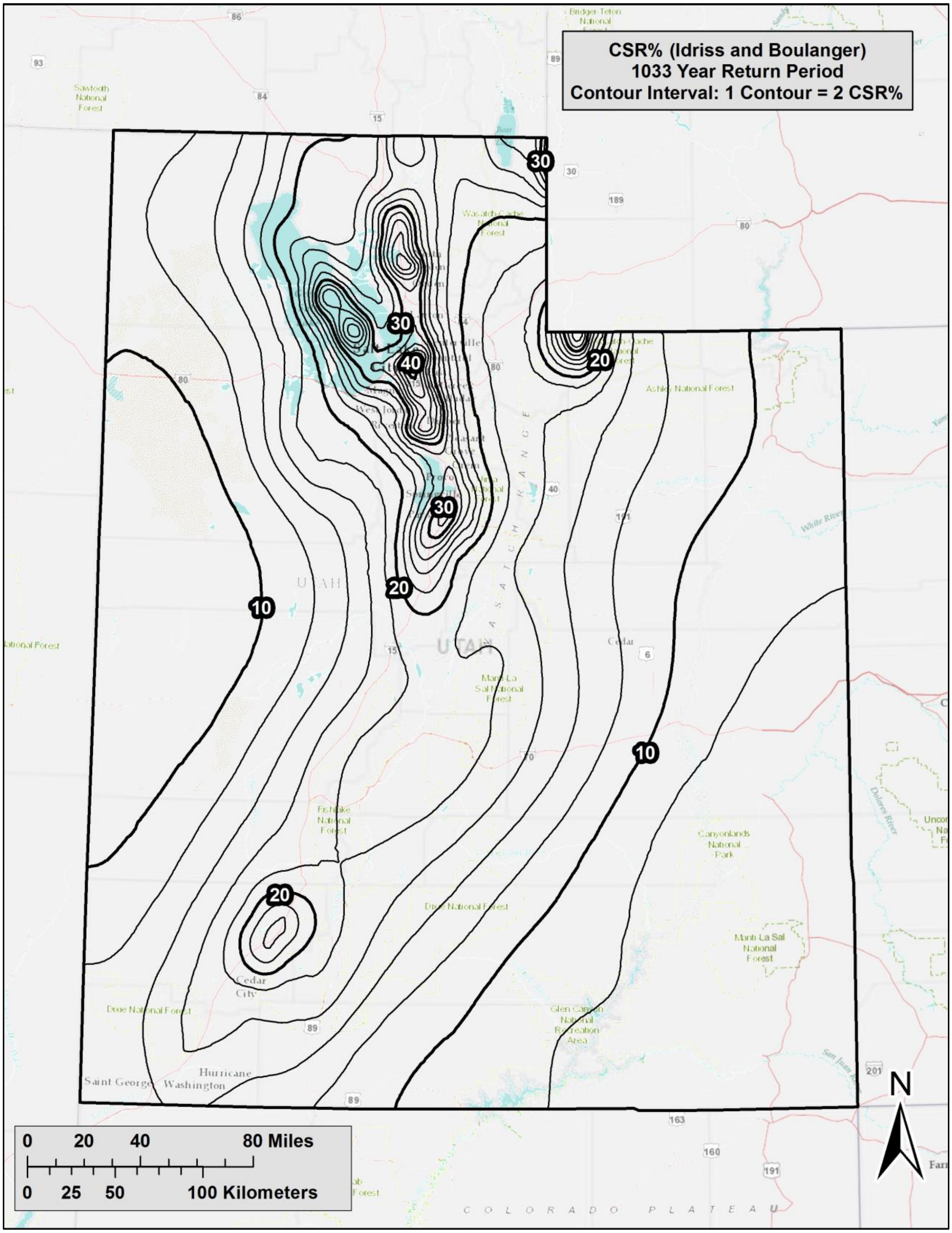


Figure A.29 – CSR% Utah (T_R = 1033 years)

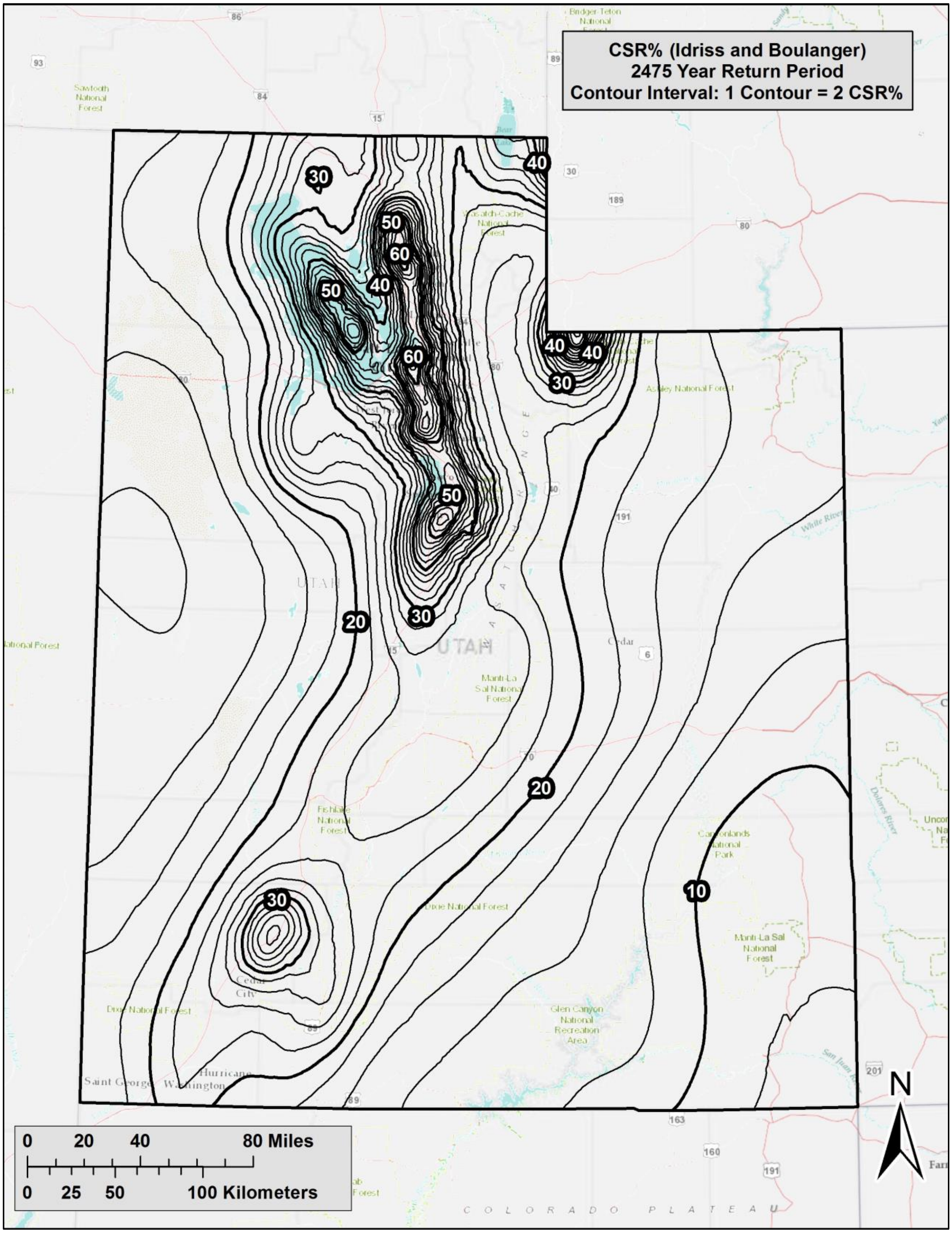


Figure A.30 – CSR% Utah (T_R = 2475 years)

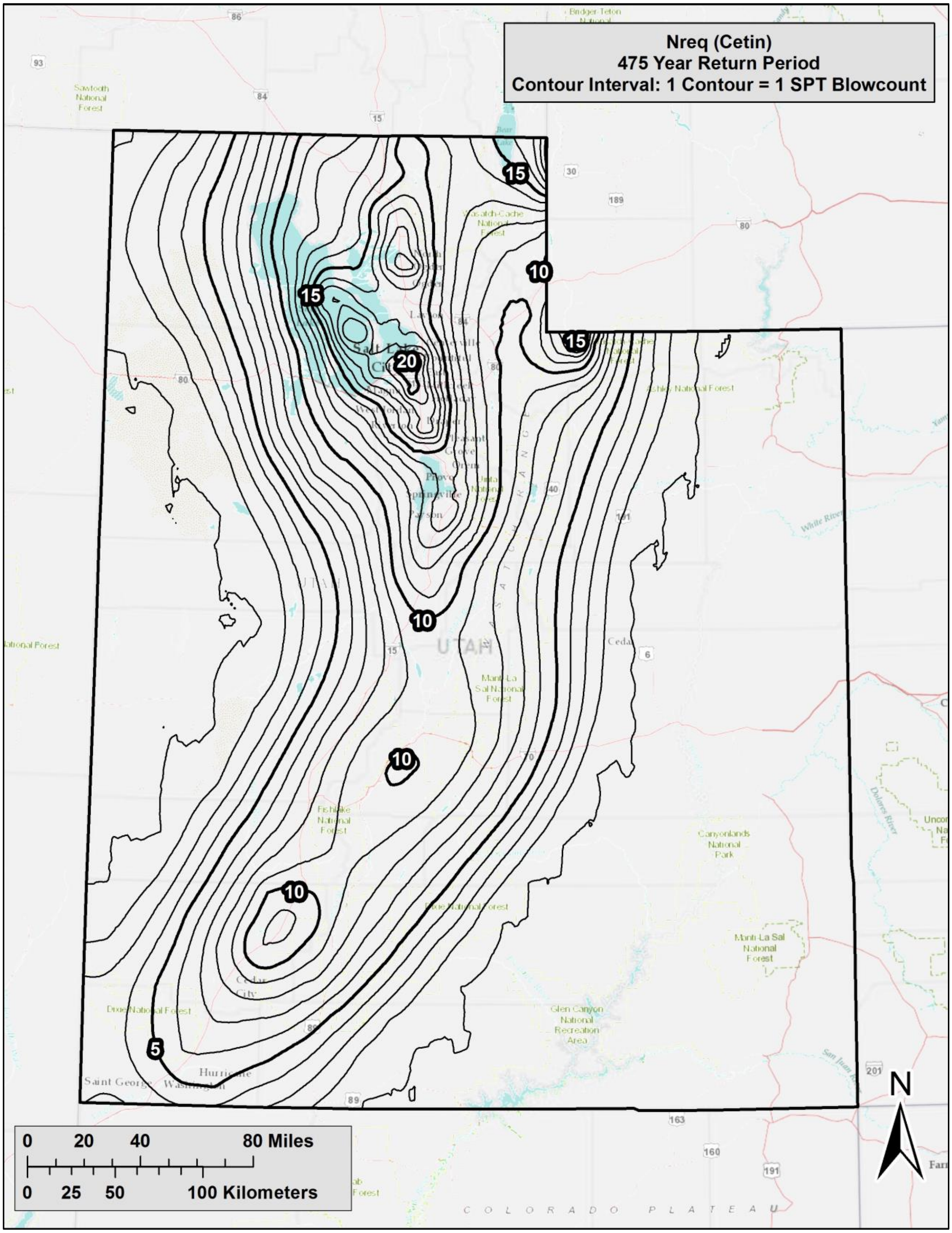


Figure A.31 – N_{req} Utah (T_R = 475 years)

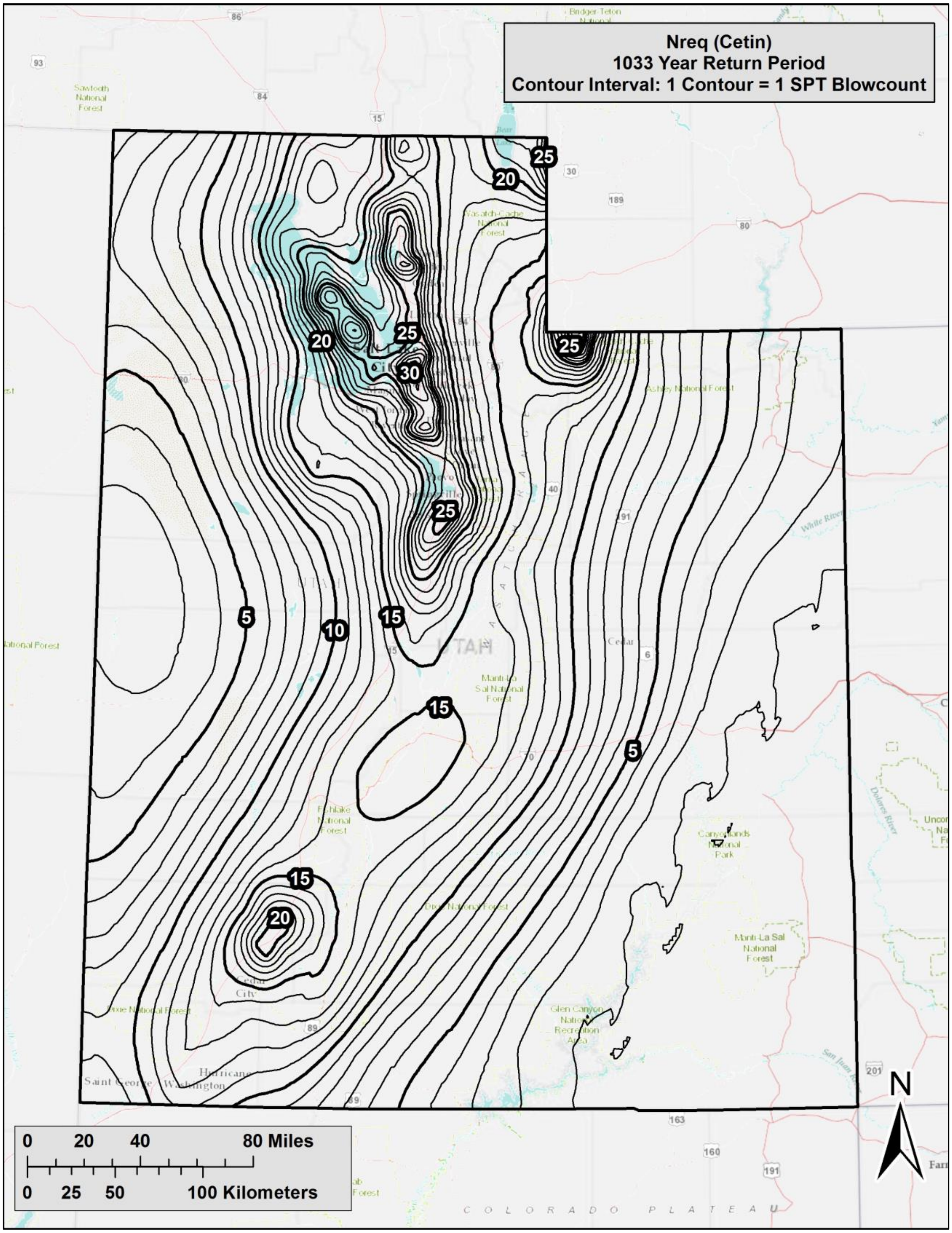


Figure A.32 – N_{req} Utah (T_R = 1033 years)

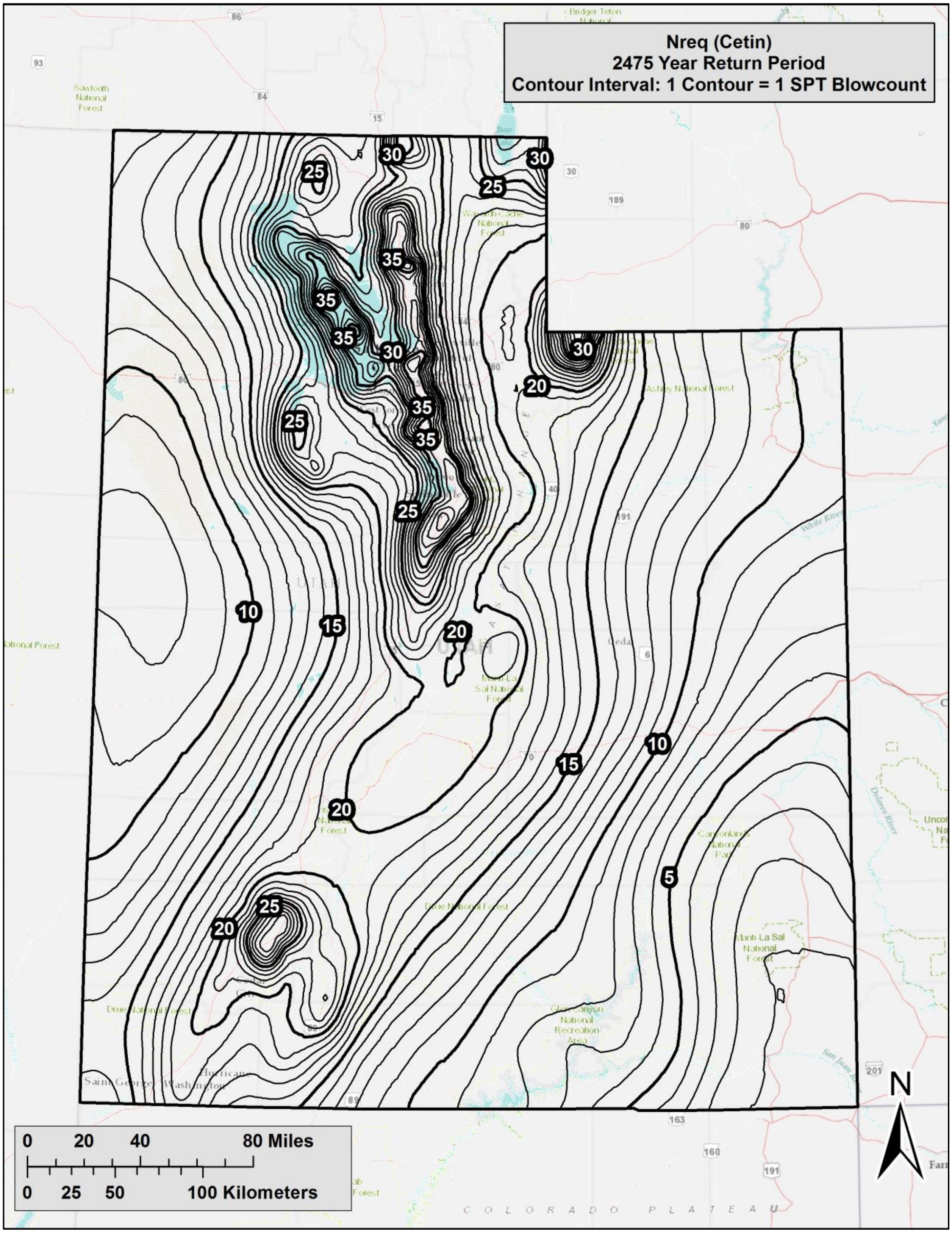


Figure A.33 – N_{req} Utah (T_R = 2475 years)

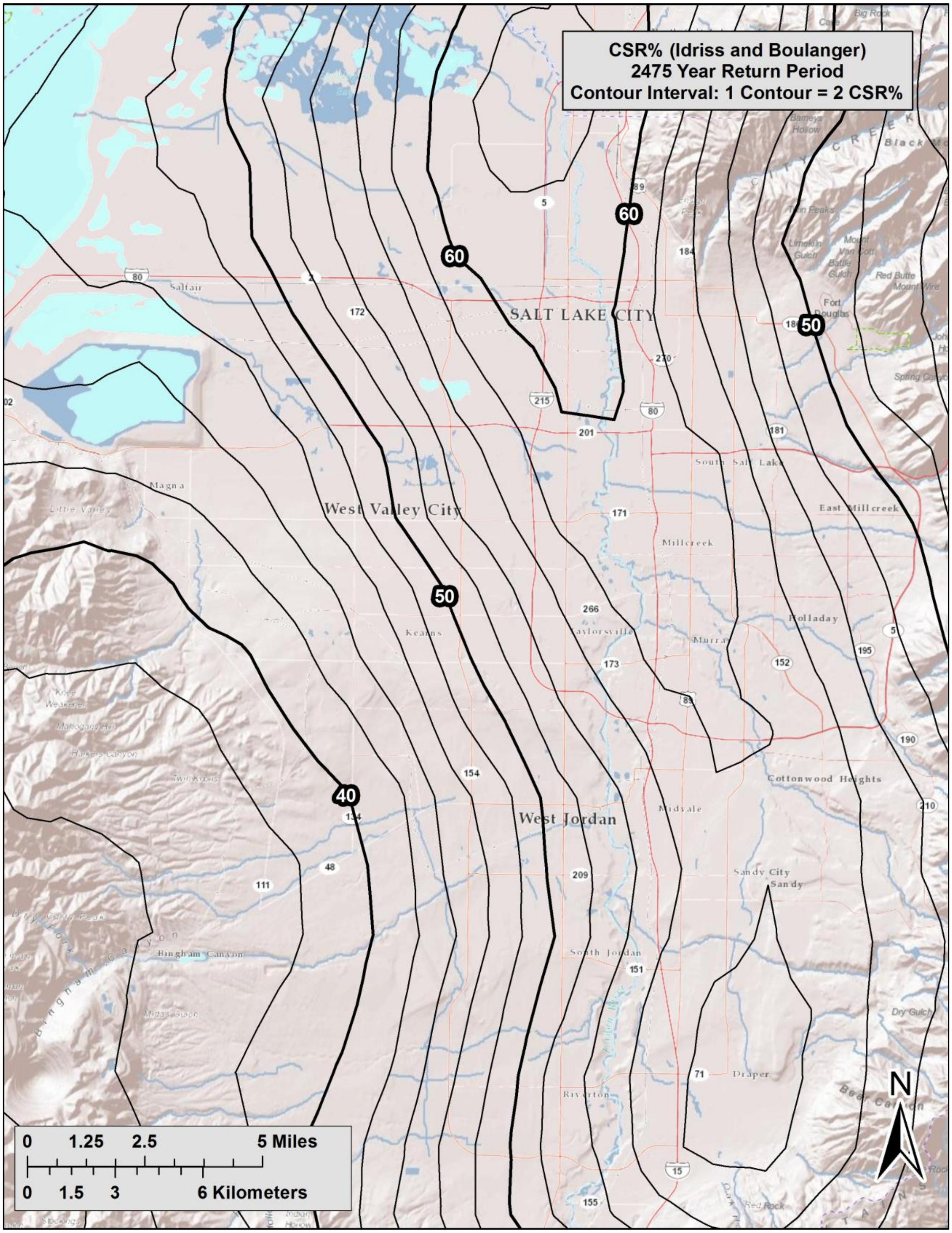


Figure A.34 – CSR% Salt Lake City, UT (T_R = 2475 years)

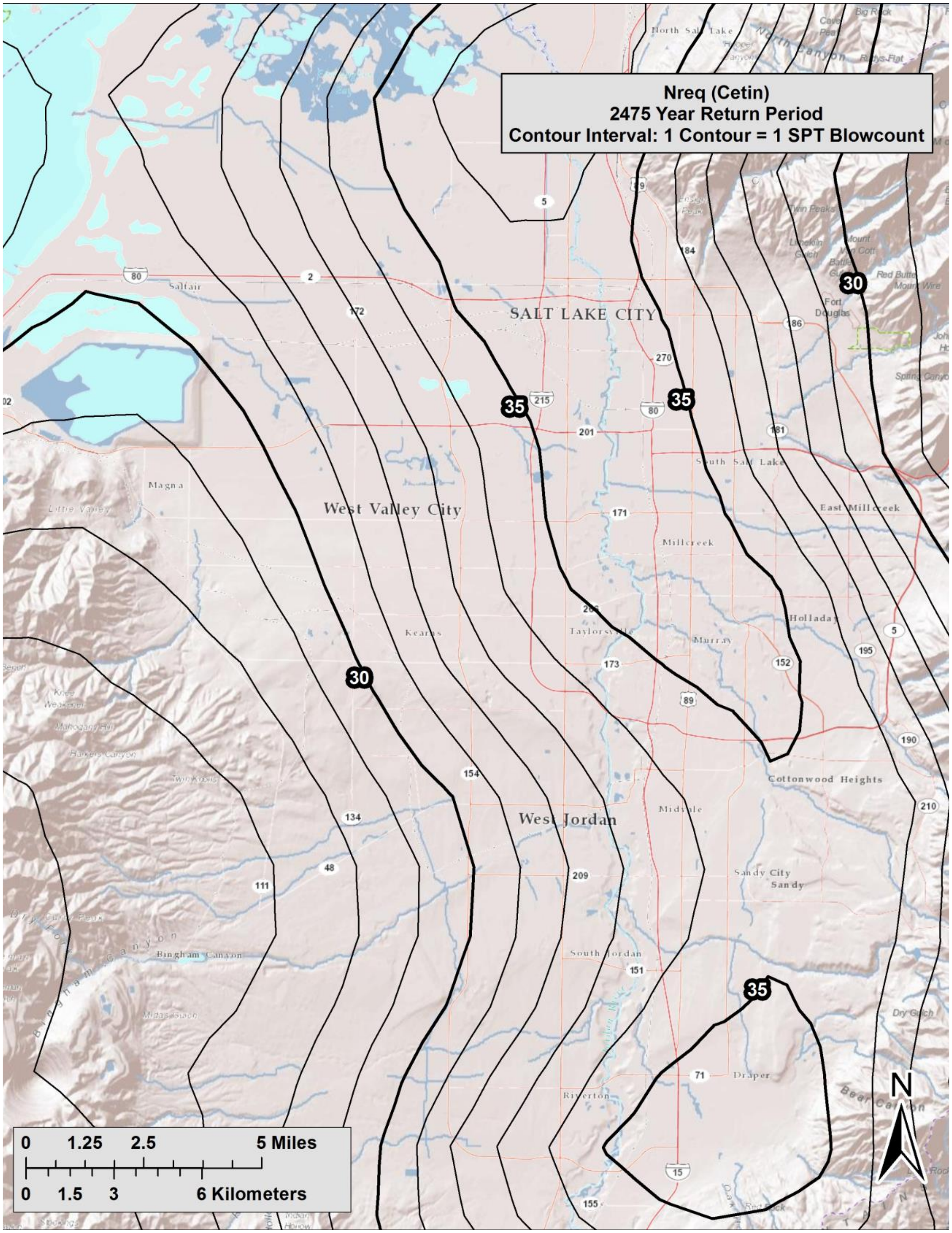


Figure A.35 – N_{req} Salt Lake City, UT (T_R = 2475 years)

APPENDIX B: Lateral Spread Hazard Maps

a) Alaska

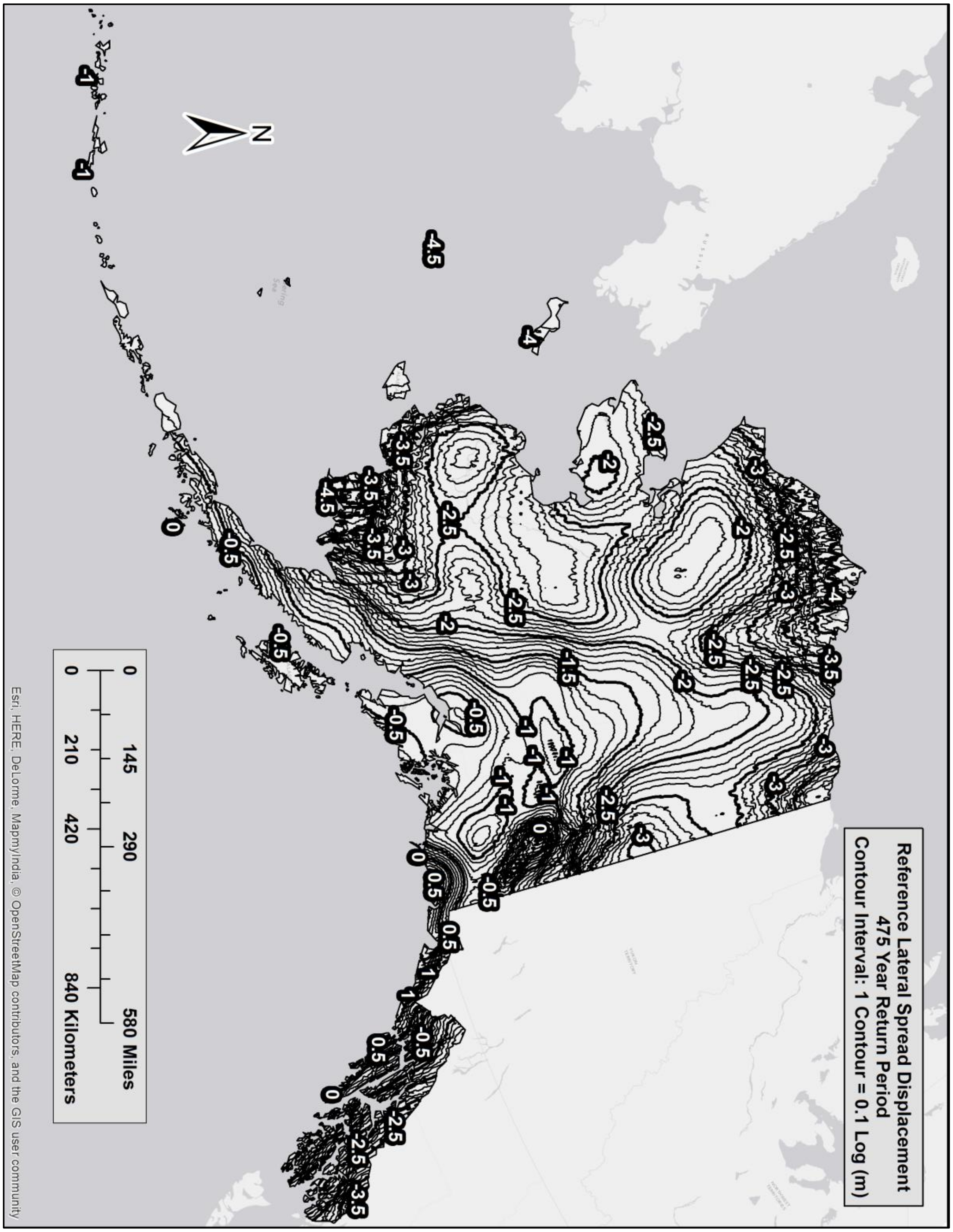


Figure B.1 – D_H^{ref} for Alaska (T_R = 475 years)

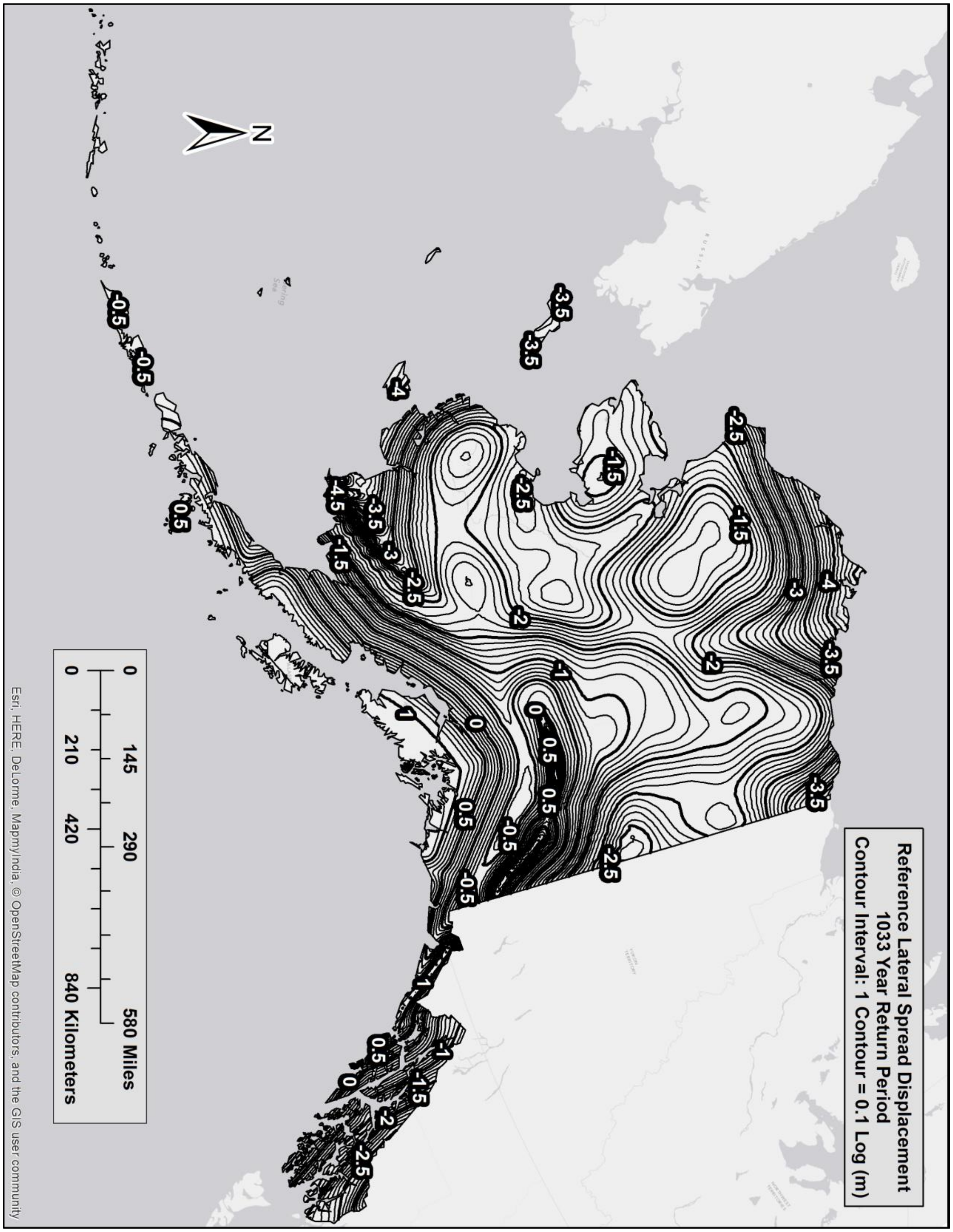


Figure B.2 – D_H^{ref} for Alaska (T_R = 1033 years)

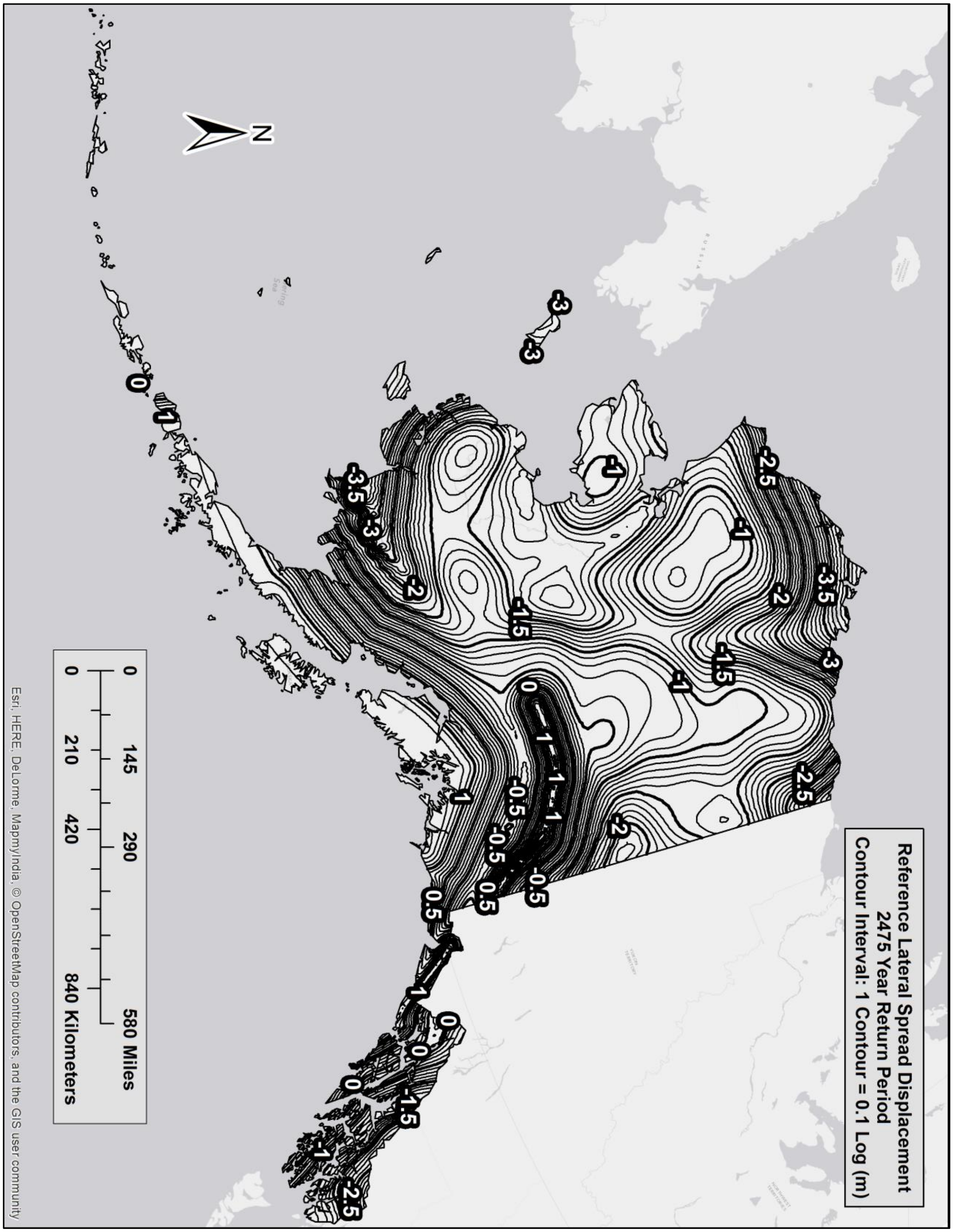


Figure B.3 – D_H^{ref} for Alaska (T_R = 2475 years)

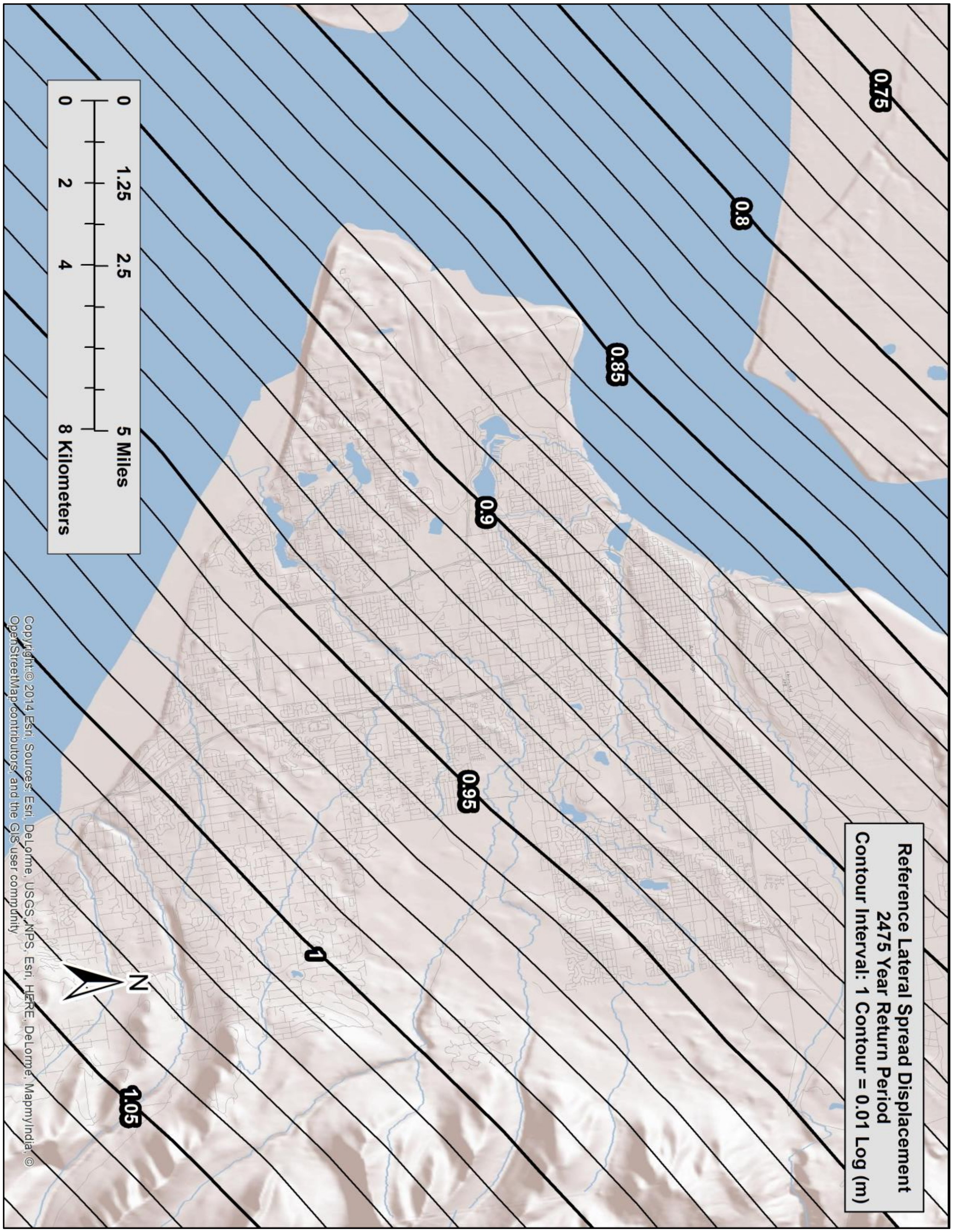


Figure B.4 – D_H^{ref} for Anchorage, AK (T_R = 2475 years)

b) Connecticut

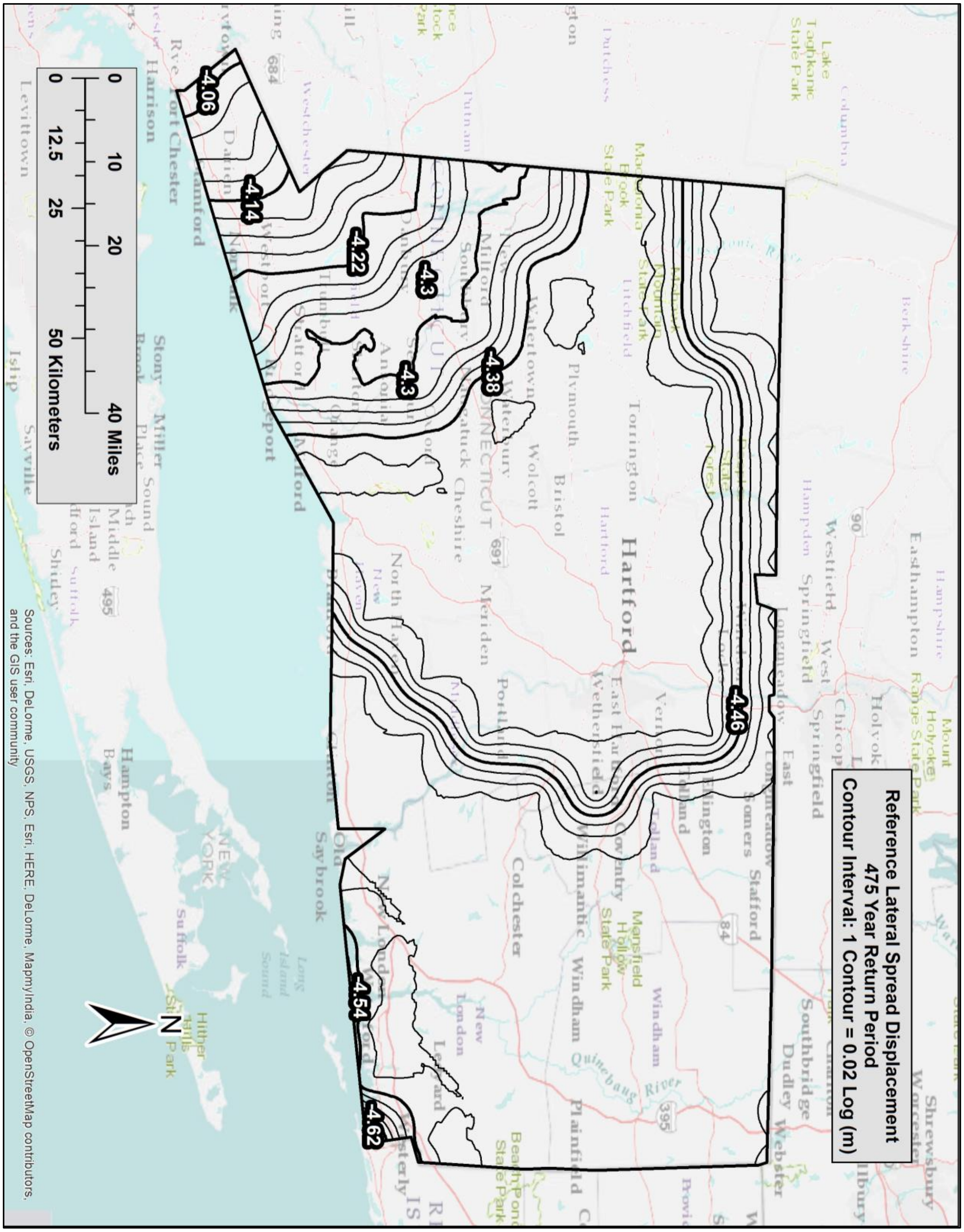


Figure B.5 – D_H^{ref} for Connecticut (T_R = 475 years)

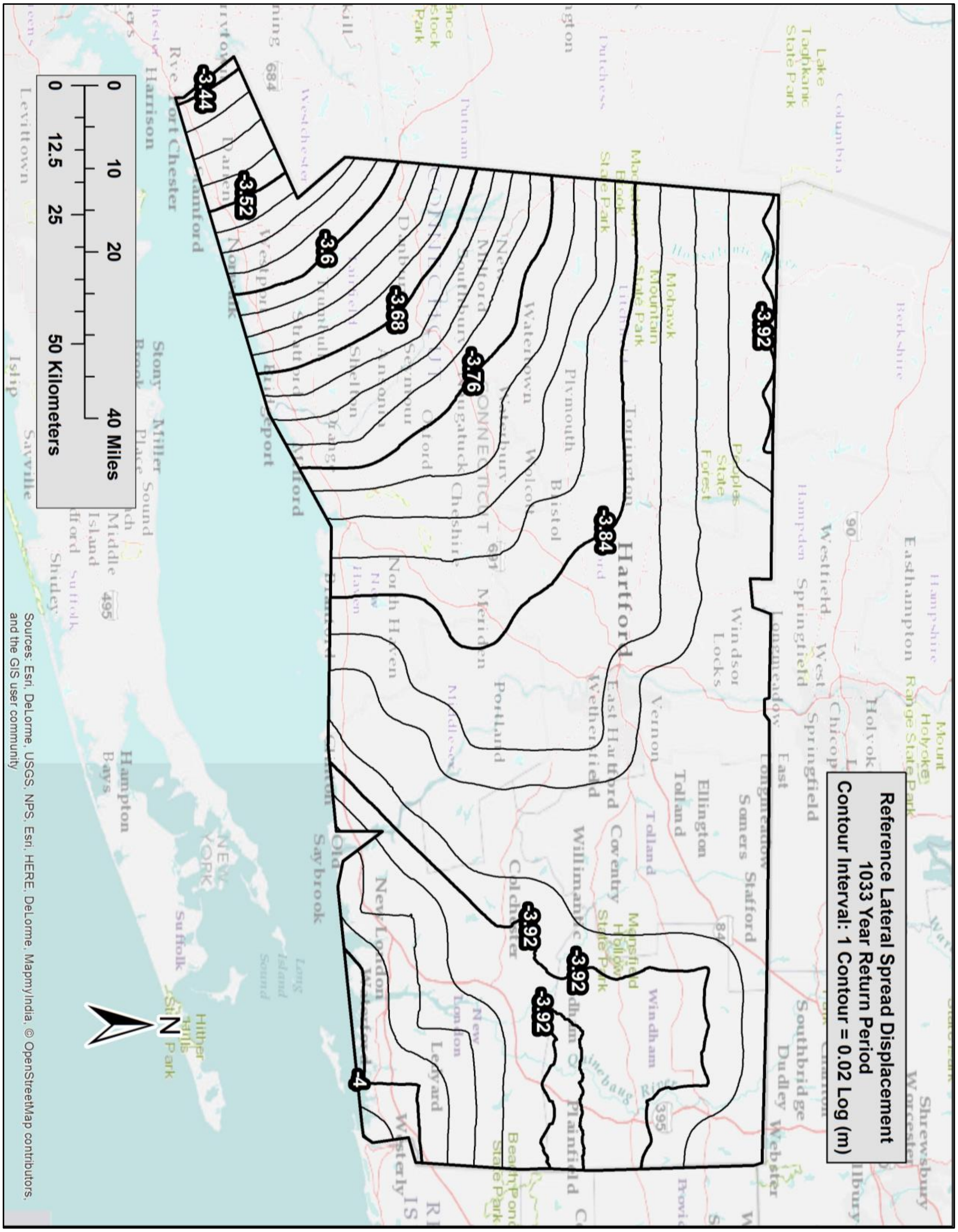


Figure B.6 – D_H^{ref} for Connecticut (T_R = 1033 years)

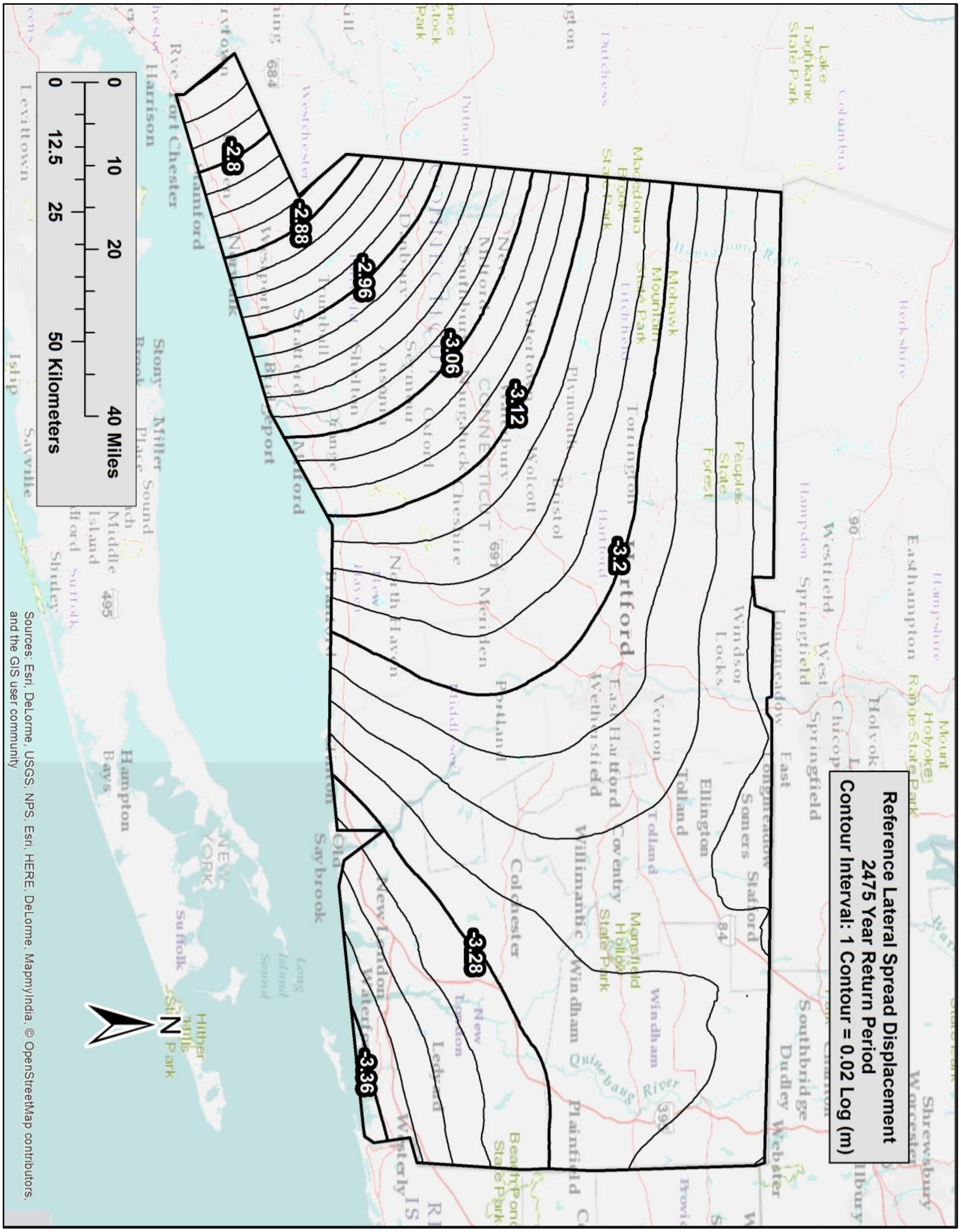


Figure B.7 – D_H^{ref} for Connecticut (T_R = 2475 years)

c) **Idaho**

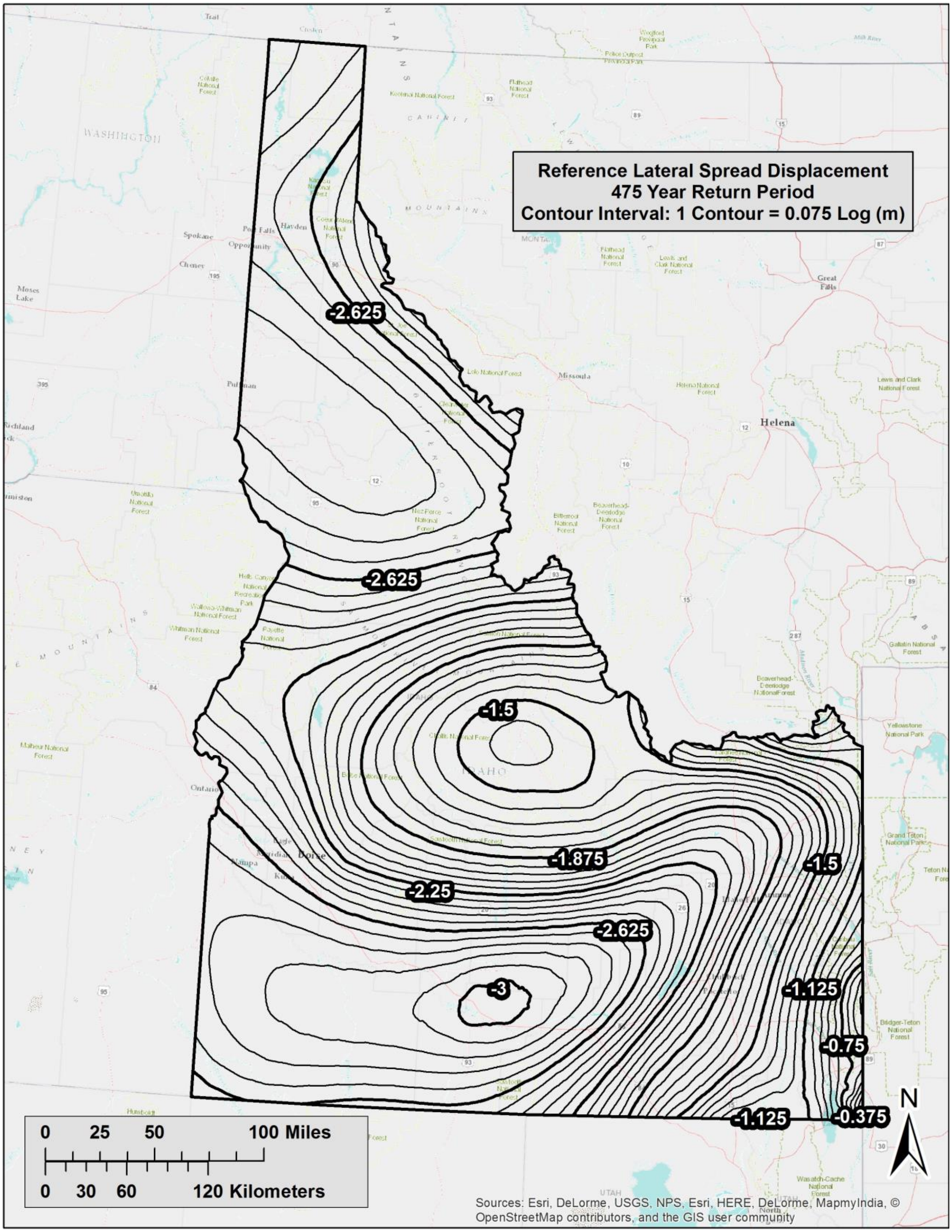


Figure B.8 – D_H^{ref} for Idaho (T_R = 475 years)

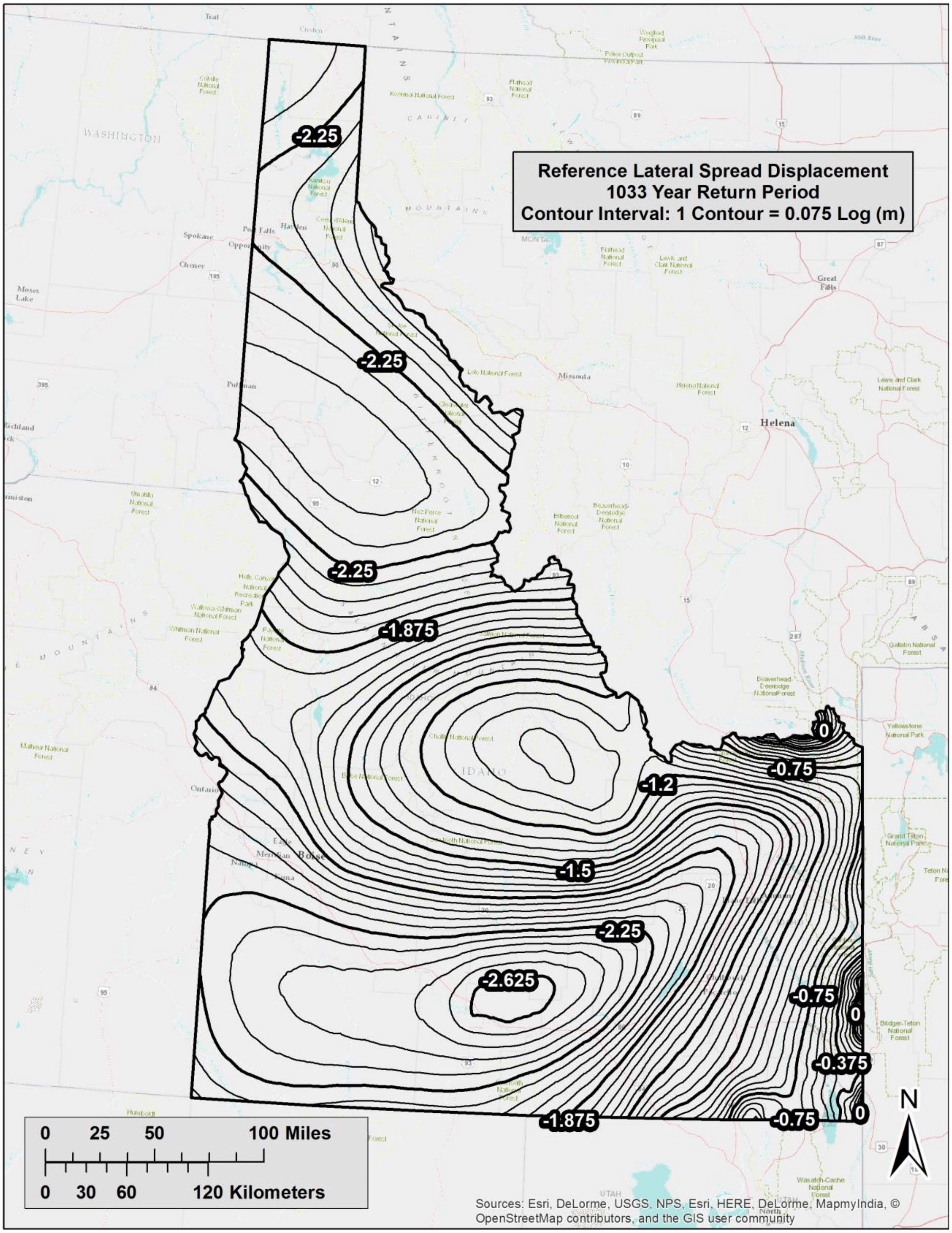


Figure B.9 – D_H^{ref} for Idaho (T_R = 1033 years)

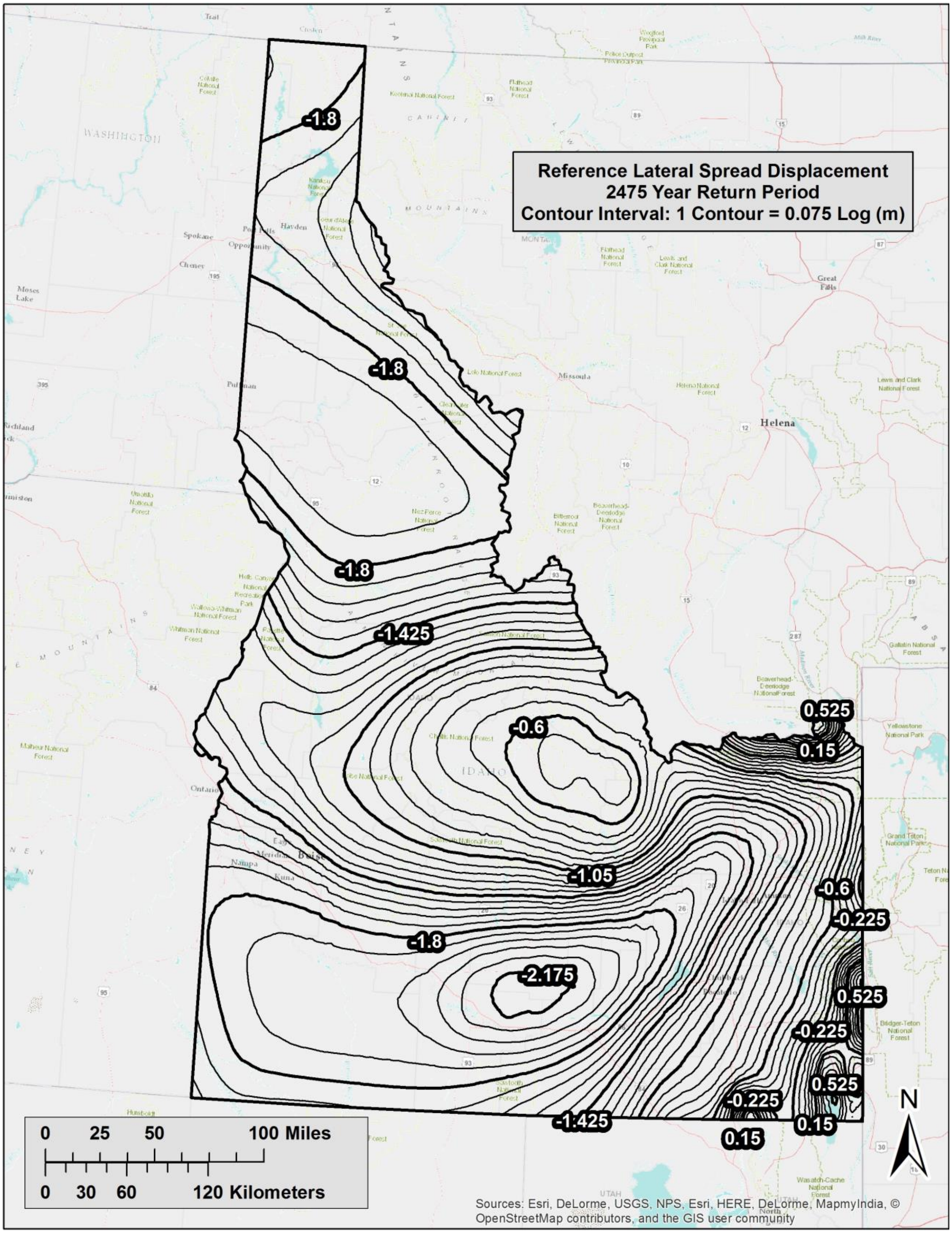


Figure B.10 – D_H^{ref} for Idaho (T_R = 2475 years)

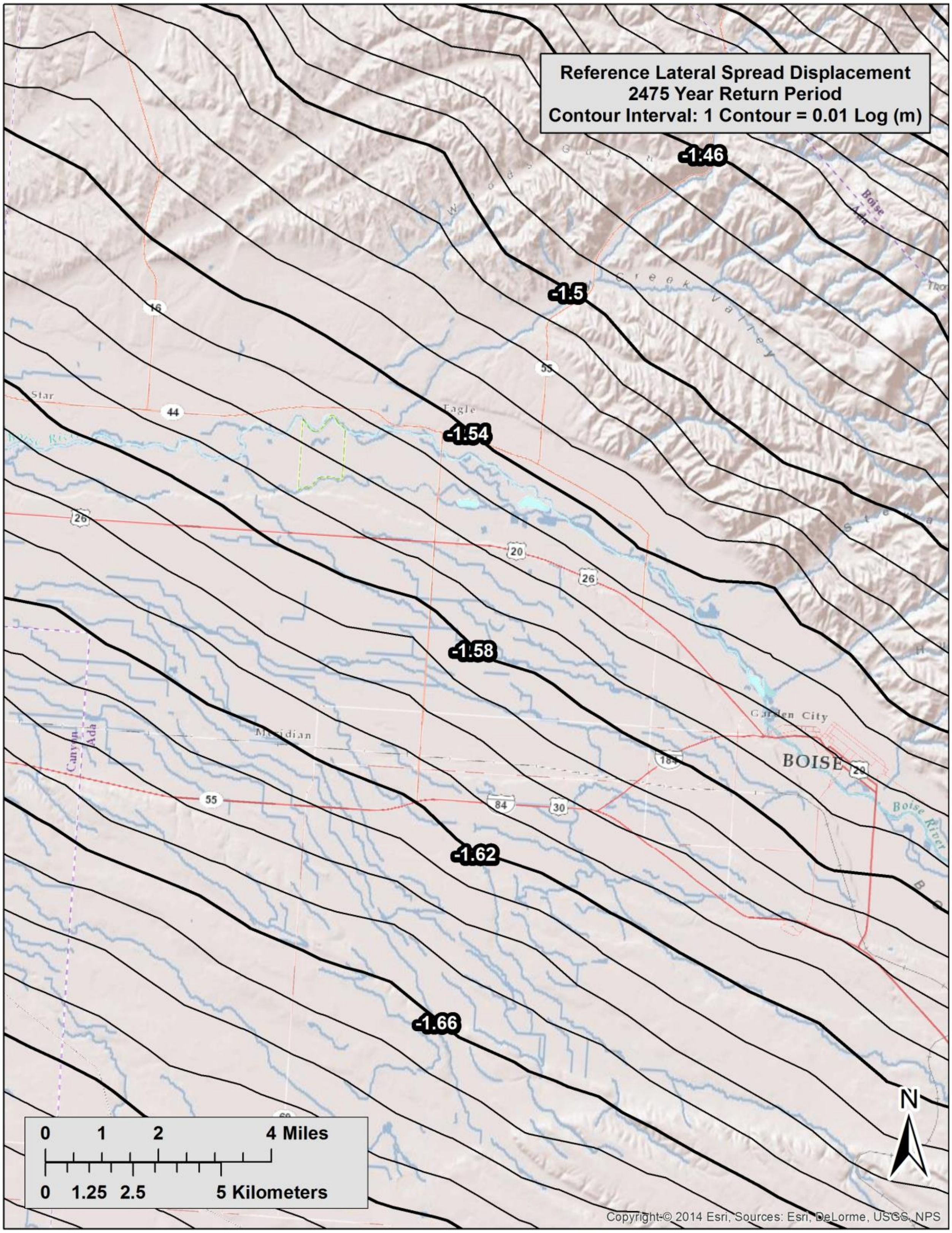
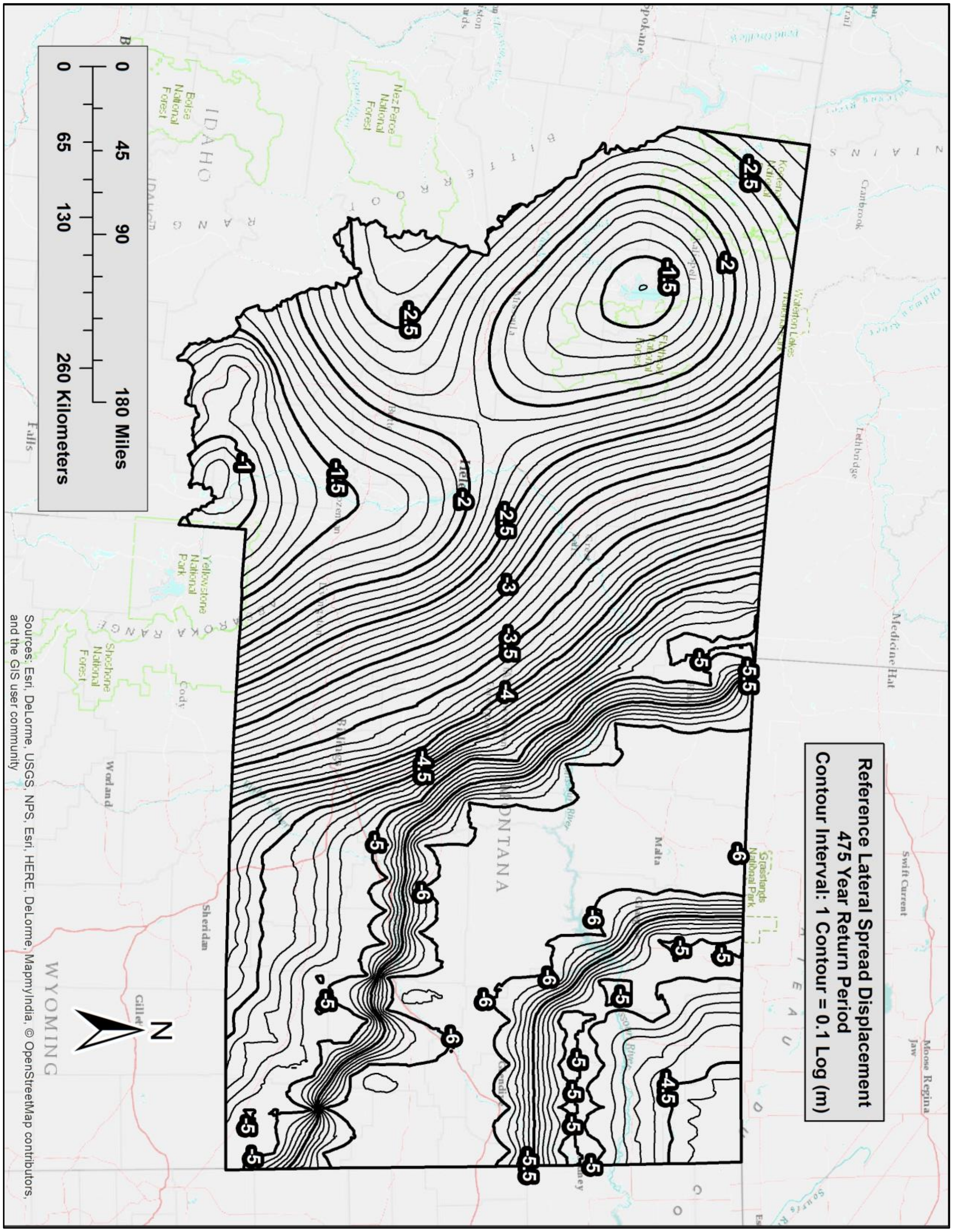


Figure B.11 – D_H^{ref} for Boise, ID (T_R = 2475 years)

d) Montana


Reference Lateral Spread Displacement
475 Year Return Period
Contour Interval: 1 Contour = 0.1 Log (m)
0 45 90 180 Miles
0 65 130 260 Kilometers
N
Sources: Esri, DeLorme, USGS, NPS, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors,
and the GIS user community

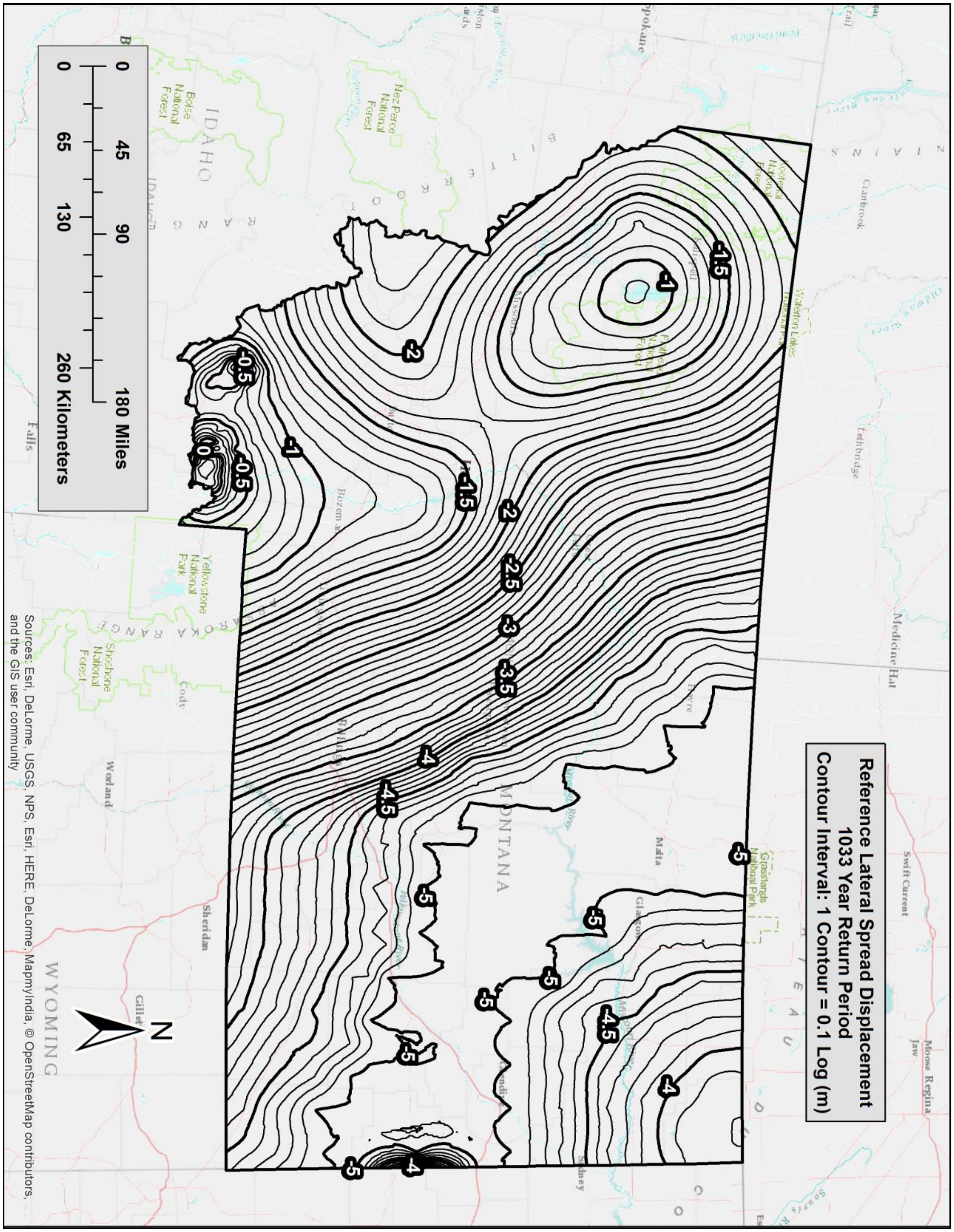


Figure B.13 – D_H^{ref} for Montana (T_R = 1033 years)

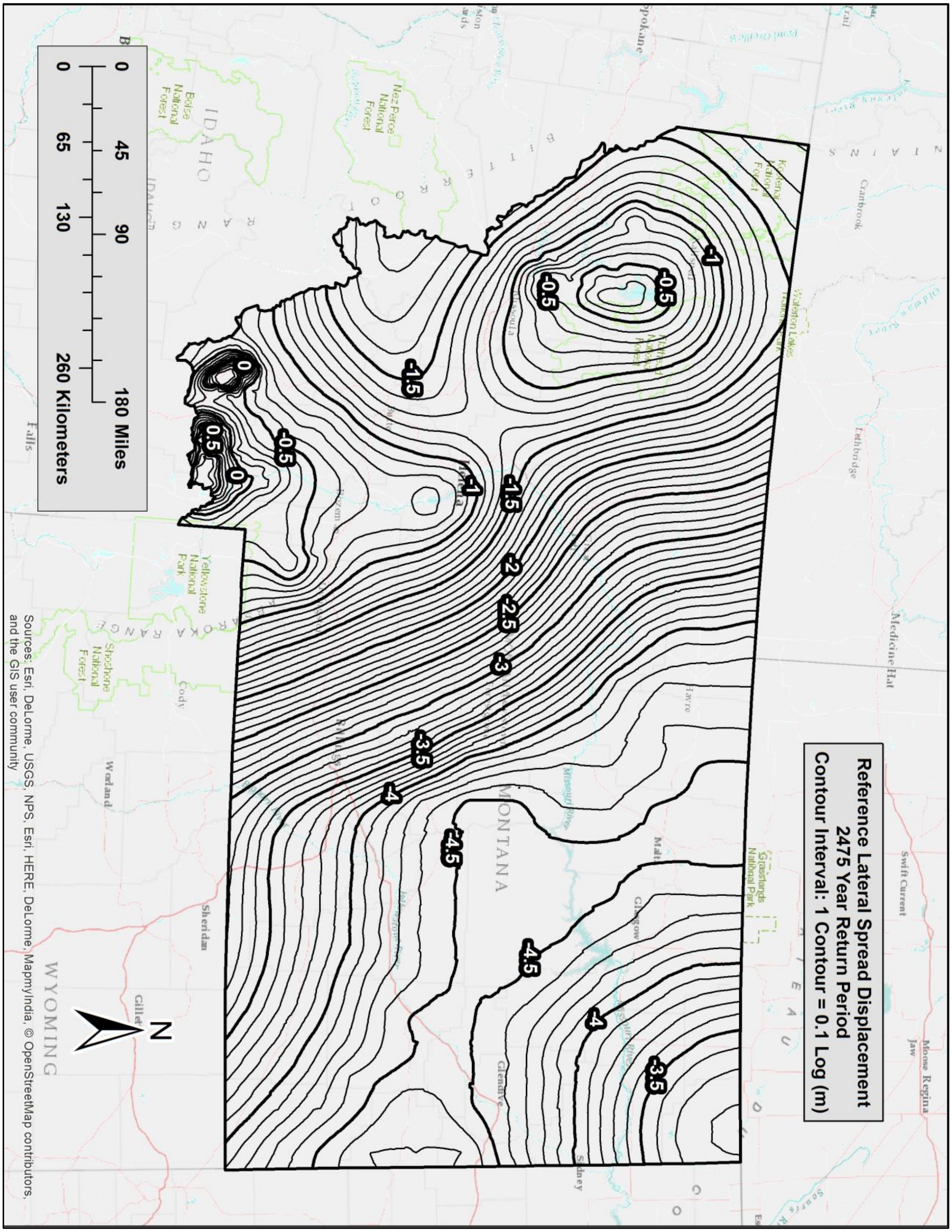


Figure B.14 – D_H^{ref} for Montana (T_R = 2475 years)

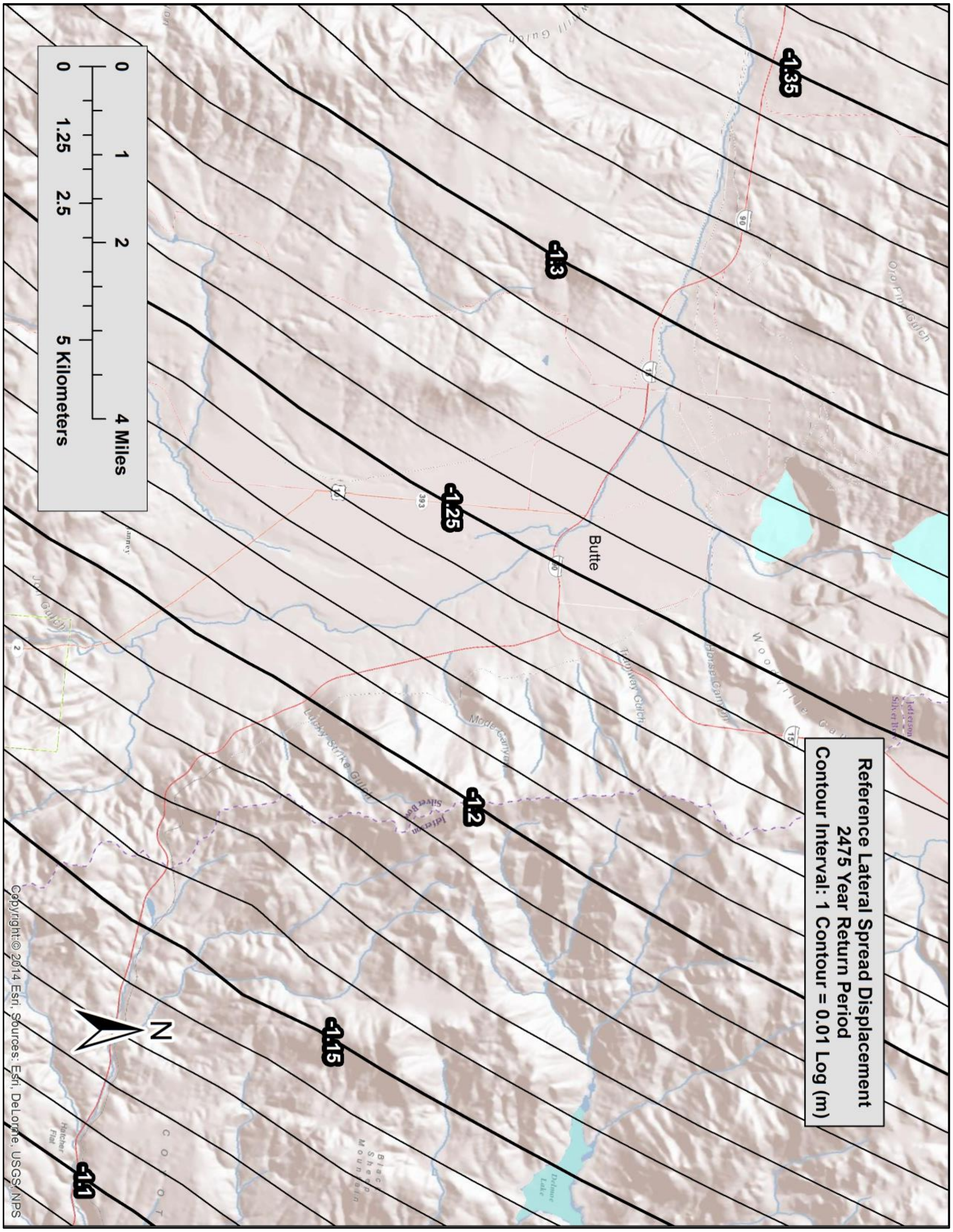


Figure B.15 – D_H^{ref} for Butte, MT (T_R = 2475 years)

e) South Carolina

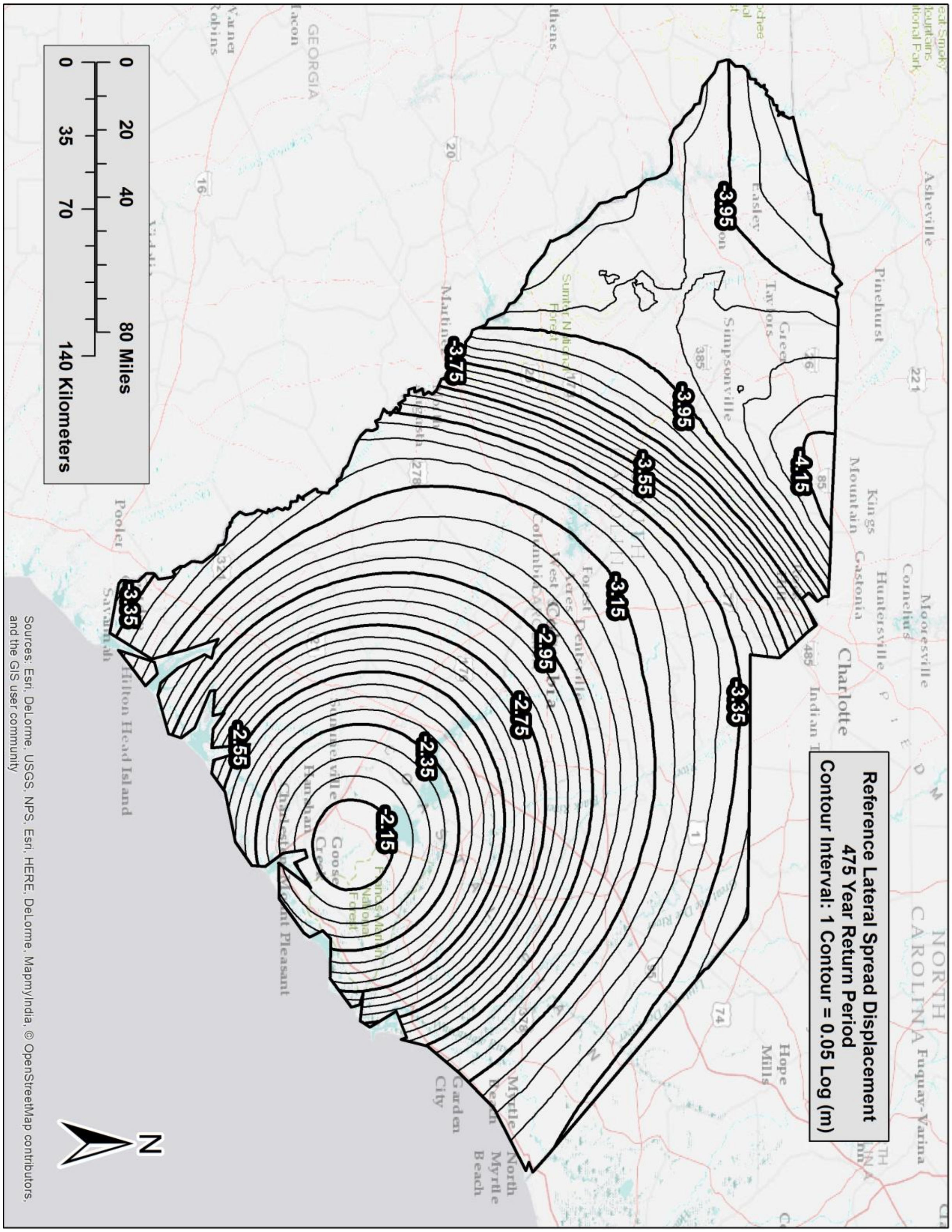


Figure B.16 – D_H^{ref} for South Carolina (T_R = 475 years)

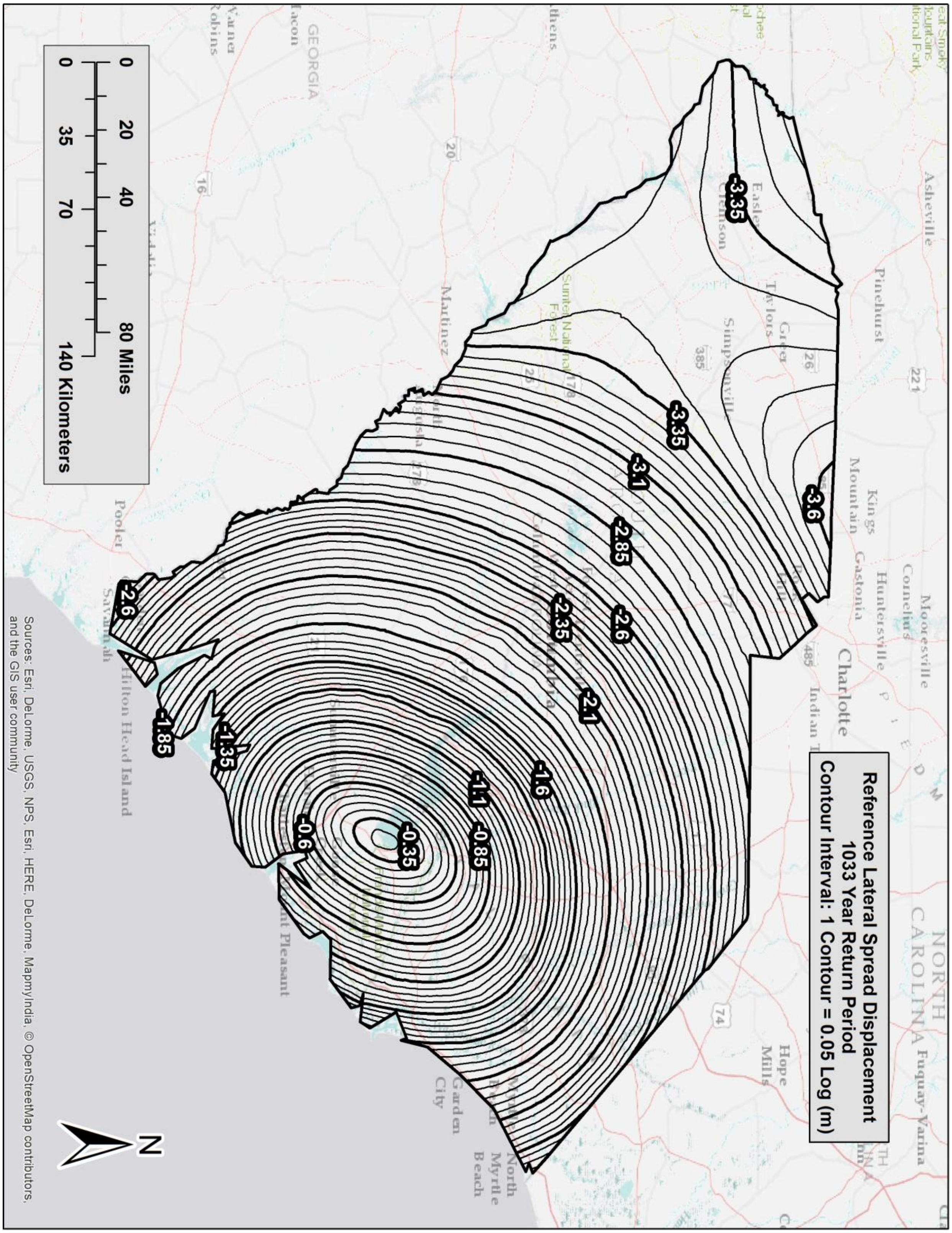


Figure B.17 – D_H^{ref} for South Carolina (T_R = 1033 years)

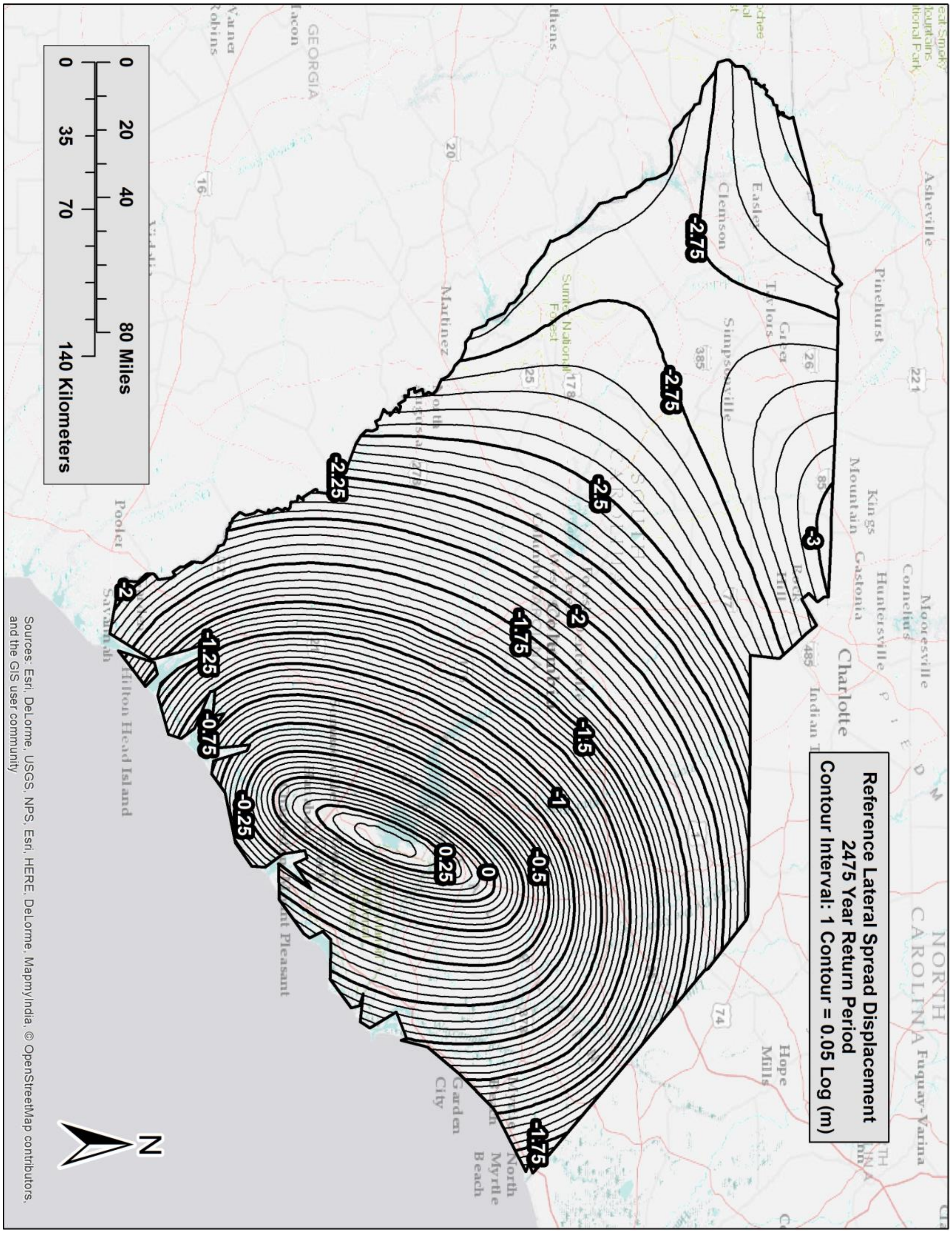


Figure B.18 – D_H^{ref} for South Carolina (T_R = 2475 years)

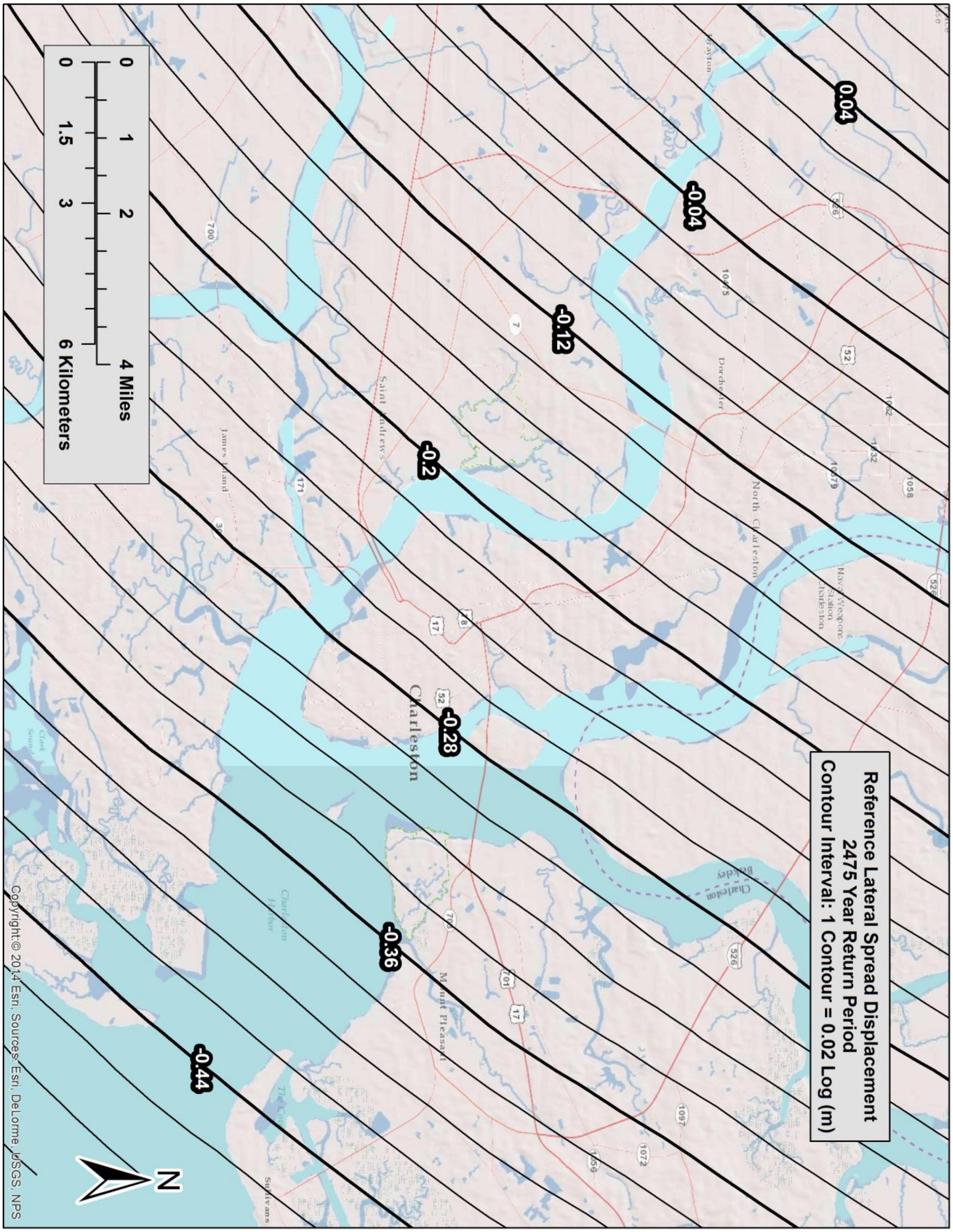


Figure B.19 – D_H^{ref} for Charleston, SC (T_R = 2475 years)

f) Utah

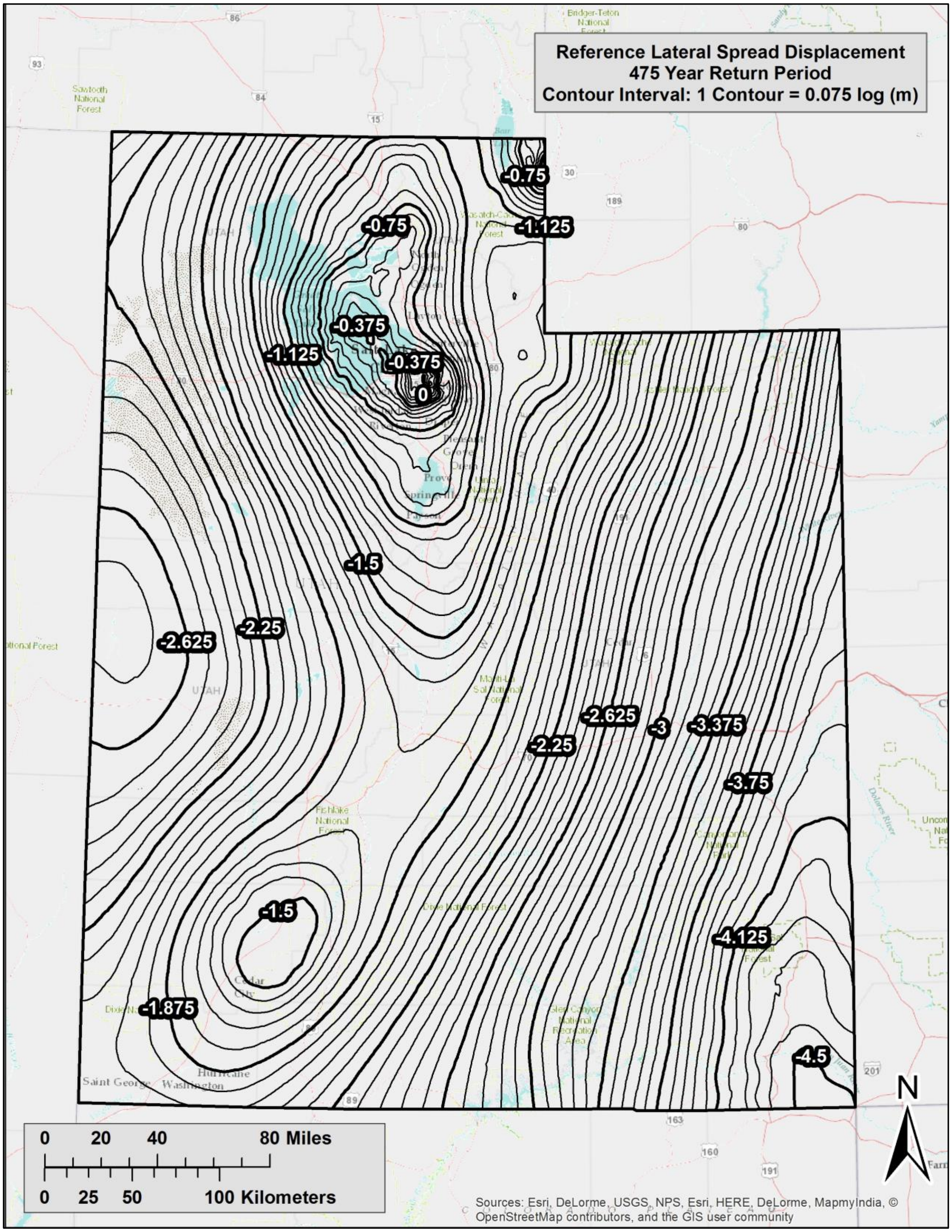


Figure B.20 – D_H^{ref} for Utah (T_R = 475 years)

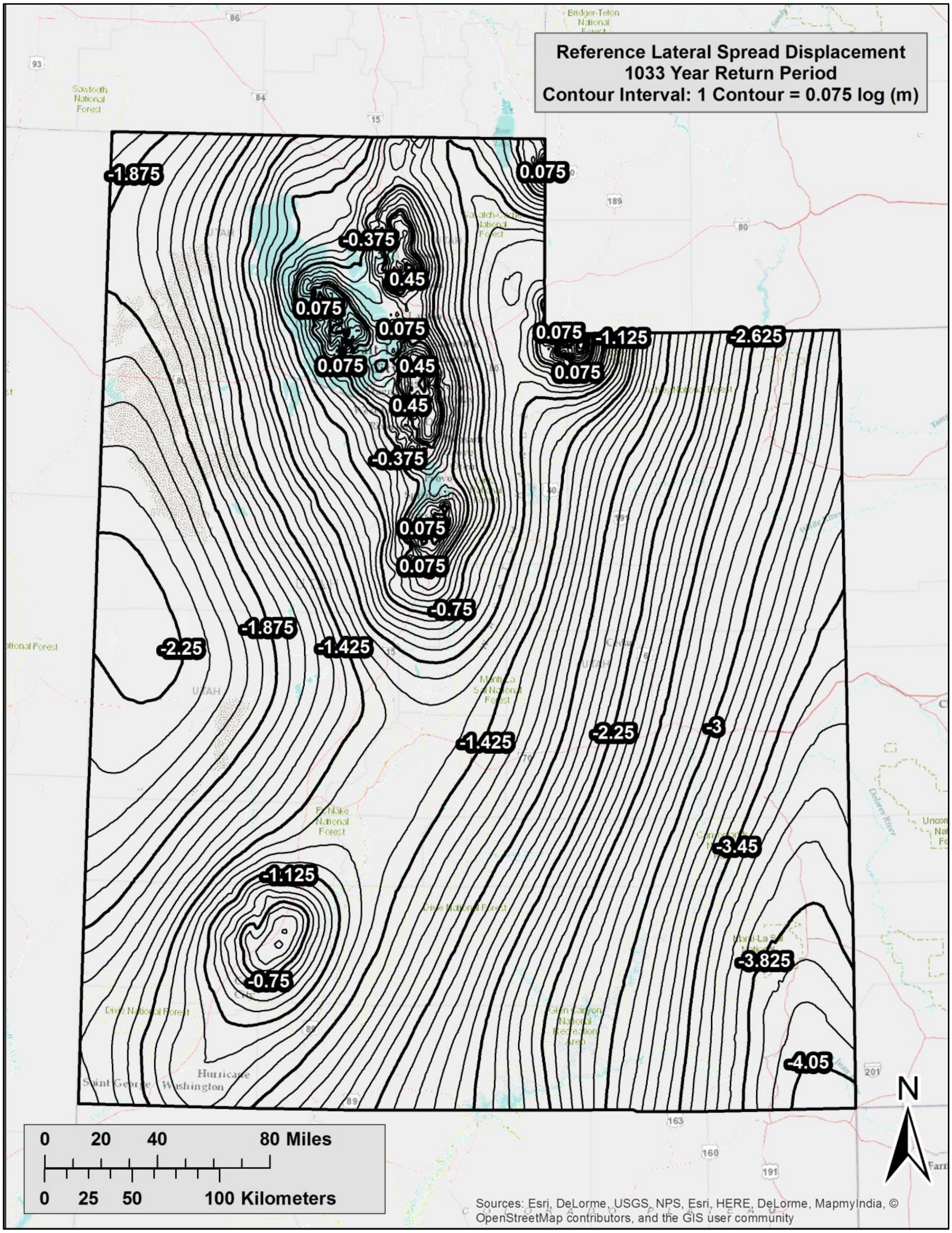


Figure B.21 – D_H^{ref} for Utah (T_R = 1033 years)

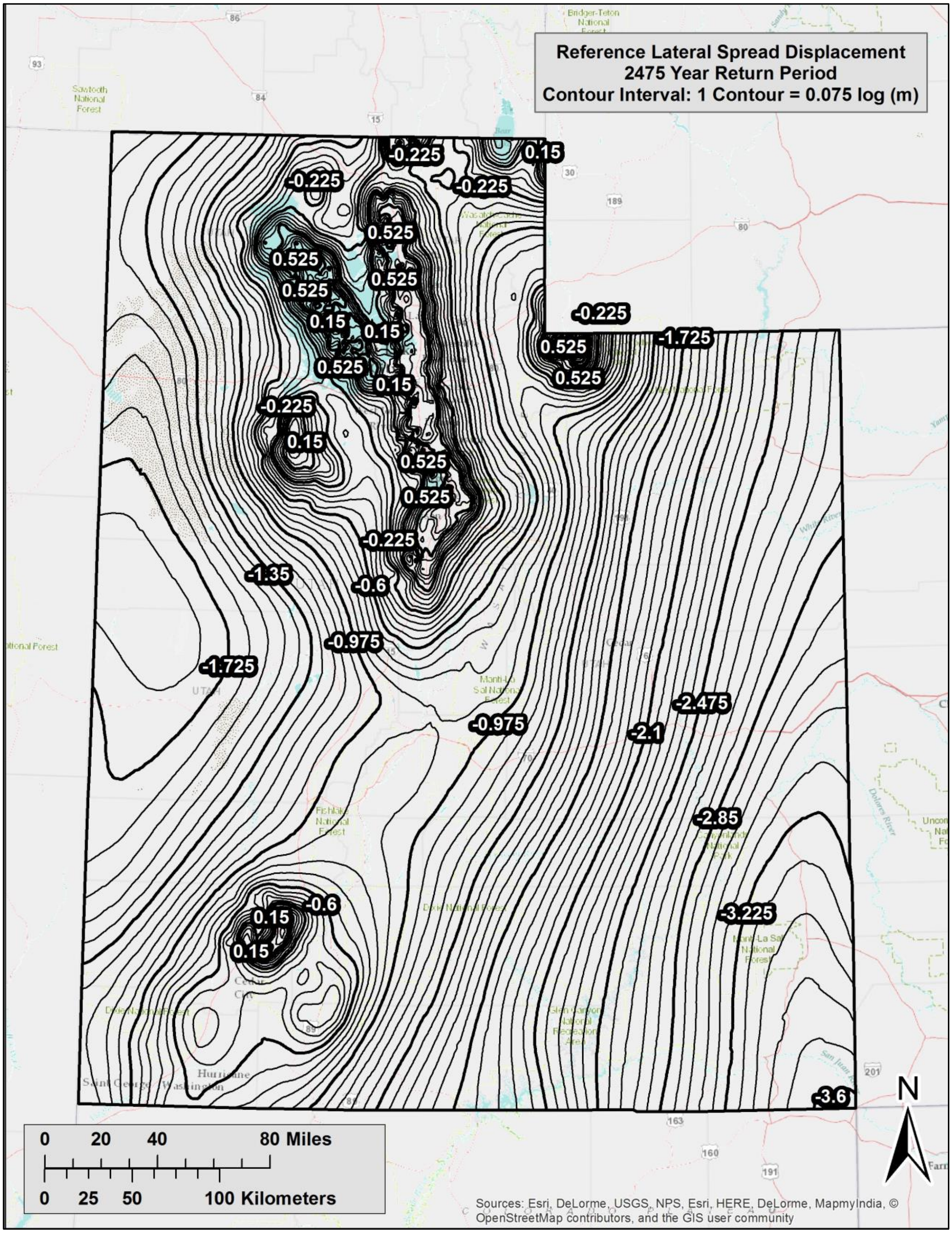


Figure B.22 – D_H^{ref} for Utah (T_R = 2475 years)

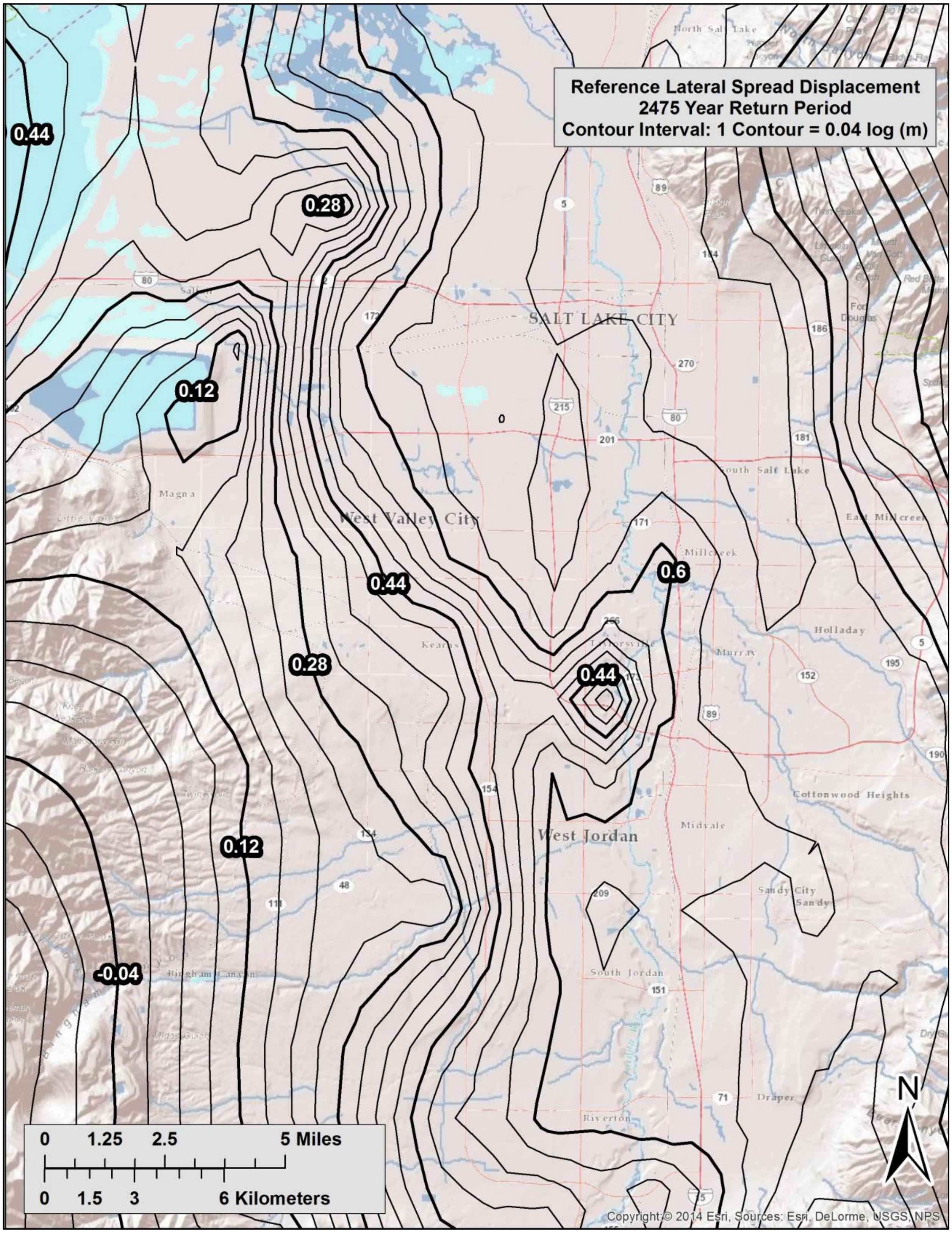


Figure B.23 – D_H^{ref} for Salt Lake City, UT (T_R = 2475 years)