STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

DRISI-2011 (REV 10/1998)

1. REPORT NUMBER CA19-2895	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE California Corrugated Steel Pipe (CSP) Culvert Service Life		5. REPORT DATE 07/17/2019
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR Dr. David Boyajian, Dr. Sarni Maalouf, Dr. Tadeh Zirakian, and CSUN Student Researchers		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS California State University, Northridge 18111 Nordhoff Street Northridge, California 91330-8232		10. WORK UNIT NUMBER
		11. CONTRACT OR GRANT NUMBER 65A0602
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research, Innovation, and System Information 1727 30th Street, MS-83, Sacramento, CA 95816		13. TYPE OF REPORT AND PERIOD COVERED Final Report
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The main objective of this research is to verify and improve upon a 2014 pilot study by Caltrans to verify the accuracy of service life predictions for Corrugated Steel Pipes (CSPs) based on 1960's research conducted by Dick Stratfull, Corrosion Engineer, California Division of Highways Materials and Research Department, Sacramento (see "Background/Business Case"). In 2014, Caltrans conducted a pilot study using a small (i.e. <50) sub-set of culverts. Because of the relatively small number of culverts studied in 2014, in order to generate reliable results, a significantly more robust research effort is required to verify the accuracy of the original research conducted by Stratfull used as the basis of Caltrans Service Life predictions today. Inaccurate predictions of the service life of CSPs has both economical as well as functional consequences.

The outcome of this research shows that pH and resistivity are directly correlated to the corrosion rate of the culvert. Empirical models were found to better correlate the service life of a culvert based on the type of land that it was being used in. If failure is to be defined at 25%, CSUN equation models behaves similar the Caltrans equation for the pile service life.

17. KEYWORDS Corrugated Steel Pipes, Culverts life	18. DISTRIBUTION STATEMENT No Restrictions	
19. SECURITY CLASSIFICATION (*of this report*) Unclassified	20. NUMBER OF PAGES 99	21. COST OF REPORT CHARGED

DISCLAIMER STATEMENT

California Corrugated Steel Pipe (CSP) Culvert Service Life

Final Report Submitted to
California Department of Transportation

Principal Investigators:

Dr. David Boyajian
Dr. Sami Maalouf
Dr. Tadeh Zirakian

Student Researchers:

George Aquino
Ryan Bratcher
David Pucio
Armando Rubalcava
Hani Salhab
Jorge Sanchez
Francisco Silva

California State University, Northridge

July 17, 2019

ACKNOWLEDGMENTS

A special word of thanks is due to our sponsor, the California Department of Transportation (Caltrans) and to the engineering oversight offered to the California State University Northridge (CSUN) research team by: Mr. Akber Ali, Mr. Gurdeep Bhattal, and Mr. Balwinder Tarlok, Mr. Stan Chow, Mr. Sukhdeep Sandher, Mr. Sukhdeep Nagra, all of whom made this project possible. We would also like to here acknowledge the original vision of Mr. Paul Davies (now retired from Caltrans), without whom, this project would never have seen the light of day. A special thanks is also due to the principal investigators (PIs): Dr. Sami Maalouf, Dr. David Boyajian, and Dr. Tadeh Zirakian who acquired this project and enabled students with the golden opportunity to both conduct cutting-edge research and to work alongside Caltrans engineers. Acknowledgements are also here due to all the previous students who helped make this three-year research effort a success: John Copello, Andre Ketchedjian, Jessica Opinion, Brandon Silva, Amirhosin Ebrahimi, Veronica Rico, Christian Daniel, and Armen Tufenkjian.

TABLE OF CONTENTS

Acronym	Meaning
AISI	American Iron and Steel Institute
ANSI	American National Standards Institute
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
CDOT	Colorado Department of Transportation
CMP	Corrugated Metal Pipe
CSP	Corrugated Steel Pipe
CSUN	California State University, Northridge
CTM	California Test Method
DMS	Degree-Minute-Second
DOT	Department of Transportation
GIS	Geographic Information System
GPS	Global Positioning System
MPY	Milli-inches per Year
ODOT	Ohio Department of Transportation
pH	potential Hydrogen
PI	Principal Investigator
SHA	State Highway Agency
TDS	Total Dissolved Solids
USDOT	United States Department of Transportation

This page is left blank intentionally

Chapter 1: Introduction

1.1 General

The goal of this project was for the California State University Northridge (CSUN) research team and its respective principal investigators (PIs) to update the current California Department of Transportation (a.k.a. Caltrans) culvert service life estimation formula by studying electrochemical properties. Culverts are pipe structures that are placed underneath roadways as a means of conveying water collected from the road surface and irrigation flows. Different abbreviations are at times used to refer to such structures, e.g. corrugated steel pipes (CSPs) or corrugated metal pipes (CMPs).

The original parametric equations used by Caltrans were based on data collected from a single Caltrans district and was used for the entire state. By increasing the scope of collected data to over 500 site visits throughout the State of California, the accuracy of the parametric formulas is believed to have been increased particularly from a land usage standpoint. The five major categories of land use considered in this study were: agricultural, rangeland, forestland, urban, and coastal.

The current Caltrans parametric equations for estimating culvert service life depends on a pair of parameters, namely that of soil resistivity and pH. These formulas are separated at a demarcation soil pH value of 7.3, with a bilateral error of around ±25 years. Resistivity is affected by factors such as salt content, moisture, and particle size. By directly measuring the conditions that cause low resistivity and comparing them to the corrosion, the direct causes of corrosion can be evaluated to gain more accurate results. More detailed information is furnished in Chapter 2 (Field Strategy and Data Collection) regarding the testing procedures utilized in collecting the pertinent data from which the CSUN parametric equations were ultimately deduced.

1.2 Literature Review

The CSUN research team convened on a weekly basis to discuss their readings of journals, articles, and other published papers in addition to updating the PIs of their field outing progress achieved from the preceding week. These weekly team exercises were important in deepening a greater understanding into the science of culvert deterioration and ensuring that the student research team was achieving the overarching goals of this project.

Multiple methods for estimating culvert life currently exist in addition to the existing California method which considers pH and resistivity. The State Department of Transportation agencies in Florida, Colorado, and New York, have proposed formulas for estimating the service life of culverts which, for instance, rely on soil parameters such as pH, sulphate, and chloride levels. In addition to these soil-based classifications, different inspection-based culvert conditions are used by different states. The Tennessee Department of Transportation used a 10-point scale, whereas Caltrans uses a four-point scale (Meegoda and Juliano, 2009). In addition to such inspection based approaches, the guidelines of the published California Test Method (CTM) 643 report was used and heavily referenced by researchers conducting studies on culverts. This CTM report attributes the corrosion of the pipe to the resistivity of the soil. Differences in oxygen content between the more aerated topsoil and the less oxygen rich bottom soil can generate an oxygen concentration causing the metal from the bottom of the pipe, oftentimes referred to as the invert, to transfer to the higher levels of oxygen concentration at the top of the culvert by using the soil around the culvert as a sort of electrolytic cell causing an accelerated incidence of corrosion of the steel pipe through the process of electrolysis. The effectiveness of this solution in causing corrosion depends on its conductivity. It had previously been noted that the resistivity of the surrounding soil can affect the corrosion of the pipe when the soil acts as a conductor (Gabriel, 1998). The behavior of corrosion on CSPs is also appreciably affected by the pH levels of the soil.

Marr (2015) references the resistivity versus pH plot that Caltrans had originally published in the above mentioned CTM report (see also Fig. 6.2 herein) and based most of their results on this graph and its equations. The author noted, “In order to generate the most accurate service-life maps possible, it is important to validate the field measured and observed data as being reasonable for inclusion as inputs into the service-life calculation” (Marr, 2015). The CSUN researchers of this present study used the 500+ data points collected from culverts in the field to form maps, using ArcGIS, that show the pH, resistivity and other such parameters according to location and the aim of this research is to make similar maps in deducing the service life equations proposed (see Chapters 6 and 7).

J.L. Beaton and R.F. Stratfull (1962) investigated soil resistivity and soil pH in relation to rainfall and the service life of corrugated metal culverts. They observed that in high rainfall areas, there were high soil resistivity values and the soil pH was less than 7. In low rainfall areas, there were low soil resistivity values and the soil pH was greater than 7. They also noted that a higher pH correlates to a decrease in the corrosion rate of steel. They concluded that the gain in service life of galvanized pipes in California could be as high as twenty years in areas of very low rainfall, such as deserts, and in general up to six years. However, they also caution that a highly abrasive flow could remove the protective coating in one period, this would significantly decrease the service life of the culvert. It was also observed that an oxide film, rust, reduces the corrosion rate of steel.

Studies show mixed data on the effect of pH on the corrosion of steel in soil with some studies showing pH influencing the corrosion rate and some show that the corrosion is independent of pH, instead depending on oxygen diffusion into the metal. In addition to pH, resistivity can be used to estimate corrosivity. Resistivity of the soil at the site has been shown to be unreliable due to the fluctuations in soil moisture over time. However, the minimum resistivity can be used to aid in finding the possible corrosion severity. The following table shows the corrosivity based on resistivity (Galtung-Døsvig, 1995). Later studies have also shown the significance of land use on the range of pH values found on site.

Table 1.1 Relationship between resistivity and corrosivity of the soil (Galtung-Døsvig, 1995)

Aggressiveness	**Resistivity [Ohm-cm]**
Very corrosive	*<700*
Corrosive	*700-2000*
Moderately corrosive	*2000-5000*
Mildly corrosive	*5000-10000*
Non-corrosive	*10000*

Throughout California, various regions differ from one another in terms of properties found in the surrounding atmosphere, water, and soil. A framework is needed to organize and classify these regions corresponding to land use. In this research effort, land use factored heavily when considering the findings from the field. **Tables 1.1** and **1.2** offer land usage guidelines as based upon the literature.

Table 1.2 Land use and land cover (Anderson et al., 1976)

Level I	Level II
1 Urban or Built-up Land	11 Residential. 12 Commercial and Services. 13 Industrial. 14 Transportation, Communications, and Utilities. 15 Industrial and Commercial Complexes. 16 Mixed Urban or Built-up Land. 17 Other Urban or Built-up Land.
2 Agricultural Land	21 Cropland and Pasture. 22 Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas. 23 Confined Feeding Operations. 24 Other Agricultural Land.
3 Rangeland	31 Herbaceous Rangeland. 32 Shrub and Brush Rangeland. 33 Mixed Rangeland.
4 Forestland	41 Deciduous Forest Land. 42 Evergreen Forest Land. 43 Mixed Forest Land.
5 Water	51 Streams and Canals. 52 Lakes. 53 Reservoirs. 54 Bays and Estuaries.
6 Wetland	61 Forested Wetland. 62 Nonforested Wetland.
7 Barren Land	71 Dry Salt Flats. 72 Beaches. 73 Sandy Areas other than Beaches. 74 Bare Exposed Rock. 75 Strip Mines, Quarries, and Gravel Pits. 76 Transitional Areas. 77 Mixed Barren Lands.
Tundra	81 Shrub and Brush Tundra. 82 Herbaceous Tundra. 83 Bare Ground Tundra. 84 Wet Tundra. 85 Mixed Tundra.
Perennial Snow or Ice	91 Perennial Snowfields. 92 Glaciers.

From the foregoing table, a “Level I” land use designation represents differing terrain considered in this study as based on satellite imagery subdivided into nine categories: Urban or Built-up land, Agricultural land, Rangeland, Forestland, Water, Wetland, Barren Land, Tundra, and Perennial Snow or Ice. Level II includes a zoomed-in resolution imagery of the subgroups from Level I. The difference between level I and II is how broad or specific an image is captured. For example, the Agricultural Land category includes crop- and pasture-lands, orchards, groves, vineyards, nurseries, ornamental horticultural areas, confined feeding operations, and other such lands. These various land categories contain specific soil characteristics.

Agricultural runoff contains high amounts of urea due to its use in more than 50 percent of nitrogenous fertilizers. In addition, urea is used in animal feeds which can cause polluted runoff from grain storage silos. (Gilbert et al., 2006)

The amount of urea in soil affects the amount of sulphate reducing bacteria in the soil. In soil where higher urea concentrations are present, such as livestock bearing agricultural land, higher levels of sulphate reducing bacteria are found. These higher urea soils cause increased Corrugated steel pipe corrosion due to the higher levels of sulphate reducing bacteria. (Cheng et al., 2012).

Much of the data collected from each culvert site is similar to what is presented in the work of Marr (2015). Methods for data collection consist of taking site locations and waypoints number using the Garmin handheld GPS, land observations, and various other data points are still implemented in the current field testing.

ArcGIS software was used to map the different parameters across the state of Minnesota to show trends between the districts and the land uses. **Fig. 1.1** shows how to map certain parameters using ArcGIS, various points are plotted and distinguished by different colors. **Fig. 1.2** shows a more advanced map using the same parameter but adding a gradient to show the average value of that area. As more culverts are inspected, the trends highlighted in this report become more visible. This is also done to help see more of a visible correlation between parameters that are affecting corrosion and see how each land use differs.

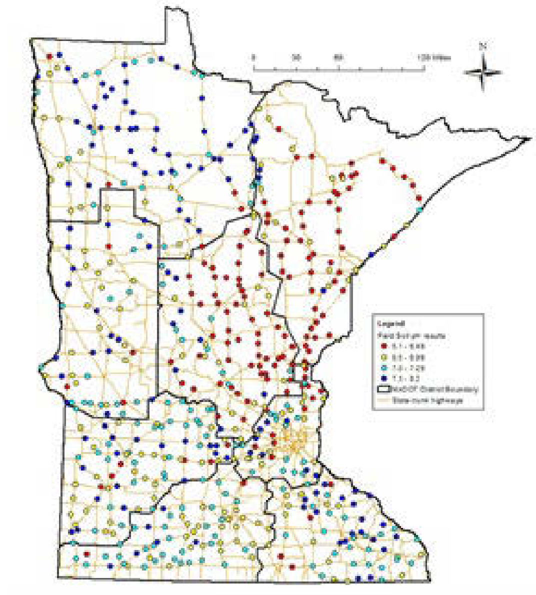


Fig. 1.1 pH Map from Minnesota report (Marr, 2015)

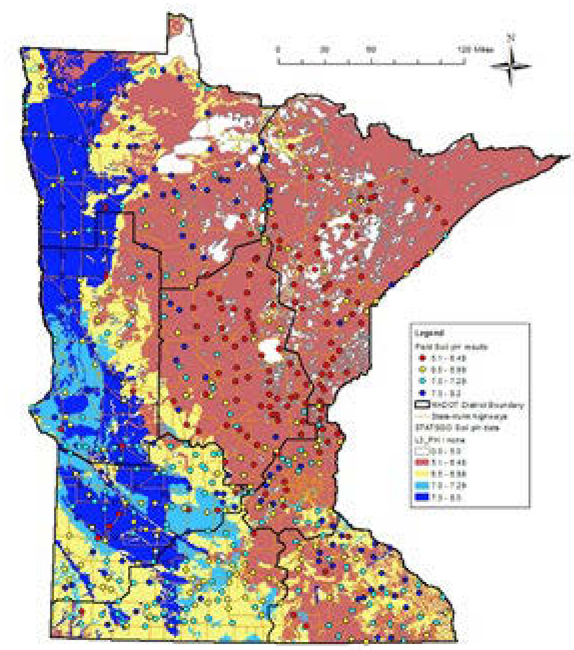


Fig. 1.2 pH Map with gradient from Minnesota report (Marr, 2015)

The work of Beben is another paper that contributes to why the team is taking the parameters pH and resistivity. Beben's research proved that those measures do significantly affect the corrosion rate of CSP culverts. His method was to take resistivity out in the field using the Wenner array method since it allowed for resistivity measurements at various depths. "Steel structures in soil (e.g., culverts, bridges, pipelines) are subject to the corrosive soil activity caused by the following factors (Cunat 2001; Hepfner 2001): (1) high moisture content; (2) pH value lower than 4.5 or higher than 8.0; (3) resistivity lower than 30 Ohm-cm; (4) presence of sulphides, chlorides, and bacteria…" (Beben, 2015). Beben's study only used 6 CSP culverts, whereas the Caltrans team is using roughly 500, and he concluded in his study that when he adhered to some of the regular testing standards, his culverts did meet the minimum service life of 40 years. Though there were some differences in his methods, the concept of using pH and resistivity was crucial. Service life can be determined with mathematical models from resistivity, pH, and thickness loss data.

Tewari used ArcGIS to illustrate corrosion zones in the state of Louisiana. He applied pH and conductivity data along with corrosion rate models from the Colorado Department of Transportation (CDOT) to create the corrosion zone map. It was observed that the corrosion rate of metal pipes decreases as one gets closer inland. He also provided a table showing which corrosion zone an area belongs to by combining values of pH and resistivity. For example, areas with pH values of 3-7.3 and resistivity values of 10-1400 Ohm-cm is associated with extremely corrosive zone and thus a culvert would have a service life of 20 years or less (Tewari, 2017).

From corrosion engineering perspective, the lower the resistivity, the higher the corrosivity and vice versa. Results show that a negative correlation represents the relationship between soil resistivity and corrosion rate. Negative logarithmic model gives the best correlation among corrosion rate and soil resistivity. It also reveals that the relationship is time dependent whereby the longer the steel coupon being exposed to underground environment, the better the correlation. Data and analysis with the understanding the fundamentals of CSP design is important to formulation a successful service life equation.

There was also a final paper from Colorado Department of Transportation who were doing a similar study like the Caltrans team. The CDOT guidelines did aid the team in determining their guidelines, which involves pH, resistivity, along with the rest of the parameters. The CDOT paper consisted mostly of analysis of all sorts of literature, much like the literature review section in the Caltrans final paper. Thus, it only proved that the more literature review is done on a topic like corrosion and CSP culverts, a more precise equation for estimating service life can be yielded by taking into consideration all the proper parameters that many authors have agreed on.
The team also investigated a paper by the USDOT that helped in understanding the hydraulics component of the project since it revolves around culverts with running water. Fundamental hydraulic concepts are covered like inlet/outlet, different types of flows, momentum, etc. Like all final papers, this one included many different sources that reinforce how a CSP can be designed depending on the environment it is placed in. Since this paper is designed for California, the team must use guidelines from the USDOT final paper that can be applied to California or adjust as needed.

The work of Sheldon (2013) showed what would happen to two corrugated steel pipes under the stress of surface live loads. This was useful for the team's design analysis portion of the project. Test culverts consisted of two corrugated metal culverts, two reinforced concrete culverts, and one high-density polyethylene culvert. Culverts were selected for backfill depths less than 1.5 m and inner diameters ranging from 0.9 to 2.1 m. Static loading was applied to the culverts by parking a heavily loaded truck at different positions above the culvert joint. Dynamic loading was applied by driving the truck over the culvert at speeds ranging from 8 to 48 km/h. Culvert deflections and strains were measured near one of the culvert's joints. Separation at the joint was also measured. The work in this paper yielded various results for which the team only used a couple of Sheldon's findings to compare with their findings.

Chaalal (2000) investigated the different behaviors of rigid CSPs, as in this present study, and the performance evaluation of flexible pipes. A flexible metal pipe was found to experience corrosion based on the soil content and flow of fluid within the pipe. Bearing in mind the similarities between flexible and rigid CSPs allowed the researchers to determine a general idea of a service life expectancy and suggesting acceptable criteria for such structures.

There was a paper that was useful in determining corrosion near *Rangeland*, land use that has the most cattle and livestock nearby, since they affect CSP culverts in a unique way. "Galvanized steel may deteriorate in contact with silage juices and slurries but is resistant to silage vapors. The order of preference for metals of construction for storage vessels is: aluminum (best), galvanized steel, mild steel." (Eker & Yuksel, 2005) "Slurry is a mixture of dung and urine, and farmyard manure is slurry composted with litter, i.e. straw or wood shavings, etc. Both ferment to release moisture, ammonia and carbon dioxide. The corrosive constituents in slurry and farmyard manure are urea, uric acid, ammonia and ammonium salts, and naturally excreted chloride , and the mixture is corrosive towards steel structures and machinery that are poorly protected and maintained." (Eker and Yuksel, 2005)

Table 1.3 Steel corrosion rates in various manures in laboratory tests at ambient temperature

Manure	Equivalent metal thickness loss after 1 year (μm)	
	Mild steel	Galvanized steel
Poultry Pig Cattle	167 130 199	160 75 95
'Controls' in clean, potable water	60	20

"According to these tests, galvanized steel has little benefit for some manures, notably that derived from poultry and cattle." (Eker and Yuksel, 2005)

Corrosion associated with wastes in contact with steel and concrete is given in **Table 1.4**.

Table 1.4 Corrosive reactions of waste

Wastes	Chemicals	Reactions with steel and concrete
Silage effluent*	Lactic Acid Acetic Acid Butyric Acid	Such acids in sufficient concentration will react with lime in cement; concrete subject to such acids should designed to a medium workability mix.
Milk wastes	Lactic acid	Any steel surfaces need suitable protection
Slurry*	Varies from neutral to slightly acidic	Special precautions are not normally needed.

*Notes: If silage effluent and slurry are mixed together, dangerous concentrations of hydrogen sulphide gas can be formed.

Temple et al. investigated the durability of metal drainage pipes in Louisiana. The research team tested ten types of culverts for six years and found that asbestos-bonded asphalt-coated, galvanized steel performed the best due to its ability to resist corrosion in low electrical resistivity environments. They also noted that in sites where both the soil and effluent had resistivity values less than 1000 Ohm-cm, "the galvanized steel pipe was completely rusted at these four sites with perforation of the metal at" three of the four sites. From the results of all ten culverts, they concluded that the primary factor affecting corrosion rate is the electrical resistivity of the surroundings (Temple et al., 1981).

The team began to investigate bacterial degradation on the culverts. Naphtha is an oil-based coating that is applied on culverts to help resist abrasion. According to this literature, naphtha increases degradation of pipe because the hydrocarbon acts as an excellent food source for a wide variety of microorganisms. The increase microbial activity leads to higher levels of turbidity and corrosion of the pipe. This is crucial to the longevity of a CSP (Rajasekar, 2004).

The effect that different types of coatings on the corrosion rate of metal culverts were studied. They analyzed more than 200 culverts and to provide an estimated service life. Sections of the culvert that were bare and exposed to the soil were corroded. They concluded that a major influence on service life was pH (Jacobs, 1982).

The next article is about how a researcher characterizes the status of a steel tank. They use non-invasive techniques to capture the effects of hazardous water on the tank wall. Hazardous water is term used for waste that is ignitable, corrosive, reactive, or toxic. When dealing with CSP, a corrosive environment was observed. The objective was to prevent seepage on the tank due to groundwater. Leaking tanks usually contained petroleum which polluted the water content (USACERL, 1998).

The team read another article that takes place in Ohio, they are trying to figure out certain soils' corrosiveness. The most corrosive areas had denser and acidic soil, they were developed by glacial material. Corrosiveness is caused by acidity, texture, and drainage. The soil that was extracted was tested for potassium chloride solution (Denison, 1931). Potassium chloride was tested to see whether at higher temperatures it would be factor to corrosion. Some culverts in Kern county, experienced high temperature level they showed smaller levels of corrosion.

In New York, a study was done using 111 uncoated galvanized steel culverts by striking the pipe with a pick and estimating the amount of metal loss. This was done to derive a durability design for New York. A sample size of 30 culverts were used because it was considered the breakpoint between large and small samples. Initial studies of aluminum culverts indicated that if any metal loss was occurring, the metal loss would be occurring evenly throughout the same geographical area as galvanized steel. Although, the metal loss on the galvanized steel did not appear critical. Other observations were seen such that if two culverts were placed side by side in a stream channel, one always appeared to carry most of the water. Another pertinent observation was that metal loss rates were generally higher in the southern portion of the state, this can be due to the amount of rain had in that year alone and structural plate culverts tend to have a lower metal loss rates than prefabricated pipes, although the differences are not high it is something to consider. Such observations are pertinent in considering how culverts should be placed and made to avoid higher corrosion rates (Betlair and Ewin, 1984).

Much of metal pipe failures are attributed to corrosion, aggressive chemicals can be found on the surface. Damages associated to water flow can be critical in culverts with continuous flows or standing water with intermittent flows. Aggressive chemicals can be in the soil originally, it can introduce contaminants in the backfill. The main corrosion factor still comes from the water, water can contain dissolved sulfur and iron sulfide that may form sulfurous and sulfuric acid. Minor corrosion and abrasion can cause superficial rust and minor pitting can be rehabilitated with non-structural method (Matthew et al., 2012).

In 1987, the Missouri DOT investigated the deterioration of corrugated steel pipes with various coatings. These pipes were investigated in two different environments, one with acidic runoff and the other an abrasive runoff. Although both runoffs led to durability problems for the coatings, the corrosion rate in abrasive runoff was much more notable (Missouri DOT, 1987). This phenomena can be noticed in culvert site with a high slope from inlet to outlet.

The corrosion of galvanized steel pipe from different climates in South America were studied. They focused on the soil and water chemistry of the environment in which the pipes existed. They found that in dry regions, values of soil resistivity and pH are sufficient for durability estimates. In wet regions, the content of the water led to some pipes corroding in 20 years. Graphs of the CTM 643 were elaborated on with the data they collected (Bednar, 1989).

Soil samples across Toronto were collected and tested for different corrosive factors such as pH and soil resistivity. They observed that the biggest correlation to external corrosion of the water was soil resistivity. A low resistivity correlates to a high corrosion rate. Tables and figures were provided to demonstrate the correlation between resistivity and corrosion rates as well (Doyle, 2000).

In Ohio, the Department of Transportation published a research report to provide a service life verification model to better predict the service life of concrete culverts. When evaluating the service life equations they were seen to be very conservative "Because it was apparent from these observations that the linear model significantly underpredicted defined service lives for the culverts…" (Hurd, 1984), they were also seen to have a crude rating system so a study was performed to update that rating system to see if that would affect the precision of the service life equations. Once completed, the research team put their efforts in creating a more linear model to derive better service life equation. Once this was done the team found that the service life predictions that ODOT had seen were reasonable, but it became more conservative as the pH increased.

The galvanizing present on the invert culvert plates contributes significantly to corrosion protection. "Zinc tends to form protective scales more readily than steel does, and scaling stifles reactivity and gives long coating life and consequent long barrier protection for the steel substrate" (Bednar, 1990) Zinc anodes find use in cathodic protection of structures in sea water because steel coupled to zinc in an electrolyte is rendered negatively charged (relative to bare steel) and the corrosion is concentrated on the zinc. It is seen that within the range of about pH 4 to 10, the corrosion rate is independent of pH, and depends only on how rapidly oxygen diffuses to the metal surface, and they concluded that there was no correlation between corrosion rate and conductivity, but this seems unrealistic as the Caltrans equations mainly concern themselves with resistivity, but it was something to consider while going forward with this research.

A study was done on 13 different controlled low strength materials, in this study it is stated that "Most SHAs accept resistivity and pH of the fill material as the main factors affecting corrosion of galvanized steel culverts." (Halmen et al., 2008). They continue to say that many State Highway Agencies (SHA) follow the California Test Method 643 to find their service life and after doing their own research and find that California Test Method 643 underestimates the service life. They mentioned in a study they researched that the first perforation occurs at 13% but AISI (American Iron and Steel Institute) defines the end of the useful service life when it reaches 25% metal loss.

Like most journal articles found they recommend a zinc coating to the pipes to slow down corrosion rate, it also mentions that they took chloride content into consideration and because the California Test Method 643 uses only pH as a guideline it provides some inaccuracy.
Damian Beben (2014) made a study on backfill corrosivity around corrugated steel plate culverts in this he used many of the same parameters as the team did, pH, resistivity, and many others that are found in California Test Method 643, and found that there is a great threat of soil corrosion when the minimum resistivity value reaches 30 Ohm-m (3000 Ohm-cm), and the minimum value decreased during the spring by 5-22%, much like pH but at a lower percentage. A correlation between backfill resistivity and moisture content was also made it stated that during the spring time it when the moisture content of the backfill rises, resistivity also rises.

Katona's paper on the "Influence of Soil Models on Structural Performance of Buried Culverts" shows that soil stiffness plays a dominant role in influencing the structural behavior of buried culverts in loading environments; however, the relative effect of the soil-model formulation has not been investigated systematically. The team recommends that Caltrans should recheck the simulations ran to inspect their culverts. Looking into newer or updated soil models might help in reaching the optimal service life of a CSP where there are constant live loads wearing them down.(Katona, 2017)

When looking into doing linear regression during the data analysis portions of the research, the works of Hadipriono and his colleagues (1988) were reviewed to find a basis on how to update Caltrans equations. In their literature review concrete pipes were reviewed, but those same techniques are considered when doing linear regression on the data collected. Similar rating techniques were employed in their research and approximately 520 culverts were inspected, very similar to the research being done. Many of the variables considered, were abrasive variables which is out of the scope of the project given, but similar to the Caltrans equations if the pH values were less than 7, a different value in the stepwise regression was used to calculate the service life. This stepwise regression is a technique that is being considered when trying to update and verify the Caltrans equations.

1.3 Corrosion Failure Point

Determining at which point a culvert has failed and can no longer reliably support the loads of traffic was another focus of the literature review. A study at the Wroclaw University of Science and Technology in Poland showed that while corrosion of the bottom of the pipe increases the strain at the top of the pipe, it does not weaken it enough to cause failure even when 48% of the bottom of the culvert had corroded. However, during backfilling, this stress is greatly increased (Kuneki & Janusz 2018).

1.4 Corrosion Guidelines

In the Caltrans Corrosion guidelines, the purpose of using two different sized resistivity boxes was to compare the resistivity values. Resistivity boxes are used to run an electrical charge through soil, it measures the resistivity of soil in Ohm-cm. The way that this was achieved was by using a 1:1 ratio while mixing the soil with water. Once the mixture was created, connect the AEMC-6470B. AEMC-6470B is multi-function digital ground resistance tester from the AEMC Instruments corporation. The data that is achieved from this technique of getting resistivity allows for a means use ion chromatography testing. Samples that have resistivity under 1000 Ohm-cm are subjected to further testing of chlorides and sulphate, as these compounds cause increased pipe corrosion while also increasing soil resistivity (Videla, 1990).

The corrosion guidelines were an essential source of information to first begin the process of research that show the effects of corrosion on corrugated steel culverts. To further understand the knowledge of the effect of corrosion, it is crucial to consistently read different articles and publications of relevance.

1.5 Techniques Followed

Culvert corrosion assessment is based on eight factors: thickness loss, soil pH, salinity, soil Total Dissolved Solids (TDS) in water, soil sulfate content, chloride content, soil resistivity, and soil temperature. The factors are separated into lab and field tests. Thickness loss and temperature are tested at the culvert site, while soil pH, salinity, TDS, sulfate content, chloride content, and resistivity are tested in the lab from the soil samples gathered at the culvert site. **Fig. 1.3** shows the design of a four-connection type soil box while **Fig. 1.4** shows the design and schematic of a two-connection type. Both designs can yield accurate results, but the two-connection type is more efficient in terms of removing soil to save time when testing and using less soil than the four-connection type.

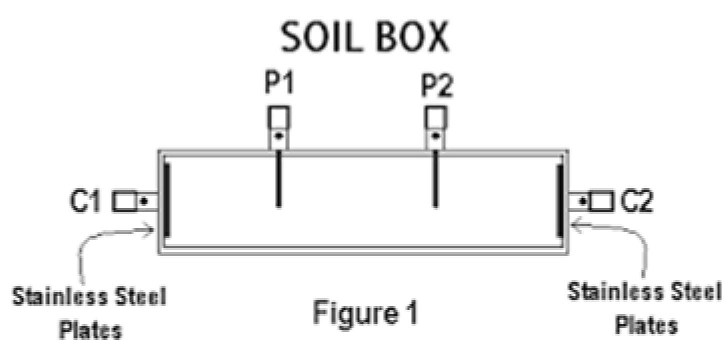
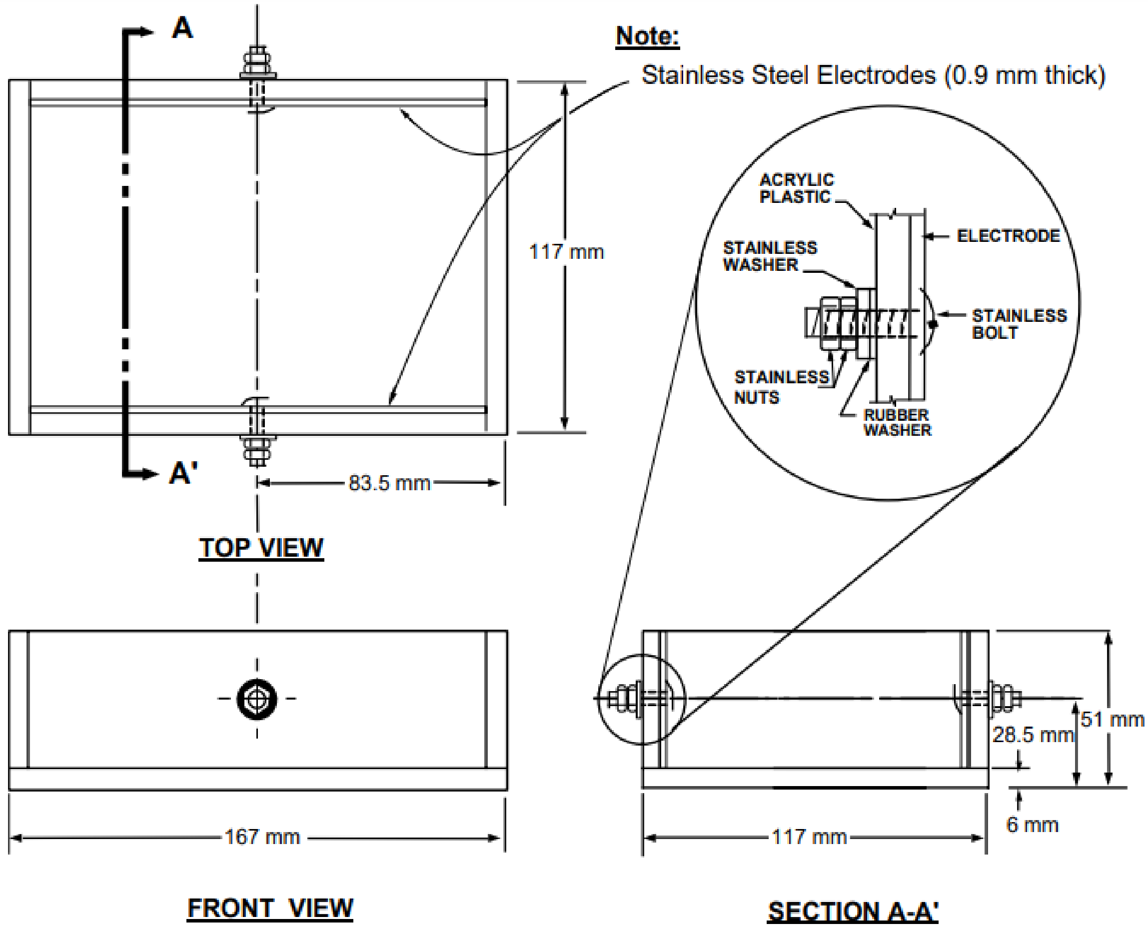


Fig. 1.3 Design of the 4-connection soil box (Florida Department of Transportation)



Plastic Material - 6 mm thick

Bottom - 1 piece (167 mm long by 117 mm wide by 6 mm thick)
Ends - 2 pieces (117 mm long by 45 mm wide by 6 mm thick)
Sides - 2 pieces (155 mm long by 45 mm wide by 6 mm thick)

Other Material

Electrodes - 2 pieces of stainless steel (155 mm long by 45 mm wide by 0.9 mm thick)
Two stainless steel machine screws (M 4 by 0.7 by 20 mm) with rubber washers, stainless steel washers and nuts.

Fig. 1.4 Schematic of the 2-connection soil box (Caltrans, 1999)

1.6 Objectives

This project aims to refute the California Department of Transportation culvert service life estimation formula. The current equation needs to be updated because it was developed based on culverts only in Caltrans District 1. This restricted the range of environments that the culverts experienced and therefore negatively affecting the estimations of culvert life in other environments. To correct this, one of the objectives was to collect culverts evenly throughout all of California. Another objective was to improve the accuracy of the current Caltrans formula, only uses pH and resistivity to calculate the service life, which ignores factors such as land use. Land use can help classify environmental characteristics of culvert corrosion, in doing so individual formulas can be obtained depending on various land uses. The final goal of the project was to use GPS locations of each culvert to show the effects of location on the culverts. By mapping the culverts in ArcGIS, the effects of location such as rainfall and salinity can be incorporated.

Chapter 2: Field Strategy and Data Collection

2.1 General

The culvert life estimation in this research was evaluated based on the following factors. Soil pH, soil Total Dissolved Solids (TDS) using Deionized water from the laboratory, soil chloride content, soil sulphate content, soil resistivity, land use, and annual rainfall. Each of these factors help to evaluate the corrosiveness of the environment that the culvert will be operating in, and therefore how long the culvert should last. By knowing this service life estimate, the culvert can be made thicker or can be coated to ensure that the culvert last the 50-year life expectancy that the California Department of Transportation requires for new installations. These various factors are being tested using the methods detailed below at 500 culvert sites in California and will be combined and analyzed to create a better method of estimating culvert life expectancy.

Fig. 2.1 500 sites inspected

2.2 Typical Site Visit

The data collection method at each of these 500 sites starts with the collection of approximately 5 lb of dirt in a one-gallon Ziplock bag. This soil is then taken back for lab analysis as detailed in the lab section below. The initial gauge thickness is then taken using a sheet metal gauge to determine the starting thickness of the metal which is used to validate the ultrasonic thickness gauge values. This thickness is taken at the least corroded section of the culvert, usually the 12 o'clock position. The exact thickness at the 3 o'clock, 6 o'clock, 9 o'clock and 12 o'clock are then taken using the Olympus 45MG Ultrasonic Gauge. Once this device has been calibrated with the step calibration gauge, it is able to measure the thickness of the culvert. The culvert is sanded at these four positions to ensure a smooth surface for testing. These four positions are then measured by applying couplant gel to the sensor and placing the probe to the flat portion of the corrugation. This gives the thickness of the remaining metal in the culvert after corrosion. The thickness loss is then found by subtracting the 6 o'clock thickness from the 12 o'clock thickness. In addition to the exact measurements of ultrasonic thickness gauge, a 5 point scoring system was used to visually gauge corrosion at the 6 o'clock.

A scoring system that scored culverts from 0-4 based on a pre-existing Caltrans method was used. This scale places corrosion free at a rating of 0 and progresses to failure at a rating of 4. For a score of 0, the culvert must have no signs of surface rust. For a score of 1, the culvert can have only surface rust but no scale or visible roughness. A rating of 2 is for culverts with notable buildup of rust that causes roughness in the culvert but without perforation. A rating of 3 is for pinhead size perforations, and finally a rating of four is for larger perforations that mean a culvert has failed. After this secondary corrosion measurement is added, the location of the culvert is then logged.

The Garmin Oregon 700 GPS is currently used for mapping data and to pinpoint precise location of culverts to be used later in ArcGIS. The Garmin also records elevations which help determine the inlet and outlet of each culvert by finding which side is higher in elevation. The location of each sample site, both inlet and outlet of the culvert, were recorded as DMS (Degrees, Minutes, and Seconds). After the field data was collected we began lab testing. The location data is also recorded onto a board and photographed with the culvert.

2.3 Land Use

Land use was classified to give an estimate of the corrosiveness of the environment as well as what corrosive conditions may be present. Different land use samples contain different levels of parameters like sulfate and chloride. Separating culverts based on land use allows the team to identify locations that may contain more culvert damage. Land use was broken down into five categories, agricultural, rangeland, forestland, urban, and coastal. These different land classifications have different trends in dissolved solids and moisture content which affects culvert life. These land use classifications are defined as follows.

Agricultural land is defined as land which is used to produce "food or fiber" (Anderson, 1976) This soil contains high amounts of fertilizer in soil and runoff. Fertilizer contains high amounts of sulfates and chlorides that accelerate the corrosion of steel. In addition, most crops have ideal growth in soil with a pH below 7.0. This acidic soil generates acidic runoff which also increases the corrosion rate of the steel culverts. Lastly, the high amount of water used to water the crops generates higher moisture content soil and higher amounts of runoff through the culvert causing increased corrosion, especially at the 6 o'clock position where runoff is most often in contact with the steel.

Range land is defined as land where vegetation is "predominantly grasses, grass-like plants, forbs or shrubs" (Anderson, 1976). This environment tends to have a moderate amount of rainfall and neutral pH.

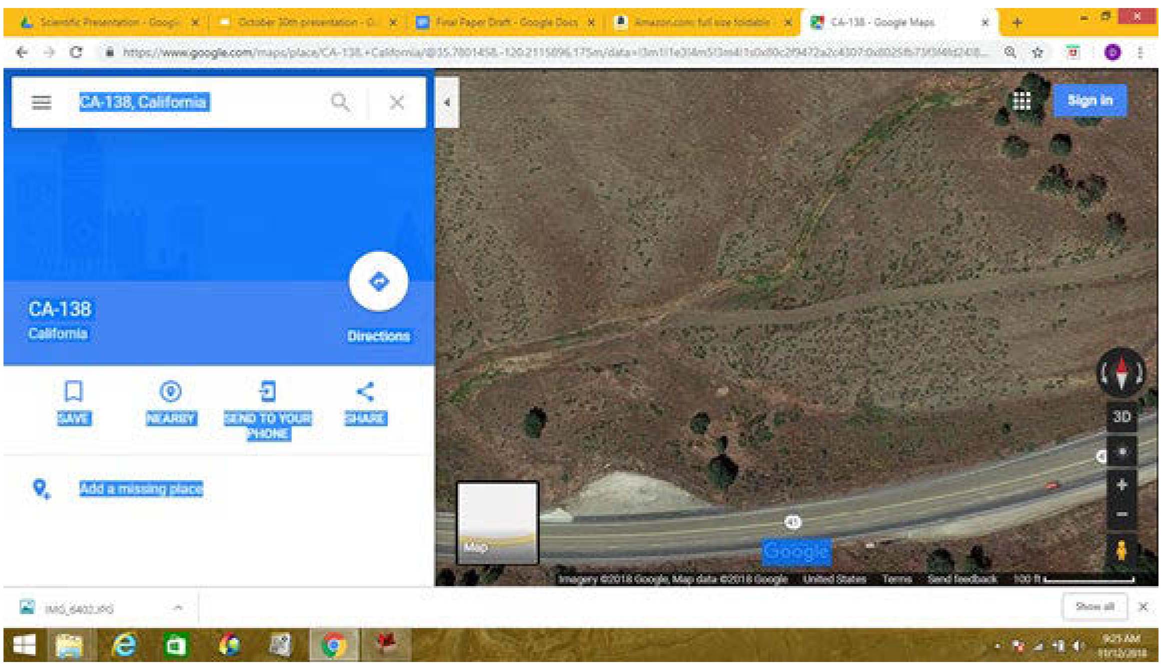


Fig. 2.2 Rangeland with small shrubs and trees

Forest land is defined as having a "tree crown aerial density of 10 percent or more" (Anderson, 1976). This classification is first checked visually, and then confirmed using the collected GPS data to inspect the site using satellite imagery. This environment has moderate to high rainfall, and a slightly acidic pH at 6 - 6.5.

Urban land is defined as land in which the aerial density of non-industrial structures is greater than 5%. This means structures like houses, stores, and offices. In cases which urban land is present in conjunction with another land category, the urban classifier will be added after the predominant land type classification. These environments have higher water runoff due to the watering of plants and lawns. Runoff from detergents, fertilizers, fuels, oils, and other items used in urban life are present, and may lead to decreased culvert life.

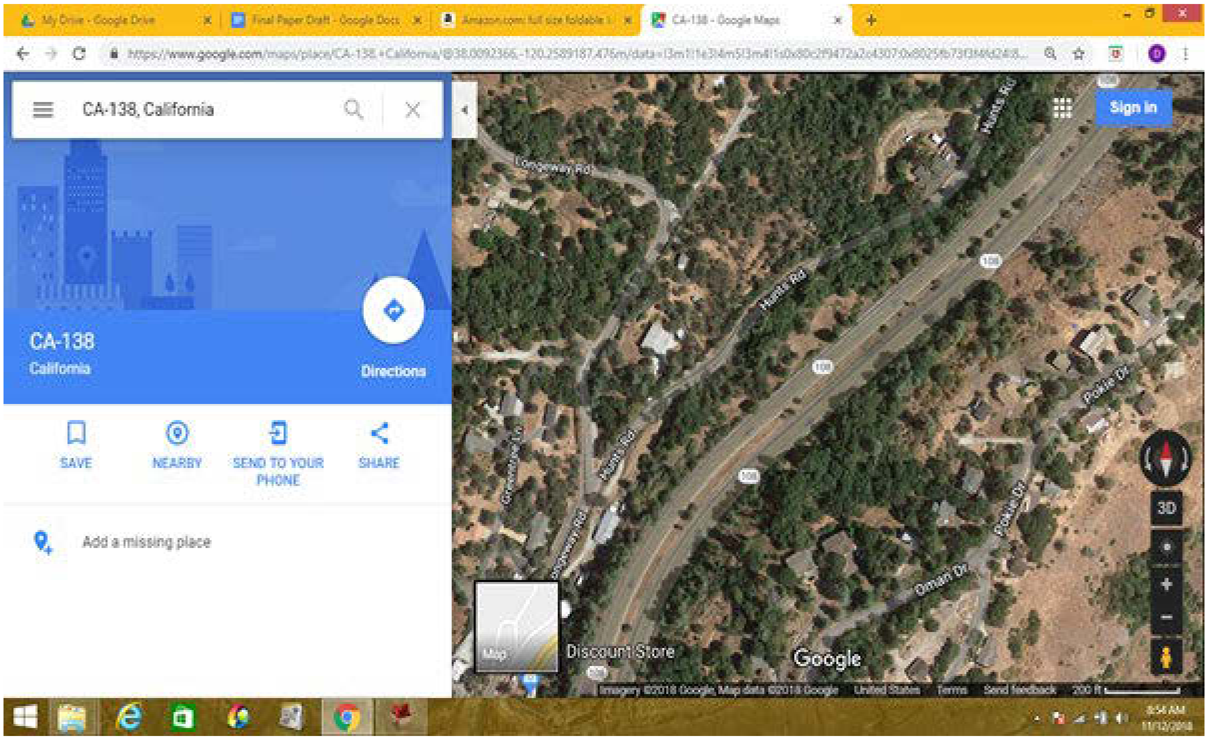


Fig. 2.3 Example of urban and forest land together

Wetland is "defined as an area in which the water table is at or near the land surface for a significant part of most years" (Anderson, 1976). Wetlands have high soil moisture and runoff, rapidly accelerating corrosion rate of culverts, in addition, high amounts of decomposed plant material and low soil aeration provide an ideal environment for bacteria to thrive. These bacteria break down plant material and generate sulfates. These sulfates then leech into the water and accelerate corrosion of culverts reducing culvert life.

Coastal land is defined as land near the ocean, or other saline body of water. The land around these bodies of water has high soil moisture and chloride levels due to the surrounding salt water. Both the moisture and chloride levels rapidly accelerate culvert corrosion, making these environments some of the most corrosive. This classification is appended to the main soil classification whether that be Forest Land, Wetlands, etc.

Fig. 2.4 Culvert with location board

Chapter 3: Observations

3.1 Soil Accumulation Failure

Through the collection of the 500 culverts, the highest corrosion rates have been observed in culverts with standing soil. This soil retains water, providing a constantly moist environment that greatly accelerates the corrosion of a culvert. This acceleration is most noticeable in culverts close to each other on a highway where one culvert will be free of soil buildup and corrosion, while another culvert will have soil buildup at the 6 o'clock and will have corroded to failure. The differing corrosion between two sides of the same culvert due to soil accumulation can be seen in **Fig. 3.1**. This corrosion is usually localized to where the soil has accumulated, only affecting the first few feet of the culvert while leaving the rest unaffected by the accelerated corrosion. This most commonly happens in culverts with low slopes, or that end in a pit, causing soil build up. This accelerated corrosion comes from two causes, the main one is the acceleration of corrosion of steel in water, and the other is the increased bacteriological activity at the soil culvert barrier.

Fig. 3.1 Left: light corrosion, Right: completely corroded

Water causes corrosion due to the oxidation reaction requiring water. In addition, the stagnant water further accelerates this by causing an ion buildup. Standing water due to a low degree of slope in the culvert can be seen in **Fig. 3.2** below. Not only does water increase the oxidation rate, the bacteriological activity is also increased, causing further corrosion. It is increased due to the higher moisture, lower oxygen, and increased soil culvert boundary. The sulphate reducing bacteria accelerates culvert corrosion, they thrive in moist low oxygen areas, and corrode the culvert where soil is contact with the culvert. Standing moist soil in the culvert allows an ideal area for these bacteria as well as contact on both the inside and outside of the culvert. Knowing how and where this corrosion occurs allows for solutions to be created.

Fig. 3.2 Low slope accumulates standing water due soil at culvert outlet

There are multiple solutions to this corrosion problem, re-designing the culvert installation for better water management, coating the ends of the pipe, and hybrid culverts with steel centers and plastic end caps. In the majority of these failures, soil buildup occurs due to a lack of drainage out of the culvert. These culverts end at a pit, causing soil to build up until the culvert is partially filled. Where possible, the outlet of the culvert should have a continuous downward slope leading away from the culvert to ensure soil and debris can be properly carried away from the culvert. However, at some locations this is not economically feasible due to the amount of soil needed to be removed, or the low grade of the land. In these cases, a heavy coating at the end of the pipes can be used. This would ensure that the common failure points are protected, while also eliminating the need to apply the more expensive coating or treatment method to the whole pipe. Using plastic ended steel culverts would also prevent the corrosion failure at the end of the culvert, while still maintaining the higher strength of a steel culvert.

3.2 Soil Texture

Soil texture can be used as an indicator for culvert corrosion. Soil in California generally falls somewhere between sand and silt. The consistency of the soil affects the corrosion rate of the culvert, with the highest corrosion in fine soils such as silt or clay, and the lowest corrosion in coarse soil like sand. This is likely due to the ability of these soils to retain moisture and trap water. Coarse soil such as the sandy soil in the desert in San Bernardino County allow water to easily permeate, while fine soil like silt and clay in Yolo county retains water within the soil. This fine grain size also prevents the water from permeating through the soil, causing surface water that stays in contact with the culverts. This increased water contact greatly increases corrosion rate. A secondary effect of these fine water retaining soils is the lack of oxygen within the soils that provides an ideal environment for sulphate reducing bacteria which cause further corrosion. These bacteria consume sulfur containing materials and generate a hydrogen layer at the surface of the culvert increasing corrosion rate. Finally, heavy organics from dead plant matter, fertilizer, or animal waste present in soil can increase water retention, and sulphate reducing bacteria concentration by increasing the available sulfur and decreasing the amount of oxygen due to the presence of decomposition bacteria such as Streptomyces that feed on decaying organic matter. Categorizing these soils using sieves and a system like the soil triangle in **Fig. 3.3** may show a more direct correlation between soil texture and corrosion.

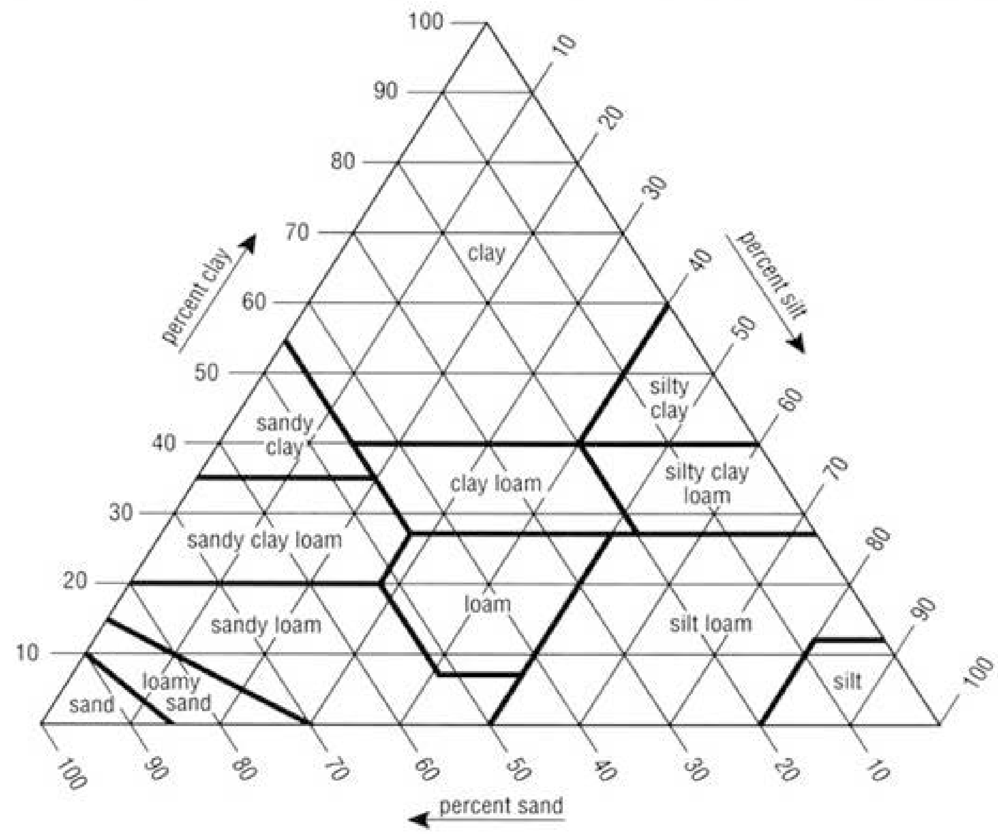


Fig. 3.3 Soil triangle used to classify soil texture

3.3 Corrosion Percentage Failure

Throughout the inspections of each culvert, we have physically seen the levels of corrosion that each culvert experiences. This can be seen during our inspections in **Fig. 3.4** we have a rating system similar to many that have been imposed to rate how much the culvert has corroded, the scale is from 0-4, going from least to worst. This does not give us a good estimation in how much "usefulness" the culvert has it has left before it starts to reach the end of its service life. ANSI states that by using the Caltrans method for testing they found that culverts started approaching the end of its usefulness when it has reached 13% metal loss to 25% metal loss that culverts have started to reach the end of their usefulness. This is seen by many as a very conservative percentage and may present why the service life equation sees so much variance in its prediction.

Fig. 3.4 Left: a culvert with a score of 3, Right: a closer look at the invert

In the field many culverts were inspected and from them the 13-25% threshold can be visibly seen as conservative, the pipes are still serving well and are still transporting water. In chapter 2, the rating system was described but the start of the end of a pipes usefulness through observation is seen somewhere between 45% and 65%, between what is seen from 3-4 rating. This varies depending on how the pipe is corroded and even varies on from situation to situation, for example, if the pipe has deep perforations at the 6 o'clock but is given only seen to be around 20% of its metal loss then this situation the culvert is reaching the end of its usefulness. In **Fig. 3.4** a pipe with the invert perforated deeply is rated 3, which would be reaching the end of its service life, this percentage is where the threshold may lie to get an accurate prediction. In most cases though increasing the percentage of usefulness can possibly decrease the variance in the prediction.

Fig. 3.5 Culvert during inspection

3.4 Land Use and Corrosion

During the collection of the corrosion data of the 500 culverts, a trend was found observationally. In certain land use types such as coastal and agricultural, corrosion was much higher, while in areas such as the desert, corrosion rate is low. In agricultural areas, especially those with cattle, corrosion was the highest. Many of these culverts had failed, or had significant corrosion at the six o'clock position. This is likely due to multiple reasons such as the high amount of runoff as well as fertilizers and animal waste. Agricultural land requires large amounts of additional water which eventually becomes runoff. This constant runoff keeps soil moist resulting in substantial increases in culvert corrosion. In addition to the added water, large amounts of nitrogenous fertilizers are used, whether this is directly applied to plants or generated as waste from livestock. This causes three additional pathways for corrosion, bacteriological , pH, and salt.

Fertilizers and animal waste washes off of agricultural land and into culverts carrying nutrients from the fertilizer and waste. This in turn provides water and nutrients that promote bacterial growth, such as the sulphate-reducing bacteria. These bacteria can accelerate the corrosion of the culvert at the culvert-soil barrier. In addition, runoff from farms is generally low in pH due to the acidic fertilizer byproducts and uric acid from animal wastes. This lower pH causes faster culvert corrosion, and makes a more suitable environment for sulphate reducing bacteria. Finally salts make up a significant portion of the nutrients used in fertilizers, and is also produced in waste by animals in agricultural land. These salts then enter runoff and cause accelerated culvert corrosion. The combination of these three factors cause agricultural culverts to have the second highest culvert corrosion rate and causes failure much more quickly than the desired 50-75 year life desired. Another land-use with high corrosion due to salts is coastal land.

Fig. 3.6 Moderate corrosion from agricultural land due to acidic soil and high bacteria content

Coastal land is classified as transition terrain between land and sea, but in addition also includes land close to inland seas or other saline bodies of water such as the Salton Sea. These bodies of water contribute salt, this salt is then carried by wind to local terrain. This was apparent in San Bernardino county where low corrosion desert culverts suddenly become high corrosion desert culverts the closer to the salton sea they are. This is due to the salt and moisture contributing to corrosive runoff and accelerating corrosion. However, the corrosion is most noticeable in culverts along the coast. While many of these culverts have been converted to concrete or plastic to reduce corrosion, many metal culverts still exist. These culverts had the highest corrosion of any other land use as shown by the fully corroded pipe in **Fig. 3.7**. Range Land and Forest Land have lower corrosion due to the lack of salt and relatively neutral pH.

Fig. 3.7 A culvert from a coastal highway in San Luis Obispo County with severe corrosion due to high salinity

Forestland and Rangeland have moderate to low corrosion due to their neutral soil. Forest land has moderate corrosion slightly higher than Rangeland due to the higher amount of rain and moisture. The soil in these areas tends to have neutral soil and lower salt causing reduced corrosion. Even in areas with high rainfall such as in northern counties like Modoc, culvert corrosion is relatively low compared to coastal and agricultural land. This is likely due to the neutral soil and constant flow of water causing a non-corrosive environment , and an unsuitable environment for bacteria due to the low amount of moist low oxygen soil. Rangeland is similar to forest and in that it has non-corrosive soil compared to agriculture and coastal land, however it has considerably less rainfall which leads to the grasses and small shrubs found in rangeland. This lower rainfall causes less soil moisture and therefore less corrosion than forest land. However, in rangeland areas near agricultural areas such as those in Central California, corrosion can be increased due to farm effluents. The lowest corrosion was found in desert land where low rainfall leads to low corrosion.

Fig. 3.8 A Forest land culvert
(heavy water flow has filled the culvert; however, very little corrosion has resulted from this due to non-corrosive soil environment)

Desert land was the least corrosive to the culverts. With the exception of culverts near the Salton sea, all desert culverts had low corrosion. This is likely due to the low amount of water not allowing an environment that will cause corrosion. From these land use based observations, it was found that the largest causes of corrosion are low pH, high salt content, and stagnant standing water. Any one of these three factors can create a corrosive environment and multiple will cause a highly corrosive environment.

Chapter 4: Data Analysis

4.1 Lab Testing

The soil taken back to the lab undergoes resistivity, pH, TDS and salinity testing. Soil pH affects the environment for soil bacteria. In general, the sulphate-reducing bacteria found in soils thrive in lower pH environments. There are also different types of bacteria which convert organic detritus in the soil, mainly decomposing plant matter, and convert them into sulphates. These sulphates are highly corrosive to steel culverts. This is especially true at the steel soil boundary present around the culvert. This has the most effect at the 6 o'clock position where dirt tends to accumulate. At this steel soil boundary, soil bacteria actively generate sulphates which constantly react with the steel culvert causing increased corrosion rate. Measuring the pH of the soil does not directly measure how much bacteriological activity the soil contains but does show what types of bacteria can live in the environment and how well suited the environment is for sulphate reducing bacteria. In addition, the high levels of sulphate reduction acidify the soil, so that the pH is also an indicator of how prevalent the sulphate reduction is.

4.2 Resistivity

To test for soil resistivity, the California Test Method 643 or small soil box method is used in the lab. This method requires a scale, a sieve, deionized water, a graduated cylinder, a container to mix all the soil with deionized water, and most importantly the AEMC 6471. As mentioned previously, AEMC 6471 is a piece of equipment used for ground resistivity testing. The soil is first dried at 125°F and ground with a mortar and pestle if necessary so that 110g of soil can be passed through a Number 8 Sieve. This sieved soil is then mixed with 15 mL of deionized water and placed in a small size resistivity box as detailed in California Test Method 643. The resistivity is then tested and recorded. After this, an additional 10 mL of water is mixed with the soil and it is retested. This is repeated once more with an additional 10 mL of water, and then is repeated with 5 mL of water until the resistivity value for the soil reaches a minimum. The minimum is reached once the resistivity increases twice. For example, a low value of 800 Ohm-cm is reached followed by 1000 Ohm-cm and 900 Ohm-cm since both values are higher than 800, 800 is recorded as the minimum. This yields the minimum resistivity environment that the culvert will encounter. If the minimum resistivity of the sample falls under 1000 Ohm-cm, it is sent to the California Department of Transportation to be tested using ion chromatography for exact salinity and sulphate measurements.

Fig. 4.1 Small soil resistivity box and meter

4.3 Ion-Chromatography

Ion-Chromatography can be very useful information. Access to this resource was only possible through California Department of Transportation laboratories, as the machine cost is extremely high. The purpose of the Ion-Chromatography is to identify the levels of sulfate and chloride. Approximately 3 lb of soil must be sent to prepare the 5 samples necessary for calibration and measurement of the chloride and sulphate levels. Regardless of resistivity, all samples are tested for salt content, as well as pH and Total dissolved solids in the CSUN Lab.

4.4 pH, TDS, and Salinity

The ExStik II pH/Salinity/TDS Meter is used to test for pH/ Salinity and TDS. The data collection process starts by first mixing 30g of soil passed through a number 8 sieve, with 30 mL of deionized water and stirring for 30 seconds. The sample is then left to rest for an hour so that the salts and other solids can fully dissolve into the water. The ExStik II is then placed in the solution and the values are recorded. The ExStik II meter is currently being used to measure pH, Salinity, and Total Dissolved Solids (TDS). These three factors influence the corrosion rate of the culverts.

Fig. 4.2 ExStik II reading soil data

4.5 GPS

ArcGIS is a geographic information system that allows easier analysis of the data by plotting it on a map of California which shows trends of corrosion or corrosion factors across the state. GIS was used to ensure that all land use types had sufficient sample sizes, as well as making sure all portions of California were equally covered. As shown below in **Fig. 4.3** areas of northern California as well as the Mojave Desert have low sample sizes which reduces the accuracy of the formula in these areas. ArcGIS comes with the ability to connect to online databases and other users maps to gather additional data without the need for additional testing. One database used was average annual rainfall. This allowed rainfall to be compared to salinity, resistivity and pH showing that pH is a direct result of rainfall, while salinity and resistivity have other significant factors. In addition, GIS allows relations between geographical location and corrosion factors. ArcGIS showed that deserts had high pH while forests had low pH. Finally each county could be separated to show counties of concern where corrosion is most likely to be an issue. The ArcGIS analysis is further explained in Chapter 5: ArcGIS

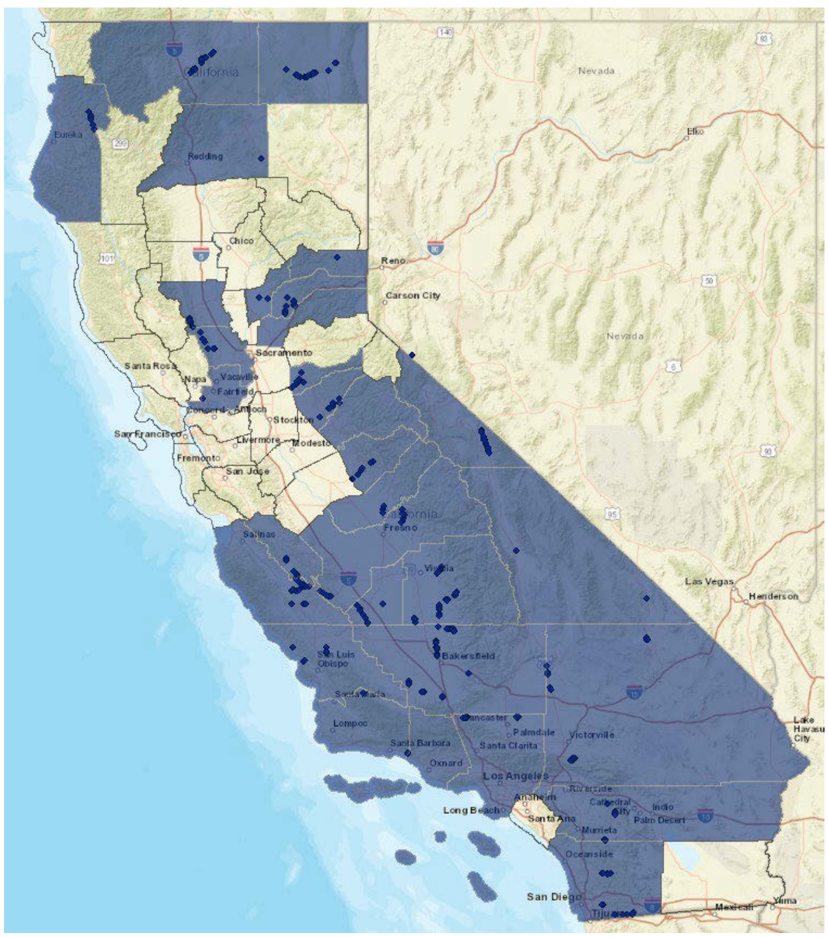


Fig. 4.3 Locations of the investigated culverts in the State of California

4.6 Land Use Descriptions

In order to form a more accurate formula, land use was taken into account. Land use can be broken into five categories Agriculture, Coastal, Forest, Rangeland, and Urban. Since each of these land use types have different characteristics, corrosion rates may vary from land use to land use. For this reason, separate formulas were made for each of the 5 land uses. In order to make land use based formulas, the land uses first had to be separated by defining factors. These land uses should be determined using the land above the inlet side of the culvert as this land directly affects the runoff into the culvert and the soil that comes in contact with the invert of the culvert.

Agricultural land is any land that is used to produce plants or livestock. This can include textiles like cotton, food like corn or livestock such as cattle. Crops require water and fertilizer to grow, while livestock produces high amounts of waste. The fertilizers used for crops are generally acidic to maintain a pH slightly below 7, and the large amounts of water required to grow crops accelerate corrosion. In addition, the waste from cows also contributes to this pH and provides nutrients to the soil. The near neutral pH of the soil combined with the constant moisture and heavy nutrient content of the soil makes it an ideal environment for corrosive sulphate reducing bacteria. This increased bacteriological activity can be included into the formula to make a more accurate formula, by forming a separate formula for the Agricultural land use section.

Coastal land use can be defined as any land within 30 miles of a saline body of water. Some examples of saline bodies are oceans, marshes, and saltwater seas such as the Salton Sea. In these coastal ranges, high levels of salt accelerate corrosion in culverts as well as providing higher levels of moisture which further accelerate corrosion. As a result of these two corrosion factors being elevated, resistivity is generally low in these environments. The coastal land classification has no effect on pH. By forming a separate formula for coastal land use, the formula can better model the corrosion characteristics of coastal culverts.

Forestland is defined as land with a tree crown density of 10% or more. This can be estimated visually at the site , but must be confirmed using satellite imagery. If the crown of the trees in the selected area comprise more than 10% of the total surface of the land when viewed perpendicular to the ground, the land can be classified as forest land. In areas where forestland and rangeland meet, an average of the first 1000ft x 1000ft land area directly above the inlet of the culvert should be taken for crown density. Forest land contains predominantly perennial plants, as grasses and other annual plants are blocked by the crown of the trees. This generates significantly less dead plant matter as perennial plants stay green throughout the year and only occasionally shed leaves or other plant matter. This results in significantly more aerated soil which can drain faster, and is less suitable for bacteria growth. In addition, forest land receives higher rainfall throughout the year lowering the pH of the soil further restricting the growth rate of bacteria. Since forestland has more permeable soil, this rainfall is able to drain more easily reducing standing water in the culvert.

Finally, the large amount of plants with large root structures reduces erosion, reducing the amount of soil that gets into the culvert greatly reducing corrosion. These reasons give forestland moderate to low corrosion.

Rangeland contains primarily low lying vegetation such as grasses, shrubs, or other low lying vegetation. This land can contain trees as long as the trees take up less than 10% of the land area as determined by crown density. Rangeland receives moderate levels of rainfall and is free from crops or livestock making the soil close to neutral pH and lowering the corrosiveness of the soil. However, rangeland shrubs and grasses are annual plants and quickly grow during the wet season and die during the dry season. This generates large amounts of decomposing biological matter which provide nutrients for sulphate reducing bacteria and lower soil permeability reducing the amount of oxygen in the soil and increasing the amount of stored water in the soil further accelerating culvert corrosion. Finally, the small root structure of grasses and other grassland plants means erosion is high allowing large amounts of soil to be pushed into culverts, which is the largest cause of culvert corrosion. Siltation in culverts occurs as a result of settlements of fine soil from the flow running through this culvert. This siltation then allows for greater layers to develop in the culvert. For this reason, Rangeland has moderate to high corrosion.

Urban land is land which is used for homes and businesses where buildings represent 5% or greater of land area. Houses and cities contribute to culvert corrosion in a multitude of ways. The first being increased water in the area. Water is used for watering plants and washing. This runs off into culverts increasing the corrosion rate. In addition effluents in runoff such as plant fertilizer animal waste and plant matter contribute nutrients to the soil and causing increased bacteriological growth and increased corrosion. Finally, additional effluents such as oil, cleaning products, and additional contaminants washed out from city life can cause increased corrosion. These factors combined cause urban land use to have moderate to high corrosion. To better represent land with urban land in conjunction with another land use type such as forest, which is common in rural areas of northern california, an average of the two land use results can be used.

Desert land is land that has rainfall below 10 inches of rain annually. The lack of rainfall annually in these locations leads to a basic soil which stops bacteria growth reducing the corrosion rate of the culvert. In addition, the low rainfall reduces the amount of water in contact with the culvert reducing corrosion. The contact between the water and the culvert is further reduced by the sandy soil which allows rain to quickly drain. Finally, desert soil has very little nutrient for bacteria to grow reducing corrosion. These factors cause desert culverts to have very little corrosion.

4.7 Selection of Failure Criteria

In order to create a formula which yields the estimated life of a steel culvert, the failure point of the culvert must be determined. This can be done as a remaining thickness or as a percentage corrosion. In order to find the failure thickness or percentage loss, the corrosion of pipes with a rating of 4 were collected and compared. A rating of 4 for a culvert indicates that the culvert has perforated due to corrosion. At this point, flow through the culvert begins to undermine the integrity of the culvert by eroding the supporting soil. This percentage corrosion is the method currently used by Caltrans and other similar organizations.

Percentage corrosion means remaining thickness of the culvert changes with the gauge of the culvert. Only using remaining thickness does not produce as reliable results. Initial failure occurred between .053" and .097" thickness of remaining metal and had no strong trend for failure thickness. For this reason, percentage corrosion is used. The majority of newly failing culverts failed at approximately 15% - 25% of the original thickness. At this point, perforations had formed possibly compromising the culvert in heavy flow conditions. Perforations were seen as low as 13% , however, as one of the goals of this formula is to create cost effective culverts, the more conservative outliers were ignored. Since these failure corrosions range from 13% to 100%, only those where perforations had just occurred were used, approximately holes up to ¼". Many culverts with a 15% - 25% failure retained the integrity of the backfill. However whether or not the backfill remained firmly packed relies on soil texture and rainfall in that area. For this reason, 15% and 25% was selected for all land types and rainfall averages.

4.8 Linear Extrapolation of Corrosion

To find estimated life spans of culverts tested in the field requires extrapolation of the thickness loss to find the final failure lifetime. To do this, thickness loss had to first be found. This was done by subtracting the most corroded point, the 6 o'clock point, from least corroded point, the 12 o’clock. This assumes that the 12 o’clock is not corroded, which was the case in all culverts except those damaged by automobiles or other impacts. This was then converted to a yearly corrosion by assuming linear corrosion from the installation date. Using the installation dates, the number of years since installation was found. By dividing the total corrosion by the years since installation, the thickness loss per year was found.

By using the previously mentioned 15% and 25% failure criteria, the estimated life in years were found. This was done by multiplying the percent failure criteria times the 12 o’clock reading (initial thickness), and dividing that product by the yearly corrosion rate. This gives the number of years that it will take for the culvert to reach the failure point. In order to linearly extrapolate the service life, **Eq. (4.1)** was used with an example calculation provided below. These values were considered as the independent variable in Chapter 7 Service Life Equation.

$$Linear\ Years = f \times \left(\frac{Culvert\ Thickness}{MPY}\right) \tag{4.1}$$

where, f = 0.15 for 15% failure criteria
f = 0.25 for 25% failure criteria

$$MPY = \left(\frac{12\ o'clock\ reading - 6\ o'clock\ reading\ [mils]}{2018 - Culvert\ Built\ Date}\right) \tag{4.2}$$

Example Calculation

When:
12 o’clock reading = 0.109 in.
6 o’clock reading = 0.091 in.
Culvert built date = 1975
Failure criteria = 15%

$$MPY = \left(\frac{(0.109\ in. - 0.091\ in.) \times 1000}{2018 - 1975}\right) = 0.4186 \text{ mils per year}$$

$$Linear\ Years = 0.15 \times \left(\frac{0.109\ in. \times 1000}{0.4186\ MPY}\right) = 39.06 \text{ years}$$

4.9 Salinity Effect On Resistivity

Salinity and resistivity are closely related. The conductivity of water or soil is dependent on the dissolved salts within. It is for this reason that distilled water conducts no electricity. Since resistivity is the inverse of conductivity, the resistivity should increase as salinity decreases. As shown in **Fig. 4.5**, the exponential relationship between salinity and resistivity is strong.

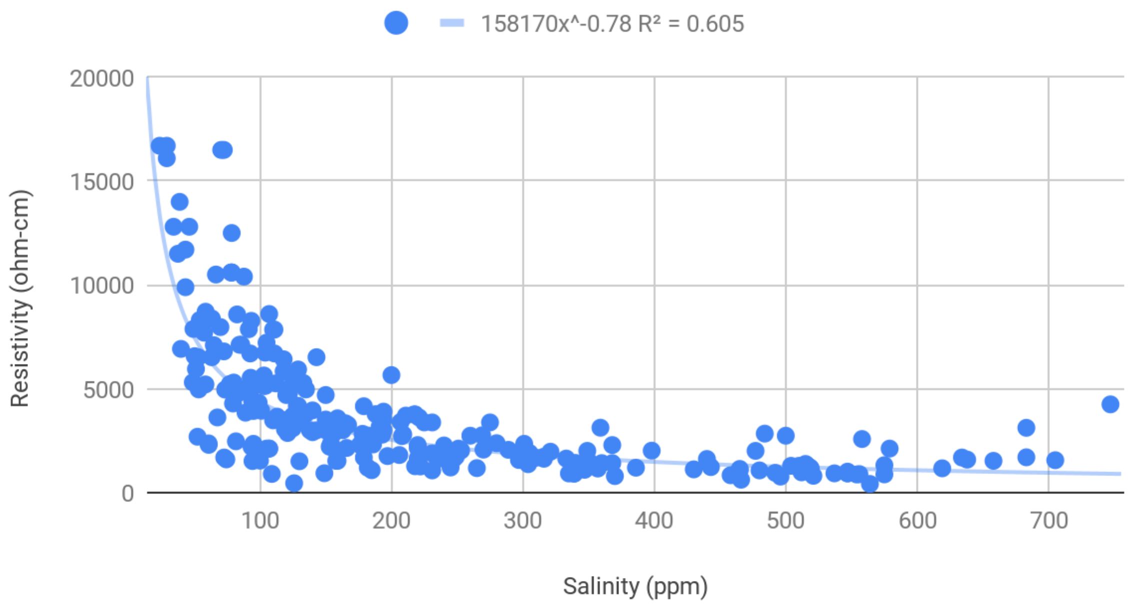


Fig. 4.5 Plot of salinity vs. resistivity

Since resistivity is so strongly dependent on salinity, the addition of salinity to the service life formula is superfluous. Since the salinity provides no extra information it can be eliminated from the formula. By eliminating this from the formula, less soil testing is required and the process for each site can be expedited. Salinities effect on the accuracy of the service life equation is further tested in the following service life equation section.

4.10 TDS Effect On Resistivity

Similarly to salinity there is a strong correlation between TDS and resistivity, as the amount of total dissolved solids decrease the greater the resistivity value is, as is seen in **Fig. 4.6,** this is because once again similar to salinity TDS measurements are derived from conductivity and the more conductive something is the less resistant it is to electricity passing, hence the correlation we see under.

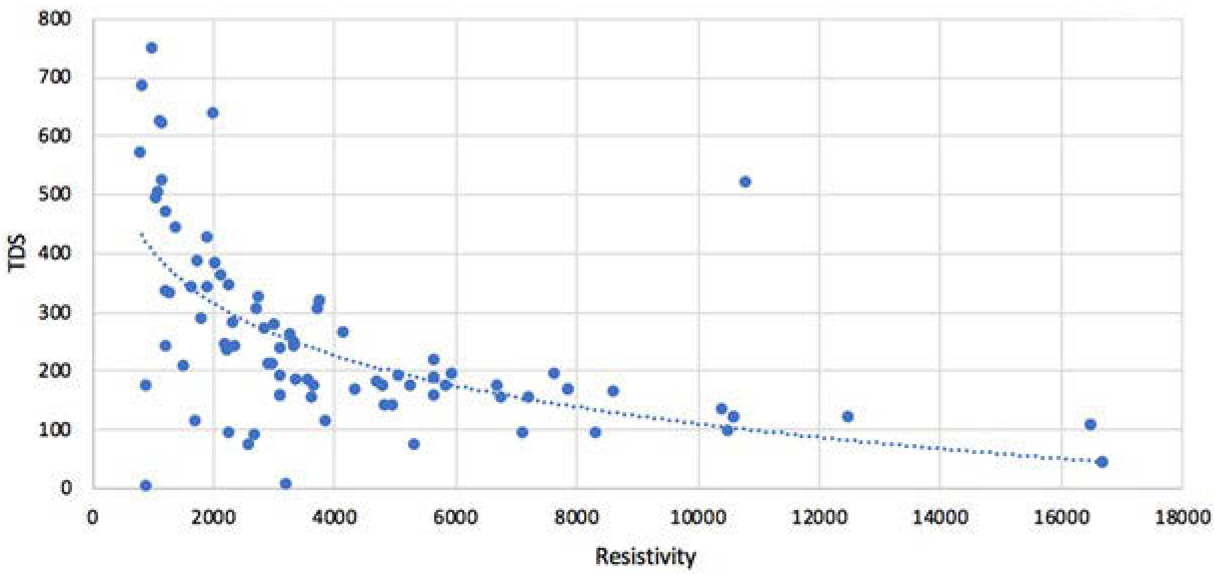


Fig. 4.6 Plot of TDS vs. resistivity for a specific land use

For this reason the team decided to disclude the TDS from the general equation, seeing as it makes it more tedious and complex on the equation and creates no significant benefit to having it part of the equation since it is closely related to resistivity, there is no need for it as well.

Chapter 5: Geographic Analysis

ArcGIS has connections to multiple databases that allow users to access information such as annual rainfall, annual temperature, soil pH, and many other factors, and integrate them with the users measured data. ArcGIS was used in this research to compare corrosion, pH, and salinity to pre-existing databases containing rainfall and temperature data to find possible new factors of corrosion. These were then used in excel data analysis to find a new, more inclusive equation to estimate the corrosion rate of culverts. In addition to geospatial analysis, the software can be used to find the value for rainfall, average temperature, or other database information, at a given culvert, and add it to the excel file. This can then be used in more traditional data analysis and formula creation.

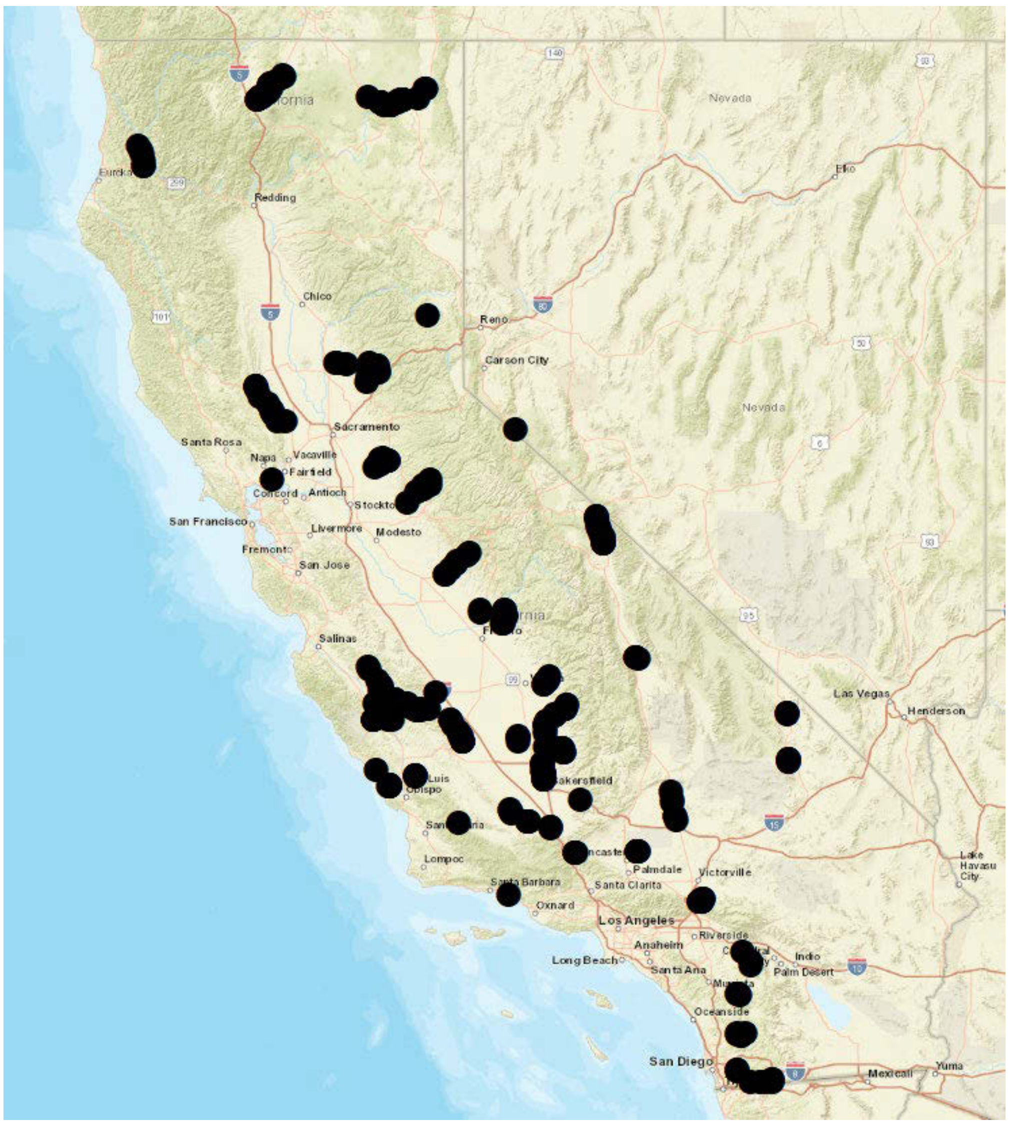


Fig. 5.1 Locations of culverts considered for field investigation and data collection

5.1 Rainfall

Rainfall determines the amount of water that flows through the culvert in a given area as well as the average soil moisture in that area. This rainfall is highest in the Sierra Nevada mountains as well as the coastal regions of California with the highest precipitation in the northern coastal areas of California. The lowest precipitation occurs in the California deserts and central California. Using ArcGIS allows access to this rainfall data that would otherwise need to be measured over years at each site. This data is obtained in ArcGIS through a series of shape files provided by the National Oceanic and Atmospheric Administration. This was then compared to culvert data by merging the culvert location data points gathered by the GPS during outings with the lab data and creating spatial relations between our data and the National Oceanic and Atmospheric Administration data. This allows comparison between the teams gathered empirical data and pre-existing data.

5.2 Salinity

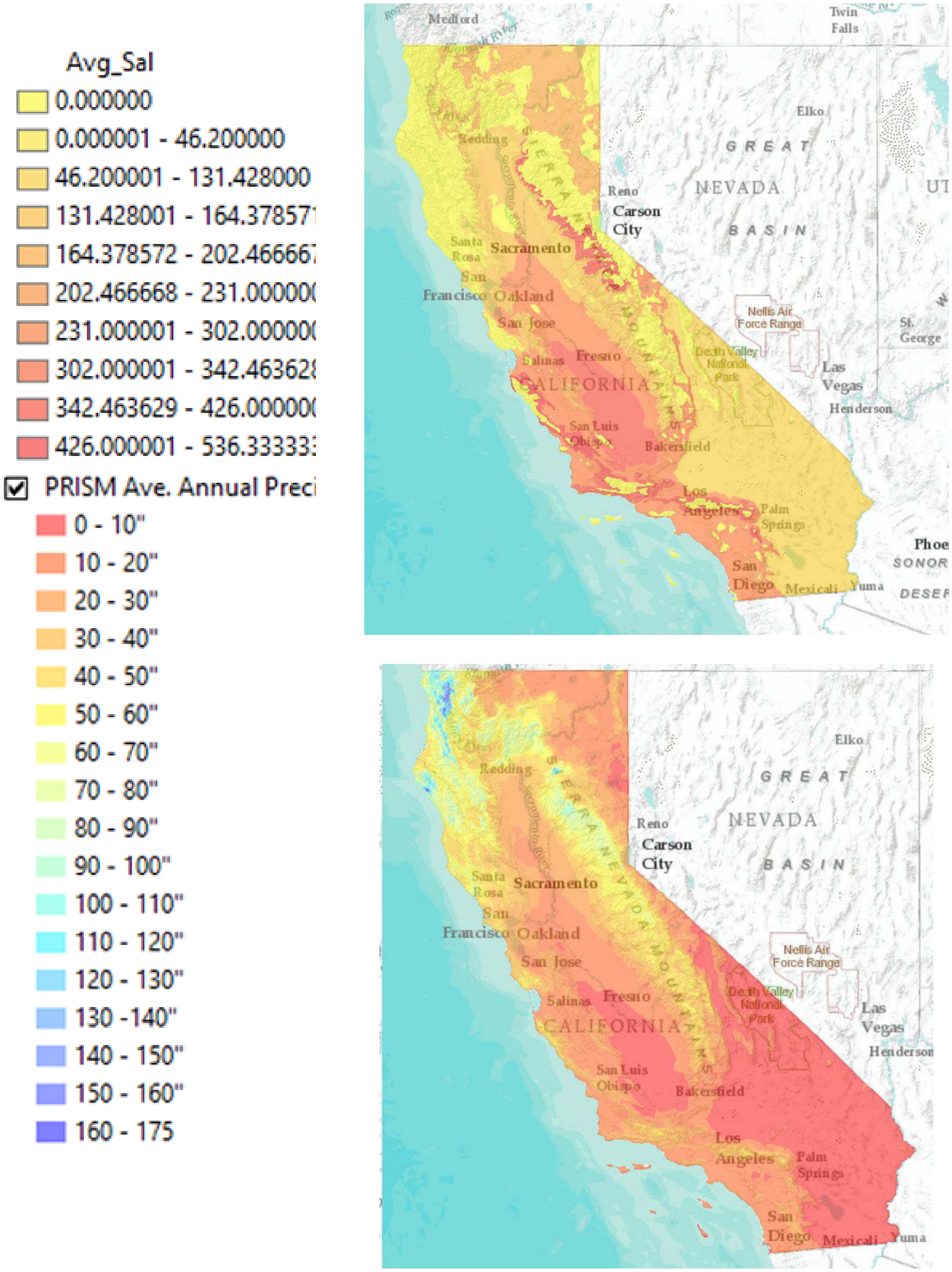


Fig. 5.2 Map of California comparing rainfall (top) to salinity (bottom)

The first aspect compared to rainfall was salinity. Salinity was chosen because it is a significant factor in the corrosion of steel culverts, and should be affected by dilution from the freshwater rain. As shown in the map **Fig. 5.2** above, the maps of salinity and rainfall closely match with the exception of Coastal and Desert areas. In areas of high rainfall such as the Sierra Nevada mountains as well as the coastal and northern regions of California, salinity should be the lowest. This is because salts have no time to build up in the soil before they are washed away by rainfall. However, coastal ranges show higher salinity than expected. This is due to wind blowing saline mist from the ocean inland which raises salt levels despite the increased rainfall at the coasts. Rainfall is highest in the northwest tip of California and declines the further southwest down the state. Elevated rainfall is also present along the Sierra Nevada Mountains. This is due to the cooling of moist air as it travels from the coast. This cooled condensed air generates rainclouds which caused the increased Sierra Nevada rainfall. Since the moisture is precipitated out of the air as it travels over the mountain range the eastern side of the Sierra Nevada has far less moisture present causing the desert landscape to the east. Salinity follows this trend east of the Sierra Nevada. The Northeastern tip of California contains the highest level of rainfall and the lowest levels of salinity. In addition, the Sierra Nevada Mountains, which have elevated rainfall due to elevation also have reduced salinity when compared to neighboring land. The highest salinities are present in central California between Bakersfield and Fresno. This is due to a combination of low rainfall and high amounts of agricultural land which adds salt from fertilizers and animal waste. The one location that does not follow this trend is the Mojave desert and surrounding areas east of the mountain range. This is due to the Sierra Nevada Mountain Range. Salt in California soil is largely from salt spray that is blown in from the Pacific Ocean. Based on **Fig 5.2** above, the Sierra Nevada blocks this salt laden wind preventing salt from reaching the Mojave Desert. For this reason, some of the lowest salinity levels occur in the Mojave desert, despite that area receiving the lowest rainfall of any area in California

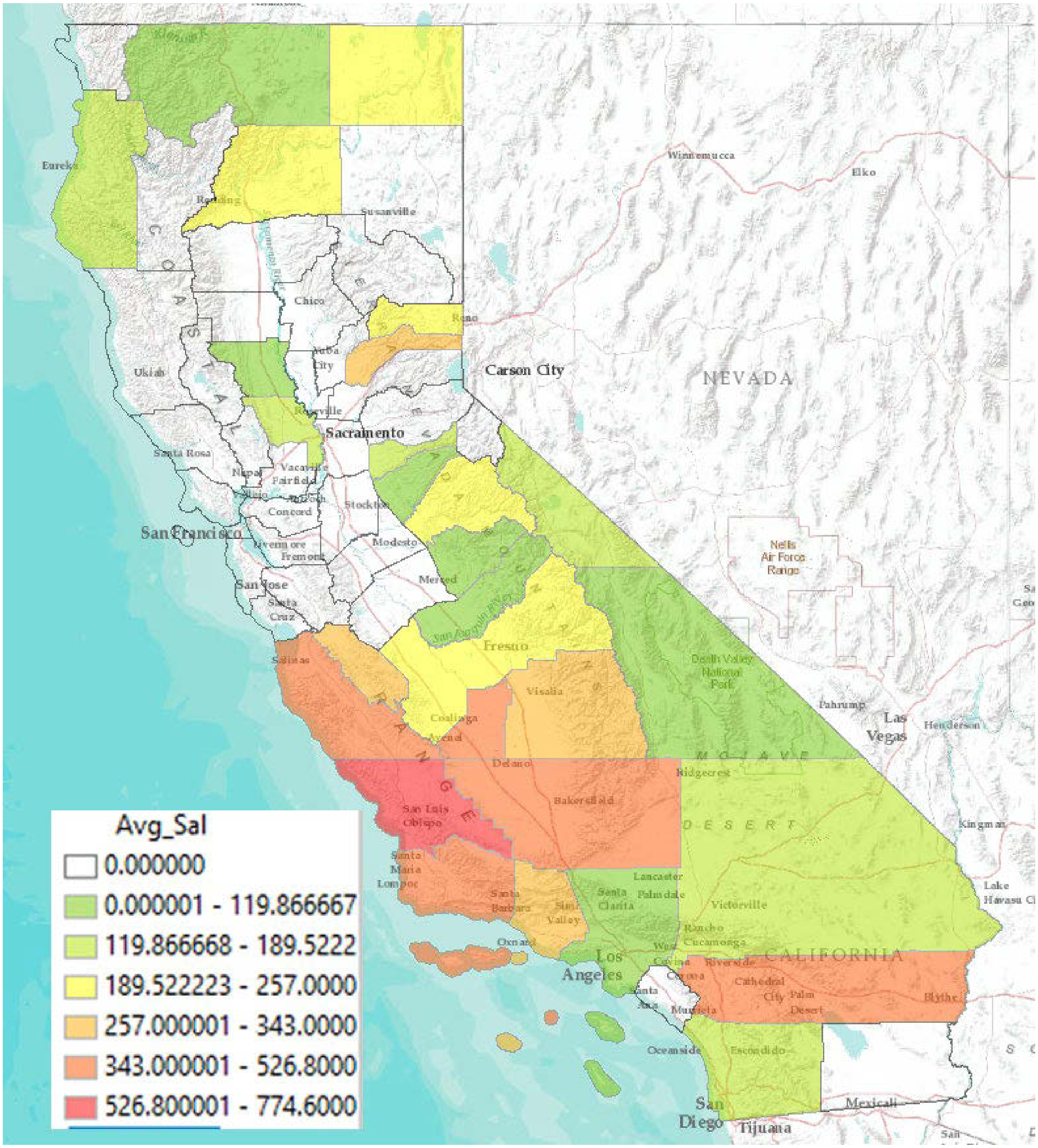


Fig. 5.3 Map of California separated into counties showing salinity levels in ppm

The County map shown in **Fig. 5.3** provides an additional visualization of the culvert data. The lowest Salinity is present in the north west corner of California. In addition, the Sierra Nevada Mountains contain some of the lowest Salinities. This is due to the higher rainfall in these mountain counties. The highest salinities are in the three southern coastal counties due to their moderate rainfall and close proximity to the Ocean. Salt spray from the ocean is blown to these counties the most. As distance from the Pacific Ocean increases, salinity decreases. This is because salt spray has a limited distance it can travel from the ocean. The lowest salinity values are to the east of the Sierra Nevada Mountains in the Mojave Desert due to the Sierra Nevadas blocking salt spray. One point of interest in this map is the high salt concentration in Riverside county. This is due to the Salton Sea, a large inland saline body of water which causes increased salinity in surrounding areas due to high wind and salt spray. With no rain to wash away the salt, the soil retains much more salt from this relatively small body of water. The county map shows the effect of proximity to saline bodies of water in addition to the relationship between salinity and rainfall shown in **Fig. 5.2**.

5.3 pH

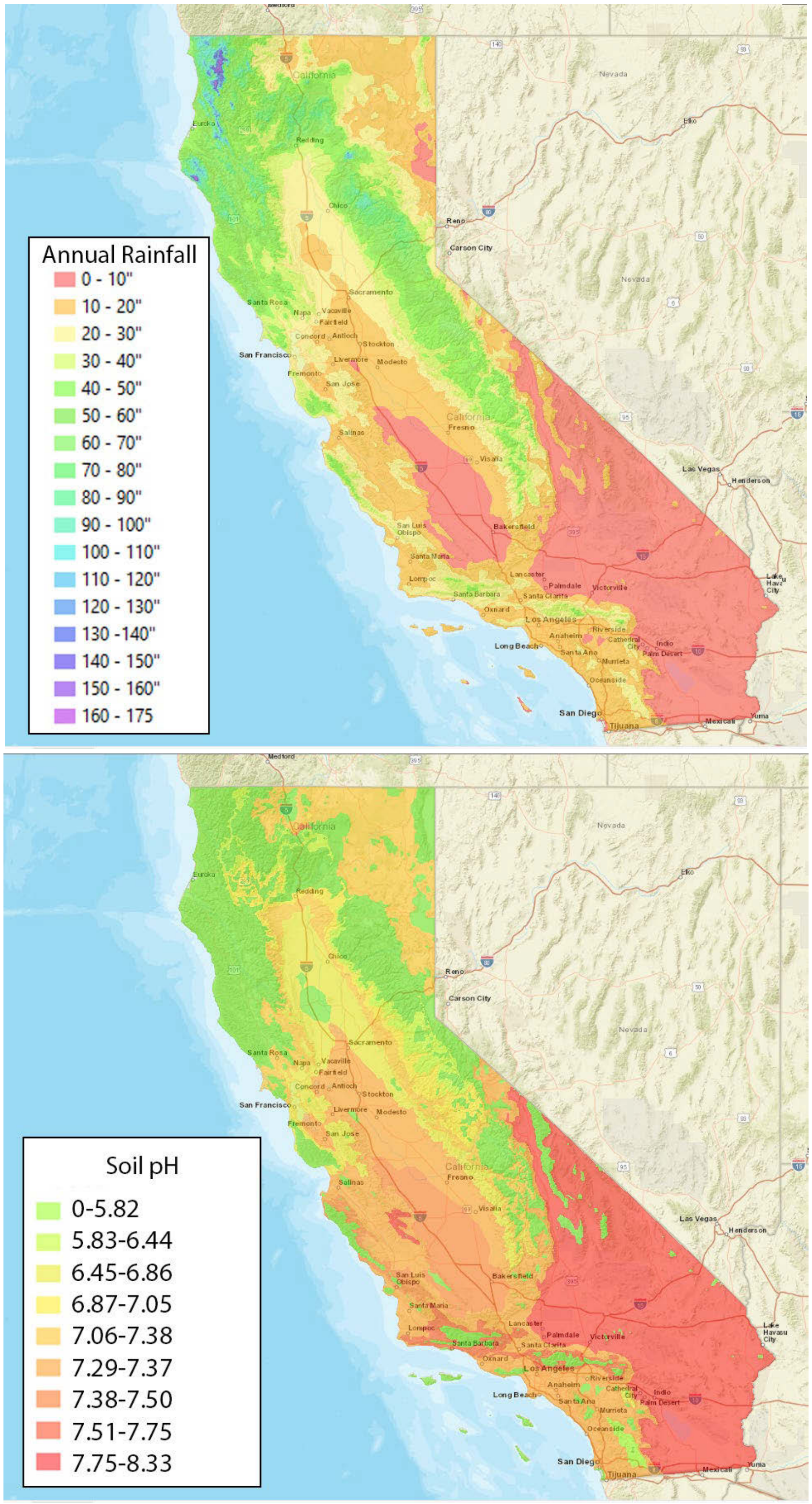


Fig. 5.4 Map of California comparing rainfall (top) to pH(bottom)

Another corrosion factor investigated through ArcGIS was pH. While pH has a direct effect on culvert corrosion, it also indirectly affects corrosion by altering the soils ability to support bacterial growth such as sulfate reducing bacteria which increase corrosion. These bacteria prefer neutral environments with pH near 7. Limestone, and gravel present in the soil raise the pH of soil, while rainfall lowers the pH due to the carbonic acid from atmospheric Carbon Dioxide. Since rain on average has a pH between 5 and 5.5 pH, It is expected that areas with highest rainfall would be more acidic and areas with lower rainfall would have more basic soil.

Fig. 5.4 shows that rainfall has the ability to lower the pH of soil. On average, lower rainfall correlates with higher more basic pH and higher rainfall correlates with lower more acidic pH. The highest rainfall areas are in the northwest of the state as well as the Sierra Nevada mountains. These areas also have the lowest pH. The highest pH soils are found in the Mojave Desert region. This is due to the Mojave Desert having the lowest rainfall in the state as well as high amounts of carbonate rich stone such as dolomite. One difference between the rainfall and pH maps is in the farmland between Bakersfield and Fresno. In this area, pH is lower than anticipated, as the low rainfall in that area would suggest that soil pH is High. This uncharacteristically low pH is due to agricultural runoff. Agricultural runoff comes from the increased water used in sustaining crops and livestock and is acidic due to animal waste and fertilizer. An additional difference between the maps is that the salinity map contains erroneous extreme low points in pH scattered through the map. This is due to the small area of these subdivisions coinciding with areas of lower pH. Since there are less data points to create a proper average pH, error is introduced. This is because ArcGIS averages the data points from the empirical data Excel data file when merging it with the National Oceanic and Atmospheric Administration shapefile. With the exception of these artifacts, the two maps closely match showing rainfall effect on the pH of the soil as well as the soil's ability to cause bacterial corrosion. Breaking down California into counties also shows a similar trend in pH and better shows the difference in pH due to rainfall between Northern and Southern California.

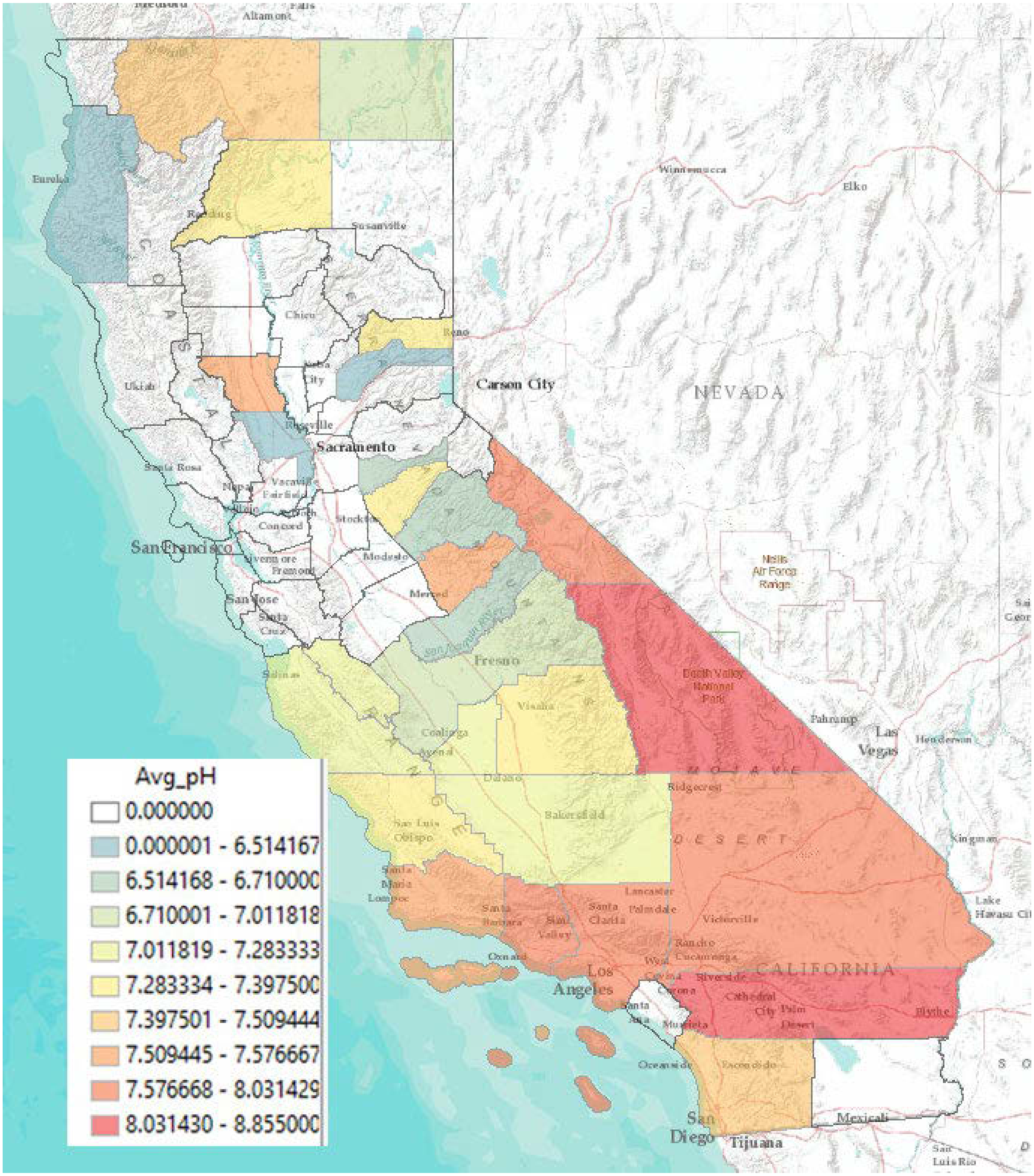


Fig. 5.5 Map of California separated into counties showing pH levels

The county map shown in **Fig. 5.5** below better shows the gradient of high to low pH from Southern California to Northern California. The southern counties where the lowest rainfall occurs contain Basic pH soil, while the northern counties and Sierra Nevada Mountain counties where the highest rainfalls occur are neutral or acidic. This graph also shows the sharp divide caused by the Sierra Nevada Mountains. The desert on the east side of the mountain range gets very little rain due to the mountains blocking the clouds. This causes much higher pH in the deserts as there is no acidic rain to lower the natural ph of the soil. The two highest pH counties in this area are Inyo and Riverside. Inyo has higher pH due to large deposits of dolomite which raise soil pH. Riverside contains the Salton Sea which is an extremely alkaline body of water with a pH of 8.8. The higher ph of the soil in these regions makes them less of an ideal environment for the corrosive sulphate reducing bacteria. However in neutral pH areas such as Central California the bacteria have ideal growth conditions and cause increased corrosion. This is only magnified by the high nutrient content of the agricultural land in this area which not only reduces the pH to an ideal environment for bacteria but also provides a food source for rapid growth. Finally in northern regions where soil pH is slightly acidic, bacteria growth is slowed but not stopped as the pH ranges present are well within the survivable conditions for most bacteria. By using multiple shapefiles to analyze the same data points different possible causes of the trends in corrosion factors can be shown in data analysis for which more in depth research can be made.

5.4 Corrosion

Comparing corrosion to rainfall shows the expected trend but has a larger number of outliers than the pH or Salinity comparisons showing a less direct correlation. Areas with higher rainfall should have higher corrosion as corrosion was originally thought to be mainly from the constant contact of water on the culverts. This remains true in areas of extremely low rainfall such as deserts, however the amount of rainfall past a certain threshold seems to have limited effect, as shown by the map in **Fig. 5.6** which shows similar corrosion in low rainfall Central California when compared to northern parts of the Sierra Nevadas and Northeast California. These all have similar corrosion despite varying levels of rainfall. This decreased effect of rainfall on corrosion is better shown in the county map.

Comparing corrosion to the county map better explains the influence of other outside factors on the corrosion rate of the pipes. While it would be expected that this state map would closely match that of the pH and salinity maps due to the increased corrosion effect of salinity and pH, many counties contradict the expected corrosion rate as seen in **Fig. 5.7**. Central California shows increased corrosion despite the low rainfall due to the high amount of agriculture there and neutral soil. The additional salt, fertilizer and water from agriculture cause these counties to have higher corrosion rates than expected. In the northern sections of the Sierra Nevadas, it would be expected that the culverts would all have high corrosion rates due to the high rainfall. However low salinity and high pH make the soil a poor environment for bacteria significantly slowing corrosion. This shows that the bacteriological component to corrosion may be a much larger factor than previously thought. The desert counties confirm this, as they have the lowest corrosion, and the least suitable environment for bacteriological growth. These counties contain high pH, and low soil moisture, making bacteriological growth near impossible. Due to this lack of bacteriological activity, there is very little corrosion in the pipes.

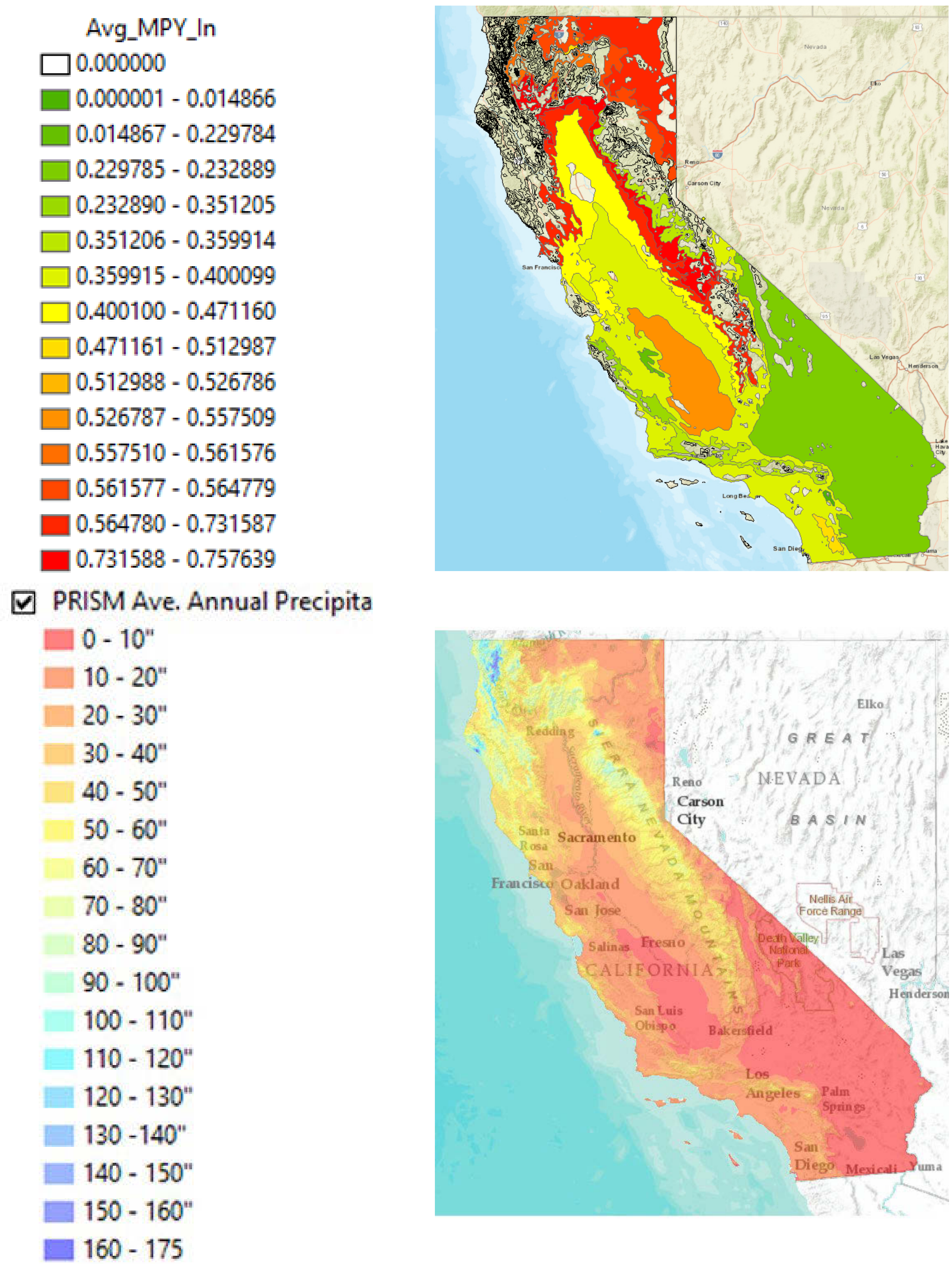


Fig. 5.6 Map of corrosion (top) vs. rainfall (bottom)

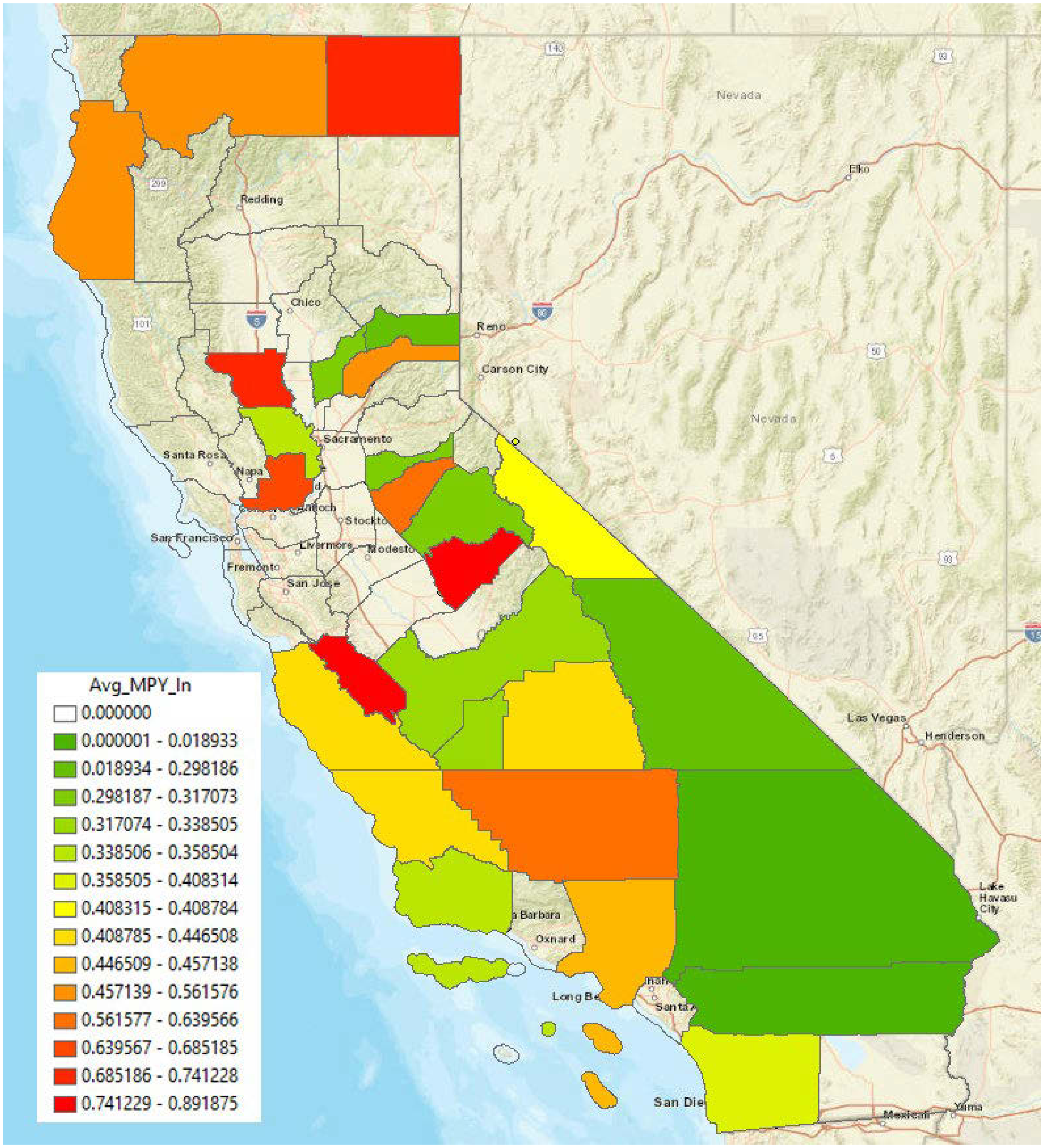


Fig. 5.7 Corrosion map of California measured in milli-inches per year

This page is left blank intentionally

Chapter 6: Service Life Equation

Non-linear multiple variable regression analysis was used to create a new service life equation. It was determined through the correlation of variables from Chapter 4 Data Analysis that the two major contributors to the estimation of years was the resistivity value and pH of the soil at the inlet of the culvert.

The matrix software developed by MathWorks called MATLAB was utilized due to an integrated non-linear regression function. The function nlinfit() was called by the syntax seen in **Fig. 6.1.** This function estimates the coefficients of the model equation specified. The model equation used in this project was a power function where the variables were raised to the power of a constant and summed together as illustrated in **Eq. (6.1)**. The values for the two dependent variable matrices are from the lab tests. The independent variable matrix is from the linear extrapolation of corrosion explained in Chapter 4. The code iterates the initial values for the constants and varies them to find a best fit model for the independent variable.

```
% EQUATION: y = ph^q + resist^r
% MAPPING: b(1) = q,  b(2) = r,  x(:,1) = pH,  x(:,2) = Resistivity
x = [ph(:), resist(:)];                 %Matrix x with pH values in column 1
                                        %and Resistivity Values in column 2
f = @(b,x) x(:,1).^b(1) + x(:,2).^b(2);%Model equation template
B0 = [1; 1];                            %Initial guess values for iteration
B = nlinfit(x, linlife, f, B0);         %Matrix B with final constants

newyears = x(:,1).^B(1) + x(:,2).^B(2);%Uses the new equation to get
                                        %estimated service life values
```

Fig. 6.1 Syntax for nonlinear regression function in MATLAB

By running the code for each individual land use, an equation for each land use can be obtained. Since there are two failure criteria, 15% and 25%, a total of ten equations equations were obtained which are illustrated on **Figs. 6.3 - 6.7** and summarized on **Table 6.1.** The previous Caltrans service life parametric equation is depicted in **Fig. 6.2.** This equation is separated by the soil pH value. When the pH is greater than 7.3, only the resistivity of the soil is considered to estimate the years to perforation. When the pH is less than 7.3, resistivity and pH of the soil is considered to estimate the years to perforation. Adversely, the CSUN equation distinguishes which equation to use according to the land use the culvert is placed in.

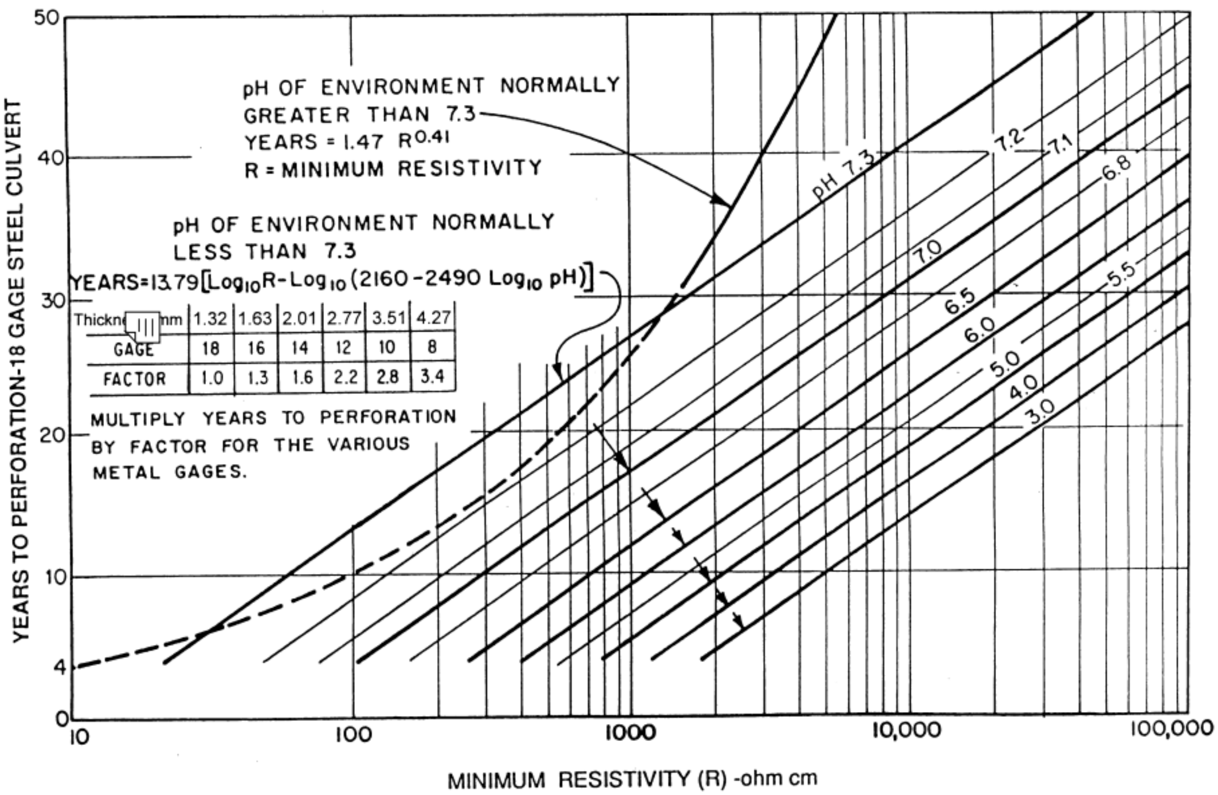


Fig. 6.2 Caltrans service life year chart

$$Years = pH^{a} + Resistivity^{b} \tag{6.1}$$

Table 6.1 Parameters for CSUN service life equation at 15% failure criteria (top) and 25% failure criteria (bottom) *

Land Use	**Exponent *a***	**Exponent *b***
Agriculture	-23.42	0.42
Coastal	-25.53	0.40
Forestland	-0.23	0.37
Rangeland	-40.79	0.39
Urban	-24.43	0.41

Land Use	**Exponent *a***	**Exponent *b***
Agriculture	-24.52	0.46
Coastal	-22.36	0.48
Forestland	0.298	0.42
Rangeland	-39.68	0.44
Urban	-22.89	0.47

The following figures seek to compare the estimations of the Caltrans equation and the CSUN equation. The blue triangles represent the linear extrapolation from corrosion data points described in Chapter 4.

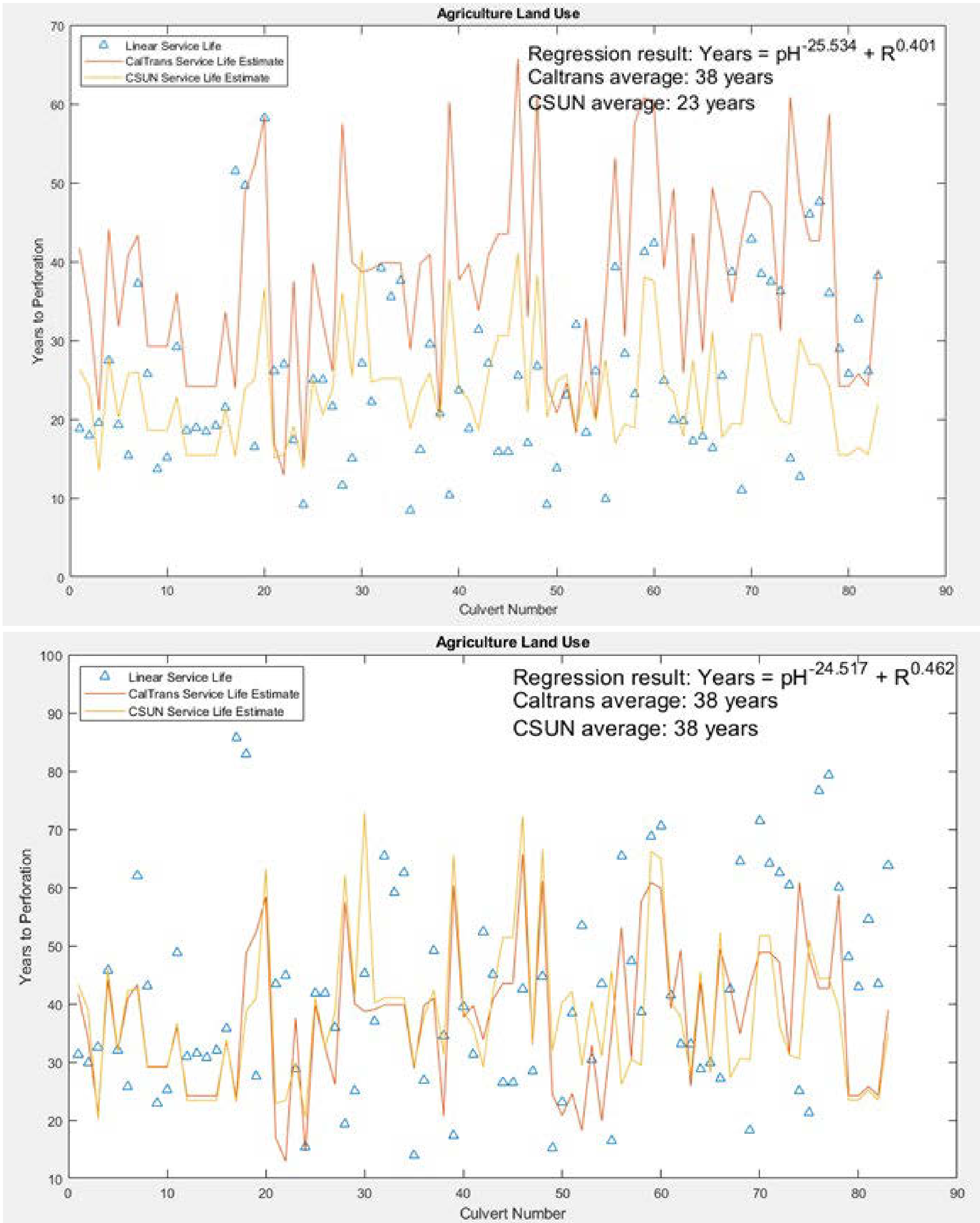


Fig. 6.3 Comparison of Caltrans and CSUN service life equations for Agriculture regions at 15% failure criteria (top) and 25% failure criteria (bottom) *

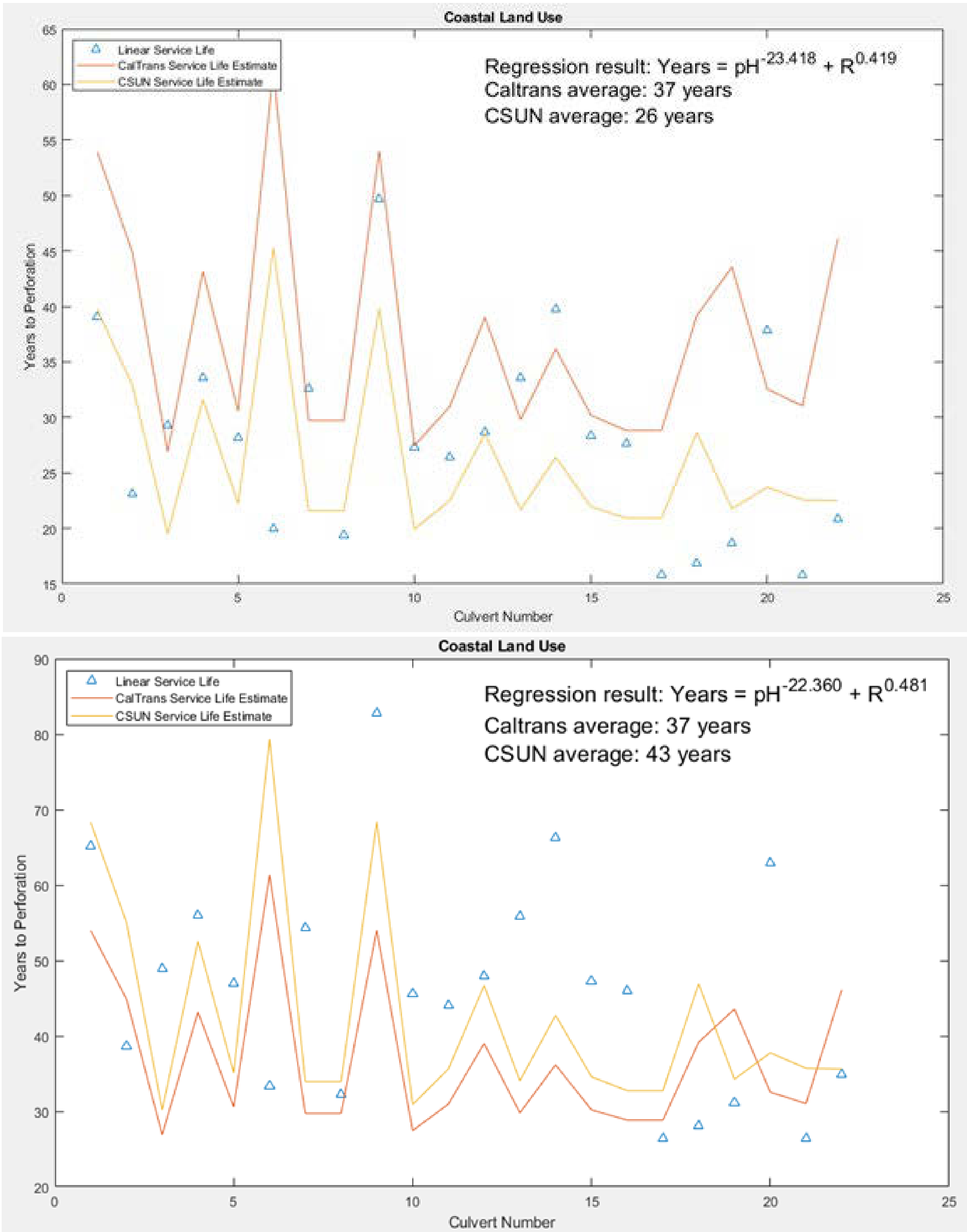


Fig. 6.4 Comparison of Caltrans and CSUN service life equations for Coastal regions at 15% failure criteria (top) and 25% failure criteria (bottom) *

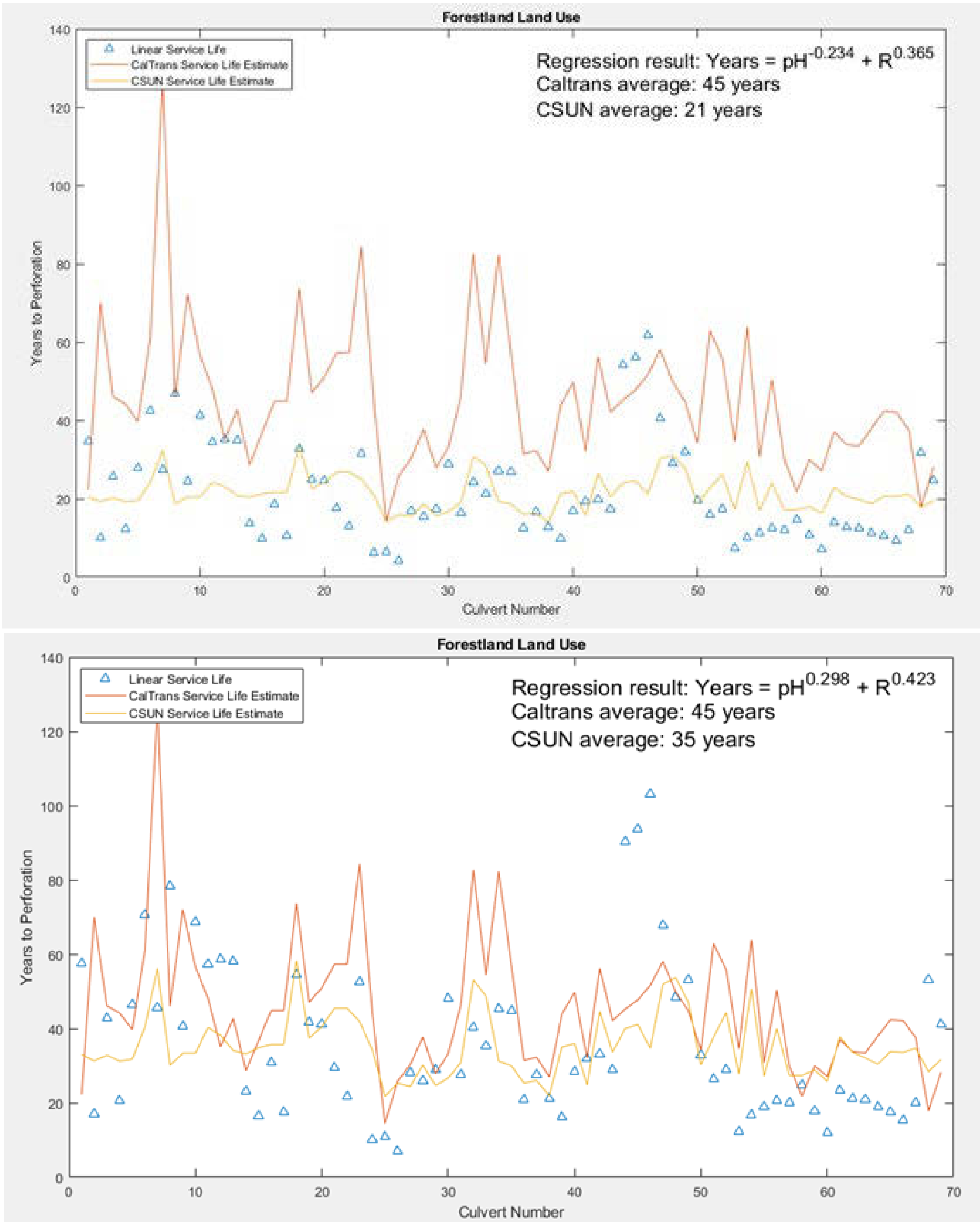


Fig. 6.5 Comparison of Caltrans and CSUN service life equations for Forestland regions at 15% failure criteria (top) and 25% failure criteria (bottom) *

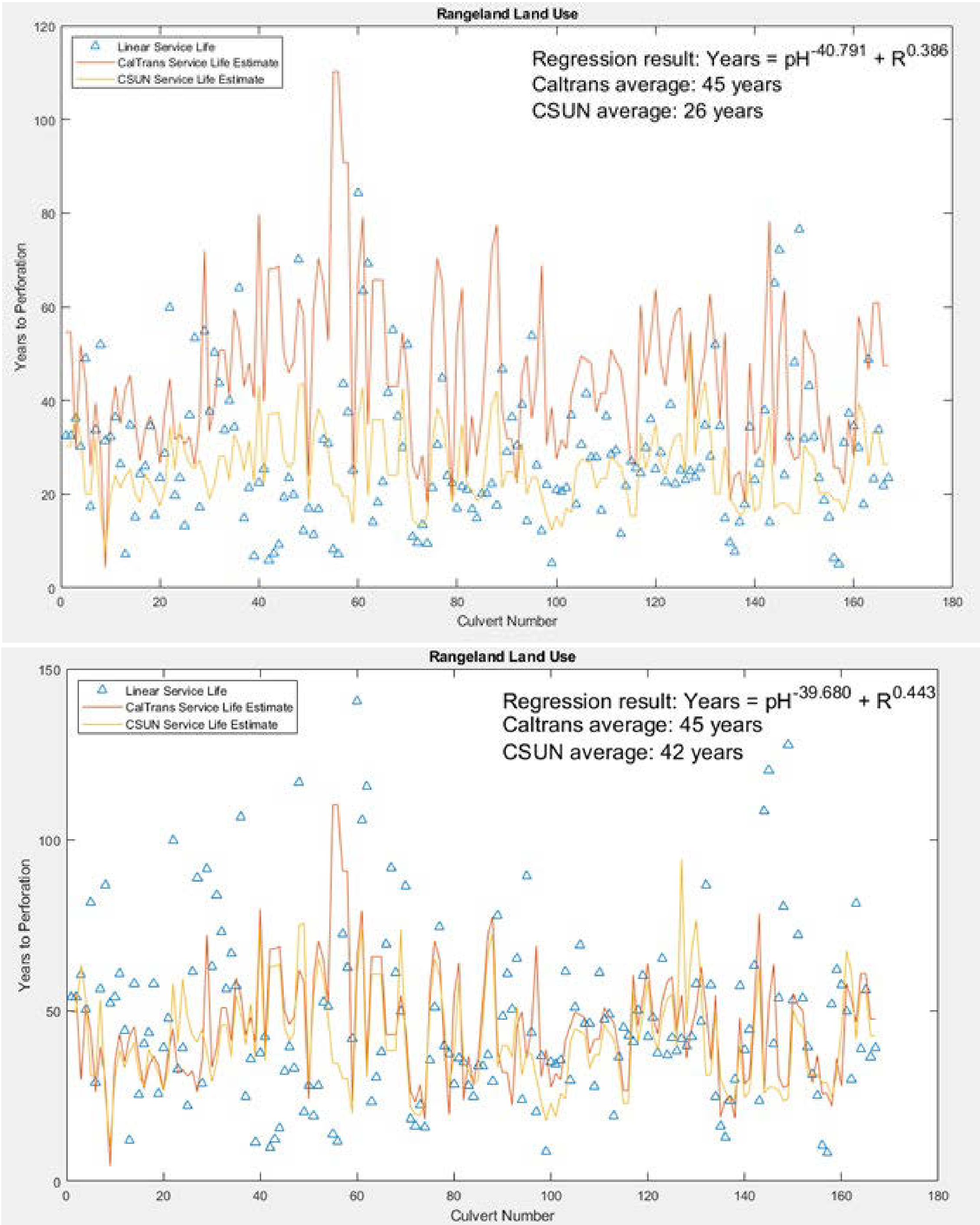


Fig. 6.6 Comparison of Caltrans and CSUN service life equations for Rangeland regions at 15% failure criteria (top) and 25% failure criteria (bottom) *

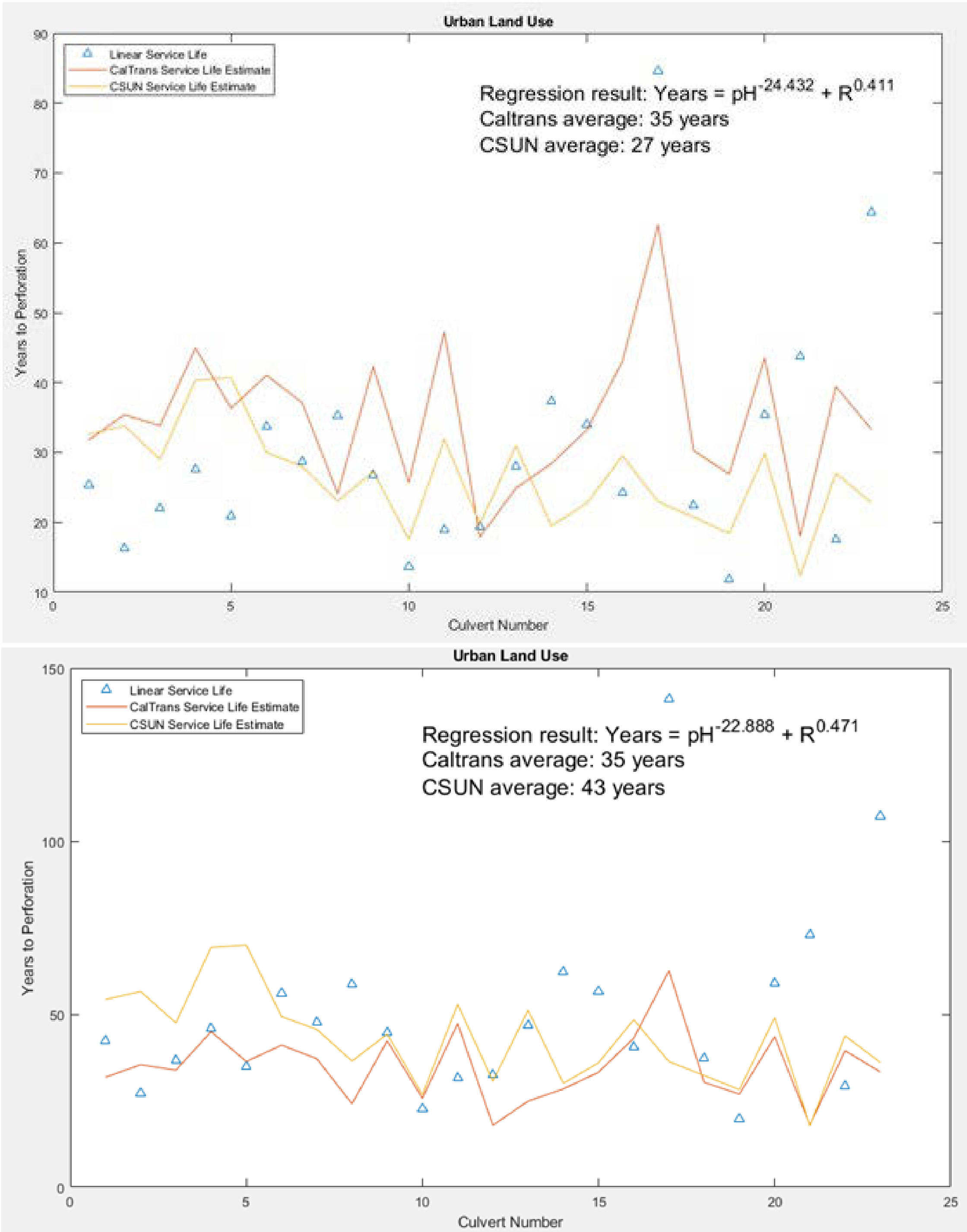


Fig. 6.7 Comparison of Caltrans and CSUN service life equations for Urban regions at 15% failure criteria (top) and 25% failure criteria (bottom) *

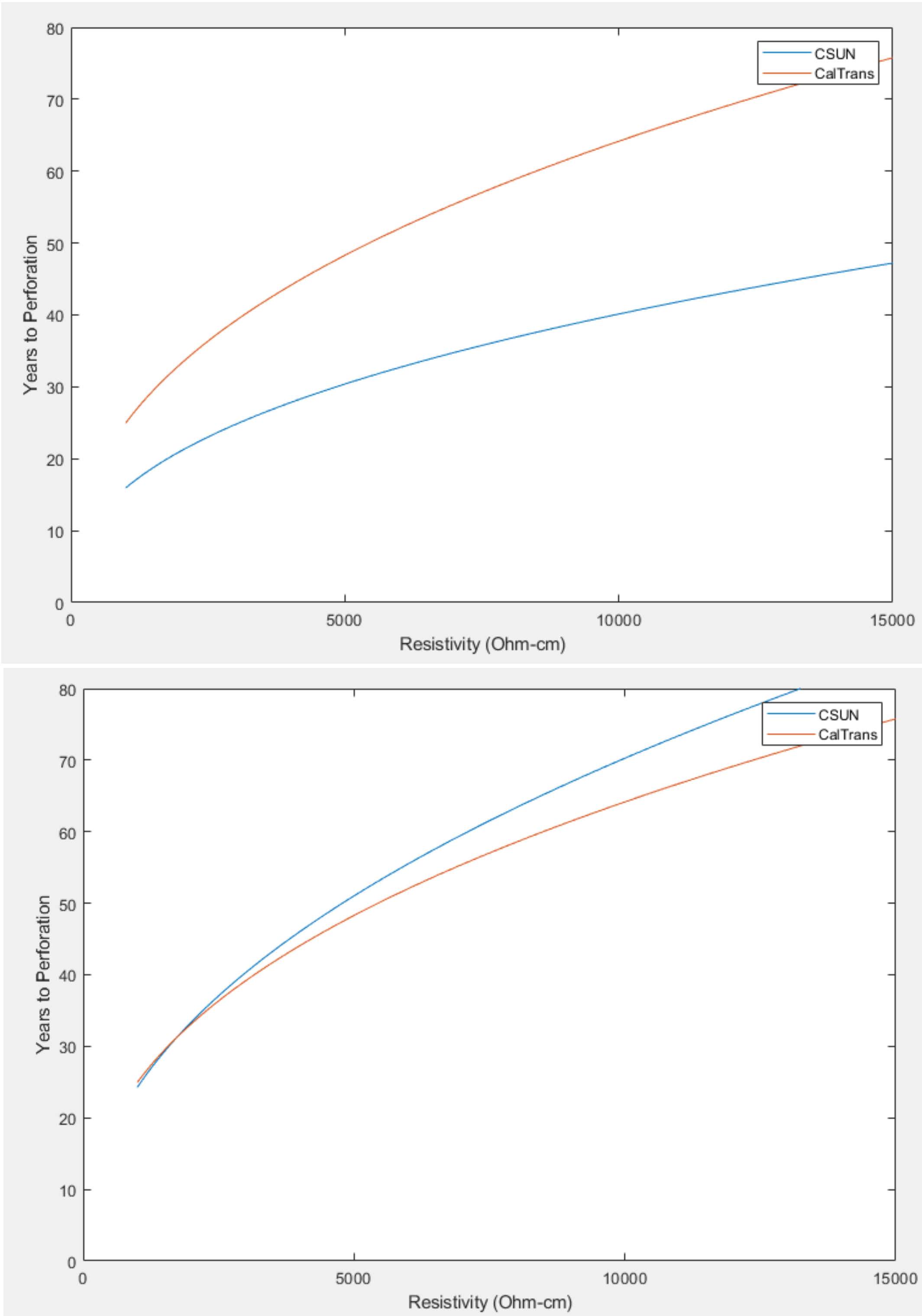


Fig. 6.8 Years vs. Resistivity with a constant pH of 7.5 at 15% failure criteria (top) and 25% failure criteria (bottom) *

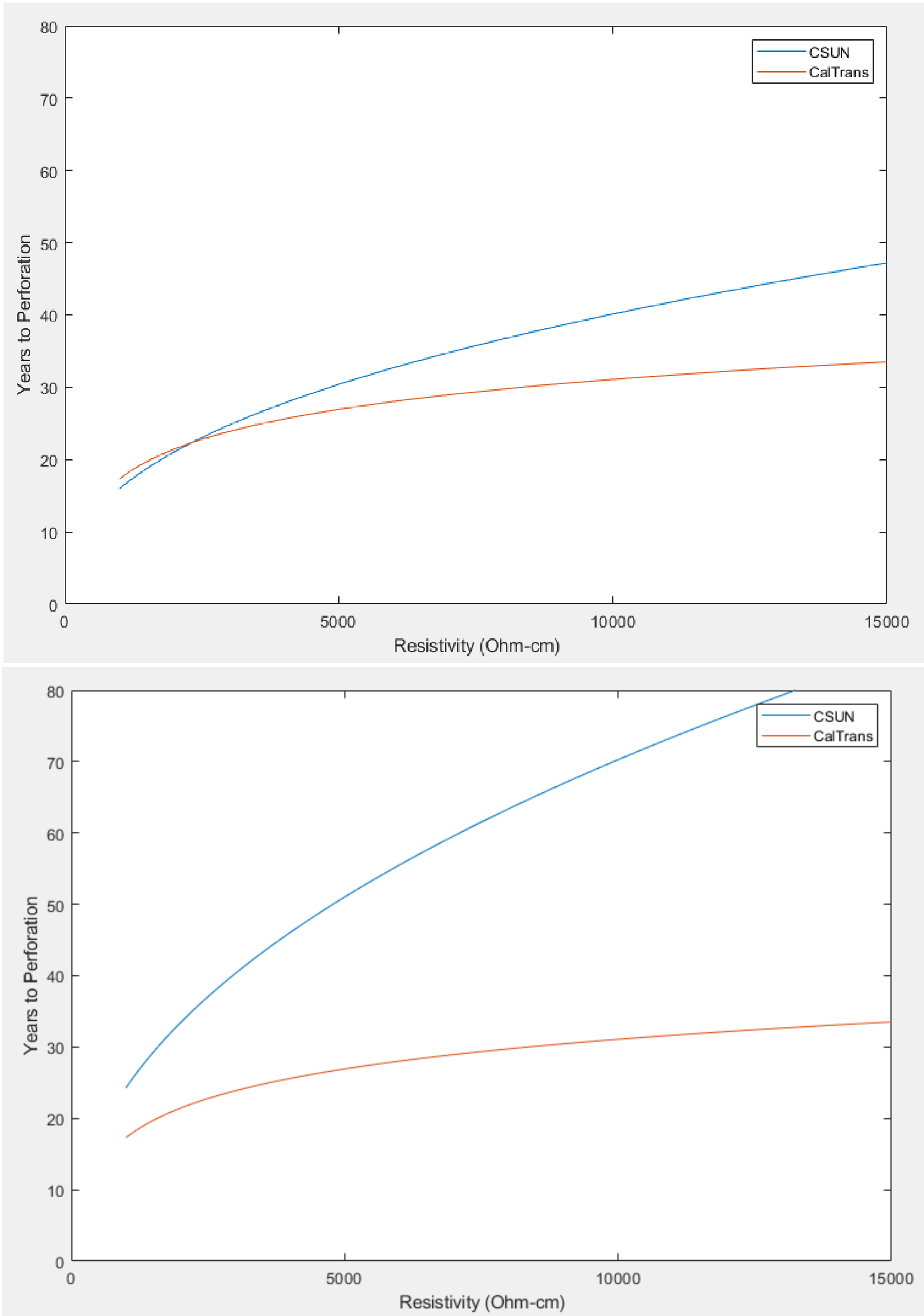


Fig. 6.9 Years vs. resistivity with a constant pH of 7 at 15% failure criteria (top) and 25% failure criteria (bottom)*

As it can be seen in **Fig. 6.3 - 6.7**, the 25% failure criteria is closer in estimated years to perforation values when compared to the standardized Caltrans equation while the 15% failure criteria generally gives more conservative estimated years to perforation. To visualize how the equations behave with different inputs, the two equations were plotted at a constant pH value. For reference, the Agriculture exponents were used for the CSUN curve at the two failure criteria percentages. **Figs. 6.8** and **6.9** shows that CSUN equation at resistivity ranges from 0 - 15,000 Ohm-cm with a constant pH of 7.5 and 7 respectively for the Agriculture regions. The resistivity range was chosen due to the minimum and maximum resistivity value in the raw data of 1,200 [Ohm-cm] and 14,000 [Ohm-cm] respectively for the Agriculture region. These figures illustrate the major differences between equations due to the parametric equation of the Caltrans equation. The average pH and resistivity value of the soil in the Agriculture region was 7.3 and 3,020 Ohm-cm respectively. The use of the 25% failure criteria CSUN equation when soil pH is above 7.3 and the 15% failure criteria CSUN equation when the soil pH is below 7.3 yields very similar values for the estimated years to perforation as the current standardized Caltrans equation. Compared to the Caltrans equation curve, The CSUN equation yields slightly conservative year values when soil resistivity is below 2,000 [Ohm-cm] and yields slightly liberal year values when above. At a soil pH value of above 7.3, the CSUN equation estimates more conservative year values to the Caltrans equation when using the 15% failure criteria for all resistivity values. At a soil pH value below 7.3, the CSUN equation estimates more liberal year values to the Caltrans equation when using the 25% failure criteria for all resistivity values.

* = Reason for use of 15% and 25% failure criteria can be found in Chapter 4.7

This page is left blank intentionally

Chapter 7: Conclusion

7.1 Field Observations

A total of 500 culvert sites across California were observed and itemized. At these locations, soil at the inlet side of the culvert was collected and tested for soil pH, soil Total Dissolved Solids (TDS), soil chloride content, soil sulphate content, and soil resistivity. Observationally, many of the corroded culverts had soil sitting in the 6 o'clock of the inlet of the culvert. Standing soil leads to standing water at the inlet. Water accelerates the corrosion of steel as well as increases bacteriological activity at the soil culvert barrier. Constant flowing of water through the culvert does not negatively affect culvert corrosion. Throughout the many field outings, rusted and failed culverts were more common in the agriculture and coastal regions.

7.2 ArcGIS

ArcGIS provided a means to quickly integrate online database information with empirical observations and data to generate new trends and hypothesis in the corrosion of the corrugated steel pipes. It shows that rainfall has a direct effect on both pH and salinity, but this effect is not absolute and can be diminished by other factors such as proximity to saltwater or local land conditions such as farms and cities. These general trends generated in ArcGIS contribute more factors to visualize the behavior with the existing Caltrans corrosion formula, and may provide additional corrections to the final revised formula. In addition, a software using average corrosion factor, rainfall and other data could be used to define design parameters for a 50 year life expectancy using GPS location to expedite the rehabilitation and new installation of culverts throughout California. In addition, ArcGIS provided a means of finding the ideal order to efficiently collect data, as well as ensuring that an even amount of culverts were taken from each area of California providing a good variety for the entire state of California as opposed to 7,000 culverts from a single district. Finally, the highest corrosion counties are those that have a near neutral pH with low salinity and moderate to high rainfall. These factors combine to provide an environment which allows bacteria to thrive, causing large amounts of corrosion in the pipe. This ArcGIS data agrees with field observations which showed that the majority of corrosion found in the corrugated steel pipes was found at the soil culvert barrier where bacteria actively break down and oxidize the steel.

7.3 Service Life Equation

MATLAB provided a means to incur non-linear regression of multiple variables to generate new service life prediction equations. This matrix software was used to iterate our dependent variables, soil pH and soil resistivity [Ohm-cm], to an exponent and find the best fit. The result was an equation whose exponents differ depending on the type of land the culvert is placed. The standardized equation current to this report changes equation depending on the soil pH level.

A table of all the exponent values correlating to each land use can be seen on **Table 7.1.**

Table 7.1 CSUN service life equation and the exponents at 15% failure criteria (top) and 25% failure criteria (bottom) *

$$Years = pH^{a} + Resistivity^{b}$$

Land Use	**Exponent *a***	**Exponent *b***
Agriculture	-23.42	0.42
Coastal	-25.53	0.40
Forestland	-0.23	0.37
Rangeland	-40.79	0.39
Urban	-24.43	0.41

$$Years = pH^{a} + Resistivity^{b}$$

Land Use	**Exponent *a***	**Exponent *b***
Agriculture	-24.52	0.46
Coastal	-22.36	0.48
Forestland	0.298	0.42
Rangeland	-39.68	0.44
Urban	-22.89	0.47

In the case that the only information available for culvert installation is the land use, **Table 7.2** can be used. This table averages the prediction years using both equations to give an approximation of the years until perforation. The difference in predicted years ranged from 8-15 years between the CSUN equation and the Caltrans equation.

Table 7.2 Average service life predictions for different land uses

Land use	CSUN equation at 15% failure criteria	CSUN equation at 25% failure criteria	Caltrans equation
Agriculture	23	38	38
Coastal	26	43	37
Forestland	21	35	45
Rangeland	26	42	45
Urban	27	43	35

When the new CSUN equation is compared with the standardized Caltrans equation, many relationships can be seen. At pH values over 7.3, the 15% failure criteria CSUN equation provides more conservative estimated years to perforation values than the Caltrans equation and the 25% failure criteria CSUN equation closely estimates similar estimated years to perforation values as the Caltrans equation. At a pH values under 7.3, the 15% failure criteria CSUN equation closely estimates similar estimated years to perforation values as the Caltrans equation and the 25% failure criteria CSUN equation provides more liberal estimated years to perforation values than the Caltrans equation.

7.4 Future Work

Given the limited time of the project, not all solutions could be visited. Parameters that would be considered, had the research effort continued, would be mechanical abrasion of the culvert and slope of the culvert. It can be noted that interactions of the soil and culvert structure ought to be considered to yield a more accurate model. Finding the cause of soil buildup in the 6 o'clock of the culvert and solution to this problem may increase culvert life expectancy. Increasing the sample size can increase the accuracy of the service life model. More sites in the desert would allow for the addition of a desert region to the equation.

* = Reason for use of 15% and 25% failure criteria can be found in Chapter 4.7

This page is left blank intentionally

References

Anderson, James R. Hardy, Ernest E. Roach, John T. and Witmer, Richard E. "A Land Use and Land Cover Classification System for Use with Remote Sensor Data" *Geological Survey Professional Paper 964*. 1976.

A.Rajasekar, S.Maruthamuthu, N.Muthukuma r, S.Mohanan, P.Subramanian ,N.Palaniswamy" Bacterial degradation of naphtha and its influence on corrosion" Corrosion Science and Engineering Division, Central Electrochemical Research Institute.July 2004rcgi

Beaton, J. Corrosion of Corrugated Metal Culverts in California. *Onlinepubs.trb.org/Onlinepubs/hrbbulletin/223/223-001.pdf.*

Beaton, J.L. and R.F. Stratfull (1962). "Field Test for Estimating the Service Life of Corrugated Metal Pipe Culverts", Report 62-06.

Beben, Damian. "Backfill Corrosivity around Corrugated Steel Plate Culverts." *Journal of Performance of Constructed Facilities*, vol. 29, no. 6, 2015

Bednar, Lawrence. "Plain Galvanized Steel Drainage Pipe Durability Estimation with a Modified California Chart ." *Online Pubs*, 1990, onlinepubs.trb.org/Onlinepubs/trr/1989/1231/1231-007.pdf.

Betlair, Peter J., and James P Ewing. "Metal-Loss Rates of Tlneoated Steet A.r'd Aluminum Culverts in New York." *Transportaion Research Record*, onlinepubs.trb.org/Onlinepubs/trr/1984/1001/1001-009.pdf

California Department of Transportation (Caltrans), *Method for Estimating the Service Life of Steel Culverts*, Caltrans, Sacramento, 1999.

California Department of Transportation (Caltrans), *Corrosion Guidelines, Version 3.0,* Caltrans Division of Engineering Services, Materials Engineering and Testing Services, Corrosion Branch, Sacramento, 2018.

Doyle, Garry. (2000) "The Role of Soil in the External Corrosion of Cast-Iron Water Mains in Toronto, Canada." *National Library of Canada,* University of Toronto.

Eker, Bülent & Yuksel, E. (2005). Solutions to corrosion caused by agricultural chemicals. Trakia J. Sci.. 3.

Gabriel, Lester H. "Service Life of Drainage Pipe." *Synthesis of Highway Practice*, vol. 254, 1998, doi:1/9/2018.

Galtung-Døsvig, T. Durability of buried galvanized steel structures in British Columbia (T). 1995. *Retrieved from* *https://open.library.ubc.ca/collections/ubctheses/831/items/1.0050395*

Glibert, P.M., Harrison, J., Heil, C. et al. Biogeochemistry (2006) 77: 441. https://doi.org/10.1007/s10533-005-3070-5

Hadipriono, Fabian C., et al. "Service Life Assessment of Concrete Pipe Culvert." *ASCE Library: Journal of Transportation Engineering / Volume 114 Issue 2- March 1998* , 1 Mar. 1998, ascelibrary.org/doi/abs/10.1061/%28ASCE%290733-947X%281988%29114%3A2%28209%29.

Halmen, C., Trejo, D., & Folliard, K. (2008, May). Service Life of Corroding Galvanized Culverts Embedded in Controlled Low-Strength Materials. Retrieved January 28, 2019, from https://ascelibrary.org/doi/abs/10.1061/(ASCE)0899-1561(2008)20:5(366)

Heitkamp, B., and Marr J. Minnesota Steel Culvert Pipe Service-Life Map. *Minnesota Department of Transportation.* 2015

Hurd, John O. "Field Performance of Concrete and Corrugated Steel Pipe Culverts and Bituminous Protection of Corrugated Steel Pipe Culverts." *Online Pubs*, Transportation Research Record 1001, onlinepubs.trb.org/Onlinepubs/trr/1984/1001/1001-007.pdf.

Hurd, John O. "Service Life Model Verification for Concrete Pipe Culverts in Ohio." *Online Pubs*, Transportation Research Record 1191, 1984, onlinepubs.trb.org/Onlinepubs/trr/1988/1191/1191-014.pdf.

I.A. Denison. "Correlation of Certain Soil Characteristics with pipeline corrosion". June 1931
Jacobs, Kenneth M. (1982) "Durability of Drainage Structures, Final Report." Transportation Research Board.

Katona, Michael G. "Influence of Soil Models on Structural Performance of Buried Culverts." International Journal of Geomechanics, vol. 17, no. 1. January 2017.

Kuneki, B. & Janusz L. "The Effect of Corrosion and Time on the Behavior of a Steel Culvert." *Shell Structures: Theory and Applications Volume 4*, vol. 4, 2018.

Matthew , John C., et al. "Decision Analysis for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology." *National Technology & Development Program* , United States Department of Agriculture , 2012, https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf11771810/pdf11771810Pdpi72.pdf.

Meegoda, Jay, and Thomas Juliano. " CORRUGATED STEEL CULVERT PIPE DETERIORATION ." *Corrugated Steel Culvert Pipe Deterioration*, 2009.

Missouri DOT (1987) "Study of Use, Durability, and Cost of Corrugated Steel Pipe on the Missouri Highway and Transportation Department's Highway System", Report MR 87-1.

Molinas, Albert Mommandi, Amanullah. "Development of New Corrosion / Abrasion Guidelines for Selection of Culvert Pipe Materials" Colorado Department of Transportation DTD Applied Research and Innovation Branch. November 2009

Omar Chaallal, Mohsen Shahawy, William Nickas. " Performance evaluation of flexible metal pipes for gravity application" U.S FDOT structures Research center. April 2000

Schall, James D. Richardson, Everett V. and Morris, Johnny L. "Introduction to Highway Hydraulics: Hydraulic Design Series Number 4, Fourth Edition." Report No. FHWA-NHI-08-090 (HDS-4). *U.S. Department of Transportation*. June 2008.

Sheldon, Timothy, et al. "Joint Response of Existing Pipe Culverts under Surface Live Loads." *Journal of Performance of Constructed Facilities*, vol. 29, no. 1, 2013, pp.

SUN Cheng, LI Xi-Ming, XU Jin, YAN Mao-Cheng, WANG Fu-Hui, WANG Zhen-Yao. Effect of Urea on Microbiologically Induced Corrosion of Carbon Steel in Soil. *Acta Phys. -Chim. Sin.*, 2012, 28(11): 2659-2668.

Tang, S. et al. (2012). Study of Corrosion in Ground Gathering Pipeline Networks and Anti-Corrosion Method in Tazhong-1 Gas Field. *International Conference on Pipelines and Trenchless Technology.* *https://ascelibrary.org/doi/abs/10.1061/9780784412619.020?src=recsys*

Temple, W.H., Rasoulian, M., and Gueho, B.J. (1981) "Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation", Louisiana DOT. Interim Report No.3.

Tewari, Sanjay. Corrosion Map for Metal Pipes in Coastal Louisiana. Louisiana Transport Research Center. Final Report 585. 2017.

USACERL. Remote Underground Storage Tank Inspection/Assessment System . June 1998, apps.dtic.mil/dtic/tr/fulltext/u2/a637451.pdf.

Yahaya, N. et al. (2013). The Relationship between Soil Resistivity and Corrosion Growth in Tropical Region. *The Journal of Corrosion Science and Engineering*, *16(54), 1.* .*https://www.researchgate.net/publication/270310264_The_Relationship_between_Soil_Resistivity_and_Corrosion_Growth_in_Tropical_Region*

Zhou, L. et al. (2011). Factor Analysis about Soil Corrosion of Buried Metal Pipe. *International Conference on Pipelines and Trenchless Technology.* https://ascelibrary.org/doi/10.1061/41202%28423%2914

Appendix

Appendix A. Raw Data for Analysis

	Culvert Built Date	6 o'clock [in.]	12 o'clock [in.]	Salinity(ppm)	TDS(ppm)	pH	Resistivity (Ohm-cm)	Land Use
AMA-88(5.39)	1,940	0.069	0.068	110	166	5.38	3,480	Forestland
CAL-4(29.25)	1,977	0.067	0.109	165	242	7.27	3,005	Forestland
CAL-4(35.83)	1,977	0.1	0.1	208	309	6.7	3,400	Forestland
CAL-4(40.47)	1,977	0.078	0.108	153	226	6.69	3,000	Forestland
CAL-4(8.55)	1,977	0.116	0.118	121	183	7.95	3,100	Forestland
FRE-168 (18.39)	1,962	0.109	0.106	206	306	7	5,660	Forestland
FRE-168 (20.04)	1,962	0.128	0.15	48.9	71.6	7.2	12,800	Forestland
FRE-180(79.99)	1,958	0.121	0.12	512	746	6.26	2,740	Forestland
FRE-180(87.22)A	1,958	0.113	0.141	123	189	7.05	3,530	Forestland
FRE-180(87.22)B	1,958	0.11	0.11	123	189	7.05	3,530	Forestland
FRE-180(88.05)	1,958	0.089	0.088	103	168	7.12	5,640	Forestland
FRE-180(88.94)	1,958	0.085	0.082	92.5	140	6.55	4,960	Forestland
FRE-198 (11.58)	1,965	0.085	0.079	217	307	7.86	3,710	Forestland
HUM-96(15.17)	1,989	0.074	0.073	130	191	6.26	3,500	Forestland
HUM-96(9.71)	1,989	0.068	0.079	103	157	6.81	3,940	Forestland
MPA-140(10.5)A	1,966	0.093	0.119	129	192	7.54	4,180	Forestland
MPA-140(10.5)B	1,966	0.055	0.118	129	192	7.54	4,180	Forestland
MPA-140(11.6)	1,966	0.107	0.109	39.9	61.4	7.33	14,000	Forestland
MPA-140(11.7)	1,966	0.099	0.109	150	220	7.48	4,700	Forestland
MPA-140(23.6)	1,966	0.074	0.073	94	141	8.1	5,680	Forestland
MPA-140(24.8)A	1,966	0.057	0.059	105	151	8.08	7,580	Forestland

MPA-140(24.8)B	1,966	0.053	0.072	105	151	8.08	7,580	Forestland
MPA-140(26.1)	1,966	0.103	0.105	94	140	7.3	6,200	Forestland
MOD-139(12.85)	1,990	0.049	0.08	135	205	7.12	3,770	Forestland
MOD-139(3.98)	1,990	0.048	0.068	398	469	6.19	1,200	Forestland
MOD-139(4.59)	1,990	0.025	0.078	200	299	6.6	1,760	Forestland
MOD-299(24.75)	1,982	0.079	0.081	77.1	118	7.34	1,600	Forestland
MOD-299(24.89)	1,982	0.069	0.069	109	166	7.54	2,730	Forestland
MOD-299(25.03)	1,982	0.084	0.087	109	172	6.78	1,650	Forestland
MOD-299(25.50)	1,982	0.115	0.112	145	266	7.65	2,000	Forestland
MOD-299(26.05)	1,982	0.1	0.113	124	191	6.8	2,890	Forestland
MOD-299(26.18)	1,982	0.135	0.143	549	6,130.00	6.84	11,180	Forestland
MOD-299(26.28)	1,982	0.109	0.114	646	447	6.44	9,040	Forestland
MOD-299(26.69)	1,982	0.165	0.176	6,180.00	7,900.00	7.02	2,990	Forestland
MOD-299(28.55)	1,982	0.135	0.139	560	802	6.78	2,700	Forestland
MOD-299(30.52)	1,982	0.071	0.083	5,120.00	6,410.00	8.03	1,750	Forestland
MOD-299(31.59)	1,982	0.082	0.086	220	297	8.68	1,870	Forestland
MOD-299(32.04)	1,982	0.058	0.059	165	247	7.45	1,210	Forestland
MOD-299(32.43)	1,982	0.069	0.085					Forestland
MOD-299(32.45)	1,982	0.052	0.063	140	207	8.19	3,960	Forestland
MOD-299(32.74)	1,982	0.084	0.088	207	293	7.21	4,270	Forestland

MOD-299(33.03)	1,982	0.088	0.089	111	170	6.98	1,670	Forestland
MOD-299(33.17)	1,982	0.096	0.099	58.8	98.4	8.25	7,230	Forestland
MOD-299(33.38)	1,982	0.097	0.106	160	233	8.23	3,580	Forestland
NEV-174(0.29)	1,931	0.109	0.112	585	833	6.24	5,560	Forestland
NEV-174(0.33)	1,931	0.11	0.112	515	740	6.36	5,950	Forestland
NEV-174(0.59)	1,931	0.11	0.109	573	812	6.86	3,900	Forestland
NEV-174(4.09)	1,931	0.098	0.109	485	695	6.54	10,600	Forestland
NEV-174(4.27)	1,931	0.084	0.109	4,950.00	6,200.00	5.79	11,500	Forestland
NEV-174(4.31)	1,931	0.089	0.11	483	694	5.69	8,390	Forestland
NEV-49(2.89)	1,960	0.068	0.079	270	395	6.86	2,760	Forestland
NEV-49(5.00)	1,960	0.079	0.122	83.5	124.7	6.64	4,790	Forestland
NEV-49(5.50)	1,960	0.085	0.122	87.8	130	7.93	7,120	Forestland
NEV-49(8.02)	1,960	0.07	0.078	197	288	6.54	3,900	Forestland
RIV-79(2.2)		0.065	0.07	477	641	8.91	16,800	Forestland
RIV-79(2.3)		0.06	0.064	539	767	8.04	6,380	Forestland
SBD-173(2.51)		0.102	0.078	468	674	6.88	12,000	Forestland
SBD-173(2.66)		0	0.091	257	364	6.18	2,800	Forestland
SBD-173(2.85)		0.034	0.07	138	212	6.69	5,440	Forestland
SBD-173(2.96)		0.089	0.098	94	142	7.12	6,630	Forestland
SBD-173(3.06)		0.069	0.076	101	161	6.85	6,380	Forestland
SBD-173(3.13)		0.069	0.123	43.1	69.6	7.38	12,100	Forestland
SBD-173(4.16)		0.075	0.094	29.8	44.8	6.84	19,600	Forestland
SBD-173(4.46)			0.138	19.5	30.4	7.1	16,400	Forestland
SBD-173(4.88)		0.086	0.108	72.1	96.8	6.59	8,260	Forestland
SBD-173(4.89)		0.062	0.087	63.4	96.6	6.67	12,600	Forestland
SBD-173(5.28)		0.094	0.089	233	350	6.95	3,610	Forestland
SBD-173(5.55)A		0.076	0.093	70.7	107.7	6.65	8,260	Forestland
SBD-173(5.55)B		0.103	0.109	70.7	107.7	6.65	8,260	Forestland

SBD-173(5.68)A		0.082	0.136	26.8	43.8	7.18	15,400	Forestland
SBD-173(5.68)B		0.115	0.143	26.8	43.8	7.18	15,400	Forestland
SBD-173(6.65)		0.096	0.092	48.7	76.9	7.25	9,200	Forestland
SBD-173(7.4)A		0.035	0.14	46.3	73.9	8.74	12,800	Forestland
SBD-173(7.4)B		0.052	0.137	46.3	73.9	8.74	12,800	Forestland
SBD-173(7.52)		0.091	0.089	114	182	6.91	4,640	Forestland
SBT-25 (17.57)	1,999	0.064	0.065	154	236	7.72	2,210	Forestland
SIS-97(10.29)	1,990	0.064	0.069	46.2	70	8.24	9,890	Forestland
SIS-97(13.23)	1,990	0.063	0.062	19.8	31.8	7.1	2,100	Forestland
SIS-97(17.08)	1,990	0.069	0.068	93.4	142	7.38	5,530	Forestland
SIS-97(20.05)	1,990	0.071	0.076	186	278	6.48		Forestland
SIS-97(22.83)	1,990	0.074	0.077	220	324	6.75	2,150	Forestland
SIS-97(23.30)	1,990	0.082	0.081	5,080.00	888	6	2,160	Forestland
SIS-97(27.38)	1,990	0.072	0.079	638	915	6.67	2,460	Forestland
SIS-97(29.58)	1,990	0.108	0.109					Forestland
SIS-97(30.22)	1,990	0.056	0.077	650	924	6.66	1,850	Forestland
SIS-97(5.58)	1,990	0.072	0.073					Forestland
SIS-97(5.69)	1,990	0.078	0.077	479	695	6.71	4,830	Forestland
SIS-97(5.79)	1,990	0.073	0.073	487	718	6.68	3,620	Forestland
SIS-97(8.79)	1,990	0.074	0.075	522	753	6.73	3,210	Forestland
SIS-97(8.94)	1,990	0.065	0.065	524	763	8	2,780	Forestland
SIS-97(9.15)	1,990	0.063	0.065	4,880.00	6,200.00	8.05	3,630	Forestland
SIS-97(9.28)	1,990	0.059	0.064	461	669	7.78	3,580	Forestland
SIS-97(9.50)	1,990	0.072	0.074	456	664	6.86	3,910	Forestland
YOL-16 (22.35)	1,964	0.068	0.059	61	76	5.9	2,370	Forestland
YUB-20(19.25)	1,963	0.07	0.069	57.7	83.3	6.33	3,110	Forestland
SBD-395 (52.00)	1,955	0.083	0.096	105	155	8.8	6,740	Rangeland
SBD-395 (52.00)	1,955	0.083	0.096	105	155	8.8	6,740	Rangeland

AMA-124(1.44)	1,955	0.066	0.069	43.3	65.3	5.81	11,700	Rangeland
AMA-124(1.72)	1,955	0.07	0.08	70.5	106.4	7.13	7,970	Rangeland
AMA-124(10.13)	1,960		-	81.7	121.8	6.74	5,300	Rangeland
AMA-124(2.48)A	1,960	0.103	0.107	178	270	6.84	2,300	Rangeland
AMA-124(2.48)B	1,965	0.052	0.068	178	270	6.84	2,300	Rangeland
AMA-124(4.34)	1,965	0.08	0.085	50.3	75.3	6.54	7,880	Rangeland
AMA-88(0.98)	1,955	0.096	0.099	357	513	7.37	1,510	Rangeland
AMA-88(1.91)	1,955	0.066	0.073	4,840.00	5,950.00	6.62	184	Rangeland
AMA-88(10.66)	1,960	0.072	0.078	333	490	6.99	2,260	Rangeland
AMA-88(11.00)	1,960	0.066	0.067	193	286	7.09	3,750	Rangeland
AMA-88(11.12)	1,960	0.062	0.07	265	386	6.9	2,740	Rangeland
CAL-4(22.97)	1,977		-	72.8	107.5	7.05	6,800	Rangeland
CAL-4(23.05)	1,977		-	38.9	57	6.85	11,500	Rangeland
CAL-4(23.84)	1,977		-	101	155	7.8	3,880	Rangeland
CAL-4(26.49)	1,977		-	150	220	7.21	3,520	Rangeland
CAL-4(26.75)	1,977		-	78	116	7.35	5,230	Rangeland
CAL-4(28.74)	1,977		-	84.5	127.8	8.18	5,010	Rangeland
COL-16(0.24)	1,961	0.086	0.072	63.3	96.6	7.78	2,300	Rangeland
COL-16(0.50)	1,961	0	0.081	67.8	101.4	7.72	3,620	Rangeland
COL-16(0.62)	1,961	0.064	0.065	80	120	7.88	4,290	Rangeland
COL-16(1.30)	1,961	0.045	0.069	99	148	7.54	2,350	Rangeland
COL-16(1.38)	1,961	0.048	0.051	125	185	7	1,820	Rangeland
COL-16(1.43)	1,961	0.058	0.064	91.5	112.6	7.03	3,850	Rangeland
COL-16(1.48)	1,961	0.079	0.085	200	296	6.93	3,070	Rangeland
COL-16(1.58)	1,961	0.048	0.074	93	120	6.9	2,440	Rangeland
COL-16(1.61)	1,961		-	100	140	6.96	2,410	Rangeland
COL-16(3.08)	1,961	0.06	0.071	58	75	6.7	1,650	Rangeland
COL-16(4.48)	1,961	0.062	0.067	53	89.1	7.46	2,690	Rangeland

FRE- 168 (27.74)	1,962	0.113	0.114	496	715	5.47	9,540	Rangeland
FRE-168 ((24.4)	1,962	0.054	0.068	4,780.00	5,910.00	6.37	4,290	Rangeland
FRE-168 (24.87)	1,962	0.058	0.067	5,540.00	6,880.00	5.43	10,100	Rangeland
FRE-168(27.43)	1,962	0.037	0.06	477	702	5.84	6,220	Rangeland
FRE-180(87.52)	1,958	0.08	0.086	92.6	142	6.32	4,820	Rangeland
FRE-180(89.27)	1,958	0.074	0.071	100	168	5.69	4,330	Rangeland
FRE-180(89.33)	1,958	0.068	0.111	104	175	5.28	5,260	Rangeland
FRE-198 (13.58)	1,965	0.097	0.096				4,050	Rangeland
FRE-198 (20.21)	1,965	0.082	0.083				2,910	Rangeland
FRE-198 (22.81)	1,965	0.069	0.075				1,520	Rangeland
FRE-198 (5.42)	1,965	0.127	0.131	222	154	7.04	3,620	Rangeland
FRE-198 (7.86)	1,965	0.086	0.09	260	383	7.48	2,030	Rangeland
FRE-198 (8.20)	1,965	0.084	0.082	194	280	7.34	3,000	Rangeland
FRE-198 (9.91) A	1,965	0.069	0.066	125	189	7.81	5,640	Rangeland
FRE-198 (9.91) B	1,965	0.067	0.068	125	189	7.58	5,640	Rangeland
IYO-127(21.04)	1,948	0.074	0.08	125	184	9.23	3,380	Rangeland
IYO-127(21.74)	1,948	0.058	0.062	56	93.6	8.86	8,310	Rangeland
IYO-127(21.87)	1,948	0.071	0.067	112	173	8.63	6,700	Rangeland
MAD-41 (9.06)	1,971			49.4	73.6	6.51	5,310	Rangeland
MAD-41 (7.32)	1,971			53.4	72.3	5.98	2,600	Rangeland
MAD-41(12.06)	1,971	NA	0.163	67.6	96.3	7.64	10,500	Rangeland
MO-198 (.82)	1,993	0.083	0.091	205	295	6.36	4,140	Rangeland
MO-198 (1.67) A	1,993	0.095	0.097	60	69.5	6.15	7,460	Rangeland
MO-198 (1.67) B	1,993	0.048	0.074	199	323	7.41	3,270	Rangeland

MO-198 (1.67) C	1,993	0.144	0.115	39.1	58.5	9.15	18,390	Rangeland
MO-198 (1.67) D	1,993	0.115	0.12	47.1	74.5	9.25	16,970	Rangeland
MO-198 (1.67) E	1,993	0.113	0.115	104.4	106	8.51	3,110	Rangeland
MO-198 (1.67) F	1,993	0.063	0.134	88.5	136.4	9.71	11,540	Rangeland
MO-198 (12.44)	1,993	0.074	0.12	92.5	168.4	10.01	11,540	Rangeland
MO-198 (12.89)	1,993	0.094	0.133	126.5	149.4	10.01	11,810	Rangeland
MO-198 (14.84)	1,993	0.069	0.067	268	338	9.61	5,440	Rangeland
MO-198 (18.12)	1,993	0.073	0.069	229	348	9.61	4,410	Rangeland
MO-198 (2.95)	1,993	0.071	0.069	233	345	9.51	4,970	Rangeland
MO-198 (5.32)	1,993	0.121	0.112	114.5	153.3	4.97	17,010	Rangeland
MO-198 (6.08)	1,993	0.113	0.142	120.5	152.3	4.47	17,510	Rangeland
MO-198 (6.88)	1,993	0.064	0.063	265	382	6.8	1,890	Rangeland
MO-198 (8.10)	1,993	?	0.115	499	672	8.06	2,750	Rangeland
MO-198 (9.08)	1,993	0.06	0.067	146	199	8.91	8,310	Rangeland
MOD-139(1.06)	1,990	0.063	0.064	79.5	119.2	7.58	12,500	Rangeland
MOD-299(28.63)	1,982	0.107	0.111	89	133.3	8.21	10,400	Rangeland
MOD-299(29.00)	1,982		-	122	191	8.08	3,400	Rangeland
MOD-299(29.22)	1,982	0.076	0.074	81.8	121.5	7.32	6,190	Rangeland
MOD-299(29.65)A	1,982	0.065	0.146	149	224	7.28	2,980	Rangeland
MOD-299(29.65)B	1,982	0.052	0.157	149	224	7.28	2,980	Rangeland
MOD-299(30.18)A	1,982	0.142	0.145	135	203	7.2	2,180	Rangeland
MOD-299(30.18)B	1,982	0.14	0.146	135	203	7.2	2,180	Rangeland
MOD-299(30.28)	1,982	0.077	0.079	435	630	7.67	869	Rangeland

SBD-127 (28.89)	1,955	0.118	0.116	465	520	7.65	10,800	Rangeland
SBD-127 (29.06)A	1,955	0.14	0.111	29.1	44.5	8.85	16,700	Rangeland
SBD-127 (29.06)B	1,955	0.112	0.114	29.1	44.5	8.85	16,700	Rangeland
SBD-127 (29.38)	1,955	0.11	0.11	63.4	94	8.21	2,250	Rangeland
SBD-127 (29.92)A	1,955	0.057	0.13	78.5	120.4	9.21	10,600	Rangeland
SBD-127 (29.92)B	1,955	0.072	0.118	78.5	120.4	9.21	10,600	Rangeland
SBD-127 (29.92)C	1,955	0.089	0.127	78.5	120.4	9.21	10,600	Rangeland
SBD-395 (46.63)A	1,955	0.066	0.066	218	319	9.01	3,760	Rangeland
SBD-395 (46.63)B	1,955	0.068	0.064	218	319	9.01	3,760	Rangeland
SBD-395 (46.63)C	1,955	0.064	0.066	218	319	9.01	3,760	Rangeland
SBD-395 (54.5)A	1,955	0.117	0.106	72.5	106.3	4.07	16,500	Rangeland
SBD-395 (54.5)B	1,955	0.108	0.136	72.5	106.3	4.07	16,500	Rangeland
SBD-395 (63.6)A	1,955		0.136	111	167	8.65	7,850	Rangeland
SBD-395 (63.6)B	1,955	0.148	0.136	111	167	8.65	7,850	Rangeland
SBD-395 (65.47)	1,955	0.127	0.137	179	264	8.75	4,160	Rangeland
SBD-395 (71.05)	1,955			129	195	8.26	5,930	Rangeland
SBT-25 (1.00)	1,999	0.06	0.061	340	494	7.13	1,040	Rangeland
SBT-25 (15.78)	1,999	0.065	0.071	465	685	7.5	837	Rangeland
SBT-25 (2.66)	1,999	0.074	0.075	386	571	7.09	797	Rangeland
SBT-25 (4.91)	1,999	0.057	0.06	247	336	6.6	1,210	Rangeland
SBT-25 (5.01)	1,999	?	0.109	466	622	7.66	1,140	Rangeland
SD-94(34.10)	1,967	0.056	0.064	105	156	8.61	7,220	Rangeland
SD-94(41.50)	1,967	0.063	0.064	79.5	119.2	7.58	12,500	Rangeland
SD-94(45.00)	1,967	0.107	0.111	89	133.3	8.21	10,400	Rangeland

SD-94(50.95)	1,967	0.051	0.053	118	174	7.13	5,840	Rangeland
SIS-97(17.28)	1,990	0.084	0.085	206	305	5.9	1,850	Rangeland
SIS-97(17.60)	1,990	0.067	0.069	177	224	7.29	3,390	Rangeland
SIS-97(17.83)	1,990	0.077	0.077	95	147	8.75	9,890	Rangeland
SIS-97(18.57)	1,990	0.067	0.065	151	230	6.46	2,980	Rangeland
SIS-97(19.00)	1,990	0.069	0.072	186	273	7.77	2,550	Rangeland
SIS-97(19.14)	1,990	0.068	0.074	269	350	6.7	1,950	Rangeland
SIS-97(19.32)	1,990	0.072	0.072	242	366	7.06	2,100	Rangeland
SIS-97(19.65)	1,990	0.072	0.072	76.6	115.6	8.05	6,380	Rangeland
SIS-97(19.98)	1,990	0	0.074					Rangeland
SIS-97(7.62)	1,990	0.075	0.074	43.6	69	7.48	13,300	Rangeland
SIS-97(8.05)	1,990	0.066	0.067	38.1	57.8	7.82	15,800	Rangeland
YOL-16(0.91)	1,964	0.072	0.069	68.7	99.6	7.76	2,780	Rangeland
YOL-16(13.99)L	1,964	0.064	0.068	280	413	6.43	4,090	Rangeland
YOL-16(13.99)R	1,964	0.064	0.063	280	413	6.43	4,090	Rangeland
YUB-20(11.36)	1,964	0.078	0.086	176	265	5.46	3,330	Rangeland
YUB-20(11.59)	1,964	0.088	0.092	44	62.5	5.95	7,230	Rangeland
YOL-16 (15.4)A	1,964	0.045	0.069	180	273	7.01	2,340	Rangeland
YOL-16 (15.93) A	1,964	0.06	0.053	125	190	7.14	3,560	Rangeland
YOL-16 (15.93) B	1,964	0.073	0.084	125	190	7.14	3,560	Rangeland
YOL-16 (16.92) Elliptical	1,964	0.047	0.097	168	235	7.29	2,200	Rangeland
MO-25 (2.14)	1,976	0.065	0.07	519	649	7.03	1,230	Rangeland
MO-25 (3.87)	1,976	0	0.078	556	700	7.29	659	Rangeland
MO-25 (4.96)	1,976	0.066	0.073	521	653	6.93	1,170	Rangeland
MO-25(10.12)	1,976	0.067	0.075	515	750	7.18	761	Rangeland
MO-25(11.28)	1,976			359	523	7.2	1,160	Rangeland
MO-25(5.88)	1,976			537	671	6.45	511	Rangeland
MO-25(6.21)	1,976	0.065	0.071	683	973	7.8	1,530	Rangeland
MO-25(9.04)	1,976	0.073	0.07	518	646	7.25	1,320	Rangeland

MO-6(2.03)	1,981			1,190.00	1,630.00	8.24	346	Rangeland
MO-6(2.09)	1,981			1,770.00	2,350.00	8.22	345	Rangeland
MO-6(10.1)	1,981	0.081	0.096	271	321	8.27	4,320	Rangeland
MO-6(10.38)	1,981	0.087	0.088	327	421	8.1	5,310	Rangeland
MO-6(10.61)	1,981	0.086	0.082	242	300	7.95	5,110	Rangeland
MO-6(10.74)	1,981	0.091	0.095	223	287	8.75	4,900	Rangeland
MO-6(11.69)	1,981	0.083	0.085	195	279	8.45	2,680	Rangeland
MO-6(11.85)A	1,981		0.088	257	365	7.35	3,470	Rangeland
MO-6(11.85)B	1,981	0.053	0.057	257	365	7.35	3,470	Rangeland
MO-6(11.85)C	1,981	0.088	0.086	257	365	7.35	3,470	Rangeland
MO-6(11.85)D	1,981		0.088	257	365	7.35	3,470	Rangeland
MO-6(13.00)	1,981	0.077	0.077	142	217	8.2	5,660	Rangeland
MO-6(13.62)	1,981	0.079	0.079	185	257	8.05	5,010	Rangeland
MO-6(13.78)	1,981	0.06	0.087	254	385	7.56	4,540	Rangeland
MO-6(14.56)	1,981	0.065	0.067	262	379	7.98	2,870	Rangeland
MO-6(15.40)L	1,981	0.069	0.068	110	175	8.79	1,165	Rangeland
MO-6(15.40)R	1,981	0.069	0.069	110	175	8.79	1,165	Rangeland
MO-6(16.64)	1,981	0.08	0.084	109	163	8.38	8,600	Rangeland
MO-6(17.33)	1,981	0.081	0.081	24.7	37.6	7.81	4,300	Rangeland
MO-6(19.27)	1,981	0.07	0.065	147	175	8.22	6,420	Rangeland
MO-6(19.75)	1,981	0.065	0.064	33.8	52	9.2	9,820	Rangeland
MO-6(20.09)	1,981	0.082	0.083	98	149	8.31	5,010	Rangeland
MO-6(21.55)	1,981	0.064	0.065	92.5	143	7.55	3,790	Rangeland
MO-6(22.30)	1,981	0.112	0.113	34.9	53.3	7.53	6,260	Rangeland
MO-6(22.85)	1,981	0.063	0.064	494	688	8.65	7,910	Rangeland
MO-6(25.95)	1,981	0.075	0.077	58.9	87.9	8.15	8,460	Rangeland
MO-6(26.13)	1,981	0.062	0.062	147	224	7.37	3,970	Rangeland
MO-6(26.47)	1,981	0.071	0.072	74.5	35.5	6.74	28,800	Rangeland
MO-6(26.55)	1,981	0.074	0.077	105	160	6.52	5,710	Rangeland
MO-6(27.00)	1,981	0.076	0.078	40.9	58.8	6.54	13,200	Rangeland
MO-6(27.61)	1,981	0.078	0.075	30.9	46.5	6.77	17,900	Rangeland

MO-6(27.82)	1,981	0.076	0.076	24.6	37.1	7.36	9,460	Rangeland
FRE-198 (2.67)	1,965	0.098	0.098	188	282	7.05	2,320	Rangeland
IYO-136(1.32)	1,955	0.076	0.084	155	242	8.35	2,370	Rangeland
IYO-136(1.61)	1,955	0.042	0.074	92.9	137.8	8.88	6,700	Rangeland
IYO-136(1.7)	1,955			120	181	9.18	4,700	Rangeland
IYO-136(3.38)	1,955	0.104	0.103	0	0	9.21	66	Rangeland
KER-155(17.15)	1,970	0.033	0.07	156	245	6.15	2,180	Rangeland
KER-155(17.57)	1,970	0.02	0.068	321	343	6.87	1,630	Rangeland
KER-155(17.81)A	1,970		0.11	640	480	6.78	1,200	Rangeland
KER-155(17.81)B	1,970	0.058	0.088	640	480	6.78	1,200	Rangeland
KER-155(17.91)	1,970	0.055	0.067	341	525	6.56	1,340	Rangeland
KER-155(19.71)	1,970	0.083	0.086	155	230	6.67	4,090	Rangeland
KER-155(21.24)	1,970	0.068	0.077	287	408	7.31	1,380	Rangeland
KER-155(21.29)	1,970		-	307	425	7.85	1,150	Rangeland
KER-155(22.91)	1,970	0.069	0.074	295	422	7.55	1,600	Rangeland
KER-155(23.01)	1,970	0.066	0.063	121	181	7.9	5,870	Rangeland
KER-223(31.95)	1,958	0.055	0.111	454	654	7.17	11,300	Rangeland
KIN-33(11.92)	1,963		0.116	568	393	7.08	1,200	Rangeland
KIN-33(12.23)	1,963		0.068	198	302	7.46	3,370	Rangeland
KIN-33(13.38)	1,963	0.07	0.063	473	674	7.02	1,520	Rangeland
KIN-33(14.81)	1,963		0.095	549	793	7.29	1,130	Rangeland
KIN-33(17.18)A	1,963	0.139	0.14	430	618	6.85	1,780	Rangeland
KIN-33(17.18)B	1,963	0.136	0.184	430	618	6.85	1,780	Rangeland
KIN-33(4.48)	1,963	0.082	0.085	559	385	6.9		Rangeland
KIN-33(4.95	1,963	0.076	0.082	184	115	7.68	1,650	Rangeland
KIN-33(7.75)	1,963	0.107	0.111	527	365	7.45	1,250	Rangeland
KIN-33(7.78)	1,963	0.131	0.13	690	477	7.44	1,330	Rangeland
LA-138(33.4)	1,975		0.07	586	845	8.08	5,060	Rangeland
LA-138(33.6)	1,975	0.086	0.089	473	684	8.38	6,890	Rangeland

LA-138(33.9)	1,975	0.083	0.066	486	695	8.28	5,420	Rangeland
LA-138(34.1)	1,975	0.078	0.065	625	892	8.22	3,000	Rangeland
LA-138(34.52)	1,975			419	606	8.53	1,630	Rangeland
LA-138(35.3) A	1,975	0.074	0.061	185	795	9.28	4,620	Rangeland
LA-138(35.3) B	1,975	0.065	0.054	185	795	9.28	4,620	Rangeland
LA-138(35.8)	1,975	0.089	0.087	490	700	8.64	5,840	Rangeland
LA-138(35)	1,975	0.071	0.07	525	744	8.03	5,390	Rangeland
LA-138(36.2)	1,975	0.068	0.073	654	919	8.59	2,370	Rangeland
MPA-140(0.54)	2,000	0.092	0.09	243	359	5.76	2,370	Rangeland
MPA-140(1.2)	2,000	0.088	0.089	198	298	6.43	2,410	Rangeland
MPA-140(10.7)	2,000		0.074	320	465	6.15	2,040	Rangeland
MPA-140(5.5)	2,005	0.093	0.081	302	434		1,900	Rangeland
MPA-140(7.1)A	2,006	0.093	-	82.8	127.3	5.68	1,980	Rangeland
MPA-140(7.1)B	2,007	0.088	-	82.8	127.3	5.68	1,980	Rangeland
MO-25(12.44)	1,976	0.079	0.08				1,430	Rangeland
MO-25(12.89)	1,976	0.058	0.071	186	242		1,200	Rangeland
MO-25(14.84)	1,976	0.07	0.069	305	444	6.84	1,370	Rangeland
MO-25(18.12)	1,976	0.069	0.065	206	304	8.19	2,440	Rangeland
RIV-243(0.75)	1,972	0.063	0.06	544	777	6.44	5,210	Rangeland
RIV-243(17.3)	1,972	0.105	0.117	4,740.00	5,950.00	6.32	13,500	Rangeland
RIV-243(3.65)	1,972	0.06	0.032	503	718	6.18	5,510	Rangeland
RIV-243(5.25)	1,972	0.095	0.074	459	659	6.82	14,300	Rangeland
RIV-243(5.3)	1,972	0.066	0.083	470	674	7.09	10,900	Rangeland
RIV-79(0.24)	1,972	0.106	0.106	694	933	7.37	4,580	Rangeland
RIV-79(0.9)	1,972		0.087	496	736	8.46	9,360	Rangeland
RIV-79(1.3)A	1,972	0.074	0.084	543	761	8.5	8,770	Rangeland
RIV-79(1.3)B	1,972	0.081	0.083	543	761	8.5	8,770	Rangeland
SD-94(52.50)A	1,967	0.076	0.094	122	176	8.24	4,790	Rangeland
SD-94(52.50)B	1,967	0.081	0.098	122	176	8.24	4,790	Rangeland
FRE-180(89.59)	1,958	0.125	0.116	66.5	95.4	6.26	7,100	Urban
FRE-180(89.98)	1,958	0.073	0.093	224	318	6.27	4,820	Urban

HUM-96(0.54)	1,989	0.071	0.079	113	168	6.53	5,260	Urban
HUM-96(1.50)	1,989	0.074	0.076	130	190	6.68	3,630	Urban
HUM-96(10.03)	1,989	0.077	0.076	57.5	86	6.88	8,100	Urban
HUM-96(11.44)	1,989	0.074	0.077	93.6	132.4	6.2	8,270	Urban
NEV-49(2.34)	1,960	0.079	0.089	95	165	7.01	3,930	Urban
SD-94(20.55)	1,967	0.057	0.06	163	242	7.18	3,330	Urban
YOL-16 (27.82)	1,964	0.06	0.061	275	410	6.76	2,070	Urban
SD-78 (34.30)	1,969	0.095	0.113	683	456	6.56	3,120	Urban
KER-155(10.75)	1,970	0.052	0.083	237	956	7.33	1,070	Urban
KER-155(23.5)	1,970	0.057	0.071	101	145	7.15	4,560	Urban
KER-155(24.57)	1,970		0.071	167	135	6.54	2,150	Urban
KER-155(24.97)	1,970	0.069	0.089	347	512	6.01	1,430	Urban
KER-155(25.44)	1,970	0.082	0.069	192	276	6.79	3,170	Urban
KER-155(25.65)	1,970	0.065	0.07	921	143	5.5	4,250	Urban
KER-155(25.73)	1,970		0.089	934	177	7.27	4,420	Urban
KER-65(10.85)	1,940	0.094	0.118	365	542	7.42	1,370	Urban
KER-65(11.26)	1,940		0.102	221	319	7.29	2,290	Urban
KER-65(11.5)	1,940	0.07	0.087	350	520	7.62	2,010	Urban
KER-65(2.4)	1,940	0.057	0.085	191	280	8.02	3,780	Urban
KER-65(5.46)	1,940	0.094	0.094	304	401	7.25	2,050	Urban
KER-65(5.54)	1,940	0.08	0.14	249	363	7.44	1,600	Urban
KER-65(5.87)	1,940	0.014	0.113	1,299.00	959	7.47	1,200	Urban
KER-65(5.94)	1,940	0.082	0.103	966	697	7.45	3,880	Urban
KER-65(6.53)	1,940		0.104	150	222	7.64	934	Urban
KER-65(6.91)	1,940	0.087	0.101	1,850.00	2,870.00	7.49	452	Urban
KER-65(7.14)	1,940		0.103	575	822	8.15	418	Urban
KER-65(7.47)	1,940	0.085	0.088	430	284	7.46	2,020	Urban
LA-138(4.3)	1,975			58.5	87.8	8.52	7,700	Urban
LA-138(4.5)	1,975	0.117	0.109	85.8	128.6	8.21	7,120	Urban
LA-138(4.7)	1,975	0.117	0.109	34.3	52.1	8.2	16,100	Urban
LA-138(4.9)	1,975	0.126	0.109	64.9	99.8	7.69	8,380	Urban

LA-138(5.1)	1,975		0.109	37.6	56.8	7.82	12,800	Urban
LA-138(8.4)	1,975	0.082	0.109	120	197	7.42	3,050	Urban
LA-138(8.7)	1,975			23.7	36.1	7.29	19,500	Urban
TUL-198(26.70)	1,962	0.081	0.112	69.9	111.3	8.19	3,500	Agriculture
TUL-198(28.46)	1,962	0.078	0.111	194	292	6.06	2,790	Agriculture
KER-166(8)	1,956	0.067	0.091	875	1,246.00	8.05	666	Agriculture
KER-166(8.6)	1,956	0.079	0.09	102	111	8.37	4,000	Agriculture
KER-166(6.7)	1,956	0.121	0.254	800	1,125.00	7.89	1,570	Agriculture
KER-166(8.2)	1,956	0.126	0.116	341	520	8.66	1,810	Agriculture
SD-78 (43.49) A	1,969	0.137	0.113	231	352	5.82	3,380	Agriculture
KER-166(8.1)	1,962	0.07	0.09	323	548	7.86	1,800	Agriculture
SD-78 (38.5)	1,969	0.102	0.076	60.9	90.7	6.72	8,710	Agriculture
KIN-41(7.77)	1,963	0.104	0.104	5,160.00	6,460.00	8	1,140	Agriculture
KER-166(8.3)	1,956	0.056	0.093	707	1,067.00	7.96	3,320	Agriculture
KIN-41(7.34)	1,963	0.105	0.105	5,580.00	6,950.00	7.87	890	Agriculture
SD-78 (43.49) B	1,969	0.115	0.119	231	352	5.82	3,380	Agriculture
SD-78(39.5)	1,969	0.123	0.117	158	234	6.84	2,860	Agriculture
KIN-41(4.57)	1,963	0.082	0.082	5,040.00	6,310.00	7.25	1,520	Agriculture
SD-78(39)	1,969	0.1	0.098	280	125	6.2	3,830	Agriculture
TUL-43(3.88)A	1,954	0.098	0.126	340	617	8.13	1,470	Agriculture
TUL-43(3.88)B	1,954	0.053	0.117	340	617	8.13	1,470	Agriculture
TUL-43(3.88)C	1,954	0.063	0.122	340	617	8.13	1,470	Agriculture
TUL-43(4.0)	1,954	0.095	0.113	263	356	8.04	2,440	Agriculture
TUL-43(1.5)A	1,954	0.078	0.123	339	1,510.00	7.62	923	Agriculture
TUL-43(1.5)B	1,954	0.078	0.121	339	1,510.00	7.62	923	Agriculture
TUL-43(1.5)C	1,954	0.078	0.124	339	1,510.00	7.62	923	Agriculture
TUL-43(1.5)D	1,954	0.078	0.119	339	1,510.00	7.62	923	Agriculture
TUL-43(3.33)	1,954	0.085	0.12	297	442	7.45	2,060	Agriculture
KIN-41(16.9)	1,963		0.079	4,880.00	6,120.00	8.07	2,840	Agriculture

FRE-41(3.99)	1,964	0.115	0.114	251	387	7.65	1,730	Agriculture
FRE-180(79.01)	1,959	0.118	0.119	1,590.00	2,310.00	7.93	897	Agriculture
FRE-180(79.22)	1,959	0.114	0.115	182	325	6.92	2,750	Agriculture
FRE-180(83.59)	1,959	0.073	0.118	128	193	6.98	3,100	Agriculture
TUL-190(21.38)A	1,961	0.14	0.141	3,010.00	4,720.00	8.06	7,940	Agriculture
TUL-190(21.38)B	1,961	0.14	0.139	3,010.00	4,720.00	8.06	7,940	Agriculture
TUL-190(21.38)C	1,961	0.144	0.146	3,010.00	4,720.00	8.06	7,940	Agriculture
TUL-198(22.32)	1,961	0.091	0.107	575	823	5.89	879	Agriculture
Tul-65(7.65)	1,961			4,870.00	6,180.00	7.27	1,560	Agriculture
Tul-65(10.39)	1,961	0.08	0.089	5,450.00	6,910.00	5.9	926	Agriculture
MOD-139(2.80)	1,990	0.081	0.064	73.5	115.5	6.81	1,690	Agriculture
MOD-139(1.27)	1,990	0.082	0.077	269	401	6.91	1,180	Agriculture
FRE-168 (23.69)	1,962	0.059	0.055	5,140.00	6,470.00	6.89	1,290	Agriculture
MOD-299(24.65)	1,983	0.074	0.079	301	436	7.16	1,570	Agriculture
MOD-299(25.13)	1,983	0.079	0.076	316	460	5.7	1,680	Agriculture
KIN-33(1.39)	1,941	0.085	0.082	261	173	7.48	3,370	Agriculture
Tul-65(11.66)	1,961	0.023	0.053	5,890.00	7,370.00	6.68	695	Agriculture
FRE-41(1.27)	1,964	0.08	0.122	220	333	6.49	1,270	Agriculture
FRE-41(2.23)	1,964	0.076	0.075	440	624	6.59	1,120	Agriculture
FRE-41(3.01)	1,964	0.074	0.074	253	362	7.27	2,120	Agriculture
FRE-41(3.20)	1,964	0.073	0.067	245	345	7.75	2,270	Agriculture
FRE-41(3.67)	1,964	0.071	0.076	156	238	8.79	3,110	Agriculture
FRE-41(3.83)	1,964	0.073	0.079	231	341	7.67	1,890	Agriculture
FRE-41(4.56)	1,964	0.087	0.085	176	263	7.87	3,260	Agriculture
FRE-41(5.13)	1,964	0.085	0.085	179	273	6.21	2,830	Agriculture
FRE-41(5.31)	1,964	0.083	0.083	349	502	6.65	1,100	Agriculture
FRE-41(6.03)	1,964	0.065	0.06	123	190	8.29	5,070	Agriculture

FRE-168 (16.21)	1,962	0.058	0.063	209	306	6.75	2,720	Agriculture
FRE-168 (17.08)	1,962	0.037	0.065	157	196	9.5	7,640	Agriculture
FRE-168 (22.17)	1,962	0.055	0.081	5,030.00	6,020.00	7.04	3,200	Agriculture
FRE-168 (23.72	1,962	0.07	0.073	4,670.00	5,910.00	6.18	10,800	Agriculture
FRE-180(82.67)	1,959	0.065	0.076	138	212	7.63	2,970	Agriculture
FRE-180(82.84)	1,959	0.131	0.086	207	289	7.66	1,810	Agriculture
FRE-180(83.09)A	1,959	0.093	0.095	107	158	7.92	3,120	Agriculture
FRE-180(83.09)B	1,959	0.084	0.086	107	158	7.92	3,120	Agriculture
FRE-180(83.09)C	1,959	0.089	0.091	107	158	7.92	3,120	Agriculture
HUM-96(2.65)	1,989	0.076	0.077	492	791	5.77	1,070	Agriculture
MAD-41 (5.40)			0.08	125	184	5.98	3,550	Agriculture
MOD-139(3.66)	1,990	0.058	0.079	133	209	6.88	1,510	Agriculture
SD-78 (33.60)	1,969	0.089	0.129	149	221	6.55	2,600	Agriculture
SD-94(51.37)	1,966	0.077	0.078	166	247	8.44	3,340	Agriculture
YOL-16 (16.92)	1,950	0.076	0.075	94.3	142	6.63	2,200	Agriculture
YOL-16 (26.4)	1,950	0.063	0.086	316	469	6.13	1,730	Agriculture
KER-166(8.7)	1,956	0.032	0.132	83.4	124.5	8.65	8,580	Agriculture
KER-65(1.38)	1,962	0.073	0.083	760	523	7.32	2,730	Agriculture
KER-65(1.84)	1,962	0.063	0.079	516	686	7.12	2,350	Agriculture
KIN-33(1.0)	1,963	0.084	0.084	588	509	7.23	2,630	Agriculture
KIN-33(1.6)	1,963	0.083	0.086	600	375	7.08	1,480	Agriculture
SLO-229(4.40)	1,935	0.081	0.074	4,670.00	5,830.00	6.94	5,640	Agriculture
SLO-229(5.4)	1,935	0.059	0.073	4,700.00	5,870.00	7.96	3,300	Agriculture
SLO-229(5.7)A	1,935	0.034	0.067	495	708	7.01	5,080	Agriculture
SLO-229(5.7)B	1,935	0.034	0.067	495	708	7.01	5,080	Agriculture
TUL-190(19.74)	1,961	0.076	0.085	663	456	7.51	10,600	Agriculture

TUL-190(20.45)	1,961	0.041	0.043	637	506	7.37	1,970	Agriculture
TUL-190(20.61)	1,961	0.074	0.08	708	487	7.9	8,890	Agriculture
Tul-65(11.58)	1,961	0.024	0.084	510	6,390.00	6.46	1,820	Agriculture
Tul-65(12.54)	1,961	0.081	0.08	492	6,160.00	6.24	3,220	Agriculture
Tul-65(13.57)	1,961	0.049	0.078	3,010.00	4,820.00	5.37	3,000	Agriculture
Tul-65(10.01)	1,961	0.076	0.09	528	753	5.83	3,290	Agriculture
Tul-65(10.73)	1,961	0.079	0.081	5,120.00	6,320.00	5.98	1,510	Agriculture
Tul- 65(10.98)	1,961	0.086	0.126	4,760.00	5,950.00	5.85	3,020	Agriculture
Tul-65(11.30)	1,961	0.074	0.081	5,050.00	6,340.00	6.05	1,700	Agriculture
FRE-41(5.01)	1,964	0.085	0.083	141	210	6.62	2,910	Agriculture
FRE-198 (13.25)	1,965	0.107	0.102	118	175	7.26	3,660	Agriculture
NEV-174(5.04)	1,969	0.047	0.111	43.3	67.4	5.71	3,920	Agriculture
KER-119(0.4)	1,955	0.113	0.089	194	282	7.4	3,510	Agriculture
KER-119(0.5)	1,955	0.088	0.09	634	912	7.23	1,170	Agriculture
KER-65(0.93)	1,941	0.067	0.08	4,650.00	5,180.00	7.46	1,630	Agriculture
KER-65(1.18)	1,941	0.063	0.087	667	937	7.24	1,520	Agriculture
TUL-190(20.09)	1,961	0.106	0.109	723	498	7.85	8,780	Agriculture
TUL-190(20.15)	1,961	0.105	0.107	4,820.00	6,060.00	7.37	8,430	Agriculture
TUL-190(27.84)	1,961	0.098	0.12	140	187	7.78	3,000	Agriculture
TUL-190(29.15)	1,961	0.079	0.105	328	508	6.96	2,600	Agriculture
TUL-190(29.28)	1,961	0.089	0.123	579	499	6.21	1,320	Agriculture
TUL-190(30.66)	1,961	0.073	0.107	2,120.00	2,700.00	7.89	3,888	Agriculture
TUL-190(32.17)	1,961	0.077	0.111	564	662	7.66	1,380	Agriculture
TUL-190(32.49)	1,961	0.07	0.107	133	191	7.6	5,280	Agriculture
TUL-198(24.0)	1,961	0.076	0.085	5,100.00	6,380.00	7.04	1,290	Agriculture
TUL-198(24.4)	1,961			91.7	140	7.97	7,870	Agriculture
TUL-198(25.72)	1,961	0.113	0.12	220	329	6.61	1,650	Agriculture
TUL-198(26.11)	1,961	0.035	0.073	443	645	6.96	1,620	Agriculture

TUL-198(26.49)A	1,961	0.126	0.133	104	154	7.56	5,140	Agriculture
TUL-198(26.49)B	1,961	0.126	0.137	104	154	7.56	5,140	Agriculture
TUL-198(26.56)	1,961	0.126	0.138	289	438	6.93	2,380	Agriculture
Tul-65(6.05)	1,961	0.096	0.1	4,990.00	6,240.00	7.67	1,720	Agriculture
KER-119(0.7)	1,955	0.065	0.124	240	351	7.08	1,640	Agriculture
KER-119(2.2)	1,955	0.045	0.101	74.4	110.7	8	4,960	Agriculture
KER-119(3) A	1,955	0.111	0.115	125	186	7.54	3,690	Agriculture
KER-119(3) B	1,955	0.111	0.114	125	186	7.54	3,690	Agriculture
KIN-41(1.32)	1,964	0.114	0.109	5,460.00	6,810.00	7.17	1,070	Agriculture
KIN-41(1.53)	1,964	0.11	0.103	5,510.00	6,900.00	6.7	885	Agriculture
KIN-41(1.87)	1,964	0.104	0.109	4,980.00	6,230.00	7.15	2,830	Agriculture
TUL-198(22.69)	1,961	0.133	0.129	211	305	6.75	2,800	Agriculture
TUL-198(23.64)A	1,961	0.122	0.146	5,470.00	6,840.00	8.67	928	Agriculture
TUL-198(23.64)C	1,961	0.118	0.148	5,470.00	6,840.00	8.67	928	Agriculture
TUL-198(23.92)	1,961	0.142	0.117	500	718	7.09	7,720	Agriculture
Tul-65(9.97)	1,961	0.133	0.154	5,210.00	6,550.00	7.78	1,080	Agriculture
TUL-198(23.64)B	1,961	0.12	0.15	5,470.00	6,840.00	8.67	928	Agriculture
L-16 (16.92) Ellipt	1,950	0.09	0.096	94.3	142	6.63	2,200	Agriculture
LA-138(10.1)	1,975	0.104	0.109	66.7	91	7.78	6,550	Coastal
LA-138(5.7)	1,975	0.057	0.061	95	147	7.75	4,180	Coastal
LA-138(5)	1,975	0.091	0.1	52.5	76.3	8.07	1,200	Coastal
LA-138(6.15)	1,975		0.17	122	182	7.83	2,870	Coastal
LA-138(6.25)	1,975		0.175	360	534	7.06	1,430	Coastal
LA-138(6.35)	1,975		0.132					Coastal
LA-138(6.45)	1,975	0.085	0.089					Coastal
LA-138(6.5)	1,975	0.093	0.099	135	319	8.25	3,800	Coastal
LA-138(6.6)	1,975	0.087	0.096	335	373	8.12	1,640	Coastal

LA-138(6.7)	1,975	0.055	0.062	58.7	86.6	8.19	8,950	Coastal
LA-138(6.82)	1,975	3.29	3.295	90.5	135.8	7.61	4,970	Coastal
LA-138(6) A	1,975	0.094	0.101	159	201	7.8	1,530	Coastal
LA-138(6) B	1,975	0.053	0.06	159	201	7.8	1,530	Coastal
LA-138(7.02)	1,975	0.127	0.131	51.3	62.5	8.07	6,570	Coastal
LA-138(7.6)	1,975	0.081	0.089	225	278	7.68	1,260	Coastal
LA-138(7.7)	1,975	0.075	0.082	182	198	7.39	1,690	Coastal
LA-138(9.1)	1,975	0.089	0.098	54.2	97.6	8.13	2,970	Coastal
LA-138(9.3)	1,975	0.097	0.104	101	137	7.52	1,540	Coastal
LA-138(9.6)	1,975	0.106	0.111	82.6	112	7.41	2,470	Coastal
SB-150(0.6)		0.016	0.082	302	359	7.28	2,350	Coastal
SB-150(1.58)			0.083	325	437	7.82	1,970	Coastal
SLO-41(0.54)	1,955	0.063	0.075	658	825	7.86	1,590	Coastal
SLO-41(1.1)	1,955		0.084	458	637	7.51	1,230	Coastal
SLO-41(1.3)A	1,955	0.063	0.076	368	520	7.97	1,420	Coastal
SLO-41(1.3)B	1,955	0.042	0.072	368	520	7.97	1,420	Coastal
SLO-41(1.4)A	1,955	0.093	0.086	143	250	7.47	3,000	Coastal
SLO-41(1.4)B	1,955	0.052	0.089	143	250	7.47	3,000	Coastal
SLO-41(1.51)	1,955	0.06	0.095	747	920	6.99	1,560	Coastal
SLO-41(1.63)	1,955	0.061	0.064	310	425	7.41	1,910	Coastal
SLO-41(1.7)	1,955	0.04	0.067	705	623	7.76	1,700	Coastal
SLO-41(1.9)	1,955	0.059	0.084	638	936	7.03	1,690	Coastal
SLO-41(2.0)	1,955	0.067	0.066	4,890.00	6,180.00	6.95	2,670	Coastal
SLO-41(2.1)	1,955			619	875	7.05	2,120	Coastal
SLO-46(3.3)	1,974	0.071	0.069	480	696	7.62		Coastal
SLO-46(3.45)	1,974	0.033	0.079	91	127.6	6.51		Coastal