Louisiana Transportation Research Center

Final Report 585

Corrosion Map for Metal Pipes in Coastal Louisiana

by

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16. Abstract

Transportation agencies often allow metal pipes as an option for cross drains under/along roads and highways. Metal culverts can corrode over time at various rates based on their environmental conditions (e.g., corrosive nature of coastal soils, high water table, and saltwater intrusion). This project was focused on applying available soil data, such as spatial distribution of soil types and soil characteristics (e.g., pH and conductivity), towards creating a Geographic Information System (GIS) based map to identify corrosion zones in coastal Louisiana. The effect of the soil characteristics (pH and conductivity) was incorporated in to the published corrosion models for calculating corrosion potential to metal pipes. A combination of data, obtained from field surveys provided by the Louisiana Transportation Research Center and Web Soil Survey Data provided by the Natural Resources Conservation Service, were used to create an interpolated surface representing zones corrosive to metal culverts. The soil properties based corrosion potential was calculated for coastal Louisiana. Areas of similar corrosion behavior were grouped together based on expected life span of metal pipes and were classified accordingly.

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Corrosion Map for Metal Pipes in Coastal Louisiana

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December 2017

ABSTRACT

Transportation agencies often allow metal pipes as an option for cross drains under/along roads and highways. Metal culverts can corrode over time at various rates based on their environmental conditions (e.g., corrosive nature of coastal soils, high water table, and saltwater intrusion).

This project was focused on applying available soil data, such as spatial distribution of soil types and soil characteristics (e.g., pH and conductivity), towards creating a Geographic Information System (GIS) based map to identify corrosion zones in coastal Louisiana. The effect of the soil characteristics (pH and conductivity) was incorporated into the published corrosion models for calculating corrosion potential to metal pipes.

A combination of data, obtained from field surveys provided by the Louisiana Transportation Research Center and Web Soil Survey Data provided by the Natural Resources Conservation Service, was used to create an interpolated GIS surface representing zones of corrosion potential to metal culverts. The corrosion potential was calculated for coastal Louisiana based on soil properties. Areas of similar corrosion behavior were grouped together based on expected life span of metal pipes and were classified accordingly.

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IMPLEMENTATION STATEMENT

The author recommends that a corrosion map may be utilized as a tool by the Department to obtain a general idea about soil in a zone in Coastal Louisiana. The maps were created using data that was collected at certain points for various soil depths. This data then was interpolated for the whole coastal region. Site specific soil investigations are suggested for more accurate assessment of corrosion potential to metal pipes. However, this map may be used as a tool for making policy related decisions, specifically, in context of the expected life span of metal pipes in any given zone in the Coastal Louisiana. An EDSM to facilitate implementation should be drafted to assist with implementation.

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INTRODUCTION

The corrosive nature of the soil in some coastal regions has led to local governing bodies and some state agencies having projects within those regions to set a policy of prohibiting the use of metal culverts. For example, environmental conditions have led to a policy of disallowing the use of metal pipes for new drainage installations in DOTD District 02, a mostly coastal region including New Orleans. Portions of other southern DOTD districts have similar environmental conditions.

Concrete pipes are less susceptible to corrosion, but the initial capital investment is more than corrugated metal pipes. Metal pipes require a lower initial capital investment; however, in corrosive soil conditions they corrode faster, and will not retain their mechanical properties needed to serve the design purpose. Thus, they will need to be changed often, which results in increased overall cost in the long-term.

Detailed on-site soil investigations are one way to determine the best material for the pipes to be used for culverts. These investigations are usually done during the design phase. More often, this kind of investigation and analysis is overlooked. The corrosive nature of environmental conditions generally tends to decrease as one moves deeper inland and away from coasts. The delineation of such areas where the corrosive soil effect is not strong enough will allow these agencies to permit the use of metal pipes and reduce overall cost. A corrosion map will provide combined corrosive effect of some of the main soil characteristics and will be an essential tool to have access to during planning phase. Also, it will ensure better selection of durable materials for drain pipes based on environmental conditions.

The combined effect of soil types and environmental conditions such as pH and conductivity (resistivity) needs to be analyzed for one to make a decision to use a metal pipe. However, when it comes to these inland locations, often it is not easily known to field engineers and designers how a metal pipe will respond to specific local soil types, soil characteristics, and the environmental conditions. This project focuses on an approach that uses spatial distribution of soil types and soil characteristics (e.g., pH and conductivity) in identifying zones where use of metal pipes is not advised as they will be susceptible to corrosion. The conductivity and resistivity are used together in this report multiple times. They are two different parameters. In fact, they are inverse of each other (conductivity = 1/resistivity). This means, a soil which has high conductivity will have low resistivity. Alternately, a soil which has high resistivity value will have low conductivity value. Some government agencies use conductivity as standard parameter while other use resistivity to measure same aspect of the soil samples. The Louisiana

Department of Transportation and Development (DOTD) uses resistivity while the Natural Resources Conservation Service (NRCS) of United States Department of Agriculture (USDA) uses conductivity.

Geographic information system (GIS) programs such as ArcGIS can provide understanding and prediction of the spatial distribution of corrosive environments through means of spatial and geostatistical interpolation. ArcGIS makes use of many interpolation methods that provide means for both the categorizing and quantifying of spatial data. Many of these interpolation techniques are used for analyzing varying datasets from various fields ranging from the agriculture to meteorology. The use of GIS is shaping the decision making across numerous fields at all scales. This project is focused on providing a mechanism of creating corrosion zones by utilizing ArcGIS and soil properties as mentioned previously.

Literature Review

Ambler and Bain studied corrosion of metals at more than 20 sites under various conditions of atmospheric humidity and salinity in tropical conditions *[1]*. The rate of corrosion of ferrous metals was found to vary little between wet and dry seasons or between day and night. Atmospheric salinity was measured by various methods and at many places. The corrosion of ferrous metals and zinc was proportional to the rate of deposit of salt on a damp textile surface. The corrosion of steel in tropical tidal waters was found to be twice as fast in tidal as in continuous immersion, and in the former case can be as high as 12 g/dm squared/month.

FitzPatrick and Ayres developed experimental corrosion probes to continuously measure seawater galvanic and crevice corrosion *[2]*. The probes were evaluated in three saline water environments at high temperature and salinities up to 20%.

Uller studied seawater corrosion, including the effects of variations in salinity, temperature, water velocity, depth, contaminants, and fouling (degradation of material surface and its mechanical properties due to strong corrosive nature of salt water and elevated biological activity) *[3]*. Melchers presented recent progress on modeling of corrosion of structural steel immersed in seawaters *[4]*. It was suggested that seawater temperature has an important influence on the rate of early corrosion and also has longer-term effects not predicted by short-term observations. Also, the influence on corrosion of small changes in metal composition and in water velocity, salinity, and pollution were described.

Trivedi *et al.* studied the effects of water salinity, dissolved compounds, dissolved oxygen, temperature, and relative velocity on the corrosion of steel because of saline and seawater *[5]*. The experimentation consisted of mild steel corrosion and its inhibition in saline water through the use of sodium benzoate, sodium hexametaphosphate, sodium nitrate and sodium sulfide. The effect of pH on the sulfide solution was also investigated. Among the inhibitors studied, sodium hexametaphosphate was found to be the most effective.

Jeffrey and Melchers investigated the influence of environmental factors on the early corrosion of steel in coastal seawater *[6]*. Overall corrosion rates for the six months were found to be in the range 150-300 micrometres/year. Seasonal factors such as rainfall appeared to have a significant influence on the corrosion behavior. Corrosion rates were found to increase with salinity, dissolved oxygen and water velocity but reduced with increasing biofouling.

Temple *et al.* evaluated the drainage pipe by field experimentation and supplemental laboratory experimentation in context of Louisiana soils *[7]*. There were a total of 11 test sites that were chosen to evaluate the effect of corrosive soil conditions on various metal pipe culverts. Six years after the installation and in-service exposure, it was found that the asbestos-bonded asphalt-coated, galvanized steel pipe was performing better than the other ten original types of culverts in resisting the corrosion. The coatings on these pipe culverts were showing the signs of distress because of environmental conditions. Pitting corrosion was significant on Aluminum alloy culverts in conditions with pH less than 5 and resistivity less than 1000 ohm-cm.

The soil pH and the effluent pH in water usually differ. The same is true in the case of resistivity measurements. In a not-so-related study Garber and Smith investigated cathodic protection of culverts on Louisiana highways *[8]*. The cost of such protection in certain cases was about $25,000. The report presented the evidence that most of the culverts showed corrosion damage (internal as well as external) in first few years of in-service operations. The soil pH and the resistivity values were the main driving environmental conditions affecting corrosion.

Hock *et al.* published a report for US Army Corps of Engineers on corrosion mitigation and material selection in a severely corrosive environment *[9]*. This report provides soil resistivity ranges and their corresponding corrosivity ratings. The resistivity values between 0-2000 ohm-cm are classified as “severe,” 2000-10,000 ohm-cm are as “severe to moderate,” 10,000-30,000 ohm-cm as “mild” and the soil resistivity values more than 30,000 ohm-cm were classified as “not likely.”

Doyle investigated the role of soil in external corrosion of cast-iron water mains in his thesis *[10]*. The thesis suggests that when corrosion is electrochemical in origin, soil resistivity plays a major factor in determining the corrosion rate. The lower the resistivity of the soil, the higher the corrosion rate. In the results and discussion section, the pH ranges of various soil types found in North America are provided *[10]*. Additionally, the thesis also provides various charts showing the nature of the relationship between soil resistivity and maximum external pitting corrosion rates.

Molinas and Mommandi published a report on development of new corrosion and abrasion guidelines for selection of culvert pipe materials for the Colorado Department of Transportation *[11]*. The report presents California Department of Transportation method for estimating service life based on evaluation of pH, sulfate-ion concentration and chloride-ion concentration in the soil and/or water environment for metal culverts. The test method is numbered 643-C and is dated 1972 (Figure 1). The Utah Department of Transportation chart (Figure 2) discussed and included in the same Colorado Department of Transportation report, presents expected ages of pipe classes A through F for three types of soils (minimum resistivity of 200 ohm-cm, 500 ohm-cm and 900 ohm-cm) at pH 7 through 10.

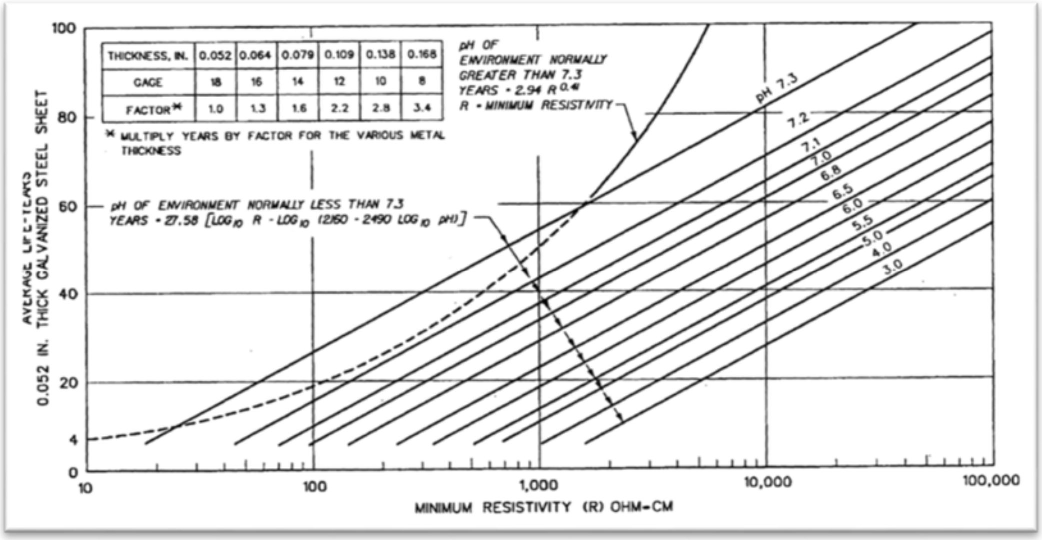
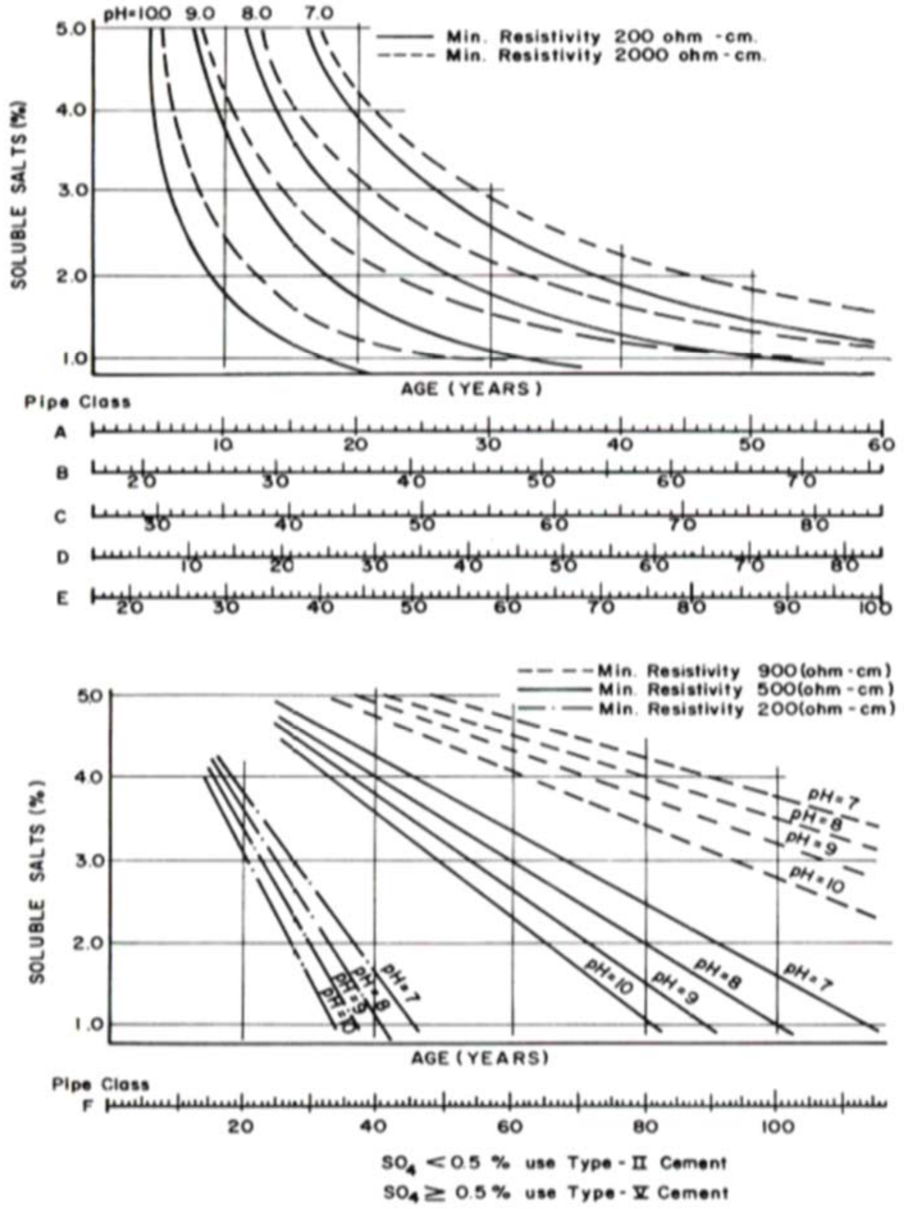


Figure 1
Corrosion model used in this work *[11]*



Pipe Class A = Plain corrugated steel

Pipe Class B = Bituminous-coated corrugated steel pipe, aluminum alloy pipe, galvalume pipe, pitch-resin adhesive-coated corrugated steel pipe (coated on exterior side only)

Pipe Class C = Asbestos-bonded bituminous-coated corrugated steel pipe, pitch-resin adhesive-coated corrugated steel pipe (coated on both sides)

Pipe Class D = Plain corrugated steel structural-plate pipe

Pipe Class E = Bituminous-coated corrugated steel structural-plate pipe, aluminum alloy structural-plate pipe

Pipe Class F = Portland cement concrete pipe

Figure 2

The Utah Department of Transportation chart showing expected ages of pipe classes A through F for three types of soils (minimum resistivity of 200 ohm-cm, 500 ohm-cm and 900 ohm-cm) at pH 7 through 10 ***[11]***

There are other publications that were referred for metal culverts and their service life *[12-14]*. One particular publication titled "Service Life of Culverts – A Synthesis of Highway Practice," Synthesis 474 by Transportation Research Board and National Cooperative Highway Research Program was useful as it provides relationship between resistivity and corrosion potential with no role of pH (**Error! Reference source not found.**). In addition to this, it also provides typical resistivity values of various soil and water types (Table 2) and typical corrosion potential of various soil types (Table 3).

Table 1

Relationship between resistivity and corrosion potential with no role of pH *[12]*

Soil Corrosion Potential	Resistivity (ohm-cm)
Negligible	$R > 10{,}000$
Very Low	$10{,}000 > R > 6{,}000$
Low	$6{,}000 > R > 4{,}500$
Moderate	$4{,}500 > R > 2{,}000$
Severe	$2{,}000 > R$

Table 2

Typical resistivity values of various soil and water types *[12]*

Classification		Resistivity (ohm-cm)
Water	Surface water	$R > 5{,}000$
	Brackish water	$R = 2{,}000$
	Seawater	$R = 25$
Soil	Rock	$R > 50{,}000$
	Sand	$50{,}000 > R > 30{,}000$
	Gravel	$30{,}000 > R > 10{,}000$
	Loam	$10{,}000 > R > 2{,}000$
	Clay	$2{,}000 > R > 750$

Table 3
Typical corrosion potential of various soil types *[12]*

Soil Type	Description of Soil	Drainage	Water Table
1 - Lightly Corrosive	Sands or sandy loam, light-textured silt loams, porous loams or clay loams thoroughly oxidized to great depths	Good	Very low
2 - Moderately Corrosive	Sandy loams, silt loams, clay loams	Fair	Low
3 - Badly Corrosive	clay loams, clays	Poor	2 to 3 ft. below surface
4 - Unusually Corrosive	Muck, peat, tidal marsh, clays and organic soils	Very poor	At surface or extreme impermeability

OBJECTIVE

The objective of this project was to create a guidance document with maps that delineates zones where metal pipe is prone to increased corrosion due to environmental conditions. Results from this project will provide a logical rationale to support DOTD restricting the use of the metal drainage pipe in certain areas.

SCOPE

This project was focused on the coastal region of Louisiana. Specifically, the study area of this project covered DOTD Districts 02, 03, 07, 61 and 62. A visual reference of the districts is provided below in Figure 3. The approximate total area of coverage was 21,877 square miles. The spatial variation of soil pH and conductivity and their combined corrosive effect on metal pipe is invested in this project. Any localized change in these environmental conditions because of anthropogenic conditions is not considered.

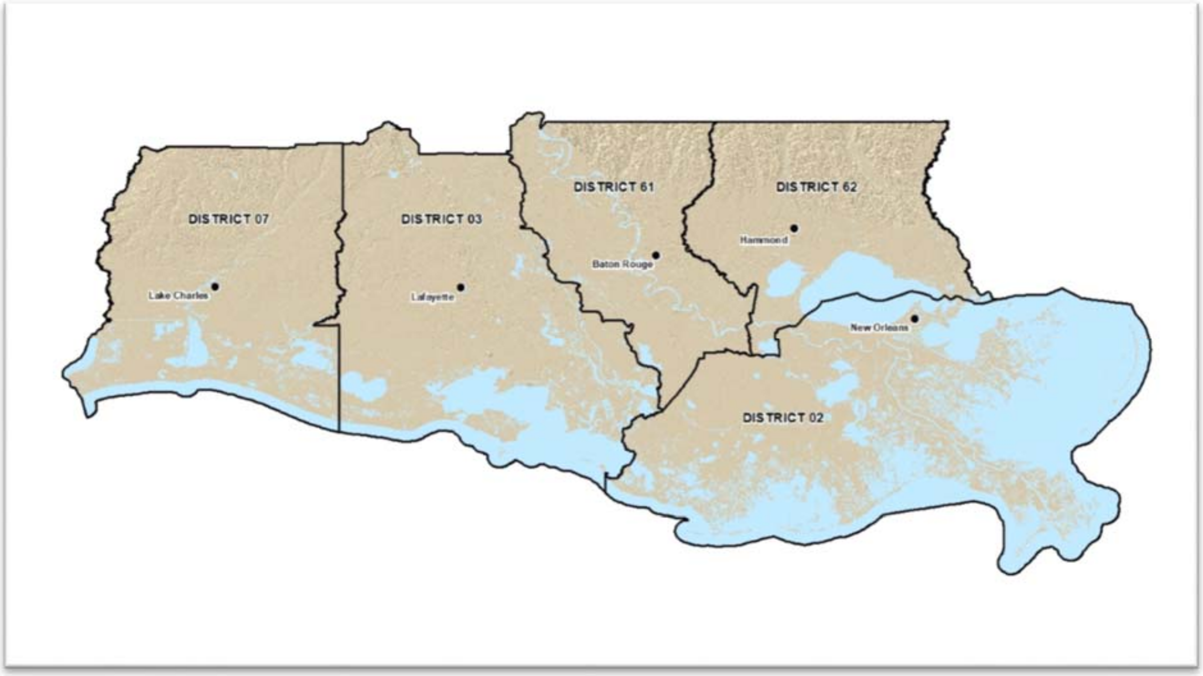


Figure 3
Louisiana coastal regions and DOTD Districts

METHODOLOGY

Work Plan

The corrosion rate varies under different environmental conditions. These conditions vary significantly throughout Louisiana. Salinity is a big concern in the coastal areas in addition to other environmental factors. A detailed study of most prevalent environmental conditions in the state based on available spatial soil data and actual field measurements helped determine conditions ideal for metal corrosion. The coastal region, based on the environmental conditions, is delineated into different zones that would help transportation agencies choose the right kind of material for pipes for cross drains under/along roads and highways.

The Implementation of GIS in the Project

GIS platforms have a wide range of capabilities for research. One of the many such capabilities is the numerous interpolation methods it provides for the prediction of surface data. These interpolation methods can be found under three toolboxes within the GIS platform ArcGIS. The toolboxes are 3D Analyst, Geostatistical Analyst, and Spatial Analyst. The 3D Analyst contains many of the same interpolation methods as other two toolboxes with one distinction. The resulting raster surface is intended to be displayed in three-dimensional space. This project only needed one toolbox, Geostatistical Analyst and two of its interpolation toolsets, Inverse Distance Weighted and Kriging. Newer visions of ArcGIS' ArcMap have both the Spatial and Geostatistical toolbar that acts as an all-in-one stop for interpolation for those looking to avoid ArcToolbox. The toolbars provide the numerous interpolation methods, method properties, and cross validations.

Interpolation within ArcMap is only as good as the input data, which is why discussing the data must come first. In a perfect world, the data would be soil properties point shapefiles or feature class datasets created from numerous field surveys spread somewhat equally across the study area. Since it is not a perfect world, the data had to be derived from multiple sources, edited, merged, and then used for interpolation. There were three datasets from two sources that were used in this research due to both their availability and spread across the study area. The first dataset were PDF copies of field surveys conducted and provided by the DOTD. The data provided by DOTD is ideal for creating a predictive GIS surface. The source and records of metadata are collected, documented, and stored. The data would also correspond to the primary areas of concern for the client which is on or within proximity of roadways and highways under the responsibility of

DOTD. Although this data had to be created from PDFs to be used on a GIS platform and some of the PDFs lack locational information this would had be the primary form of data to be used for interpolation if there was enough coverage and spread of the data throughout the coastal part of Louisiana. The field surveys comprised (only) just over a hundred locations, which identified both pH and resistivity readings. This quantity and quality of data would suit many GIS researchers since many soil studies are on localized regions for agricultural or soil science purposes. The issue was the size of the study area for this project which spans approximately 21, 877 square miles along the lack of locations in District 02. The field survey dataset just did not have enough locations to accurately predict the chemical nature of the over such a large area. To assist with the DOTD dataset, Web Soil Survey datasets were used. Web Soil Survey data is made available both on-line and CD-ROM by the Natural Resources Conservation Services (NRCS), which falls under the USDA. Its use and applications are primarily centered around the conservation of soil and agricultural. The data does require some know how before being loaded into an ArcGIS service. The data comes with a point, line, and polygon shapefile, tabular dataset, and Microsoft Access Database. The shapefiles provide the spatial location and pull the attribute data from the tabular dataset which is population by the Access database. The links between the tabular dataset and Access database are established through Access by linking two through a pathway. The connection between the shapefile and tabular is established by Soil Data Viewer. Soil data viewer is a free application found and downloaded from the NRCS Web Soil Survey website. Once downloaded the application must be added into ArcMap and enabled as a Toolset. When done correctly, ArcMap will allow the user use of the application via the toolbar menu. Once the Soil Data viewer is open, the user has access to copious amounts of soil datasets ranging from Land Classification and Soil Chemical Properties to Military Operations and Waste Management. The issue with NRCS soil data is that it can be tremendously difficult to derive the locations and amounts of the field surveys used to compose some of their datasets. The datasets used for this study were Electrical Conductivity and pH polygon files that were display at the parish level. A parish is a geographically large area for soil pH and conductivity environments. There was no information regarding the quantity and locations of the field surveys within those polygons. Considering that the data is primarily used for agricultural and conservational purposes this could also create a bias spatial representation of areas where these activities are not as strong. So, to create an accurate predictive surface for which the data allows, the datasets were merged together after they were processed.

With so many choices for interpolation offered by ArcGIS, how does one pick the correct method? First, they must consider the data that they are using. While there is not a definite wrong interpolation method or technique to use, error is recorded in all predictive surfaces, and there are methods which are better fitting to certain dataset types, scales, and size. The best way to discover them is by reviewing the individual methods and historical research conducted by others. There were two prior research reports and one journal article reviewed when making the decision on which interpolation methods to use. The articles must be viewed in the years they were released. In terms of the ArcGIS platform, the last decade has seen huge improvements and additions to the services offered to its users.

The focus of accurately predicting the spatial patterns of numerous chemical properties of soil is the center proposition of “Improving the Prediction Accuracy of Soil Mapping through Geostatistics” authored by El-Sayed Ewis Omran *[15]*. The study area is a total area of 50 hectares or 0.2 square miles with 146 sampling points. The chemical properties of the soil that were tested are electric conductivity, pH, and calcium carbonate. The four techniques of interpolation that were used on the three separate chemical properties were Universal Kriging (UK), Ordinary Kriging (OK), Inverse Distance Weighted (IDW), and Spline. The method was geostatistical as opposed to spatial. The techniques were conducted using all their parameters that were available at the time of the study. Each type of interpolation can be set with numerous different parameters such as the power parameters or neighbors. The purpose of this was to explore the differences of results within each interpolator. After running the interpolations, a cross validation was performed on each of the predicted surfaces. Cross validation depicts different means of measurements for error and prediction, depending on the interpolation method used. It compares measured values with the predicted from the predicted surface. The mean error and standard deviation were used to rank the methods. The resulting cross validations showed that UK had the lowest mean error and standard deviation amongst the methods used. The UK interpolator often times proves to have greater accuracies with the predictive surfaces they produce. Kriging interpolations make their predictions from the statistical values of the data as oppose to the spatial values. The research also verifies that the same interpolation method can be run on multiple types of data and produce surfaces with similar accuracy. This is not covered in the research, but the tables that were outcomes of the cross validations were and could be compared. Through this comparison there is a noticeable similarity of the errors.

Zandi et al. shared a similar approach to the interpolation of soil chemical properties *[16]*. The study area was much smaller for this research, accounting for an area approximately 400 meters by 150 meters with 54 sampled locations. The research focused on one chemical property of the soil which was pH. The researchers applied three interpolation methods: OK, IDW, and Radial Base Function (RBF). The researchers did not outright note whether they used they used geostatistical or spatial. In reading the described methods they used, it can be concluded the OK method used was from the geostatistical toolbox, and the IDW and RBF methods used were from the spatial toolbox. The interpolations were run using all their parameters as with the previous study. The researchers did run the IDW and RBF interpolations multiple times, adjusting the power parameter for their greatness accuracy. The cross validations were performed on the resulting predicted surfaces. The results of the cross validations revealed the RBF interpolator as producing the greatness accuracy amongst the three. RBF is an exact interpolator, meaning that the surface must run through each measured location. There are five basic functions, such as the multiquadric and spline functions. The RBF works very well over areas that have gradual value changes, which will ideally produce a smooth surface. When there are large changes in the surface or outliners, the resulting predictive surface is prone to much higher errors or uncertainty. In the case of pH measurements, the values of soil pH are confined to a smaller range. The small range controls the variance of the data which works well with the RBF interpolator. This accounts for only one form of data. In regards to resistivity, which is being measured from 100 ohm centimeters, into the 20,000s ohm centimeters, the opportunity for large variance within the datasets is impossible to avoid. Another factor is that as the study area increases, the data begins to have greater variance from the mean center. In the case of this study, the area was much smaller than coastal Louisiana, which is one reason why RBF was ruled out.

Childs' article in ArcUser discusses some of the interpolation techniques which were available upon the ArcGIS 9.0 release *[17]*. The article discusses exactly how a spatial surface within the ArcGIS platform works and correlates to creating predictive surfaces. The article then continues to explain the bases of the separate techniques and methods of interpolation. One interpolation technique, the PointInterp, is no longer available in current versions of ArcGIS. Many of the techniques listed are the core of the interpolation techniques available now, which assists in establishing how the individual interpolators work.

PROJECT APPROACH AND DISCUSSION OF RESULTS

The data used in this project was derived from Web Soil Survey data provided by the NRCS, USDA, and field surveys provided by DOTD. NRCS data consisted of multiple soil and environmental datasets which are presented in polygon format covering the area of individual parishes and countries. The specific NRCS datasets that were used in this project are soil pH and resistivity. The standard map unit for this data set is at 24,000 scale. The pH and conductivity data both had to be modified for the research. The units of measurement for the NRCS conductivity dataset had originally been in decisiemens per meter, which is a standard among soil scientists. The conductivity units of measurements had to be converted to resistivity to match DOTD units of measurements, which are ohm per centimeter. The conversion of units was done so that DOTD field datasets once created could be merged with NRCS datasets.

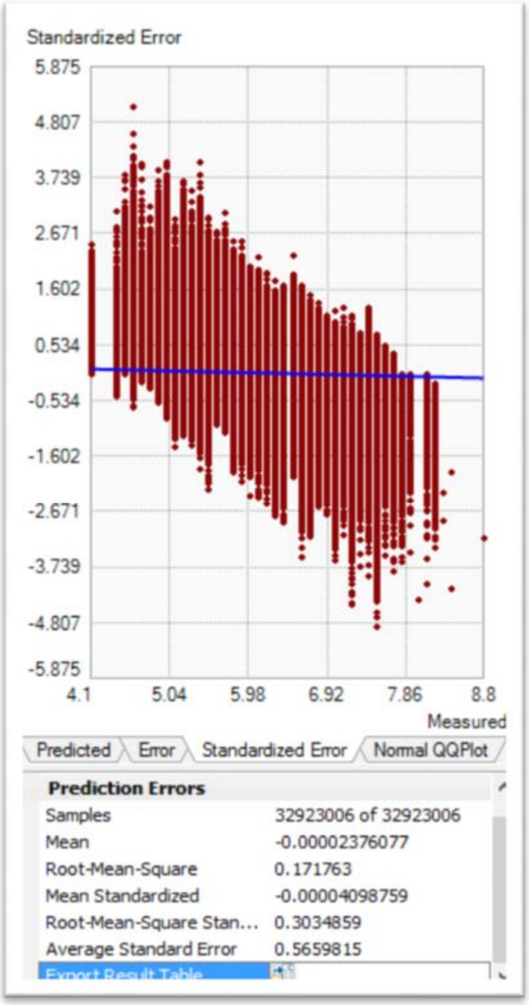
The creation of a resistivity dataset was achieved in a two-step method. First, values of 0 decisiemens per meter or Null values were eliminated from the datasets which voided correlating spatial data. Then the attribute table of the data set was modified. A column was added into the original dataset attribute table and field, calculating the conversion between decisiemen per meter and ohm per centimeter, which resulted in the dataset having both resistivity and conductivity readings. The NRCS pH dataset was not edited. The resistivity and pH datasets were converted to point data to merge with the NRCS field surveys. The conversion of a data from polygon format to a point format does not suit the purpose of the project as it alters the data so that one single point centered within the polygon represents the value of such a large area. Therefore, multiple methods were used to accurately depict polygon data and point data format, the method displaying the greatest spatial relationship between the two was adopted for the project. The polygon datasets were first converted to raster to control the spatial variance of the data. The polygon to raster tool in ArcGIS allows the user to control the pixel or cell value of a raster regarding size, which represents the squared meter area of the surface if the data is presented in a projected coordinate system. The cell size was set to 25 meters. This value was chosen so that the spacing in the DOTD field surveys would be considered during the interpolation of the merged datasets.

The raster datasets were then converted to points using the raster to point tool. This tool assigns a point value of each raster cell that is spatial center within the perimeters of that cell. The converted datasets consisted of points and their correlating values spaced 25 meter apart for areas with raster coverage.

The next step was to create spatially correlated GIS data for field surveys provided by the DOTD which covered Districts 03, 07, 61, and 62. District 02 had no field surveys and due to the extremely corrosive nature of soil it disallowed the use of metal culverts and therefore required no field surveys. The DOTD field surveys that were used to get soil data were in pdf format and their numbers are as follows: 713-32-0108, 713-32-0109, 713-46-0112,713-59-0221, 713-59-0222, 276-03-0016, 848-12-0016, 261-06-0030, 013-11-0026, 713-17-0041, 267-02-0022, 713-19-0109, 713-04-0001,713-59-0053, 713-63-0103, 713-63-0104, 019-30-0016, 019-30-0017, 450-91-0171, 713-27-0110, 713-27-0111, 201-01-0013, 849-02-0014, and 213-06-0008. Resistivity and pH feature classes were created by deriving a spatial location from these field surveys. To identify spatial locations from these field surveys the different descriptions were used, some of them are control segments, log miles, intersections, bridge numbers, google earth attachments, and field drawings included in the field surveys. While there were many more field surveys available, only the ones noted earlier had recordings which could be used to derive spatial locations. The remaining field surveys were not used in this study. The units of measurements were not altered from the PDF copies since the DOTD units of measurement were the standard for the project.

Once the four separate points feature classes (e.g., DOTD pH, DOTD resistivity, NRCS pH, NRCS resistivity) were created, the datasets were merged per their chemical properties. The merging of the data was performed using the ArcGIS' geoprocessing merge tool. The resulting point feature classes were one pH and one resistivity datasets covering the study area and consisting of a combined 60,540,719 individual points.

The same interpolation techniques were run on the both merged datasets parameters. The first interpolation technique was the IDW which is a deterministic method. The IDW assumes that the value of the point decreases in weight or influence as it increases in distance from that point *[15]*. The default value of the power remained the same as this method was used only as a comparison tool with the Kriging Method. The power parameter within the IDW tool controls the weight of individual points, which can be used to increase the accuracy of the interpolation method. The chemical nature of soil is heavily dependent on its immediate area and the variance of the local environmental conditions, meaning that the soil environment of an area can be vastly different then the soil environment 50 meters away specially in terms of pH. To account for this, the weight of the power was decreased. This means that the weight of individual soil point data only impacted its immediate spatial environment and had a far less impact as the distance increased away from the point. The Z valued field was set to pH and resistivity values of the dataset. Within the environments under the raster analysis tab, a mask was set with a shapefile of the study area. The mask limits the extent of the interpolation within the study area. The processing of both the pH and resistivity dataset total an approximate time of six and a half hours with a 64-bit geoprocessing ArcGIS service. That does not mean that all IDW processes will run in this time window, just these datasets with their parameters. The mean error for this dataset was approximately 0.2 as shown in Figure 4 and was checked through cross-validation of the datasets. Other similar sample cross-validation tables are provided in the Appendix as Figure 8 and Figure 9. The IDW provides a quick reference to the nature of the chemical properties of soil but should not be used for accurate predictions for soil chemical properties. The IDW relies heavily on the assumptions of a predicted area by the measured values of the surroundings and is confined by those values *[15]*. The chemical nature of soil proves that this is not always the case.



Prediction Errors	
Samples	32923006 of 32923006
Mean	-0.00002376077
Root-Mean-Square	0.171763
Mean Standardized	-0.00004098759
Root-Mean-Square Stan...	0.3034859
Average Standard Error	0.5659815

Figure 4
Cross-validation of IDW pH results

The second interpolation technique used was Empirical Bayesian Kriging (EBK). EBK is another of several interpolation methods offered in ArcGIS. Kriging techniques are commonly used in agriculture, soil science and predicting pollution concentration *[17]*. EBK accounts for error that may be introduced during statistical prediction of data. The interpolation values of predicted areas are allowed to exceed the parameters of the neighboring measured values. The parameters of the EBK tool were set with some similarities to the IDW tool. The Z value field was set to the pH and resistivity readings of the datasets. The data transformation type was left at none due to possible outliners within the data. The semivariogarm model type was set to power. The data transformation type should remain at none since there should be no negative values with the data. The mask in raster analysis under the environments was also set to the same shapefile as the IDW. The mean error for the dataset was less than 0.2. During cross-validation the individual points and their errors are displayed and points with higher errors were removed. The process took 24-36 hours to interpolate for both datasets. The EBK resistivity raster format dataset is presented below in Figure 5.

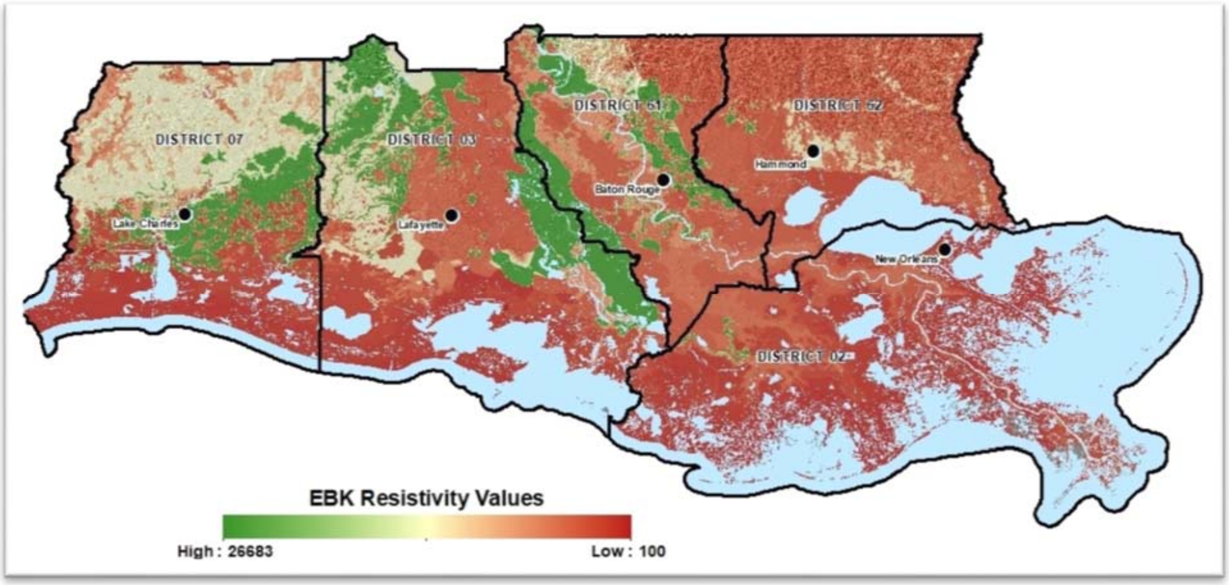


Figure 5
EBK resistivity raster format dataset

The resulting four raster datasets (e.g., pH IDW, Resistivity IDW, pH EBK, Resistivity EBK) still required some refining. The interpolations that were run also accounted for numerous areas that consisted of water bodies. These water bodies had to be erased from the datasets. The shapefile that provided the mask for the interpolation were generated by Erase Feature using a Louisiana Tiger water body dataset. That shapefile was then used to run an extract by mask on all four datasets. This extracts the areas of the raster inside the waterbodies present in coastal region of Louisiana omitting the results that fell within waterbodies.

At this stage of the project, the pH and resistivity values were in a raster format and needed to be converted to polygon format so both datasets could be combined displaying intersecting spatial values. There are multiple ways to achieve this in ArcGIS depending on data format. The data needed again to be formatted due to the difference in the data type between the datasets. The raster datasets that resulted from the IDW techniques were in integer types which can be easily converted from raster to polygon. This was done using the Raster to Polygon tool in the Conversion toolset. The pH and resistivity raster datasets, outcomes of the EBK technique, were in float types and had to be converted into the integer type. The resistivity raster which had no decimal values outside of zero was converted using the Int tool within the Math toolset. This tool converts values that are not integers into integers. The dataset was then converted to polygon using the Raster to Polygon tool. The pH raster which had decimal values needed to be converted in a different manner. The values of the raster had to be calculated using the raster calculator to zero out the decimal places. The dataset was multiplied by 10000 to eliminate the values that were within the decimal places. The Int tool was then used to convert the values for float type to integer type. The dataset was converted to polygon using the raster to polygon tool. The polygon values for pH then had to be converted back which was done by using the field calculator made available in the attribute table menu. The pH values that were multiplied by 10,000 had to be divided by 10,000. Figure 6 presents EBK pH polygon formatted dataset that was created in this project.

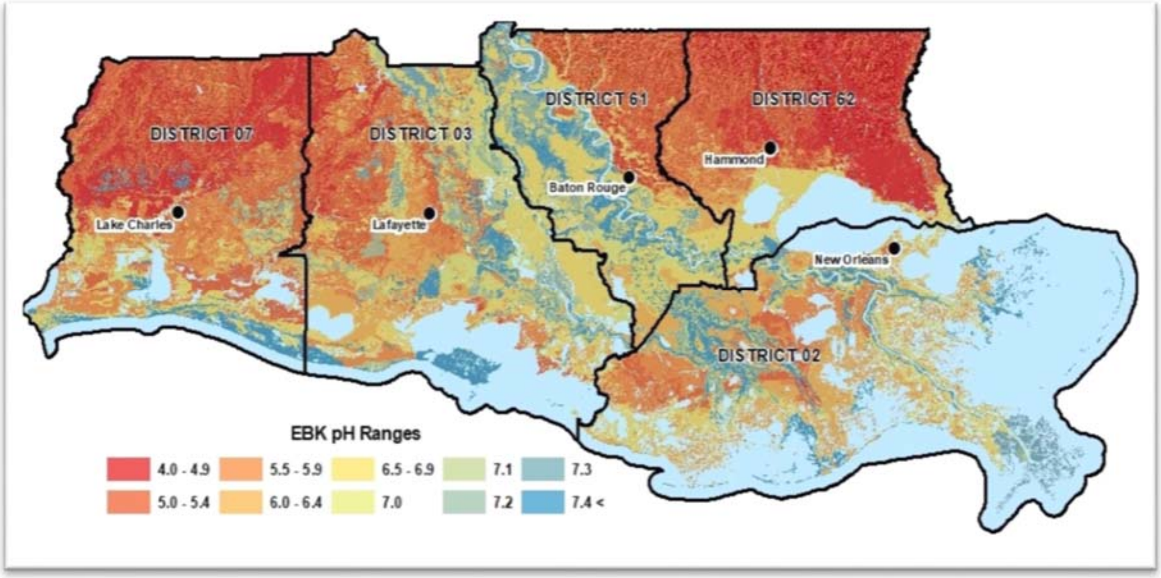


Figure 6
EBK pH polygon formatted dataset

The two separate interpolation datasets needed to be unionized so that pH and resistivity values could be combined spatially representing combined effect which is a measure of a likelihood of metal corrosion. The union computes a geometric union of the input features. All features and their attributes will be written to the output feature class. All input feature classes or feature layers must be polygons. The output feature class contains polygons representing the geometric union of all the inputs as well as all the fields from all the input feature classes. In the context of this project, when polygon pH input feature and polygon resistivity feature are unionized, the output feature will be a polygon but will have both pH and resistivity assigned spatially. It is required as locations within the project area are evaluated for the combined corrosive effect of pH and resistivity.

The combined corrosive effect of pH and resistivity was calculated based on many published models that combine soil pH and conductivity (resistivity) to occurrence of corrosion. This was done by running dissolves on the four datasets based on the pH and resistivity values. The EBK and IDW datasets were then unionized so that the new polygon data represented boundary areas of shared values between pH and resistivity. The refinement of the attribute tables was the most time-consuming part of the research. The attribute values had to be categorized in a manner of life span of metal culvert and corrosive nature of the soil. The Colorado Department of Transportation (CDOT) study on determining the lifespan of metal pipes and DOTD study on drainage pipes were referenced for determining the values of the final symbolization of the data *[18]*. Figure 1 presents this model as shown previously in this report. The attribute tables of the EBK and IDW union datasets were modified by adding two columns, one for determining average pipe life span and the other for determining the corrosive value of the soil. A screen shot of the attribute table is included in the Appendix as Figure 10. A table presented in Appendix as Figure 11 shows how combined values of pH and resistivity values are used to determine corrosive environment of the soil. The table refers to Figure 1 and compares the attribute values of pH (3-7.3) and resistivity (10-1400 ohm-cm) for average life of 0-20 years thus classifying the zone as Extremely Corrosive (EC). Similar deductions were made for different pH values over resistivity values up to 100,000 ohm-cm. In cases, where, either pH or resistivity values were not available after interpolation, the appropriate zone was assigned based on either pH or resistivity. The analysis resulted into four corrosion zones. These zones correspond to expected life of metal pipes under field conditions (soil pH and resistivity) and are defined as mildly corrosive for 60-80 years, corrosive for 40-60 years, highly corrosive for 20-40 years and extremely corrosive for 0-20 years. The resulting corrosion map is shown in Figure 7. The additional corrosion maps and expected life span of metal pipes of each District along with parish boundaries are provided in the appendix as Figure 12 through Figure 17.

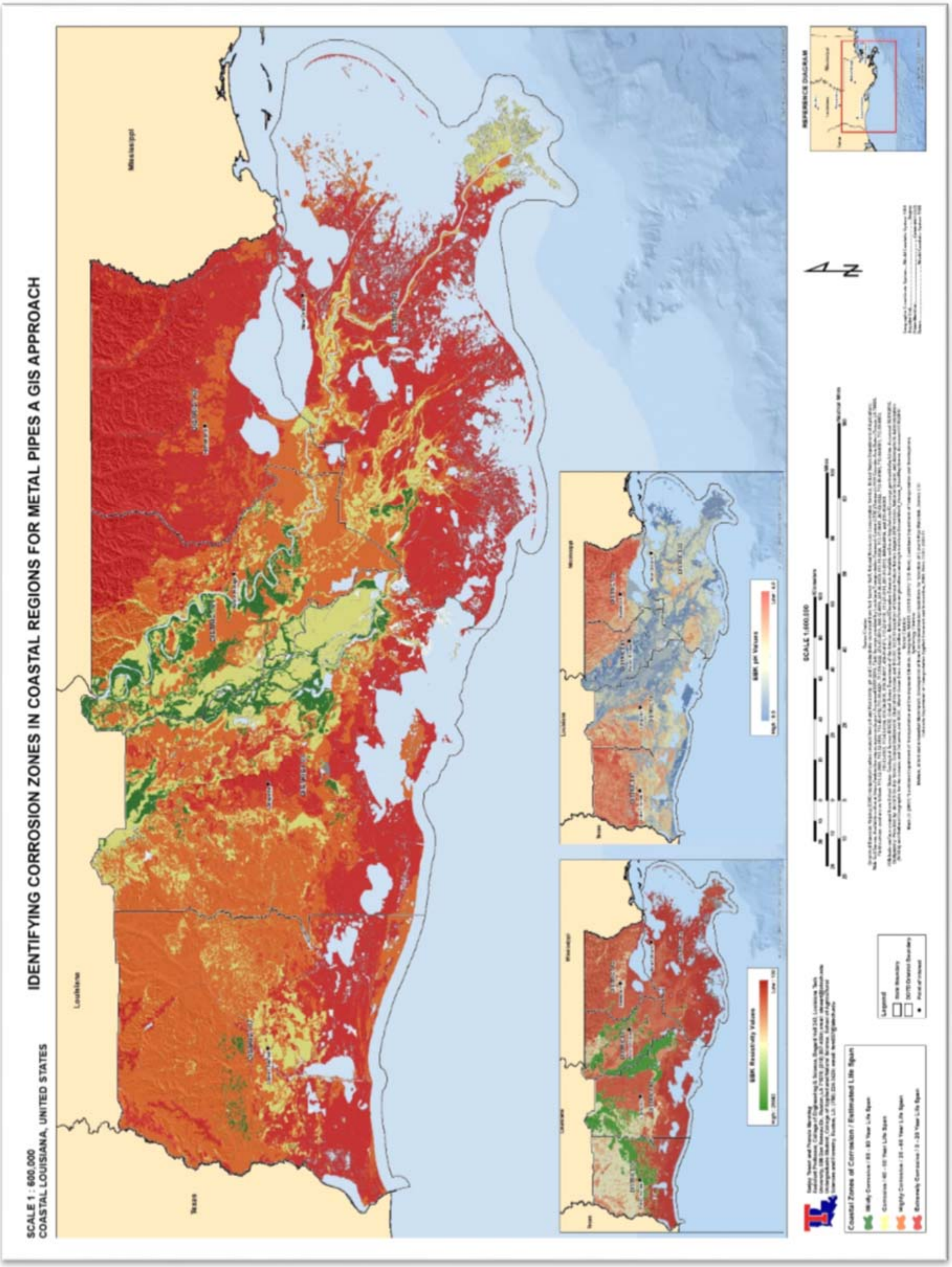


Figure 7

Corrosion zones in coastal Louisiana

The combined area of each corrosion zone in the study area is provided below in Table 4. The total percentage area of Extremely Corrosive Zone and Highly Corrosive Zone in the five studied DOTD districts is 80% of the total area. This means that the expected service life of metal pipes is equal or less than 40 years in about 80% of the study area in the coastal Louisiana. Conversely, only about 20% area provides expected service of metal pipes more than 40 years. There is a little bit less than 5% area in the study area that provides expected service life of metal pipes between 60 to 80 years.

Table 4
Area distribution of corrosion zones

Corrosion Zone (Expected Service Life of a Metal Pipe)	Total Area (Mile^2)	Percentage Area
Extremely Corrosive (0-20 yrs.)	9,259.06	42.5%
Highly Corrosive (20-40 yrs.)	8,177.88	37.5%
Corrosive (40-60 yrs.)	3,339.57	15.3%
Mildly Corrosive (60-80 yrs.)	1,004.15	4.6%

The DOTD district corrosion maps (Figure 12 through Figure 16) may have possible errors due to the fact each parish data may have been collected in batches at different times and for that reason there may be a sudden difference in pH and resistivity values at the parish boundaries. There may not be a smooth transition at parish boundaries between two or more parishes. Ideally, the parish data should be edge-matched with features in adjacent files or other artificial boundaries within a file.

Life-Cycle Cost Analysis

Selecting pipe materials best suited for a culvert replacement is of primary importance to a design engineer. The selection is based on hydraulic efficiency, structural integrity, durability, and cost. The selection of pipe material is too often based on the initial (low) cost. However, the pipe material with the lowest initial cost may not be the most economical selection for the design life of the project. In many instances, transportation authorities are having to repair and replace (or part of) a culvert with low initial cost before it could serve its designed life because of premature degradation induced by environmental parameters. This results in higher costs to maintain these culverts in long terms. The life-cycle cost analysis (LCCA) and selection of culvert pipe material on the basis of minimizing the cost makes good sense. Thus an analysis for the least (life-cycle) cost for road and drainage projects must be done.

Local and state governments have increasingly included some type of analysis in their material selection process. LCCA's value as a decision-support tool is contingent upon its proper use. While the economic concepts that support this type of analysis are fairly straightforward, their application presents a number of challenges. It should be noted that a LCCA, if done without considering critical factors, may not provide accurate and meaningful understanding of the life-cycle cost.

In this simple and straight-forward LCCA, the effect of soil conditions on pipe material is the single most important factor that is considered in the analysis. In addition to durability of culverts, the cost associated with installation, maintenance and replacement is also considered. It is assumed that the standard designed life of a metal culvert pipe is valid only in mildly corrosive soil environment. A combination of field environmental and soil conditions may create more corrosive conditions to pipe material and expedite its degradation at a higher rate than it was expected. One of LTRC's previous studies (Garber, J. D., and Smith, L. G. Cathodic Protection of Culverts Field Application and Expert System, LTRC LA-99/324, Louisiana Department of Transportation and Development, 1999), provided some of the cost associated with earth work needed to rehabilitate and additional cost for the cathodic protection itself *[8]*. During preliminary analysis, it was evident to us that replacement and rehabilitation process would cost more.

This project investigated such conditions that are present in coastal Louisiana and delineated them in corrosion maps. From the data and corresponding maps, it is clearly evident that in extremely corrosive and highly corrosive zones metal pipes may not be ideal choice as they will not be able to serve their full designed life. In many cases they will not be able to serve even half of their designed life, requiring costly maintenance and replacement.

CONCLUSIONS

The corrosion map presented in this report is based on combined values of spatial soil pH and spatial soil resistivity. In the presented example map, the corrosive zones are divided into four categories that are mildly corrosive, corrosive, highly corrosive, and extremely corrosive. These categories correspond to expected life of metal pipes under field conditions (soil pH and resistivity) and are defined as mildly corrosive for 60-80 years, corrosive for 40-60 years, highly corrosive for 20-40 years and extremely corrosive for 0-20 years. The classification of zones is based on the research described in the Literature Review section of this report. The relevant data that was processed and used to create the maps presented in this report is provided to LTRC along with this report.

The results of this study indicate that the most of the soil environment is corrosive in nature to metal culverts in coastal Louisiana. However, there are exceptions to this in the greater Baton Rouge area and the Atchafalaya River Basin. The data shows that the corrosive nature of about 80% area of the coastal region is not ideal for metal pipes as the expected service life is less than 40 years. There is about15% of the area, as shown in corrosion Figure 7, where metal pipes are expected to have service life between 40 to 60 years. There is even smaller percentage (less than 5%) of area where expected life of metal culverts is between 60 to 80 years.

RECOMMENDATIONS

The results of this project should be used as a general tool for project planning and culvert material selection in the coastal region of the Louisiana. The results presented in this report have some limitations. The pH and resistivity data obtained from various sources was valid for a few points, and suitable interpolation techniques were used to create data for points that did not have any data originally. Whenever any kind of interpolation is done, there is possibility that the interpolated data may not match the real spatial values and conditions. Also, there may be some local variations in corrosive environments because of other local environmental parameters not considered in this study. Also, soil properties at a given point vary with the depth of the soil. The soil samples used in this study were not collected at the same depth. Therefore, the pH and resistivity were weighted at a certain depth and these weighted values were used for further spatial interpolation.

It is recommended that for higher accuracy, site specific soil investigations should be used. The accuracy of this map can be increased in the future if soil properties (pH and resistivity) from more field investigations are incorporated in as calibration data. It is recommended that this data be frequently updated and re-calibrated often (every 4-5 years) for it to be even more useful and accurate. The author recommends that DOTD should specify standard guidelines for field soil investigations that are specific to number of soil samples to be collected and their respective depths for pH and resistivity values and their spatial locations to be recorded. These days, it has become a lot easier to record a geo-location using a smart phone. It is recommended that the corrosion maps be utilized in the design process to optimize design life of culverts.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cm	centimeter(s)
CDOT	Colorado Department of Transportation
DOTD	Louisiana Department of Transportation and Development
EBK	Empirical Bayesian Kriging
EDSM	Engineering Directives and Standards Manual
FHWA	Federal Highway Administration
ft.	foot (feet)
GIS	Geographic Information System
IDW	Inverse Distance Weighted
in.	inch(es)
lb.	pound(s)
LCCA	Life-Cycle Cost Analysis
LTRC	Louisiana Transportation Research Center
LTU	Louisiana Tech University
m	meter(s)
NRCS	Natural Resources Conservation Service
OK	Ordinary Kriging
PRC	Project Review Committee
RBF	Radial Base Function
TRID	Transport Research International Documentation
TRIS	Transportation Research Information Services
UK	Universal Kriging
USDA	United States Department of Agricultural

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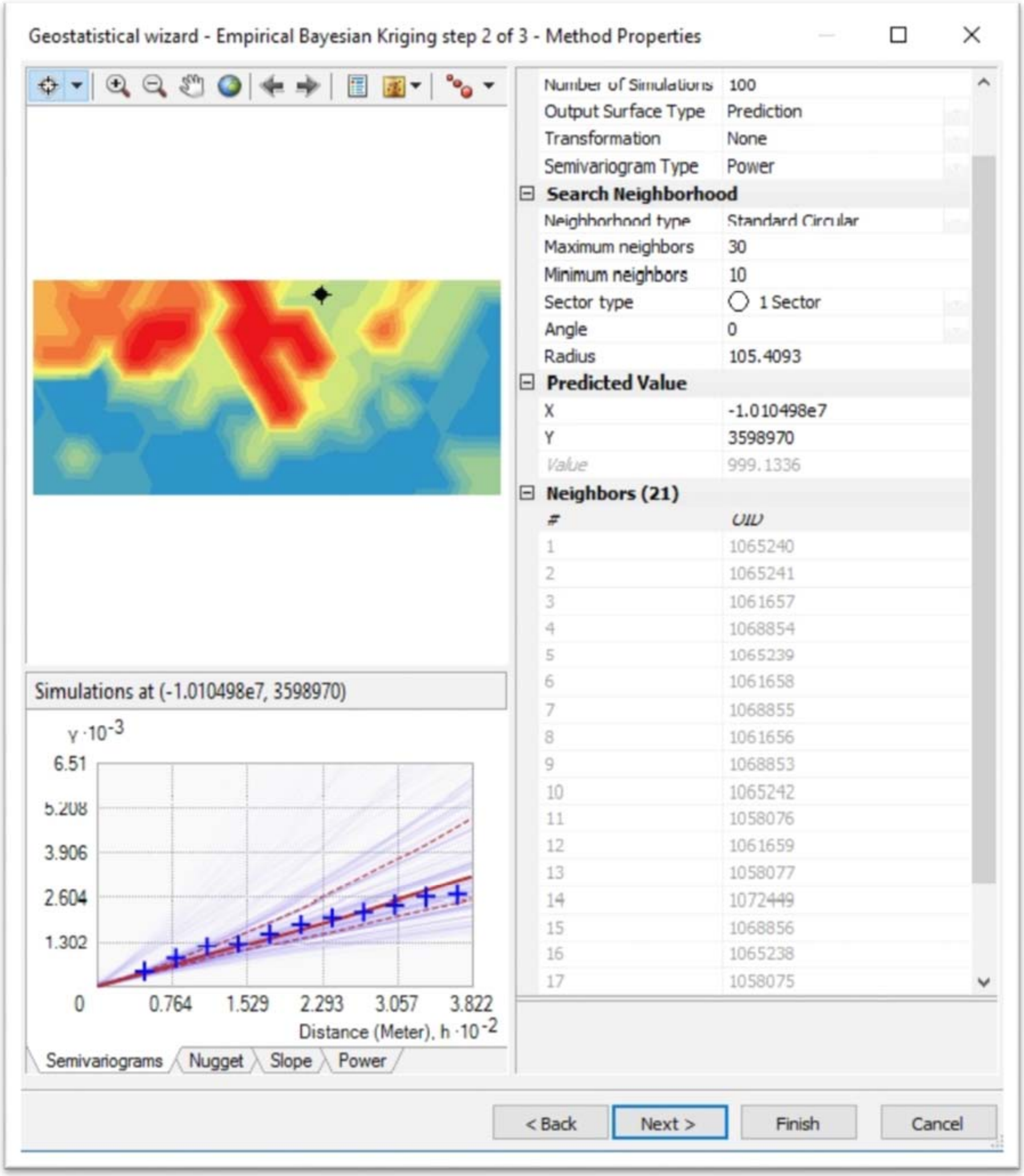
APPENDIX



Geostatistical wizard - Empirical Bayesian Kriging step 2 of 3 - Method Properties

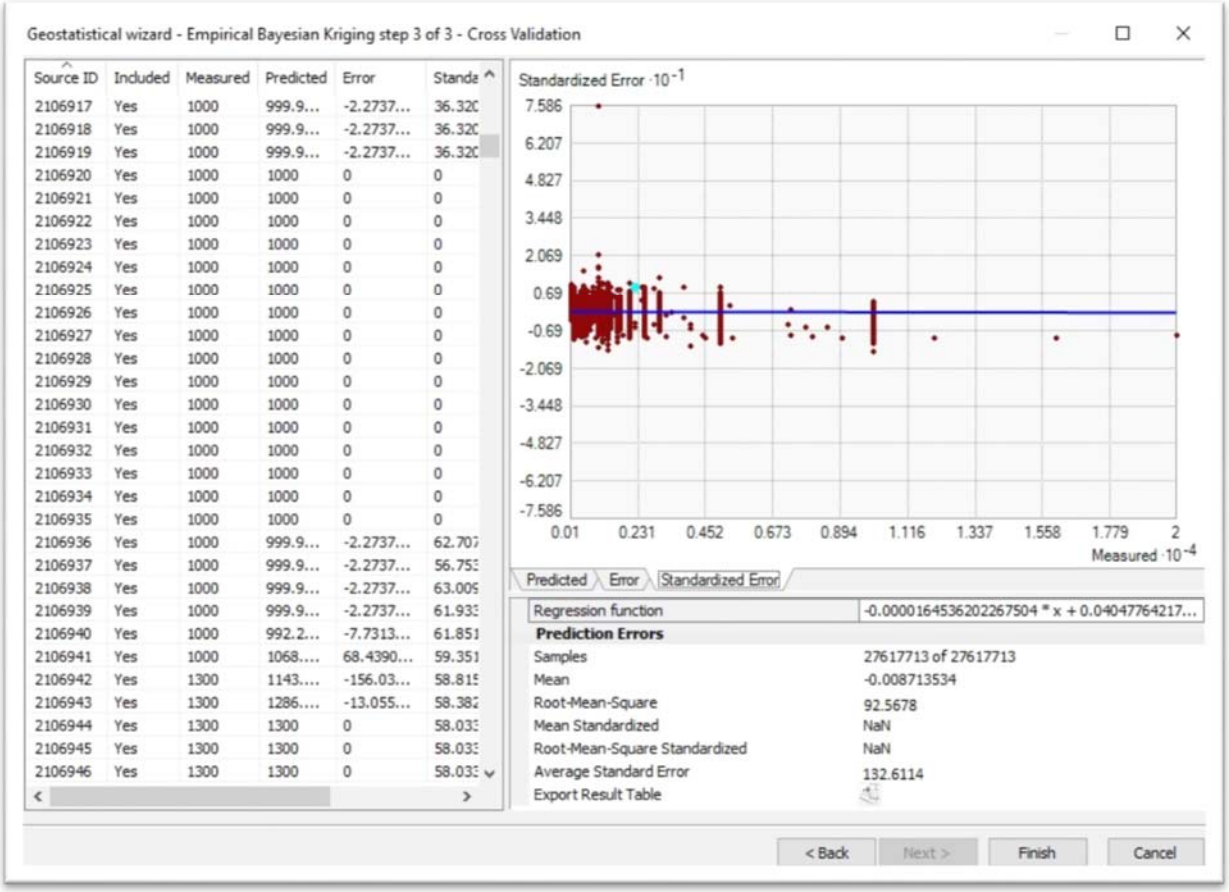
Number of Simulations	100
Output Surface Type	Prediction
Transformation	None
Semivariogram Type	Power
Search Neighborhood	
Neighborhood type	Standard Circular
Maximum neighbors	30
Minimum neighbors	10
Sector type	○ 1 Sector
Angle	0
Radius	105.4093
Predicted Value	
X	-1.010498e7
Y	3598970
Value	999.1336

Neighbors (21)

#	OID
1	1065240
2	1065241
3	1061657
4	1068854
5	1065239
6	1061658
7	1068855
8	1061656
9	1068853
10	1065242
11	1058076
12	1061659
13	1058077
14	1072449
15	1068856
16	1065238
17	1058075

Simulations at (-1.010498e7, 3598970)

Figure 8
The EBK processing of the data



Geostatistical wizard - Empirical Bayesian Kriging step 3 of 3 - Cross Validation

Source ID	Included	Measured	Predicted	Error	Standa
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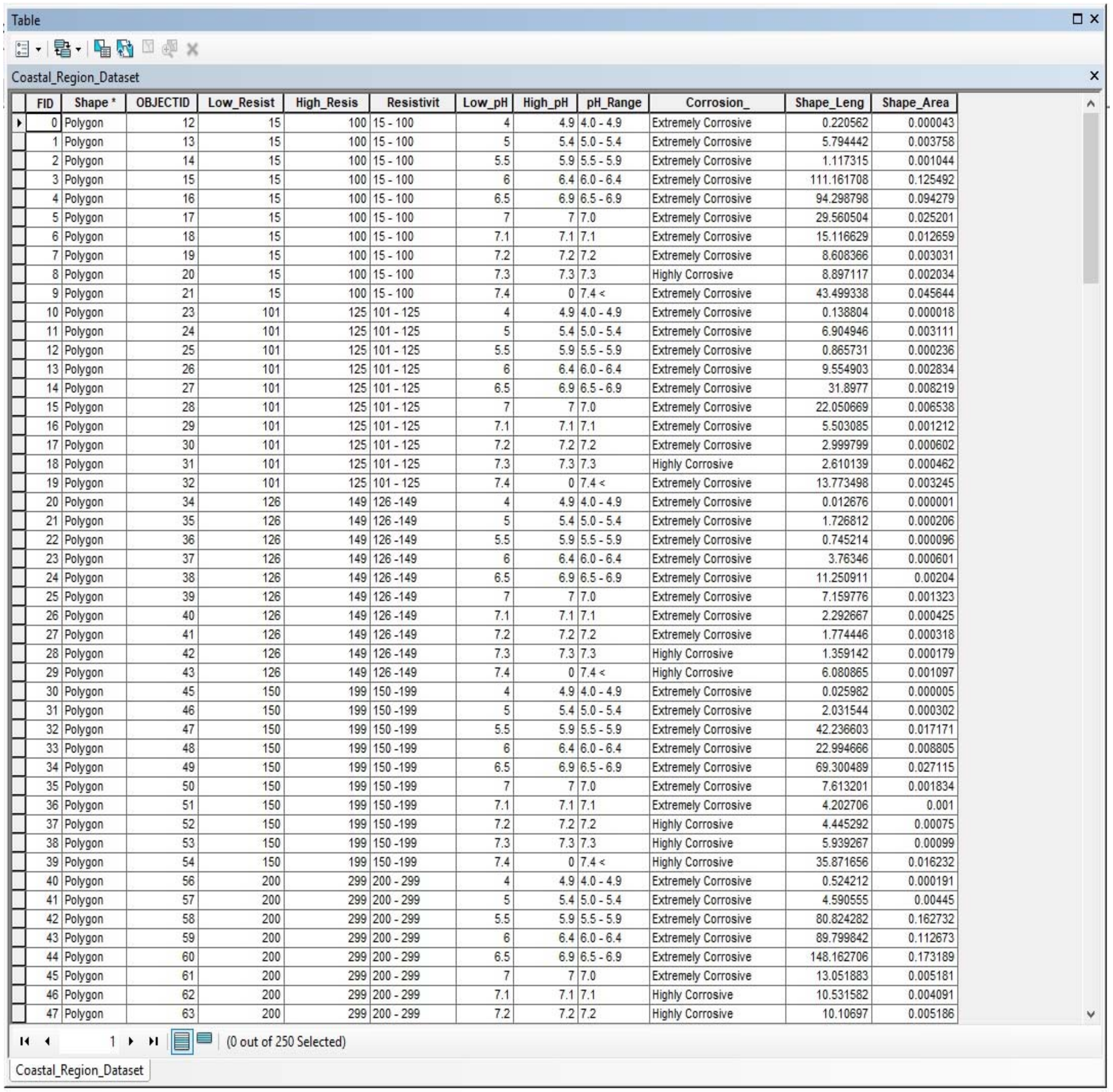
2106918	Yes	1000	999.9...	-2.2737...	36.320
2106919	Yes	1000	999.9...	-2.2737...	36.320
2106920	Yes	1000	1000	0	0
2106921	Yes	1000	1000	0	0
2106922	Yes	1000	1000	0	0
2106923	Yes	1000	1000	0	0
2106924	Yes	1000	1000	0	0
2106925	Yes	1000	1000	0	0
2106926	Yes	1000	1000	0	0
2106927	Yes	1000	1000	0	0
2106928	Yes	1000	1000	0	0
2106929	Yes	1000	1000	0	0
2106930	Yes	1000	1000	0	0
2106931	Yes	1000	1000	0	0
2106932	Yes	1000	1000	0	0
2106933	Yes	1000	1000	0	0
2106934	Yes	1000	1000	0	0
2106935	Yes	1000	1000	0	0
2106936	Yes	1000	999.9...	-2.2737...	62.707
2106937	Yes	1000	999.9...	-2.2737...	56.753
2106938	Yes	1000	999.9...	-2.2737...	63.009
2106939	Yes	1000	999.9...	-2.2737...	61.933
2106940	Yes	1000	992.2...	-7.7313...	61.851
2106941	Yes	1000	1068....	68.4390...	59.351
2106942	Yes	1300	1143....	-156.03...	58.815
2106943	Yes	1300	1286....	-13.055...	58.382
2106944	Yes	1300	1300	0	58.033
2106945	Yes	1300	1300	0	58.033
2106946	Yes	1300	1300	0	58.033

Regression function	-0.0000164536202267504 * x + 0.04047764217...
Prediction Errors	
Samples	27617713 of 27617713
Mean	-0.008713534
Root-Mean-Square	92.5678
Mean Standardized	NaN
Root-Mean-Square Standardized	NaN
Average Standard Error	132.6114
Export Result Table	

Figure 9

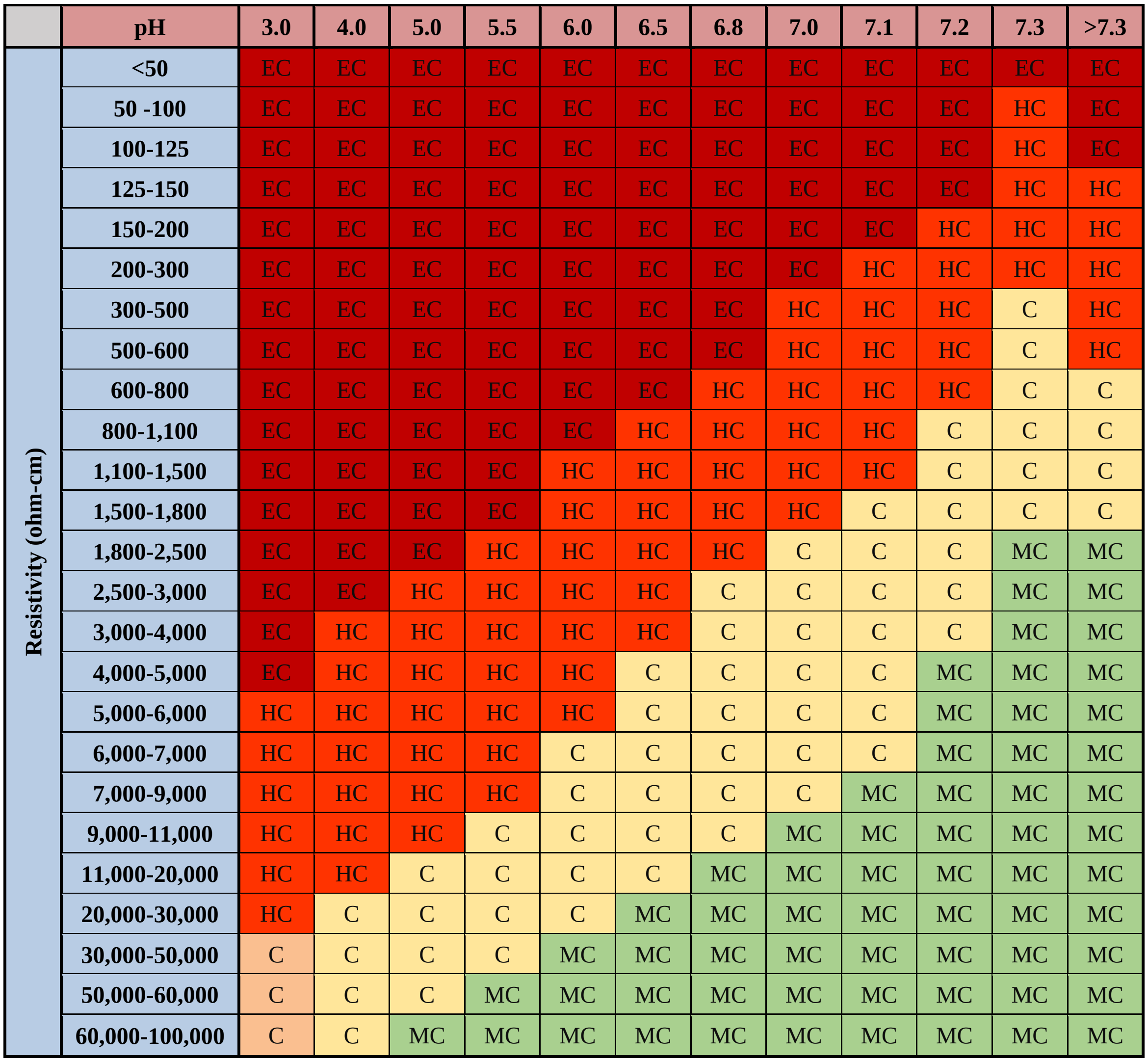
EBK processing of the data – cross validation



FID	Shape *	OBJECTID	Low_Resist	High_Resis	Resistivit	Low_pH	High_pH	pH_Range	Corrosion_	Shape_Leng	Shape_Area
0	Polygon	12	15	100	15 - 100	4	4.9	4.0 - 4.9	Extremely Corrosive	0.220562	0.000043
1	Polygon	13	15	100	15 - 100	5	5.4	5.0 - 5.4	Extremely Corrosive	5.794442	0.003758
2	Polygon	14	15	100	15 - 100	5.5	5.9	5.5 - 5.9	Extremely Corrosive	1.117315	0.001044
3	Polygon	15	15	100	15 - 100	6	6.4	6.0 - 6.4	Extremely Corrosive	111.161708	0.125492
4	Polygon	16	15	100	15 - 100	6.5	6.9	6.5 - 6.9	Extremely Corrosive	94.298798	0.094279
5	Polygon	17	15	100	15 - 100	7	7	7.0	Extremely Corrosive	29.560504	0.025201
6	Polygon	18	15	100	15 - 100	7.1	7.1	7.1	Extremely Corrosive	15.116629	0.012659
7	Polygon	19	15	100	15 - 100	7.2	7.2	7.2	Extremely Corrosive	8.608366	0.003031
8	Polygon	20	15	100	15 - 100	7.3	7.3	7.3	Highly Corrosive	8.897117	0.002034
9	Polygon	21	15	100	15 - 100	7.4	0	7.4 <	Extremely Corrosive	43.499338	0.045644
10	Polygon	23	101	125	101 - 125	4	4.9	4.0 - 4.9	Extremely Corrosive	0.138804	0.000018
11	Polygon	24	101	125	101 - 125	5	5.4	5.0 - 5.4	Extremely Corrosive	6.904946	0.003111
12	Polygon	25	101	125	101 - 125	5.5	5.9	5.5 - 5.9	Extremely Corrosive	0.865731	0.000236
13	Polygon	26	101	125	101 - 125	6	6.4	6.0 - 6.4	Extremely Corrosive	9.554903	0.002834
14	Polygon	27	101	125	101 - 125	6.5	6.9	6.5 - 6.9	Extremely Corrosive	31.8977	0.008219
15	Polygon	28	101	125	101 - 125	7	7	7.0	Extremely Corrosive	22.050669	0.006538
16	Polygon	29	101	125	101 - 125	7.1	7.1	7.1	Extremely Corrosive	5.503085	0.001212
17	Polygon	30	101	125	101 - 125	7.2	7.2	7.2	Extremely Corrosive	2.999799	0.000602
18	Polygon	31	101	125	101 - 125	7.3	7.3	7.3	Highly Corrosive	2.610139	0.000462
19	Polygon	32	101	125	101 - 125	7.4	0	7.4 <	Extremely Corrosive	13.773498	0.003245
20	Polygon	34	126	149	126 -149	4	4.9	4.0 - 4.9	Extremely Corrosive	0.012676	0.000001
21	Polygon	35	126	149	126 -149	5	5.4	5.0 - 5.4	Extremely Corrosive	1.726812	0.000206
22	Polygon	36	126	149	126 -149	5.5	5.9	5.5 - 5.9	Extremely Corrosive	0.745214	0.000096
23	Polygon	37	126	149	126 -149	6	6.4	6.0 - 6.4	Extremely Corrosive	3.76346	0.000601
24	Polygon	38	126	149	126 -149	6.5	6.9	6.5 - 6.9	Extremely Corrosive	11.250911	0.00204
25	Polygon	39	126	149	126 -149	7	7	7.0	Extremely Corrosive	7.159776	0.001323
26	Polygon	40	126	149	126 -149	7.1	7.1	7.1	Extremely Corrosive	2.292667	0.000425
27	Polygon	41	126	149	126 -149	7.2	7.2	7.2	Extremely Corrosive	1.774446	0.000318
28	Polygon	42	126	149	126 -149	7.3	7.3	7.3	Highly Corrosive	1.359142	0.000179
29	Polygon	43	126	149	126 -149	7.4	0	7.4 <	Highly Corrosive	6.080865	0.001097
30	Polygon	45	150	199	150 -199	4	4.9	4.0 - 4.9	Extremely Corrosive	0.025982	0.000005
31	Polygon	46	150	199	150 -199	5	5.4	5.0 - 5.4	Extremely Corrosive	2.031544	0.000302
32	Polygon	47	150	199	150 -199	5.5	5.9	5.5 - 5.9	Extremely Corrosive	42.236603	0.017171
33	Polygon	48	150	199	150 -199	6	6.4	6.0 - 6.4	Extremely Corrosive	22.994666	0.008805
34	Polygon	49	150	199	150 -199	6.5	6.9	6.5 - 6.9	Extremely Corrosive	69.300489	0.027115
35	Polygon	50	150	199	150 -199	7	7	7.0	Extremely Corrosive	7.613201	0.001834
36	Polygon	51	150	199	150 -199	7.1	7.1	7.1	Extremely Corrosive	4.202706	0.001
37	Polygon	52	150	199	150 -199	7.2	7.2	7.2	Highly Corrosive	4.445292	0.00075
38	Polygon	53	150	199	150 -199	7.3	7.3	7.3	Highly Corrosive	5.939267	0.00099
39	Polygon	54	150	199	150 -199	7.4	0	7.4 <	Highly Corrosive	35.871656	0.016232
40	Polygon	56	200	299	200 - 299	4	4.9	4.0 - 4.9	Extremely Corrosive	0.524212	0.000191
41	Polygon	57	200	299	200 - 299	5	5.4	5.0 - 5.4	Extremely Corrosive	4.590555	0.00445
42	Polygon	58	200	299	200 - 299	5.5	5.9	5.5 - 5.9	Extremely Corrosive	80.824282	0.162732
43	Polygon	59	200	299	200 - 299	6	6.4	6.0 - 6.4	Extremely Corrosive	89.799842	0.112673
44	Polygon	60	200	299	200 - 299	6.5	6.9	6.5 - 6.9	Extremely Corrosive	148.162706	0.173189
45	Polygon	61	200	299	200 - 299	7	7	7.0	Extremely Corrosive	13.051883	0.005181
46	Polygon	62	200	299	200 - 299	7.1	7.1	7.1	Highly Corrosive	10.531582	0.004091
47	Polygon	63	200	299	200 - 299	7.2	7.2	7.2	Highly Corrosive	10.10697	0.005186

Figure 10

A screenshot of the attribute table showing how the combined corrosive effect of pH and resistivity values are used in classifying the soil environment as mildly corrosive for 60-80 years of expected service life, corrosive for 40-60 years, highly corrosive for 20-40 years, and extremely corrosive for 0-20 years



	pH	3.0	4.0	5.0	5.5	6.0	6.5	6.8	7.0	7.1	7.2	7.3	>7.3
Resistivity (ohm-cm)	**<50**	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC
	50 -100	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	HC	EC
	100-125	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	HC	EC
	125-150	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	HC	HC
	150-200	EC	EC	EC	EC	EC	EC	EC	EC	EC	HC	HC	HC
	200-300	EC	EC	EC	EC	EC	EC	EC	EC	HC	HC	HC	HC
	300-500	EC	EC	EC	EC	EC	EC	EC	HC	HC	HC	C	HC
	500-600	EC	EC	EC	EC	EC	EC	EC	HC	HC	HC	C	HC
	600-800	EC	EC	EC	EC	EC	EC	HC	HC	HC	HC	C	C
	800-1,100	EC	EC	EC	EC	EC	HC	HC	HC	HC	C	C	C
	1,100-1,500	EC	EC	EC	EC	HC	HC	HC	HC	HC	C	C	C
	1,500-1,800	EC	EC	EC	EC	HC	HC	HC	HC	C	C	C	C
	1,800-2,500	EC	EC	EC	HC	HC	HC	HC	C	C	C	MC	MC
	2,500-3,000	EC	EC	HC	HC	HC	HC	C	C	C	C	MC	MC
	3,000-4,000	EC	HC	HC	HC	HC	HC	C	C	C	C	MC	MC
	4,000-5,000	EC	HC	HC	HC	HC	C	C	C	C	MC	MC	MC
	5,000-6,000	HC	HC	HC	HC	HC	C	C	C	C	MC	MC	MC
	6,000-7,000	HC	HC	HC	HC	C	C	C	C	C	MC	MC	MC
	7,000-9,000	HC	HC	HC	HC	C	C	C	C	MC	MC	MC	MC
	9,000-11,000	HC	HC	HC	C	C	C	C	MC	MC	MC	MC	MC
	11,000-20,000	HC	HC	C	C	C	C	MC	MC	MC	MC	MC	MC
	20,000-30,000	HC	C	C	C	C	MC	MC	MC	MC	MC	MC	MC
	30,000-50,000	C	C	C	C	MC	MC	MC	MC	MC	MC	MC	MC
	50,000-60,000	C	C	C	MC	MC	MC	MC	MC	MC	MC	MC	MC
	60,000-100,000	C	C	MC	MC	MC	MC	MC	MC	MC	MC	MC	MC

Figure 11

The combined corrosion attribute values of pH (3-7.3) and resistivity (up to 100,000 ohm-cm) for expected average life of metal pipes. EC is extremely corrosive (0-20 years), HC is highly corrosive (20-40 years), C is corrosive (40-60 years), and MC is mildly corrosive (60-80 years)

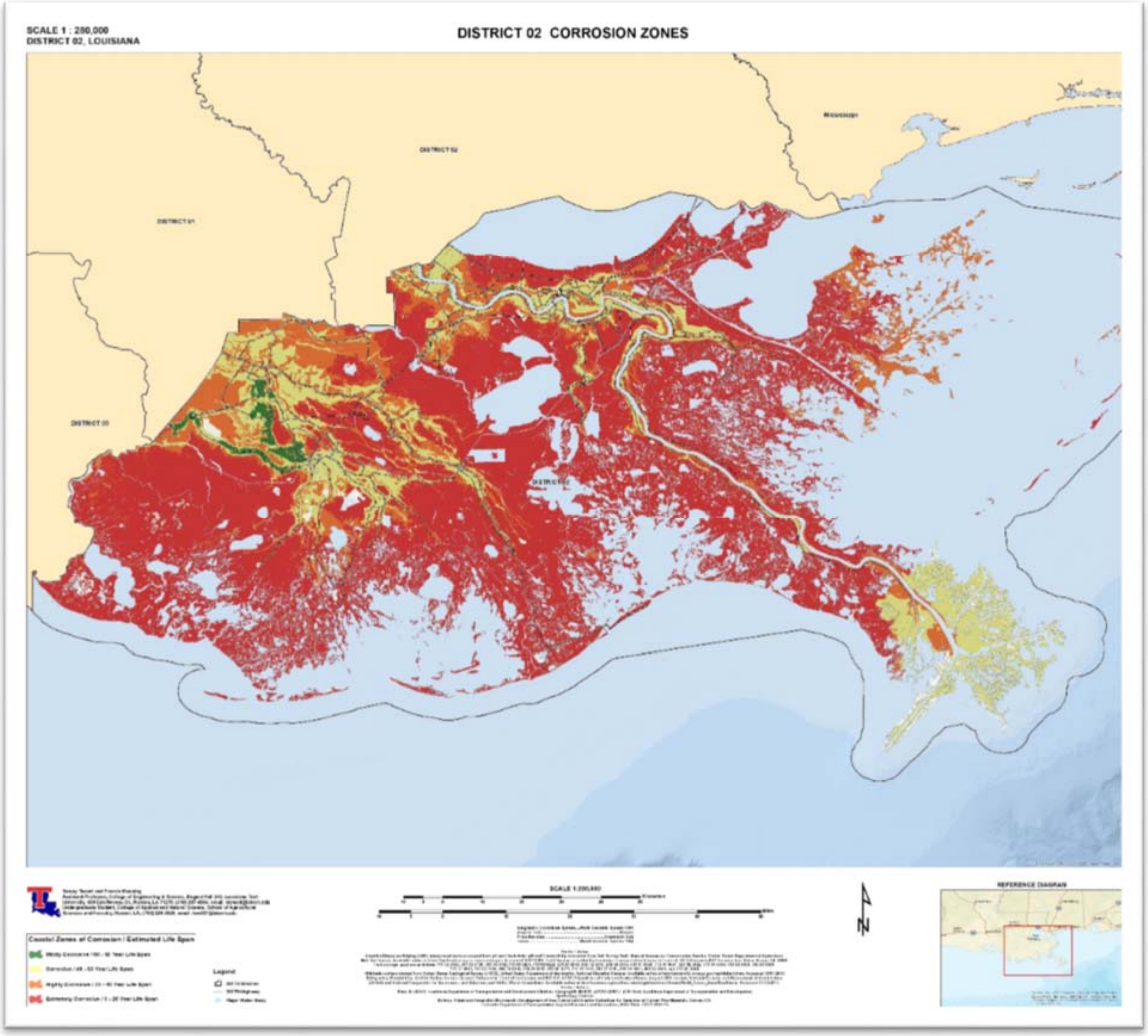


Figure 12

Corrosion map of District 02

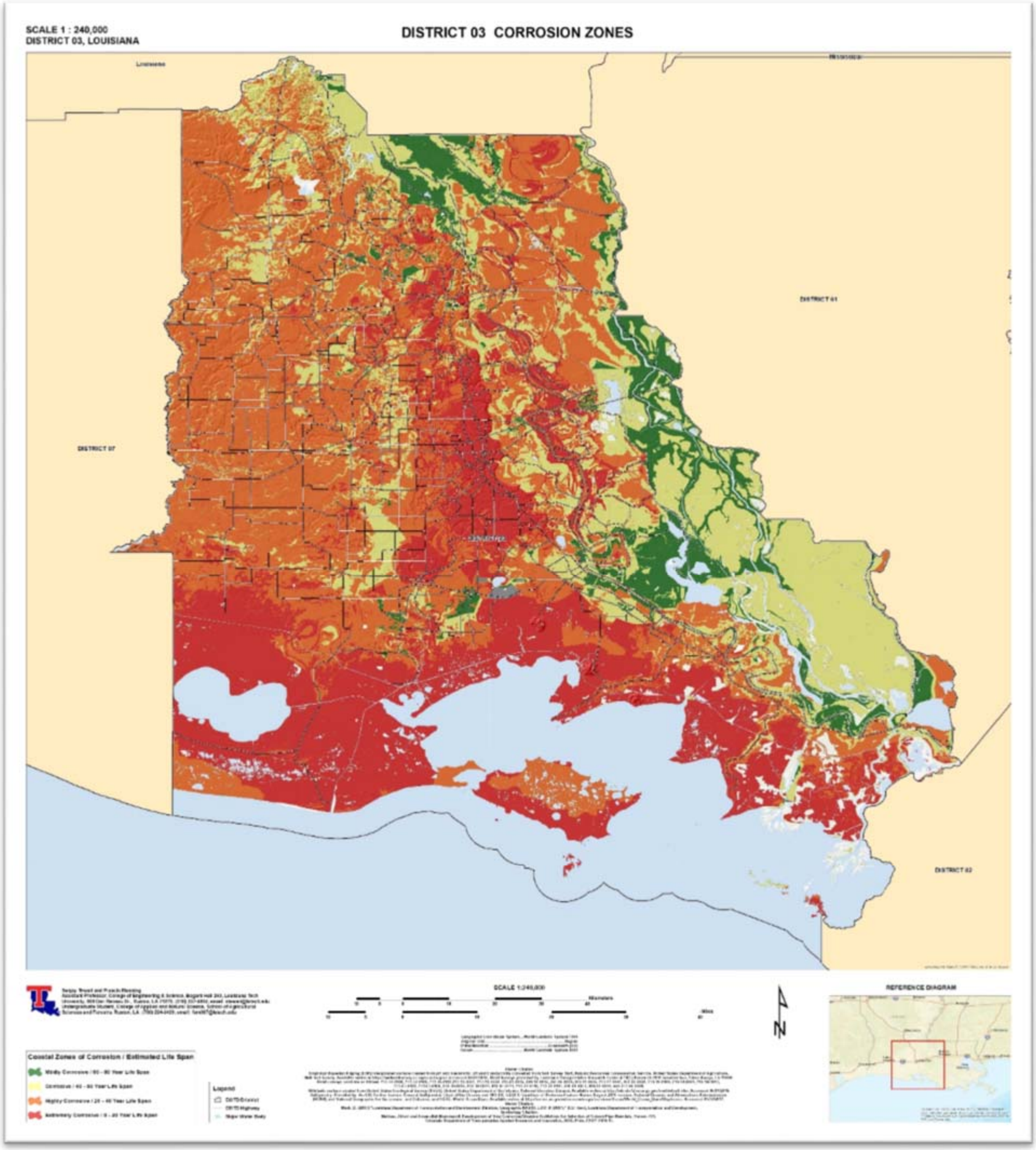


Figure 13

Corrosion map of District 03

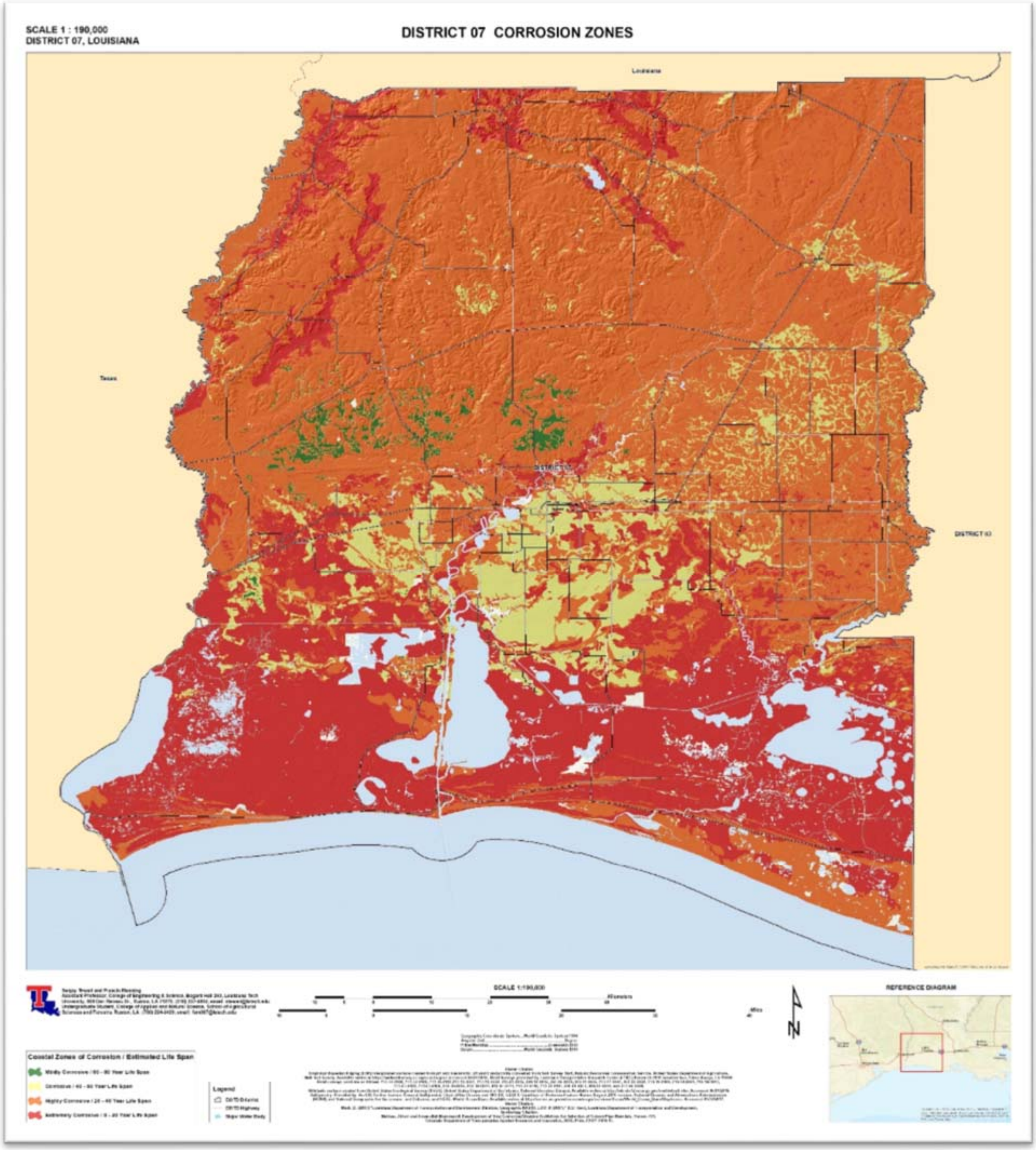


Figure 14

Corrosion map of District 07

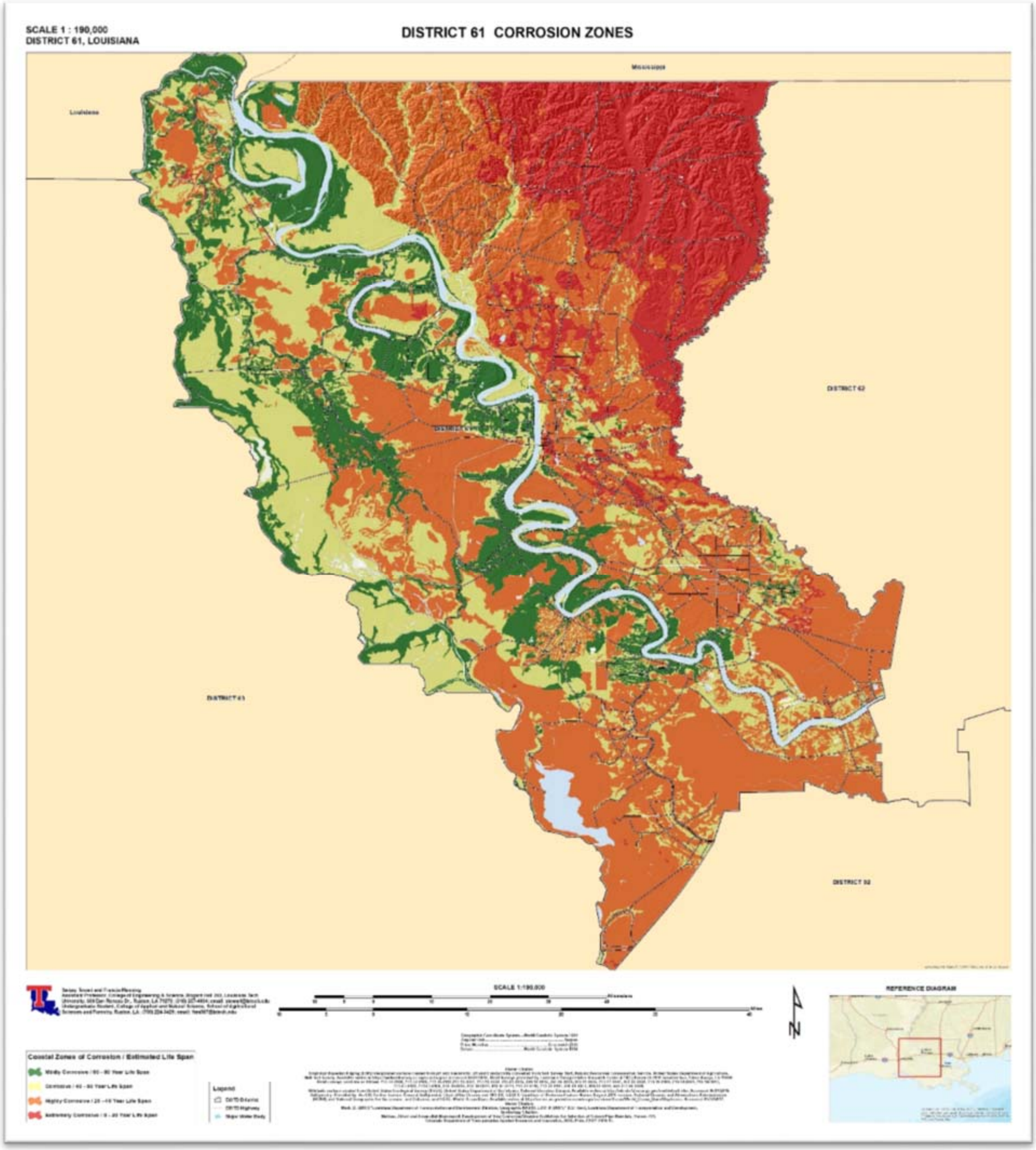


Figure 15

Corrosion map of District 61

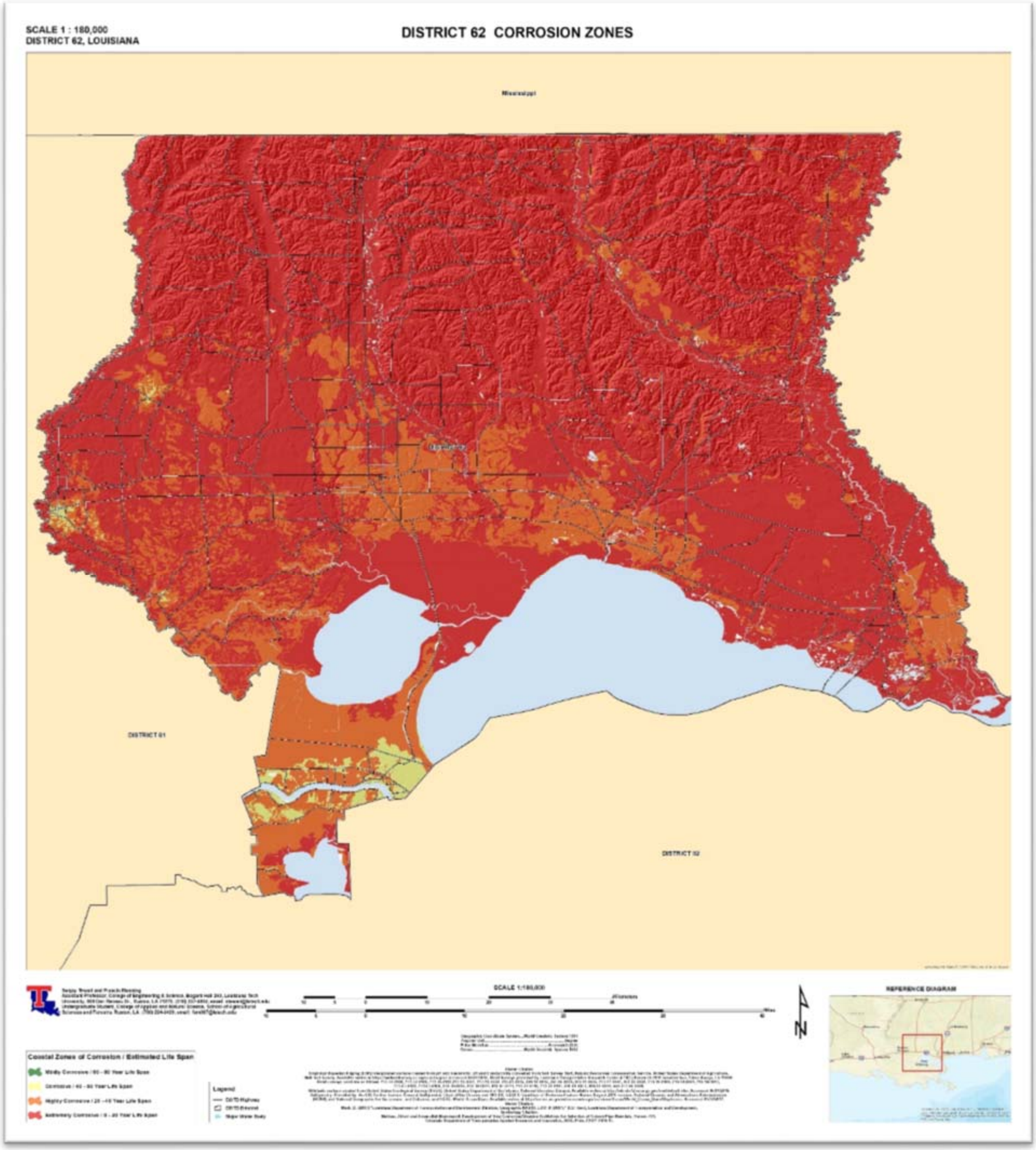
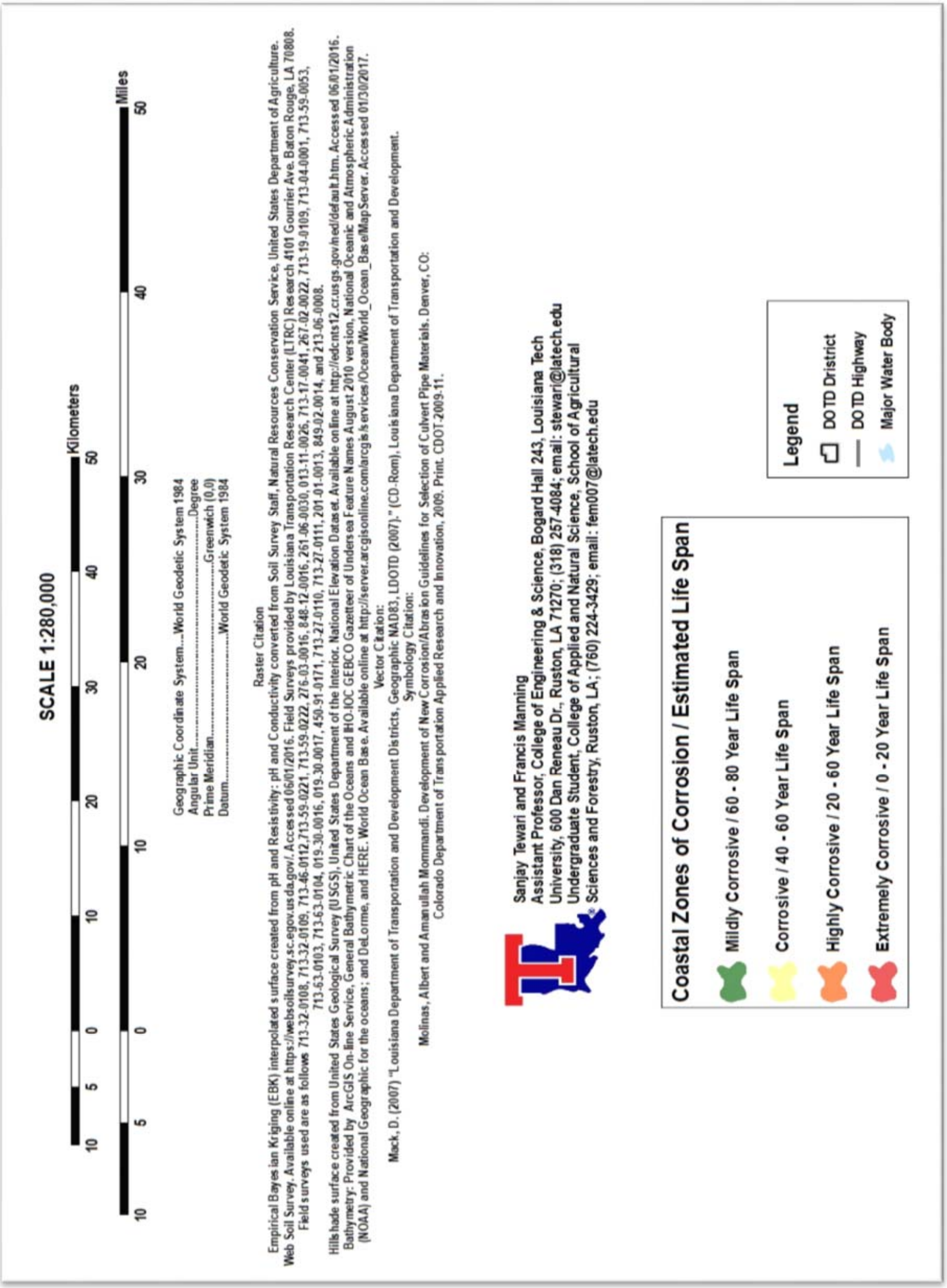


Figure 16

Corrosion map of District 62



SCALE 1:280,000

Geographic Coordinate System....World Geodetic System 1984
Angular Unit..Degree
Prime Meridian..Greenwich (0,0)
Datum.....................................World Geodetic System 1984

Raster Citation

Empirical Bayesian Kriging (EBK) interpolated surface created from pH and Resistivity: pH and Conductivity converted from Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at https://websoilsurvey.sc.egov.usda.gov/. Accessed 06/01/2016. Field Surveys provided by Louisiana Transportation Research Center (LTRC) Research 4101 Gourrier Ave. Baton Rouge, LA 70808. Field surveys used are as follows 713-32-0108, 713-32-0109, 713-46-0112,713-59-0221, 713-59-0222, 276-03-0016, 848-12-0016, 261-06-0030, 013-11-0026, 713-17-0041, 267-02-0022, 713-19-0109, 713-04-0001, 713-59-0053, 713-63-0103, 713-63-0104, 019-30-0016, 019-30-0017, 450-91-0171, 713-27-0110, 713-27-0111, 201-01-0013, 849-02-0014, and 213-06-0008.

Hillshade surface created from United States Geological Survey (USGS), United States Department of the Interior. National Elevation Dataset. Available online at http://edcnts12.cr.usgs.gov/ned/default.htm. Accessed 06/01/2016. Bathymetry: Provided by ArcGIS On-line Service, General Bathymetric Chart of the Oceans and IHO-IOC GEBCO Gazetteer of Undersea Feature Names August 2010 version, National Oceanic and Atmospheric Administration (NOAA) and National Geographic for the oceans; and DeLorme, and HERE. World Ocean Base. Available online at http://server.arcgisonline.com/arcgis/services/Ocean/World_Ocean_Base/MapServer. Accessed 01/30/2017.

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Mack, D. (2007) "Louisiana Department of Transportation and Development Districts, Geographic NAD83, LDOTD (2007)." (CD-Rom), Louisiana Department of Transportation and Development.

Symbology Citation:

Molinas, Albert and Amanullah Mommandi. Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials. Denver, CO: Colorado Department of Transportation Applied Research and Innovation, 2009. Print. CDOT-2009-11.

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Coastal Zones of Corrosion / Estimated Life Span

- 🟩 Mildly Corrosive / 60 - 80 Year Life Span
- 🟨 Corrosive / 40 - 60 Year Life Span
- 🟧 Highly Corrosive / 20 - 60 Year Life Span
- 🟥 Extremely Corrosive / 0 - 20 Year Life Span

Legend

- ☐ DOTD Dristrict
- — DOTD Highway
- Major Water Body

Figure 17

Details of fine print included in each map

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