Utility Pole Failures in Relation to Soil and Terrain

Analyzing utility pole relationships with soil hydrography and terrain using GIS and R

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Background

The United States has approximately 160 million wood utility poles in service. These poles include electric utility poles, telephone poles, and cable TV (CATV) poles, along with joint use (used by multiple entities). Wood poles are used because they are relatively inexpensive compared to underground install and have some natural insulation unlike concrete or steel poles (Shafieezadeh, et al. 2014). The National Electric Safety Code governs safety requirements for US Utilities. It requires a pole to be replaced if the strength is below 2/3 of the required install strength (3/4 if in extreme wind or extreme ice zone) (United States Department of Agriculture Rural Utilities Service 13). How long a pole lasts once installed is dependent on a variety of factors including: pole species, pole treatment, and conditions installed in. The Rural Utilities Service under the United States Department of Agriculture has issued a bulletin with a map showing the decay zones based on humidity within the United States (Figure 1).

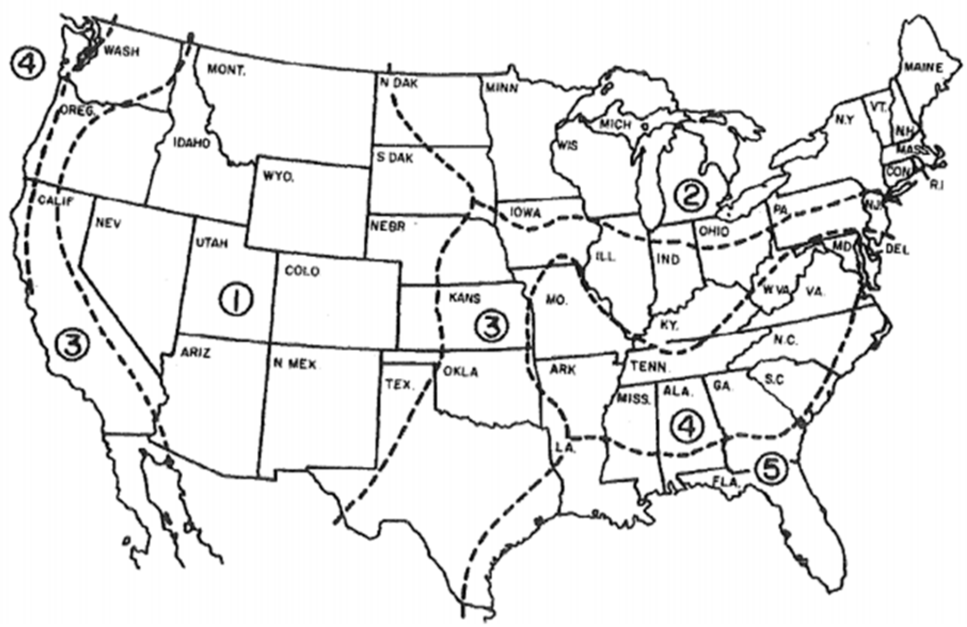

Figure 1. Decay Zones for the continental U.S. Zone 1 is least severe; Zone 5 is most severe (United States Department of Agriculture Rural Utilities Service 13)

System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are both used to show how reliable an Electric Utility is. SAIDI is usually measured in minutes and is found by taking the sum of all customer interruption duration and dividing it by the total number of customer served by the utility. SAIFI is measured in number of outages and is found by taking the number of outages and dividing it by the total number of customers. A strong distribution system, especially the utility poles, is required to keep SAIDI and SAIFI low and show the utility is reliable.

Utility pole failure is also a safety hazard for the public and for utility workers. In 2004 a pole owned by CenturyLink was rotten and broke 6 inches from ground, causing a lineman to fall and become paralyzed (Hosier 2011). This cost the company a total of $85 million. The cost was $39.5 million but the judge increased the punitive damages due to Centurylink not having a formal inspection and maintenance program for poles (Oh-Willeke 2007).

Minnesota Power (MP) is an Investor Owned Utitility (IOU) in Northern and Central Minnesota. MP has approximately 160,000 utility poles in their distribution system and conducts groundline inspections on a 10 year cycle (10%/year). Rejected poles found during the inspection are broken down into four categories: reject reinforceable (RR), reject pole (RP), priority reinforceable (PR), and priority reject (PX). The categories are assigned based on shell thickness at the groundline, 15 inches above groundline, and 48 inches above groundline. 3 borings are done at each level to determine shell thickness. The reason for the determination by drilling is because most of the poles in the system are Cedar which typically decays from the inside out. If decay is found when boring the pole, chemicals are inserted to retard the decay. Other useful data collected is the pole height, class, and year installed.

Objective

The goal of this project is to analyze utility pole failure rates in relation to soil hydrography, terrain aspect, and terrain slope using ESRI's ArcGIS, Excel, and R. High moisture content increases the probability of biological attack on a pole (Rahman and Chattopadhyay 2007). By identifying features that affect increased failure rate, inspection cycles could be adjusted to increase frequency in at risk areas or initial pole installs could be modified to provide a barrier between the pole and the environment. Planned routes for lines could also be adjusted to avoid conditions that decrease the lifetime of utility poles. The general rule at Minnesota Power is that utility poles fail faster in wet environments such as wetlands vs. conditions where water readily drains. The expected outcome from the final analysis of this study is that poorly drained soils with low slope and a northern aspect will have a lower survivability compared to other combination of factors.

Research on this topic showed that this type of analysis has not been done before. Most of the studies were conducted based on pole age or exposure to extreme conditions such as hurricanes. The studies that focused on decay of the poles took local soil samples from a sampling of utility poles and were not conducted system wide. This study aims to show that GIS is a feasible tool to conduct this type of analysis.

Study Area

The study area for the project is the Minnesota Power distribution service territory (Figure 2). It was chosen for the availability of the data and its coverage of many aspects of drainage, aspect, and slope. Minnesota Power breaks their territory down into three areas. The western area covers the lakes area in central Minnesota. This area contains recreational lake property and agriculture. The northern area covers International Falls on the Canadian border and the Iron Range in Northern Minnesota. This area contains open pit mines and wetlands. The central area covers the I-35 Corridor along with Duluth and up the Lake Superior shore. This area contains an urban area along with a wetlands and agriculture mix.

The average date of soil freeze up is between November and December every year (Seeley n.d.). The last freeze for the year is typically between the end of April and the end of May for a total of 5-6 months of frozen ground. During the frozen months not much decay can happen but the freeze/thaw causes cyclic stresses on poles (Rahman and Chattopadhyay 2007).

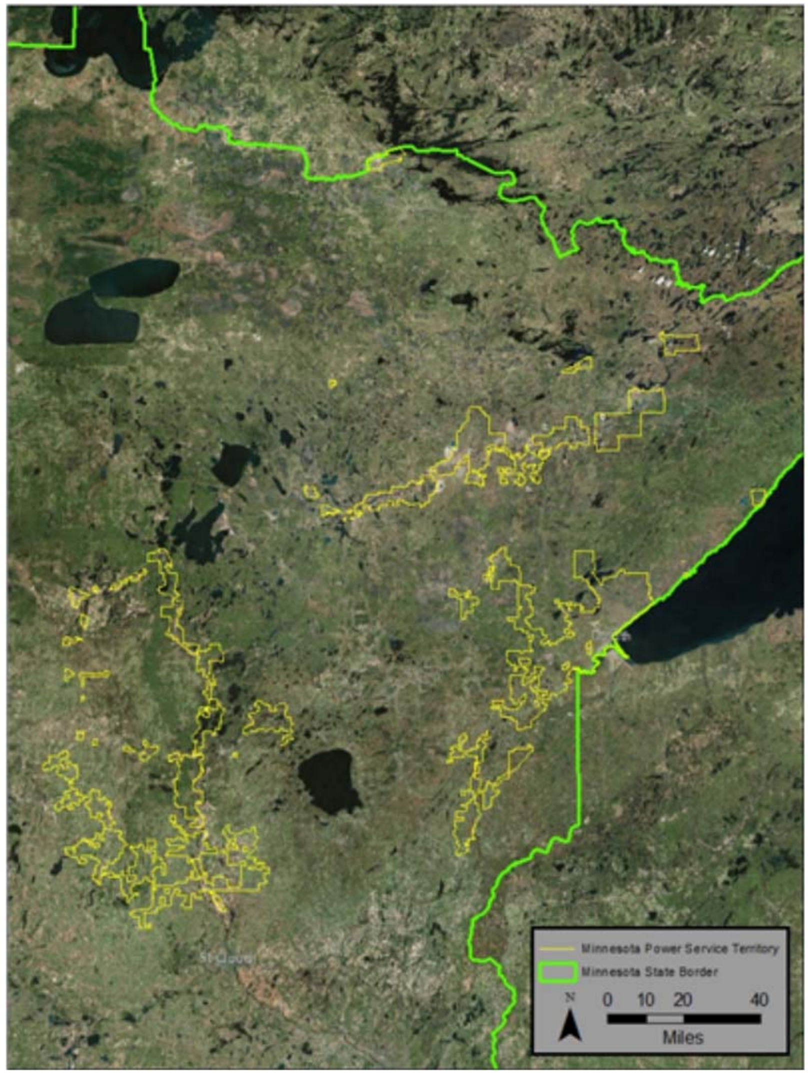

Figure 2. Minnesota Power Service Territory

Data Used

The three main data sets used for this project all came from different sources. Utility poles came from the Minnesota Groundline Inspection Records and provided points with information on whether or not a pole failed inspection. Soil drainage for the study area was pulled from the Soil Survey Geographic Database (SSURGO). Light Detection and Ranging (LiDAR) was downloaded from the State of Minnesota and used to generate the required slope and aspect of the terrain for the study. These datasets were processed separately and then spatially joined in GIS to produce one table for the final analysis.

Minnesota Power Groundline Inspection Records

The utility poles included in the study are from the MP groundline inspection records (Minnesota Power 2015). The inspections started in 2007 and contain approximately 108,000 records. The data is right censored due to the company not always waiting for failure to replace the poles. Other reasons for replacing the poles are a line upgrade or an increase in clearance requirements in the span between poles. In the first years of the groundline inspections, pole year was a free text field with no requirements (such as 4 digits). This allowed bad data in that had to be evaluated. Most of the bad data could not be reinterpreted so was left out of the evaluation dataset. The inspection records included a latitude and longitude which were used to plot their locations in ArcGIS.

The assumptions for the poles in this dataset are that they have all been treated from the factory to prevent decay. Without treatment, the expected time to pole failure would be 2-10 years, dependent on environment (United States Department of Agriculture Rural Utilities Service 13). It is assumed that none of the poles are structurally overloaded. Structural overloading can cause a pole to fail earlier due to the additional stress (Rahman and Chattopadhyay 2007). The final assumptions are that there is no mechanical damage to the poles that could allow fungus or water to infiltrate past treatment and that a pole is in its initial install location. Utility pole treatment protection does lessen with time and replanting a pole with less protection would lessen its service life (Rahman and Chattopadhyay 2007).

Soil Data

The soil data used for this study was SSURGO data (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture 2016). This dataset contains information on water capacity, soil reaction, electrical conductivity, frequency of flooding, and the soil drainage information used for this study (United States Department of Agriculture n.d.). This data scale ranges from 1:63360 to 1:12000 and is useful for landowners, townships, and counties. In a previous class, the United States General Soil Map (STATSGO) was used (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture 2016). This scale was 1:250000 and useful for State, Regional, and Multi-state studies.

The data was broken up by county and downloaded as tables and an Access template. Linking the data required opening a separate Access template for each county and referencing the folder where the county data resided. Once this was complete for each county, the Soil Data Viewer tool in ArcGIS was used to generate a soil drainage shapefile for each county from the soil dataset (Figure 3). Unfortunately, as seen in the figure, there was not 100% coverage of poles in the study. These were then merged into a study area wide soil drainage dataset.

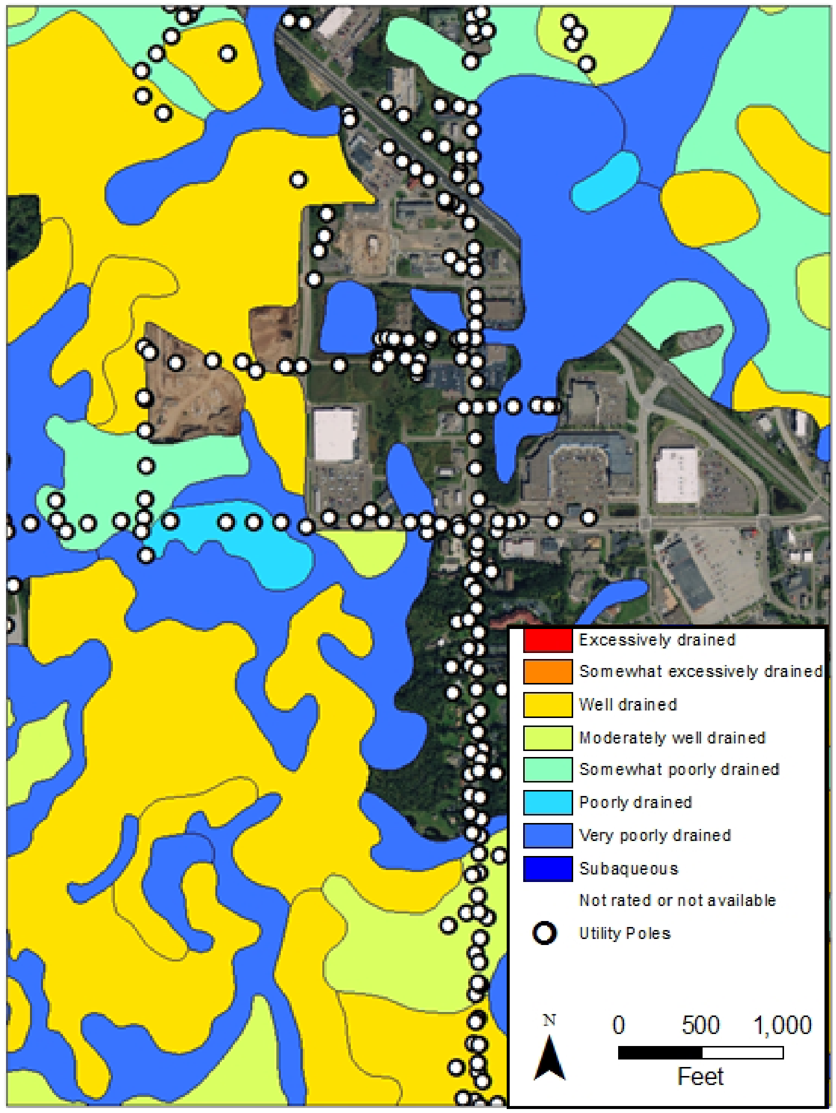

Figure 3. Soil Drainage with Utility Poles

Elevation Data

From 2010-2012 the State of Minnesota flew LiDAR over the entire state (MnGEO 2016). The standards used were a mean post spacing of 1.5 meters and 1 meter horizontal accuracy (MnGEO n.d.). From this project, digital elevation models (DEM) rasters were created for the entire state. The data is broken up by county and provided on an FTP site. Once downloaded, the DEM's were filtered out to include only areas where utility poles were located. An aspect raster and slope raster was generated from each DEM via a ArcGIS model (Figure 4).

Figure 4. ArcGIS Modelbuilder model used to generate aspect and slope raster from each DEM

Workflow

Once each dataset was cleaned up and prepared, the values for soil, slope, and aspect needed to be joined to the pole dataset. This was done differently within ArcMap dependent on the data type. A standard spatial join was done for the soil shapefile while an Extract Multi Values to Points tool was used to join the raster values to the corresponding utility pole. Once all the values were joined into one table, it was exported into excel for cleanup. Due to the way the rasters were broken down, there were approximately 400 extra fields from the Extract Multi Values to Points tool which needed to have the values combined into two fields (one for aspect and one for slope). Due to an upgrade to Windows 10 and the changing file permission, a script was not able to combine the fields and it was handled manually. The final table for the analysis consisted of 76,746 records with 2,452 identified as failures the fields listed below:

InspectAge: age of the pole when identified as failed

Slope: slope of the ground at the pole in degrees (0-90)

Aspect: aspect of the ground at the pole in degrees (1-360)

Drain_num: The SSURGO drain class represented as a number:

1 = Very poorly drained
2 = Poorly drained
3 = Somewhat poorly drained
4 = Moderately well drained
5 = Well drained
6 = Somewhat excessively drained
7 = Excessively drained

Fail: Binary field for if a pole failed inspection (1=failed)

Decade: Decade pole was installed

A preliminary table was created to compare this study with an analysis conducted in a previous class using the STATSGO soil data (Table 1). This shows that the finer scale soil data changed which drainage type contained the greatest percentage of failed poles. With soil drainage data at the state level this would not seem to be supported but with finder scale data the general rule it looks more likely with the finer scale soil data. This shows that finer resolution data will increase the reliability and accuracy of studies.

	Total Poles	Average Pole Age	Reject Poles	Average Reject Age	SSURGO Reject %	STATSGO Reject %
Excessively drained	12259	33	276	58	2.25%	2.60%
Somewhat excessively drained	11157	35	283	58	2.54%	2.67%
Well drained	17763	34	603	59	3.39%	3.56%
Moderately well drained	15022	35	525	59	3.49%	3.86%
Somewhat poorly drained	8126	34	265	58	3.26%	3.37%
Poorly drained	6357	33	264	52	4.15%	3.10%
Very poorly drained	6062	33	236	56	3.89%	3.12%
	76746		2452			

Table 1. Difference in failure percentage based on SSURGO and STATSGO data.

The next step in the workflow was to conduct a survival analysis to examine the time it takes for failure to occur. A Cox Proportional-Hazards Regression in R was chosen for multiple reasons. One of the reasons was the not having to make arbitrary and possible false assumptions about a baseline hazard on the poles. Another reason was that the poles hazard curves could not cross. In other words, a utility pole with a failure at groundline due to rot will not correct itself; it will only stay constant or get worse. The final reason was due to the R survival package having diagnostic tests for the Cox model, especially the testing of proportional hazards assumptions which help to determine if a model is correctly applied.

A cox model is written as:

$$h(t) = h_0(t)\exp(b_1X_1 + b_2X_2 + \ldots + b_PX_P)$$

where h(t) is the hazard at a certain time. The baseline hazard is represented by $h_0(t)$ and represents when all the variables are zero. For this study the baseline would be a slope of 0, an aspect of 0, and a drainage type of very poorly drained (drainage is a classification not a numerical value). Creating a hazard ratio takes observations with different variables and gives a proportional hazard of one observation to another. The downside to the model is that it does not give a maximum-likelihood estimate of failure but instead a proportional hazard (Fox and Weisberg 2011). Due to this constraint, the model output will not give a time to failure for poles but instead will give a percentage likelihood of failure between different soil types.

The important parts of the model outputs are the statistical significance, regression coefficients, hazard ratios, confidence intervals of the hazard ratios, and the global statistical significance of the model. The statistical significance is shown in the "z" column of an output. The further away from 0 the more significant. The regression coefficents are shown in the "coef" column of the output. A positive coefficient means failure risk is proportionally higher while a negative shows the risk is proportionally lower. The hazard ratio is found by taking the exponent of the coefficient and is shown in the "exp(coef)" column. A value greater than 1 shows a greater proportional hazard while a value less than 1 shows a reduction in proportional hazard compared to the baseline case. R has built in diagnostics to run on the cox model which will show if a variable or the entire model violate the proportional hazards assumption (Kassambara n.d.). For the diagnostic a value closer to zero signifies a violation while a larger number does not signify a violation of the proportional hazards assumption.

Results

	coef	exp(coef)	se(coef)	z-score	p-score
Slope	-0.00385	0.99616	0.00069	-5.58	0.0000
Aspect	0.0000991	1	0.000154	0.64	0.5200
Poorly Drained	0.0699	1.0724	0.0896	0.78	0.4360
Somewhat Poorly Drained	-0.2232	0.8	0.0895	-2.49	0.0130
Moderately Well Drained	-0.399	0.671	0.0784	-5.09	0.0000
Well drained	-0.3729	0.6887	0.0768	-4.85	0.0000
Somewhat Excessively Drained	-0.576	0.5621	0.0882	-6.53	0.0000
Excessively Drained	-0.6647	0.5144	0.0888	-7.49	0.0000

Table 2. Initial Cox Model results for each variable run individually.

The model was run multiple times with different combination of inputs. To start with the cox regression was run on each variable (slope, aspect, and drainage) (Table 2) individually to find significance (p-value, smaller values indicate higher significance). Drainage had to be factored due to it being a categorical variable. After multiple models were run with different relations, aspect was found to not be significant in this study (Table 3). All the models coefficients were showing a decrease in the hazard with the increase in drainage of the soil. The differences between models run with aspect and without aspect did not change the hazards of the other variables so it was removed from further models. Slope by itself, while significant, had a limited effect on pole failure rate. When slope was input with an interaction to soil drainage, the variables with the interaction showed significance in the model. The second to final model had aspect removed and contained

Variable(s)	Reason Rejected
Slope	violated proportional hazards assumption
Aspect	Aspect not significant
Drainage	violated proportional hazards assumption
Slope,Aspect, Drainage	violated proportional hazards assumption
Slope, Aspect, Drainage, Slope interaction with Drainage	Aspect not significant
Slope, Aspect, Drainage, Slope interaction with Drainage, Stratified	Aspect not significant
Slope, Aspect, Drainage, Slope Interaction with Drainage, Aspect Interaction with Drainage	No significance
Slope,Drainage, Slope Interaction with Drainage	violated proportional hazards assumption
Slope,Drinage, Slope interaction with drainage, Stratified	Final Model for Analysis

Table 3. Combinations of variables run in different models and the reason each combination was rejected

interaction (signified with ":" in R) between slope and drainage types (Table 4). Many of the values were showing significance and the model was showing promise but as diagnostics were completed on the model, the overall model failed a portion of the diagnostic tests. The diagnostics tests are built into R and provide a way to test the proportional hazards assumption for the variable s and the model as a whole. The model diagnostic showed a value of .0450 for the overall model value which is statistically significant meaning the proportional hazards assumption was not supported (Table 4).

The method used to accommodate the proportional hazards was to stratify the data by decade. Stratification allows for each stratum to have a different baseline hazard while the other values stay the same. The disadvantage for stratifying the model is that the stratified variable is not able to be examined (Fox and Weisberg 2011). For this reason the variable "Decade" was chosen as it was not

	Non Stratified Model				Stratified by Decade Model			
	coef	exp(coef)	z-score	p-score	coef	exp(coef)	z-score	p-score
Slope	0.0042	1.0042	1.43	0.1526	0.0020	1.0020	0.67	0.5042
Poorly Drained	0.1223	1.1305	1.11	0.2680	-0.1533	0.8579	-1.38	0.1691
Somewhat Poorly Drained	-0.2011	0.8178	-1.80	0.0726	-0.2528	0.7766	-2.25	0.0245
Moderately Poorly Drained	-0.2792	0.7564	-2.85	0.0044	-0.3213	0.7252	-3.26	0.0011
Well drained	-0.1926	0.8248	-2.01	0.0447	-0.2352	0.7904	-2.44	0.0146
Somewhat Excessively Drained	-0.4308	0.6500	-3.87	0.0001	-0.5395	0.5831	-4.82	0.0000
Excessively Drained	-0.5802	0.5598	-5.35	0.0000	-0.3372	0.7137	-3.09	0.0020
Slope:Poorly Drained	-0.0035	0.9650	-0.89	0.3761	-0.0027	0.9973	-0.67	0.5009
Slope:Somewhat Poorly Drained	-0.0019	0.9981	-0.50	0.6161	-0.0023	0.9977	-0.59	0.5572
Slope:Moderately Poorly Drained	-0.0068	0.9932	-2.01	0.0444	-0.0062	0.9938	-1.81	0.0696
Slope:Well drained	-0.0098	0.9903	-2.90	0.0038	-0.0082	0.9918	-2.41	0.0159
Slope:Somewhat Excessively Drained	-0.0078	0.9923	-2.10	0.0358	-0.0075	0.9925	-2.02	0.0432
Slope:Excessively Drained	-0.0054	0.9946	-2.61	0.1541	-0.0100	0.9900	-2.61	0.0090
Proportional Hazards Assumed				0.045				0.0981

Table 4. Model results for non-stratified and stratified by decade models along with the p value for the proportional hazards assumption (higher value shows can safely assume proportional hazards in model)

part of the study. With the stratification, there were some changes to the coefficient values. The most dramatic change was for somewhat poorly drained which changed from positive (more hazardous than the baseline) to negative (signifies a protective effect). A comparison of the two models p-scores shows that more variables became significant (lower score) and stratified model is most applicable to classifications Somewhat Poorly Drained through Excessively Drained (Table 4).

The coefficients from the final stratified model were copied into a table to create a proportional Hazard Matrix for the study (Table 5). This table can be read by column to show the proportional hazard of one type of soil to another. For example, based on the "Well Drained" column, utility poles in poorly drained soil would have a 9.1% greater chance of failing an inspection than a pole in well-drained soil and excessively drained poles have a 9.9% greater chance of passing inspection.

	Very Poorly Drained	Poorly Drained	Somewhat Poorly Drained	Moderately Well Drained	Well Drained	Somewhat Excessively Drained	Excessively Drained
Very Poorly Drained	0.0%	-16.9%	-29.1%	-38.8%	-27.6%	-72.8%	-41.5%
Poorly Drained	14.4%	0.0%	-10.4%	-18.7%	-9.1%	-47.9%	-21.1%
Somewhat Poorly Drained	22.5%	9.4%	0.0%	-7.5%	1.2%	-33.9%	-9.7%
Moderately Well Drained	27.9%	15.8%	7.0%	0.0%	8.1%	-24.5%	-2.0%
Well Drained	21.6%	8.4%	-1.2%	-8.8%	0.0%	-35.5%	-10.9%
Somewhat Excessively Drained	42.1%	32.4%	25.3%	19.7%	26.2%	0.0%	18.1%
Excessively Drained	29.3%	17.4%	8.8%	2.0%	9.9%	-22.1%	0.0%

Table 5. Proportional Hazard Matrix for utility poles based on soil drainage and slope.

Conclusion

This study did correlate with the industry standard thought that poles in wetlands are more likely to fail than other poles. According to the proportional hazard matrix (table 5), utility poles in very poorly drained areas are 41.5% more likely to fail an inspection vs. an excessively drained pole. It was surprising that aspect had no significance and slope had limited significance in the models. These two variables were the most labor intensive portion of the study with the large amounts of data having to be managed and the number of files that had to be merged to get the required values in one table. With the p-scores from each variable it was interesting to see that the significance did not hold through all classes of the soil (Table 4). The model was more significant as the drainage type increased which means the right side of the proportional hazards table holds more significance than the left side.

The results of this study show that utility poles in poorly drained soils need to be inspected more often or more thoroughly to account for the increased likelihood of failure. It also means that soil drainage should be taken into consideration in distribution line design to increase the longevity of a lines service life. Designing to avoid wetlands can save money on pole failures and on install due to the difficulty of setting and anchoring a pole in wet soils. Another option to counteract the effect of the soil drainage would be to apply a barrier around the pole to isolate it from the soil.

Conducting a study at this scale without GIS would have been near impossible. Inspecting each pole and measuring the terrain and soil drainage would have been extremely expensive and time consuming. This study shows that GIS is an ideal way to conduct these types of studies and can produce valuable results as long as fine enough resolution data is used.

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