Minnesota Department of Transportation

RESEARCH SERVICES & LIBRARY

Office of Transportation System Management

Minnesota Steel Culvert Pipe Service-Life Map

Jeffrey Marr, Principal Investigator
St. Anthony Falls Laboratory
University of Minnesota

June 2015

Research Project
Final Report 2015-31

LRRB
LOCAL ROAD RESEARCH BOARD

To request this document in an alternative format call 651-366-4718 or 1-800-657-3774 (Greater Minnesota) or email your request to ADArequest.dot@state.mn.us. Please request at least one week in advance.

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2015-31		

4. Title and Subtitle	5. Report Date
Minnesota Steel Culvert Pipe Service-Life Map	June 2015
	6.
7. Author(s) Barbara Heitkamp, Jeffrey Marr	8. Performing Organization Report No.
9. Performing Organization Name and Address St Anthony Falls Laboratory University of Minnesota 2 3rd Ave SE Minneapolis, MN 55414	10. Project/Task/Work Unit No. CTS # 2014001 11. Contract (C) or Grant (G) No. (c) 99008 (wo) 96
12. Sponsoring Organization Name and Address Local Road Research Board Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

http://www.lrrb.org/pdf/201531.pdf

16. Abstract (Limit: 250 words)

The goal of this project was to develop a series of steel pipe service-life maps for the state of Minnesota. The California Method 643 is utilized to estimate steel pipe service life at locations throughout the state.

Over 560 soil resistivity and pH samples were collected statewide during summer 2014 along embankments of state-trunk and county highways. Concurrent observations of soil texture, surrounding landscape, roadway type, and water presence were also made; water pH and conductivity measures were made where applicable.

Data verification efforts to build confidence in field-measured soil pH and soil resistivity included comparing data to other available datasets including geology, soil pH, electrical conductivity, and soil texture, as well as observations available from district and county engineers. Field-measured soil pH data, with some exceptions in Districts 2 and 6, generally aligned with the available STATSGO soil pH data, indicating that this layer could reasonably be used in service-life calculations as it has greater resolution than provided by field data. In the absence of a statewide soil resistivity or electrical conductivity map, field-classified soil textures and the statewide STATSGO soil texture map were used to estimate soil resistivity values.

Calculations of service life using the above data were completed for 18-, 16-, 14-, 12-, 10- and 8-gage galvanized and aluminized steel pipe across Minnesota. These maps were then compiled into a zone map and table that presents the 90th percentile service- life estimate for various gages and types of steel pipe. Caveats and limitations to this analysis are also discussed.

17. Document Analysis/Descriptors	18. Availability Statement
Steel pipe, Service life, Minnesota, Soils by chemical content or action, Pervious soils, Soil mechanics, Galvanized metals, Alloy steel	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	72	

Minnesota Steel Culvert Pipe Service-Life Map

Final Report

Prepared by:

Barbara Heitkamp
Jeffrey Marr
St. Anthony Falls Laboratory
University of Minnesota

June 2015

Published by:

Minnesota Department of Transportation
Research Services and Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

A special thanks to Andrea Hendrickson, MnDOT state hydraulic engineer, and Bonnie Peterson, MnDOT hydraulic infrastructure inspection and management coordinator, whose guidance made this project possible. A special thanks also to Ethan Lipscomb for his dedication and work on the field campaign.

We would also like to thank the MnDOT Technical Advisory Panel Members: Andrea Hendrickson, Bonnie Peterson, James Kochsiek, Khalid Obeidat, Jon Bergstrand, Tracey Vonbargen, Bruces Holdhusen, and Shirlee Sherkow.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This study develops a series of statewide steel pipe service-life maps for the state of Minnesota. The *MnDOT Drainage Manual* refers to the California Method 643 (Caltrans, 1999) for estimating service life for different types of steel pipe culverts. The two key parameters required for use of the California Method are pH and resistivity. This study describes the efforts of a statewide field campaign to map soil pH and soil resistivity and the resulting analysis to generate steel pipe service-life maps for the state of Minnesota.

Following are key results and findings:

- Over 560 soil resistivity and pH samples were collected statewide during summer 2014 along embankments of state-trunk and county highways. Concurrent observations of soil texture, surrounding landscape, roadway type, and water presence were also made, with water pH and conductivity measures made where applicable.
- Data verification efforts to build confidence in field-measured soil pH and soil resistivity included comparing data to other available datasets including soil pH, electrical conductivity, and soil texture, as well as observations available from district and county engineers.
- Field-measured soil pH data, with some exceptions, generally aligned with the available statewide STATSGO soil pH data, indicating that this layer could reasonably be used in service-life calculations.
- Field-measured soil resistivity data was considered unreliable due to consistently higher than anticipated values in different parts of Minnesota. In the absence of a statewide soil resistivity or electrical conductivity map, field-classified soil textures and the statewide STATSGO soil texture map were used to estimate soil resistivity values.
- No significant relationships between land use and soil pH or resistivity were noted. Acidic conditions tend to occur in proximity (<10 miles) to wetlands and lakes, but more basic conditions were also observed at similar proximities.
- Calculations of service life using the STATSGO data and California Method 643 were completed for 18-, 16-, 14-, 12-, 10- and 8-gage galvanized and aluminized steel pipe across Minnesota.
- A more simplified zonal map of Minnesota is presented, which shows the 90th percentile service-life estimate for various gages and types of steel pipe.
- While this analysis presents service-life estimates based on estimates of soil pH and resistivity, several limitations and caveats must be noted that may significantly alter service-life estimates. These include: the potential for culvert abrasion, changing soil moisture or temperature conditions, wet conditions, channel aggradation, presence of chloride in the soil, and proximity to lakes or wetlands.
- The summary information provided in this report is a generalized estimate of service life based on regional trends within the state. It remains the reasonability of the user/designer/engineer to understand that limitation of these tools and utilize them, along with other data and methodologies, to determine an appropriate service-life estimate.

CHAPTER 1: INTRODUCTION

The *MnDOT Drainage Manual* refers to the California Method (Caltrans, 1999) for estimating service life for different types of steel pipe culverts. The two key parameters required for use of the California Method are pH and resistivity (Figure 1.1). The current method for estimating steel pipe life is for the designer to take field samples for these two parameters. Although this method is desirable, time and expense restrictions often make sampling impractical. A statewide steel pipe service life map based on the California Method is needed to improve steel pipe design efficiency throughout Minnesota.

While some resources are available for estimating soil pH and soil resistivity for parts of the state, they are generally insufficient to develop a statewide steel pipe service-life map. Furthermore, the lack of field data to ground truth soil pH and resistivity estimates in areas with data limit confidence in service-life calculations.

The goal of this project was to develop a series of steel pipe service-life maps for the state of Minnesota. The California Method 643 (Caltrans, 1999) was utilized to estimate steel pipe service life at locations throughout the state. A field campaign focused on collecting soil resistivity and soil pH data statewide (along with other observations) provided the data needed to calculate the service-life estimates for different types of steel pipe. Roughly 50-90 sample sites were selected per district, with samples taken from the embankments of state-trunk and county highways. Where applicable, water pH and conductivity were also taken at the sample sites for comparison with soil samples.

Chapter 2 describes the data collection efforts and results of the summer 2014 field campaign, including descriptions of data collection methodologies and equipment. Chapter 3 includes details for field pH and soil resistivity data verification, as well as additional analysis of other observed parameters from the field campaign. Chapter 4 presents the calculation of service-life estimates for various steel pipe gages and types, as well as a list of limitations and caveats for the generated estimates. The desired service-life design for culverts is a minimum of 50 years, and the resultant maps generated show users the type and gage of pipe to consider to achieve the minimum service life. Chapter 5 uses the maps generated in Chapter 4 to create a zonal delineation of service life throughout Minnesota that can be used to select pipe material, as well as outlining caveats and limitations to the maps and analysis.

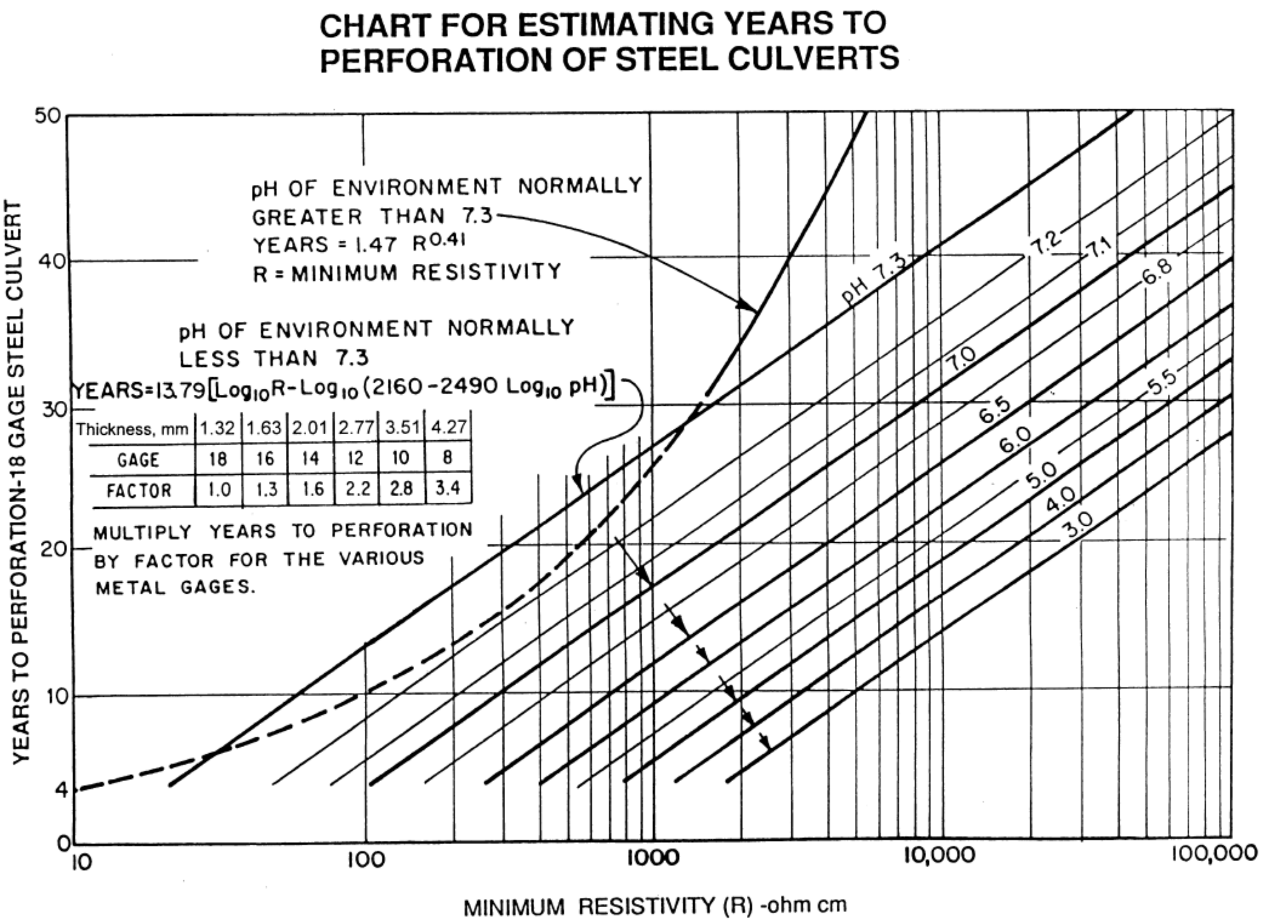


Figure 1.1: California Method for estimating steel pipe service life.

CHAPTER 2: FIELD CAMPAIGN AND DATA COLLECTION

2.1 Introduction

This section describes the data collection efforts for the project during the summer 2014 field campaign. A field researcher was tasked with collecting 50-90 samples per MnDOT district, with site selection focused on state-trunk and county roadway embankments. Generally, major multi-lane highways were excluded due to a lower frequency of steel pipes along those roadways. Sample sites were selected approximately every 15 minutes of driving, with data collection efforts taking approximately 15 minutes per site.

Site routes for each district were mapped using Google Maps and provided to the district representative one to two weeks prior to sampling in that district. This allowed the opportunity for district representatives to provide input on potential hot spots and suggest alternative routes if needed.

The following data were collected at each sample location:

- Date/time
- Road system & route
- Waypoint number
- Site location (northing and easting)
- Soil pH
- Soil resistivity
- Presence of flowing water
- Presence of standing water
- Water pH (if applicable)
- Water conductivity (if applicable)
- Soil texture
- Adjacent land use
- Roadway surface type (gravel, asphalt, concrete, asphalt over concrete)
- Number of roadway lanes
- Signs of recent rainfall
- Any additional observations/comments

2.2 Data Collection Methodology

The following methodologies were used to collect data at each sample location. More information about data collection equipment can be found in Appendix A.

2.2.1 Site Location and Waypoint Number

The coordinates of each sampling site were recorded as northings and eastings in the UTM coordinate system using a Garmin eTrex 20 handheld GPS. Each location was also assigned a waypoint number for ease of reference. The GPS is WAAS (Wide Area Augmentation System) enabled, improving position accuracy. The unit is capable of storing 2,000 waypoints.

2.2.2 Soil pH

Soil pH was tested at each location using a handheld direct soil pH meter. Two meters were used throughout the summer field campaign, including the HANNA Instruments HI 99121N Direct Soil pH Meter and the Spectrum Technologies, Inc. IQ 150 Soil pH Meter. Both meters meet the specification in Section 4.2.2 of ASTM G51-95 (2012) and are used in lieu of Part 3 of the California Test 643, as they are equally (or more) accurate.

Each pH meter was calibrated daily using a two-point buffer calibration method. At each sample site, the soil pH was measured at the soil surface near the invert of the road ditch, and the measurements were replicated until three measurements were recorded within 10% of each other. If the soil was very dry, it was wetted with either deionized water or a Soil Test Preparation Solution to help ensure more proper soil contact with the meter probe.

The HANNA Instruments probe was only used during the first few weeks of the field campaign, as it had a very fragile glass probe attachment that easily scratched when sampling coarser materials. The scratches caused probe readings to start drifting, lowering confidence in accurate measurements. Three glass probes were replaced before the team decided to replace the meter with the Spectrum Technologies pH Meter. The Spectrum Technologies meter had a metal probe which was much more durable in field conditions. To check agreement between the two probes, both were used in the field for 1-2 days at sample sites. Soil pH measurements were consistent between the two meters, providing confidence that the meter transition did not impact sample accuracy.

2.2.3 Soil Resistivity

Soil resistivity samples were collected using a Gardco CD-SR-2 Soil Resistivity Meter. The measurements were taken according to the Wenner Four-Electrode Method presented in ASTM G57-06 (2012), specifically in accordance with the in situ method described in sections 5.1 and 7.1 of ASTM G57-06. (2012) These testing methods fulfill Part 1 of California Test 643.

The resistivity meter was calibrated weekly. At each sampling site the soil resistivity was measured at a depth of 1 foot halfway down the road embankment to avoid the potential for artificially low resistivity measures near the road shoulder where de-icing activities introduce infiltrating brine water (Figure 2.1). The soil probes were placed at 5-foot intervals, either pushed into the ground by hand or hammered if soils were rocky and/or hard. At least three replicate measurements were recorded for each location without moving the soil probes until sample measurements were within 10% of each other.

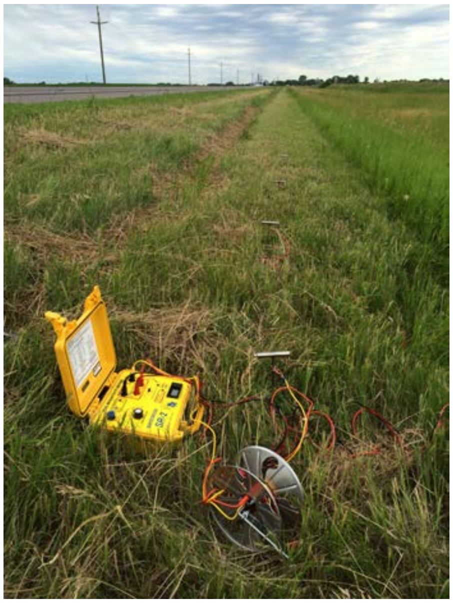


Figure 2.1: Equipment set up for soil resistivity sampling.

Rocky soils were problematic for taking soil resistivity measurements along many roadsides, as it made it very difficult to insert the soil probes to a sufficient depth to take measurements. Also, the presence of larger particles/clasts in the subsurface can potentially compromise the resistivity measurement by returning higher resistivity measurements.

2.2.4 Water pH

If water was present on site at the time of sampling, water pH samples were collected and tested on site in accordance with ASTM D6569-14 (2014). This method was used to fulfill Part 2 of California Test 643. Water samples were collected in a 50-mL beaker and tested with a field pH tester accurate to 0.02 pH.

The measurements were taken with the HANNA Instruments model HI 9812 Water pH Meter. The pH meter was calibrated daily. A water sample was collected from the edge of the water body and placed in a non-conductive beaker. Any surface debris was poured off and the meter probe was inserted into the beaker for the measurement. Replicate water samples were taken at each site until three samples were recorded within 10% of each other.

2.2.5 Water Conductivity

If water was present on site at the time of sampling, water conductivity samples were collected and tested on site in accordance with ASTM D1125-14 (2014) Test Method A. The inverse of the conductivity measurements were taken as the water resistivity measurement in lieu of Part 4G of California Test 643. California Test 643 considers the maximum possible resistivity of water to be 20 kohm-cm; consequently, this technique is valid provided the conductivity meter can resolve down to 50 uS/cm or 0.05 mS/cm.

The measurements were taken with the Hanna Instruments model HI 993310: Portable Water Conductivity & Soil Salinity Meter. The conductivity meter was calibrated daily. The basic sample procedure included collecting a water sample in a non-conductive beaker, pouring off any surface debris, and taking a measurement from the middle of the sample using the calibrated conductivity meter. Replicate water samples were taken at each until three samples recorded within 10% of each other.

2.2.6 Land Use Observations

Land use classifications were recorded for areas adjacent to the sampling sites, particularly upland areas that drain to the sample site.

Land use was classified as:

1) residential
2) commercial
3) industrial
4) agricultural corn/soybeans
5) agricultural other
6) feedlot
7) stream

8) wetland
9) bog/fen
10) wooded
11) lawn
12) prairie/fallow

2.2.7 Soil Texture

At each site a soil sample was taken from just below the topsoil horizon. The soil texture was determined using the field test method provided by MnDNR's Ecological Land Classification Program (Appendix B).

2.3 Data Collection Results

A total of 564 data points were collected throughout the state of Minnesota (Figure 2.2) during the 2014 summer campaign, with roughly 50-90 points per district (Table 2.1). For week by week summaries of data collection efforts, see Appendix A. Each data point was assigned a unique identifier. However, due to field conditions it was not possible to collect all parameters at particular locations; for instance, shallow bedrock and hard soil conditions made it relatively impossible to properly install the resistivity pins to take a soil resistivity measurement. At some sites with dry and/or sandier soils, it was difficult to ensure proper soil contact with the soil pH meter probe to take a reading.

The following subsections provide an overview of data results for different parameters.

Table 2.1: Sample dates and number of data points for each MnDOT District.

Sampling Week(s)	District Number	Number of Samples
7/7-10/2014; 8/10-11/2014	1	80
7/21-24/2014; 7/28-31/2014	2	82
7/14-17/2014; 7/21-24/2014; 7/28-31/2014	3	88
7/14-17/2014; 7/21-24/2014	4	51
6/2-5/2014; 8/7/2014	Metro	51
6/9-12/2014; 8/18-19/2014	6	62
6/16-19/2014; 8/4-6/2014	7	64
6/30-7/3/2014	8	86

2.3.1 Soil pH Data

Soil pH data were successfully obtained at 559 sample locations. pH values ranged from 5.11 to 8.19. See Figure 2.3 for the spatial distribution of the data.

Soil pH values, in general, were most acidic in the northeastern portion of the state (District 1 and parts of District 3), with more acidic values (6.5-6.9) scattered throughout the state. Neutral and basic pH values were generally recorded in southern and western Minnesota.

To capture local variability, the field researcher often took two different points along an embankment at a sample site. The soil pH could change significantly – up to a 1.5 measured difference – at a sample location. Thus for reporting, generally the range was noted and an average value calculated for the site.

2.3.2 Soil Resistivity Data

Soil resistivity data were successfully obtained at 548 sample locations. Values ranged from 574 to 5,772,768 ohm-cm. See Figure 2.4 for the spatial distribution of the data.

Soil resistivity values generally ranged very high in northeastern Minnesota (>6,000 ohm-cm), but were lower in the Metro area and most of southwestern Minnesota (<6,000 ohm-cm).

2.3.3 Water Conductivity and pH Data

Water samples were collected and tested at approximately 53 sites. Most water samples were collected in flooded fields and drainage ditches during the first three weeks of the field campaign, as several storms moved through southern Minnesota.

Water pH results ranged 6.5 to 7.8. As the majority of these samples came from areas flooded by recent storms, it was not surprising they were near neutral pH and are not likely indicative of ambient water chemistry. Water conductivity results ranged from 0.0 to 2.0 mS/cm, which translates to resistivity values near 500 ohm-cm.

2.3.4 Soil Texture

The field researcher classified soil texture at each sample site. The majority of samples were comprised of sandy loam (110 samples), sandy clay loam (105 samples), and sandy clay (81 samples). See Figure 2.5 for the spatial distribution of the soil texture data.

2.3.5 Land Use

Information regarding the adjacent land use was collected at each sample location to potentially provide insight of the influence of specific local conditions on soil pH and resistivity. Table 2.2 summarizes the general land uses associated with the number of samples.

Table 2.2: Sample collection by adjacent land use.

Surrounding Land Use	**Number of Sample Locations**	**Number of Water Samples**
Agricultural	252	30
Commercial	49	4
Residential/Rural	81	8
Pasture	25	4
Wooded	146	4
Wetland	3	2
Railway/Industrial	4	1

2.3.6 Road Surface Type and Number of Lanes

The majority of samples were collected on the embankment of asphalt roadways (512 samples), followed by concrete roadways (48 samples), and one gravel roadway sample. Most samples were also collected on 2-lane roadways (449 samples), followed by 4-lane roadways (111 samples), and one 6-lane roadway sample.

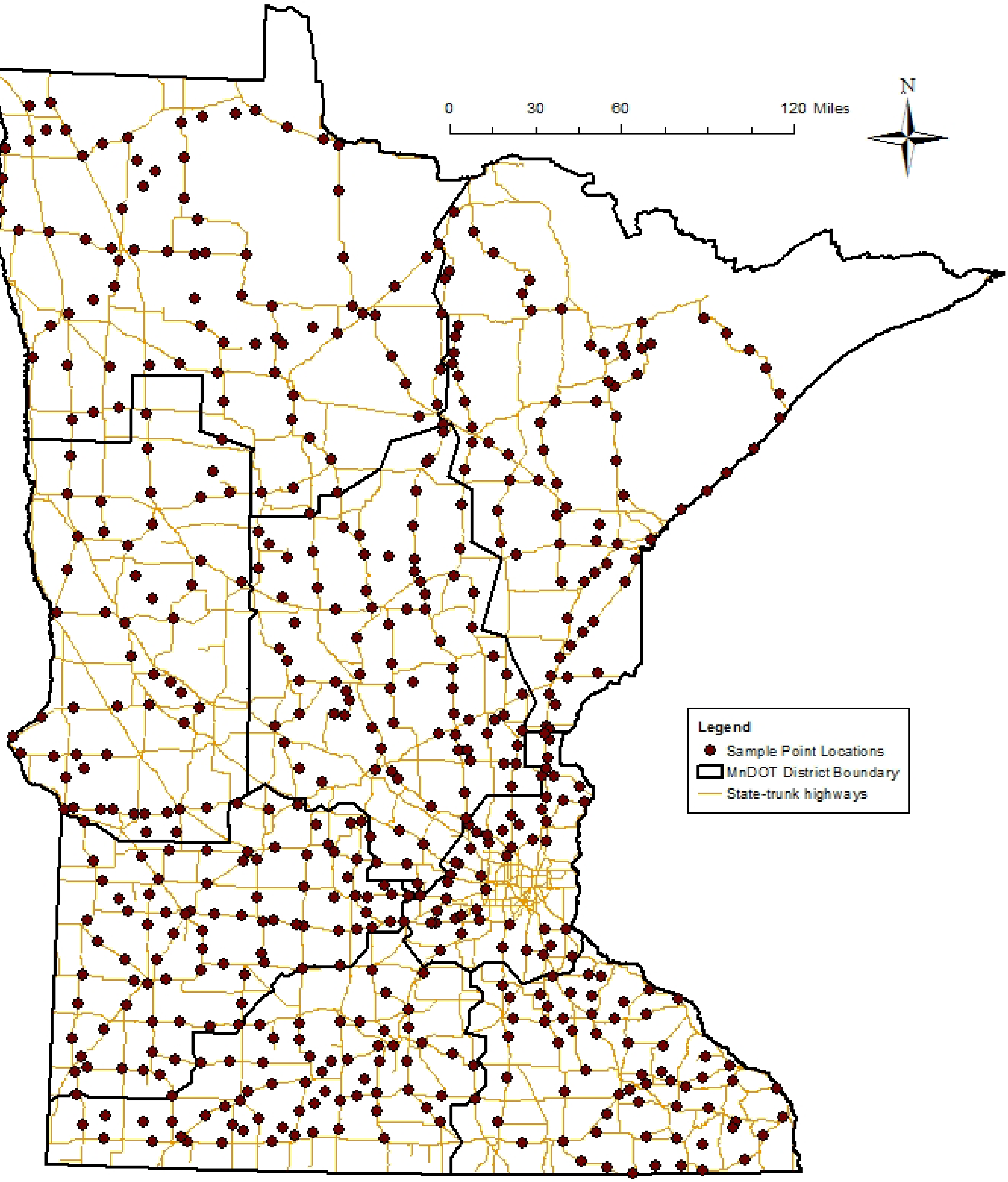


Figure 2.2: Sample point locations from summer 2014 field campaign.

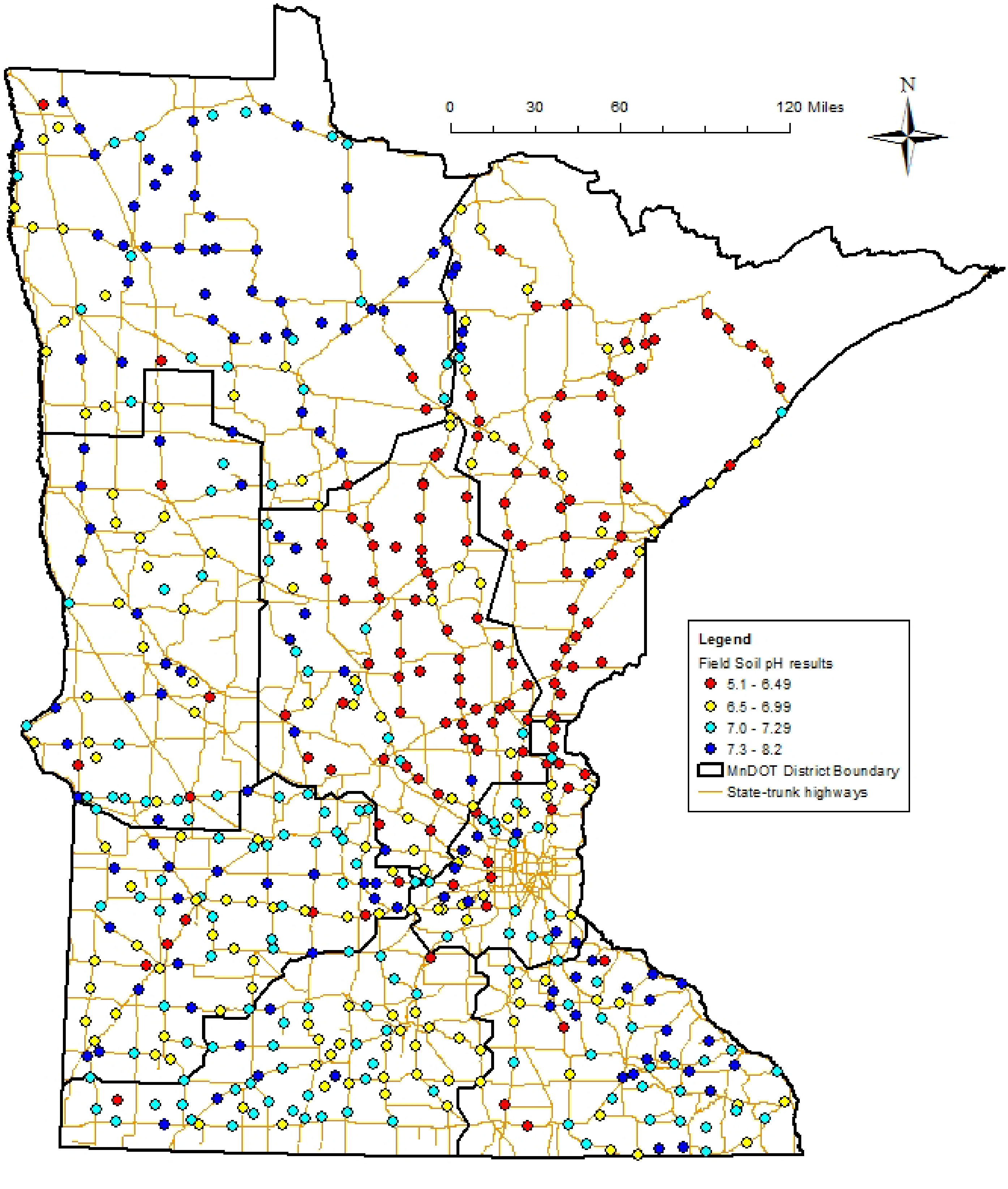


Figure 2.3: Field-collected soil pH results.

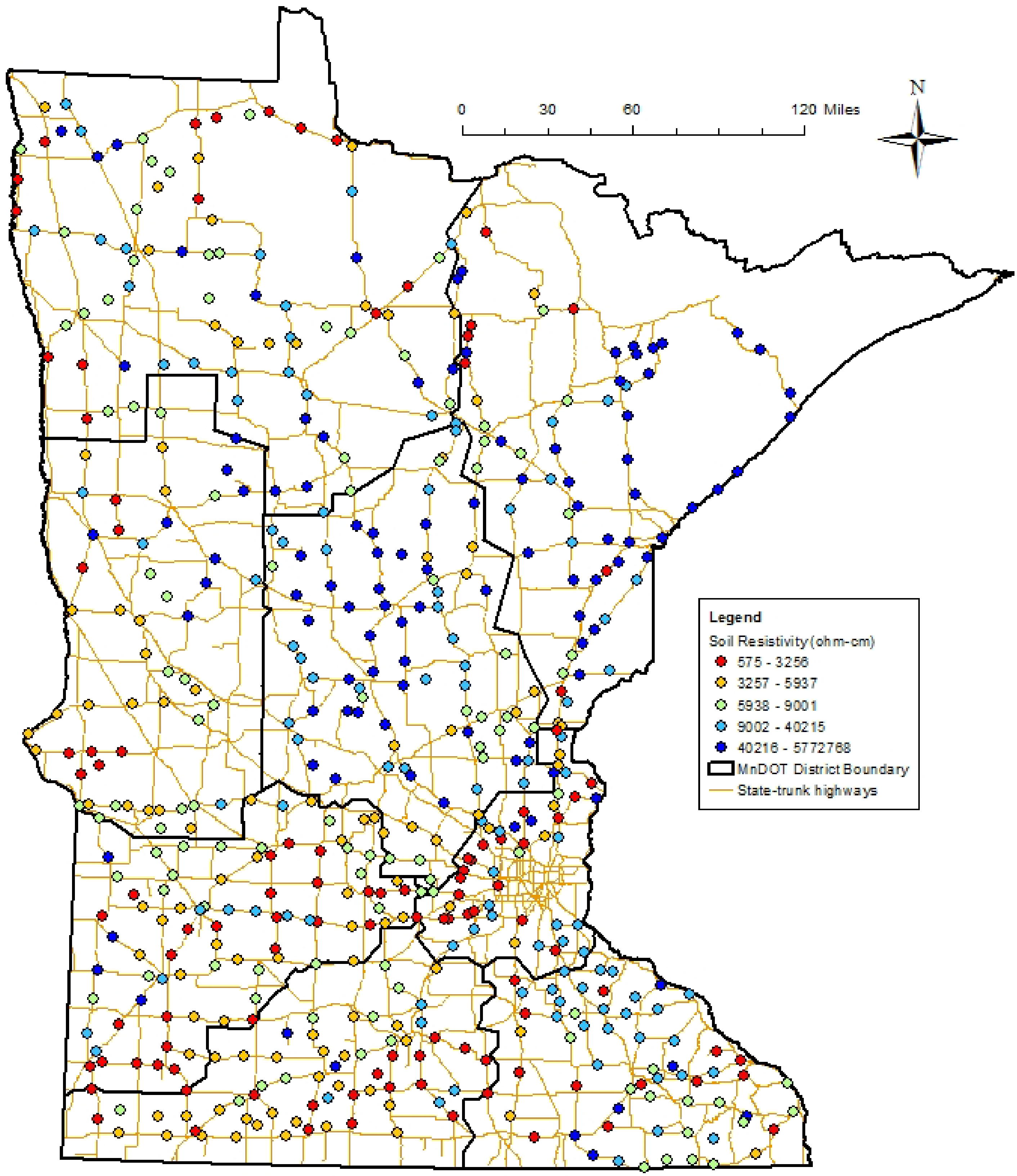


Figure 2.4: Field-collected soil resistivity results.

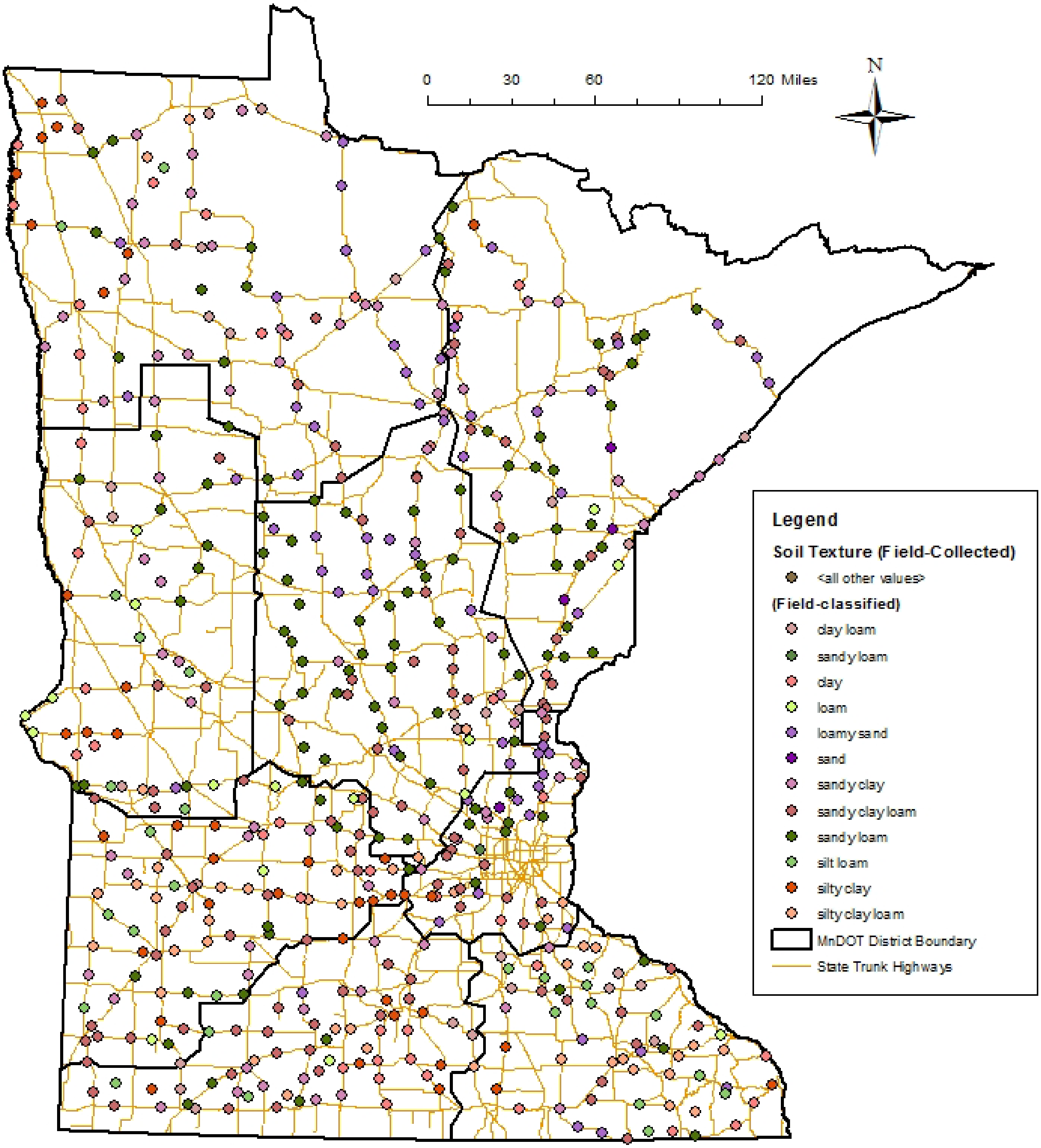


Figure 2.5: Soil texture field classification results.

CHAPTER 3: DATA VALIDATION AND ANALYSIS

In order to generate the most accurate service-life maps possible, it is important to validate the field measured and observed data as being reasonable for inclusion as inputs into the service-life calculation. This section of the report attempts to identify additional lines of evidence, including existing soil, geology, and other data sets to help explain trends and patterns observed in the field data. As soil pH and soil resistivity were the most successfully collected data and are the inputs that feed directly into the California Test 643 equation, the majority of this chapter focuses on these two parameters.

3.1 Soil pH

As shown in Figure 2.3, soil pH values generally were most acidic in the northeastern portion of the state (District 1 and parts of District 3), with some more acidic values (6.5-6.9) scattered throughout the state. Neutral and basic pH values were generally recorded in southern and western Minnesota.

Two methods were used to validate the soil pH data. The first was using the USDA-NRCS regional state soil geographic data base (STATSGO), which includes a soil pH layer (Miller and White, 1998). The data were plotted behind the observed sample points with the same colors and pH ranges (Figure 3.1). The second data validation method included observations from state and county engineers on whether they have observed or measured similar values to this data.

Overall, the STATSGO data and the measured soil pH data show agreement to one another, demonstrating that this layer may represent a reasonable proxy to statewide soil pH trends. There are two areas of the state, however, that show general disagreement. These two areas include southeastern Minnesota (District 6) and north central Minnesota (District 2). From the STATSGO data, more acidic values are predicted than were observed in both areas. Conversations with district engineers in both districts provided some insight into why measured field pH is more basic than anticipated. In District 6, engineers generally use crushed limestone (calcium carbonate) in road construction activities (Meath, personal communication). As crushed limestone would provide a more basic pH value, it is probable that the introduction of such material into the native soil may provide a more basic soil pH reading.

In District 2, the materials engineer indicated that only native material is used in road construction activities and that groundwater chemistry may be influencing pH readings (Bittmann, personal communication). Given the extensive amount of peat mapped in District 2, a soil material that is widely known for creating more acidic conditions, this analysis uses the STATSGO data, as it provides a more conservative estimate of service life.

Other involved Technical Advisory Panel (TAP) members, including present state and county officials, generally agreed with the soil pH data, specifically noting that the most acidic values would likely be due to the frequent presence of peat and wetlands in northeastern Minnesota.

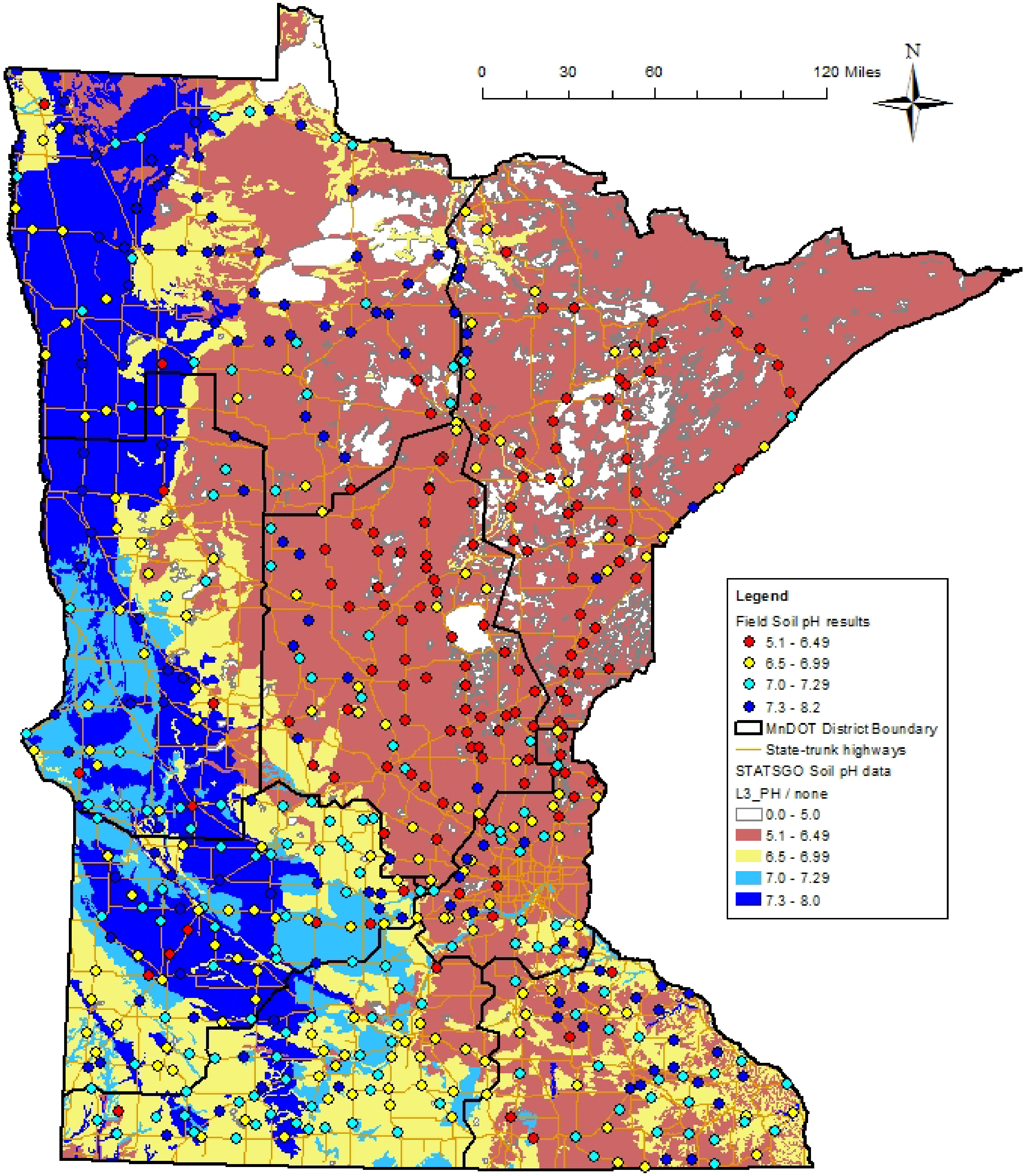


Figure 3.1: Comparison of field-collect soil pH data (points) with soil pH layer from STATSGO data set.

These two lines of data verification demonstrate that the measured soil pH data are reasonable and can be used for providing reasonable estimates of steel pipe service life. Furthermore, the general agreement with the STATSGO soil pH data indicates that the STATSGO data provides reasonable estimates of soil pH, with one major exception in District 6.

3.2 Soil Resistivity

As shown in Figure 2.3, soil resistivity values generally ranged very high in northeastern Minnesota (>6,000 ohm-cm), but were lower in the Metro area and most of southwestern Minnesota (<6,000 ohm-cm). For reference, soil resistivity values in other studies generally range from 500-1,000,000 ohm-cm (Samouelian et al., 2005).

Validating the soil resistivity data is trickier than the pH data, as several more factors can influence resistivity values. Specifically, soil resistivity depends largely on soil texture, soil moisture, and soil temperature. It varies seasonally, and values can be skewed if bedrock is close to the surface or if there are larger rocks or rock fragments in the sampling area.

Overall, observations made by county and state officials disagree with the high resistivity values measured in northeastern Minnesota, specifically in District 1. Fifteen resistivity measurements were unable to be taken due to shallow bedrock or difficulty of getting the resistivity meter pins into the ground. Ten of those fifteen measurements are in District 1 and four of them in District 3. It is likely that a large portion of the data taken in northeastern Minnesota is not reasonable, which makes it difficult to use the data to create relevant estimates of steel pipe service life for that area. It also puts the validity of resistivity values throughout the remainder of the state into question, as large ranges in resistivity were observed in adjacent sample areas and locations.

Efforts to identify other sources of soil resistivity data included locating available soil electrical conductivity data, which can be used to calculate soil resistivity by taking the inverse of the electrical conductivity value. Electrical conductivity data exists for the state of Minnesota through the Natural Resource Conservation Service (NRCS) gSSURGO data (NRCS, 2015), however the data is extremely limited and not useful for this project.

Soil texture is a potential soil resistivity proxy, as soil cohesiveness influences how easily an electrical impulse is able to transmit through the soil. Clay soils are more cohesive, which generally means soil resistivity values are going to be lower as electrical currents will be able to smoothly transmit through the soil. Tables 3.1 and 3.2 shows general ranges of soil resistivity for different types of soil, and Table 3.2 describes generally how different soil types translate to overall corrosive conditions, including other potential factors such as the level of soil drainage, color, and the level of the water table.

Although soil texture is only one driver of soil resistivity and can be highly spatially variable depending on the overall soil structure, it provides a more consistent state for a soil resistivity proxy versus the spatially and temporally variable soil moisture and soil temperature. However, it is important to note that changes in soil moisture content and soil temperature can have significant impact on estimates in soil resistivity (Samouëlian et al., 2005), and therefore highly varying service-life estimates for steel pipe culverts. Accounting for such conditions is discussed later in Chapters 4 and 5.

Table 3.1: General resistivity values for different soil types (soil types described in Table 3.2) (Molinas and Mommandi, 2009).

Soil Type	Degree of Corrosiveness	Electrical Resistivity Ohm-cm
1	Very low	10,000-6,000
2	Low	6,000-4,500
3	Moderate	4,500-2,000
4	Severe	2,000-0

Table 3.2: Degree of corrosion for different soil types (Molinas and Mommandi, 2009).

Soil Type	Description of Soil	Aeration	Drainage	Color	Water Table
I - Lightly Corrosive	1. Sands or sandy loams 2. Light textured silt loams 3. Porous loams or clay loams thoroughly oxidized to great depths	Good	Good	Uniform Color	Very low
II - Moderately Corrosive	1. Sandy loams 2. Silt loams 3. Clay loams	Fair	Fair	Slight mottling	Low
III - Badly Corrosive	1. Clay loams 2. Clays	Poor	Poor	Heavy texture Moderate mottling	2ft to 3 ft below surface
IV - Unusually Corrosive	1. Muck 2. Peat 3. Tidal marsh 4. Clays and organic soils	Very poor	Very Poor	Bluish grey mottling	At surface; or extreme impermeability

As described in Chapter 2, soil texture was collected at each sample site during the 2014 field campaign using the Minnesota DNR soil texture classification system (Appendix B). Furthermore, soil texture is available as a statewide STATSGO map (Miller and White, 1998). Figure 3.2 compares the field-classified soil texture against the standard layer 3 (to a depth of 10 centimeters) of the STATSGO statewide soil texture map. Overall, the maps show good agreement, with sand and sandy loams comprising central and parts of northern Minnesota and clay, clay loams, and sandy clay loams largely comprising southern Minnesota. It is of note that none of the field soil texture samples were classified as organic materials (generally located in north central Minnesota), as road embankments would not include such soils as fill.

A proxy soil resistivity map was built using the STATSGO soil resistivity map and average values of resistivity using the ranges provided in the Molinas and Mommandi (2009) report are shown in Tables 3.1 and 3.2. As the field campaign and STATSGO map contained more categories of soil texture versus what is reported in Molinas and Mommandi (2009), remaining soil texture categories were assigned a value based on their constituent components, with more conservative numbers (more prone to corrosion) assigned to those textures containing clay and organic materials (Table 3.3). Figure 3.3 shows the resultant soil resistivity map based on soil texture.

Table 3.3: Resistivity values used for different soil types, using Molinas and Mommandi, 2009 values to guide selection (Tables 3.1 and 3.2).

	Electrical Resistivity (ohm-cm)		
Soil texture	**Minimum**	**Average**	**Maximum**
Peat/Organic Material	0	1000	2000
Sandy Clay	2000	3250	4500
Silty Clay Loam	2000	3250	4500
Silty Clay	2000	3250	4500
Clay	0	1000	2000
Sandy Clay Loam	2000	3250	4500
Clay Loam	2000	3250	4500
Silt Loam	2000	3250	4500
Loam	2000	6000	10000
Loamy Sand	6000	8000	10000
Sandy loam	4500	5250	6000
Sand	6000	8000	10000

3.3 Additional Collected Data Analysis

This section addresses other data collected in summer 2014 that may be useful in illustrating potential patterns or trends in soil pH and soil resistivity. These parameters may be useful in generating service-life guidelines for local conditions.

3.3.1 Water Sample Analysis

Approximately 53 water samples were collected and tested onsite for water pH and water conductivity. Water conductivity values were converted to water resistivity in order to compare values with soil resistivity. As shown in Figures 3.4 and 3.5, no apparent relationship appears to exist between water and soil pH values or water and soil resistivity values. Most water samples collected were associated with recent rainfall or storm conditions, which indicates that the residence time of the sampled water was too short to equilibrate to ambient soil and water conditions.

3.3.2 Proximity to Lakes and Wetlands

To determine whether soil pH or soil resistivity values were influenced by the proximity to a nearby waterbody such as a lake or wetland, a GIS analysis was used to determine the closest lake and wetland to each of the sample locations. Figures 3.6-3.9 show the results of this analysis.

The majority of acidic samples (< 7 pH) were located less than 10 miles away from either wetlands or lakes (Figures 3.6 and 3.8). However, many basic samples (≥ 7 pH) were also sampled at those same distances, indicating that proximity to waterbodies does not necessarily suggest acidic soil conditions.

No discernable influence of waterbody proximity for soil resistivity values appears to exist, with wide-ranging values of soil resistivity across distances (Figures 3.7 and 3.9). However, as soil resistivity is very dependent on soil moisture content, it is worthwhile to note where wetter conditions exist (such as near a wetland or lake), as these may significantly impact soil resistivity values, and hence, service-life estimates.

3.3.3 Land Use Analysis

Soil pH and soil resistivity results were reviewed for each major class of land use identified from the field campaign (results in Chapter 2.3.5). Overall a broad range of soil pH and soil resistivity was noted with each land use designation, indicating that land use specifically will not likely predict soil pH or soil resistivity values that determine service-life estimates.

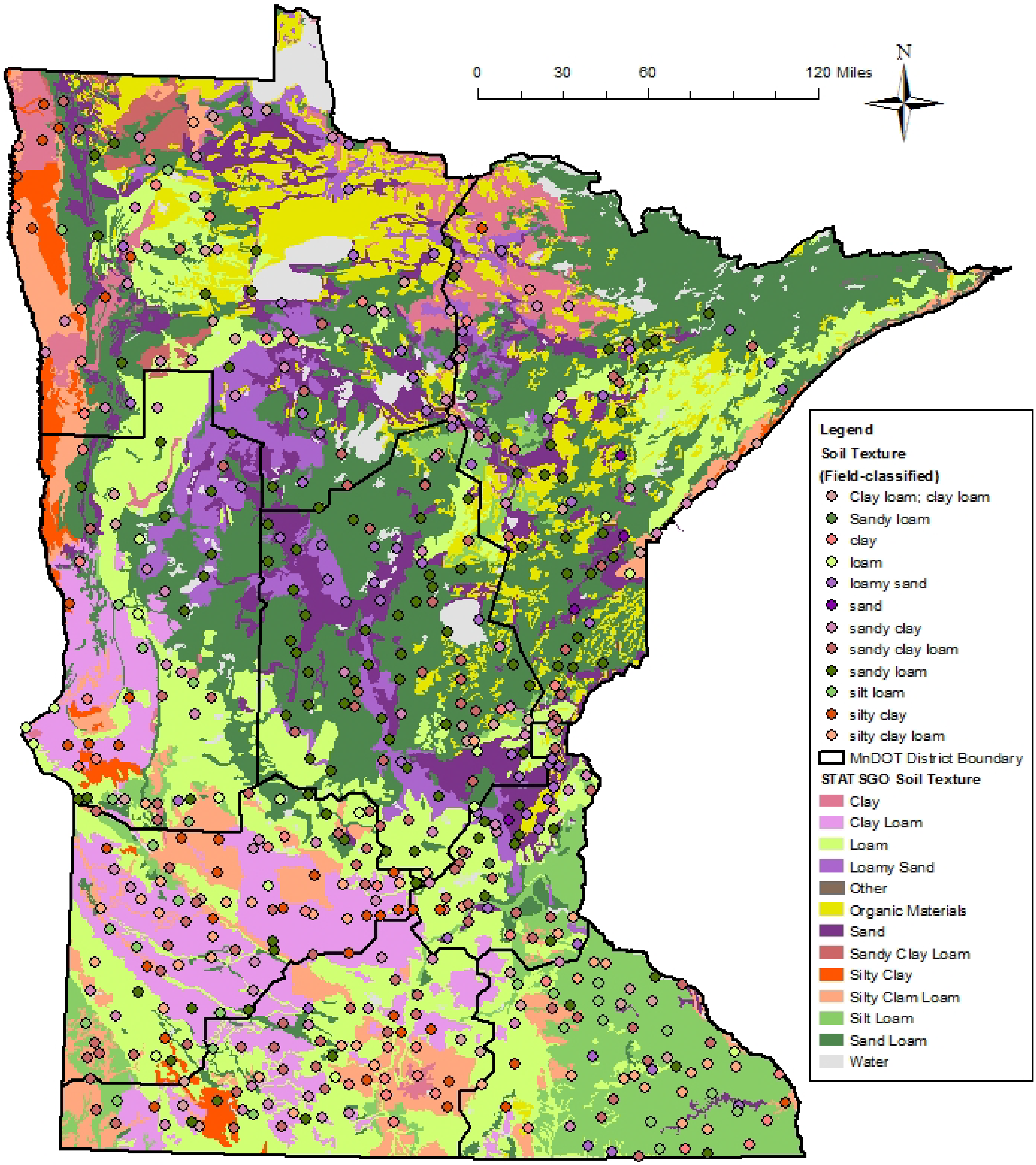


Figure 3.2: Comparison of field-classified soil texture and STATSGO statewide soil texture map.

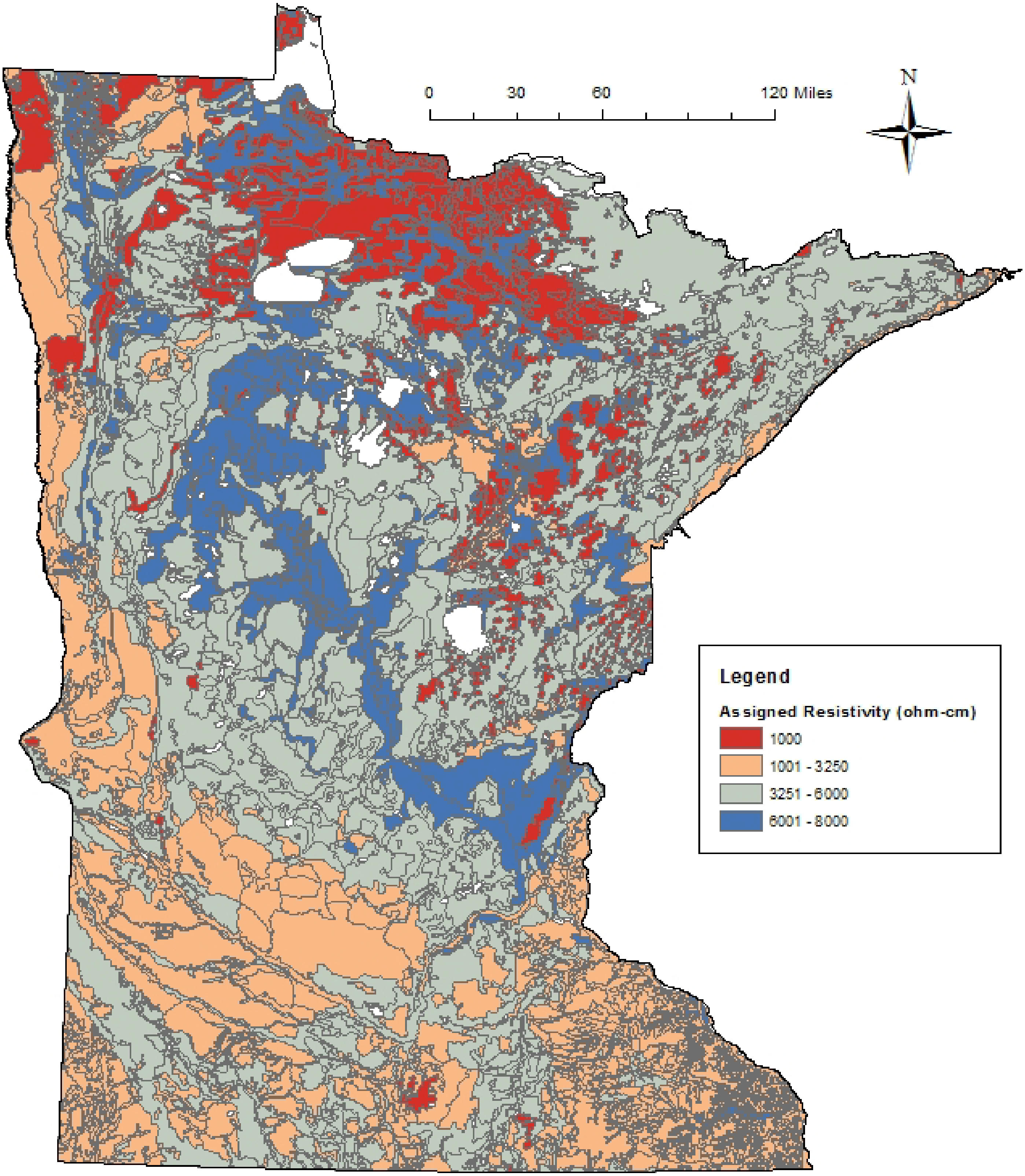


Figure 3.3: Soil resistivity map generated using STATSGO soil texture map and average values of soil resistivity from Table 3.3.

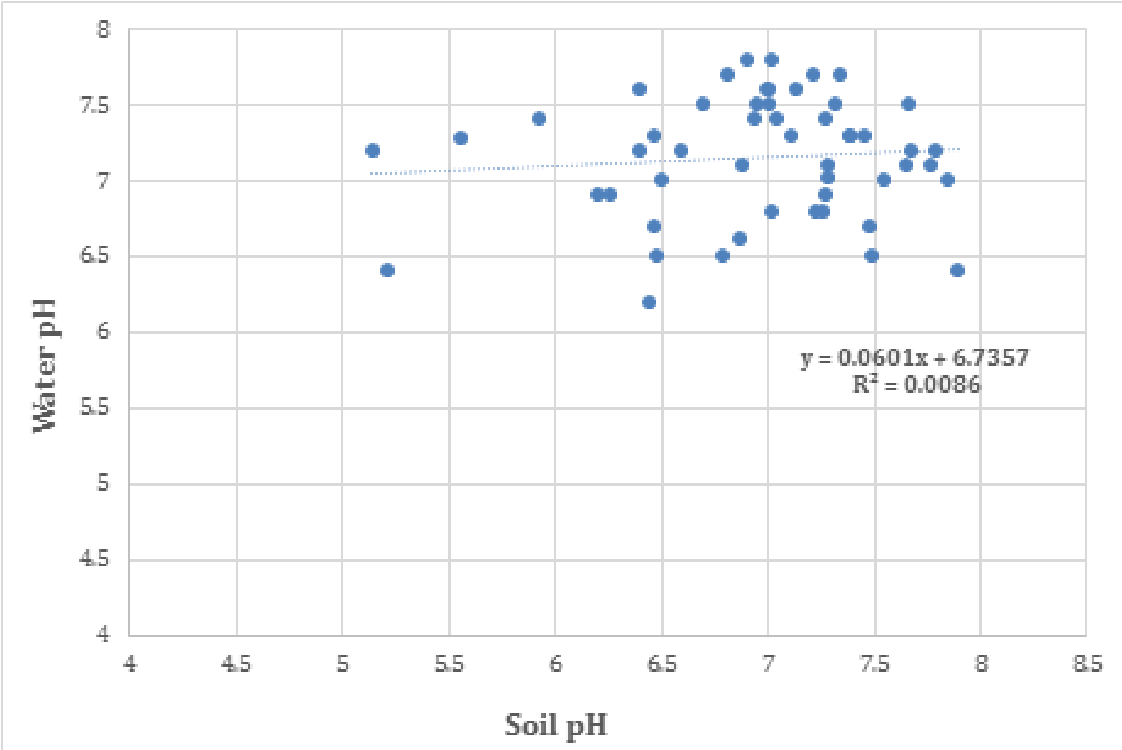


Figure 3.4: Field water pH results against field soil pH results.

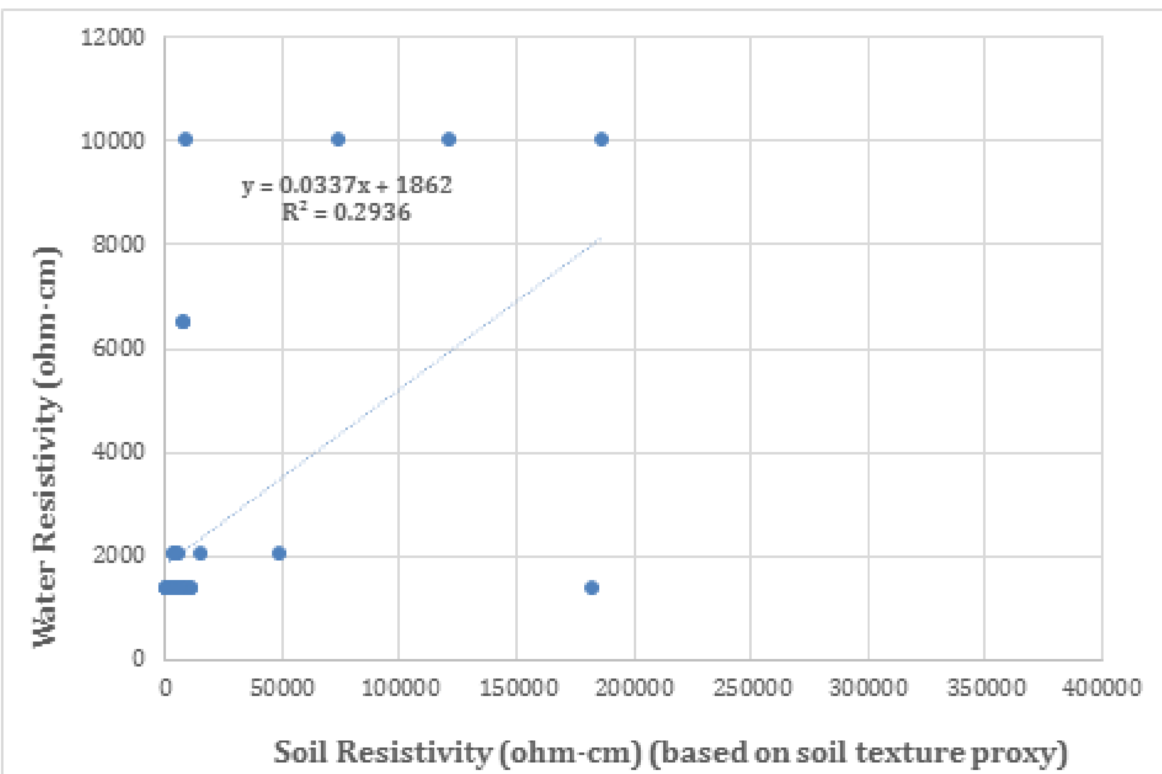


Figure 3.5: Soil versus water resistivity values (using soil texture resistivity proxy).

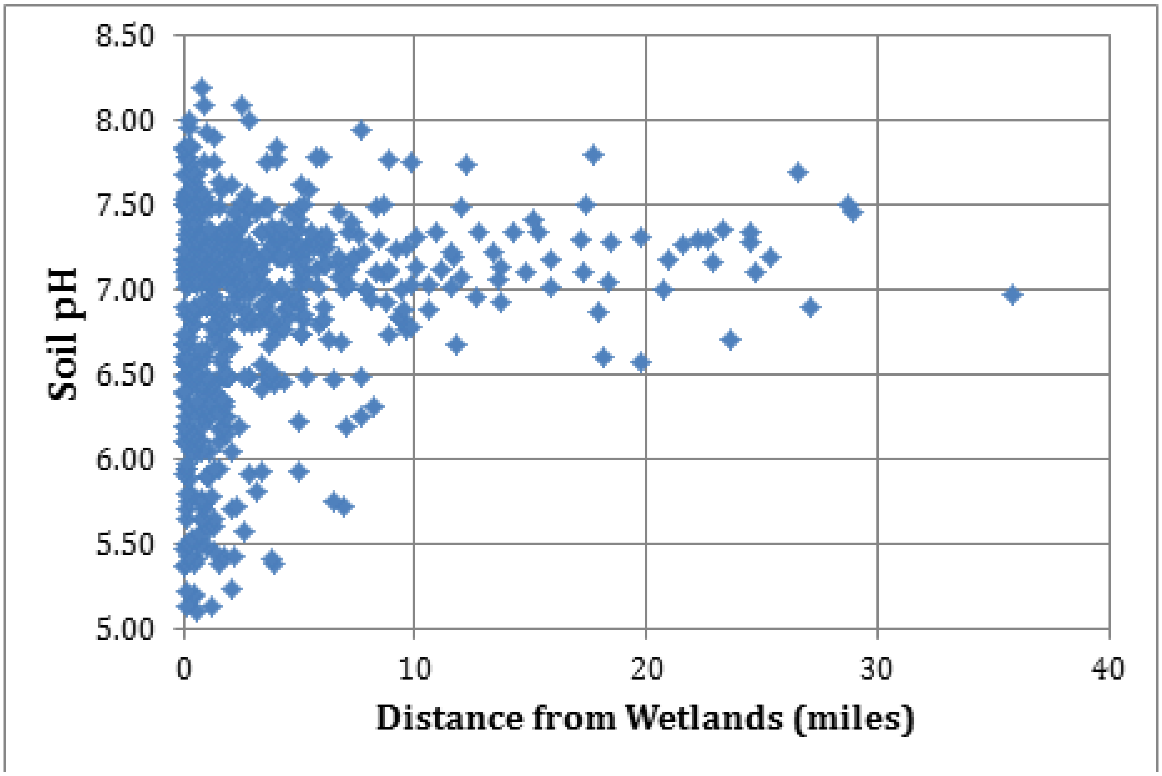


Figure 3.6: Field measured soil pH versus distance to closest mapped wetland.

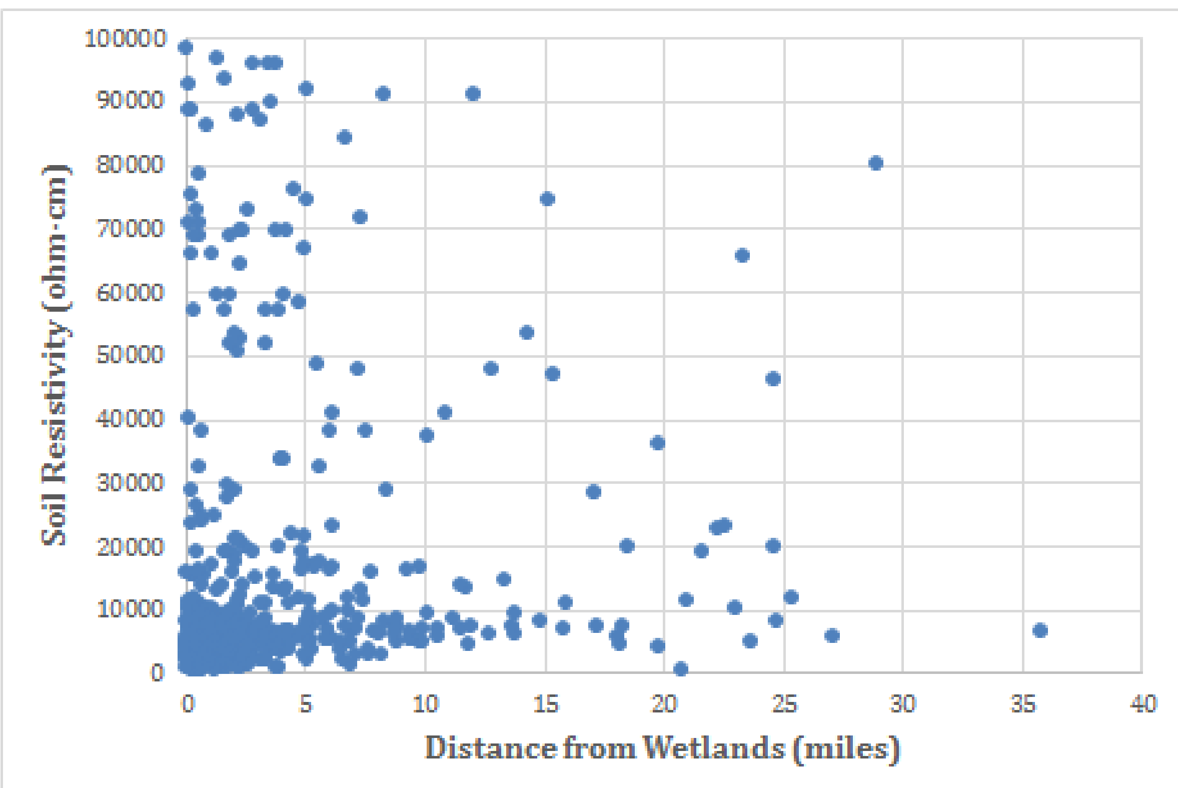


Figure 3.7: Field soil resistivity versus proximity to nearest wetland.

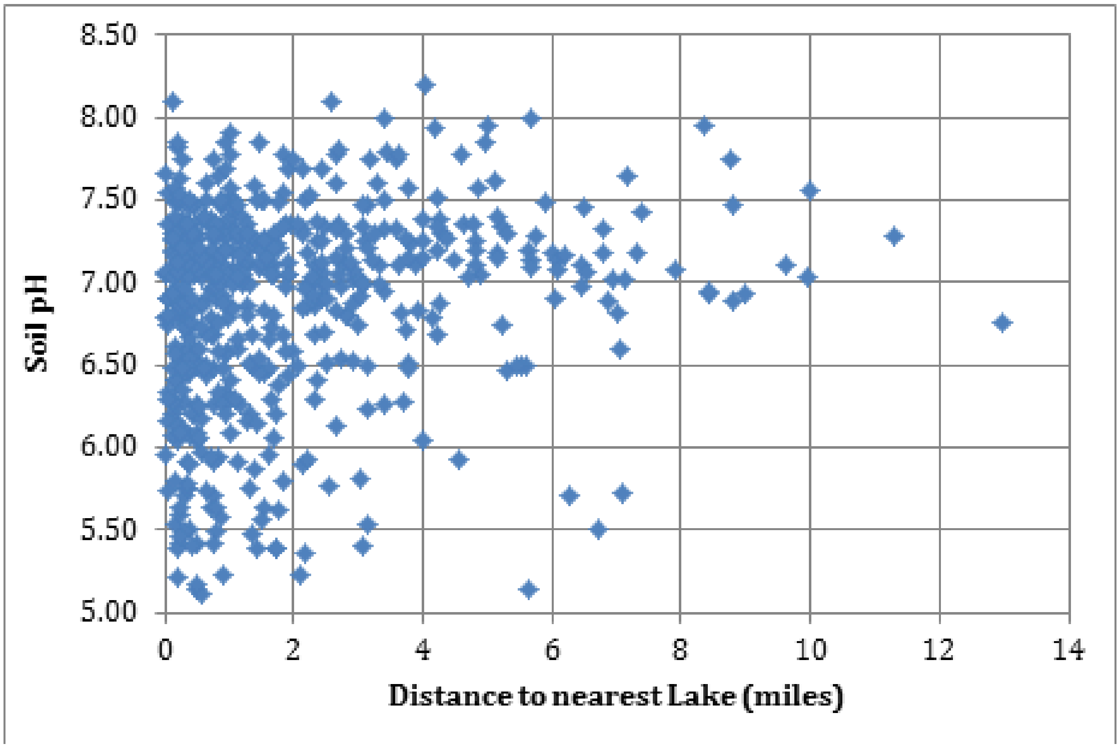


Figure 3.8: Field soil pH versus proximity to nearest lake.

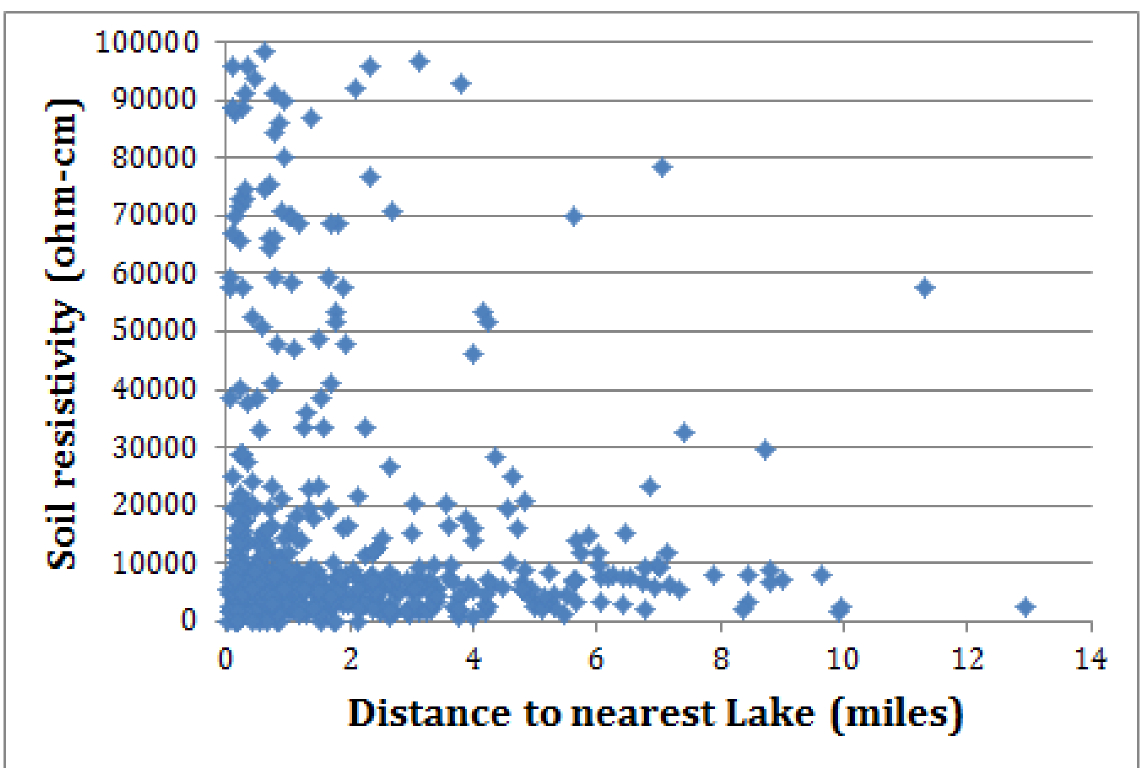


Figure 3.9: Field soil resistivity versus proximity to nearest lake.

CHAPTER 4: SERVICE LIFE ESTIMATES AND MAP GENERATION

4.1 Selection of Data for Use in Service-Life Calculation

Two approaches were considered when determining the best data to use for calculating service-life estimates: 1) interpolating the field-collected soil pH and resistivity data to create a statewide map for each parameter, or 2) using existing statewide datasets to calculate service-life estimates. While the intent of this project initially was to use field-collected data as the driving inputs for the service-life calculation and map generation, there are limitations to this approach. First, while the field-collected soil pH data overall is considered reasonable and valid, the field-collected soil resistivity data does not provide enough confidence for use in calculating service life. Furthermore, creating an interpolated statewide map from such data points is very dependent on the interpolation method selected, and the resolution offered with such an approach is generally coarse. Outlier data points could also significantly skew interpolation results and there is not a clear method for identifying and removing suspect data.

In considering use of existing data sets for the calculation input data, the STATSGO data has statewide cover and the method for generating it is well established throughout the contiguous United States. Furthermore, as demonstrated in the previous chapter, the field-collected data, specifically soil pH and soil texture (used as a soil resistivity proxy), do a reasonable job in validating the general statewide trends and patterns seen in the existing STATSGO data sets. The field data is also useful in demonstrating areas where the STATSGO data may not accurately capture local conditions (such as the soil pH data in Districts 2 and 6), providing the opportunity to study and understand where calculations of service life may be over or underestimated.

The remainder of this chapter describes the service-life calculation for different pipe gages and types of steel pipe, including 18-, 16-, 14-, 12-, 10-, and 8-gage galvanized and aluminized steel pipe, as these are the types of steel pipe generally considered for installation. A section on caveats and local conditions is also included to provide guidance of when these maps could be most useful or when they should not be used.

4.2 Service-Life Calculation and Map Generation

4.2.1 Service-Life Equation for Steel Pipe of Various Gage and Types

The Caltrans 643 service-life equation is as follows:

For pH values greater than 7.3 (pH > 7.3):

$$\text{YEARS} = 1.47R^{0.41} \quad \text{where R = resistivity in ohm-cm}$$

For pH values less than 7.3 (pH < 7.3):

$$\text{YEARS} = 13.79[\mathit{Log}_{10}\text{R}-\mathit{Log}_{10}(2160-2490(\mathit{Log}_{10}\text{pH}))$$

where R = resistivity in ohm-cm and pH = pH value (unitless)

This base equation calculates service life for 18-gage galvanized steel pipe. In order to calculate service-life estimates for other gages and types of pipe, the result of this equation is multiplied by a multiplier (Table 4.1). For example, to predict the service life of 12-gage aluminized pipe, the result of the service-life equation must be multiplied by 3.5.

Table 4.1: Service-life equation multipliers for different gages and types of steel pipe. GALV = Galvanized and ALT2 = Aluminized.

Gage	18	16	14	12	10	8
Thickness (inches)	0.052	0.064	0.079	0.109	0.138	0.168
Thickness (mm)	1.32	1.63	2.01	2.77	3.51	4.27
GALV.	1	1.3	1.6	2.2	2.8	3.4
ALT2.	2.3	2.6	2.9	3.5	4.1	4.7

4.2.2 Generation of Base 18-Gage Galvanized Map

Service-life maps were generated using the raster calculator in ArcGIS (version 10.1). The STATSGO pH layer and soil resistivity layer (based on soil texture) were converted into gridded raster layers with a grid cell size of 1 square kilometer. The service-life equation was then entered into the raster calculator, incorporating the conditional service-life equation if the soil pH was equal to or greater than 7.3. Figure 4.1 shows the resultant service-life map for 18-gage galvanized steel pipe.

Generally, the map indicates that service-life estimates are lower throughout eastern Minnesota (<25 years) for 18-gage galvanized pipe and increase in western Minnesota with a linear north-south feature of higher service life (50-74 years) near the western border. The line of highest service life coincides with the area of soil pH estimated to exceed 7.3, which means the service-life equation relies solely on soil resistivity values.

One check of this map is an uncoated steel corrosion map developed by NRCS that has incomplete coverage throughout Minnesota (Figure 4.2). While this map does not specify an actual value of estimated service life for uncoated steel, it does provide some context on whether highly corrosive conditions likely exist in an area. There are some similarities with the 18-gage galvanized service-life map. It also shows an outline of low-moderate corrosion conditions in the linear north-south feature in western Minnesota and generally shows the potential for more corrosive conditions throughout the state. A large discrepancy between the maps is in southeastern Minnesota, where the NRCS map indicates low corrosion potential versus that area having a < 25-year service life, as predicted in this analysis. This supports the observation that the basic pH conditions noted in the field (> 7) are more likely reflective of conditions in that area than captured in the STATSGO dataset and indicates the need to provide some adjustment of those service-life estimates. This will be expanded upon in the zone delineation analysis in Chapter 5, but will not be incorporated in the maps generated in this chapter.

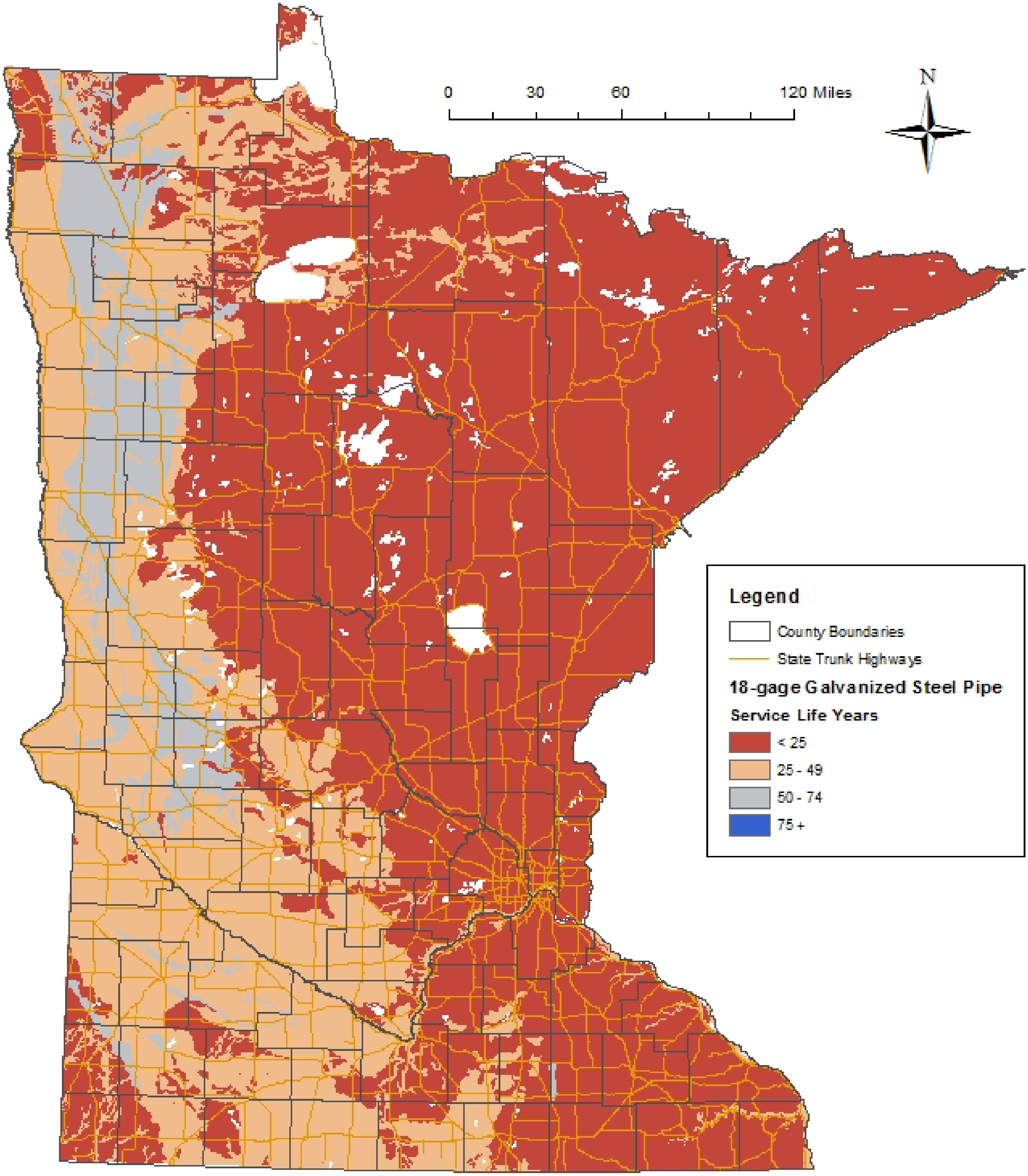


Figure 4.1: Service-life year calculation based on Caltrans 643 method for 18-gage galvanized steel pipe.

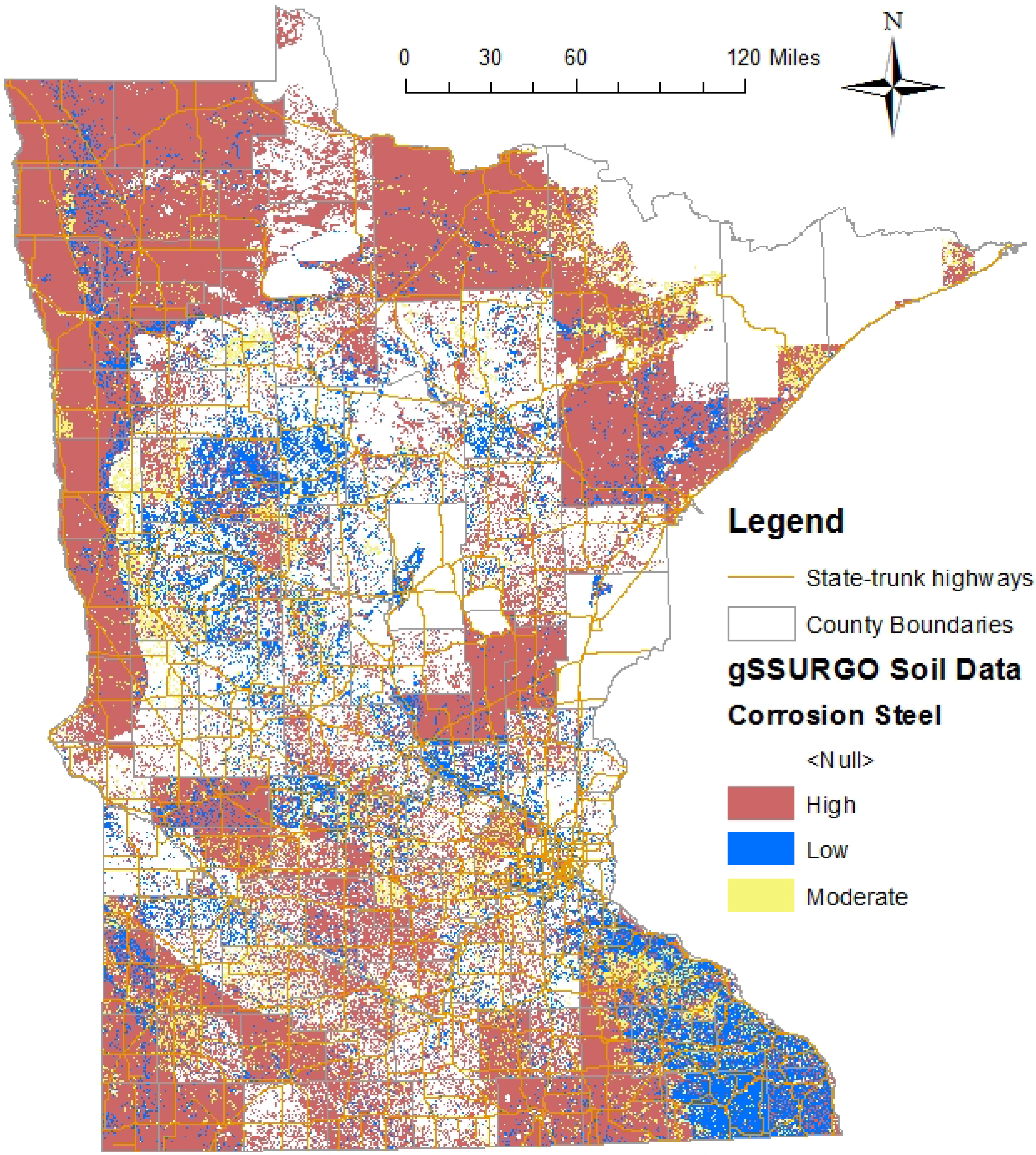


Figure 4.2: Uncoated steel corrosion map developed by NRCS.

4.2.3 Service-life Estimates for Various Gages and Types of Steel Pipe

Maps were generated using the ArcGIS raster calculator for 16-, 14-, 12-, 10-, and 8-gage galvanized and aluminized pipe using the multipliers stated in Table 4.1. Maps for 16- and 12-gage galvanized and aluminized pipe are presented here for comparison purposes, but all maps are included in Appendix C.

Figures 4.3 and 4.4 compare service-life estimates between 16-gage galvanized and aluminized steel pipe, and Figures 4.5 and 4.6 compare service-life estimates between 12-gage galvanized and aluminized steel pipe. The most prominent observation between these four maps illustrates how aluminized pipe overall provides a greater potential for a higher service life. In the 16-gage galvanized pipe (Figure 4.3), the majority of the map predicts service life under the design goal of 50 years, with the majority of areas in northeastern Minnesota still less than 25 years expected service life. In the 16-gage aluminized map (Figure 4.4), the majority of the map is in the 50-75 year range, with areas in northeastern Minnesota in the 24-49 year range. For the 12-gage galvanized map (Figure 4.5), a larger proportion of the map is in the 24-49 year category, although still not to the extent found in the 16-gage aluminized map. For the 12-gage aluminized map, most service-life estimates in western Minnesota are in the 75 + year category, with 50-74 year estimates for the rest of the state.

Throughout all of the maps, there are sections of northeastern and north central Minnesota that consistently remain in the < 25-year category. These areas generally have a very low pH (4-5) and the soil texture is generally classified as organic material, giving them a lower resistivity value. Many of these features are mapped wetlands, which may potentially impact adjacent service-life estimates by contributing to local conditions that reduce service life. This will be addressed in the following section.

4.3 Service-Life Map Constraints and Limitations

While the generated maps provide a reasonable overview of steel pipe service life throughout the state of Minnesota, several constraints and limitations to this analysis could significantly alter service-life estimates in particular areas. This section of the report outlines several constraints and limitations to the generated maps and analysis that should be considered during culvert material selection. Several of these caveats are also included again in the Chapter 5 discussion.

- **Abrasion:** The overall service-life equation does not take the potential for abrasion into account. If the stream or river of interest has significant bedload transport, the resulting potential abrasion could significantly reduce service-life estimates by wearing away the culvert wall. While this study does not address abrasion guidelines, general guidelines are present the in the current MnDOT drainage manual (MnDOT, 2000). Other references such as Molina and Mommandi (2009) also provide a review of various DOT methods for addressing abrasion.
- **Soil moisture:** As mentioned previously, soil resistivity values vary seasonally with soil moisture and soil temperature. As soil moisture and/or soil temperature increase, soil resistivity and subsequent service-life estimates decrease. While this analysis attempts to use conservative values for soil resistivity through the soil texture proxy, it does not address soil moisture or soil temperature. If the area of interest has high soil moisture

content and/or consistently warmer soil, these criteria suggest more corrosive conditions that could likely lead to lower service-life conditions than portrayed on the maps in this analysis.

- **Wet conditions:** Wet conditions refer to when there is standing or flowing water in/through a culvert generally year-round. Previous observations have demonstrated that wet conditions can accelerate steel pipe deterioration (Taylor and Marr, 2012). High water tables, consistent flow through a ditch or stream, or even channel bed aggradation can create wet conditions that can reduce service-life estimates.
- **Chloride:** Soil resistivity is also dependent on the soluble salts present in the soil. If an area of interest has had significant de-icing activities over a period of time, this can create more corrosive conditions that will reduce service-life estimates.
- **Proximity to wetlands/lakes:** As noted in Chapter 2, acidic and wet conditions are more likely to be present when located less than 10 miles from a wetland or lake. Even if a service-life estimate indicates an area should have a service life of 50 years of more, it is important to understand what local conditions may be contributing.
- **Southeast Minnesota:** As mentioned in sections 3.1, 4.1 and 4.2.2, this analysis underestimates service-life estimates in southeastern Minnesota due to lower pH values in the STATSGO data than those observed in the field. The zonal delineation in Chapter 5 will make this section into a separate zone with a modified service-life estimate.
- **Service-life estimate boundaries:** It is important to treat transitional areas in the map conservatively. For example, as mentioned in the previous section, northeastern Minnesota has wetland areas that generally have corrosive conditions (service-life estimates of < 25 years). While changing the pipe material may increase service-life estimates in areas *adjacent* to the wetlands, the boundary between these areas and the surrounding landscape is likely much more diffuse. It is important to understand local conditions to better constrain service-life estimates.

In the following chapter, a zonal delineation of service life is discussed and these constraints are again described and where possible, accounted for.

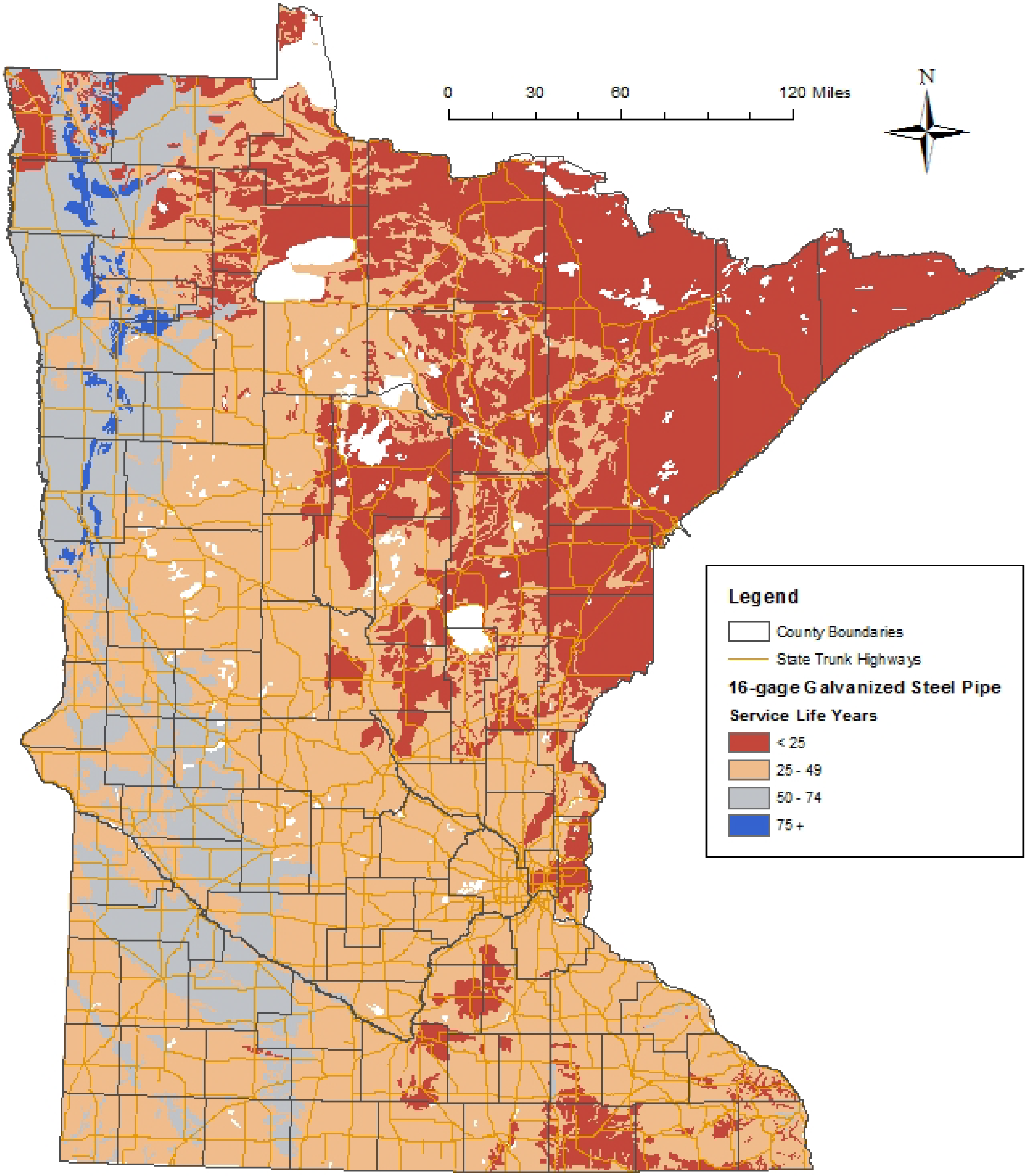


Figure 4.3: Service-life estimates for 16-gage galvanized steel pipe.

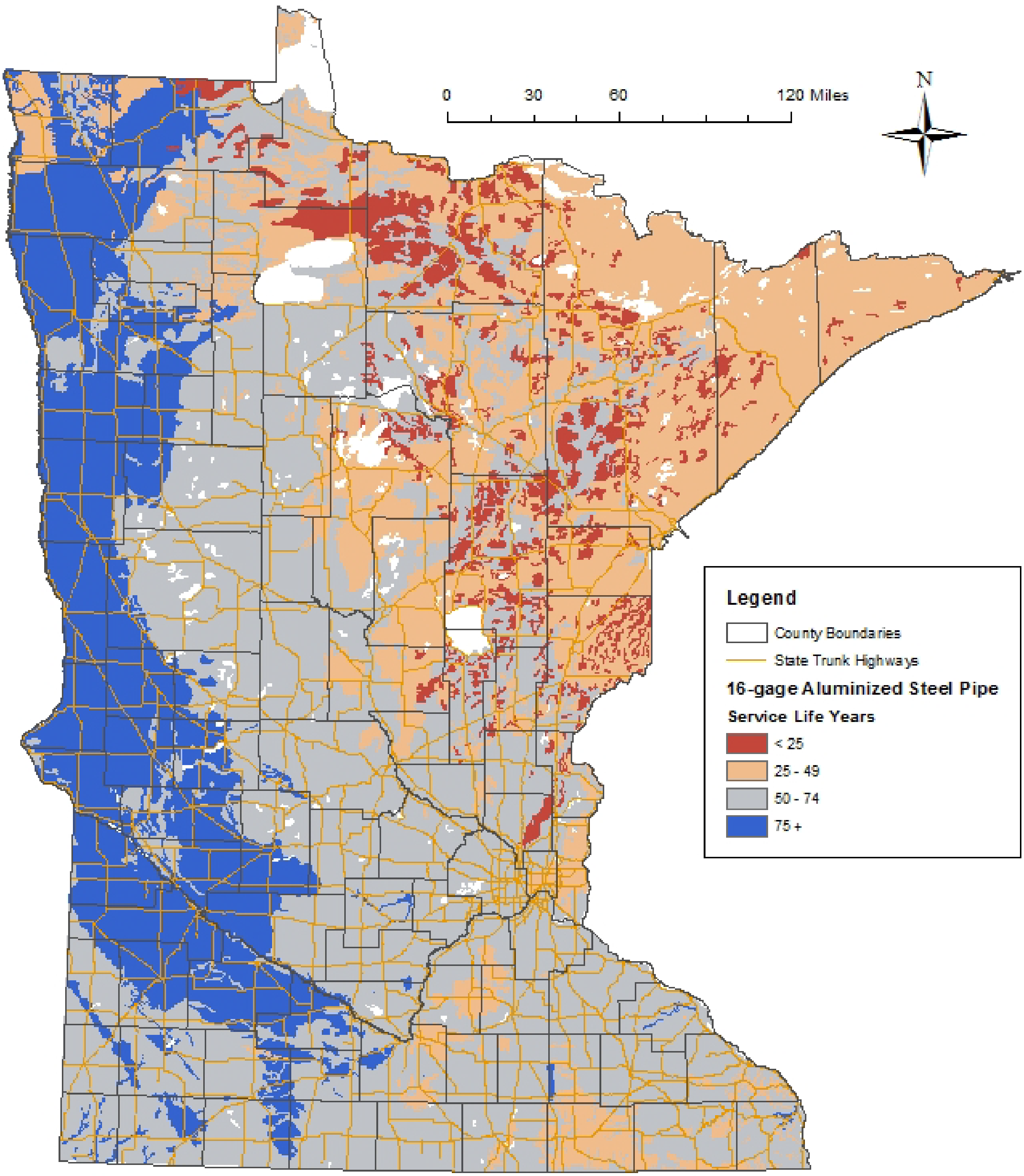


Figure 4.4: Service-life estimates for 16-gage aluminized steel pipe.

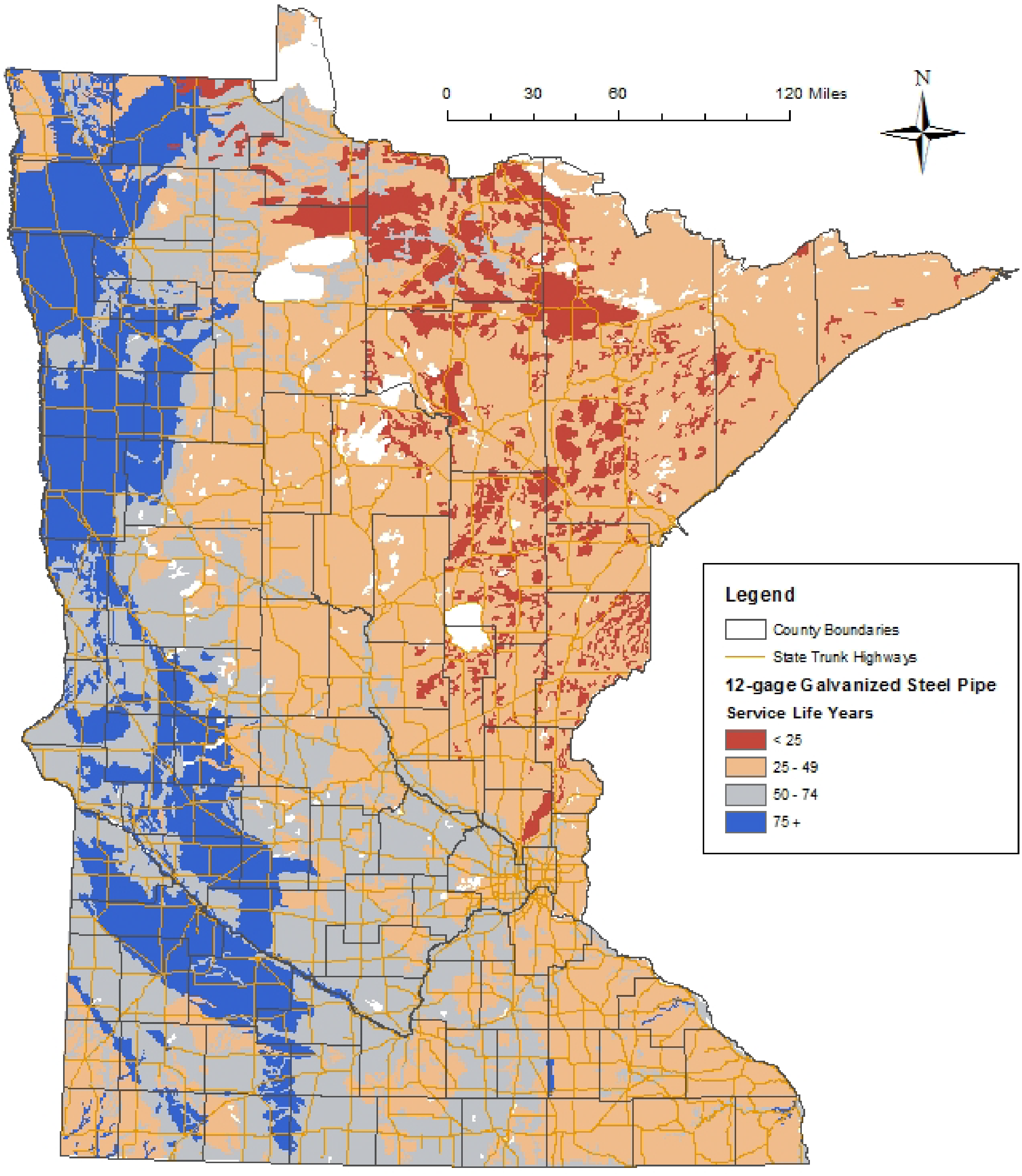


Figure 4.5: Service-life year calculation for 12-gage galvanized steel pipe.

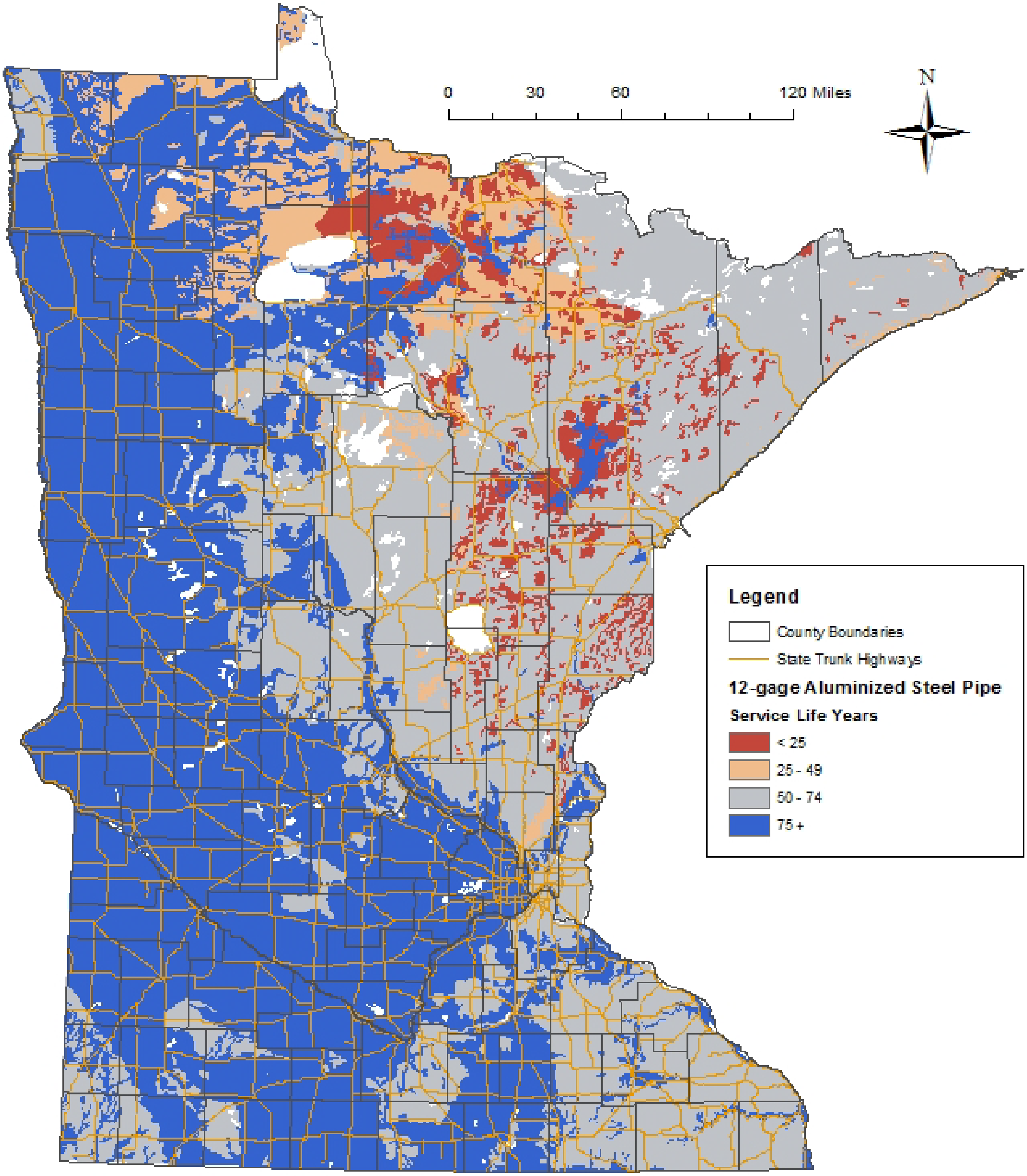


Figure 4.6: Service-life estimates for 12-gage aluminized steel pipe.

CHAPTER 5: SERVICE LIFE YEAR ZONE DELINEATION

5.1 Service-Life Map Zone Delineation

To facilitate the selection of appropriate pipe material, regional areas of similar character were grouped together into zones using the service-life maps generated in the previous chapter. The use of zones provides a quick reference for the end user to help guide their pipe material selection, while also addressing some concerns about the transitions between service-life boundaries on the more detailed maps.

Six zones were delineated using the base 18-gage galvanized steel pipe map generated by the Caltrans 643 equation (Figure 5.1). A histogram counting the number of service-life estimates within each zone based on the 1 km grid cell size (Figure 5.2) helps illustrate the rationale for delineation. The different zones are as follows:

- **Zone 1**: This zone is characterized by areas that predominantly have higher service-life estimates (greater than 45 years).
- **Zone 2:** This zone is characterized by areas that predominantly have moderate to higher service-life estimates (26-45 years).
- **Zone 3**: This zone, located in southeast Minnesota, was delineated by tracing the more basic field soil pH values collected during the summer 2014 campaign. As supported by the field data and the NRCS general Minnesota corrosion map, service-life estimates are likely too conservative as reported on the maps generated in Chapter 4. While the histogram indicates this area is characterized by service-life estimates between 15-20 years, the more probable estimate is more similar to that of Zone 2 (26-45 years).
- **Zone 4:** This zone is characterized by areas that predominantly have lower service-life estimates (21-25 years).
- **Zone 5:** This zone is characterized by areas that predominantly have lower service-life estimates (16-20 years).
- **Zone 6:** This zone has the largest spread of service-life estimates, including the highest count of the lowest service life estimates (< 10 years). However, these areas are adjacent to areas of higher service life (predominately 16-20 years).

All zones include areas that have higher and lower service-life estimates than the majority of what is found in a particular zone. Such spatial heterogeneity makes it difficult to provide guidance on pipe material selection as local conditions may or may not be consistent with what is reported in this analysis. The following section provides a conservative approach to selecting steel pipe material for the different zones, including several caveats that must also be considered when selecting pipe.

5.2 Zone Map and Pipe Selection Table

The zone delineation map with county boundaries and major state-trunk highways is located in Figure 5.3. To address the issue of service-life variability within zones and provide a more conservative estimate of service life when considering steel pipe selection for a particular location, Table 5.1 provides the 90th percentile estimate of minimum service life for the base 18-gage galvanized steel pipe (that is, the service-life estimate that 90% of the zone data exceeds).

Service-life estimates for the other gages and aluminized pipe type are then generated using the multiplier associated with the Caltrans 643 equation (Table 4.1). If the service-life estimate exceeds 75 years, the table simply lists 75+ years.

Table 5.1: 90th percentile estimate of service life of various steep pipe types and gages.

Pipe Type	Gage	Zone 1	Zone 2	Zone 3*	Zone 4	Zone 5	Zone 6
Galvanized	18	31	25	25	19	17	5
	16	40	33	33	25	22	7
	14	50	40	40	30	27	8
	12	68	55	55	42	37	11
	10	75+	70	70	53	48	14
	8	75+	75+	75+	65	58	17
Aluminized	16	75+	65	65	49	44	13
	14	75+	75+	73	55	49	15
	12	75+	75+	75+	67	60	18
	10	75+	75+	75+	75+	70	21
	8	75+	75+	75+	75+	75+	24

*Zone 3 is assumed to have similar service-life estimates to Zone 2.

For example, if a potential culvert location is in Zone 4, a 10- or 8-gage galvanized pipe or any gage higher than 16-gage aluminized pipe would likely last at least 50 years. This table indicates that in Zone 6, a non-homogenous area with significant variation in service-life estimates, any type of steel pipe will result in lower service life (< 25 years). This is reflective of the conservative approach to this analysis, as that zone incorporates wetland areas with the lowest service-life estimates along with areas that are predicted to have higher service-life estimates. In such areas, engineering judgement should be used when selecting an appropriate culvert material. Localized conditions can be considered on a case by case basis.

5.3 Limitations and Caveats to Zone Map and Pipe Selection Table

The zone map and accompanying table are subject to a number of caveats. While the table shows the minimum service life predict in a zone (90th percentile), the zones still do not account for local conditions that can significantly impact service-life estimates. Such local conditions can include:

- **Abrasion:** The overall service-life equation does not take the potential for abrasion into account. If the stream or river of interest has significant bedload transport, the resulting potential abrasion could significantly reduce service life estimates by wearing away the culvert wall. While this study does not address abrasion guidelines, general guidelines are present the in the current MnDOT drainage manual (MnDOT, 2000). Other references such as Molina and Mommandi (2009) also provide a review of various DOT methods for addressing abrasion.

- **Soil moisture:** As mentioned previously, soil resistivity values vary seasonally with soil moisture and soil temperature. As soil moisture and/or soil temperature increase, soil resistivity and subsequent service-life estimates decrease. While this analysis attempts to use conservative values for soil resistivity through the soil texture proxy, it does not address soil moisture or soil temperature. If the area of interest has high soil moisture content and/or consistently warmer soil, these criteria suggest more corrosive conditions that could likely lead to lower service-life conditions than portrayed on the maps in this analysis.
- **Wet conditions:** Wet conditions refer to when there is standing or flowing water in/through a culvert generally year-round. Previous observations have demonstrated that wet conditions can accelerate steel pipe deterioration (Taylor and Marr, 2012). High water tables, consistent flow through a ditch or stream, or even channel bed aggradation can create wet conditions that can reduce service-life estimates.
- **Chloride:** Soil resistivity is also dependent on the soluble salts present in the soil. If an area of interest has had significant de-icing activities over a period of time, this can create more corrosive conditions that would reduce service-life estimates.
- **Proximity to wetlands/lakes:** As noted in Chapter 2, acidic and wet conditions are more likely to be present when less than 10 miles from a wetland or lake. Even if a service-life estimate indicates an area should have a service life of 50 years, proximity to wetlands/lakes may reduce the estimate of service life. This is of particular importance in Zone 6, where wetlands lie adjacent to lands that have higher service-life estimates.

While Table 5.1 provides a conservative estimate for service life of various gages and types of steel pipe, it remains the responsibility of the user to determine whether local conditions justify a particular culvert material.

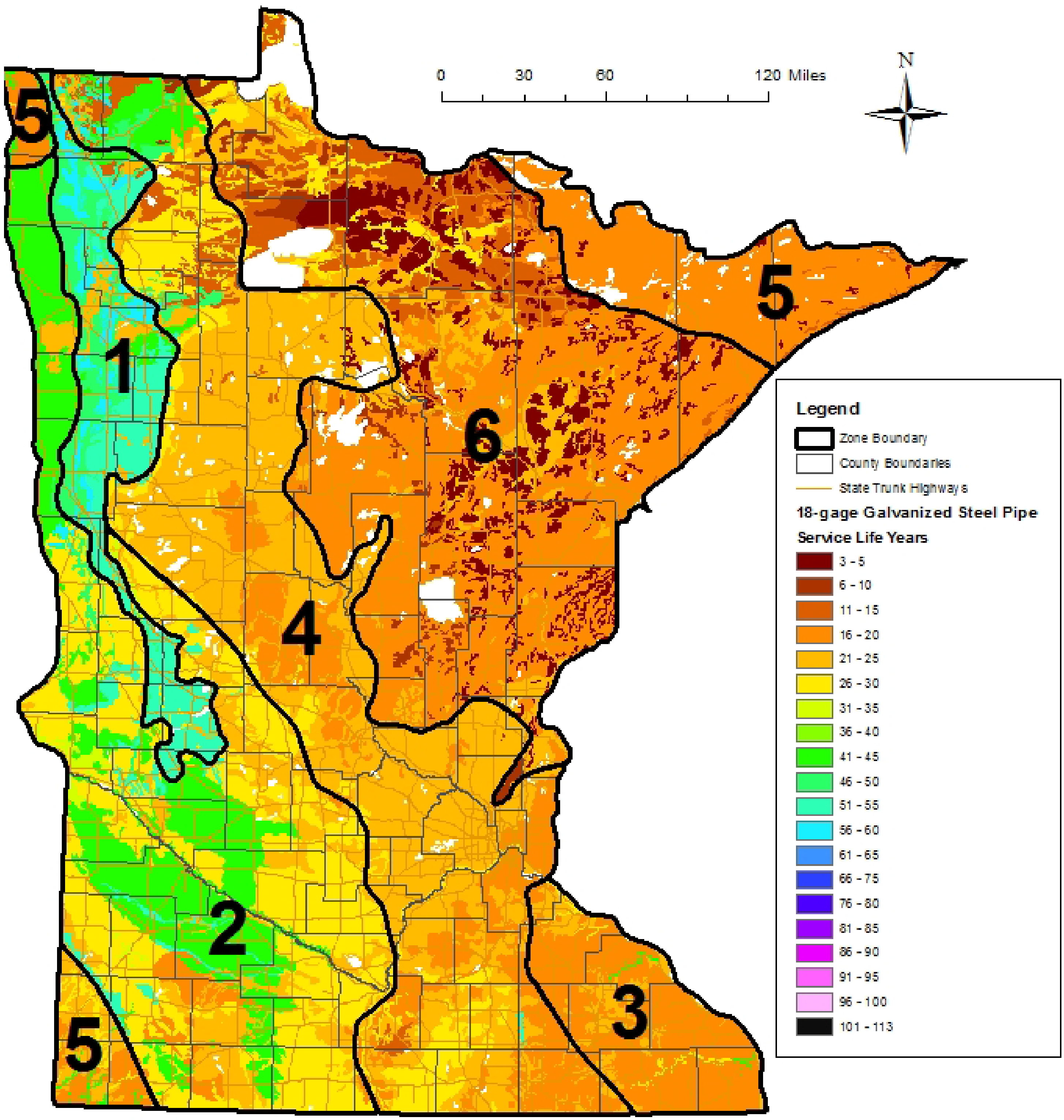


Figure 5.1: Delineation of zones using base 18-gage galvanized steel pipe service-life map.

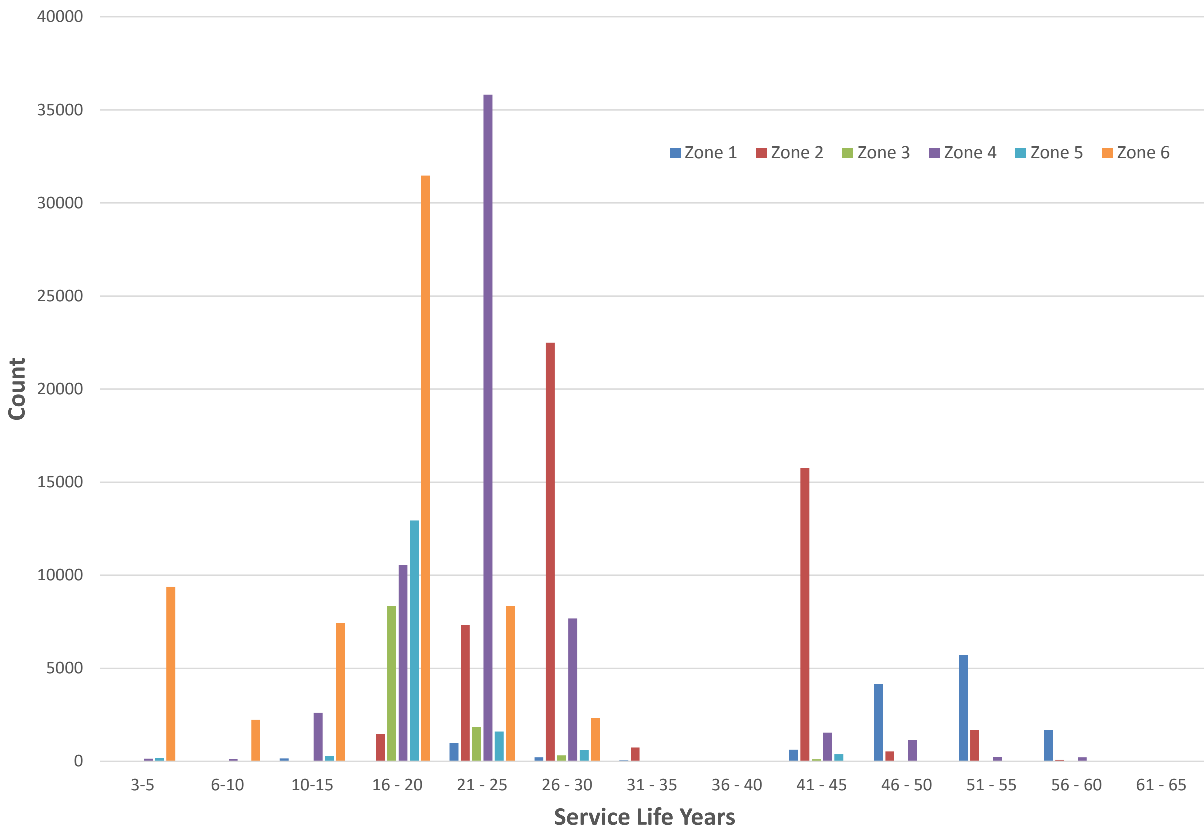


Figure 5.2: Histogram illustrating the count of service-life estimates within different zones for 18-gage galvanized steel pipe.

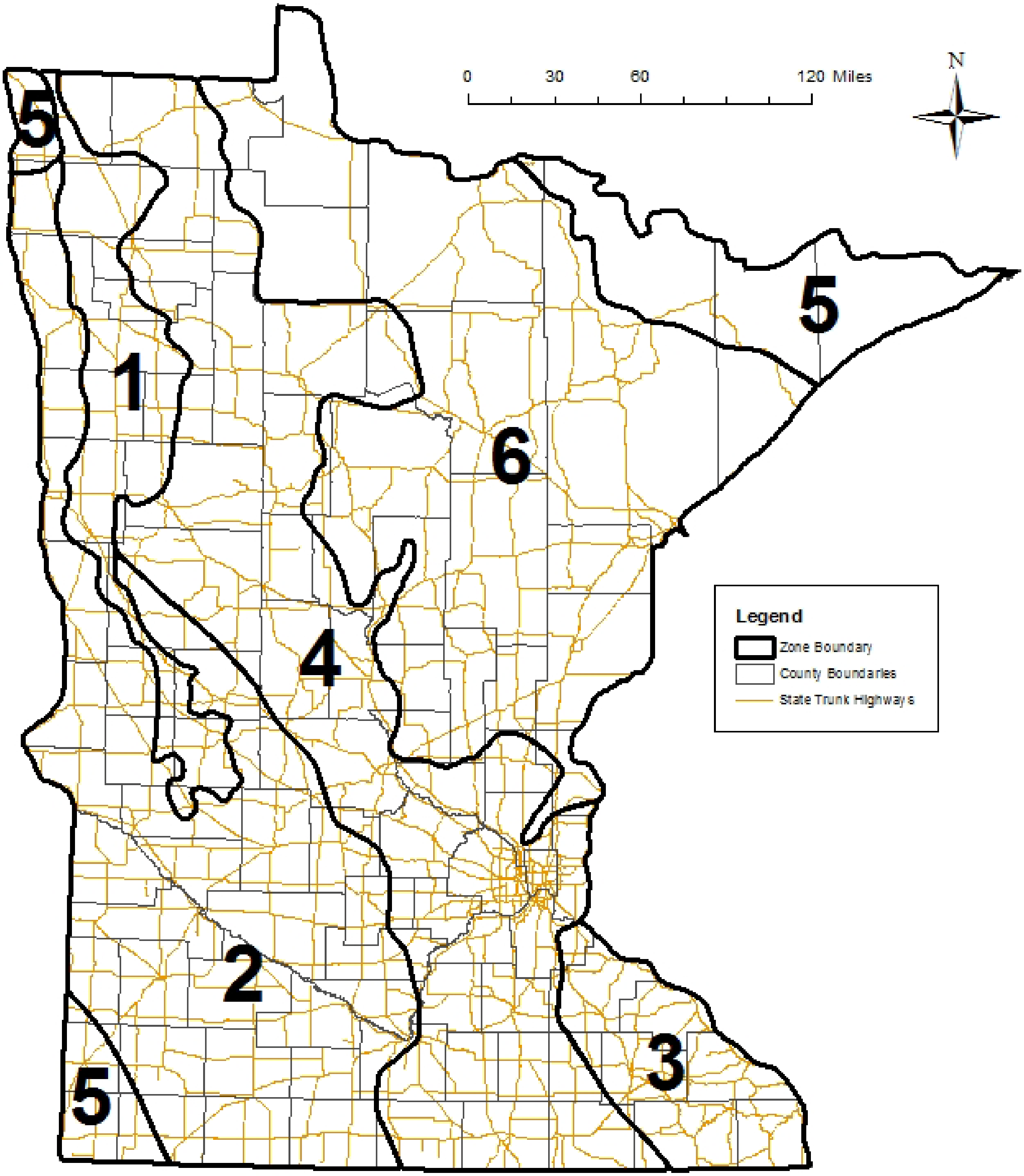


Figure 5.3: Zone map for use in determining culvert pipe selection.

CHAPTER 6: CONCLUSIONS

The project objective was to generate a series of steel pipe service-life maps for the state of Minnesota, using the California Method 643 (Caltrans, 1999) that relies on soil pH and soil resistivity values. A summer field campaign collected over 560 soil pH and soil resistivity samples statewide along embankments of state-trunk and county highways. Concurrent observations of soil texture, surrounding landscape, roadway type, and water presence were also made, with water pH and conductivity measures made where applicable.

Field data were verified through comparing data to other available datasets including soil pH, electrical conductivity, and soil texture, as well as observations available from district and county engineers. While field-measured soil pH data, with some exception, generally aligned with available statewide STATSGO soil pH data, field-measured soil resistivity data were considered unreliable due to consistently higher than anticipated values in different parts of Minnesota. In the absence of a statewide soil resistivity or electrical conductivity map, field-classified soil textures and the statewide STATSGO soil texture map were used to estimate soil resistivity values. No significant relationships between land use and soil pH or resistivity were noted. Acidic conditions tend to occur in proximity (<10 miles) to wetlands and lakes, but more basic conditions were also observed at similar proximities.

Calculations of service life using the STATSGO data and California Method 643 were completed for 18-, 16-, 14-, 12-, 10- and 8-gage galvanized and aluminized steel pipe across Minnesota. The maps demonstrate that aluminized pipe overall provides a greater potential for higher service life than galvanized pipe. To provide a quick reference for the end user in guiding pipe material selection, regional areas of similar character were grouped together into six zones using the generated service-life maps. As the areas within the zones have a distribution of service-life estimates, the 90th percentile service-life estimate for the 18-gage galvanized steel pipe was used to provide a conservative baseline service-life estimate within each zone. This service-life estimate was then modified using the California Method multiplier for different types and gages of steel pipe.

While this analysis presents service-life estimates based on estimates of soil pH and resistivity, several limitations and caveats must be noted that may significantly alter service-life estimates. These include: the potential for culvert abrasion, changing soil moisture or temperature conditions, wet conditions, channel aggradation, presence of chloride in the soil, and proximity to lakes or wetlands. Boundaries between areas with different service-life estimates should also be treated conservatively, as local conditions may vary from what is predicted in the broader area.

The summary information provided in this report is a generalized estimate of service life based on regional trends within the state. It remains the reasonability of the user/designer/engineer to understand that limitation of these tools and utilize them, along with other data and methodologies, to determine an appropriate service-life estimate.

REFERENCES

ASTM G51-95, 2012, *Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing*, ASTM International, West Conshohocken, PA, www.astm.org

ASTM G57-06, 2012, *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*, ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D6569-14, 2014, *Standard Test Method for On-Line Measurement of pH*, ASTM International, West Conshohocken, PA, www.astm.org.

ASTM D1125-14, 2014, *Standard Test Methods for Electrical Conductivity and Resistivity of Water*, ASTM International, West Conshohocken, PA, 2014, www.astm.org.

Jim Bittmann (MnDot District 2 engineer) in discussion with the author, March 2015.

Caltrans, 1999, *California Test 643: Method for Estimating the Service Life of Steel Culverts*. California Department of Transportation, Engineering Service Center; Sacramento, California.

Tom Meath (MnDOT District 6 engineer) in discussion with the author, March 2015.

Miller, D.A. and R.A. White, 1998, A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. *Earth Interactions,* 2. Available on-line at http://EarthInteractions.org, Accessed November 2014.

Minnesota DNR, 2006, "Soil Texture Key" Ecological Land Classification Program, MN Department of Natural Resources, Division of Forestry, St. Paul, MN.

Molinas, A. and A. Mommandi, 2009, *Development of New Corrosion/Abrasion Guidelines for selection of Culvert Pipe Materials*. Colorado Department of Transportation, DTD Applied Research and Innovation Branch, Denver, CO.

NRCS, 2015, *Gridded Soil Survey Geographic (gSSURGO) Database for Minnesota.* United States Department of Agriculture, Natural Resources Conservation Service. Available online at http://datagateway.nrcs.usda.gov/. Accessed *March 1, 2015.*

Samouelian, A., I. Cousin, A. Tabbagh, A. Bruand, and G. Richard, 2005, "Electrical resistivity survey in soil science: a review." *Soil & Tillage Research* 83: 173-193.

Taylor, C. and J. Marr, 2012, *Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota – Final Report*. For Minnesota Department of Transportation, St. Paul, MN

APPENDIX A

Data Collection Equipment and Field Methodology

Tinker & Rasor Model SR-2 Soil Resistivity Meter

Intended Use: This instrument is used to measure how resistant a soil is to electrical impulses. This in turn will help understand the relative ion content, sediment consolidation, and water content which all may influence steel culvert pipe corrosion potential.

The SR-2 Meter is advertised as a reliable and accurate piece of equipment. The meter is calibrated and came with a calibration certification form that expired in October 2014. There is no noted limitation for the piece of equipment. The soil resistivity meter is an appropriate tool for checking subsurface conditions that might influence service life of culverts.

Field use: Although the meter came with a certification of calibration form, this study suggests checking the accuracy of the reader with a precision resistor every week. For a sample reading, four pins are placed in a line, 5 feet apart and sunk 1 foot into the ground. The line should run parallel to the road and be located halfway down the ditch slope (the ASTM Wenner 4-Pin method chooses halfway down a ditch because ion concentrations tend to be higher in the ditch invert in long-winter areas that use salt). The pins are pushed into the ground, unless the ground conditions are such that the pins need to be hammered in the ground (hard and/or rocky soil). Irregularities in the ground between pins are checked for holes, pipes, or different ground from the majority of land in the area.

To take readings, the dial is started farthest counter-clockwise and rotated clockwise when the ‘1’ is shown on the screen. The pins are spaced 5 feet apart so the resistivity values are reported for depths up to 5 feet.

Field issues: Over the course of the project, one of the pins became slightly bent due to hammering it into the ground. This affects data accuracy slightly, but not to a significant degree, according to the manufacturer. In Week 4, two additional pins were ordered – one replaced the bent pin, and the other was used as a backup in case another pin became bent.

The unit (reader) began to drift starting late in Week 2 (District 6) and consistently in Week 3 (District 7). Readings were markedly low, but how unreliable these values were was uncertain because other factors such as flooding and very saturated soils that could also influence the readings. By checking the accuracy of the resistivity reader on June 23, 2014 using a precision resistor, it was determined that the unit was off by 11 to 45%. The resistivity unit was sent to the manufacturer to be repaired.

Since the resistivity meter was returned and used during Week 5, it was realized that the meter was still drifting when used in the field. We contacted the manufacturer and they determined that the issue must be a loose blocker in the unit, which would not have been detected by the initial repair. The engineer explained that a polarizing effect was happening in the ground because of the loose blocker, so as the ‘read’ button would be pressed, the readings would drift all around. The true reading, however, would be the first reading and can be rechecked by waiting 10 seconds between readings. This method was followed from Week 4 until the end of the project. To check the accuracy of Week 3 (week before sending the unit to be repaired) resistivity data, resistivity was measured at the same sites and there was good agreement between the values.

Rocky soils were problematic for taking soil resistivity measurements along many roadsides. Difficulty nailing the pins into the ground, while also trying to determine the presence of other rocks and subsurface obstacles in the soil matrix, generally led to unusually high resistivity readings or no successful readings at all. At the end of the project the pin tips had become so dull from being nailed into rocky soils that this may have made nailing the pins in the ground more difficult. The dullness of the pin tips does not affect the accuracy of the measurements as long as the pins can be put into the ground to the right depth.

Results: Results in the first four weeks are mostly in the range of 750 to 10,000 ohm-cm. Approximately less than one third of the data in the first four weeks ranges between 10,000 and 100,000 ohm-cm. Both ranges are reasonable because sediment consolidation, sediment content, and soil saturation varied over the areas sampled. There are some large-value outliers, which probably are due to unnoted subsurface structures or gaps.

Especially in north Minnesota and rocky areas, resistivity values are larger. There were many spots where approximately ten minutes was spent trying to insert the pins into rocky areas without success. This explains gaps in data spots where resistivity was not taken.

Hanna Instruments Model HI 99121: Soil pH Meter

Intended use: Soft soils, primarily for gardening or plant environment control. Temperature is not an issue because the probe has an automatic temperature compensation function. The hole-starter stick is inserted into the soil of interest to create a space in which to insert the probe. The soil pH probe should have the cap removed, be shaken down like a thermometer to remove air bubbles in the bulb, and be wetted with tap water before insertion in the ground. For best accuracy, once in the ground, the probe should be pushed a little to ensure proper soil contact with the tip. Turn on the reader and wait for the “unstable” text to disappear on the screen. Record the value.

Field use: The meter must be calibrated each day, ideally by a 2-point calibration using pH4 and pH7 buffers. The probe is plugged into the reader, the cap is removed from the probe tip, the probe is rinsed/wetted with tap water, and the probe is shaken down to remove air bubbles from the liquid. Soil is crushed up in one spot within the first 10 cm of soil surface at the ditch invert. If the ground is very dry, the ground is wetted with HI 7051 Soil Test Preparation Solution or deionized water. The reader is powered on and measurements are checked until three values within 10% of one another are achieved. After getting the data, turn the reader off and disconnect it from the probe. Rinse the dirt off the probe with the water squirt bottle and use a finger to wipe off dirt. Put the cap back on the tip, place the probe and hole-starter in the original probe box, and place the box back in the probe kit case.

Field issues: A significant deviation of field use from the intended use is that most soils along Minnesota roadsides are not ‘soft planting soils.’ Soil in roadside ditches frequently contain pebbles, sand grains, and other objects that can scratch the delicate glass probe surface. Scratches and cracks were noticed on the probes in the first three weeks of data collection. We have been through several ruined probes. As the probes are scratched, the probe readings begin to drift and eventually the probes cannot be calibrated any longer. The technical support staff at HI said scratches and cracks on the probe glass are the likely causes of drifting. They recommend using a soil test box (50-50 water-soil mixture in beaker) to do readings of rocky or sandy soil, but this would add time to the data collection sampling procedure. At about the midpoint of the project, a new device was ordered and used instead of the delicate HI 99121.

Results: pH ranges for soils in Minnesota ranged from 5.0 to about 8.20. There have been no noticeable patterns or characteristics that link land use or area with pH values. Saturated soils are clearly closer to 7 than other dryer soils. It might also be an issue of how 'immersed' the probe can be in certain soils such as clay or lose sand. Sandy soils and well-sorted grains in soils will naturally hare more porosity and thus less contact with a small probe surface.

Spectrum Technologies, Inc. IQ 150: Soil pH Meter

Intended use: This device is meant to be used for a larger variety of soils than glass probes and is unique in its durability in addition to its accuracy. It is pushed directly into the soil and will give a reading when the meter is turned on. It is calibrated by a 2-point calibration method. For drier soils, the soil should be wetted with deionized water before the probe takes a reading. The probe is rinsed with deionized water between measurements and every week or so cleaned with deionized water and detergent. A toothbrush can be used to clean clay or mud off the sensor mechanism.

Field use: This device is used in the field as said in the intended use. Measurements are taken in three different parts of the ditch.

Field issues: One of the issues with field use is variability in measurements in different parts of the ditch. For example, a reading two inches from the first reading might differ by as much as 1.5 pH values. This was found to occur for the HI 99121 also, so result variation might be a natural consequence of non-uniform soils rather than due to issues with the instruments.

Another issue with the probe is ensuring proper sensor contact with the soil. Many soils in Minnesota are sandy or contain coarse grains that will have greater porosity and thus less contact with the small sensor. This lessens confidence in values and proper contact cannot be ensured because the probe takes readings below the surface.

Results: Soil pH measurements have ranged from under 5 to 8.20. While transitioning from use of the HI 99121 to the IQ 150, both probes were used to check agreement and their measurements were consistent at those sites.

Hanna Instruments model HI 9812: Water pH Meter

Intended use: Place water or liquid in a beaker. The probe is placed in the beaker of water and tapped at the bottom of the beaker to remove bubbles from the probe bulb. Temperature should be considered because this meter lacks the automatic temperature compensation feature. The instrument manual provides a temperature-pH value table to adjust measurements of water less than or more than 25 C. It is suggested to use a thermometer to measure the temperature of the water, but the pH soil probe will be used in place of an actual thermometer for the sake of not needing another instrument.

Field use: Water is taken from the edge of the water body (edge of a puddle or pond). The probe is put into the beaker of water, turned on, and allowed to sit while the reader settles on a value. This is repeated three times (getting three values within 10% of the others) until an average value is calculated. The probe and beaker are then rinsed with tap water and the outside protective covering of the probe (not the bulb) is dried with a paper towel before placing the instrument back into the case.

Field issues: None.

Results: Almost all results have been in the same range; 6.5 to 7.8. This makes sense, since almost all the water samples came from rainwater washing through or sitting in ditches. No pattern or trend is apparent.

Rain does affect soil pH values. High water content can dissolve certain ions and increase acidity in the soil. Nonetheless, this effect has not been noticed in data collection so far.

Hanna Instruments HI 993310: Portable Water Conductivity & Soil Salinity Meter

Intended use: Place water in beaker. Make sure there is enough water so the metal parts of the probe are completely immersed in the water. Turn on the reader and record the value. Rinse the probe after use and dry the protective outside covering before returning the probe to the case. The instrument does have an automatic temperature compensation feature, so readings are accurate as they appear on the screen.

Field use: Same as intended use.

Field issues: Occasionally the probe would have scattered readings or readings close to 0.0 mS/cm. There is no explanation found for this so far. Since this problem in the field, the probe has been cleaned with a paper towel and tested with calibration solution, and the probe could be calibrated. Use of this probe is straightforward. However, the probe had not been in use for some years; the sudden problems in the field might have been due to former wear and age to the equipment.

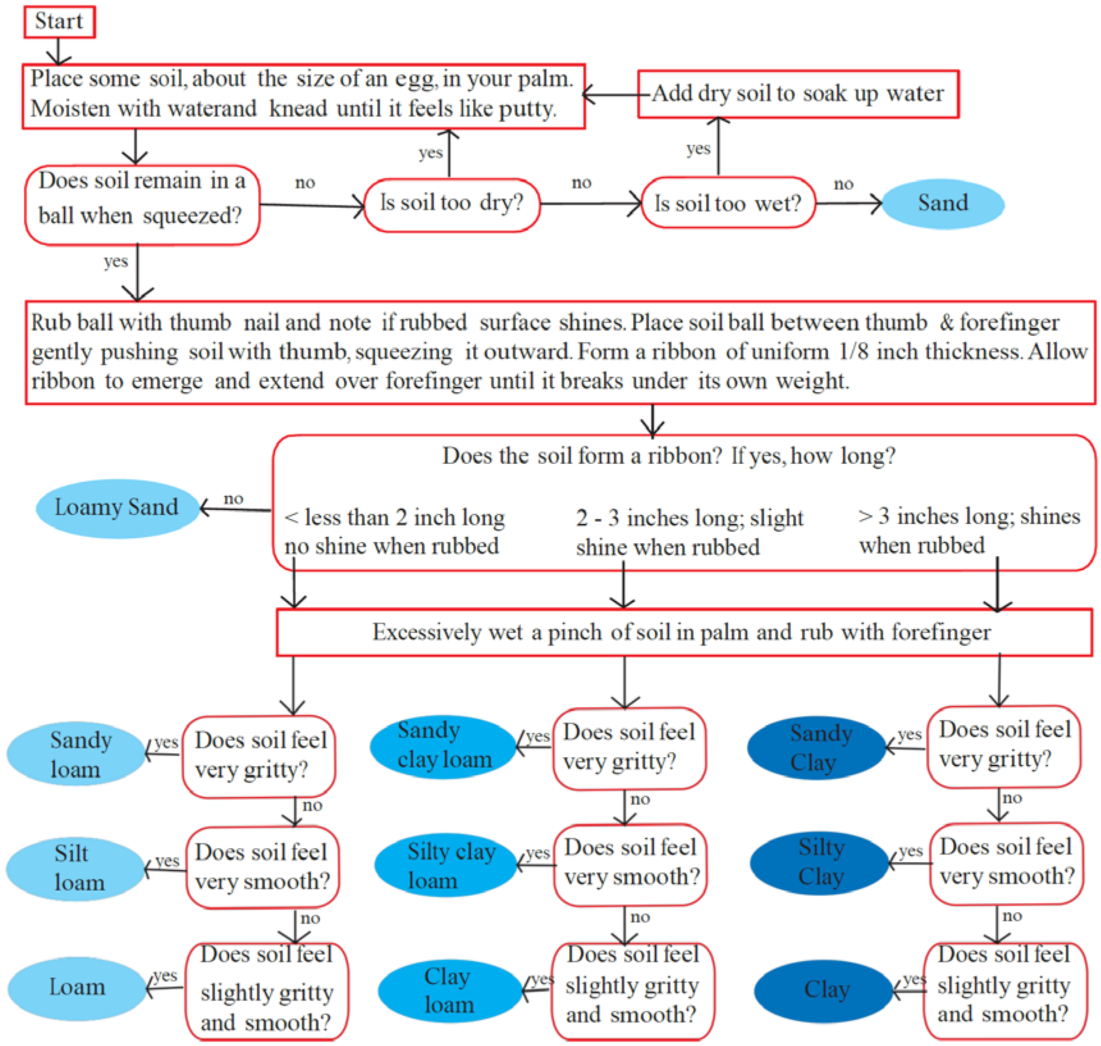
The original probe attached to the reader had a dirt clod in it, so the secondary probe was used in its place. After having problems with the sensor, however, the original probe was cleaned and used instead. Since then, the probe would drift slightly during calibration but was relatively steady and during sampling readings was very steady.

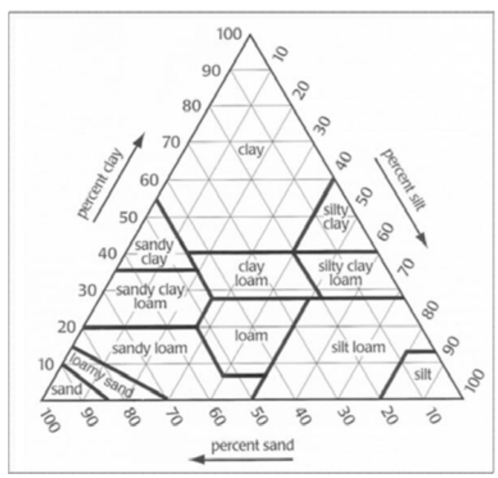
Results: Water conductivity results have varied from around 0.0 to 2.0 mS/cm. Accuracy of these values is difficult to determine, as there does not seem to be a record of these and certainly not for flooded fields or ditch puddles.

APPENDIX B

Soil Texture Field Classification Method

Soil Texture Key





Source: "Wetland Soils Genesis Hydrology, Landscape Classification"
J.L. Richardson & M.J. Veprakas eds. 2001
Adapted from Thein, S.J. 1979.
A flow diagram for teaching texture by-feel analysis.
J.Agron.Ed.8:54-55

DNR Divison of Forestry Ecological Land Classification Program- 2005

Soil Texture Field Tests

Moist Ball Test – Compress ***moist**** soil by squeezing it in your hand. If the soil holds together (i.e. forms a ball) when your hand is opened, then test the strength of the ball by tossing it from hand to hand. The more durable the ball, the more clay is in the soil.

Shine Test – Roll ***moist**** soil into a ball and rub once or twice against a hard, smooth object such as a knife blade or a thumb nail. A shine on the rubbed surface indicates clay in the soil. The more it shines, the more clay is in the soil.

Ribbon Test – Roll ***moist**** soil into a long thin shape and then squeeze out between the thumb and forefinger to form the longest and thinnest ribbon possible. The longer the ribbon, the more clay is in the the soil. Soils with high silt content will tend to flake rather than ribbon.

Feel Test – Rub *moist to wet* soil between the thumb and fingers to assess the percentage of sand (sand feels gritty). Silt feels smooth and silky like talcum powder but is not sticky.

Sticky Test – Compress ***moist* to wet*** soil between the thumb and forefinger. Note how strongly it adheres to the thumb and forefinger upon release of pressure and how much it stretches. Alternatively, throw it at your partner's forehead or the truck window. The more it sticks the more clay is in the soil.

Taste Test - A small amount of soil is worked between the front teeth. Sand is distinguished as individual grains which grit sharply against the teeth. Silt particles produce a general fine grittiness, but individual grains cannot be identified. Clay particles have no grittiness.

* ***Moist*** soil feels damp but no visible water is present. A small amount of moisture can be observed on the palm of the hand when a sample is very tightly squeezed and then released. Moist soils can be molded into shapes like potting clay.

Adapted From:
Field Manual for Describing Soils
3rd edition
Ontario Institute of Pedology, 1985

APPENDIX C

Service-Life Maps

This appendix includes all service-life maps generated in Chapter 4.

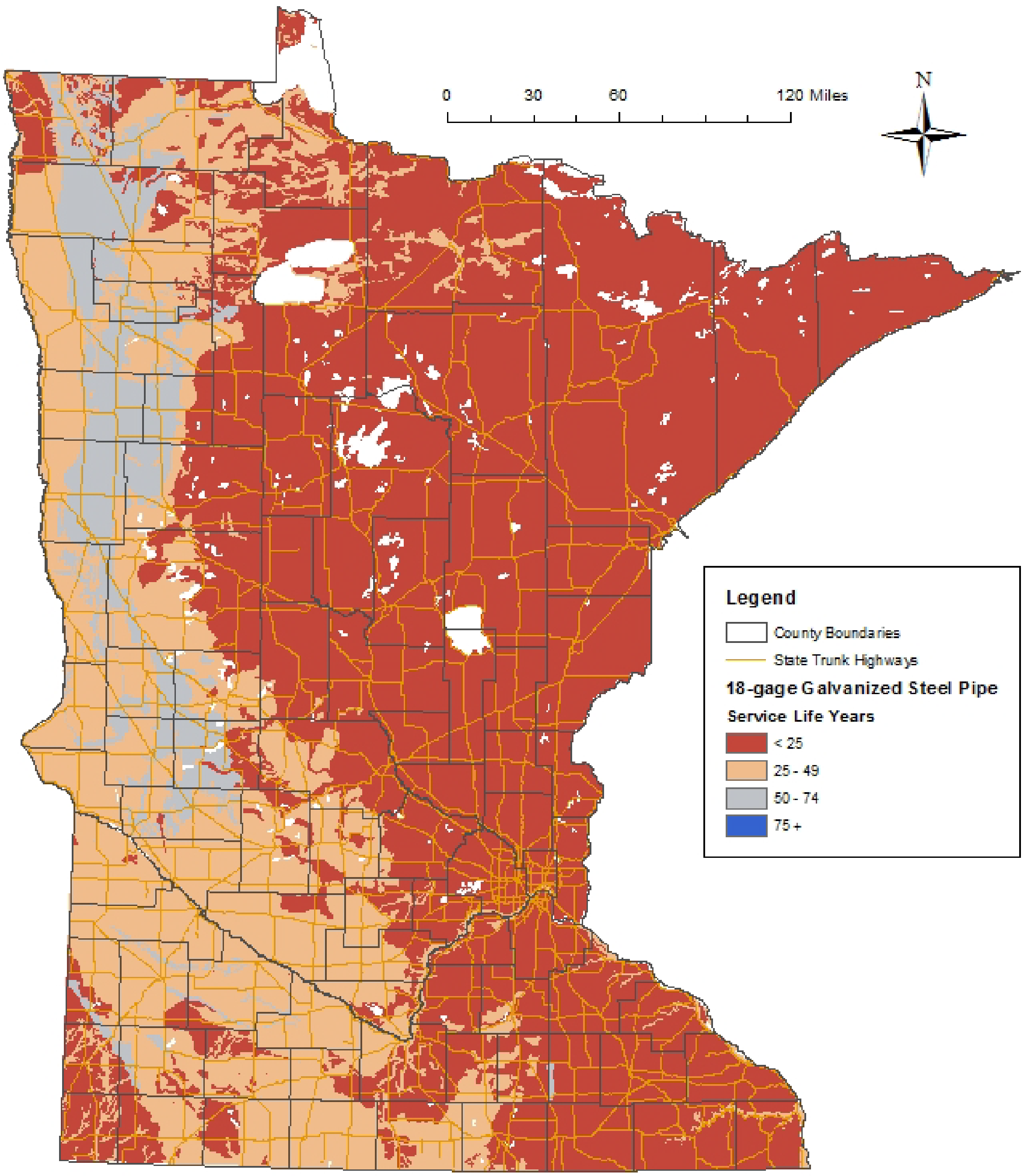


Figure C.1: Service-life estimates calculated using Caltrans 643 method for 18-gage galvanized steel pipe.

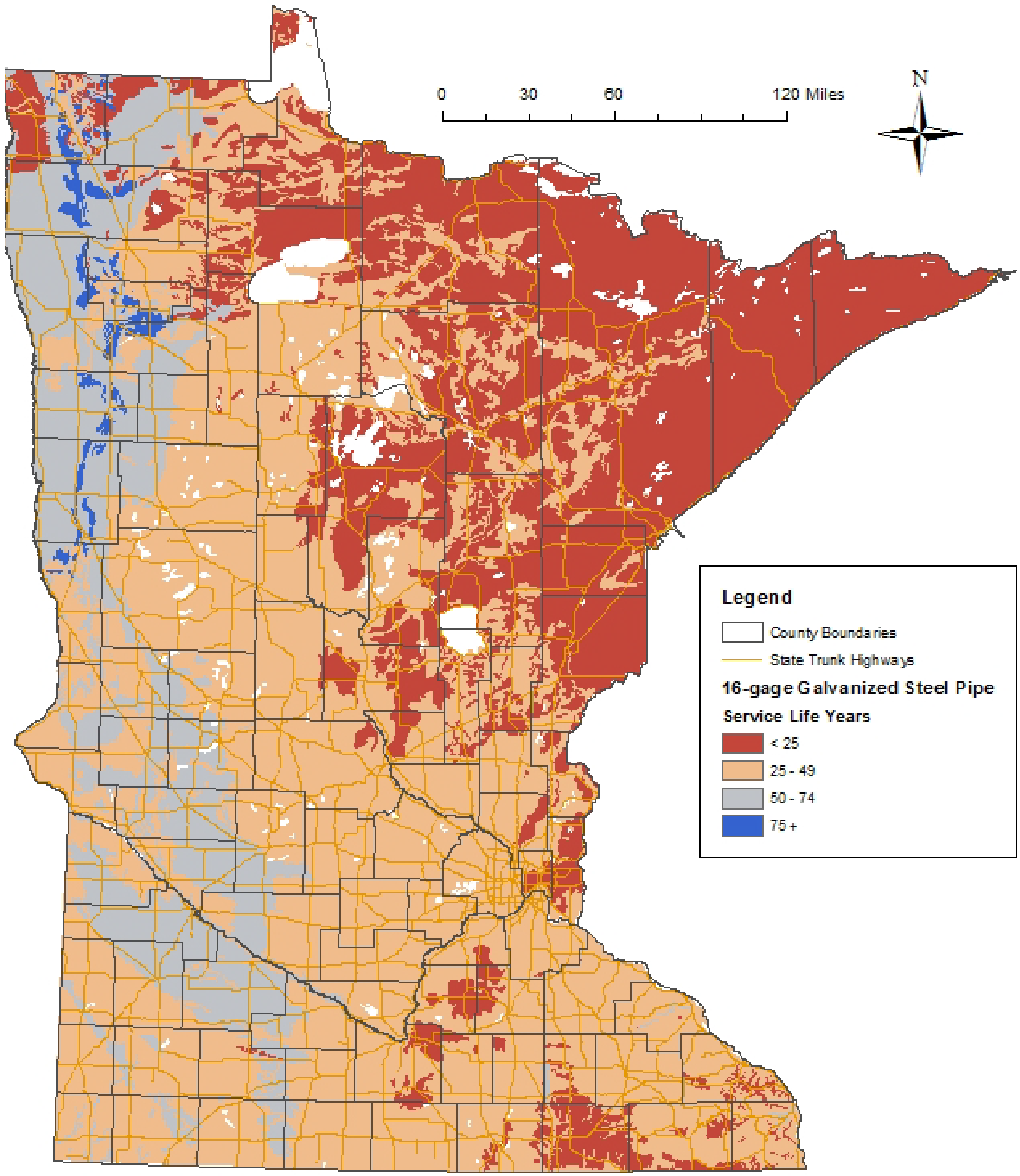


Figure C.2: Service-life estimates calculated using Caltrans 643 method for 16-gage galvanized steel pipe.

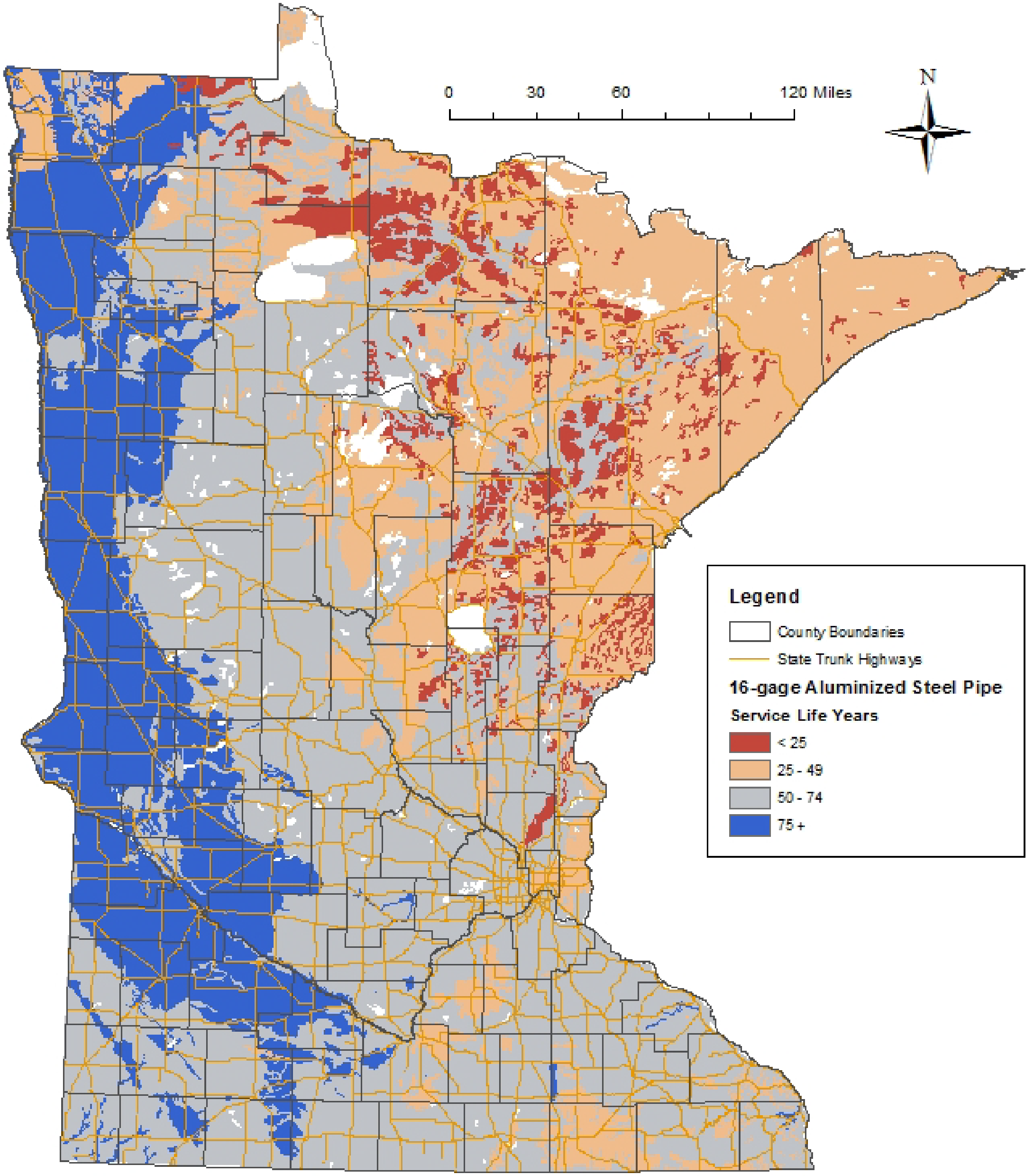


Figure C.3: Service-life estimates calculated using Caltrans 643 method for 16-gage aluminized steel pipe.

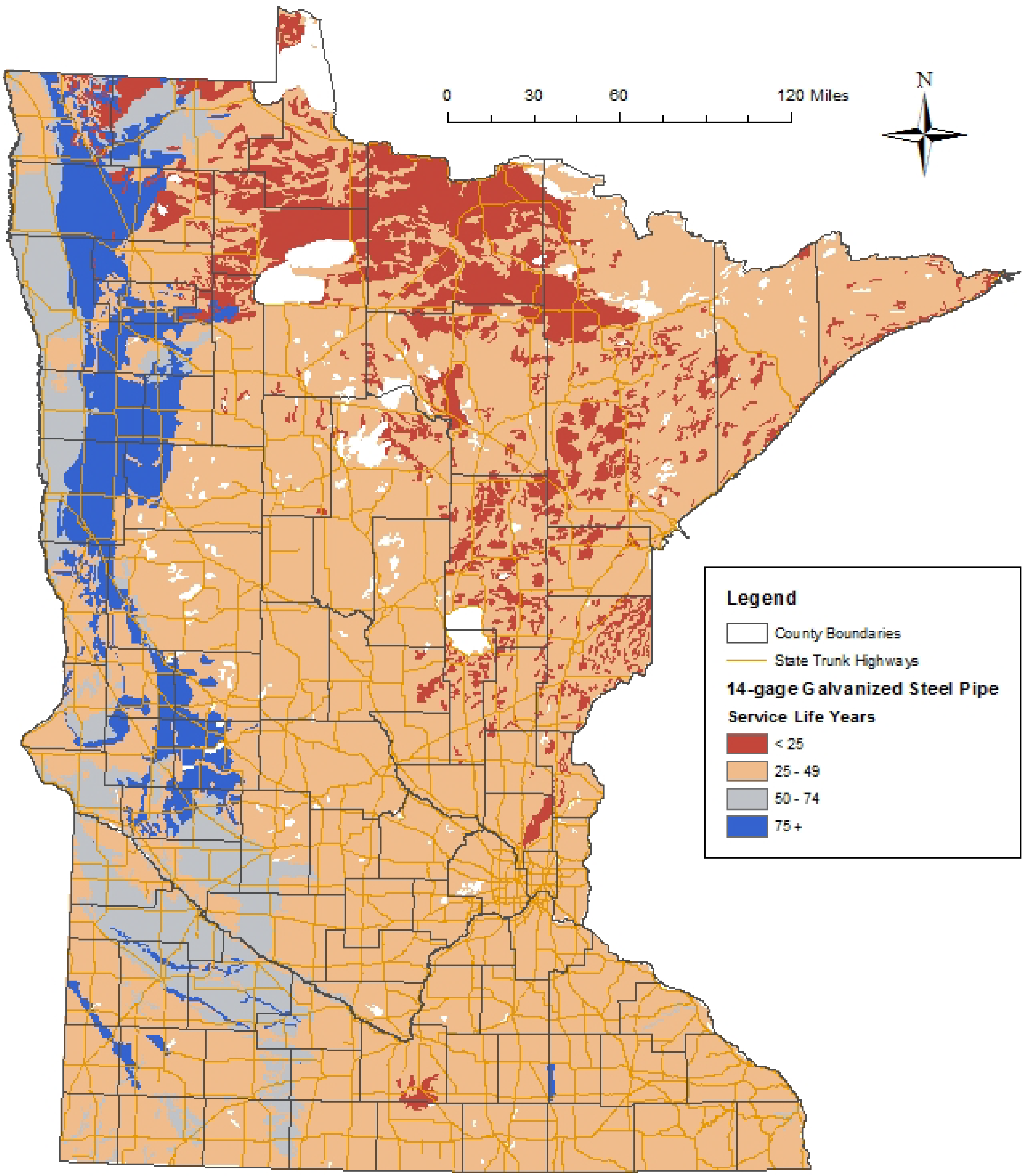


Figure C.4: Service-life estimates calculated using Caltrans 643 method for 14-gage galvanized steel pipe.

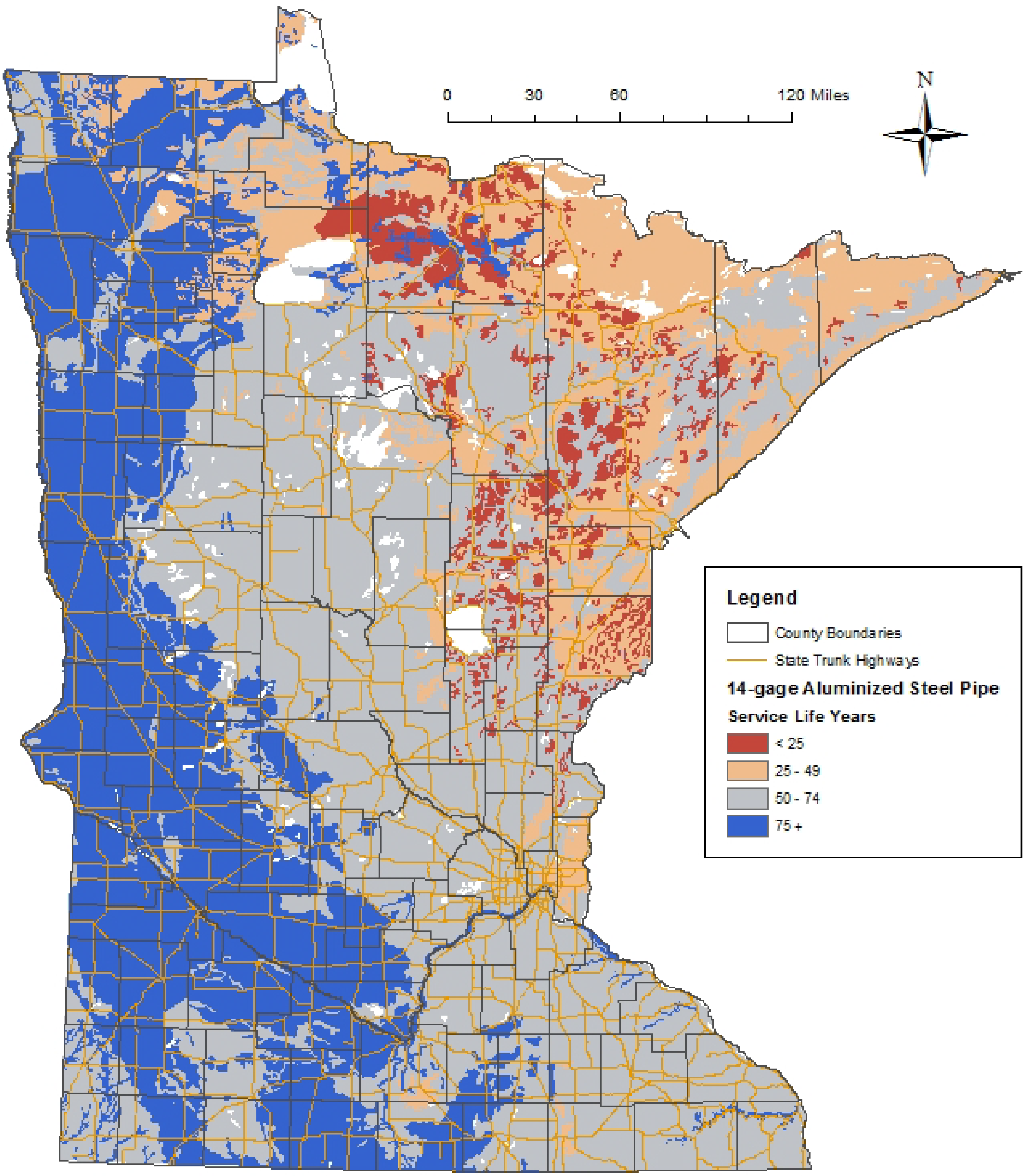


Figure C.5: Service-life estimates calculated using Caltrans 643 method for 14-gage aluminized steel pipe.

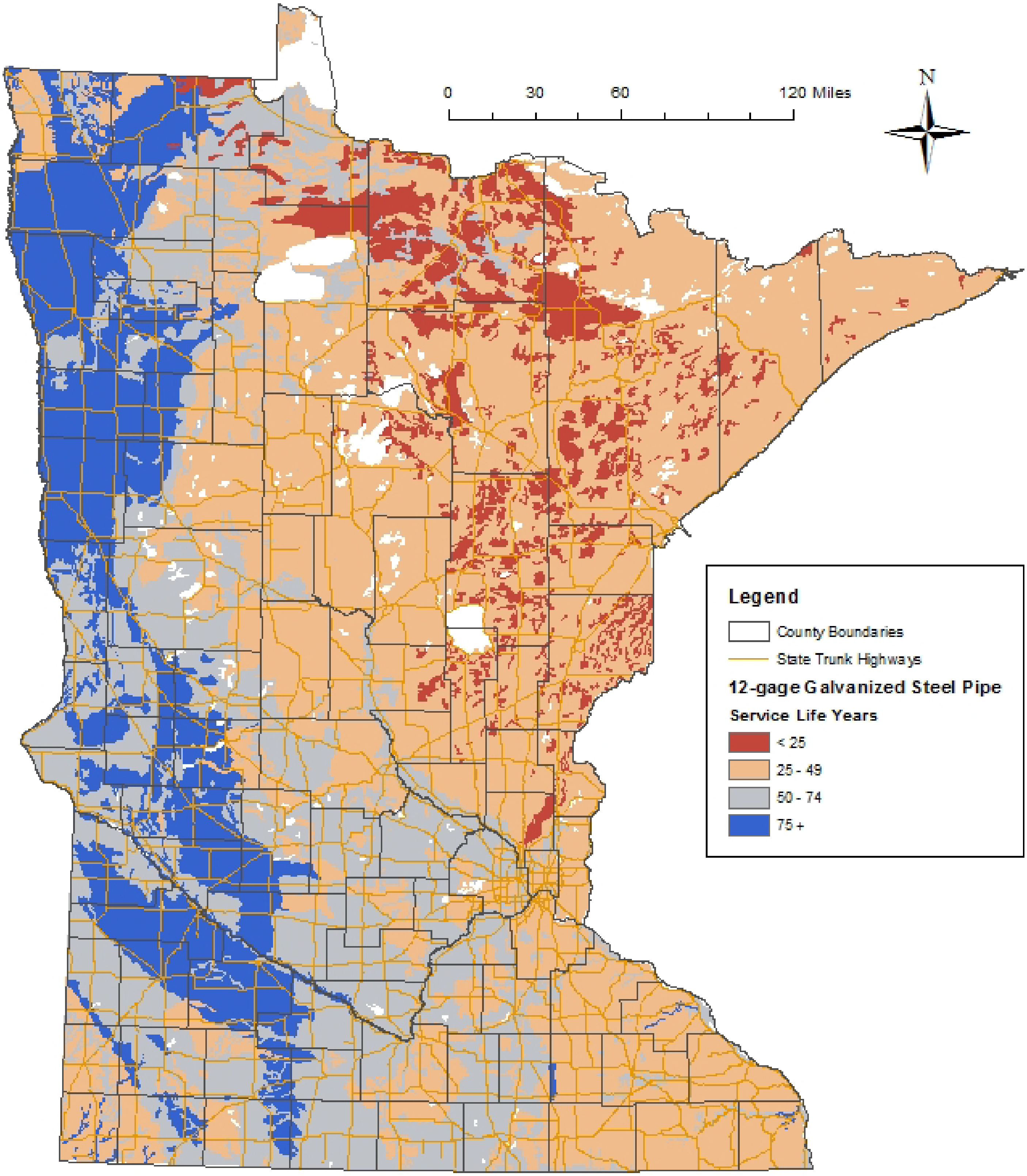


Figure C.6: Service-life estimates calculated using Caltrans 643 method for 12-gage galvanized steel pipe.

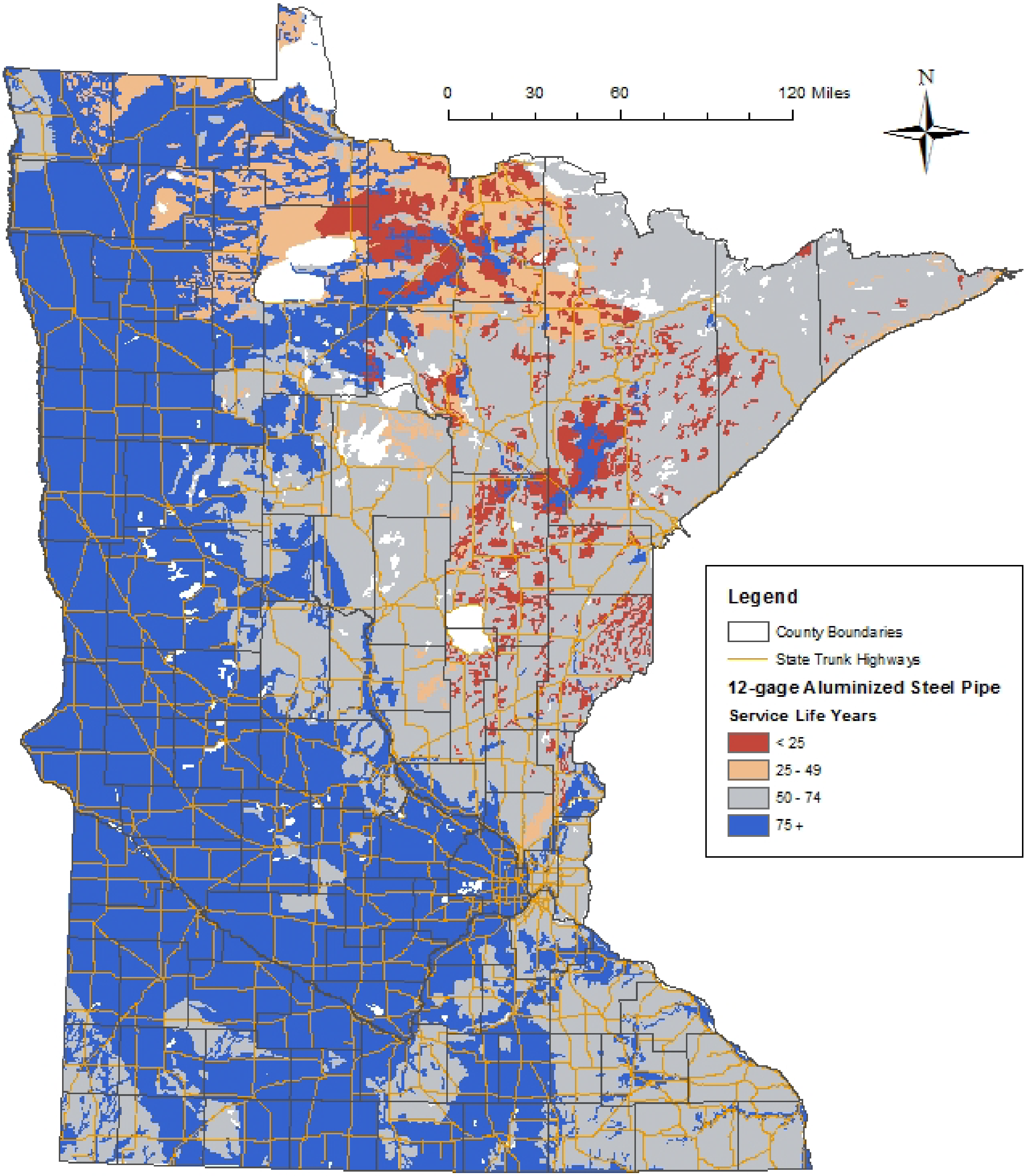


Figure C.7: Service-life estimates calculated using Caltrans 643 method for 12-gage aluminized steel pipe.

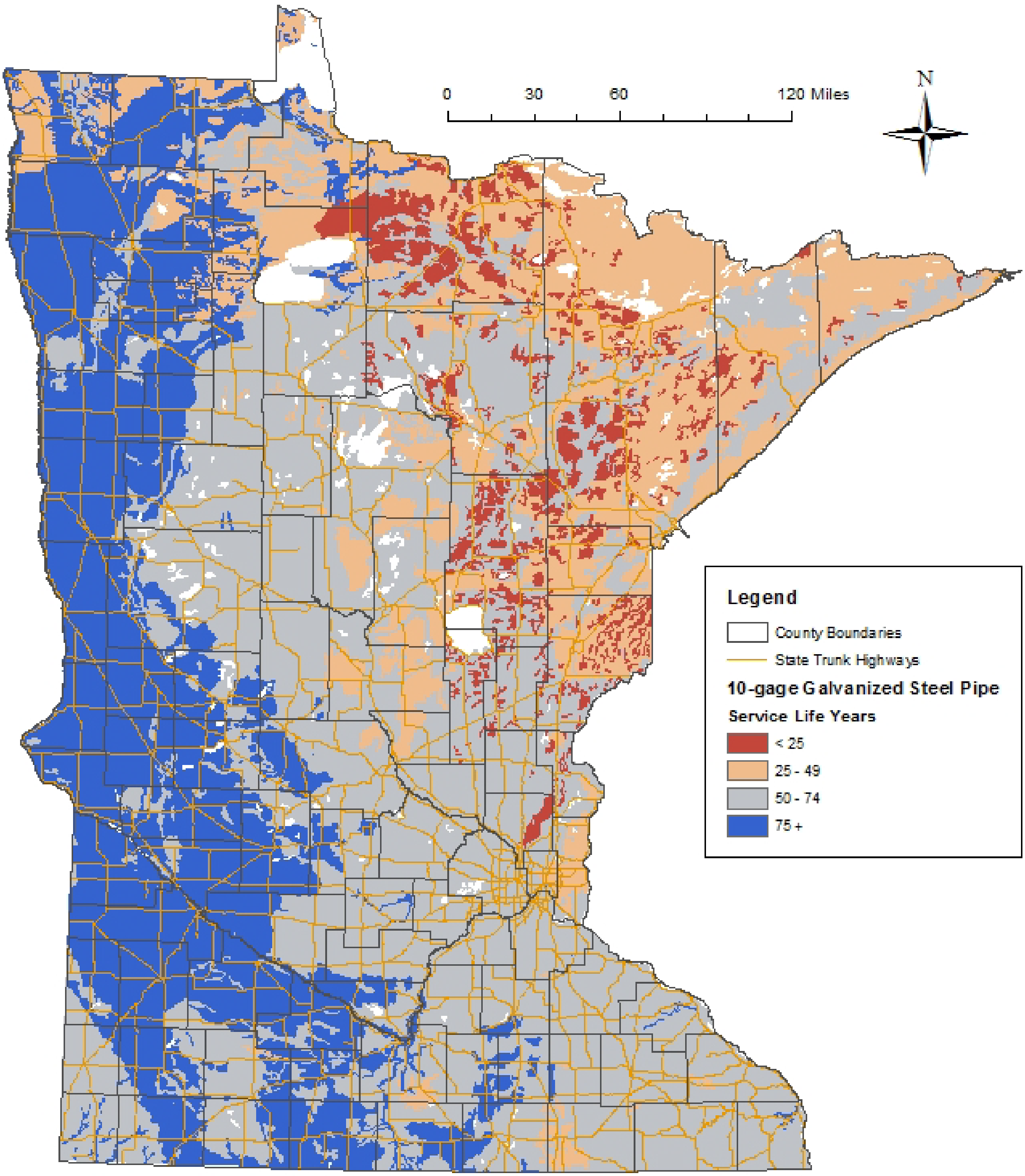


Figure C.8: Service-life estimates calculated using Caltrans 643 method for 10-gage galvanized steel pipe.

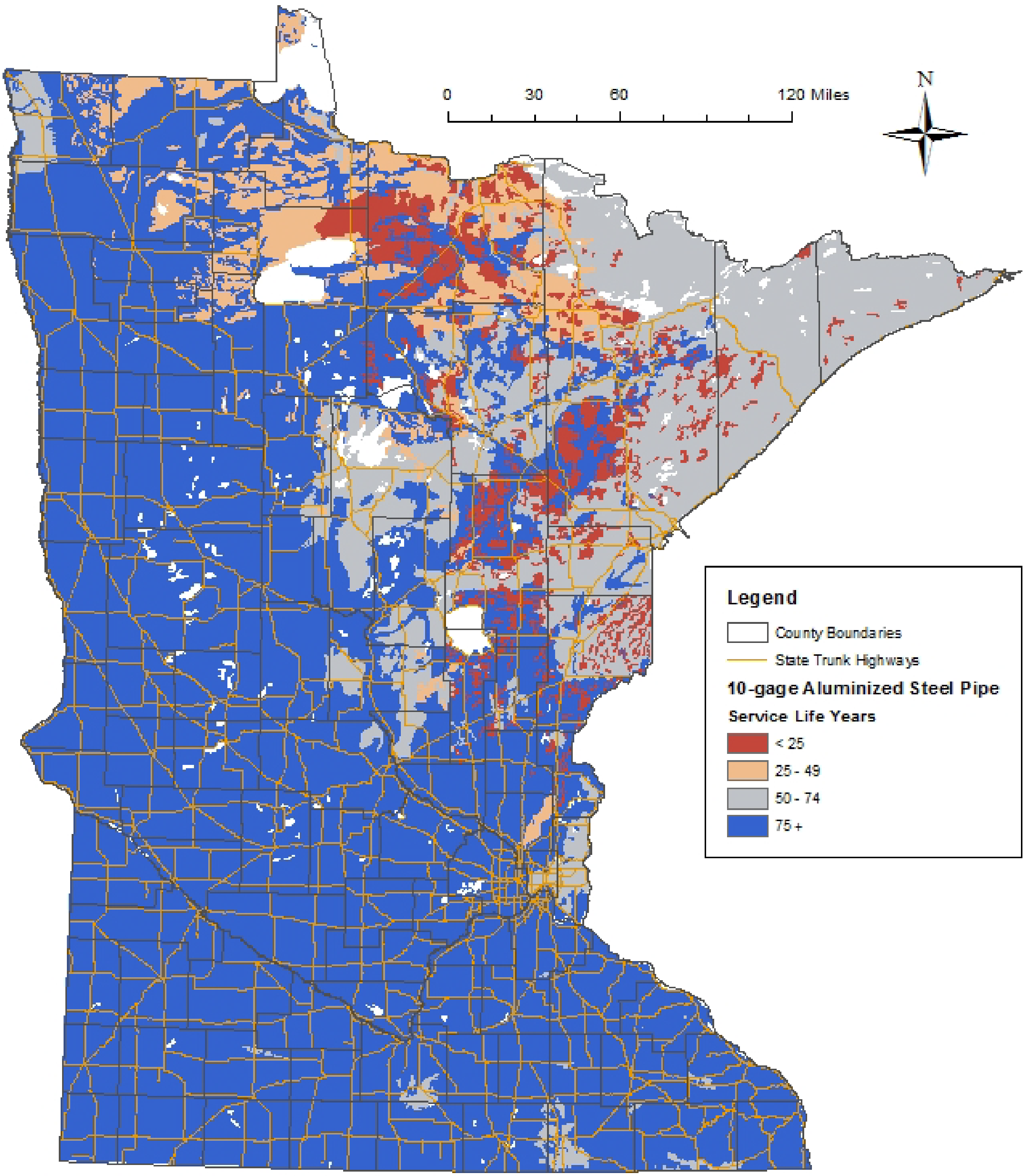


Figure C.9: Service-life estimates calculated using Caltrans 643 method for 10-gage aluminized steel pipe.

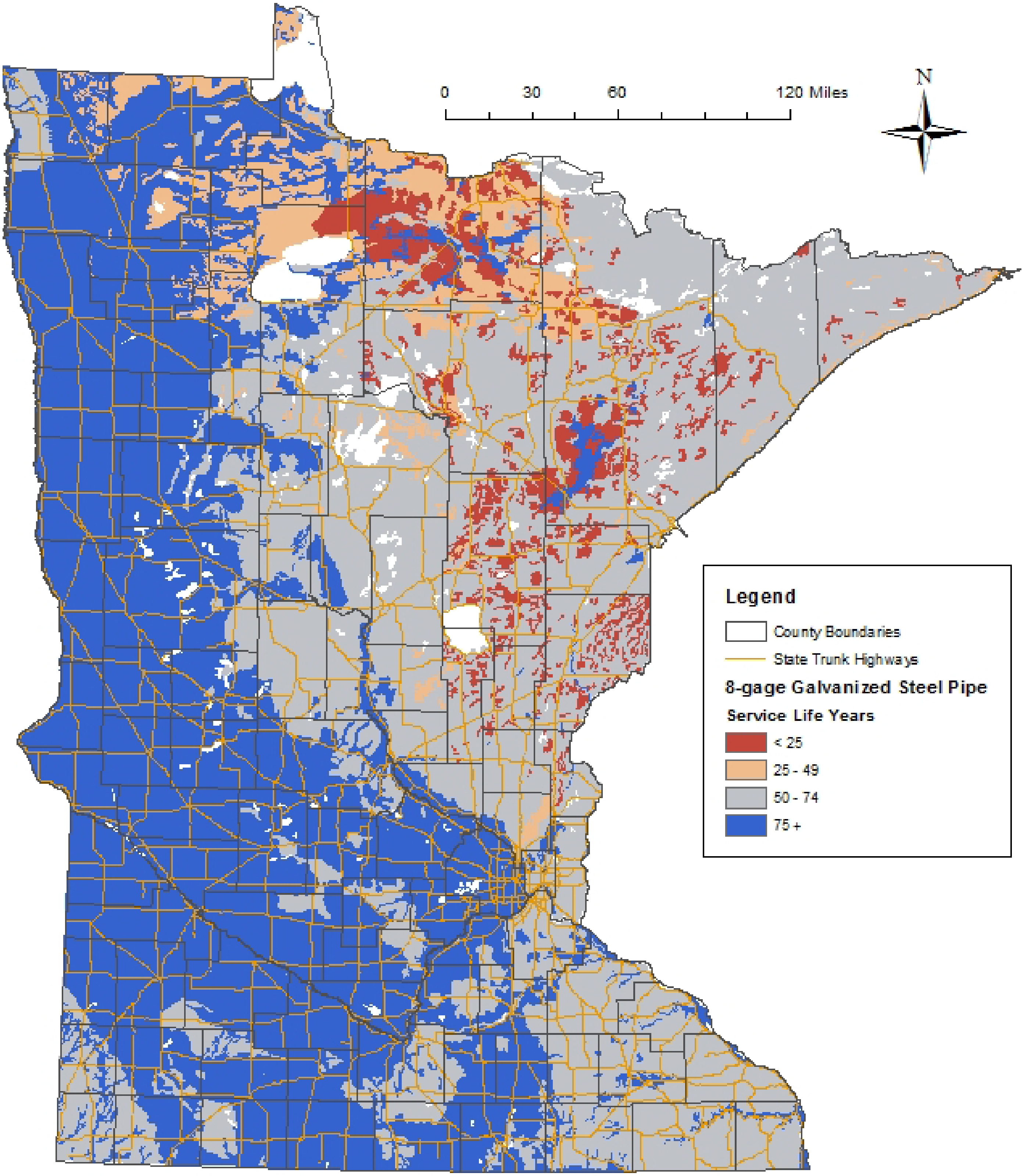


Figure C.1: Service-life estimates calculated using Caltrans 643 method for 8-gage galvanized steel pipe.

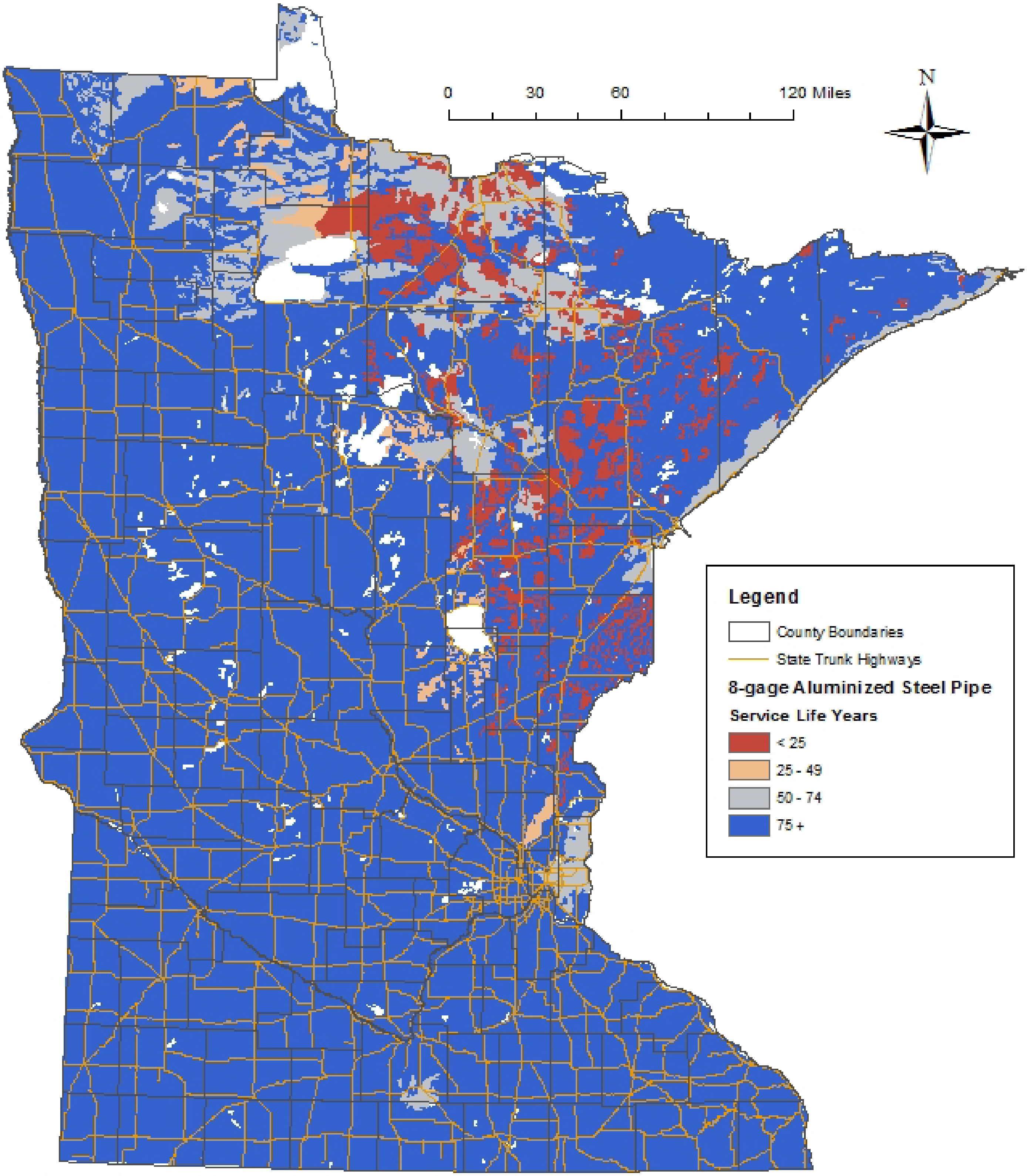


Figure C.2: Service-life estimates calculated using Caltrans 643 method for 8-gage aluminized steel pipe.