Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development of Metals Corrosion Maps of Arkansas and Maintenance of Cross-Drains

Project No. 18GTASU01

Lead University: Arkansas State University

Final Report

August 2019

Disclaimer

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16. Abstract

Corrosion potential of metallic structures in alluvial soils is governed by chemical and electromagnetic properties of the soils. Geotechnical engineers are generally more concerned about different types of soils and their physical and mechanical properties than the chemical aspects. The main objective of this study is to analyze the geotechnical, electrochemical and electromagnetic properties of soils in Arkansas. Important parameters (e.g., soil resistivity) related to corrosion potential of metal culverts have been predicted through neural network (NN) models. The developed NN models have been trained and verified by using laboratory test results of soil samples collected from Arkansas Department of Transportation (ARDOT), and survey data obtained from the United States Department of Agriculture (USDA) and Arkansas Department of Environmental Quality (ADEQ). Finally, the Geographic Information System (GIS) based corrosion risk maps of three different types of metal pipes have been developed based on the available soil properties, metal properties, and water quality data. The developed maps will help ARDOT engineers to assess corrosion potential of metal pipes prior to the new construction and repair projects and use proper culvert and cross drain materials.

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ADEQ	Arkansas Department of Environmental Quality
AISI	American Iron and Steel Institute
AL_T2	Aluminized (Type II) Corrugated Steel Pipe
ARDOT	Arkansas Department of Transportation
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Materials
CESUR	Center for Efficient and Sustainable Use of Resources
DOT	Department of Transportation
EPA	Environmental Protection Agency
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GCSP	Galvanized Corrugated Steel Pipe
GSP	Galvanized Steel Pipe
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
NCHRP	National Cooperative Highway Research Program
NCSPA	National Corrugated Steel Pipe Association
NN	Neural Network
NRCS	Natural Resources Conservation Service
PCA	Principal Component Analysis
SSURGO	Soil Survey Geographic Database
SVM	Support Vector Machine
Tran-SET	Transportation Consortium of South Central States
TRB	Transportation Research Board
USDA	United States Department of Agriculture
USGS	United States Geological Survey

WSS	Web Soil Survey

EXECUTIVE SUMMARY

Arkansas Department of Transportation (ARDOT) spends a significant amount of money in installation, and maintenance of culverts along the highways. Different types of metal culverts and reinforced concrete culverts are commonly used. Corrosion is one of the major reasons for replacement, removal, and cleaning of these culverts. However, ARDOT does not have any detail guideline or specification for selection of metal types based on the corrosion susceptibility of culvert materials. The main objective of this study is to develop user-friendly corrosion and life cycle cost maps for different metal pipes in Arkansas by analyzing soil properties, water properties, and environmental data collected from public domains as well as those gathered from laboratory experiments.

Region-specific metal corrosion risk prediction requires reliable sources of data. The United States Department of Agriculture (USDA)'s Soil Survey Geographic Database (SSUSGO) has an extensive array of data related to the physical and chemical properties of topsoil. The Arkansas Department of Environmental Quality (ADEQ) along with the US Environmental Protection Agency (EPA) and the United States Geological Survey (USGS) also monitors and collects the surface water quality data at different locations (stations) within the state. Important geotechnical, geochemical properties, and soil and water quality parameter data were collected for all 75 counties in Arkansas. These data were analyzed to develop metal corrosion risk maps and life cycle cost maps for the state. Soil samples were collected from ARDOT's Districts 10 and 02. Laboratory test results were combined with thousands of datasets collected from the aforementioned source. Afterward, neural network-based models have been developed for predicting soil resistivity. Finally, using soil pH, resistivity, and surface water pH, the expected service life of three different metal types were estimated. Geostatistical interpolation methods were applied for developing GIS-based maps, which illustrate estimate service lives of Galvanized Steel, Aluminized Steel Type II, and Aluminum pipe culverts.

Data presented in the maps can be extrapolated for different gage thickness and other types of metal culverts. The findings of this study are expected to help ARDOT engineers in planning and maintaining highway drainage systems and minimize unexpected/unplanned future removal and/or replacement of metal culverts. The developed maps will also help the agency in evaluating the existing condition of culverts based on the critical locations and taking necessary measures to save future expenditure.

1. INTRODUCTION

Metal culverts or pipes are frequently used in Arkansas for different highway drainage structures. These culverts are susceptible to significant corrosion. Arkansas Department of Transportation (ARDOT) spends a significant amount of money in replacing and installing different types of culverts for cross-drains. However, the number of catastrophic failures and replacements of culverts can be reduced by selecting proper types of metal. The ARDOT's *2014 Standard Specifications for Highway Construction* document does not provide enough details about the measures to be taken to reduce the effects of corrosion *(1)*. The ARDOT uses different types of culverts for temporary and permanent structures. Corrugated steel pipes, aluminum-coated steel pipe culverts and reinforced concrete pipes are commonly used for drainage structures. Corrosion of these pipes depends on the pipe material properties, properties of soils around the pipes, the quality of waters passing through the pipe, the ambient temperature, and other environmental factors. Highly corrosive surface water, abrasive bed materials, and corrosive ground water can also influence the corrosion of the culverts. Multiple research studies have been conducted in nearby states to analyze the service life of metal culverts and to prepare risk maps. The ARDOT does not have detail information about the probable spatial distribution of corrosion rates in Arkansas. No specific guidelines exist for pipe material selection and their installation and/or replacement schedule. The main objective of this project is to develop a corrosion map for Arkansas based on laboratory test results and neural network (NN) models. Relevant literature and guidelines have been reviewed to analyze the best options of the targeted index parameters based on the available data sources. Specific gaps are assessed and addressed accordingly. A number of assumptions were made to develop the models after a thorough review of the existing conditions. A research plan has been formulated to fulfill the target. Relevant data and soil samples are analyzed, and the findings are reported.

According to the National Cooperative Highway Research Program (NCHRP) Report No. 474, materials such as concrete, galvanized steel (corrugated), aluminized steel, aluminum, High-density polyethylene (HDPE), ductile iron and polyvinyl chloride (PVC) plastics are used as for cross-drainage structures *(2)*. In most of the cases, state transportation agencies have a qualified product list (QPL) for culvert and pipe materials. The products are usually listed based on the established American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) standard requirements. Instead of being selecting materials based on the QPL, the corrosion potentials of these materials in the field can vary unpredictably because of the wide variability of soil, water, and atmospheric conditions related to corrosion protection. Electrical resistivity (ER) and pH are primarily considered as two major indicators of corrosivity of these materials. In general, the ER of surface water is higher than 5000 ohm.cm, and seawater is around 25 ohm.cm, which implies that the addition of salts in water reduces the resistivity. For various types of soils, the typical ER values are as follows: for rock usually greater than 50,000 ohm.cm, for sand 30,000 to 50,000 ohm.cm, for gravel 10,000 ohm.cm to 30,000 ohm.cm, and for clay 2,000 ohm.cm to 750 ohm.cm *(2)*. State agencies suggested different protection methods based on the analyses of pH and ER. However, several other factors can significantly influence the corrosion behavior and service life of metal culverts. A detailed discussion is presented in the following sections of this report.

The project targeted to analyze the available data to assess the prospect of metal corrosion in different areas within Arkansas. To this end, existing practices and solutions were thoroughly analyzed under this project. Available methods in literature were studied to find out the best-suited method for conditions prevailing in Arkansas. Data related to soil physical and chemical properties along with water quality data were extracted from different sources such as the United States Department of Agriculture (USDA) and the Arkansas Department of Environmental Quality (ADEQ). The combination of laboratory test results of sixteen soil samples and twenty-one (21) parameters of the USDA and two different ADEQ databases were analyzed to develop neural network models and corrosion risk maps for Arkansas. Finally, a life cycle cost analysis of metal pipes was conducted as part of this study. Adopted methodologies and outcomes are discussed in this report.

2. OBJECTIVES

The main objective of the project is to develop a corrosion map of Arkansas after evaluating soil, water, and environmental factors. The specific objectives of the project are to:

1. Analyze soils, materials and environmental data from historical and new construction projects,
2. Develop a user-friendly corrosion map of Arkansas,
3. Conduct life cycle cost analysis of different metal pipes, and
4. Suggest cost-effective maintenance options of cross-drains to lengthen their service lives.

To fulfill the objectives of this project, a project plan including several tasks were identified. The scope and methodologies of this project are explained in the subsequent sections of this report.

3. LITERATURE REVIEW

3.1. Factors Affecting Service Life of Culverts

The service life of a culvert is an important factor for investment and planning of highway drainage structures. In the NCHRP Synthesis No. 474, the agency detailed several factors that control the service life of culverts *(2)*. The corrosion rate is considered as one of the most important factors that govern the service life of culverts. The corrosion rate of metals varies over the regions, and it is controlled by metal properties, soil physical and chemical properties, and environmental conditions. In different environments, different types of corrosions are critical. According to the NCHRP, in highway culvert's metallic environment, among many others, galvanic corrosion, crevice corrosion, pitting, erosion-corrosion, stress corrosion, and biological corrosion are the most susceptible types. These types of corrosion can be present in a combined environment of soil and water with metal *(2)*. Again, the inner and outer sides of metal culverts are prone to different types of corrosions. Among several factors, the chemical compositions of surrounding media, pH, the presence of Hydrogen disulfide (H_2S), chloride ion, gravitational, or pellicular water are the major driving forces for corrosion. In most of the studies, the pH and resistivity of soil and water were found to be common and correlated with the durability of metal pipes. It has been reported that the soil-side corrosion controls the service life of culverts when pH is greater than 7.3, and the water-side corrosion plays a major role in the overall corrosion in the presence of abrasive bed loads. In a study in Ohio, the researchers found that the water-side corrosions are critical for metal loss and failure *(3)*. Moisture content, pH, resistivity, and redox potential also have strong correlations with corrosivity *(4)*. For lower pH, redox potential and resistivity values, the corrosivity is high. A few researchers [e.g., *(5)*] studied the impacts of geotechnical properties such as the clay content, plasticity index on the corrosion rates. These researchers found that increases in clay content and plasticity index trigger the corrosion potentials. Again, soil chemical compositions have a significant influence on corrosivity potential *(6, 7)*.

In most of the cases, highway culverts are surrounded by backfill materials, and the backfill material properties have significant influence on the corrosion of culverts. In different state transportation agencies, several researchers have worked or are still working on evaluating the impacts of backfill material properties. For example, Elias et al. *(8)*, Thapalia *(9)*, Brady *(10)*, Tucker-Kulesza et al. *(11)*, and Crowder *(12)* have analyzed important aspects of metal pipes and properties of backfill materials for corrosion potential assessment. In general, most of the properties are not considered during the corrosion rate prediction modeling work or in the corrosion risk analysis. For bedding and backfill material usage, the ARDOT has standard specifications about the gradation and compaction requirements *(1)*. However, no studies have been carried out to determine the corrosion properties recommended backfill materials. In the case of controlled backfill conditions, drainage water quality and bedload materials govern the service life of culverts *(7)*.

3.2. Service Life Estimation of Metal Culverts

The American Iron and Steel Institute (AISI), the National Corrugated Steel Pipe Association (NCSPA) and a few other transportation agencies developed their own methods of evaluation of service life of different culverts *(2)*. For galvanized steel pipes (GSP), the "California Method" is widely accepted among practitioners. The AISI, the Florida Department of Transportation (FDOT), the Federal Lands Highway (FLH), the Colorado Department of Transportation, the

NCSPA, the Utah DOT have also developed their own methods of evaluating service life of GSPs. Most of the methods including, the “California Method” uses resistivity and pH for evaluation of service life of GSPs. The graphical form of the “California Method” is shown in Figure 1 *(13)*. The method adopted by the AISI and the FDOT are shown in Figures 2 and 3, respectively. The FDOT modified the “California Method” based on the findings of their own studies. The “California Method” is used for estimating the service life of GSPs in this study.

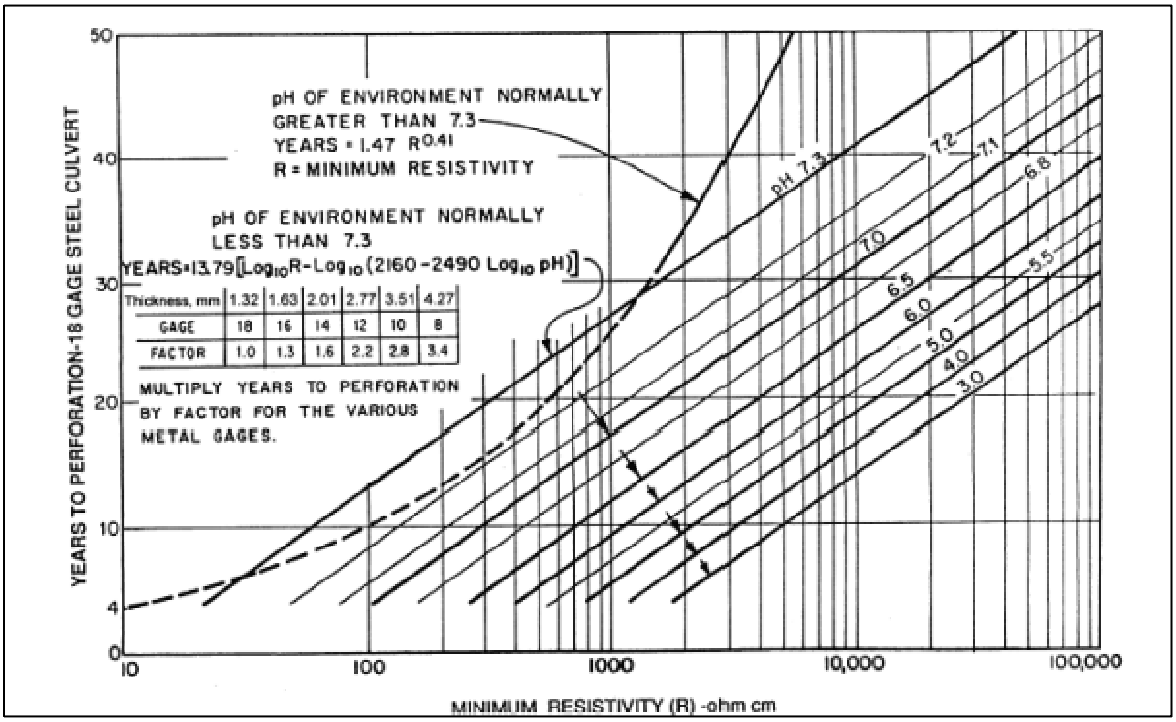


Figure 1. Graphical representation of California Method *(13)*.

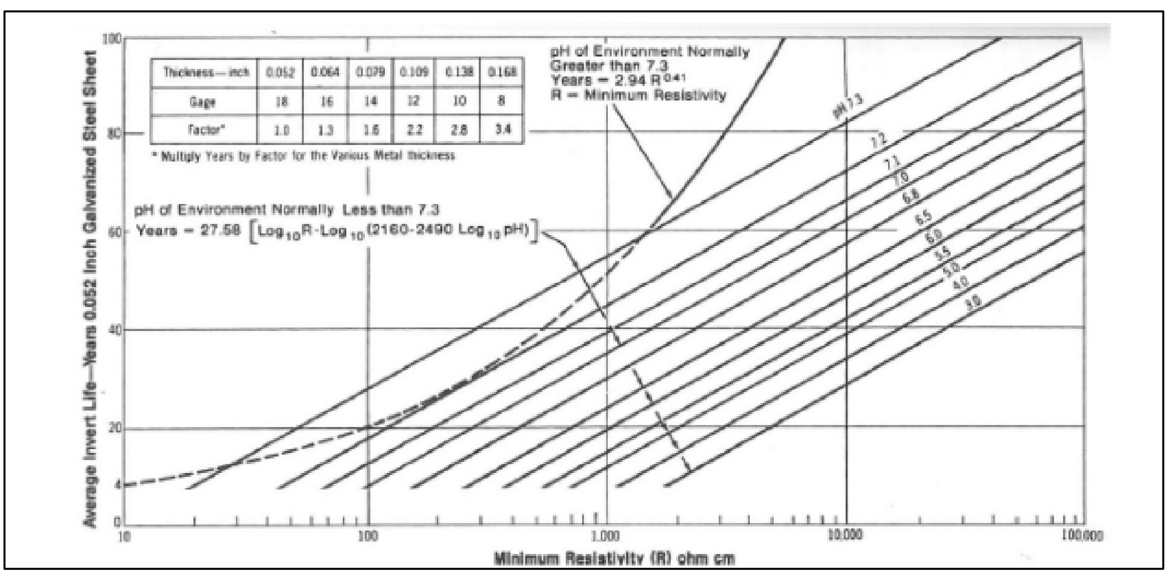


Figure 2. Graphical representation of AISI method for estimation of service life of GSPs *(14)*.

Aluminized steel (Type II) pipe is another common type of culvert used by the ARDOT. The FDOT developed a method based on resistivity, gage thickness and pH to estimated service lives of aluminized steel culverts, as presented in Figure 4. Aluminum pipe is material that is commonly used by different state agencies. The FDOT also developed a method to estimate the service life of this type of culverts. A graphical representation of this method is shown in Figure 5.

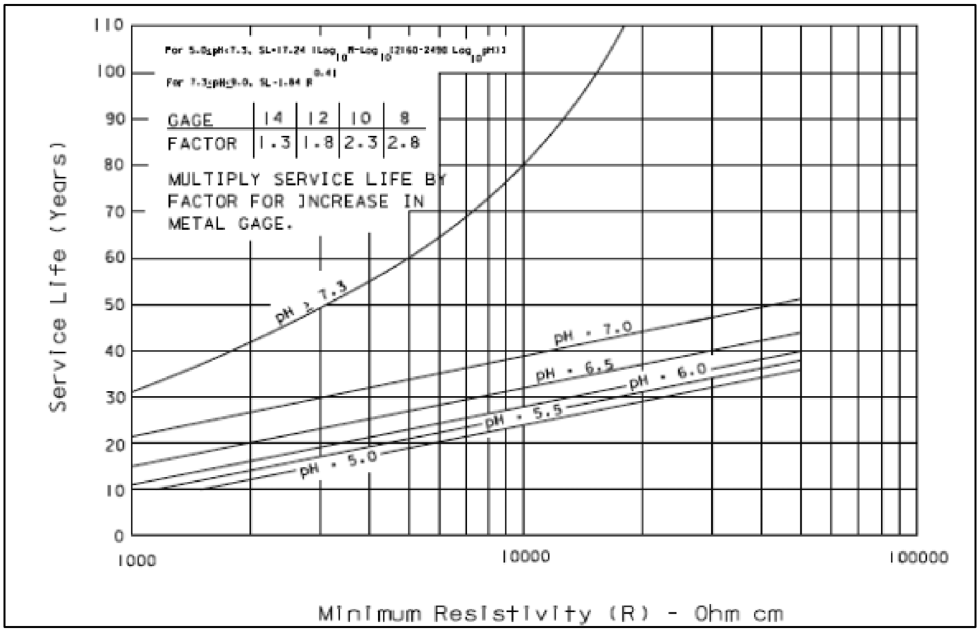


Figure 3. Modified California Method, developed by FDOT *(15)*.

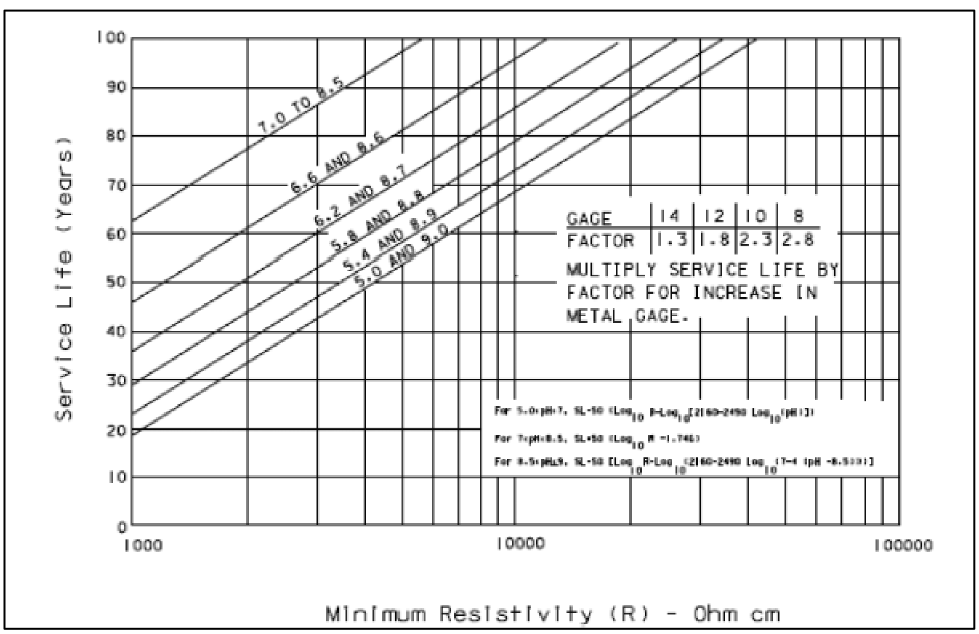


Figure 4. Estimated Service Life of Aluminized Steel (Type II) pipe, FDOT (2012) method *(15)*.

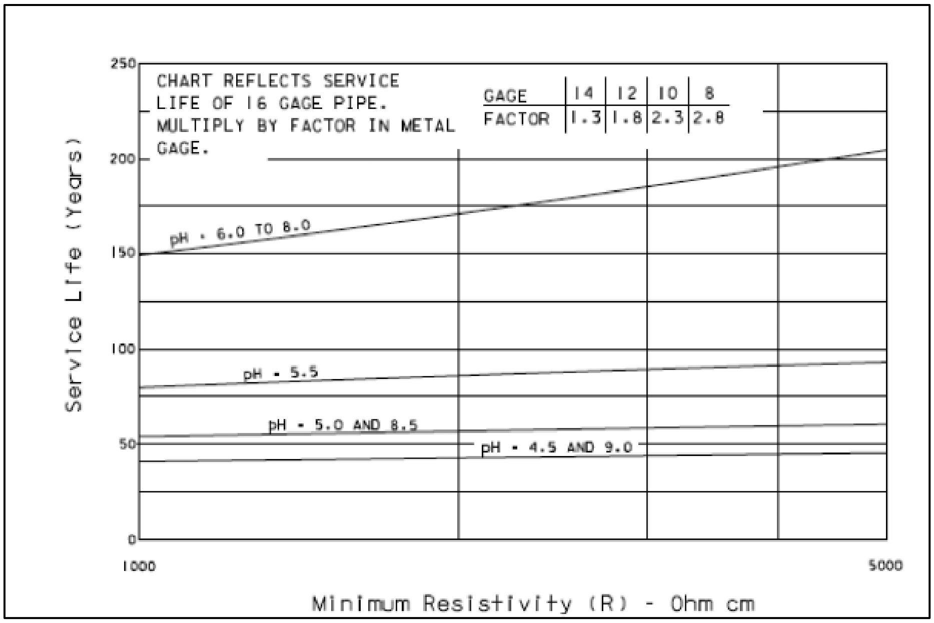


Figure 5. Service life estimation of Aluminum pipe using FDOT (2012) method *(15)*.

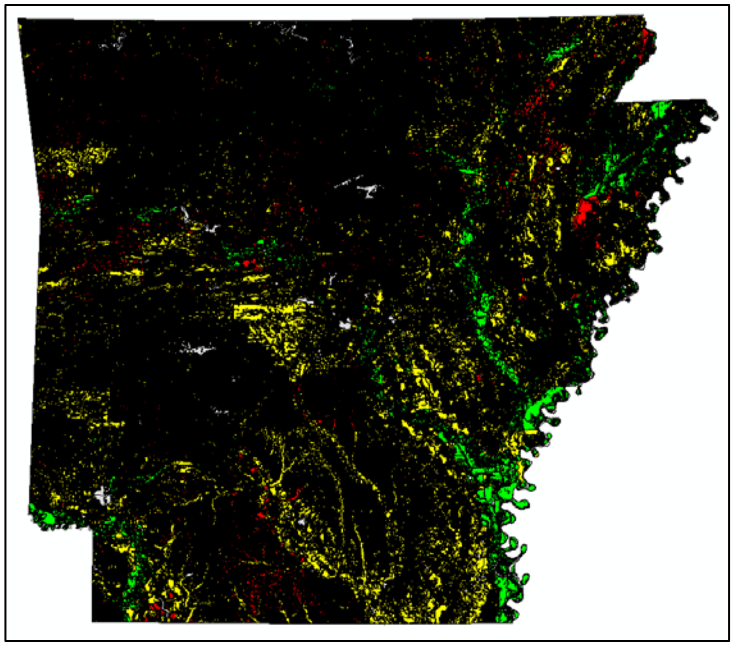
3.3. Corrosion Mapping Methods

Corrosion risk maps show the risk of corrosions in different spatial locations. For the corrosion risk mapping for concrete, the National Resource Conservation Services (NRCS) used the US Soil Survey Geographic Database (SSURGO) and calibrated the risk attribute based on the soil texture and reaction, Sodium (Na) and Magnesium (Mg) sulfate contents, and Sodium Chloride (NaCl) *(16 & 17)*. Based on a set of criteria, the NRCS categorized corrosion risk features into three different classes: Low, Moderate, and High. According to the 2018 National Soil Survey Handbook *(13)*, sandy and organic soils with pH greater than 6.5 or fine-textured soils with pH greater than 6.0 with Sodium (Na) and/or Magnesium (Mg) sulfate content less than 1,000 ppm, and the NaCl content less than 2,000 ppm are defined as the "Low" risk category. Sandy and organic soils with pH ranging from 5.5 to 6.5 or fine-textured soils with pH ranging from 5.0 to 6.0 with Sodium (Na) and/or Magnesium (Mg) sulfate content ranging within 1,000 ppm to 7,000 ppm, and the NaCl content ranging from 2,000 ppm to 10,000 ppm are defined as the "Moderate" risk category. Sandy and organic soils with pH less than 5.5 or fine-textured soils with pH less than 5.0 with Sodium (Na) and/or Magnesium (Mg) sulfate content greater than 7,000 ppm, and the NaCl content more than 10,000 ppm are defined as the "High" risk category. Figure 6 (a) shows the overall concrete corrosion risk map of Arkansas based on the existing approaches followed by the NRCS *(16, 17)*.

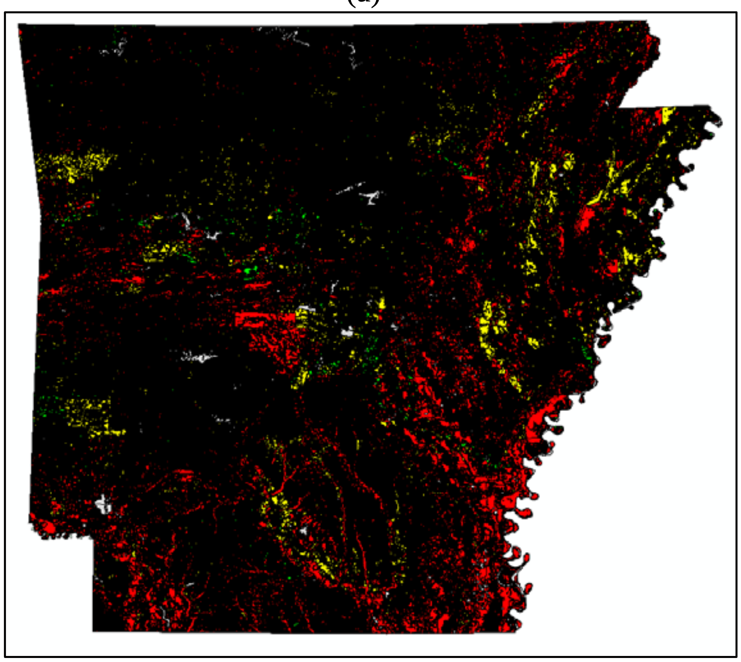
In the case of uncoated steel, the NRCS used the SSURGO and categorized the steel corrosion risk potentials in three (Low, Moderate and High) different categories *(17)*. These classifications are based on drainage class and texture of soils, the total acidity of the soil, soil resistivity at saturation, and conductivity of saturated extract. Class type "Low" is defined when the soil is well-drained with coarse-textured soils, in combination with a total acidity less than 8 meq/100g, the resistivity at saturation is at least 5000 ohms/cm, and conductivity of saturated extract less than 0.3 mmhos cm^{-1}. Class type "Moderate" is defined when the soil is moderately well-drained, in general, with moderately coarse-textured soils, in combination with the total acidity ranges from 8 meq/100g to

12 meq/100g, resistivity at saturation lies within 2000 ohms/cm to 5000 ohms/cm, and conductivity of saturated extract lies within 0.3 mmhos cm^{-1} to 0.8 mmhos cm^{-1}. Type "High" risk of corrosion potential is considered for fine-textured soils with varied draining conditions, along with the total acidity is at least 12 meq/100g, the resistivity at saturation is less than 2000 ohms/cm, and conductivity of saturated extract is greater than or equal to 0.8 mmhos cm^{-1} *(7, 16, & 17)*. Figure 6 (b) shows a corrosion risk map of uncoated steel in Arkansas based on the NRCS approach *(7, 16, 17).* In Figure 6, risk category "Low" is marked with *green*, risk category "Moderate" is marked with *yellow*, and risk category "High" is marked with *red*.

Louisiana DOT has developed metal corrosion risk maps for the coastal parts of Louisiana *(18)*. These researchers categorized corrosion potentials as "Mildly Corrosive," "Corrosive," "Highly Corrosive," and "Extremely Corrosive," based on the expected average life of metal pipes. A weighted doubly 25 x 12 matrix was used to categorize the risk potentials based on pH and resistivity of soil *(18)*. These corrosion risk metrics were categorized based on guidelines of the NCHRP Synthesis No. 474 titled "Service Life of Culverts – A Synthesis of Highway Practice" *(2)*. While determining the final lifespan of culverts, the Louisiana study followed the study of the Colorado Department of Transportation *(19)*. However, these studies did not consider all possible related soil parameters used by geotechnical engineers. Thus, a combined index or an agglomerated model is required to categorize risk potential based on the routine engineering properties of site soils and other information available in the secondary literature.



(a)



(b)

Figure 6**. NRCS approach of corrosion risk mapping: (a) concrete corrosion risk *(16)*, and (b) uncoated steel corrosion risk *(16)*.**

4. METHODOLOGY

The development of metal corrosion map requires an extensive amount of data and a rigorous analysis of the data. To this end, literature review, relevant data source identification, data collection, materials collection, test matric development, experimentation, data preprocessing and analysis, and the final mapping are different stages of works completed under this project. A detailed flowchart of the steps involved in this project is presented in Figure 7.

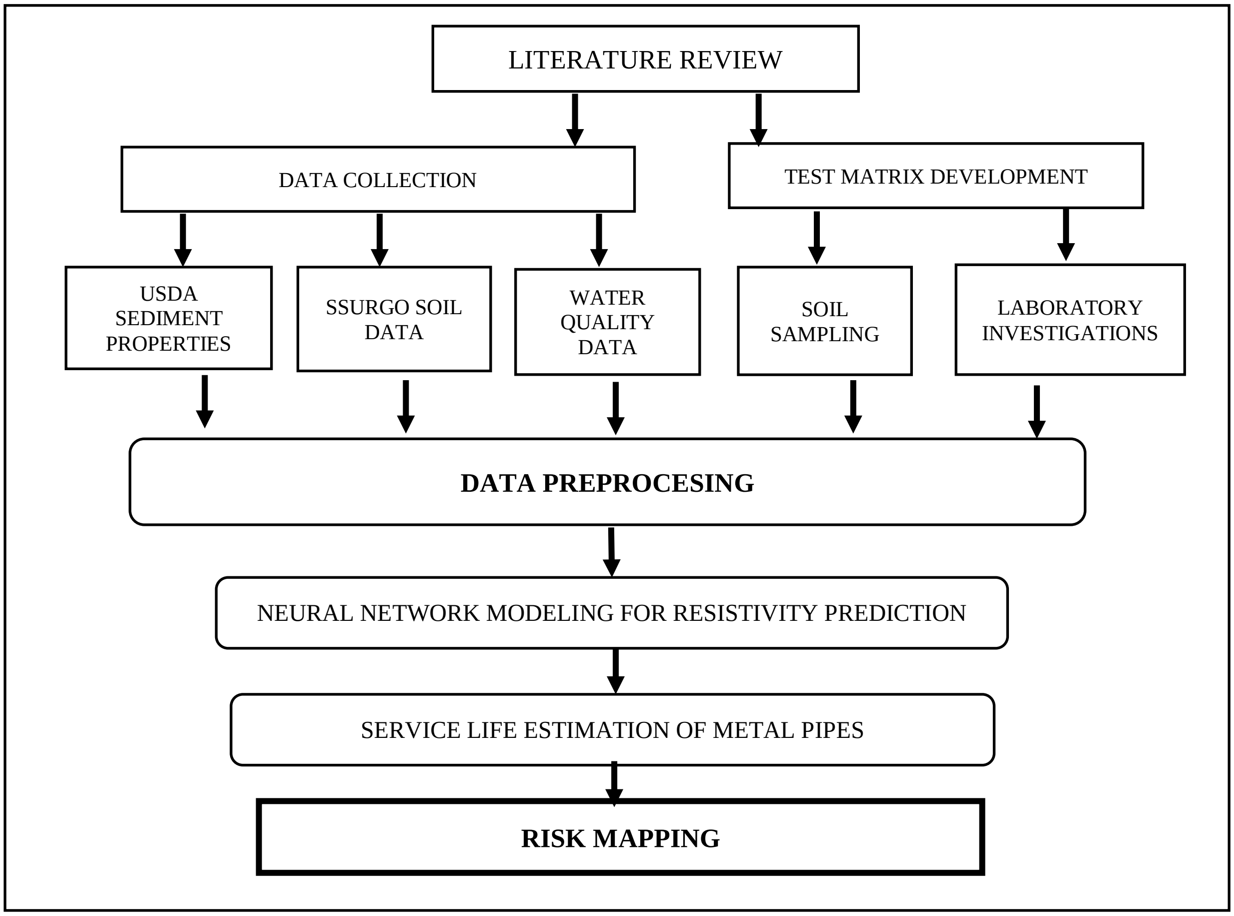


Figure 7. Flowchart of the study methodology.

4.1. Data Collection

As mentioned earlier, both the outer and inner sides of metal culverts are susceptible to corrosion. Corrosion in the outer side of the culverts is governed by the soil or backfill material properties and groundwater quality parameters. On the other hand, the inner side corrosion of the culverts is predominately governed by the drainage water quality parameters and abrasive properties of sediments passing through the culverts *(2)*. After an extensive literature review, important secondary sources of data for corrosion risk assessment are targeted for this project. The ARDOT has a database of geotechnical reports from previous construction projects. However, the ARDOT does not have enough data related to electric resistivity and electric conductivity of soils. On the other hand, the United States Department of Agriculture (USDA) has conducted soil surveys over the times. Most of these data are accessible by public users. The SSURGO also has an extensive extractable database comprised of important soil physical, chemical and quality-related data *(20)*.

The SSURGO has relevant data in the form of 68 different Microsoft-Access (MS-Access) data sets for all the 75 counties in Arkansas. These data can be extracted as polygon shape files of different parishes with corresponding soil properties. Soil Data Viewer, an add-ins software which can be downloaded from the USDA website, is used to visualize these data using the ArcGIS tool. Shape files related to each county are extracted with twenty-one data features. Each feature represents one property of individual soil parish specific properties. Finally, twenty (20) feature properties are joined and a combined dataset with different soil properties are prepared. These features are selected based on the factors that are important for corrosion predictions. The features selected from the SSURGO are as follows: potential risks of corrosion in concrete (categorized as high, moderate and low), and uncoated steel (categorized as high, moderate and low), calcium carbonate equivalent (percent of carbonates, by weight, in the fraction of soil mass which are less than 2 mm in size), cation exchange capacity (CEC-7), effective cation-exchange capacity (ECEC), electric conductivity (EC), gypsum (percent by weight), pH, sodium adsorption ratio (SAR), liquid limit, organic matter, percent clay (soil particles that are less than 0.002 millimeter in diameter), percent sand (soil particles that are 0.05 millimeter to 2 millimeters in diameter), percent silt (soil particles that are 0.002 to 0.05 millimeter in diameter), plasticity index, saturated hydraulic conductivity (micrometers per second), AASHTO soil classification, drainage class, depth of water table, flooding frequency class(categorized as none, very rare, rare, occasional, frequent and very frequent), and ponding frequency class (categorized as none, rare, occasional and frequent).

The ADEQ also has an extensive database of water quality parameters from different monitoring stations within individual counties. These datasets are extractable in the Microsoft Excel spreadsheet format. Water quality data of the 75 counties are collected with location details and extracted as point feature layers based on the locations of the stations. The ADEQ dataset has records for pH of the water and total dissolved solid contents (mg/l), which is an indirect predicting parameter of the resistivity of water. Data related to specific conductance of water is also available for a few counties. Resistivity (ohm-cm) of freshwater can be converted from total dissolved solids (mg/l), by simply dividing 0.65 by the total dissolved solids (mg/l) *(21)*. For the current study, this conversion method has been used to estimate the resistivity of water. Later, water pH data and resistivity data are merged for all the counties. Finally, the pH and converted resistivity data have been joined with the dataset acquired from the SSURGO, based on the spatial locations. The USGS has sediment water quality at different measuring stations covering the entire state. The locations and details of the sediments in different locations are collected and used for abrasion evaluation of the inner part of the culverts.

4.2. Soil Sampling

Geotechnical parameters and geochemical parameters have a significant influence on the corrosion potential of soils. For primary data from the field, soil samples were collected from different construction projects in ARDOT Districts 10 and 02. Regional district offices were contacted and with the help ARDOT District engineer, 22 soil samples have been collected. ARDOT engineers supplied the soil samples required for laboratory testing of this project. The locations of the collected soil samples are also collected through ARDOT engineers. A list of project job no. and locations are detailed in Table 1. Figure 8 shows the pictorial views of soil samples collected from ARDOT District 10.

Figure 8. Soil samples collected for laboratory investigations.

4.3. Laboratory Testing

Soil resistivity and pH are the most widely used parameters for the evaluation of the service life of metals in the soil and water environment. For laboratory analysis of resistivity, ASTM G57 and

AASHTO T 288 are two widely used methods. The ASTM G187 method is also used for this purpose. In this study, ASTM G57 is followed to estimate the minimum resistivity of the soil samples. A four-pin soil resistivity box, manufactured by MC Miller Company, has been used in measuring soil resistivity. A BK precision 4040 20 MHZ Sweep function generator has been used to generate a current flow through the samples placed in the box. The soil samples have been saturated for 24 hours before placing them in the box, and an A/C current with 97 Hz frequency has been passed through the soil samples *(22)*. The voltage drop and the current flow have been measured by using a KEITHLEY 2000 MULTIMETER and CENTECH P9674 digital multimeter. Finally, the soil resistivity has been calculated according to ASTM G57. The set of arrangement for the testing of soil resistivity is shown in Figure 9.

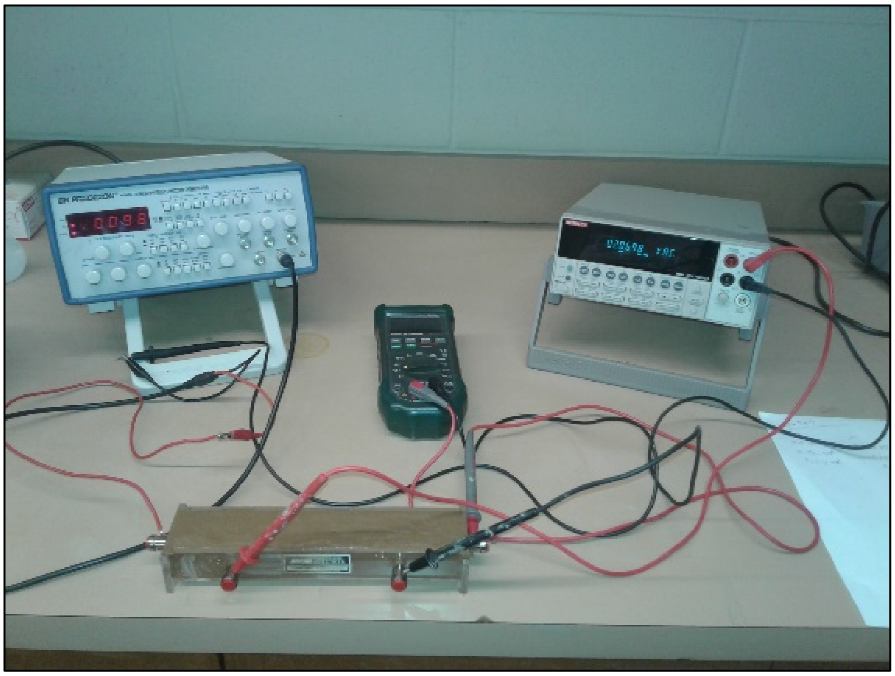


Figure 9. Soil resistivity testing using Miller box.

The collected soil samples are also tested for pH by following ASTM G51. Routine geotechnical parameters (e.g., liquid limit, plastic limit, and soil classification) for all soil samples are also evaluated in the laboratory. Arkansas State University soil lab has been used for this purpose. The descriptions, locations, resistivity and pH values of tested soil samples are presented in Table 1.

Establishing a correlation between corrosion parameters and geotechnical routine parameters is one of the major goals of this project. Specific gravity, percent clay, percent sand, percent silt, Atterberg limits, and AASHTO soil classification have been identified as the critical parameters, which can be used to correlate the information detailed in the SSURGO. For being consistent, these routine geotechnical parameters are evaluated in the laboratory. For specific gravity analysis, ASTM D854 has been followed. For sieve and hydrometer analysis, ASTM D422 has been followed. ASTM D4318 has been followed for determining the Atterberg limits. The grain size distribution curves of the soil samples collected from Districts 10 and 02 are shown in Figures 10 and 11, respectively. A summarized form of the soil data, which are used for regression analysis and neural network modeling, are presented in Table 2.

Table 1. Resistivity and pH testing results of soils.

ID	Description	Latitude	Longitude	pH	R_{min} (ohm-cm)
D10-01	Job No: BR1610	35.830528	-90.764481	6.44	10682.25
D10-02	Monette, AR	35.890578	-90.324728	6.69	11364.82
D10-03	Job No: BB1006	35.984167	-89.875556	6.44	2271.28
D10-04	Job No:100760	35.611944	-90.203889	7.23	1107.73
D10-05	Job No: 100654	35.903611	-90.291944	6.49	8077.66
D10-06	Job No: 100740	35.888889	-89.911667	6.70	1339.86
D10-07	Job No:100653	35.903056	-90.237222	6.44	5395.69
D10-08	Job No: 100708	35.997157	-90.562616	7.28	6392.07
D10-09	Job No:100708	36.056047	-90.621886	7.04	7305.18
D10-10	Job No: 100708	35.830966	-90.512811	6.08	6933.06
D10-11	Job No: 100708	35.830966	-90.512811	7.03	6891.44
D10-12	S Caraway Road, Jonesboro	35.800625	-90.678611	8.33	9187.68
D02-01	Job No: GF 0270	33.654583	-91.211944	7.80	4028.17
D02-02	Job No: 020534	33.134944	-91.855556	6.48	16480.59
D02-03	Job No: 20584	34.100817	-92.001944	5.06	9710.39
D02-04	Job No: BB0203	34.221944	-92.074444	6.49	2168.77
D10-SR01	S. Caraway Road, Jonesboro	35.802683	-090.67863	6.40	9234.50
D10-SR02	S Caraway Road, Jonesboro	35.792397	-090.678437	7.26	6770.66
D10-SR03	S Caraway Road, Jonesboro	35.778245	-090.679274	5.66	7608.75
D10-SR04	S Caraway Road, Jonesboro	35.761323	-090.679531	5.91	3448.44
D10-SR05	S Caraway Road, Jonesboro	35.781553	-090.679059	4.78	3569.53
D10-SR06	S Caraway Road, Jonesboro	35.793668	-090.678716	6.21	34554.10

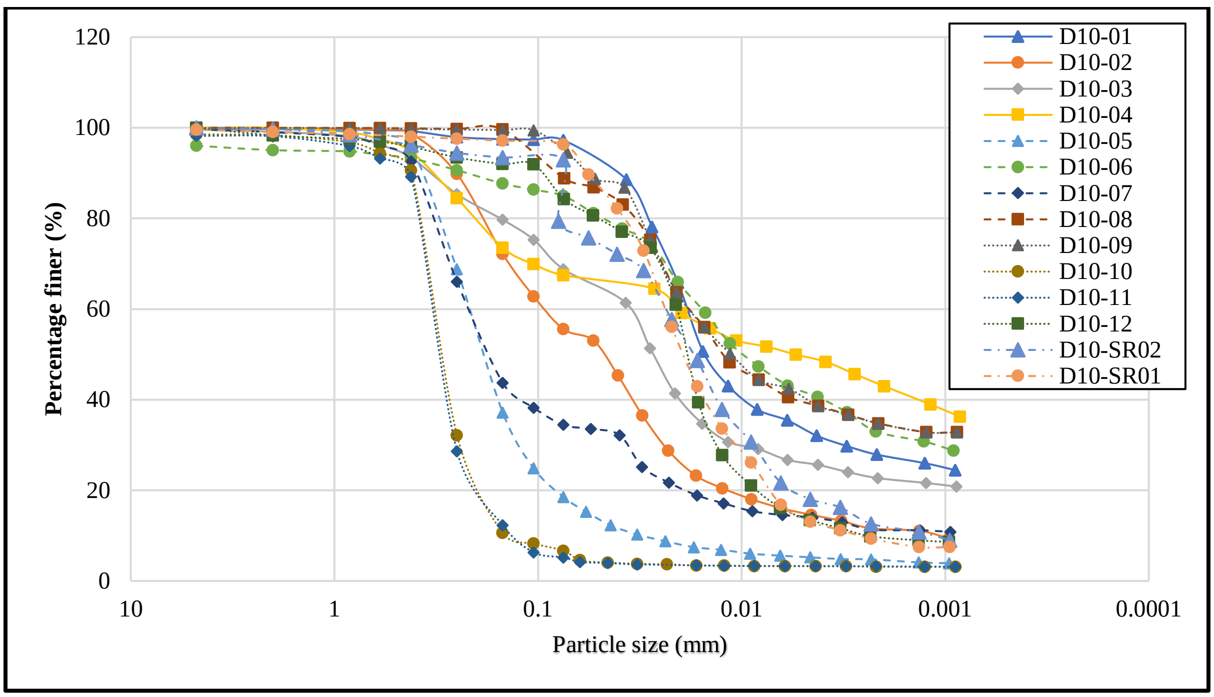


Figure 10. Grain size distribution curves of District 10 soils.

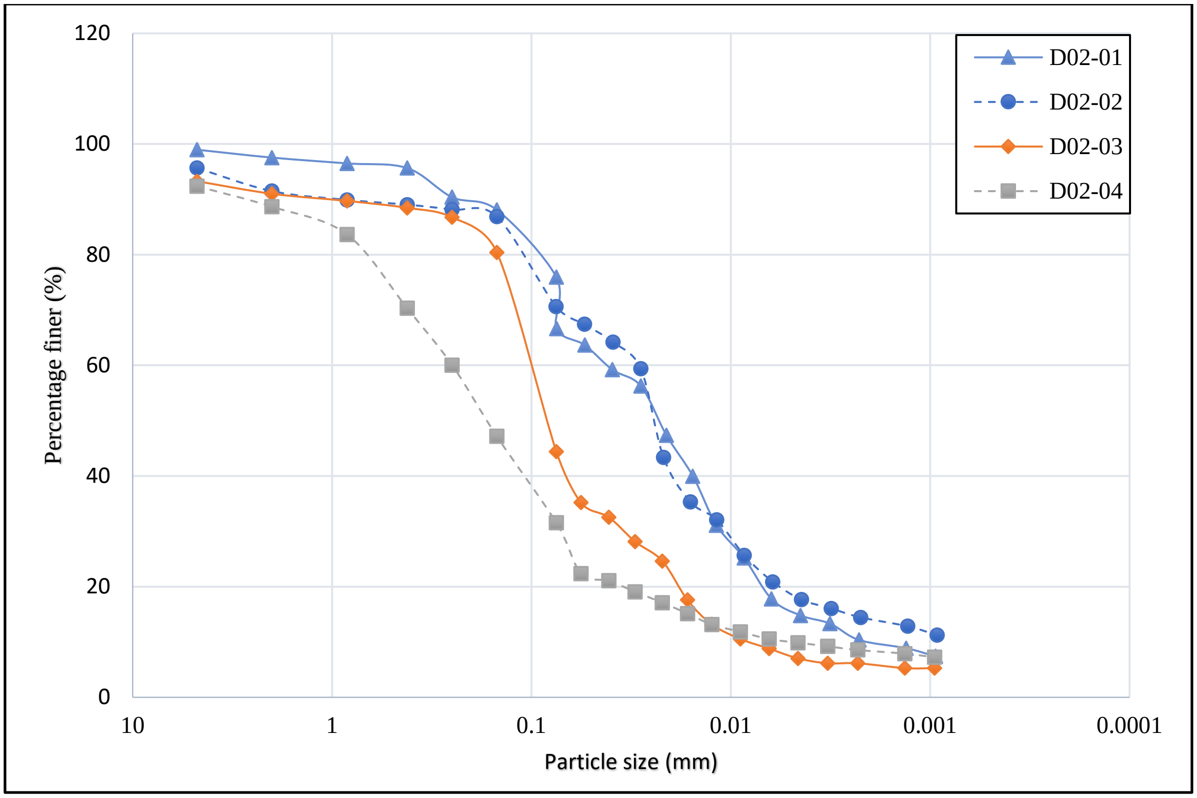


Figure 11. Grain size distribution curves of District 02 soils.

The Arkansas Department of Environmental Quality (ADEQ) has an extensive database of heavy metal concentrations, metallic ions, chloride concentration for several counties. Thus, laboratory testing related to dissolve metallic ions and chloride concentration in surface water deemed to be unnecessary. After detail scoping and screening of these datasets, the total dissolved solids (TDS) concentration has been used for water resistivity determination. The water resistivity has been used for service life estimation of metal pipes in different locations.

4.4. Data Preprocessing

The SSURGO has been explored for data related to geotechnical and geochemical properties of soils within Arkansas. Based on the literature review, twenty-one different geotechnical and chemical properties of soil, of individual parishes, are selected and extracted for further analysis. Soil properties or indexes that are collected for this study are: potential of corrosion of concrete, corrosion of steel, amount of calcium carbonate, CEC, EC, gypsum, pH, SAR. In addition, liquid limit, organic matter, % clay, % sand, % silt, plasticity index, saturated hydraulic conductivity, AASHO group classification, drainage class, depth of water table, flood frequency class, and ponding frequency class data are also extracted. Among the 21 parameters, six variables are categorical. In total, 301,035 different parishes are found in Arkansas. Among the total datasets, 15,423 parishes do not have any of the targeted data. Among the rest of the data, 17,818 parishes do not have any AASHTO soil classification details. After deleting duplicate records, a total of 1,604 different datasets of samples have been found. Among the 1,604 datasets, 148 have electric conductivity values other than ‘zero’.

4.5. Data Classification and PCA

Support Vector Machine (SVM) is a useful tool for data classification analysis. SSURGO's corrosion potential of uncoated steel data (CorSteel) generated based on the NRCS's established criteria, categorized as high, moderate and low risks, is trained as response variable and rest of the twenty parameters as predictor variables in MATLAB's classification learner. For developing the classification models, a total of 22 variables have been trained. Geographic location data – latitude and longitude values - are considered as two additional predictor variables. Linear, quadratic, cubic, fine Gaussian, medium Gaussian, and coarse Gaussian SVMs enabled principal component analysis (PCA) option have been applied. The analysis reveals that the fine Gaussian method gives about 95% accuracy in predicting results, and the prediction with eight variables can give values with a p-value less than 0.05. The Quadratic SVM and Medium Gaussian SVM also give about 92% accuracy. The remaining five categorical variables - corrosion of concrete, AASHTO soil class type, soil drainage class, flooding frequency class, and ponding frequency class, and three numerical variables - SAR, $CaCo_3$, and electric conductivity are found to be the most important predictors during classification analysis. The gypsum content, liquid limit, plastic limit, CEC-7, and ECEC are also found as important classes in the prediction models. Most importantly, other geotechnical parameters, percent clay, percent sand, and percent silt have been found to have very low impacts on the prediction of corrosion risk of steel. Based on this analysis, it has been concluded that for better prediction and regularization of corrosion assessment SAR, $CaCO_3$, EC, Gypsum contents are significant and needed to be included for better prediction. However, the presence of these components may not be obvious in a small area, but it is wise to avoid these parameters during the prediction process of corrosion parameters.

Table 2. Geotechnical properties of the soil samples.

Sample ID	G_s	LL	PI	Percent Sand	Percent Silt	Percent Clay
D10-01	2.78	36	14	9	65	27
D10-02	2.67	20.42	0*	48	29	11
D10-03	3.00	22.84	12	33	41	23
D10-04	2.67	28.16	14	34	23	43
D10-05	2.63	32	0*	86	10	4
D10-06	2.67	41	28	15	48	32
D10-07	2.57	25	0*	66	22	11
D10-08	2.99	30.56	16	12	52	35
D10-09	2.99	29.43	15	11.5	50	36
D10-10	2.72	26	0*	93	2	3.5
D10-11	2.72	26	0*	94	1	3
D10-12	2.74	28.16	14	17	71	10
D02-01	2.786	29.20	9.34	33	53	10
D02-02	2.837	27.27	7.49	25	52	14
D02-03	2.699	18.46	0.34	58	28	6
D02-04	2.110	17.99	2.73	66	12	8
D10-SR01	2.80	-	-	12	78	8
D10-SR02	2.856	39.91	13.43	26	62	12

*NP – Non-plastic

4.6. Data Regularization

To select an appropriate algorithm and neural network architecture for regularization of the rest of the datasets, 148 different soil samples are trained with shallow neural networks. Additional 12 different datasets with 'zero' conductivity values are added for maintaining continuity of data. The electric conductivity has been converted to electrical resistivity before the modeling work. For 'zero' conductivity values, a marginal value of 100,000 ohm-cm is considered. The summary of the training performance results is shown in Table 3. For neural network fitting, datasets were programmed to divide randomly- 70% for training, 15% for validation, and the rest of 15 % for testing purposes. The number of hidden layers has been kept as 10. The structure of the neural network is shown in Figure 12 below.

Table 3. Shallow NN training results for regularization of the soil resistivity data.

MATLAB built-in functions	**trainlm**	**trainbr**	**trainbfg**	**trainrp**	**trainscg**	**traincgb**
Number of hidden layers	10	10	10	10	10	10
Number of epochs	14	605	360	9	36	46
Remarks	Validation stop	Max Mu reached	Validation stop	Validation stop	Validation stop	Validation stop
Training - R Value	0.89953	0.99969	0.78361	0.62674	0.79516	0.90073
Validation – R Value	0.37723	-	0.85962	0.16998	0.66735	0.74199
Testing – R value	0.79129	0.36663	0.83985	0.10356	0.57465	0.98487
Overall – R value	0.86957	0.76028	0.80835	0.54286	0.7192	0.87352

Based on the performance of the study, the Bayesian regularization has been found as one of the most appropriate one based on prediction errors. Among the models used for the regularization process, "trainbfg" has found as the most suitable because the training, validation, and testing converge nicely, and the results are stable for a longer time. However, based on the regression plots, it seems the overall model is highly influenced by the additional 12 datasets added in place as a replacement of "zero" EC values.

4.7. Service Life Estimation

For galvanized steel pipes (GSP), the California method is widely accepted by professionals. In this study, the California method (1993) has been used for the estimation of the service life of GSPs. For aluminized steel Type II, the method adopted by the FDOT in 2012 has been used. For corrugated aluminum pipes, the 2012 Florida DOT method for Aluminum pipe has also been followed. These methods are summarized in the literature review part of this report.

4.8. Mapping

For mapping purposes, the ArcGIS tool has been used. In the mapping process, interpolation techniques such as Empirical Bayesian Kriging (EBK) and Inverse Distance Weighted (IDW) have been applied. Six different maps have been prepared for the three selected types of metal pipes mentioned earlier. For each metal type, the IDW and EBK are applied and the variations are analyzed to see if major fluctuation can be noticed.

5. ANALYSIS AND FINDINGS

In Section 601 of the ARDOT's *2014 Standard Specifications for Highway Construction*, the types of metal culverts that can be used in Arkansas are enlisted. Accordingly, Zinc coated (Galvanized) corrugated steel pipes, Aluminum coated corrugated steel pipes, Aluminum-Zinc alloy coated corrugated steel pipes, corrugated aluminum pipe, Asphalt coated corrugated metal pipe, polymer precoated metallic coated corrugated steel pipe culverts, and smooth lined polymer precoated metallic coated corrugated steel pipes can be used *(1)*. In this research, Galvanized steel pipes (plain and corrugated), Aluminum (Type II) coated corrugated steel pipes, corrugated Aluminum pipe, asphalt coated corrugated metal pipes and polymer-coated corrugated metal pipes are considered for service life estimation and life cycle cost analysis.

5.1. Regression Analysis

Based on the observations of the SSURGO database, A-2-4, A-4 and A-6 types of soil, classified according to the AASHTO Classification System, are dominant in Arkansas. The corrosion potential based on soil classification is easy to apply in the design and construction projects. The establishment of correlations between geotechnical parameters and soil resistivity is an effective way to accomplish this goal. So, linear regression models and support vector machines are applied to 168 independent datasets obtained from the SSURGO and laboratory test results to correlate percent clay, percent sand, percent silt, liquid limit, plastic limit, and soil resistivity. The Gaussian process regression analysis with the exponential kernel function has given the maximum R-Squared value of 0.21 with a Root Mean Square of Error (RMSE) value of 2727.6. The results indicate the models are not effective for predicting resistivity, based on the R-Squared value, RMSE value, initial data classification analysis, and principal component analysis results.

5.2. Soil Resistivity Prediction

After collecting all the soil data from SSURGO, series of geoprocessing tasks are completed using the ArcMap's Geoprocessing toolbox and "ArcPy" module commands. All the datasets have been cleaned and all the fields have been renamed for keeping the database clean and easily exportable. The corrosion risk of concrete renamed as "CorConcrete," corrosion risk of concrete as "CorSteel," Calcium Carbonate as "CaC03," Cation Exchange Capacity as "CEC7," effective cation exchange capacity as "ECEC," electric conductivity as "EC," Sodium absorption ration as "SAR," Liquid Limit as "LiqLim," Organic Content as "OrgMatter," plasticity index as "PlasInd," hydraulic conductivity as "KsatClass," AASHTO soil class type as "AASHTO," drainage class as "DrainClass," depth of water table as "Dep2WatTbl," flooding frequency as "FloodFCls," and ponding frequency as "PondFCls." Polygons with no field data have been deleted and finally, data of all 75 counties have been merged. Then, all the polygon layers have been dissolved into one layer. The initial geographic coordinate reference, GCS_North_American_1983, for all polygons have been also converted to the projected coordinate system, NAD_1983_UTM_ZONE_15N. NAD_1983_UTM_Zone_15N is used for applying all the geospatial interpolation. Geometric features, X and Y coordinates of the center of each polygon, are also added with the attribute table. The final polygon shapefile has been named as "AR_Dissolved_SSURGO.shp," which has 334,102 polygons in total. Now, all the polygons have some preassigned feature data fields with their locations. Finally, the dataset, "AR_Dissolved_SSURGO.dBase" file, has been extracted as a Microsoft Excel spreadsheet. The data has been saved in a different place for further processing and use in MATLAB programs.

In the next stage, all the data obtained from laboratory investigation are imported to ArcGIS as "soil_sample_data" data. The soil sample dataset has sampling location, sample ID, pH, resistivity, specific gravity, LL, PL, percent sand, percent clay and percent silt data only. Additional data related to the soil samples are combined based on the location of samples and joined with "soil_sample_data" point shapefile. The joined data has been finally converted to an Excel-readable format and moved to a different location.

For neural network modeling, it is important to use independent rows during the model development work. So, the exported datasheet (in spreadsheet format) with all dissolved values are treated for removing duplicate rows irrespective of their metadata. After treating 334, 102 rows, 1, 927 rows were found as independent rows. Again, all of these values do not have values of EC. So, the dataset has been filtered for rows with EC values only. One hundred fifty-two (152) rows are found to be independent, which also have EC values. Now, the EC values are converted to resistivity values with a conversion factor. Then 16 laboratory test parameters are added with this 152 different sets. In total, 168 datasets have been trained with a neural network fitting tool. Based on the experience of initial data classification and PCA, ten parameters are selected for the prediction of soil resistivity.

Because of a very limited number of samples, the Bayesian regularization based "trainbr," a MATLAB function, is used for developing the neural network models. In the case of selecting a number of hidden layers and the number of neurons, a simplified approach is used. According to Erzin et al. (2010), the maximum number of neurons can be used for any given number of variables (I) is 2I + 1*(23)*. Considering the rule of thumb, for ten predictors, a maximum of 21 number of neurons have been considered for training the model. The best performing function has been selected for prediction purposes. While programming, the dataset has been selected randomly for training, validation, and testing in a ratio of 75 %, 5%, and 20%, respectively. However, it should be mentioned that the network performance can always be improved.

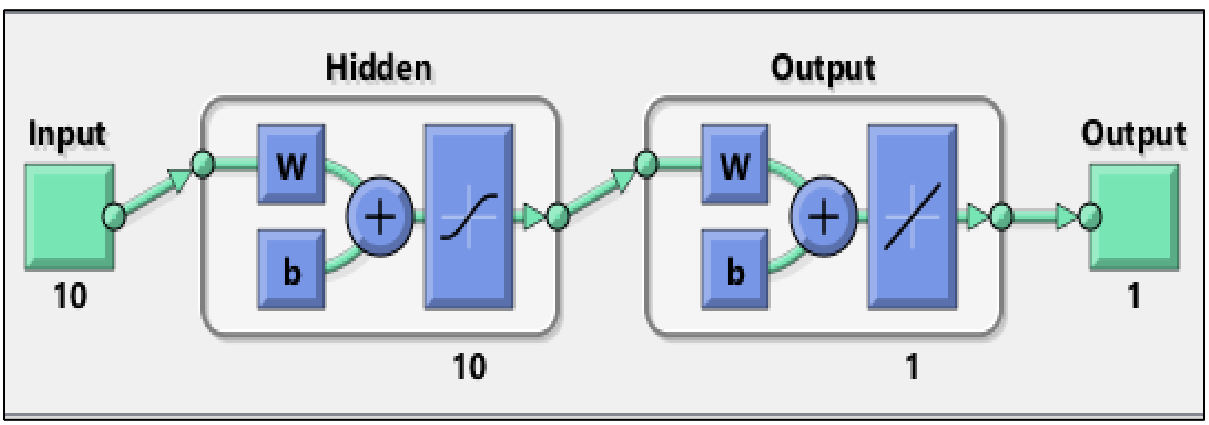


Figure 12. Structure of hidden layers used for prediction of resistivity.

Based on the trial results of the model, it has been noticed that lower numbers of hidden layer showed better consistency in predicting soil resistivity (Table 4 and Table 5). After several trial and error analyses, a neural network prediction function generated based on a hidden layer with 10 neurons has been selected (Figure 12). A MATLAB function, named "myNeuralNetworkFunction" has been generated, and the function is used for the prediction of resistivity.

Table 4. Shallow NN training results for regularization of the soil resistivity data after including laboratory test results.

Training function	trainbr	trainbr	trainbr	trainbr	trainbr
Hidden Neuron Structure	[10]	[12]	[14]	[16]	[8]
Number of Epochs	572	285	1000	331	504
Training – R Value	0.99349	0.98374	0.99313	1	0.97869
Testing – R Value	0.34666	0.073232	0.05848	-0.18422	0.20458
Overall – R Value	0.75391	0.60994	0.59307	0.46703	0.74

Table 5. NN training results, continued.

Algorithms	trainbr	trainbr	trainbr	trainbr	trainbr
Hidden Layer Structure	[8 4]	[10 6]	[10 6 2]	[7 3]	[7]
Number of Epochs	437	683	1000	432	1000
Training – R Value	1	0.97981	0.99988	0.97754	0.41707
Testing – R Value	0.22048	0.37649	0.135	0.21218	0.13472
Overall – R Value	0.51236	0.68836	0.67883	0.74229	0.3523

5.3. Corrosion Mapping

ArcMap 10.1 has been used for the mapping and interpolation of estimated service lives of metal pipes for any intermediate location. For geostatistical analysis, ArcGIS's Geostatistical analysis tool has been used for this project. For adjusting the grid size and smoothing of the interpolation, the dissolved polygon of Arkansas, prepared from the SSURGO, is converted into raster data of cell size equal to 250 based on the soil pH values. Using the "To Raster" tool, the total dissolved soil layer, with available data, are converted to 2,137,685 number of rasters. Later, each raster is converted to point features, by transforming the raster to a point feature at the center of the raster. Then, the probable water resistivity and water pH, which can affect any future metal culverts in those points, are assigned. For assigning the corresponding water pH and water resistivity related to the points, the nearest neighbor approach has been adopted. All the filtered water pH and estimated water resistivity have been assigned to each point based on the nearest source of ADEQ water quality monitoring stations.

Now, 20 other features, which are extracted from the SSURGO, related to each raster are joined with each point feature's table. Then, the dataset has become a 2,137,685 x (1 + 2 + 20) matrix, excluding the metadata. Then the whole dataset is exported to ".dBase" files and subsequently in three different ".xlsx" files. The Excel worksheets are then exported to MATLAB and the resistivity value based on the ten different parameters, related to each point features are estimated using the selected neural network function, "myNeuralNetworkFunction.m." The negative prediction is considered as overfitted and refined to a minimum of 10 ohm-cm for this research. Now, based on each points soil pH, soil resistivity, water pH and water resistivity, service life of based on outer side of the metal pipe and service life based on inner side of metal culverts are evaluated using MATLAB functions, programmed based on the California Method *(13)*, and Florida DOT (2012) methods *(15)*. To consider the effect of water and soil, the service life of each Galvanized Steel Pipe, Aluminized Steel Type II pipe, and Aluminum pipes are estimated separately. First, the service lives are estimated based on soil resistivity and Ph, and later water resistivity and water pH. Finally, the minimum of the estimated of service lives based on inner corrosion (water quality-based) and outer condition (soil pH, and resistivity based) is selected as the probable service of any metal pipe in that point *(24)*. After completion of these steps, the predicted soil resistivity, and service lives of three different types of metal are joined back to the table matrix and converted to ".csv" files. Then final ".csv" file is extracted back to ArcGIS for further interpolation of the service life around the point features. The summary of the findings of the governing parameters is presented in Table 6.

Table 6. Summary of the major findings for the state of Arkansas.

Parameter	Count	Minimum	Maximum	Mean	STD
Soil pH	2,137,685	4.3	8.3	5.51	0.77
Soil Resistivity (ohm-cm)	2,137,685	7.42	2,2515.1	3,523.67	4034.80
Water pH	2,137,685	1.5	10.28	6.99	0.83
Water Resistivity (ohm-cm)	2,137,685	264.23	162,500	9,156.1	8,133.28
ESL_GSP* (yrs)	2,137,685	Not Suitable	50	14.24	11.84
ESL_AL_T2(yrs)**	2,137,685	Not Suitable	125.68	40.18	27.95
ESL_AL (yrs)* **	2,137,685	37.99	204	83.43	46.16

*ESL_GSP = Estimated Service Life of Galvanized Steel Pipe (GSP), using California Method
** ESL_AL_T2 = Estimated Service Life of Aluminized Steel Pipe (Type II), using FDOT (2012) method
*** ESL_AL = Estimated Service Life of Aluminum Pipe, using FDOT (2012) method

The life cycle analysis results show the service life of the Galvanized Steel Pipe (GSP) can vary from a very short time (indicated as "zero" in Table 6) to a period up to 50 years. The average service life of GSPs is about 14 years. On the other hand, the Estimated Service Life (ESL) of Aluminized Steel (Type II) can vary from a very short time (indicated as "one" in Table 6) to 125 years. The average ESL of this type of metal pipes is about 40 years, which seems significantly better than that of GSP. Similarly, Aluminum pipes can serve significantly longer than the other two metal types. However, the Aluminum pipes can be adversely affected by abrasion parameters, which are not evaluated during this modeling. All ESLs are estimated for 16 gage pipes.

The Inverse Weighted Distance (IDW) and Empirical Bayesian Kriging (EBK) are two methods suggested by different researchers have been used for this analysis *(18)*. The estimated service life for each type of metals is interpolated and grouped into five different risk categories.

5.3.1. GSP

For GSP, an estimated service life between 0 and 10 years is considered extremely corrosive, 10-20 years as highly corrosive, 20 – 30 years as moderately corrosive, 30 to 40 years as corrosive, and 40-50 years as mildly corrosive. However, in the "California Method" the maximum service life of GSP can be 50 years *(13)*. The interpolated maps for each category of metals are shown in Figures 13 and 14. Figure 13 shows the IDW predicted raster maps of risk indices, and Figure 14 shows the EBK predicted rasters. The rasters show most of the counties and districts are extremely to highly risky for 16-gage GSPs. For a different gage of GSP, the service life can be estimated by using multiplying factors. These factors are 1.6, 2.2, 2.8 and 3.4 for 14 gage, 12 gage, 10 gage, and 8 gage GSPs *(13)*. Based on the maps, only in the northeast part of Arkansas, GSPs has higher expected service lives. In general, most of the part of the state should be given careful thoughts about using any 16 and 18-gage GSPs. Any existing GSPs with a service life of 10 years should be checked as the precautionary steps. For future development or construction projects, alternative pipe materials should be taken into consideration for achieving better service lives.

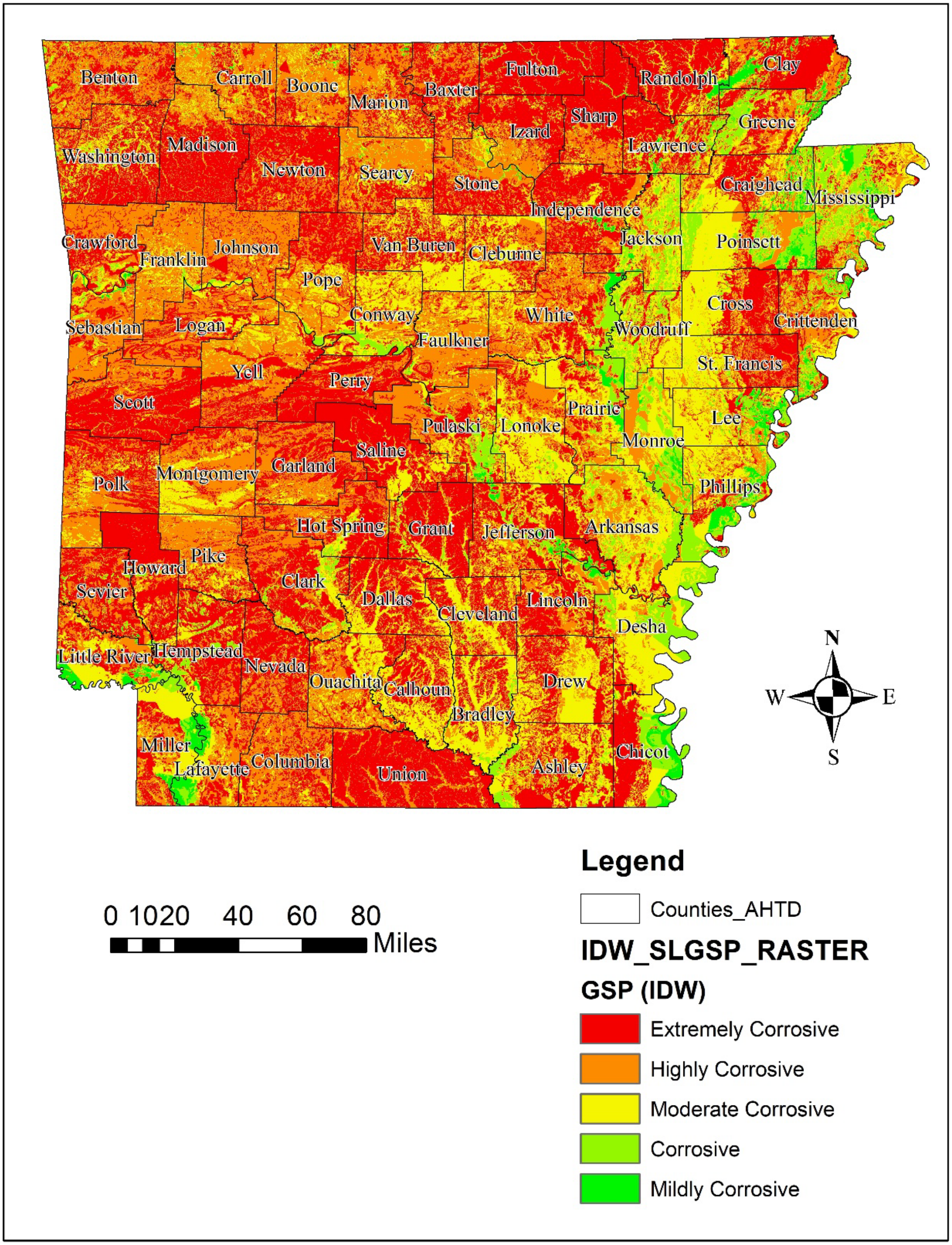


Figure 13. Galvanized steel corrosion risk prediction map (generated using IDW).

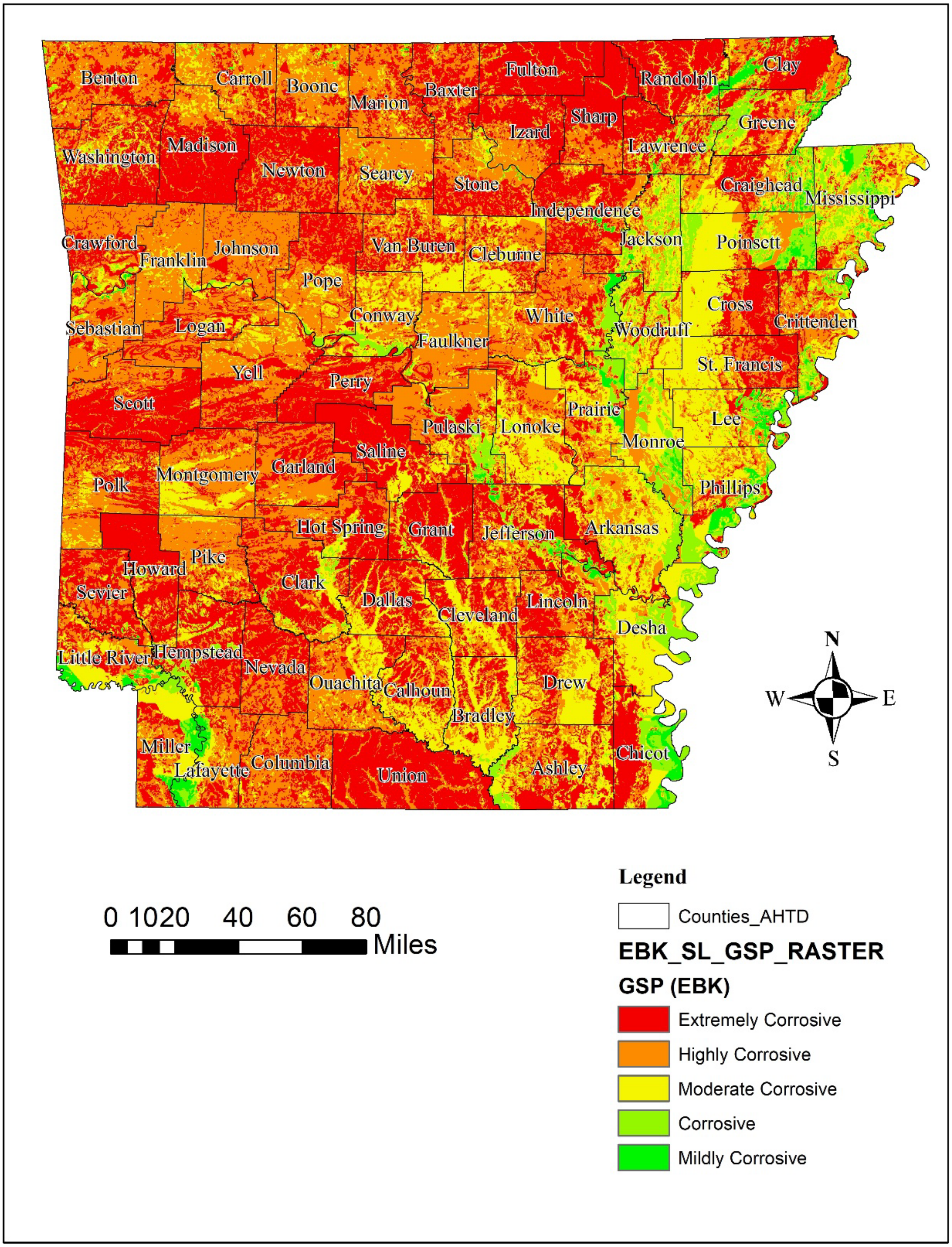


Figure 14. Galvanized steel pipe corrosion risk prediction map (generated using EBK).

5.3.2. Aluminized Steel Type II

For Aluminized Corrugated Steel Type II pipes, an estimated service life between 0 and 20 years is considered extremely corrosive, 20-40 years as highly corrosive, 40 – 60 years is considered moderately corrosive, 60 to 80 years is considered as corrosive, and more than 80 years is considered as mildly corrosive in the interpolated maps. The interpolated maps for this category of metals are shown in Figures 15 and 16. Both maps show a significant portion of the state has moderate to mild corrosion risks, which indicates higher service lives for this type of pipes. In some part of ARDOT Districts 7, 6, 4, 2, 9, and 3, this type of pipe has very low ESLs. Precaution showed be taken to choose this type of pipes in these regions.The rasters show most of the counties and districts are extremely to highly risky for 16 gage pipes. For a different gage of similar pipes, the service life can be estimated by using multiplying factors. These factors are 1.3, 1.8, 2.3 and 2.8 for 14 gage, 12 gage, 10 gage, and 8 gage pipes, respectively *(15)*.

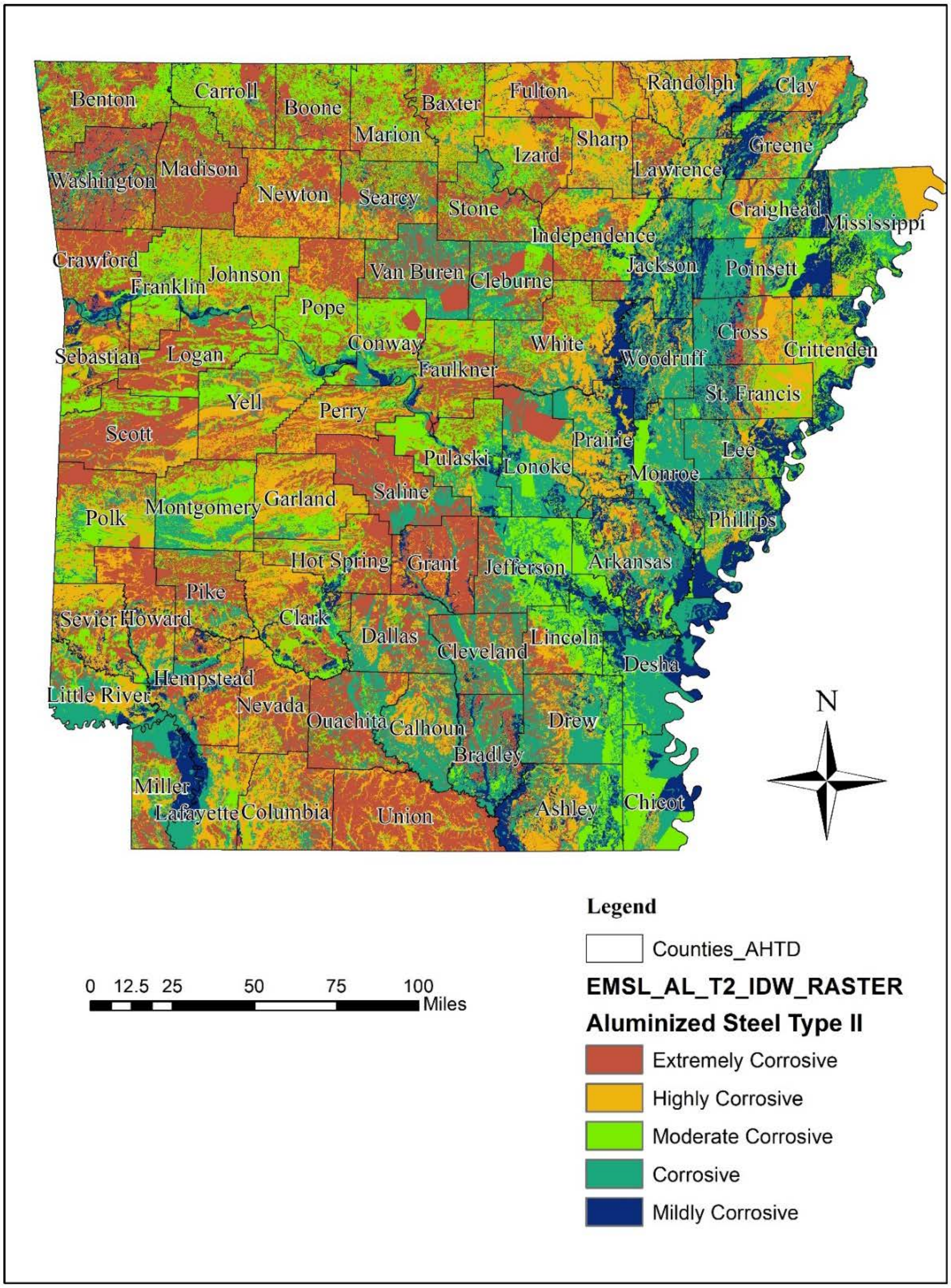


Figure 15. Aluminized steel (Type II) pipe corrosion risk prediction map (generated using IDW).

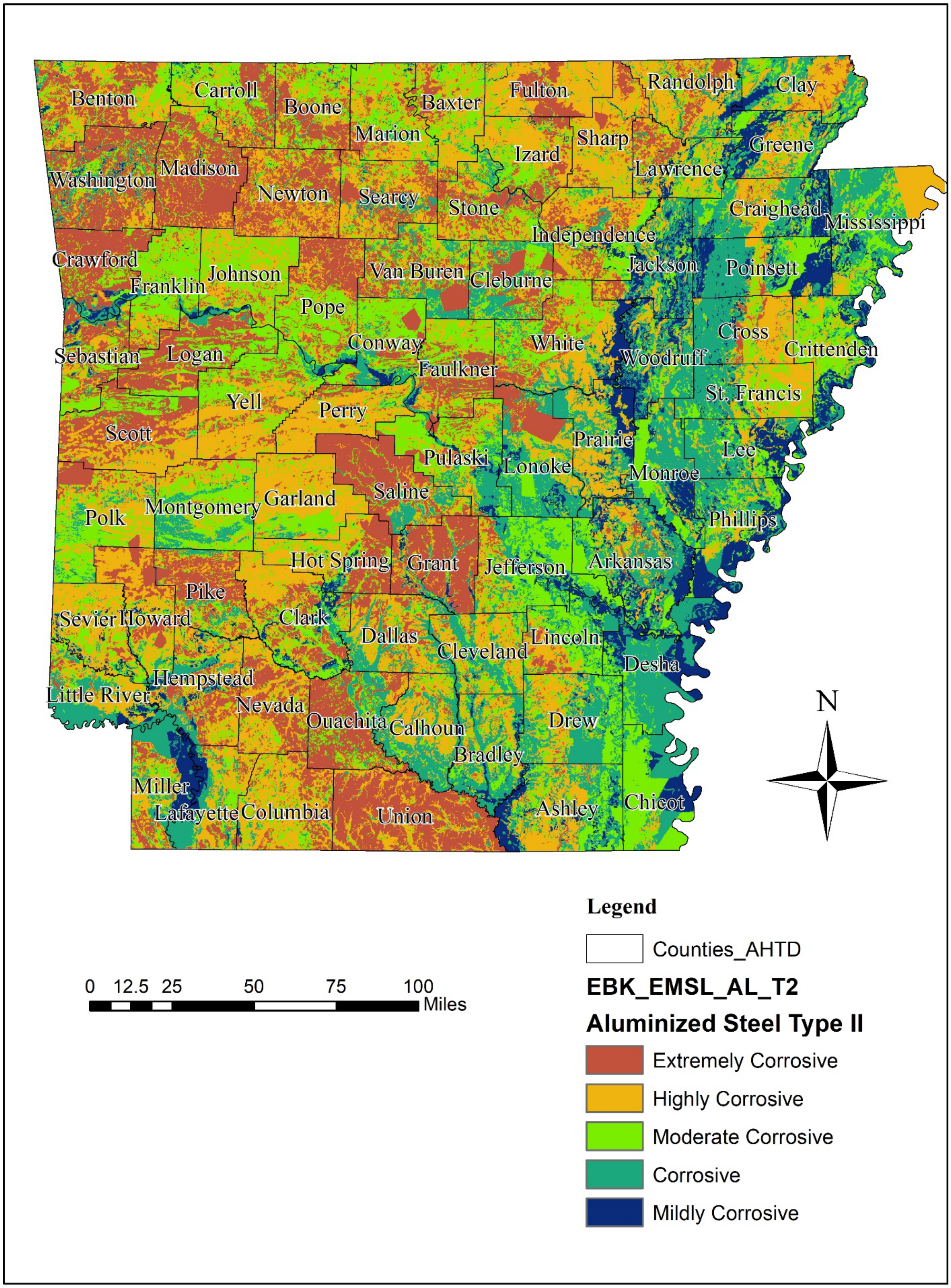


Figure 16. Aluminized steel (Type II) pipe corrosion risk prediction map (generated using EBK).

5.3.3. Aluminum Pipe

For corrugated Aluminum pipes, an estimated service life between 0 and 40 years is considered extremely corrosive, 40-60 years as highly corrosive, 60 – 80 years as moderately corrosive, 80 to 100 years as corrosive, and more than 100 years as mildly corrosive. Even the environment is extremely corrosive, the analysis shows that this type of metal can survive up to a very long period of time. So, options should be explored based on the life cycle costs of this type of culverts. Abrasion risk of these type of metals is high. So, in the case of selecting this type of metal pipes, the type of sediments that pass through the pipes or culverts should be analyzed prior to the selection process. The interpolated maps of service lives of Aluminum type are shown in Figures 17 and 18. Based on this analysis, except some counties (Union, Logan, Grant, Newton, Lonoke, Independent, Washington, and Crawford), most of the state has soils that are less corrosive to this type of pipes. For a different gage of similar pipes, the service life can be estimated by using multiplying factors described in FDOT (2012) method *(15)*. These factors are 1.3, 1.8, 2.3 and 2.8 for 14 gage, 12 gage, 10 gage, and 8 gage Aluminum pipes, respectively.

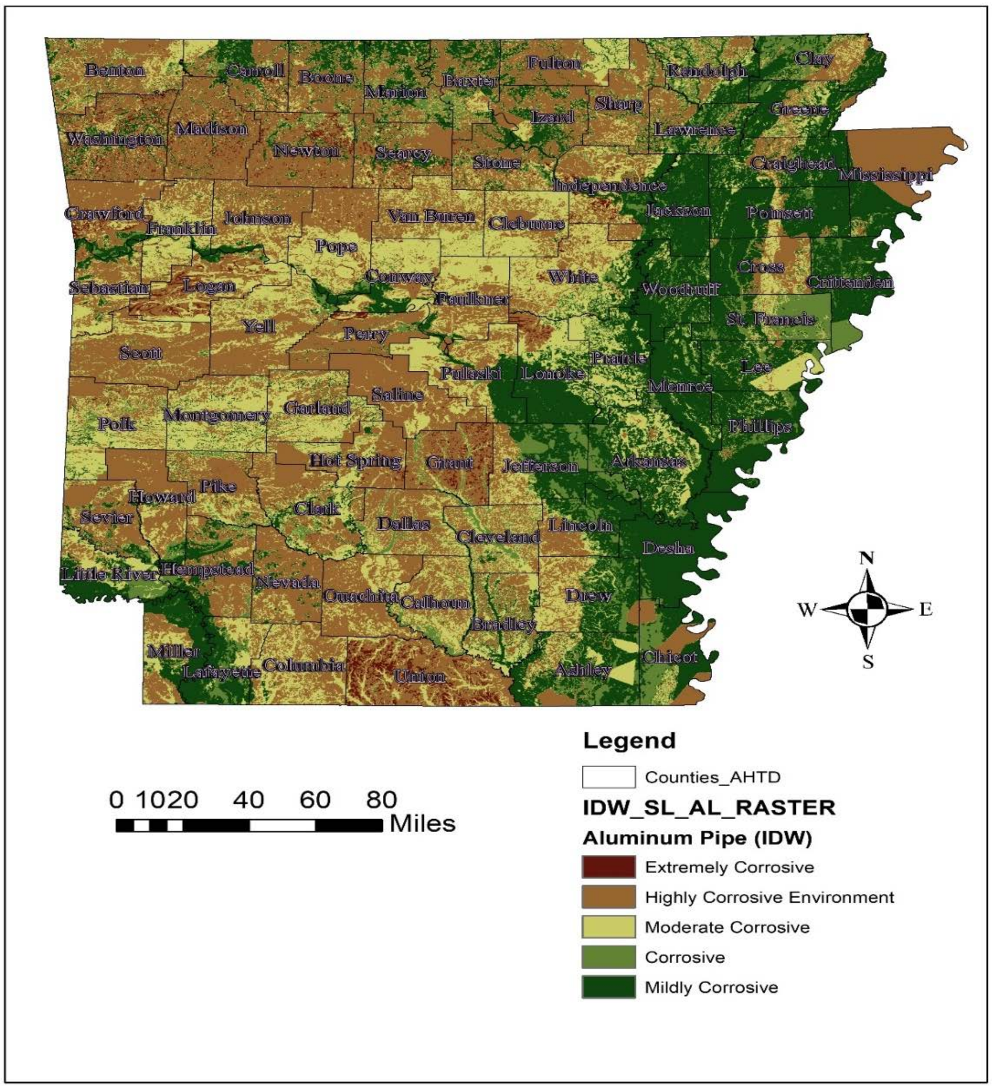


Figure 17. Aluminum pipe corrosion risk prediction map (developed using IDW).

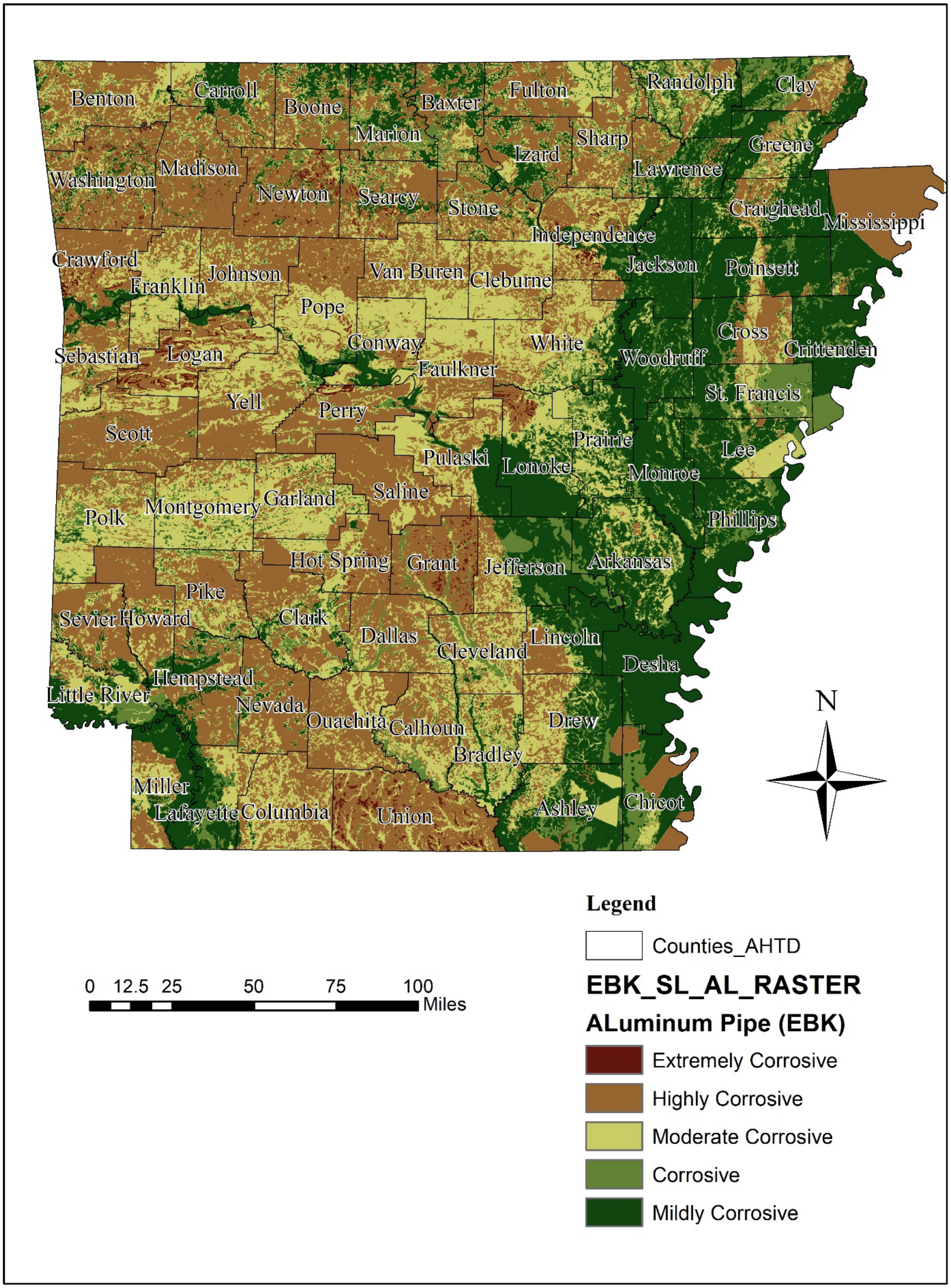


Figure 18. Aluminum pipe corrosion risk prediction map (generated using EBK).

5.4. Life Cycle Cost Analysis

The ARDOT uses Galvanized Corrugated Steel Pipe Culverts on a regular basis. According to the unit price for projects awarded to contract, in total $223,325 has been allocated for Corrugated Steel Pipes. Approximately an amount of $77,943 has been allocated for Aluminum-Coated Steel Pipe (Aluminized Steel), $ 3,420,710 for all the pipe culverts in total and $18,179,219 for concrete pipe culverts. From January 2018, steel pipes are being recommended for Marion County. However, Marion County has high corrosion risk for GSPs, moderate to high corrosion risk for Aluminized Steel Type II metal pipes and mildly corrosive risks for Aluminum pipes. After reviewing all the facts, it is evident that a detailed life cycle cost analysis is a prerequisite for choosing the best type of metal culvert for any particular area.

Perrin and Jhaveri (2004) analyzed the life cycle cost for corrugated metal pipes. They estimated the total costs based on initial installation costs, replacement costs over the times, and user delay costs *(26)*. In this research, a modified version of this method is used. The total cost (T) can be expressed using Equation 1, where IR is the summation of the present value of the costs associated with installation and replacements for the time horizon of H and user delay costs related to traffic interruptions. In here, user delay is the costs associated with traffic interruptions in the point of construction. Following the method, replacement cost (IR) can be expressed using Equation 3, and user delay costs are estimated using Equation 4.

$$\text{Total Cost (T)} = \text{Initial Installation Cost} + \Sigma_{k=0}^{n}(\text{IR}\ \ (1+\text{r})^{\text{kL}}) \qquad [1]$$

where:

$$\text{n} = (\text{H/L})-1 \qquad [2]$$

$$\text{IR} = \text{Culvert Replacement Cost} + \text{User Delay Cost (D)} \qquad [3]$$

$$D = \text{AADT} * t * d * (c_v * v_v * v_{of} + c_f * v_f) \qquad [4]$$

Here n stands for number of replacement require over the time horizon H/L is the estimated service life of culverts, and r is the discount rate.

In Equation 4, AADT is the annual average daily traffic of nearby station of the location of the culvert, $t_k$is the average increase in delay per day causing to each traffics during installation. The term 'd' is the number of days the installation will take, c_v is the average rate of person-delay in dollars per hour, c_f is the average rate of freight-delay in dollars per hour, $v_v$is the percentage of passenger vehicles traffic, $v_{of}$is the vehicles occupancy factor, and $v_f$is the percentage of truck traffic.

In a busy Interstate or highway, the selection of material will be governed by the user delay costs in the case of replacement. So, a comprehensive study of possible life cycle costs in any location is required for selecting the best material. In this research, for comparative analysis and procreating decision making analysis procedure life cycle cost of different types of metal culverts are analyzed using a modified approach of this method discussed by these researchers. The total life cycle cost is estimated for different locations of Arkansas based on the estimated service life, traffic volume, and associated unit bidding price of different items to be spent by ARDOT. In the previous sections, the distributions of the probable service life of three different metal pipes were depicted in Figures 13 through 18. The spatial distributions of service life data are used for life cycle cost assessment. In addition, AADT of a nearby station is also considered a variable for the modified approach. For completing a comprehensive analysis, detailed database related to future costs of different items and future traffic conditions estimation is required. ARDOT has unit-cost databases of different items associated with the installation and replacement of culverts in the contracts and consultant information section of the website. In initial installation cost calculation, user delay, removal and repair costs have not been considered. But, in the calculation of replacement cost, the removal and clearing costs, pavement repair costs and temporary culverts costs are added with initial installation costs. The future values of the replacement costs at the end of service life are calculated based on the present values. Finally, all the predicted costs over 100 years are summed up to get the life cycle cost. The analysis results are mapped for three metal types over different locations in the state. Figure 19, 20, and 21 shows the feasible location of metal pipes based on estimated life cycle costs.

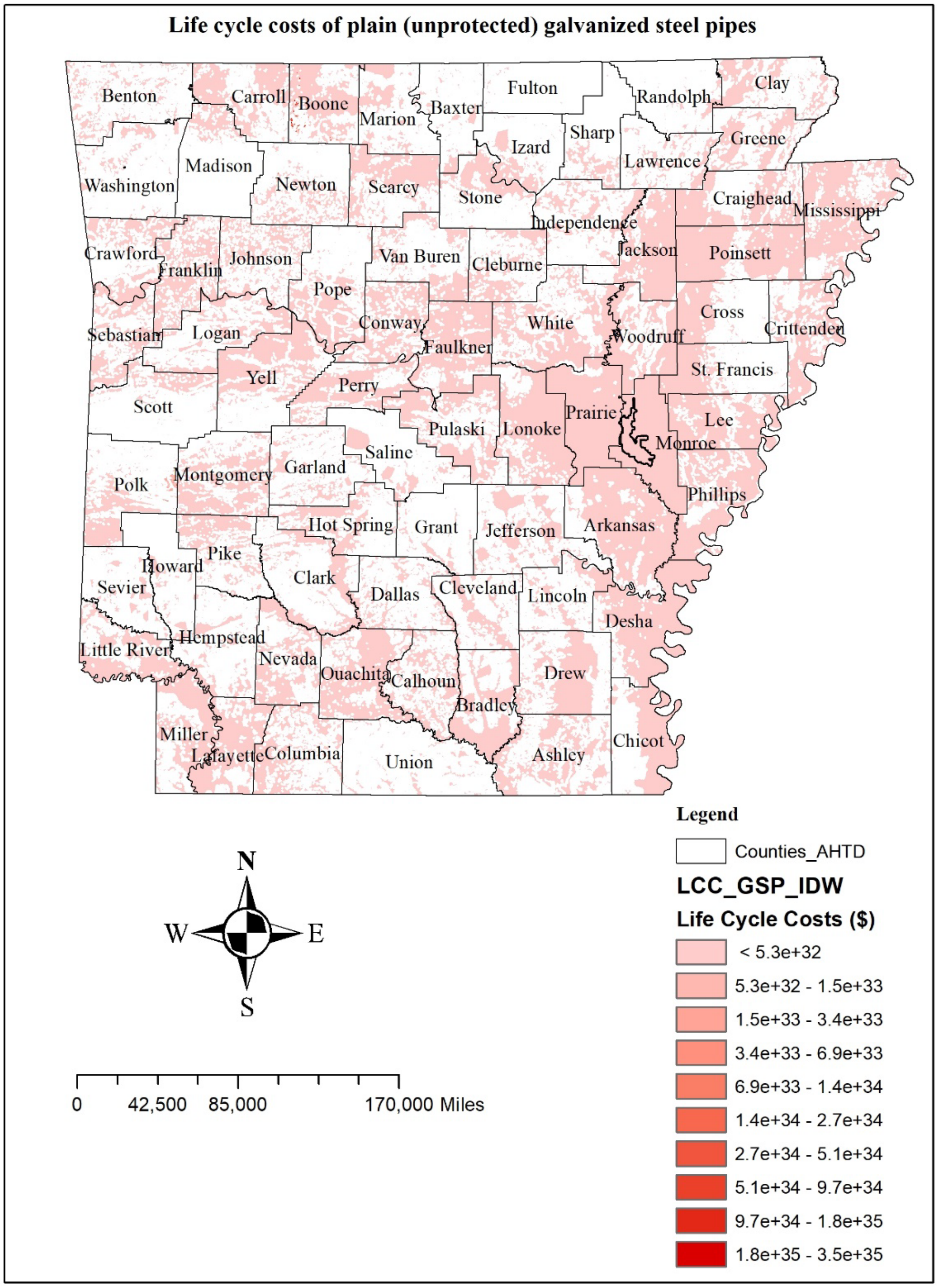


Figure 19. Spatial distribution of areas where GSP can be used based on LCCs.

The ARDOT have unit cost data of bidding results stored on their website. Unit price data for culvert installation, culvert removal, and pavement repair over culvert (concrete work and asphalt work) for different years are collected for the year of 2017, 2018 and 2017. However, for the unit rate estimation, the data as of 2018 have been considered for representing the current economic condition. For user delay analysis, AADT data are extracted from the ARDOT GIS database. Data related to the percent of trucks on the highway are also taken from the ARDOT websites. The ARDOT website has traffic classification data up to 2014. For simplicity of calculation, 5% of truck traffic is considered in this analysis. The unit costs of different sizes of metal culverts are different. However, the size of the culvert is mainly governed by the drainage requirements and the gage thickness is governed by corrosion and structural requirements. Thus, the average unit costs of individual gaged pipes are taken irrespective of sizes for this comparative analysis. In the case of, any missing unit costs data, nearby state's transportation agency's data is taken for the comparative analysis.

For developing maps for life cycle costs at each location for all three metal pipes, a 50 ft long culvert with corresponding average unit costs of 16-gage metal pipes, irrespective of size, are considered. Thus, the spatial point-based total costs for 100 years are estimated and plotted using spatial interpolation. The inverse weighted distance method is adopted in the interpolation step. The raster map for the interpolated costs for plain galvanized steel pipes is shown in Figure 19. For a 100-year of time horizon, a complete galvanized pipe culvert with flared end section is considered for this analysis. The cost of 16-gage metal pipe (irrespective of size) has been considered as $46.5 per linear foot (LF). The cost of a flared end section is considered as $906 based on the ARDOT's 2018 cost database. The bedding and backfill materials costs are not considered in this analysis. In the case of replacement costs, the removal cost of each culvert has been taken as $1051, based on the average cost. The temporary culvert required during the replacement phase is considered with a unit rate of $123/LF. Twenty cubic yards (CUYD) of concrete work with a rate of $625/CUYD and thirty tons of asphalt work with a rate of $352/ton have been considered for pavement repair over the replaced culvert.

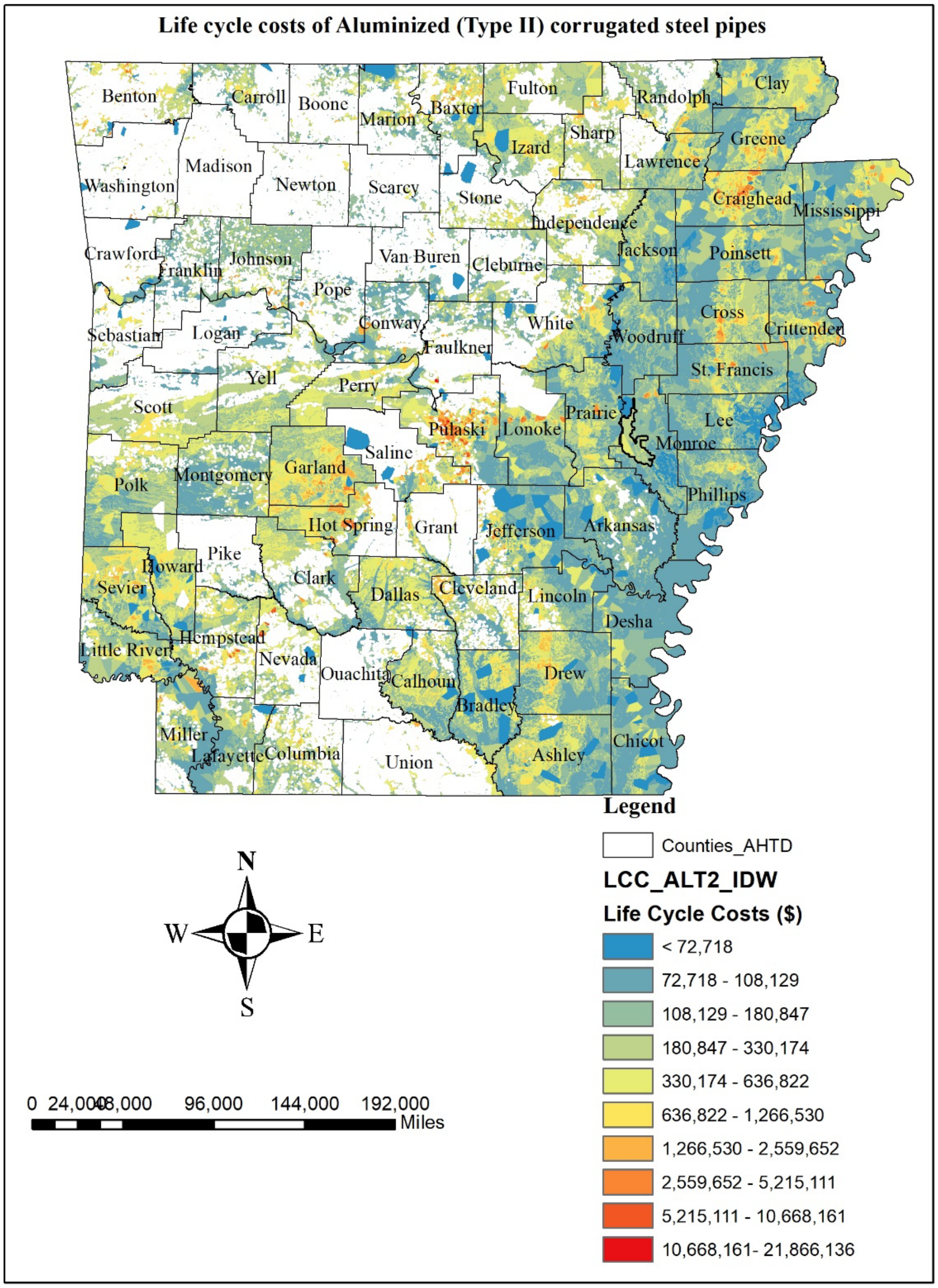


Figure 20. Spatial distribution of areas where AL_T2 CSP can be used based on LCCs.

In the user delay cost calculation, location-specific AADT is considered based on nearest neighbor measuring stations. The average increase in delay of each vehicle is considered as one hour. The project duration is considered as one day, irrespective of the requirements of temporary culverts. The average rate of person-delay is taken as $17.18/person-hour and for freight or truck, the average rate of freight-delay has taken as $50/freight-hour *(26)*. These values are taken only in the user delay part of the comparative LLC maps. The ultimate output maps have no direct usage other than guidance to select the best alternative metal culverts for a particular location based on the

LCC. Considering these parameters along with the unit galvanized steel culvert cost of $46.5/LF, a spatial LLC map of GSP is developed, as shown in Figure 19. Similarly, two other maps shown in Figures 20 are developed using a unit Aluminzed (Type II) corrugated steel pipe cost of $80.75/LF and a unit corrugated aluminum pipe cost of $188/LF. The cost of GSP and Aluminized (Type II) steel are taken from the ARDOT bidding cost data, and the cost of corrugated aluminum pipe has been taken from the Wisconsin DOT cost data.

From the LCC of GSPs shown in Figure 19, it is evident that most of the locations are not suitable due to very short service life spans. As seen in Figure 19, only colored areas are feasible to install GSPs. However, the overall LCC is exorbitant for almost all part of the state. In the case of Aluminzed (Type II), the extent of the feasible area is quite good, and the LCC is also comparable. In the eastern part of the state, these type of culverts is feasible, as shown in Figure 20. Aluminum pipe can be used almost everywhere with feasible costs, as shown in Figure 21. However, the initial cost of these metal culverts is comparatively high.

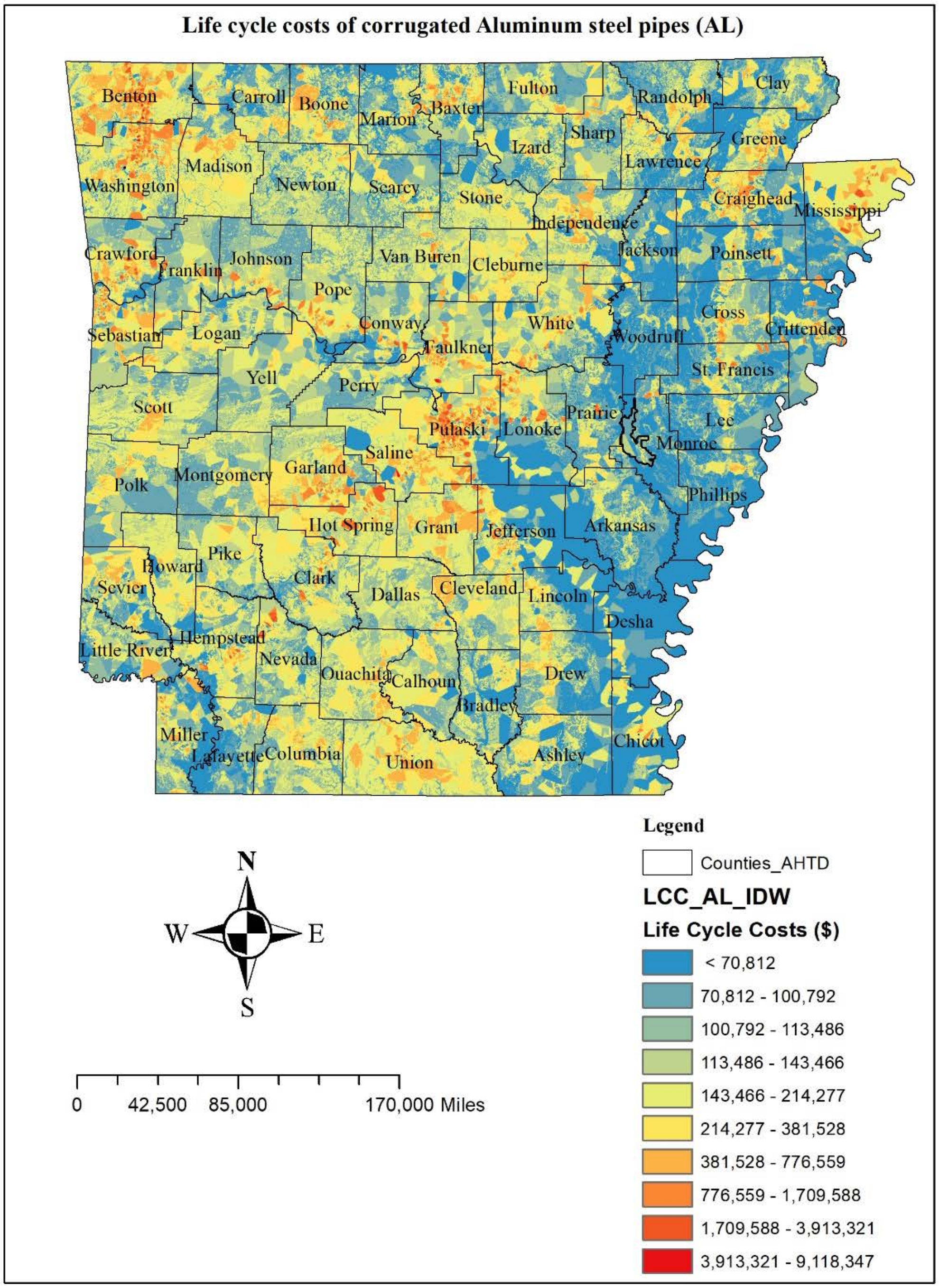


Figure 21. Life cycle costs of corrugated Aluminum pipes (CAP) over Arkansas.

5.5. Maintenance Options

Life cycle cost analysis results are critical during the selection process of new culverts or replacement of existing culverts. Since thousands of culverts are already in place at different parts of the state, their remaining service lives are expected to be very useful for the maintenance division. The service life estimation maps have some common areas where all three types of metals are marked as critical. For example, several counties (Union, Grant, Lonoke, Madison, Logan, Crawford, Newton, Washington, Independence, Scott, Ouachita, and Searcy) have critical locations where all three metal pipes can corrode very fast. Thus, existing culverts are recommended to be inspected and county-wise inventory lists can be prepared so that appropriate measures can be undertaken. Based on developed maps, special observations are also recommended in the critical locations during the routine maintenance of these culverts. Based on the inspection data, preventive measures, rehabilitation or replacement decisions should be undertaken to avoid any future catastrophic damages. In the case of selecting new materials, service life and life cycle cost maps can be considered. Again, the life cycle analysis maps of the current study give ArDOT a cost-effective tool to minimize maintenance costs in any location within the state.

6. CONCLUSIONS

The Arkansas Department of Transportation (ARDOT) uses different types of metal culverts and reinforced concrete culverts for highway cross-drains. The agency invests a significant amount of money in installing and replacement of metal culverts. Corrosion due to soil and water is one of the major reasons for replacement, removal, and cleaning of these culverts. The agency does not have detail guidelines for selection of metal types based on the corrosion susceptibility of different regions in Arkansas. The main objective of this study is to develop corrosion risks of metal pipes based on soil and water properties, and pipe materials.

Important geotechnical and geochemical properties of soil and water quality data were collected for all 75 counties of Arkansas. They were analyzed for developing metal corrosion risk maps. Several soil samples were collected from different locations in the state. Based on the experimental results and collected data from public domains, neural network (NN) based models were developed to predict soil resistivity. Finally, combining soil pH, resistivity, and surface water pH, and resistivity, the expected service lives of three different metal types were estimated for the entire state. The Empirical Bayesian Kriging (EBK) and Inverse Distance Weighted (IDW) interpolation methods were applied while developing the GIS-based prediction maps that estimate probable service lives of three culvert metals (Galvanized Steel, Aluminized Steel Type II, and Aluminum pipes). The estimated corrosion risks presented in the maps can be extrapolated for different gage thickness and for other types of metal culverts and coated pipes. Several counties (Union, Logan, Grant, Newton, Washington, Crawford, Ouachita, Saline, Madison, and Pike) are marked as critical for all three types of metal culverts. The selection of any metal culverts in the future should be examined thoroughly for these counties.

The service life of a culvert is an important decision-making parameter in selecting pipe materials. Thus, the developed service life maps can play a significant role in the selection of metal pipe culverts. In the case of replacement of a pipe culvert of an important highway, the user delay costs can exceed the total cost of installation. So, the life cycle costs are analyzed after considering the user delay and other construction-related costs. The cost analysis results show that the eastern part of the state is feasible for Aluminized (Type II) corrugated steel pipes and corrugated Aluminum pipes. Aluminum pipe can be used almost everywhere in the state. In the case of GSPs, expected service life is very low, and the LCC is exorbitant for most of the areas. However, for more reliable prediction of expected service lives of different metals, field measurements and investigations are strongly suggested.

The findings of this study are expected to help ARDOT engineers in planning and maintaining the highway drainage pipes and thereby avoid unexpected or unplanned future removal and/or replacement of metal culverts. The maps will also help the agency in evaluating the existing condition of culverts based on the critical locations and taking measures to reduce extra expenditure.

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