A COMPARISON OF WATER MAIN FAILURE PREDICTION MODELS

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ABSTRACT

A Comparison of Water Main Failure Prediction Models in San Luis Obispo, CA

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This study compared four different water main failure prediction models: a statistically simple model, a statistically complex model, a statistically complex model with modifications termed the 2019 model, and an age-based model. The statistically complex models compute the probability of failure based on age, size, internal pressure, length of pipe in corrosive soil, land use, and material of the. These two values are then used to prioritize a water main rehabilitation program to effectively use the municipality's funds. The 2019 model calculates the probability of failure and consequence of failure differently than the statistically complex model by considering corrosive soil data instead of assuming all the pipes are in highly corrosive soil and average daily traffic volume data instead of using street classifications. The statistically simple model only uses the pipe age and material for probability of failure. The age-based model relies purely on the age of the pipe to determine its probability of failure. Consequences of failure are determined by the proximity of the pipe to highly trafficked streets, critical services, pipe replacement cost, and the flow capacity of the pipe. Risk of failure score is the product of the consequence of failure score and probability of failure score. Pipes are then ranked based on risk of failure scores to allow municipalities to determine their pipe rehabilitation schedule.

The results showed that the statistically complex models were preferred because results varied between all four models. The 2019 model is preferred for long-term analysis because it can better account for future traffic growth using the average daily traffic volume. Corrosive soil data did not have a significant impact on the results, which can be attributed to the relatively small regression parameter for corrosive soil. The age-based model is not recommended because results of this study shows it places a significantly high number of pipes in the high and critical risk categories compared to the other models that account for more factors. This could result in the unnecessary replacement of pipes leading to an inefficient allocation of funds.

Keywords: Risk of Failure, Consequence of Failure, Probability of Failure

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1. INTRODUCTION

1.1 Background

Physical, environmental, and chemical factors wear down infrastructure on a continual basis. This deterioration process can be exacerbated over time with a growing population. These factors can lead to failing infrastructure with disastrous consequences for the population it serves. Municipalities are responsible for maintaining all infrastructure within their jurisdiction to provide their citizens with critical services. One of these critical services is water distribution and ensuring that the water mains are properly maintained. A failed water main may not only disrupt water service but may block traffic, impact critical services, and can cause potentially dangerous mudslides on steep slopes. Therefore, it is crucial for a municipality to have an accurate model of their water distribution system to ensure public safety and proper function in an economically efficient manner.

This study refined a previous water main prediction model and compared it to other prediction models to find a more accurate model for the City of San Luis Obispo. Critical components and consequences of failure were identified through a risk assessment model.

1.2 Scope of Work

This study refined and compared two existing risk assessment models that were initially introduced by Cortez (2015) and Devera (2013) that were later refined by Nemeth (2016) and Kahn (2018). Devera (2013) presented a model that accounted for the pipe material, age, breakage history, and the potential consequence of failure for each pipe in a water distribution system. Cortez (2015) introduced more factors into a statistically complex model that accounted for corrosive soil, internal pressures in the pipes, and land use in addition to the parameters in Devera's (2013) model. Both Cortez (2015) and Devera (2013) analyzed their models on the City of Arroyo Grande's water distribution system. The results of these studies were similar which lead to the conclusion that the simplified approach was preferred based on less data being necessary to achieve the desired results, although further investigation was recommended.

Nemeth (2016) compared both models presented by Cortez (2015) and Devera (2013) on the water distribution system in the City of Buellton. The study concluded with similar results for

both models, however, Nemeth (2016) recommended using the complex model if the necessary data was available. Kahn (2018) compared these two models on the downtown pressure zone of the City of San Luis Obispo's water distribution system. The conclusions from this study also confirmed that similar results will be obtained between the two models.

This study not only compares the statistically simple and complex models for the entire City of San Luis Obispo water distribution system, but also the current pipe replacement recommendations in the most current San Luis Obispo Master Water Plan prepared by Wallace Group in 2015. The Master Water Plan recommends that pipes that pipes with over 50 years of service life be replaced as a second priority and all pipes over 75 years of age be replaced as a first priority. In addition to these suggestions, the Master Plan includes recommendations based on hydraulic capacity upgrades for fire flows and pressure demands. These hydraulic considerations are not used in this comparison because these parameters are based solely on hydraulic requirements and not on the deterioration of the pipes themselves. Therefore, only the pipe's age is required for this analysis.

The statistical models calculate the risk of failure using the probability and consequence of failure for each pipe in the system. The calculations for the remaining useful life of the pipes in the system is the only difference between the statistically complex model and the statistically simple model. The statistically complex model factors in pipe material, length in highly corrosive soil, internal pressure, size, land use, and age. The statistically simple model only accounts for pipe age and material. A main difference between the recommended rehabilitation schedule from the statistically simple model and the San Luis Obispo Master Water Plan is that the Master Plan does not calculate a consequence of failure. The consequence of failure parameters used in both the statistically complex and statistically simple models are cost of pipe replacement, flow capacity, traffic impact, and critical customer impact.

Several software programs were used in the analysis. Bentley's WaterCAD, Microsoft Excel, and ESRI ArcMap. ArcMap was used to obtain current water distribution data from the City of San Luis Obispo and represent the results of the study. Microsoft Excel was used to compute each of

the models for each scenario. WaterCAD calculated the hydraulic parameters such as flow and pressure in the pipes under each scenario.

This study modified the statistically complex model with more accurate corrosive soil data, future hydraulic parameters based on projected population growth, and replacing the traffic impact score from street classification to average daily traffic volume. Each model was run for the entire water distribution system in San Luis Obispo and compared to each other. If the results differ significantly from each other, then the statistically complex model with the new modifications, termed the 2019 model, will be the recommended model. If the results are similar between the statistically based models, then the statistically simple model will be recommended because less time and resources will be needed to achieve the same result. If all four models yield similar results, then the age-based model would be preferred due to its simplicity.

1.3 Research Objective

A reliable source of drinking water is crucial for everyday life. Water distribution systems that are not well maintained will result in unexpected disruption of services that have real impacts of the people it serves. Municipalities can improve the function of their water distribution system by using a risk assessment model to keep its system in optimum condition.

Accurate risk assessment models allow for cost efficient maintenance of a water distribution system that prevent water main breaks from occurring. This will result in a safer, more reliable system that will keep businesses running, traffic flowing, and critical services operating. An accurate risk assessment model will keep the water distribution system operating, which will enhance the lives of the people it serves.

This study aimed to find the most cost effective and beneficial prediction model for municipalities out of the four models presented. This is determined by the amount of data necessary, complexity of calculations, and accuracy of the results.

2. LITERATURE REVIEW

2.1 General Overview

Any material will degrade with time, especially water mains that are subjected to internal pressures and corrosive soils. Because the mains are underground, it is extremely difficult to monitor each pipes condition in real time. This has created a continual challenge for municipalities to constantly improve their ability to determine which pipes need to be replaced. Deterioration of water mains increases the likelihood of failure, reduces the hydraulic capacity of the pipe, and reduces the water quality. Figure 2.1 provides a picture of what a deteriorated water main can look like.

Figure 2.1 Deteriorated Pipe (Petersen and Melchers 2012)

2.2 Causes of Pipe Failures

Water mains fail due to physical, environmental, and operational factors. Each pipe in a water distribution system deteriorates at different rates because of the multitude of factors that affect a pipe's lifespan. The factors that can result in a pipe failure include:

1. Manufacturing defects

2. Poor storage and handling

3. Improper installation

4. Erosion of soil bed

5. Physical damage

6. Corrosion

These factors are combated with having licensed contractors handling the installation and storage of pipes as well as optimizing material selection. Pipes that are more brittle and susceptible to corrosion are being replaced with more ductile and corrosive resistance materials

such as polyvinyl chloride (PVC). Asbestos cement and cast iron pipes were popular in the mid to early 1900's for water distribution. However, in the latter half of the 20th century to present, PVC has become commonly used in water distribution systems.

Brittle and corrosive pipes such as cast iron and steel fail from mechanical and corrosive factors. Failures of these mains result in bell splits, circumferential cracks, spiral cracks, spiral failures, split at tees, and tap or joint blowout (Kleiner and Rajani, 2001).

2.3 Classification of Pipe Failures

Many factors that lead to water main failures include environmental stresses, operational stresses, and corrosion. The breakage types in pipes were placed into three main categories by O'Day et al. (1986). The three categories include: (1) circumferential break from longitudinal stresses; (2) longitudinal breaks caused by hoop stress; and (3) split bell caused by transverse stresses on the pipe joint. Kleiner and Rajani (2001) suggested that holes due to corrosion can be added to the last category. Longitudinal breaks from transverse stresses can be attributed to one of the following factors: (1) hoop stress due to pipe pressure; (2) ring stress from soil loading; (3) ring stress from traffic loads; and (4) increase in ring stress from frost and moisture expansion in the surrounding soil (Kleiner and Rajani 2001). Depictions of these pipe failures is shown below in Figures 2.2 and 2.3.
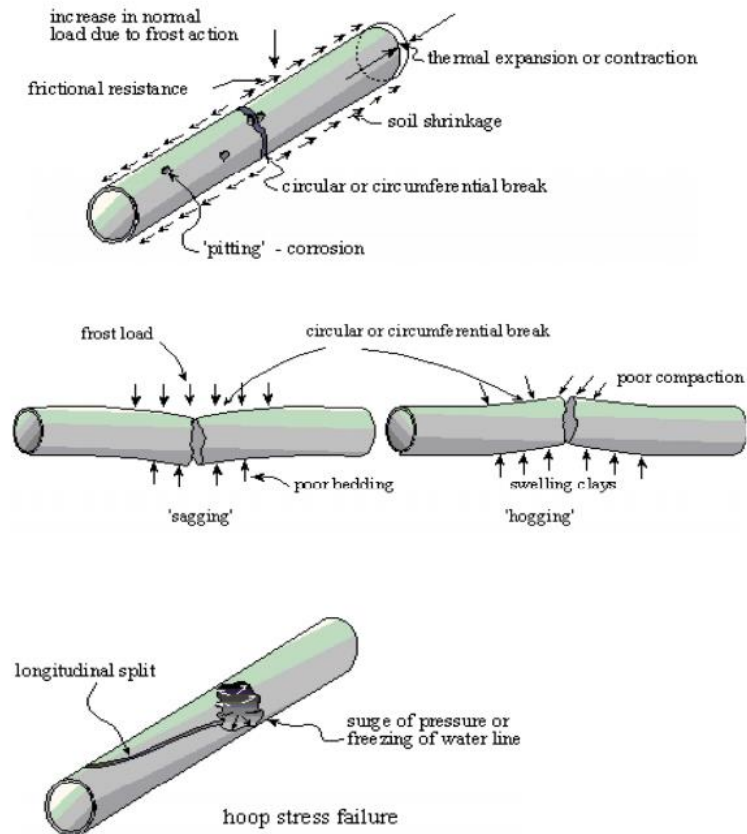
Figure 2.2 Pipe Break Types

The corrosion process of pipes in a water distribution system is depicted on Figure 2.3.
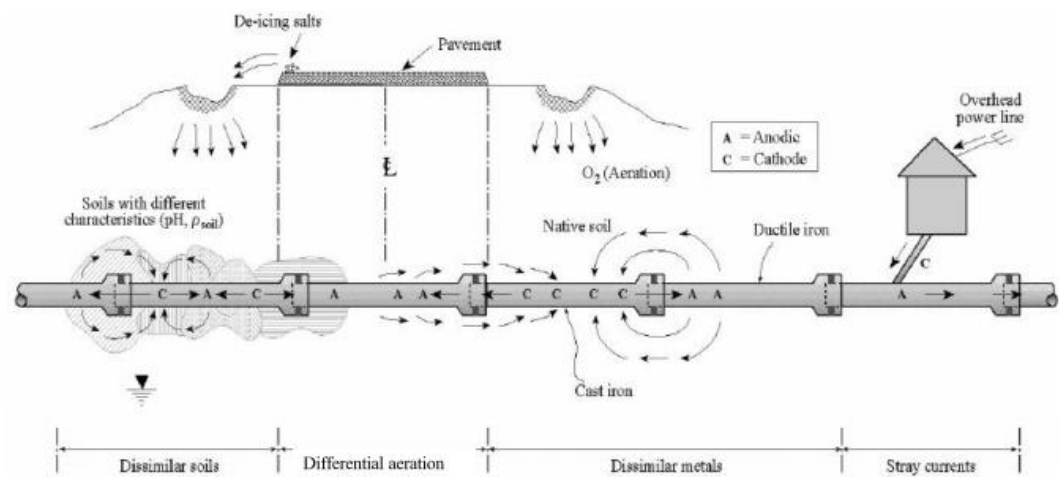
Figure 2.3 Corrosion Process of Water Mains (Kleiner and Rajani 2001)

2.4 Effects of Pipe Failures

The effects of pipe failures can cause a loss of service for critical customers, significantly restrict traffic access, can potentially cause harmful mudslides on steep slopes, and can negatively impact local businesses. Unexpected failures place a financial burden on municipalities. The pipe size, severity of break, local traffic conditions, paving requirements, and customers served are important factors that determine what the consequences of failure will be (AWWA, 2014).

An accurate water main failure prediction model will save the municipality from these negative financial consequences by allowing for proper rehabilitation and maintenance of the water distribution system, ideally before breaks occur.

2.5 Methods to Predict Pipe Failures

A pipe's life cycle can be presented by a bathtub curve that shows the rate of failure over time (Kleiner and Rajani, 2001). The hazard rate or ROCOF stands for the rate of occurrence of failure and it forms a similar shape to a bathtub. There are three phases: (1) burn-in phase; (2) in-usage phase; and (3) wear-out phase. The burn-in phase represents a high rate of failure from manufacturer defects and improper construction. The in-usage phase has a significantly lower ROCOF and is representative of the normal service life of a pipe. Finally, the wear-in phase models the end of the pipe's life span where it fails due to degradation factors that occur over time resulting in an increase in the ROCOF. The length of each phase is determined on an individual basis due to the variation of deterioration factors on each pipe. The bathtub curve is shown below in Figure 2.4.
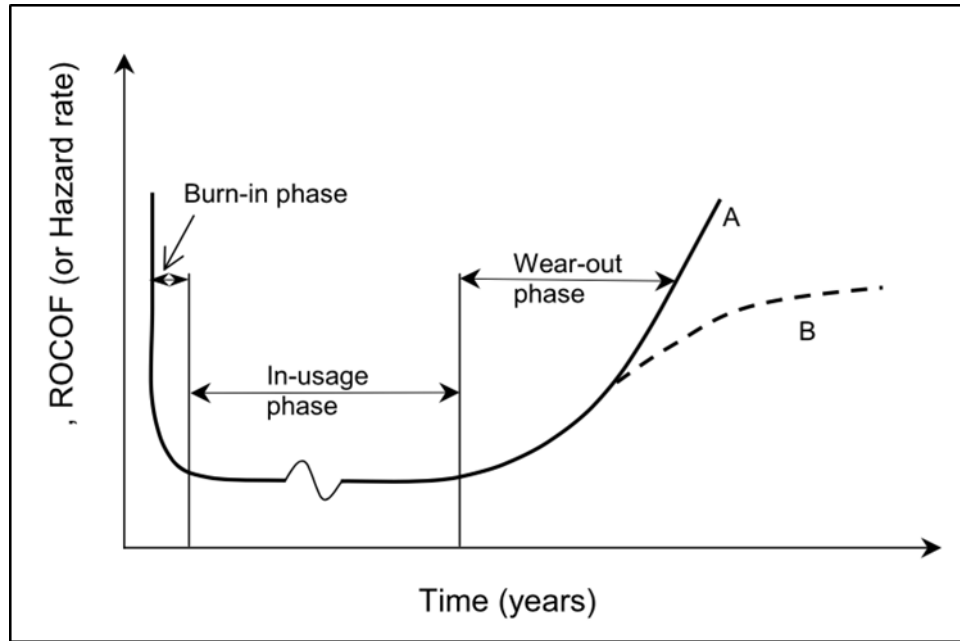
Figure 2.4 Watermain Bathtub Curve (Kleiner and Rajani, 2001)

Many different types of models are used to predict water main failures. These models include probabilistic models, deterministic models, and physical models. Kleiner and Rajani (2001) provided an analysis and critique of the existing water main failure prediction models.

2.5.1 Statistical Models

Statistical models predict future failures based on the pipe's similarities with pipes that have failed in the past. Two main categories of statistical models are deterministic and probabilistic models.

2.5.1.1 Deterministic Models

Deterministic models analyze pipes with similar characteristics in groups and apply the same factors that affect the pipe's probability of failure and breakage rate. This is done to acknowledge the amount of uncertainty when predicting water main failures and creating a simple mathematical model.

A regression analysis from Shamir and Howard (1979) was used to create the model that can predict the pipe's breakage rate from its age. The model is shown in Equation 1.

$$N(t) = N(t_0)e^{A(t+g)} \hspace{4cm} \text{(Eq. 1)}$$

Where: $N(t)$ = number of breaks per unit length per year (-)

$N(t_0)$ = number of breaks per unit length per year at the year of

installation of the pipe (-)

A = growth rate coefficient (years^{-1})

t = time since the previous break (years)

g = age of pipe (years)

This model requires data on the installation date of each pipe, length of each pipe, and the breakage history of each pipe. The formation of homogeneous groups requires further information on the material, diameter, soil type of bedding, and break type among others. Kleiner and Rajani (2001) recommended that careful treatment should be applied when using this model in groups as it is assuming many different types of data are similar for each pipe in the group.

This model was improved upon with the application of two factors based on field observations in the Binghamton, New York by the US Army Corps of Engineers. The modified model proposed by Walski and Pellicia (1982) is presented in Equation 2.

$$N(t) = C_1 C_2 N(t_0)e^{A(t+g)} \qquad \text{(Eq. 2)}$$

Where: C_1 = ratio between {break frequency for pit/sandspun) cast iron

with no/one or more) previous breaks} and {overall break frequency for

pit/sandspun) cast iron}

C_2 = ratio between {break frequency for pit cast pipes 500 mm diameter}

and {overall break frequency for pit cast pipes}

The factors account for the breakage history of the pipes and the observed changes in breakage rates in large diameter pit cast iron pipes. Pipe casting is an additional dataset that will need to be collected to properly run this model. Walski and Pellicia (1982) did not explain the derivation of the correction factors and did not provide information that showed the model's improved prediction ability.

In addition to the model by Shamir and Howard (1979), Kutylkowska (2015) introduced three constant coefficients: C, D, and E. These constants are determined on a case by case basis

depending on the operational and maintenance procedures on the water distribution system. Equation 3 shows these modifications.

$$N(t) = N(t_0)e^{a(t-t_0)} - [D(t-t_0)^2 + C(t-t_0) + E] \qquad \text{(Eq. 3)}$$

Where: $N(t)$ = The failure rate at time t (km * a)

$N(t_0)$ = The failure rate at time t_0 (km * a)

t = current time of analysis (year)

t_0 = The initial time of analysis (years)

a = coefficient dependent on diameter and material of the pipe

C, D, and E = regression coefficients based on operational and

maintenance factors (-)

A linear regression model that predicted failure based on the properties of the pipe's surrounding soil was introduced by McMullen (1982). The regression model is shown in Equation 4.

$$\text{Age} = 0.028\text{SR} - 6.22\text{pH} - 0.049r_d \qquad \text{(Eq. 4)}$$

Where: Age = age of pipe at first break (years)

SR = saturated soil resistivity (Ω cm)

pH = surrounding soil's pH

r_d = redox potential (millivolts)

This model was the result of a study completed on the water distribution system in Des Moines, Iowa. Soils with saturated soil resistivity of less than 2000 Ω centimeters resulted in 94% of pipe failures in the study. The study concluded that saturated soil resistivity is the main factor in reducing a pipe's life span by an average of 28 years for every 1000 Ω cm reduction (Kleiner and Rajani, 2001). Some limitations of this model are that this model can only predict first break for each pipe and the data needed is not readily available. This study resulted in relatively low correlation values, however it can be used as a building block to achieve more accurate results.

Clark, Stafford, and Goodrich (1982) proposed a model that used a linear equation to predict the first break and an exponential model that predicts additional breaks. The model is shown below in Equations 5 and 6.

$$NY = x_1 + x_2D + x_3P + x_4I + x_5RES + x_6LH + x_7T \qquad \text{(Eq. 5)}$$

Where: NY = number of years from installation to first repair (years)

x_i = regression parameters (-)

D = pipe diameter (in)

P = absolute pressure within the pipe (psi)

I = percentage of pipe overlain by industrial development (-)

RES = percentage of pipe overlain by residential development (-)

LH = length of pipe in highly corrosive soil (ft)

T = pipe type (-)

$$REP = y_1\theta_{y2t}\theta_{y3T}\theta_{y4PRD}\theta_{y5DEV}SL_{y6}SH_{y7} \qquad \text{(Eq. 6)}$$

Where: REP = number of repairs (-)

y_i = regression parameters (-)

t = age of pipe from its first break (years)

T = pipe type (-)

RRD = pressure differential (psi)

DEV = percentage of pipe in low and moderately corrosive soil (%)

SL = surface area of pipe in low corrosive soil

SH = surface area of pipe in highly corrosive soil

Pipe age, break history, pipe material, pipe diameter, soil corrosiveness, land use, and internal pressure information are necessary to perform this model. One of the main conclusions of this paper were that metallic pipes were active for about 13 more years than concrete pipes before the first repair however, the metallic pipes needed more repairs after the first break. Additionally, smaller diameter pipes and large industrial development above pipes both resulted in less time until first repair. These conclusions are reflected in the regression parameters for the above equations. The results of this model produced low correlation factors, however lack of available data was cited in the conclusions as one possibility for this result. Clark, Stafford, and Goodrich (1982) concluded that the equations could be used to develop the time for optimal pipe

replacement and as an indication of which variables increase or decrease the rate of deterioration.

A simple linear equation to predict pipe breaks with age was proposed by Kettler and Goulter (1985) and is shown in Equation 7.

$$N = k_0 A$$ (Eq. 7)

Where: N = number of breaks per pipe per year (-)

                       K_0 = regression parameter (-)

                       A = age of pipe (years)

The water distribution system in Winnipeg, Manitoba was analyzed for 10 years which resulted in the proposed model. This resulted in a strong correlation factors with an r-squared value of 0.884 for asbestos cement pipes and 0.672 for cast iron pipes. The study found a strong indication that smaller pipes break more frequently than larger diameter pipes. This model requires knowledge of the pipe length, installation date, and breakage history. The regression parameter is specific to a water distribution system based on the composition of the homogenous groups of pipes it contains. The homogenous groups are based on pipe material, pipe diameter, soil type, break type, and other characteristics. This makes it difficult to perform because a wide variety of accurate data is necessary to perform this model for an entire water distribution system.

Another linear regression model correlated pipe length and age to breaks. The model proposed by Jacobs and Karney (1994) is presented below in Equation 8.

$$P = a_0 + a_1 L + a_2 A$$ (Eq. 8)

Where: P = reciprocal of the probability of a day with no breaks (-)

                       a_i = regression coefficients (-)

                       L = length of pipe (m)

                       A = age of pipe (years)

This model was formulated after a study of six-inch cast iron water mains with over 3500 breakage events in 390 kilometers of pipes in Winnipeg. Jacobs and Karney (1994) created three homogenous groups of pipes based on age. The necessary information needed to complete this model are pipe length, pipe age, and breakage history. The model resulted in r-squared values of

0.704 - 0.937 for the pipes due to cluster breaks. Cluster breaks refers to a break that occurs within 90 days of a previous break and/or 20 meters of the previous break (Kleiner and Rajani, 2001). The first break of a pipe is called an independent break. When Jacobs and Karney applied the model to independent breaks, it resulted in a high r-sqaured values of 0.957 – 0.969 for the same three homogenous groups (Kleiner and Rajani, 2001). This shows that independent breaks follow a normal distribution more closely than other types of breaks.

2.5.1.2 Probabilistic Models

Probabilistic models have a more complex mathematical framework that can input many variables to determine the likelihood of homogenous groups of water mains to fail (Kleiner and Rajani, 2001). One limitation of this model is the large amount of data that is required.

Marks et al. (1985) proposed that the determination of the probability of time between each consecutive break could allow for the harzard function created by Cox (1972) to be used to prediction water main failures. The hazard function created by Cox (1972) and the modified hazard function for water mains by Marks et al. (1985) are shown below in Equations 9 and 10, respectively.

$$h(t, Z) = h_0(t)eb_T Z \qquad \text{(Eq. 9)}$$

$$h_0(t) = 2x10 - 4 - 10 - 5t + 2x10 - 7t2 \qquad \text{(Eq. 10)}$$

Where: $h(t, Z)$ = hazard function, instantaneous rate of failure (probability of failure at time $t + \Delta t$ given survival time t)

t = survival time (years)

b = vector of coefficients to be estimated by regression (-)

T = time to next break (years)

Z = vector of covariates acting multiplicatively on the hazard function

The modified hazard function prepared by Marks et al. (1985) is a time dependent model with the covariates accounting for operational and environmental stresses (Kleiner and Rajani, 2001). The data necessary for this model includes the pipe length, operating pressure,

percentage of low land development, pipe "vintage" or time of installation, pipe age at repetitive

breaks, number of previous breaks in pipe, and soil corrosiveness (Kleiner and Rajani, 2001).

2.5.2 Physical Models

Physical models analyze the stresses and physical factors that work to degrade pipes

over time. The pipe's strength and ability to resist corrosiveness are then used to predict when

the pipe will failure. This is the ideal model that would be able to account for every factor that

degrades each pipe; however, it is very difficult to obtain the data necessary to accurately model

every physical factor acting on each pipe in the system. Physical models currently only make

financial sense for large mains because of the cost of data acquisition (Kleiner and Rajani, 2001).

Doleac et al. (1980) proposed a model that utilized a function developed by Rossum

(1969) to predict the time to corrosive failure of water mains. Corrosive rates are important to

determine the structural integrity of the pipe to handle the internal and external loads it is

subjected to. This model was applied to pipes in Vancouver, Canada. The model is presented in

Equation 11.

$$P = K_n K_a (10\text{-}pH)^n \rho^{-n} t^n A^a \qquad \text{(Eq. 11)}$$

Where:　　　　p = average pit depth

K_n, K_a, a = empirical constants

A_a = pipe surface area exposed to corrosion

pH = soil pH

ρ = soil resistivity

n = soil aeration constant

t = time (years)

Rajani et al. (1996) proposed a pipe-soil interaction model for longitudinal stresses of

jointed water mains in response to pressures and temperature changes. The model indicated that

ductile iron and PVC pipes experienced substantial stress increases with a decrease in pipe size.

The model calculated the hoop stress and axial stresses on the pipes. The model confirmed that

additional loads from cold ground temperatures can increase circular breaks in corroded water

mains (Kleiner and Rajani 2001). The equations for axial and hoop stresses used for this model is shown below in Equations 12 and 13, respectively.

$$S_x = C_1 E_p \frac{\partial u}{\partial x} + C_2 P_i - C_3 E_p a_p \Delta T \qquad \text{(Eq. 12)}$$

Where: S_x = axial stress

E_p = elastic modulus of pipe

u, x = axial displacement in longitudinal direction

a_p = coefficient of pipe linear thermal expansion

P_i = internal pressure of pipe

ΔT = temperature differential

C_1, C_2, and C_3 = soil and pipe property functions

$$S_q = \frac{P_i D}{t} h(\frac{D}{t}, \frac{E_p}{E_s}, n_p, k_s, K) \qquad \text{(Eq. 13)}$$

Where: S_q = hoop stress

D = pipe diameter

P_i = internal pressure of pipe

t = pipe thickness

n_p = pipe Poisson ratio

E_s = elastic soil modulus

E_p = elastic modulus of pipe

k_s = pipe-soil reaction modulus

K = function of soil and pipe property constant

2.5.3 Model Limitations

Statistical and physical models are not perfect, and more research needs to be completed to continue to work towards a more perfect model. The accuracy of these models is limited by the availability of accurate data that will enable these models to be applied to their full potential. Municipalities have differing primary factors degrading their water mains. A model that may work well in one municipality may not be as accurate in another municipality. In addition to availability of data, the statistical complexity and time required of some models can pose a

limitation to certain municipalities. The ideal model is one that has simple calculations and requires data that is readily available.

2.6 Jan Devera's Risk Assessment Model

A statistically simple model developed by Devera (2013) required data that is typically available to municipalities. Devera (2013) improved upon an unfinished model created by Water Systems Consulting Inc. (WSC) with a goal of creating a model that could be used universally. The model contains three main calculations: (1) remaining useful life (RUL) and probability of failure for each pipe (PF); (2) degree of impact score (IS) after a failure; and (3) risk of failure score (RF).

The pipe age, material, and break history are necessary to calculate the remaining useful life of each pipe. The pipe age is compared with the manufacturer's anticipated service life (ASL) based solely on the pipe's material. The average ASL for each pipe material was used in Devera's model for the range of years given by the manufacturer. Each previous break in a pipe reduces the RUL by a percentage. The ASL and break history adjustments used in Devera's model are shown in Tables 2.5 and 2.6.

Table 2.5 Anticipated Service for Each Pipe Material (Devera, 2013)

Pipe Material	Abbreviation	Manufacturer's Service Life (Years)	Anticipated Service Life (ASL)
Cast Iron	CIP	50-100	75
Ductile Iron	DIP	75-125	100
Galvanized Iron	GALV	40-60	50
Steel	STL	30 - 75	40
PVC	PVC	50-150	100
Composite (Techite)	COMP	50 -150	50
Asbestos Cement	ACP	75-125	100
unknown	-	50-150	50

Table 2.6 Remaining Useful Life Break History Adjustment (Devera, 2013)

Original RUL	Break History Adjustment (Frequency within the last 20 years)				Number of Incidents
	No incidents	*1 incident*	*2 incidents*	*3 or more incidents*	
	100%	*30%*	*20%*	*10%*	*Percent Adjustment*
100	100	30	20	10	
90	90	27	18	9	
80	80	24	16	8	
70	70	21	14	7	**Adjusted Remaining Useful Life (RUL)**
60	60	18	12	6	
50	50	15	10	5	
40	40	12	8	4	
30	30	9	6	3	
20	20	6	4	2	
10	10	3	2	1	

The RUL for each pipe in the analyzed water distribution system is calculated according to Equation 14.

$$RUL = (ASL - Age) \times P_{adj} \qquad \text{(Eq. 14)}$$

Where: RUL = remaining useful life (years)

ASL = anticipated service life (years)

Age = pipe age at time of calculation (years)

P_{adj} = break history adjustment (%)

The probability of failure score ranks the severity of the risk of failure based on the remaining useful life score for each pipe and is shown in Table 2.7.

Table 2.7 Probability of Failure Score (Devera, 2013)

Remaining Useful Life (RUL) in Years	Probability of Failure (PF) Score	Risk Level
Less than 2	10	High
2 to 4	9	↑
4 to 6	8	
6 to 8	7	
8 to 10	6	
10 to 12	5	
12 to 14	4	
14 to 17	3	
17 to 19	2	↓
Greater than or equal to 20	1	Low

The degree of impact score quantifies the negative economic and critical service impacts of each failed pipe in the analyzed system. This allows for pipes that will provide more serious consequences to have a higher priority on the rehabilitation list. The factors that affect the impact score are service demand, critical customers, land use, traffic impact, material phasing, and estimated total cost for repair. Table 2.8 summarizes the degree of impact score criteria.

Table 2.8 Degree of Impact Score Criteria (Devera, 2013)

Impact Criterion	Impact Score				
	1	2	3	4	5
Service Demand	<160gpm	between 160-320gpm	between 320-480gpm	between 480-640gpm	≥ 640 gpm
Customer Criticality	No critical customers or pipe size < 8"	At least 1 Critical Customer	2 Critical Customers	3 Critical Customers	4 or more Critical Customers
Land Use	Agriculture, Open Space	Very low to low medium Density Residential	Low medium to high Density residential	High to very high Density residential, Village core, or mixed use	Office professional, Regional Commercial, or Community Facility
Traffic Impact	Local Streets	Collector Street	Priority 2 Transit	Priority 1 Transit	Arterial Street
Material Phasing	PVC and ACP	Ductile Iron	Steel & Techite	Galvanized Iron	Unlined Cast Iron or unknown material
Estimated Total Cost for Repair	≤ $26,440	between $26,440 - $52,882	between $52,882 - $79,322	between $79,322 - $105,762	≥ $105,762

Equation 15 demonstrates how the degree of impact score is calculated.

$$\text{Total IS} = IS_{demand} + IS_{criticality} + IS_{land\ use} + IS_{traffic} + IS_{phasing} + IS_{cost} \qquad \text{(Eq. 15)}$$

Where: Total IS = cumulative impact score for each pipe

IS_i = impact score for each criteria

The risk of failure score is determined by Equation 16, which is the product of the

probability of failure score and total degree of impact score.

$$\text{RFS} = \text{Total IS} \times \text{PF} \qquad \text{(Eq.16)}$$

Where: RFS = risk of failure score

Total IS = cumulative impact score

PF = probability of failure score

The risk of failure scores corresponding to the total impact score and probability of failure

score is shown on Table 2.9. Table 2.10 displays a legend for the risk failure score to the failure

risk level of each pipe.

Table 2.9 Risk of Failure Score for Varied PF and IS (Devera, 2013)

Table 2.10 Risk of Failure Category (Devera, 2013)

RFS Value	Color	Failure Risk Level
≤ 20	Blue	Very Low
21 to 70	Green	Low
71 to 150	Orange	Medium
≥ 151	Red	High

2.7 Hernan Cortez's Risk Assessment Model

A more statistically complex model was proposed by Cortez (2015) and was subsequently compared to Devera's model to verify its capabilities. The determination of the remaining useful life of the pipes was the only major difference between the two models. The main procedure of the model is similar to Devera's model and proceeds as follows: (1) calculation of probability of failure score (PF) and remaining useful life (RUL); (2) degree of impact score (IS); and (3) the risk of failure score (RFS).

Pipe age, expected service life, pipe size, pipe material, pipe length, internal pressure, percent of pipe overlain by residential areas, percent of pipe covered by industrial areas, and previous break history data are necessary to calculate the remaining useful life of each pipe (Cortez, 2015). These additional factors were added to determine if the simplified model over looked important information that could impact the results of the model in a significant way. The model proposed by Cortez is based on a linear regression model first introduced by Clark, Stafford, and Goodrich (1982) because the data necessary for the model is readily available. The model developed by Clark, Goodrich, and Stafford is shown in Equation 5.

Cortez (2015) modeled the anticipated service life parameter, x_1, as a normal random variable because of the uncertainty of the exact anticipated service life value within the range provided the manufacturer. To account for this uncertainty, Cortez (2015) performed 100,000 Monte Carlo simulations to determine the most likely value for each pipe. The results of these simulations were inputted into Equation 5 for each pipe to solve for the amount of years from installation to first failure. The other regression parameters in the model were determined from findings in the Clark, Stafford, and Goodrich (1982) model. Table 2.11 summarizes these values.

Table 2.11 Regression Parameters (Cortez, 2015)

Regression Parameter	Definition	Assigned Value
X_1	Anticipated serviceable life. Modeled as a random variable	Varies based on Monte Carlo Simulation
X_2	Diameter parameter	0.338
X_3	Pressure parameter based on the magnitude of pressure within pipe	-0.022
X_4	Industrial cover parameter	-0.265
X_5	Residential cover parameter	-0.0983
X_6	Length parameter	-0.003
X_7	Pipe material parameter	13.28

The remaining useful life of each pipe is calculated by subtracting the number of years from installation to its first failure by the current age of the pipe as shown in Equation 17.

$$RUL = (NY - Age) \hspace{4cm} \text{(Eq. 17)}$$

Where: RUL = remaining useful life (years)

NY = number of years from installation to first failure (years)

Age = current age of pipe since installation (years)

A 10% decrease in the RUL was applied for each previous break in a pipe. The RUL was then used to calculate the probability of failure according to Table 2.7.

The degree of impact score was then calculated according to Equation 15. The risk of failure is the product of the total degree of impact score and the probability of failure for each pipe. Table 2.12 shows the relationship between the risk of failure score and the risk category.

Table 2.12 Risk of Failure Criteria (Cortez, 2015)

Risk Score	Risk Category and Color Designation
0 to 40	Low Risk
40 to 80	Medium Risk
80 to 100	High Risk
≥ 100	Critical Risk

2.8 Lyle Nemeth's Risk Assessment Model

Nemeth (2016) compared Devera's simplified model and Cortez's complex model on the City of Buellton's water distribution system. Both models follow the same procedure in which the

remaining useful life, probability of failure score, degree of impact score, and the risk of failure are calculated for each pipe in the system. Cortez (2015) factored in the pipe diameter, pipe length, internal pressure, and land use in addition to the pipe age, pipe material, and breakage history factors accounted for by Devera (2013) in the calculation of the remaining useful life.

A worst-case scenario analysis was introduced by Nemeth (2016) to determine the pipe age and anticipated service. The factors evaluated the worst-case scenario because the lack of pipe age data for the analyzed municipality. Tables 2.13 and 2.14 show the adjusted installation years and anticipated service life, respectively.

Table 2.13 Adjusted Pipe Material Installation Year (Nemeth, 2016)

Pipe Material	Abbreviation	Common Installation Periods	Mean Installation Year	Standard Deviation of Installation Year
Asbestos Cement	ACP	1950-1970	1960	3.33
Ductile Iron	DIP	1960-2016	1988	9.33
Polyvinyl Chloride	PVC	1970-2016	1993	7.67
Steel	STL	1940-2016	1978	12.67

Table 2.14 Adjusted Material Anticipated Service Life (Nemeth, 2016)

Pipe Material	Abbreviation	MRSL (years)	ASL (years)	Standard Deviation of ASL (years)
Asbestos Cement	ACP	75-125	100	8.33
Ductile Iron	DIP	75-125	100	8.33
Polyvinyl Chloride	PVC	50-150	100	16.67
Steel	STL	30 - 75	52.5	7.5
unknown	-	50-150	100	16.67

2.9 Ashruf Khan's Risk Assessment Model

Khan (2018) compared the models proposed by Devera (2013), Cortez (2015), and Nemeth (2016) on the City of San Luis Obispo's water distribution system. The model followed the same procedures explained in the previous sections for each model. This was done to provide further research into a preferred model as Nemeth (2016) and Cortez (2015) reached different conclusions. Khan (2018) concluded that the statistically simple model was preferred because

both analyzes yielded similar results. Khan's findings for the downtown pressure zone in the City of San Luis Obispo are summarized in Table 2.15. Kahn (2018) did not account for cast iron pipes due lack of available data. Kahn (2018) concluded that the simplified model was preferred because of similar results between the models in the study.

Table 2.15 Average Risk of Failure Category Summary (Khan, 2018)

Risk of Failure Category	Average ROF Score Simplified Model	Average ROF Score Complex Model
Low Risk	23.30	29.39
Medium Risk	71.94	69.39
High Risk	95.18	98.30
Critical Risk	122.80	129.02

3. RISK ASSESSMENT METHODOLOGY

3.1 Overview

This study compared water main failure prediction models presented by Devera (2013) and Cortez (2015) along with Nemeth's (2016) worst-case scenario analysis to find the optimal model. The age-based model that the City of San Luis Obispo currently uses was also included in this comparison. Kahn (2018) provided a similar comparison between the statistical models for the City of San Luis Obispo's water distribution system and concluded that the simplified model is preferred. This study added to the previously accomplished analysis by including corrosive soil information, average daily traffic volume provided by the City of San Luis Obispo, and introducing a new analysis scenario for future projected population growth in according to the SLO General Plan 2035. The goal of this study is to find the prediction model that will create the most accurate, practical, and cost-effective solution for municipalities to plan a pipe replacement/rehabilitation schedule.

The three statistical models consist of three stages. These stages include the calculations of the following variables: 1) the remaining useful life (RUL) and probability of failure (PF); 2) the degree of impact score (DI); and 3) the risk of failure score (RF).

The difference between the Devera (2013) model and the Cortez (2015) model is the determination of the probability of failure score. The Cortez (2015) model included pipe size, land use, anticipated service life, internal pressure, and pipe length in corrosive soils in addition to pipe material, breakage history, and installation year accounted for in Devera's (2013) model. Kahn (2018) was unable to attain corrosive soil information and assumed the worst-case scenario to be conservative. Corrosive soil data was available for this model, which allowed for the Cortez (2015) model to be refined in this study.

Both models calculate the degree of impact score for each pipe in the system to determine the consequences of failure. Cost of repair, traffic impacts, interruption in service, and the impact of critical customers are factored into the degree of impact score. The traffic impacts in the Devera (2013, Cortez (2015), Nemeth (2016), and Kahn (2018) studies were analyzed by street classification. This study recognized that street classifications do not always correlate with traffic volume. Therefore, traffic count data obtained from the City of San Luis Obispo determined the

traffic impact due to water main failure for this study. Each individual factor receives a score that is then summed together for the total degree of impact score for each pipe in the system.

The last stage calculates the risk of failure for each pipe. The risk of failure is the product of the probability of failure score and total degree of impact score. This score places the pipes into categories that determine the recommended replacement/rehabilitation schedule.

The current system to determine the water main rehabilitation for the City of San Luis Obispo is based solely on age. The current Master Water Plan for the City of San Luis Obispo places pipes that are over 75 years of age in the first priority replacement category and pipes over 50 years of age in the second priority category.

3.2 Remaining Useful Life

The remaining useful life is the estimated number of years until a water main will fail. The complex model accounts for more factors in this determination than the simplified model.

3.2.1 Pipe Age

The age of pipe is calculated by subtracting the installation year from the current year at the time of calculation. This assumes that the pipe began service in the same year it was installed and that it has always remained in continuous use.

This calculation can be difficult to conduct as installation records for each pipe in a municipality's water distribution system may not be readily available. This leads to further assumptions when installation data is unavailable. Particular pipe materials were standard at different periods of time for water distribution mains which allows for the installation year to be narrowed down into a range of years AWWA (2011). The average year and standard deviation for each pipe material is used to determine the most likely installation year for a pipe with no installation year data. Table 3.1 summarizes each pipe material's common installation years, mean installation year, and standard deviation.

The City of San Luis Obispo has the installation data of its water main distribution system available in a database that was used in this study. This allowed for the installation years for each of the pipes to be accurately determined.

Table 3.1 Typical Installation Periods for Pipe Materials

Material	Installation Year	Standard Deviation of Installation Year (years)
AC	1950-1970	3.33
CI	1920-1970	8.33
DI	1960-2019	9.83
PVC	1970-2019	8.16
Steel	1940-2019	13.16
Unknown	1920-1970	8.33

3.2.2 Statistically Simple Model

Each pipe material in a water distribution system has a manufacturer recommended service life (MRSL) which is used to calculate the anticipated service life (ASL). The ASL is the mean value of the MRSL and is the expected life cycle of the water main. Pipes with missing material data are given a conservative ASL. Table 3.2 shows the MRSL and ASL values for different pipe materials.

Table 3.2 Anticipated Service Life Values

Material	Manufacturer's Recommended Service Life (years)	ASL (years)	Standard Deviation of ASL (years)
AC	75-125	100	8.33
CI	50-100	75	8.33
DI	75-125	100	8.33
PVC	50-150	100	16.67
STL	30-75	52.5	7.5
Unknown	30-75	52.5	7.5

The ASL was calculated by computing Monte Carlo simulations from the information provided on Table 3.2 based on the pipe material. These ASL values were then used in Equation 18 for each Monte Carlo simulation to determine the RUL. The mean value of these simulations for each pipe is the RUL used for the rest of the model's calculations (Nemeth, 2016).

$$RUL = (ASL - Age) \hspace{4cm} \text{(Eq. 18)}$$

Where: RUL = remaining useful life (years)

                  ASL = anticipated service life (years)

                  Age = pipe age (years)

3.2.3 Statistically Complex Model and 2019 Model

The following sections detail the process of the complex model and the 2019 model due to the multitude of steps. The complex model is a model carried over previous studies, while the 2019 model contains improvements from this study. The complex model and 2019 model are very similar except for how the traffic impact is scored and how the length of pipe laid in corrosive soil is determined. All of the steps for these models are described in the following sections.

3.2.3.1 Clark, Stafford, and Goodrich (1982)

Clark, Stafford, and Goodrich (1982) modeled the predicted number of years to a water main failure with a linear model that has been used to calculate the remaining useful life of the pipes in the following studies Cortez (2015), Nemeth (2016), and Khan (2018). The necessary information for the linear model is the pipe size, pipe material, internal pressure, land use above the pipe, anticipated service life, and the corrosiveness of the nearby soil. This information is commonly available to municipalities. The linear model introduced by Clark, Stafford, and Goodrich (1982) is shown in Equation 5.

Regression parameters in the linear model were defined by Clark, Stafford, and Goodrich (1982) and are displayed on Table 3.3.

Table 3.3 Linear Model Regression Parameters (Clark, Stafford, and Goodrich 1982)

Regression Parameter	Definition	Assigned Value
x_1	Anticipated Service Life Parameter (modeled as a random variable)	Varies based on Monte Carlo simulation and pipe material
x_2	Diameter Parameter	0.338
x_3	Pressure Parameter	-0.022
x_4	Industrial Land Use Parameter	-0.265
x_5	Residential Land Use Parameter	-0.0983
x_6	Corrosive Soil Length Parameter	-0.003
x_7	Pipe Material Parameter	13.28

3.2.3.2 Internal Pipe Pressure

The internal pressures of the pipes in the system were determined by the water pressure zones each pipe was a member of within the City of San Luis Obispo. Wallace Group modeled the City of San Luis Obispo's water distribution system in WaterCAD and provided maximum and minimum pressures in each of the City's water pressure zones under current and conditions. Furthermore, the plan called for a consolidation of the water pressure zones in the future with predicted maximum and minimum pressure values if the City accepts the recommendations to consolidate pressure zones. Maximum values were used in the analysis to account for the worst-case scenario. These values are summarized below in Table 3.4.

Table 3.4 Current and Future Pressure Conditions (Wallace Group, 2015)

	Current Conditions			Future Conditions		
Pressure Zone	Max Pressure (psi)	Min Pressure (psi)		Pressure Zone	Max Pressure (psi)	Min Pressure (psi)
Alrita	84	47		Alrita	84	47
Andrews	72	34		Andrews	72	34
Bishop	109	34		Downtown	93	44
Downtown	93	44		Edna Saddle	104	50
Edna Saddle	104	50		Foothill	106	37
Ferrini	114	72		High Pressure	114	22
Foothill	103	42		Resevoir Canyon	89	37
High Pressure	134	60		Rosemont	76	48
Highland	95	22		Terrace Hill	108	31
Patricia	75	41				
Reservoir 1	89	37				
Rosemont	76	48				
Serrano	106	76				
Slack	101	37				
Terrace Hill	108	31				

3.2.3.3 Land Use

Clark, Stafford, and Goodrich (1982) presented values correlating the percent of residential and industrial land cover for each type of land use. This provides an approximation for how many trucks are traveling over the water main. Truck loads are significantly higher than passenger car loads, which could impact the remaining useful life of the underground water main. These values are shown in Table 3.5

Table 3.5 Residential and Industrial Correlation to Land Use (Cortez, 2015)

Land Use	% Residential	% Industrial
Agricultural	75	25
Commercial	96	4
Industrial	50	50
Public	96	4
Residential	100	0
*Mixed Use	96	4
**Industrial Mixed Use	25	75

3.2.3.4 Length of Pipe in Corrosive Soil

Previous studies including Khan (2018) lacked the necessary data to determine the length of pipe in highly corrosive soil and therefore assumed that every pipe was fully covered by corrosive soil to account for the worst-case scenario. This study was able to obtain corrosive soil data to more accurately represent the pipes covered in highly corrosive soil. The complex model assumes all pipes are lain in highly corrosive soil, while the 2019 complex model uses corrosive soil data from a Natural Resources Conservation Service (NRCS) Soil Survey. This will be used as a method of comparison between the two models.

3.2.3.5 Pipe Material Value

The "T" values for each pipe material, in Equation 5, correspond to the material's durability in comparison to fully metallic materials. Clark, Stafford, and Goodrich (1982) found that fully metallic pipes remained in operation for about 13 more years before the first repair with respect to concrete pipes. Initial values for each pipe material were provided by Nemeth (2016). Cast iron was not considered by Nemeth (2016), however, cast iron and ductile iron are comprised of similar percentages of metals. Therefore, the value used for cast iron in this study was 0.8 which is the same as the ductile iron value. All the pipe type values for each material used in this study is shown in Table 3.6.

Table 3.6 Pipe Type Values

Pipe Material	Abbreviation	Pipe Type
Asbestos Cement	ACP	0.1
Cast Iron	CI	0.8
Ductile Iron	DIP	0.8
Polyvinyl Chloride	PVC	0.3
Steel	STL	1

3.2.3.6 Calculating Remaining Useful Life

The equation for the remaining useful life of a water main is shown in Equation 19 (Cortez, 2015).

$$RUL = NY - Age \tag{Eq. 19}$$

Where: RUL = remaining useful life (years)

NY = number of years from installation to failure (years)

Age = current age of pipe (years)

Nemeth (2016), Cortez (2015), and Khan (2018) used Equation 18 to determine the remaining useful life of the pipes in the system. However, 10,000 Monte Carlo Simulations on the ASL gave 10,000 RUL results for each pipe. The average value of these simulations provided the RUL used for the remaining calculations in the model.

3.2.4 Break History Adjustment

Cortez (2015) presented a RUL adjustment factor based on the previous break history of the pipe. Cortez (2015) found that each break in a pipe reduces the RUL by 10%. This factor system is shown below in Equations 20 and 21. These factors only apply to pipes that have been rehabilitated and not fully replaced. This study was able to obtain break history data from the City of San Luis Obispo.

$$\text{Hist}_{adj} = 1 - (0.1 * N) \qquad \text{(Eq. 20)}$$

Where: Hist_{adj} = break history adjustment factor (-)

N = number of previous breaks (-)

$$\text{RULadj} = \text{RUL} * \text{Hist}_{adj} \qquad \text{(Eq. 21)}$$

Where: RULadj = adjusted remaining useful life (years)

RUL = remaining useful life (years)

Hist_{adj} = break history adjustment factor (-)

3.3 Stage 1: Determining Probability of Failure

The probability of failure score (PF) is a numerical scoring system that ranks pipes on the likelihood of failure based on the remaining useful life values. The probability of failure score is inversely proportional to the remaining useful life of each pipe. The probability of failure criteria was first introduced by Devera (2013).

Table 3.7 Probability of Failure Scoring Criteria

RUL (years)		Failure Score	Risk Level
Min	Max		
0	2	10	High
2	4	9	↑
4	6	8	
6	8	7	
8	10	6	
10	12	5	
12	14	4	
14	16	3	
16	20	2	↓
20	-	1	Low

3.4 Stage 2: Degree of Impact Scoring System

The next step after the probability scores have been determined is to calculate the degree of impact for each pipe in the system. The degree of impact score aims to assign a numerical value for the severity of negative consequences in a failure scenario for each pipe in the system. The consequences considered are traffic impacts, loss of service, critical customers, and cost of replacing the pipe. This scoring system was first introduced by Devera (2013) and can be modified for concerns of the municipality performing the analysis. The degree of impact score is calculated according to Equation 22.

$$DI = \Sigma\ IS_i \qquad\qquad (Eq.\ 22)$$

Where: DI = degree of impact (total weighted score)

IS_i = impact score for the ith component

3.4.1 Cost of Pipe Replacement

Previous studies only accounted for the cost of the material for this impact score. Kahn (2018) used the "City of San Luis Obispo: Final Potable Water Distribution System Operations Master Plan" (SLOWDSMP) that was prepared by Wallace Group in 2015 to determine the total cost of construction including labor for repairing water mains. Cost estimates were determined

based from engineering judgement, confirmed bid prices for similar work in the area, estimated

unit prices for work, and consultation with contractors (Wallace Group, 2015). These costs don't

include traffic control and fittings. This estimate needs to be evaluated each year for inflation and

changes in the economy at the time of analysis. Table 3.8 lists the price per linear foot for each

diameter of pipe in the system for ductile iron and polyvinyl chloride. Ductile iron and polyvinyl

chloride are the only materials considered because those are the only two materials on the

current City of San Luis Obispo Engineering Standards (2018) for water distribution mains.

Polyvinyl chloride pipe cost of replacement values were used for all other materials except for the

ductile iron pipes currently in the system because all other materials would most likely be

replaced by PVC pipes according to the current engineering standards. This differs from Kahn

(2018) which considered replacement costs for all existing pipe materials in the current City of

San Luis Obispo Water Distribution System.

Table 3.8 Pipe Cost Estimates Per Linear Foot

Pipe Material Cost Per Linear Foot		
Pipe Material	Diameter (in)	Price Per Linear Foot
Polyvinyl Chloride	4	$150.00
Polyvinyl Chloride	6	$170.00
Polyvinyl Chloride	8	$185.00
Polyvinyl Chloride	10	$225.00
Polyvinyl Chloride	12	$265.00
Polyvinyl Chloride	14	$285.00
Polyvinyl Chloride	16	$315.00
Polyvinyl Chloride	18	$350.00
Polyvinyl Chloride	20	$375.00
Polyvinyl Chloride	24	$400.00
Polyvinyl Chloride	27	$410.00
Polyvinyl Chloride	30	$425.00
Ductile Iron	4	$120.00
Ductile Iron	6	$135.00
Ductile Iron	8	$215.00
Ductile Iron	10	$240.00
Ductile Iron	12	$295.00
Ductile Iron	14	$315.00
Ductile Iron	16	$325.00
Ductile Iron	18	$405.00
Ductile Iron	20	$430.00
Ductile Iron	24	$440.00
Ductile Iron	27	$455.00
Ductile Iron	30	$475.00

The total cost for each pipe in the system is then converted into a ranking system based on the total price of replacement. The scoring system is broken down into five categories. These categories are based on the scoring system introduced by Khan (2018) and are shown below in Table 3.9.

Table 3.9 Cost Impact Scoring System (Khan, 2018)

Cost		Cost Impact Score	Critical Customer Impact Level
Min	Max		
$80,000	-	5	High
$50,000	$80,000	4	
$25,000	$50,000	3	↕
$10,000	$25,000	2	
-	$10,000	1	Low

3.4.2 Loss of Service Impact Scoring

Water distribution main failures have a direct impact on local businesses and residences resulting in negative economic impacts and a reduced quality of life. Additionally, this can result in the system not being able to handle fire flows while the main is broken. The model presented by Cortez (2015) ranks the negative impacts from loss of service by the amount of flow being carried by each pipe in gallons per minute (GPM). The Wallace Group (2015) created a model of the San Luis Obispo water distribution system in Bentley System's WaterCAD program. This model was used in this study to obtain the flow rate in each pipe for each analyzed scenario. The peak hour demand flow rate was used for all scenarios in this study to account for the worst-case scenario. A numerical scoring system was presented by Kahn (2018) to rate the loss of service impact for each pipe in the water distribution system. The criteria are shown below in Table 3.10.

Table 3.10 Loss of Service Impact Criteria (Khan, 2018)

Flow Rate (GPM)		Flow Rate Impact Score	Loss of Service Impact Score
Min	Max		
800	-	5	High
600	800	4	↑
400	600	3	
200	400	2	↓
0	200	1	Low

3.4.3 Traffic Impact Scoring System

Water main failures require construction crews to close access to the road above the failed pipe to repair the break. This will have an impact on the traffic flow, which can have greater impacts across the city. Previous studies, used street classification to determine the impact to traffic however, street classification does not always correlate with traffic volume. Therefore, traffic counts provided by the City of San Luis Obispo allowed for average daily traffic volumes for each street to be determined. Streets without traffic count data was assumed to not have a significant impact on the City of San Luis Obispo's overall traffic and were given a traffic impact score of 1. Pipes that are not overlain by roads receive a traffic impact score of zero. The traffic impact scoring criteria are summarized in Table 3.11. This varies from the previous traffic impact scoring criteria based on street classification shown in Table 3.12. The complex model uses the street classification method and the 2019 complex model uses the average daily traffic volume method. This will be used as a method of comparison.

Table 3.11 2019 Model Traffic Score Criteria

Average Daily Volume		Traffic Impact Score	Traffic Impact Level
Min	Max		
8000	-	5	High
6000	8000	4	↑
4000	6000	3	
2000	4000	2	
0	2000	1	↓
-	0	0	Low

Table 3.12 Complex Model Traffic Impact Scoring Criteria (Khan, 2018)

Traffic Class	Impact Score	Risk Level
Highway	5	High
Arterial	4	
Collector	3	
Residential	2	
Local	1	Low

3.4.4 Critical Customers

Customers that provide important services to the community would have a greater negative impact from a loss of service. For example, critical services such as hospitals, schools, police stations, senior care centers, and fire departments need to have access to water in order to perform their work that benefits the community has a whole. A scoring system was introduced by Devera (2013) that accounted for critical customers that raised the total impact score of any pipes within a quarter mile radius of these critical customers. The critical customer scoring criteria used for this study is shown below in Table 3.13

Table 3.13 Critical Customer Impact Score Criteria (Khan, 2018)

Critical Customer	Critical Customer Impact Score	Critical Customer Impact Level
Hospital	5	High
Fire Station	4	
Police Facilities	3	
School	3	
Senior Care Center	2	
Other	0	Low

3.5 Stage 3: Risk of Failure Computation

The last stage of the model is to calculate each pipe's risk of failure score. This ranks each pipe in the system based on both the likelihood of failure and consequence of failure. This scoring system attempts to allow for municipalities to identify the most critical pipes in the system to

budget for rehabilitation/replacement. The risk of failure score is the product of the probability of

failure and total degree of impact score for each pipe as shown in the Equation 23.

$$RF = PF * DI \qquad \text{(Eq. 23)}$$

Where: RF = risk of failure score (-)

PF = probability of failure score (-)

DI = total degree of impact score (-)

The risk of failure for each pipe can be directly compared to each other pipe in the

system. A higher risk of failure score correlates to a higher priority for the pipe to be replaced or

rehabilitated. Colors are associated with each category to allow for a more visual representation

for each pipe's replacement/rehabilitation priority. The risk of failure score criteria is summarized

below in Table 3.14.

Table 3.14 Risk of Failure Criteria

Risk Score		Risk Category
Min	Max	
100	-	Critical Risk
80	100	High Risk
40	80	Moderate Risk
0	40	Low Risk

3.6 Age-Based Model

The SLOWDSMP provided recommendations for the replacement and rehabilitation of water

main pipes in the City of San Luis Obispo. These recommendations were strongly influenced by

hydraulic conditions that must be met for fire flow conditions, however, the recommendations also

considered age. Because this study's goal is to predict the likelihood and consequence of water

main failure and not hydraulic requirements, the previous models will only be compared with the

age recommendations in the SLOWDSMP. The SLOWDSMP splits its recommendations into

three categories: first priority, second priority, and third priority. First priority pipes are any pipes

exceeding 75 years of age along with other hydraulic factors not taken into consideration in this

study. Second priority pipes have been in service between 50 to 75 years and third priority pipes have been in service for less than 50 years. Ignoring the hydraulic parameters in these priority categories simplifies these recommendations significantly, but the goal of this comparison is to compare how these models predict the deterioration of pipes. The ability of the pipes to meet hydraulic parameters is beyond the scope of this study. The first priority pipes are assumed to be in the critical risk of failure category, while second priority pipes are in the high risk of failure category. Third priority pipes will be placed into the low risk of failure category. This was determined through communication with an author of the SLOWDSMP. A summary of the criteria is shown below in Table 3.15.

Table 3.15 Age Based Risk Category Criteria

Pipe Age (years)	Priority	Risk of Failure Category
>75	First	Critical
50-75	Second	High
50<	Third	Low

3.7 Low ASL Scenario

Nemeth (2016) introduced a low age and low ASL analysis to the Devera (2013) and Cortez (2015) models. The purpose was to determine the effect of unknown variables used in the model. This study relied on a range of years provided by the manufacturer's recommended service life for each pipe material in the water distribution system. Because a range of years were given, values were adjusted for the worst-case scenario. Table 3.16 shows the adjusted anticipated service life values for each pipe material in the City of San Luis Obispo's water distribution system. The pipe age was determined from the City of San Luis Obispo's database and therefore, a worst-case scenario for pipe age was not necessary for this study.

Table 3.16 Adjusted Anticipated Service Life Values

Material	Manufacturer's Recommended Service Life (years)	ASL (years)	Standard Deviation of ASL (years)
AC	75-125	75	8.33
CI	50-100	50	8.33
DI	75-125	75	8.33
PVC	50-150	50	16.67
STL	30-75	30	7.5
Unknown	50-150	50	16.67

3.8 Future Scenario

All models are also analyzed during the future scenario which includes the construction of planned developments in the City of San Luis Obispo and consolidation of pressure zones in accordance with the recommendations form the SLOWDSMP.

Traffic volumes are increased in this scenario to account for the population increase. The San Luis Obispo General Plan projects the City of San Luis Obispo's population to increase to around 60,000 residents by 2035 after the completion of the planned developments. The percentage of traffic on each road in the City is assumed to be unchanged in this future scenario and just to increase in volume based on the population growth. This resulted in all current average daily traffic volumes being increased by a factor of 1.27 which was determined by divided the projected population in 2035 by the current population in the SLO General Plan.

Flow rates in the pipes are increased in this scenario according to values provided by the SLOWDSMP WaterCAD model that accounted for the projected increase in population from the SLO General Plan. The peak hour demand will be used to account for the worst-case scenario. Future pressures for each pressure zone after the proposed developments are constructed was also provided in the SLOWDSMP. The pipes will also reflect their future age in the year of 2035 for this scenario.

4. CITY OF SAN LUIS OBISPO CASE STUDY

4.1 Data Acquisition

The City of San Luis Obispo's potable water distribution system is composed of

approximately 145 miles of pipe (Wallace, 2015). The model contains information from the City of

San Luis Obispo's Graphic Information System (GIS) database. This database contained

shapefiles detailing land use, critical customer locations, and water mains in the city. Additional

information from the City of San Luis Obispo's official website provided traffic counts that was

manually inputted into Excel. A shapefile of break histories of current water main distribution

pipes in the city were provided by the City of San Luis Obispo Utilities Department. The

percentage of each pipe material in the water distribution system is shown below in Table 4.1.

The City of San Luis Obispo also provided installation dates for the distribution pipes in the

system.

Table 4.1 San Luis Obispo Water Distribution Pipe Material Percentages (Wallace, 2015)

Pipe Material	Percentage
Polyvinyl Chloride	42.8
Cast Iron	27.2
Ductile Iron	14.2
Asbestos Cement	12.6
Steel	0.5
Other	2.7

The Wallace Group (2015) modeled the San Luis Obispo Potable Water Distribution

System in Bentley's WaterCAD hydraulic modeling application. In addition to modeling the

current water distribution system in San Luis Obispo, Wallace Group also modeled the future

water distribution system after projected population increases and water pressure zones are

consolidated. The SLOWDMSP provided the pressures and flow rates for each water

pressure zone in the City of San Luis Obispo for each hydraulic scenario performed by The

Wallace Group. The peak hour demand and maximum pressure for each pressure zone in

the SLOWDMSP were used in this study.

The Natural Resources Conservation Service (NRCS) Soil Survey provided shapefiles on the areas containing corrosive in the City of San Luis Obispo. This data was used to determine the length of each pipe overlain in highly corrosive soil.

4.2 Computer Modeling and Data Analysis

The large volume of water distribution mains within the City of San Luis Obispo required the use of computer modeling and analysis programs for efficient calculations, while minimizing error. The programs used for this analysis are Microsoft Excel and Visual Basic Applications (VBA) and Environmental Systems Research Institute (ESRI) ArcMap 10.6. The following sections detail the use of each of these programs during this study's analysis.

4.2.1 ESRI ArcMap 10.6

ESRI ArcMap 10.6 provides tools to analyze, compile, and visualize data. This was used to compile shapefiles obtained from the City of San Luis Obispo's GIS Department and NRCS Soil Survey. The City provided shapefiles for the water distribution mains, critical customer locations, water main break history, roads, water pressure zones, and land use areas. The NRCS Soil Survey provided corrosive soil locations within the City of San Luis Obispo. The water main shapefile included information on the installation date, diameter, material, and pipe length. A break history shapefile was also provided by the City of San Luis Obispo's GIS Department and Table 4.2 summarizes the given information. Geographical relationships between these data sources were then used to combine the attribute data and export them into Excel spread sheets for computations. The results calculated in Excel were then imported back into ArcMap for visual representation.

Table 4.2 Water Main Repairs in 2019 in San Luis Obispo by Pipe Material

Pipe Material	Number Broken
Asbestos Cement	15
Cast Iron	39
Ductile Iron	11
Polyvinyl Chloride	2

4.2.1.1 Establishment of ArcMap Model for Analysis

A variety of shapefiles contained both spatial and attribute data relevant to the water main failure prediction models analyzed in this study. Tools in ArcMap allowed for consolidation of the data in a single attribute table that was exported into Excel for further calculations. The attribute data contained the following data: pipe ID, pipe material, pipe size, pipe length, installation date, land use, critical customer locations, and corrosive soil locations. The shapefiles were then used to visually represent the data. Figure 4.1 represents the corrosive soil locations in the area of interest of this study. Figure 4.2 displays the current water pressure zones from a shapefile obtained from the City of San Luis Obispo's GIS Department, while Figure 4.3 is adjusted for the future water pressure zones in San Luis Obispo. Figure 4.4 shows the areas of land use and street classifications in the City of San Luis Obispo. The water main break history was also shared from the City's GIS Department and is shown in Figure 4.5. Figure 4.6 shows the critical customers with the 0.25-mile buffer around them.
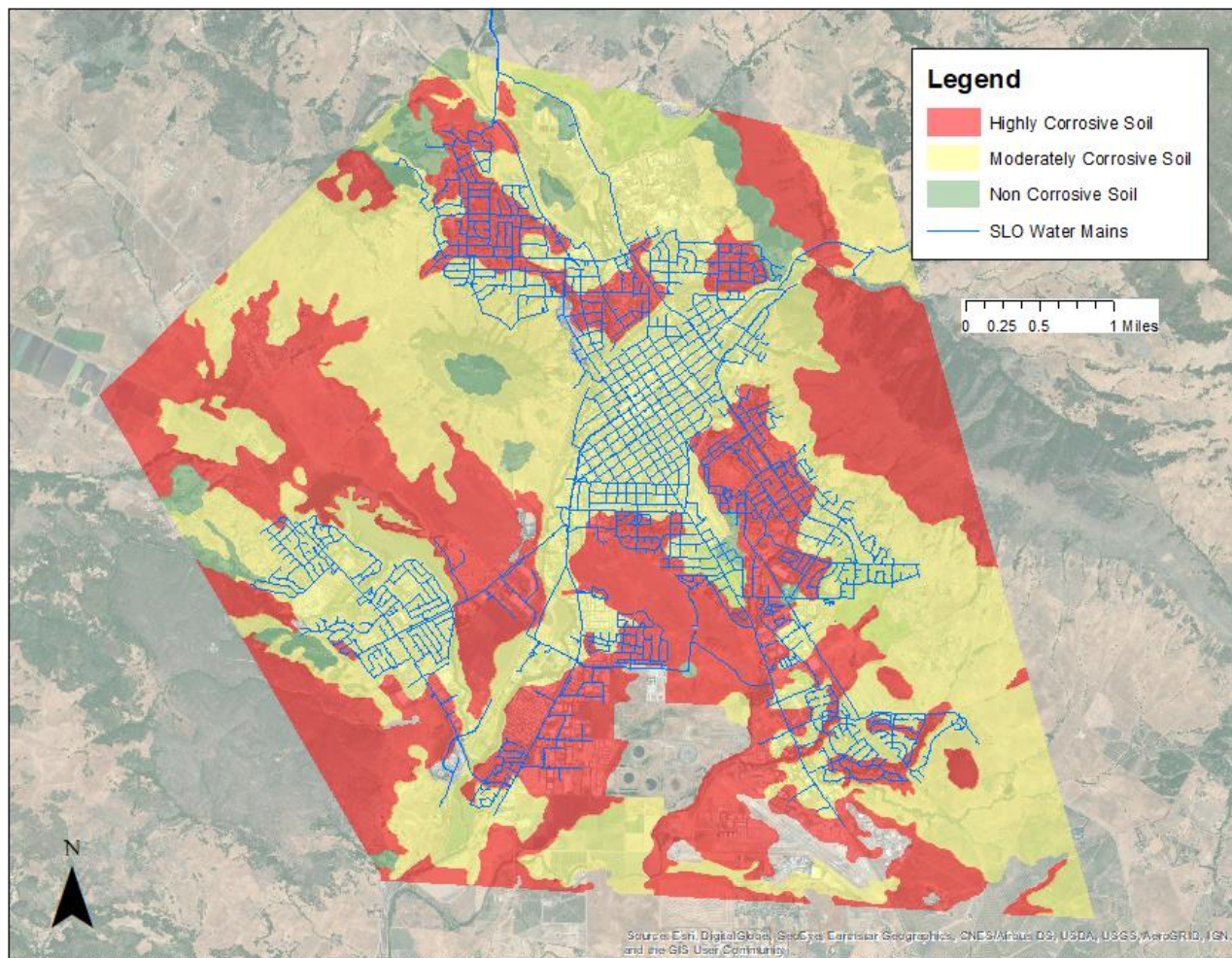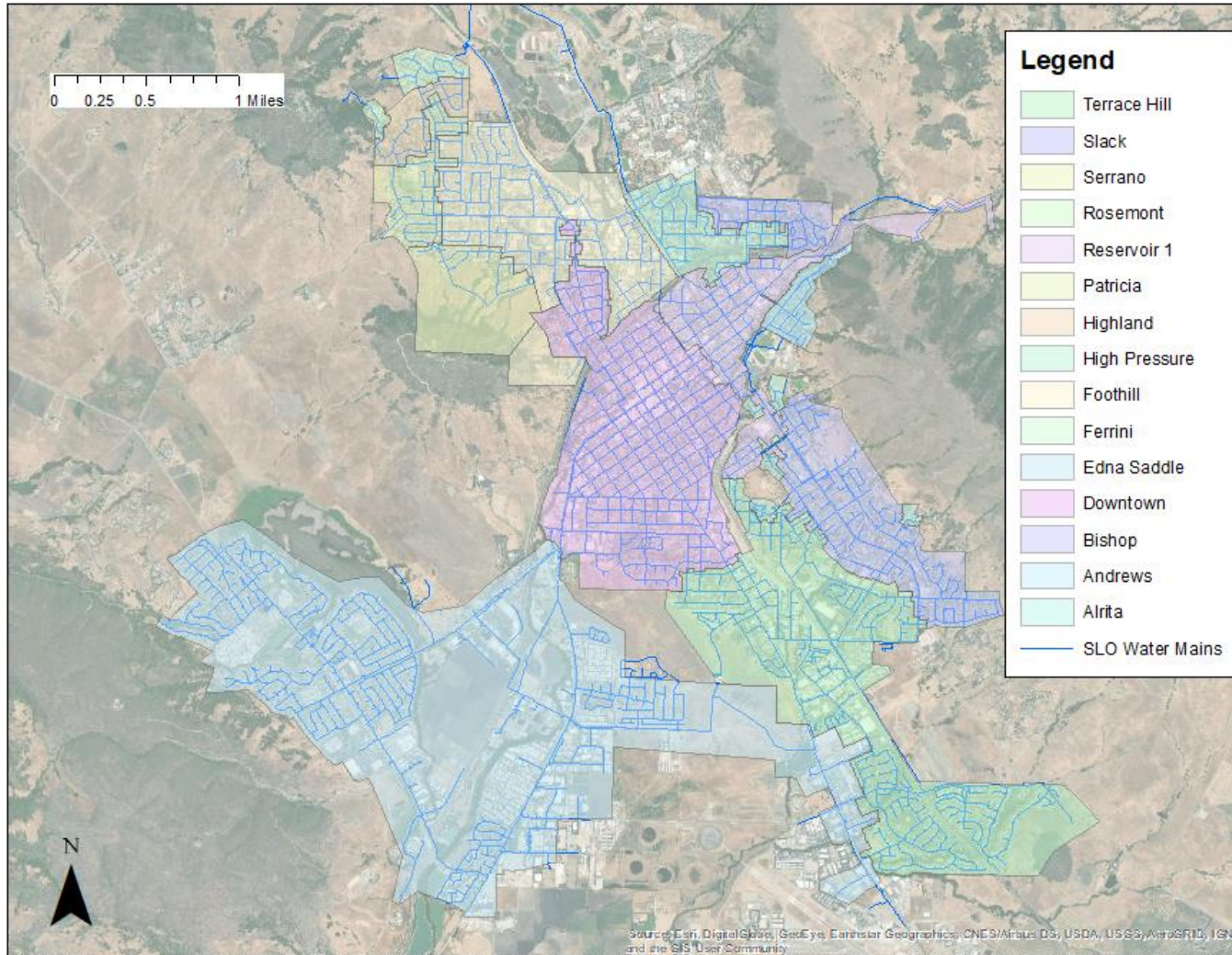
Figure 4.1 NRCS Corrosive Soil Survey
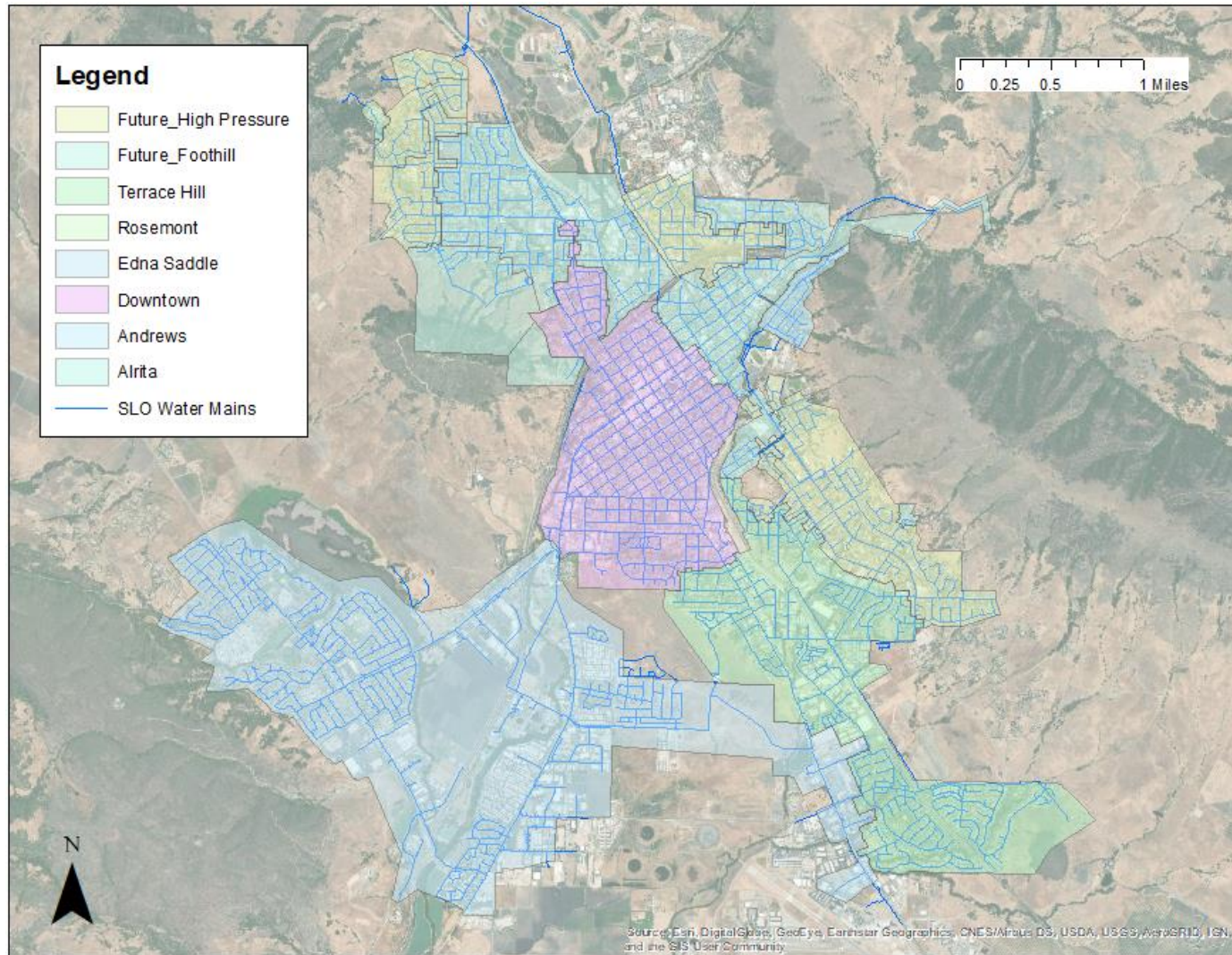
Figure 4.2 Current Water Pressure Zones in San Luis Obispo

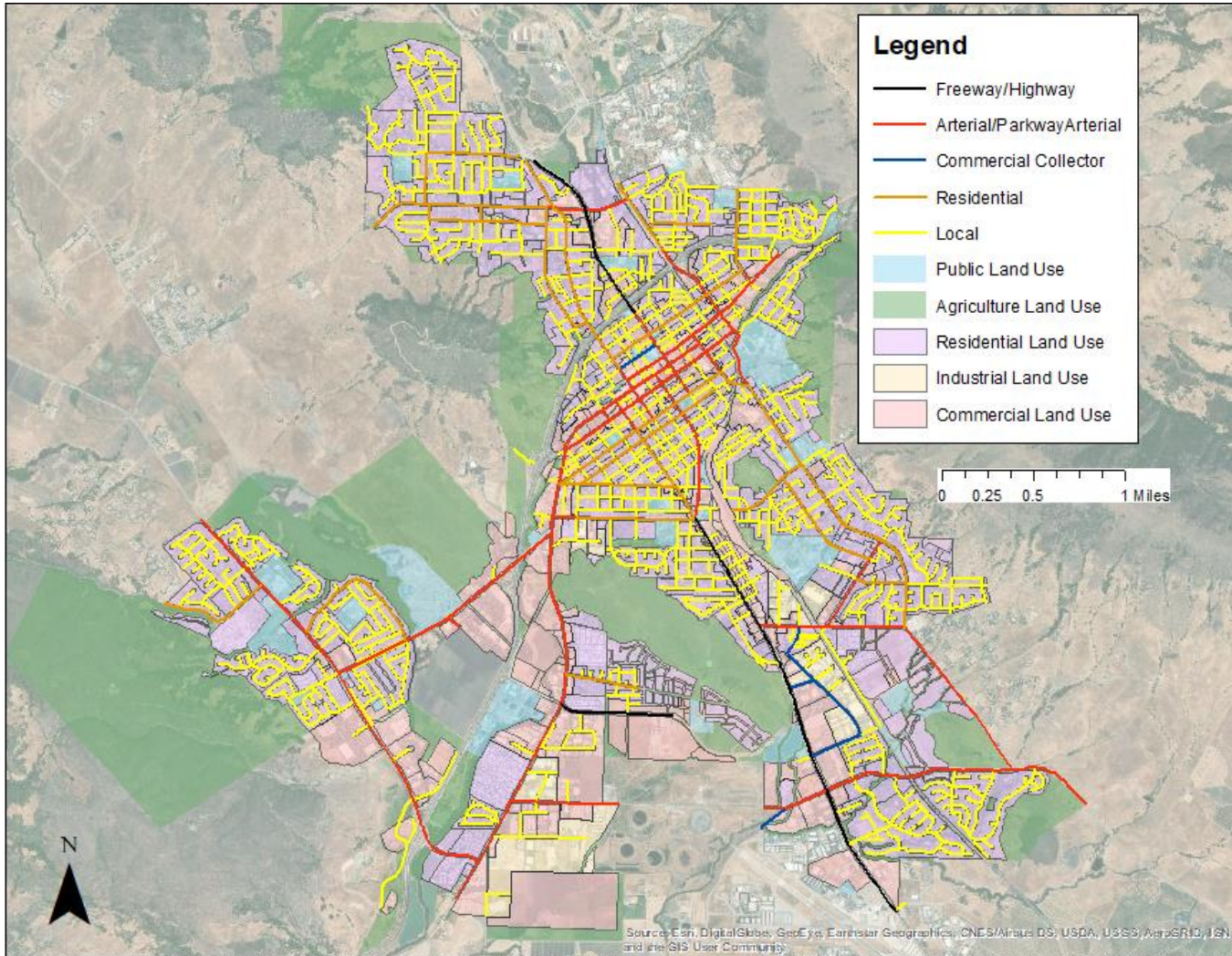**Figure 4.3** Future Water Pressure Zones in San Luis Obispo

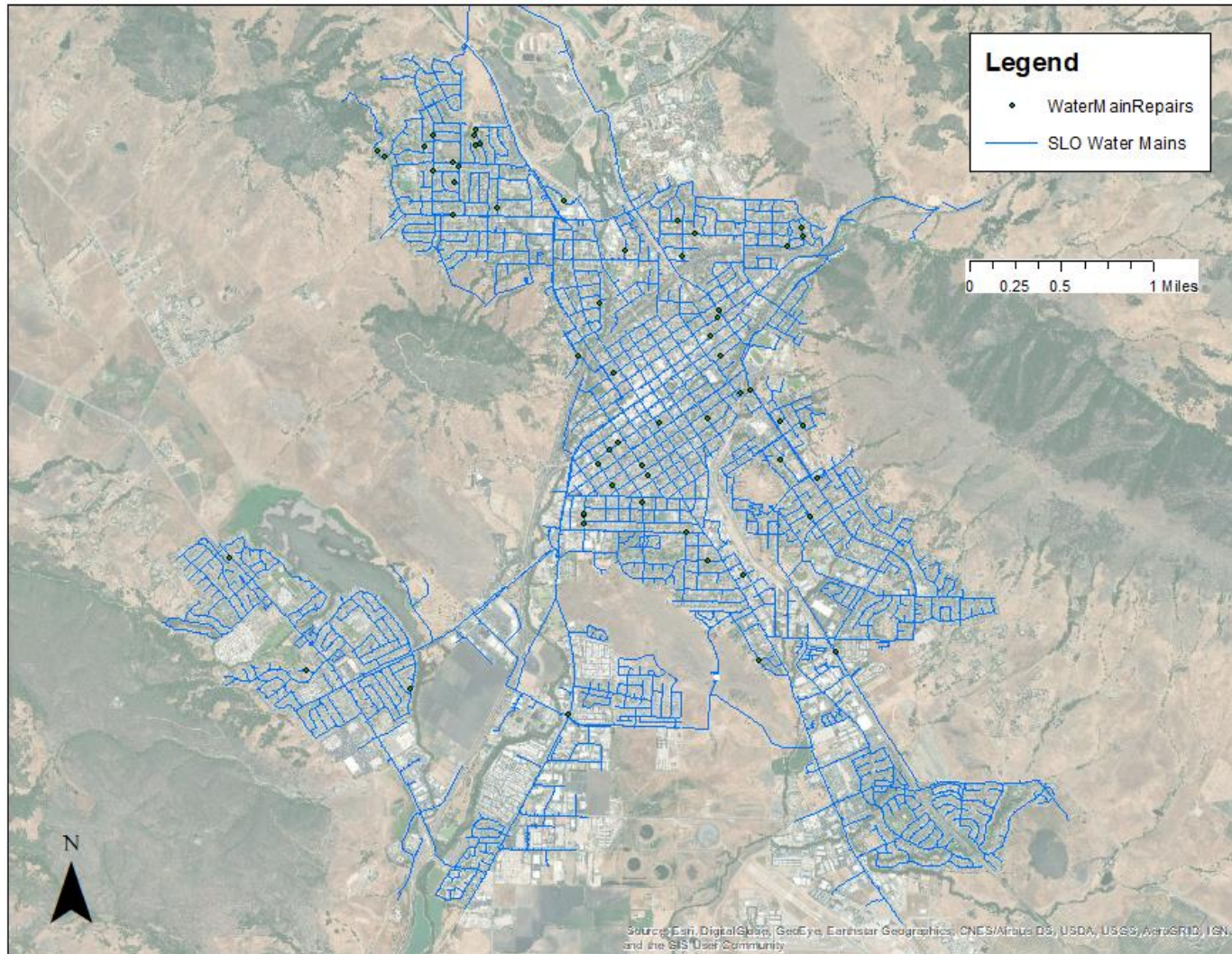**Figure 4.4** Land Use Areas and Street Classifications in San Luis Obispo

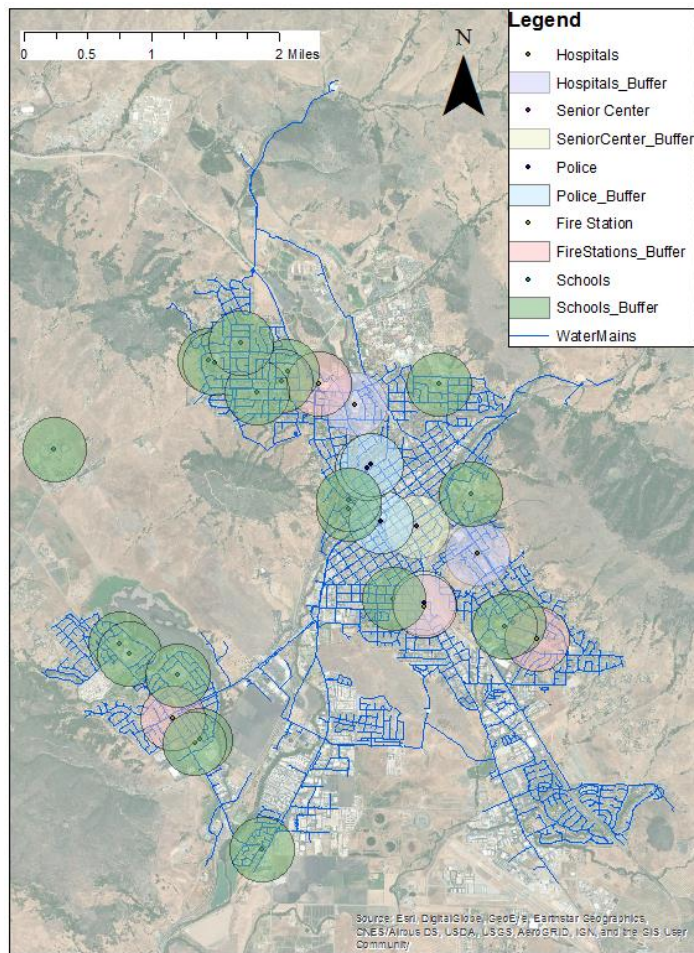**Figure 4.5** Water Main Break History

Figure 4.6 Critical Customers in San Luis Obispo

4.2.2 Microsoft Excel and Visual Basic for Applications (VBA)

Microsoft Excel was the primary data organizational tool used in this study. Excel allowed for efficient and accurate calculations for the large volume of pipes. Data imported from ArcMap was organized into spreadsheets in Excel. Criteria for degree of impact scores, probability of failure scores, and risk of failure categories previously introduced in this paper were manually inputted into Excel. Formulas and functions allowed for the proper organization of pipe ID's into the appropriate risk of failure categories. The risk of failure categories assigned to each pipe ID were imported into ArcMap as shapefiles to visually represent the results of each scenario.

Microsoft Visual Basic for Applications (VBA) is a programming language that is a part of Excel. VBA provides an additional calculation tool to Microsoft Excel. VBA is the primary

calculation tool for this study because of the increased functionality which allowed for the 10,000

Monte Carlo simulations for the RUL for every pipe. A VBA code was written to determine the

ASL, NY assuming every pipe is lain in highly corrosive soil, NY_CS which uses the given

corrosive soil data, and RUL for each model except for the age-based model. These calculations

in VBA were determined by 10,000 Monte Carlo simulations to provide for the most likely value.

The given age from the City of San Luis Obispo's shapefiles were imported into Excel. The code

modeled the ASL as a normal random variable and is shown in Appendix B.

4.2.3 Visual Representation of Results in ArcMap 10.6

Excel organized the results from the Monte Carlo simulations completed with the VBA

code shown in Appendix B. These results were then used to determine each pipe's risk of failure

category based on the equations and criteria described in Chapter 3. Once this was completed,

the "Excel to Table" tool in ArcMap imported the data back in ArcMap and was joined with the

"SLO WaterMains" shapefile from the City of San Luis Obispo. Each risk of failure category was

color coded for clear visualization of the data. Exhibits were made in ArcMap to spatially

represent the results and are shown in the following chapter with analysis.

5.1 Risk Analysis Visual Representation

Visual representation of the results is necessary to provide an easy determination of where

the critical pipes are located throughout the City. Exhibits of the results provide information on the

proximity of critical/high risk pipes in a system. Pipes are more cost efficient to replace if they are

grouped together. Therefore, visual representations of results allow for a more optimized

replacement/rehabilitation plan for municipalities.

Risk of failure results are visually represented in ArcMap based on the criteria shown in

Chapter 3 in Table 3.14.

5.2 Risk Analysis Results

Results of the simplified, complex, 2019, and age-based models were compared using three

different analyses; 1) Present scenario under current conditions, 2) Future scenario under

predicted average daily traffic volume increases, flow rate increases, and changes in water

pressure zones, 3) Low ASL scenario where the lowest ASL value was assumed for each pipe in

the system. The peak hour demand and maximum pressure were used for each pressure zone in

all the above scenarios.

5.2.1 Present Scenario Results

This scenario accounted for current traffic conditions, internal pressure, flow rates, and

age of the pipes from the available data. The ASL range, standard deviation, and mean ASL were

used to calculate 10,000 Monte Carlo simulations which assisted in determining the risk of failure

categories. Figures 5.1, 5.2, 5.3, and 5.4 display the results for the simple model, 2019 model,

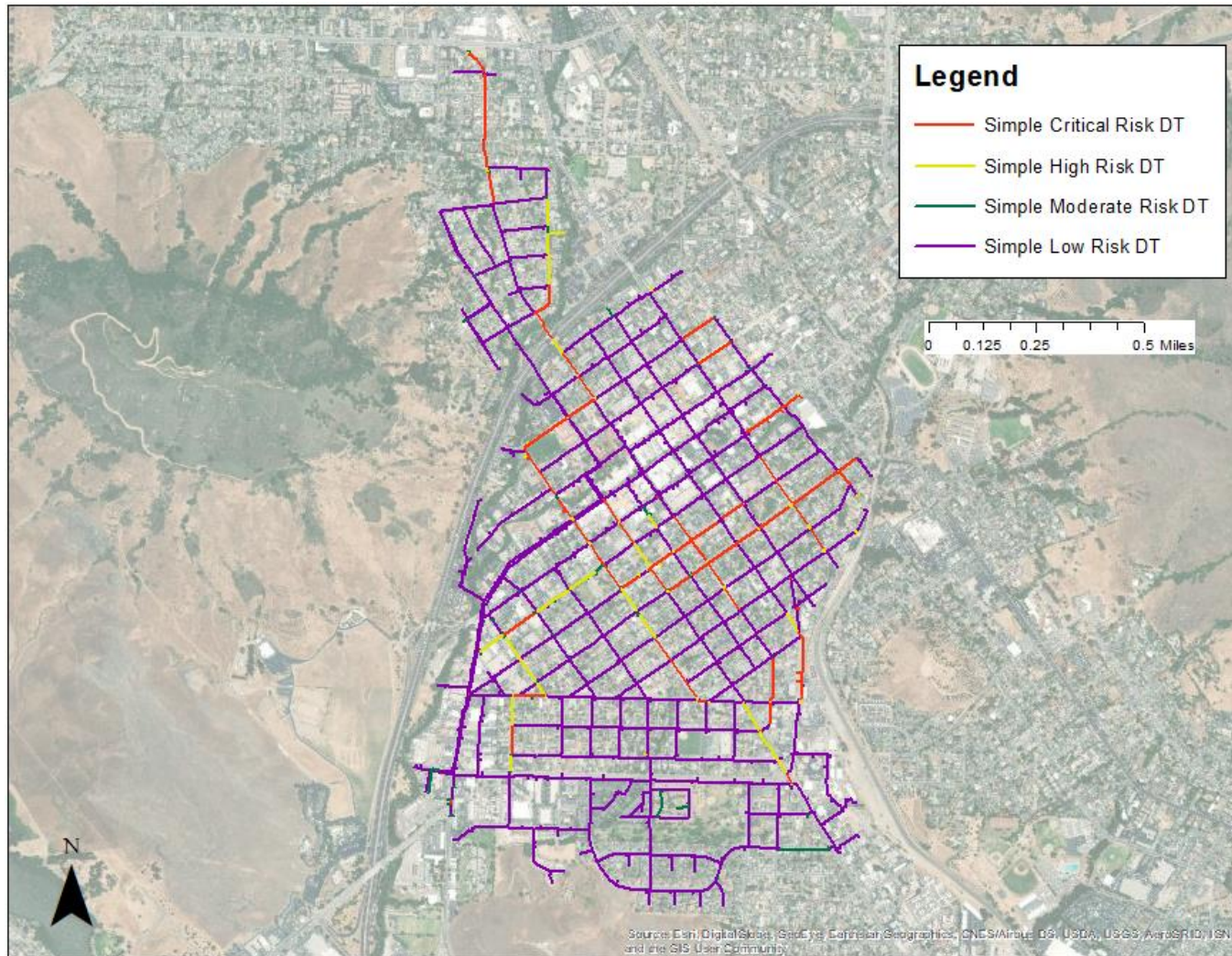complex model, and age-based model for the downtown water pressure zone, respectively.

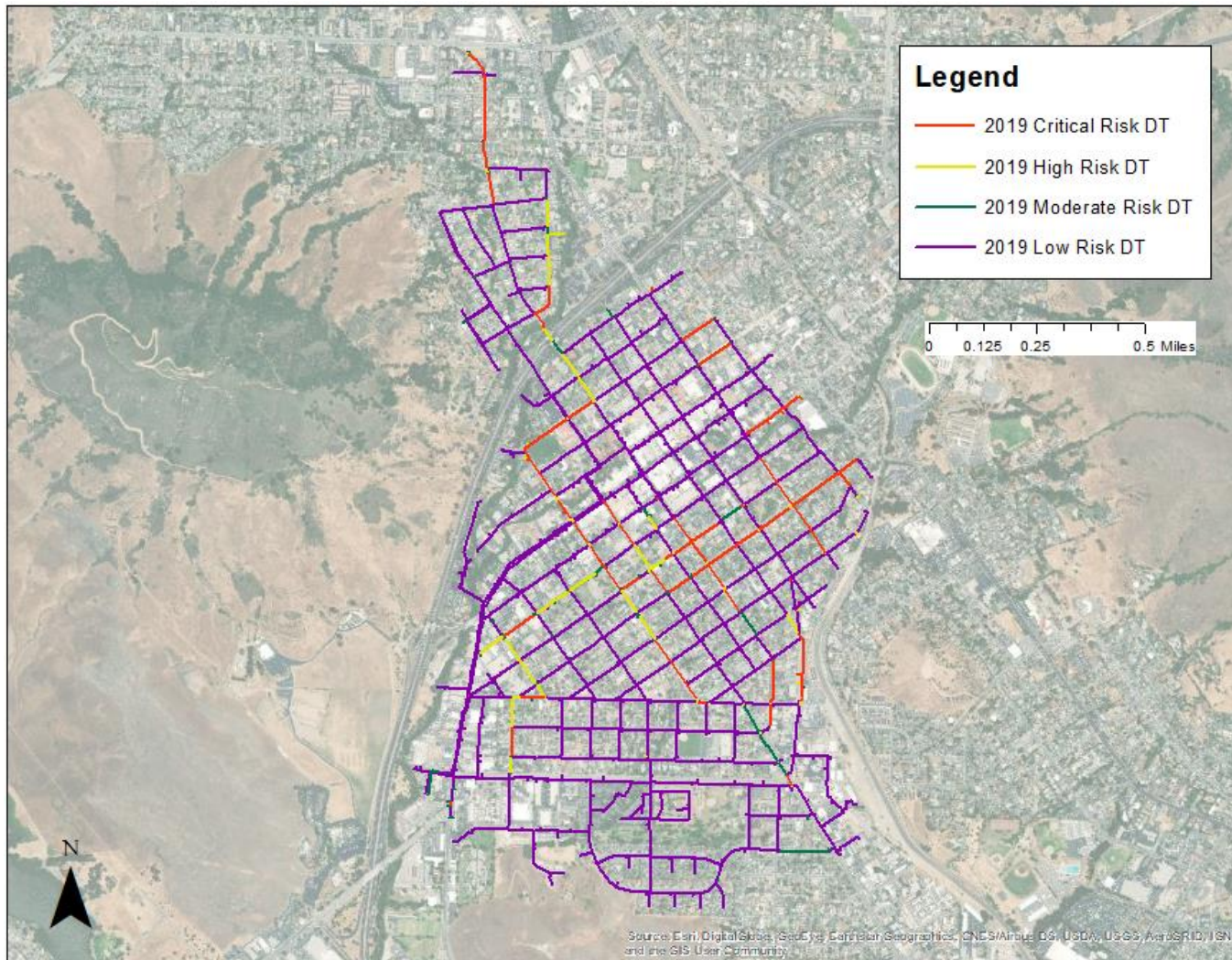**Figure 5.1** Present Scenario Simple Model Downtown Pressure Zone

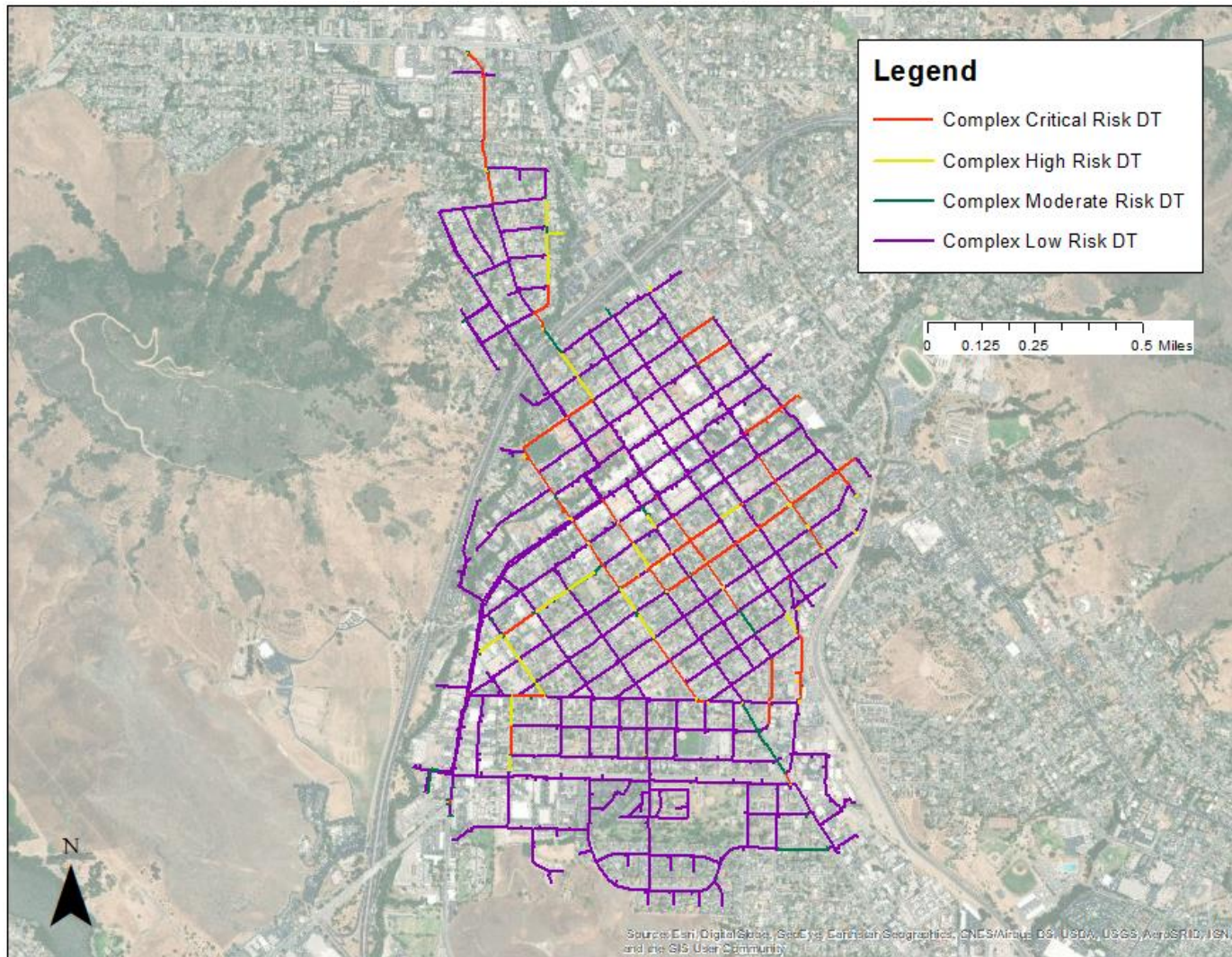**Figure 5.2** Present Scenario 2019 Model Downtown Pressure Zone

Figure 5.3 Present Scenario Complex Scenario Downtown Pressure Zone
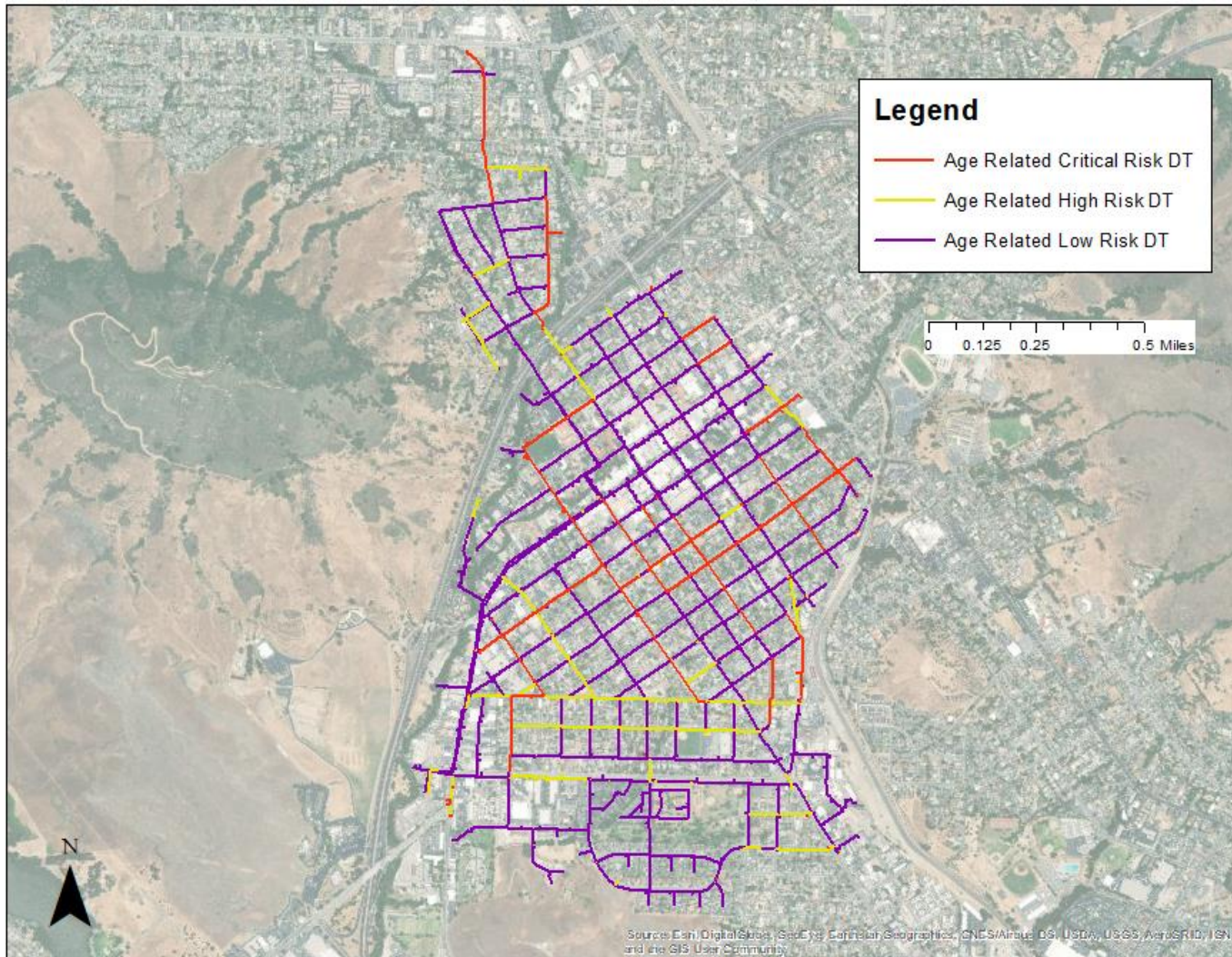
Figure 5.4 Present Scenario Age-Based Model Downtown Pressure Zone

Tables 5.1 shows the number of pipes in each risk of failure category for each model during the present scenario. Table 5.2 displays the results for the RUL calculations from Excel for each pipe material from the downtown pressure zone.

Table 5.1 Present Scenario Risk of Failure Comparison for Downtown Pressure Zone

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	146	153	392	143
High	120	131	339	129
Moderate	161	150	0	154
Low	2421	2414	2117	2422

The exhibits and table for all of the models show relatively similar results for the statistically simple, statistically complex, and 2019 models. However, the age-related model has more than double the number of pipes in the critical and high-risk categories. Although the results are similar for the three statistical models, there are slight differences. The 2019 model, which takes into consideration average daily traffic volume and corrosive soil data, would be assumed to be the most accurate and has roughly 10 fewer pipes in the high-risk category compared to the simple and complex models. In addition, the 2019 model has 3 more pipes in the critical risk category than the complex model and 7 fewer pipes in the critical risk category than the simple model.

These results suggest that municipalities would greatly benefit from using one of the statistically based models over a purely age-based model. A purely age-based model, according to these results, would declare too many pipes as high and critical risk. This would result in an unnecessary financial burden to replace or rehabilitate all of these pipes and may lead to an inefficient use of financial resources. The purely age-based model is the current proposed model by Wallace Group to determine the likelihood of water main failure for the City of San Luis Obispo. Table 5.2 summarizes average values for main parameters used in the calculation of the RUL for each statistical model by pipe material for the downtown pressure zone.

Table 5.2 Present Scenario RUL Comparison for Downtown Pressure Zone

Pipe Material	Average Given Age (years)	Average ASL (years)	Average NY (years)	Average NY 2019 (years)	Average RUL 2019 (years)	Average RUL Simplified (years)	Average RUL Complex (years)
Asbestos Cement	58.89	100.01	91.42	91.43	32.54	41.12	32.53
Ductile Iron	44.76	100.00	101.59	101.61	56.84	55.24	56.83
Cast Iron	77.50	75.00	77.43	77.45	-0.05	-2.50	-0.07
Polyvinyl Chloride	24.42	100.00	94.10	94.11	69.70	75.58	69.68
Steel	76.00	50.01	52.77	52.77	-23.23	-25.99	-23.23
Unknown	45.64	50.05	52.19	52.20	6.56	4.41	6.55

The difference between the simplified RUL and the other two RUL values are significantly different. The simplified model has an average RUL value greater than the complex and 2019 RUL values except for the unknown pipe materials, cast iron pipes, and the ductile iron pipes, however, it is only lower by about one year for ductile iron pipes. The only difference in these calculations between the 2019 model and complex model is that corrosive soil data was used in the 2019 model to determine the length of each pipe lain in highly corrosive soil, while the complex model assumed all pipes were laid in highly corrosive soil. The additional corrosive soil data provided a negligible difference in RUL values for the downtown pressure zone. This suggests that assuming the worst-case scenario when lacking corrosive soil data can lead to accurate results.

The steel and cast-iron pipes average RUL values for all the statistical models are negative numbers. This is because they are the oldest two materials by a significant margin and have the two lowest ASL values. The majority of pipes in the critical risk or high-risk categories are either steel or cast iron because the average RUL values for these materials are negative.

5.2.2 Future Scenario Results

The SLOWDMSP prepared by The Wallace Group provided future recommendations for the City of San Luis Obispo's water distribution system to be able to supply the additional population and planned developments outlined in the 2035 San Luis Obispo General Plan. These recommendations included predicted peak hour flow rates and maximum pressures for each water pressure zone. Additionally, SLOWDMSP recommended a consolidation of water pressure zones which are shown in Figures 4.2 and 4.3. The current average daily traffic volumes were

multiplied by a factor of 1.27 that was calculated by dividing the 2035 population goal for the City

of San Luis Obispo outlined in the General Plan by the current population of San Luis Obispo.

The only difference between the future and present scenarios is the change in pipe age, flow rate,

traffic volume, and internal pressure. No expected construction of new pipes or replacement of

pipes recommended from the SLOWDMSP were analyzed for deterioration, but the effects of

these proposed changes on the flow rate and internal pressure for all current pipes in the system

were considered. Figures 5.5-5.8 display the results for the four models during the future scenario
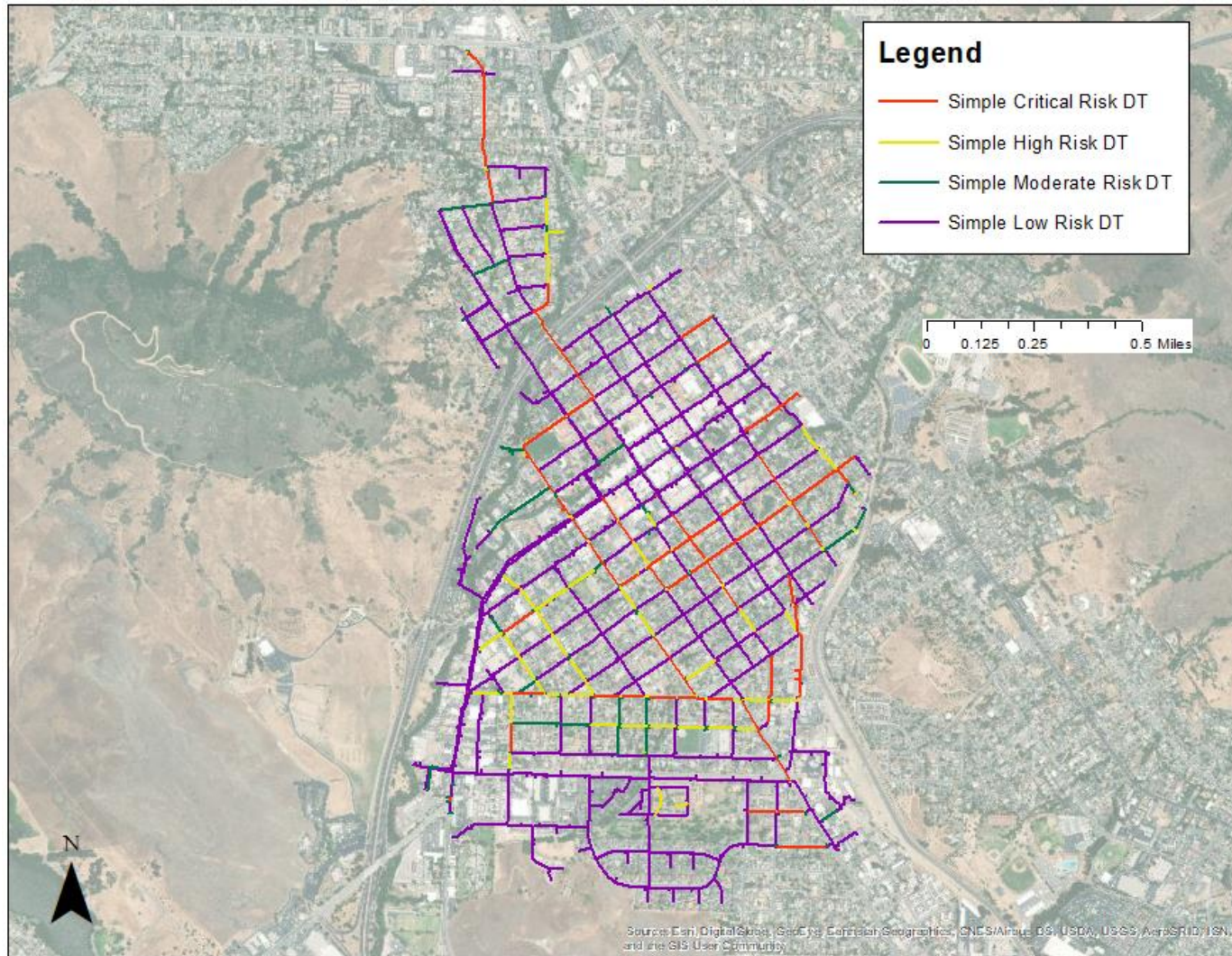
for the downtown pressure zone.

Figure 5.5 Future Scenario Simplified Model for Downtown Pressure Zone
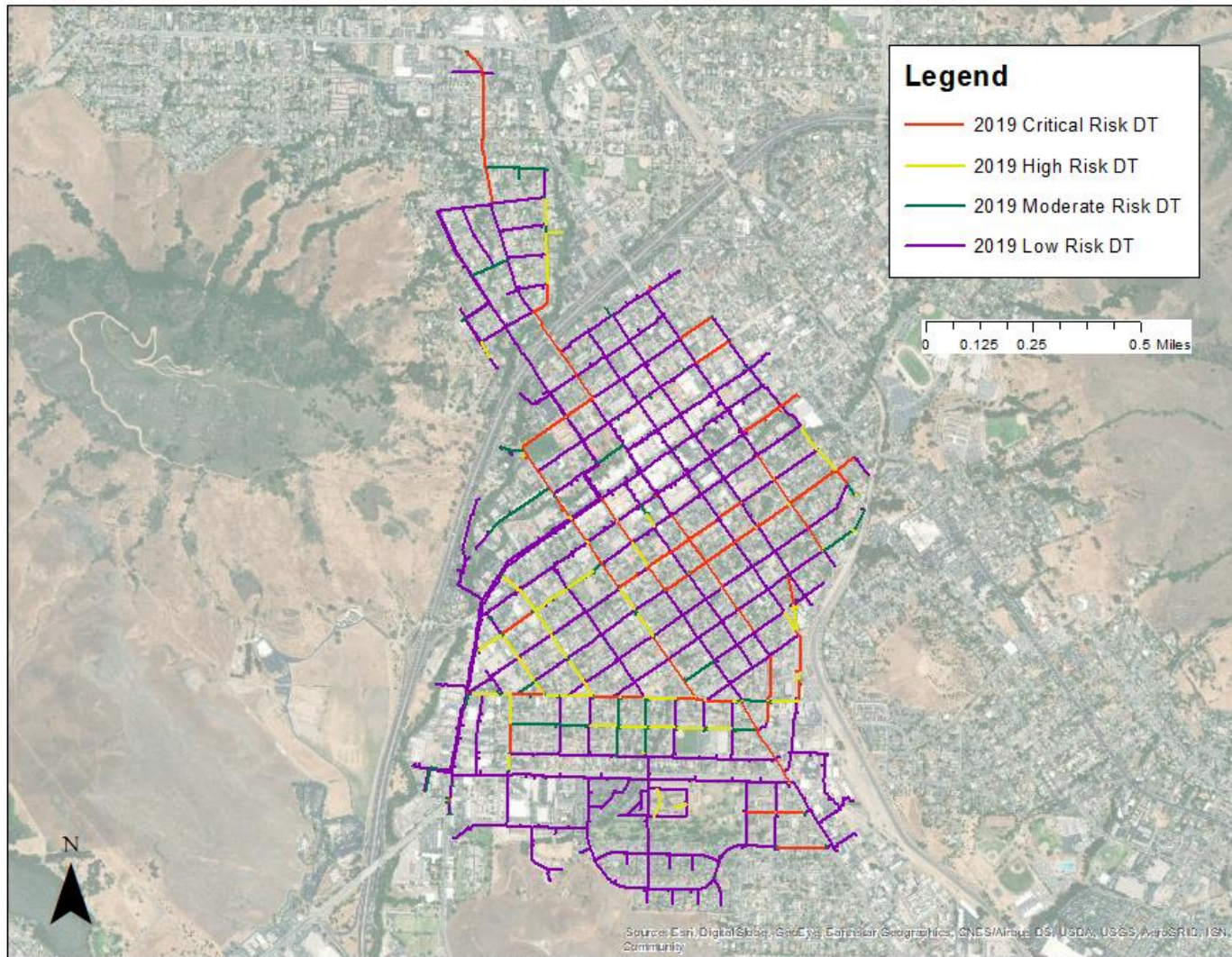
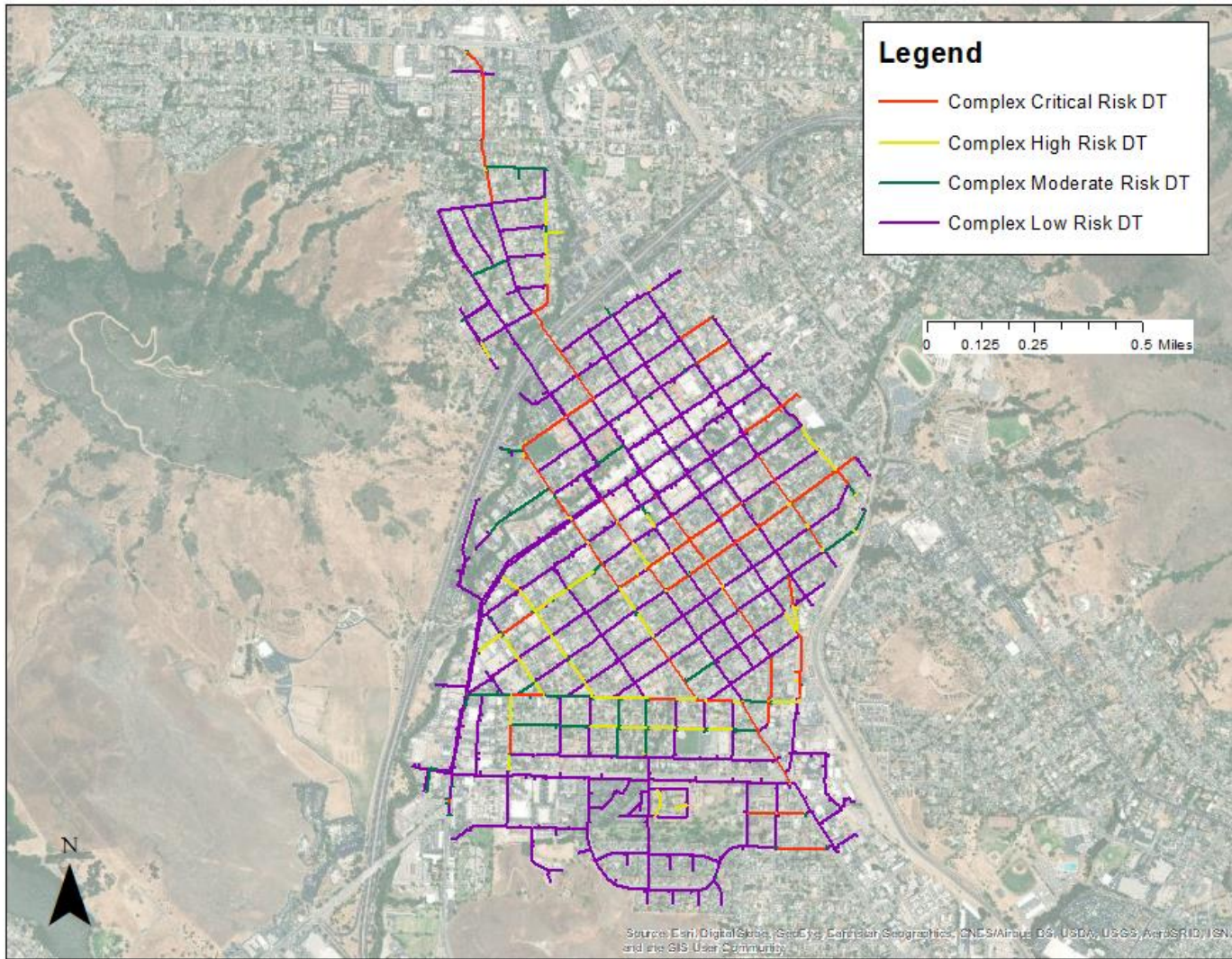**Figure 5.6** Future Scenario 2019 Model for Downtown Pressure Zone

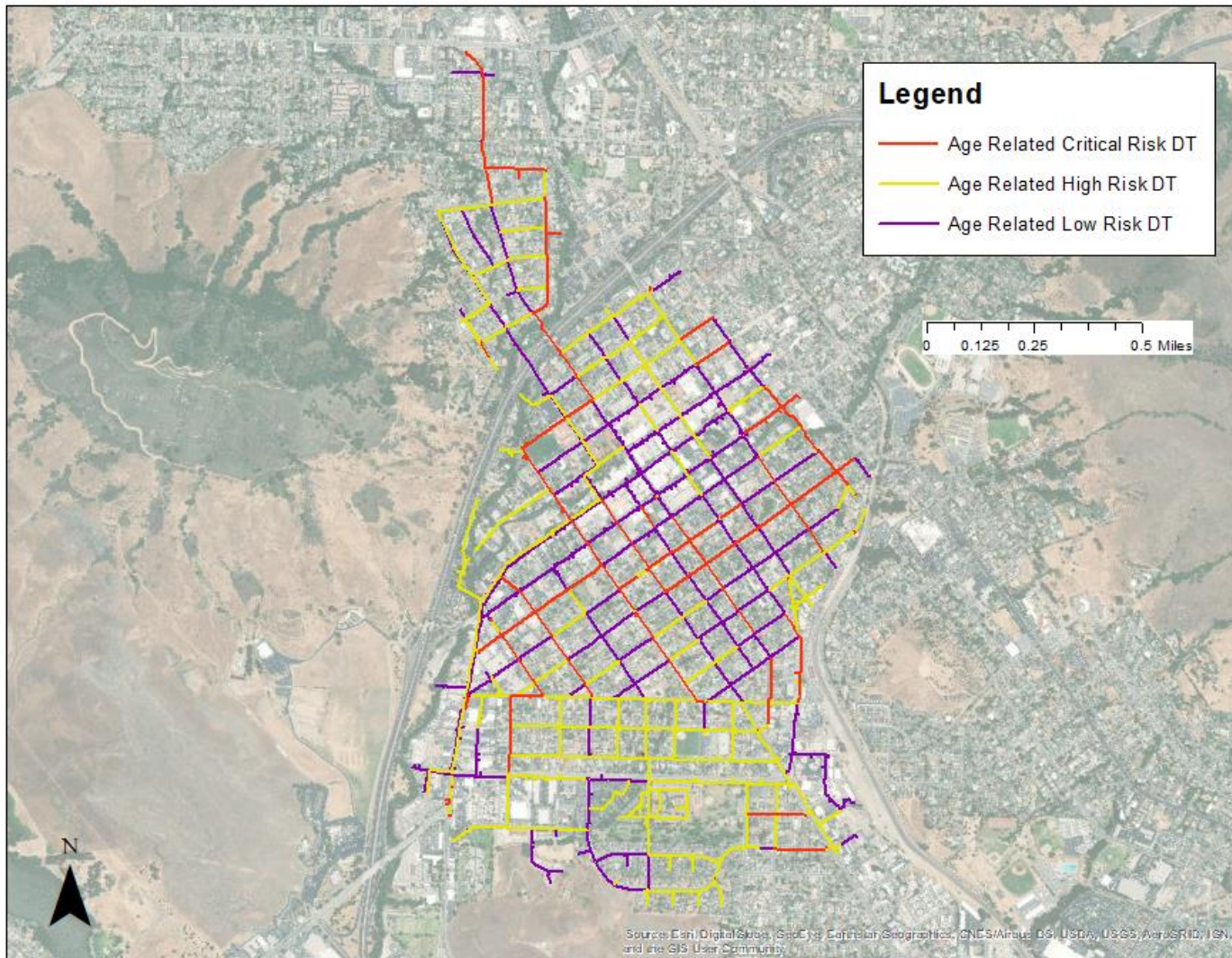**Figure 5.7** Future Scenario Complex Model for Downtown Pressure Zone

Figure 5.8 Future Scenario Age-Based Model for Downtown Pressure Zone

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Table 5.3 displays the number of pipes in each of risk of failure category for all models in the future scenario. Table 5.4 shows the averages values used in the RUL calculation based on pipe material for all models in the downtown pressure zone future scenario.

Table 5.3 Future Scenario Risk of Failure Comparison for Downtown Pressure Zone

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	190	181	451	169
High	168	183	1142	183
Moderate	302	320	0	306
Low	2188	2164	1255	2190

Table 5.4 Future Scenario Remaining Useful Life Comparison for Downtown Pressure Zone

Pipe Material	Given Age (years)	Average ASL (years)	Average NY (years)	Average NY 2019 (years)	Average RUL 2019 (years)	Average RUL Simplified (years)	Average RUL Complex (years)
Asbestos Cement	58.89	75.01	66.42	66.43	7.54	16.12	7.53
Ductile Iron	44.76	75.00	76.59	76.61	31.82	30.24	31.83
Cast Iron	77.50	50.00	52.43	52.45	-24.99	-27.50	-25.07
Polyvinyl Chloride	24.42	50.00	44.10	44.11	19.70	25.58	19.68
Steel	76.00	30.01	32.77	32.77	-43.23	-45.99	-43.23
Unknown	45.64	30.05	32.19	32.20	-13.44	-15.59	-13.45

The number of pipes in the critical and high-risk categories all increased in the future scenario from the present scenario as expected. Once again, the age-based model has a significantly higher number of pipes in the critical and high-risk categories than the statistical models, however, it has become even more significant in the future scenario for the high-risk category. The number of pipes in the high-risk category for the age-based scenario is nearly 10 times the number of pipes in the high-risk category for the statistically based models. The 2019 model has 9 more pipes in the critical risk category than the simple model and 21 more pipes in the critical risk category than the complex model. This difference is more significant than in the present scenario's results. The number of high-risk pipes for both of the simple and complex

models are exactly the same while the 2019 model has 14 less pipes in the high-risk category comparatively.

The average RUL values for all the pipe materials decreased from the present scenario as expected. The same general trends between pipe materials are shown with steel and cast iron pipes both averaging a RUL value that is negative. The simple model has an average RUL value that is greater than the average RUL value for the 2019 and complex models except for ductile iron category. The average RUL values for the 2019 model and complex model are once again similar suggesting that the difference in the number of pipes in each risk category is based on the differences in the traffic impact score calculation instead of the corrosive soil data. Asbestos cement, PVC, and ductile iron pipes all have a high RUL value for being 20 years in the future. Based on average values, asbestos cement, PVC, and ductile iron pipes would all have a probability of failure score of 3 or lower according to Table 3.7.

5.2.3 Low ASL Scenario Results

The low ASL scenario assumed the worst-case anticipated service life value for all of the pipe materials. Figures 5.9-5.12 display the results for the low ASL scenario for all four models.
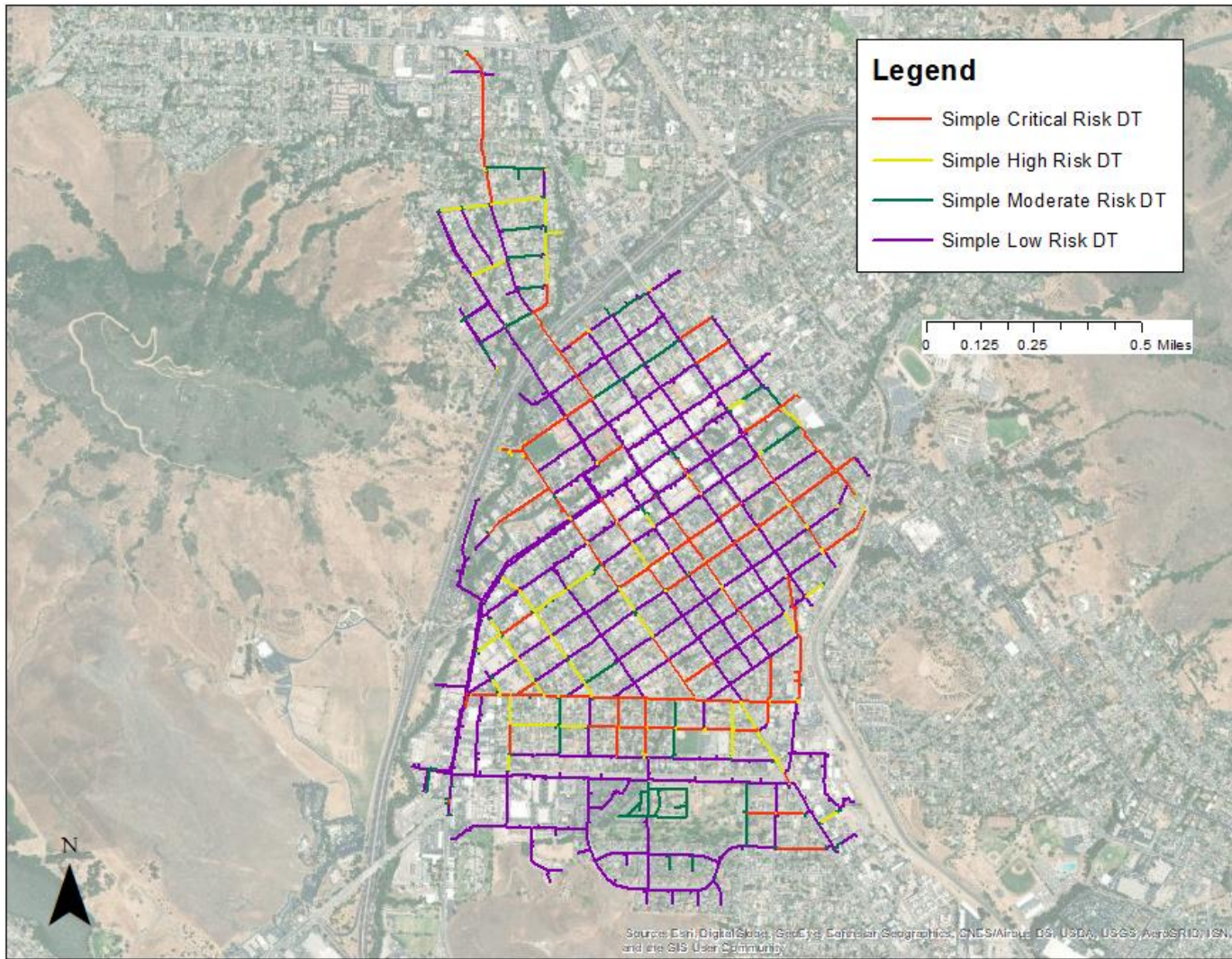
Figure 5.9 Low ASL Scenario Simple Method for Downtown Pressure Zone
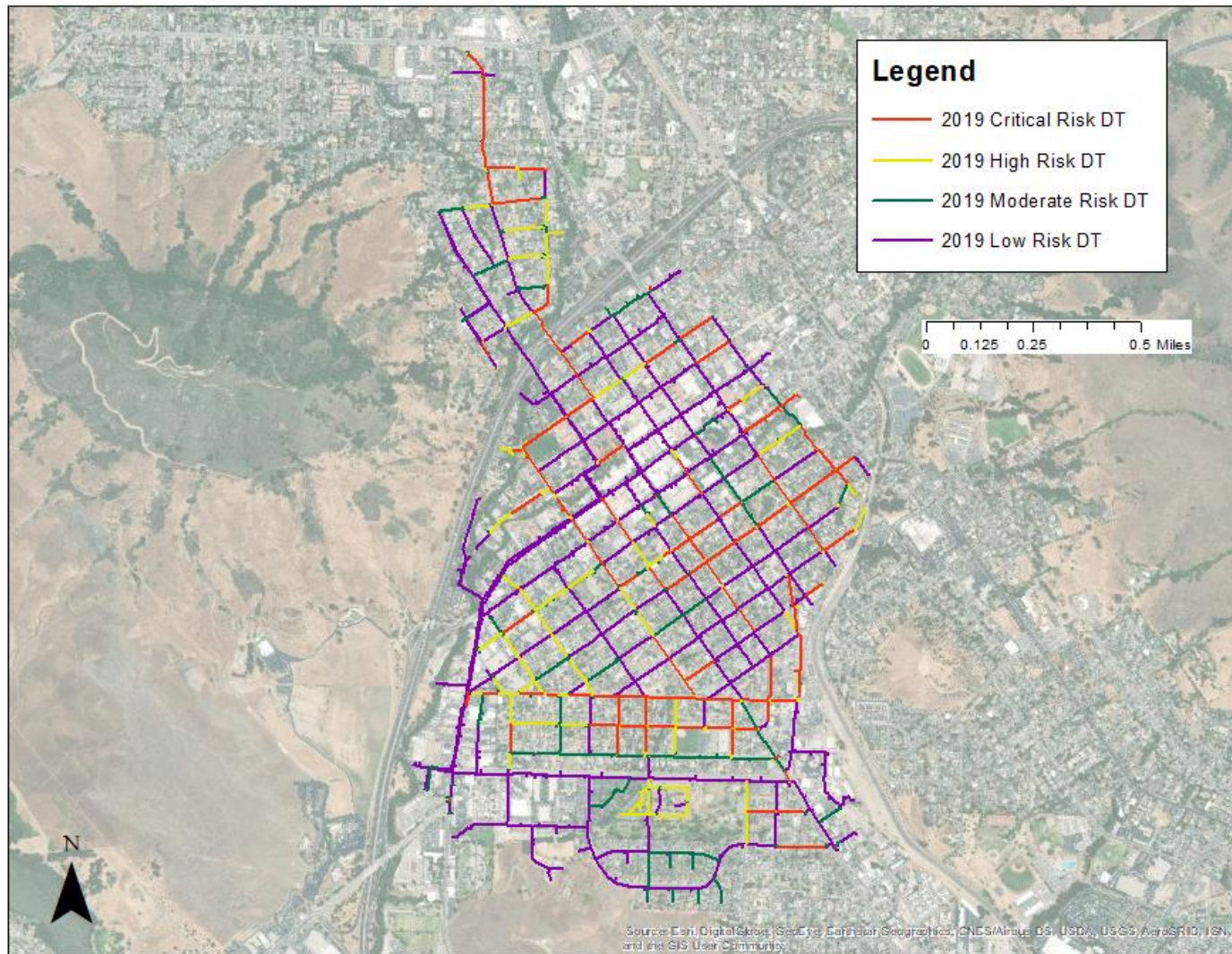
Figure 5.10 Low ASL Scenario 2019 Model for Downtown Pressure Zone
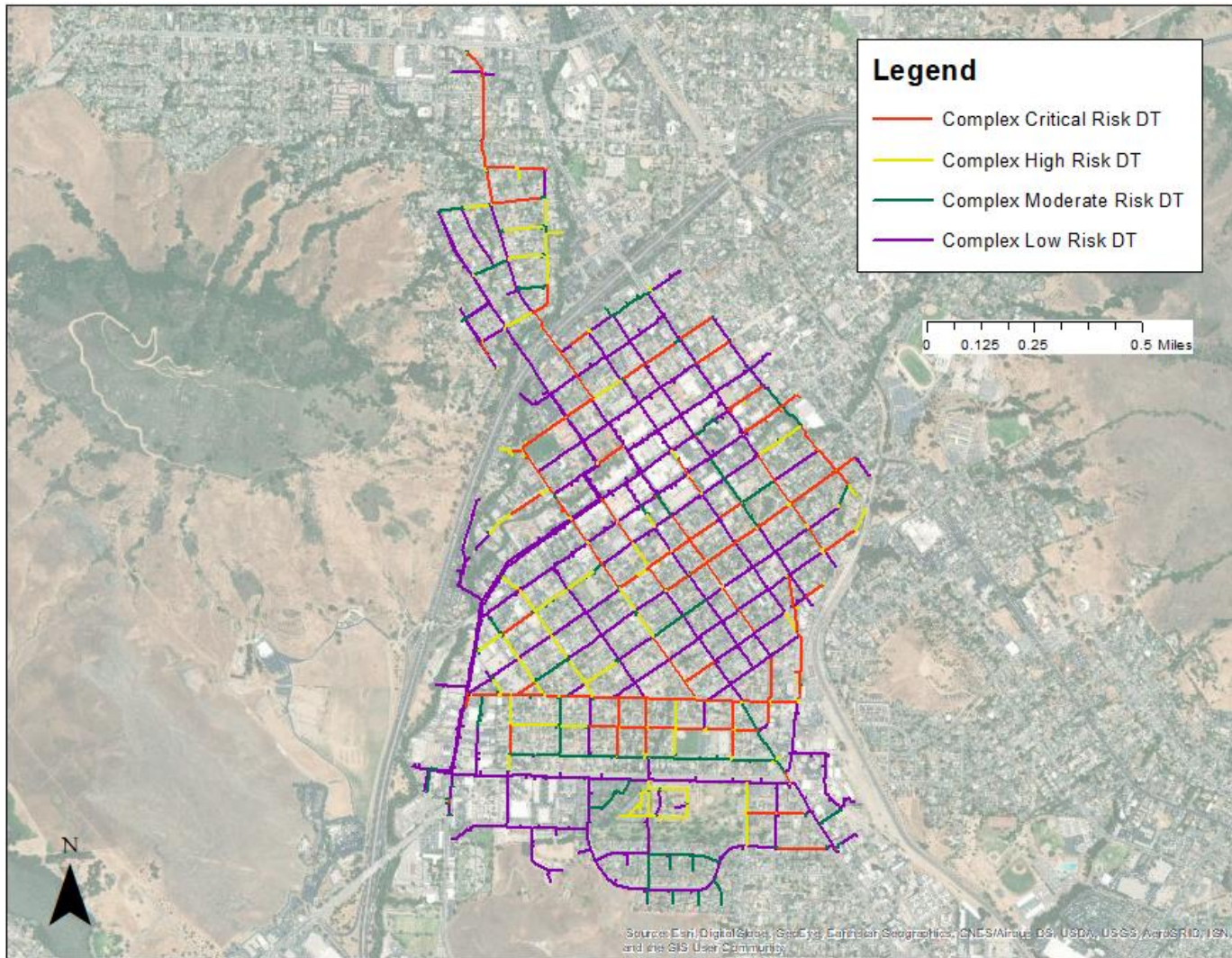
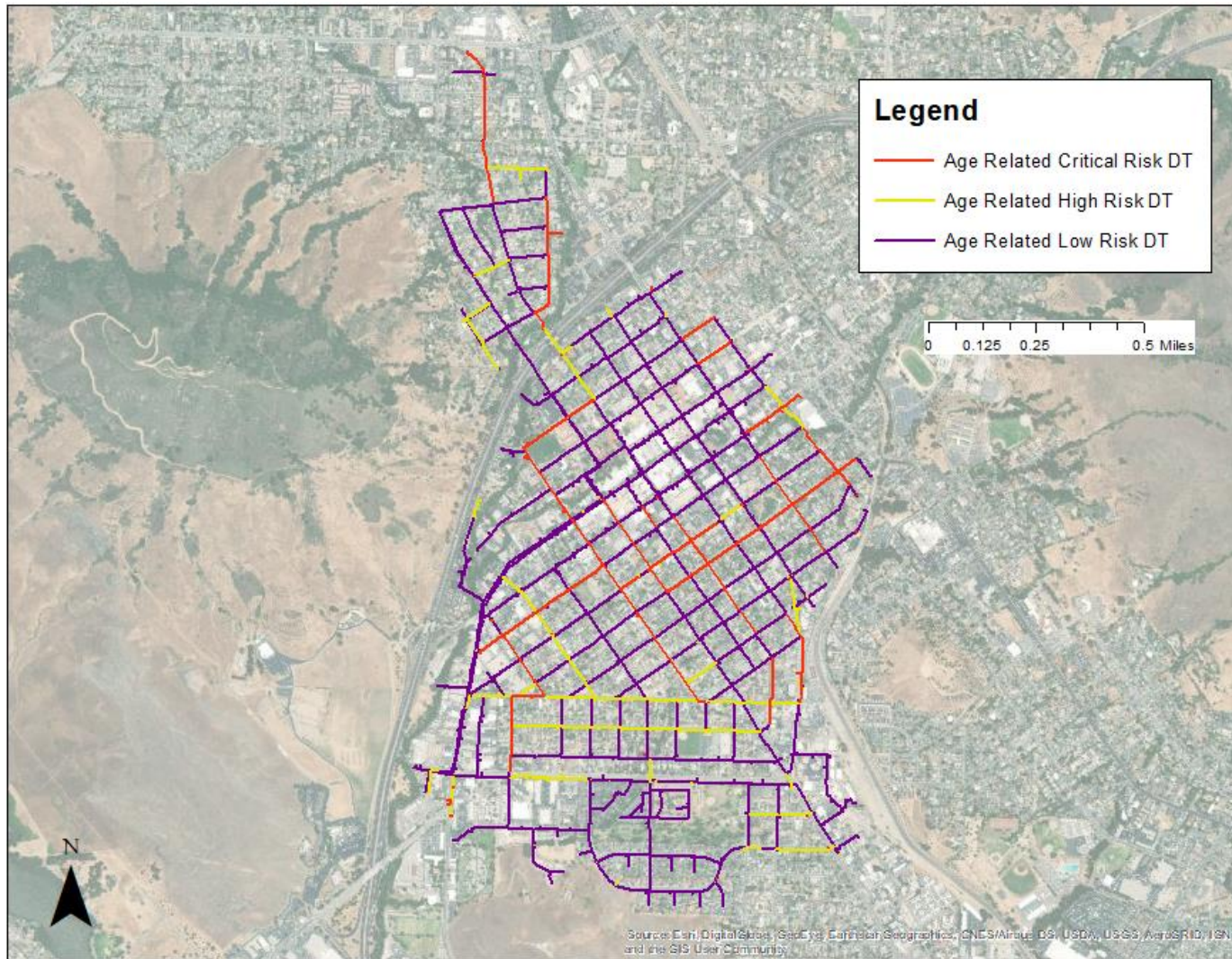**Figure 5.11** Low ASL Scenario Complex Method for Downtown Pressure Zone

Figure 5.12 Low ASL Scenario Age-Based Model for Downtown Pressure Zone

Tables 5.5 and 5.6 display the number of pipes in each risk category for each of the models during the sensitivity scenario and the average remaining useful life values by pipe material for the downtown pressure zone.

Table 5.5 Low ASL Scenario Risk of Failure Comparison for Downtown Pressure Zone

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	250	249	392	248
High	334	287	339	348
Moderate	499	390	0	489
Low	1765	1922	2117	1763

Table 5.6 Low ASL Scenario RUL Comparison for Downtown Pressure Zone

Pipe Material	Given Age (years)	Average ASL (years)	Average NY (years)	Average NY 2019 (years)	Average RUL 2019 (years)	Average RUL Simplified (years)	Average RUL Complex (years)
Asbestos Cement	58.89	75.01	66.42	66.43	7.54	16.12	7.53
Ductile Iron	44.76	75.00	76.59	76.61	31.82	30.24	31.83
Cast Iron	77.50	50.00	52.43	52.45	-24.99	-27.50	-25.07
Polyvinyl Chloride	24.42	50.00	44.10	44.11	19.70	25.58	19.68
Steel	76.00	30.01	32.77	32.77	-43.23	-45.99	-43.23
Unknown	45.64	50.05	52.19	52.20	6.56	4.41	6.55

This scenario resulted in a significant increase in the number of pipes in the critical and high-risk categories for all statistical models. The age-based model, however, remained the same as in the present scenario because the anticipated service life of the pipe is not taken into consideration for this model. The simple, complex, and 2019 models had similar numbers of pipes in the critical risk category, however, the 2019 and complex models had significantly more high and moderate risk pipes than the simple model. The age-based model had similar numbers of pipes in the high-risk category in comparison to the 2019 and complex model. The age-based model was most similar to other models in the sensitivity scenario; however, it still has over 150 more pipes in the critical risk category than the other models.

The sensitivity scenario resulted in the ductile iron pipes having the highest remaining useful life, while PVC pipes had the highest remaining useful life in present and future scenarios. This occurred because the anticipated service life for PVC ranged over 100 years, while the ductile iron anticipated service life ranged over 50 years. The simplified model produced average remaining useful life values for asbestos cement and PVC that were about 6 years higher than the average remaining useful life values for the same materials for the complex and 2019 models.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Evaluation of Results

The results demonstrated that a purely age-based model may present inflated critical and high-risk numbers of pipes. This is detrimental for municipalities because if a purely age-based model is used, then the municipality may be wasting resources on pipes that do not need to be rehabilitated. Furthermore, the municipalities may not have the financial means to replace or rehabilitate all the pipes an age-based model may place in the high or critical risk categories and would result in only a percentage of pipes being replaced or rehabilitated. This would put the municipality in a position where it has about a 50 percent chance of choosing to rehabilitate or replace pipes that would also be a critical risk pipe in one of the statistically based models. It is important to note that the SLOWDSMP uses hydraulic capacity as its primary criterion for recommendations for replacement and age as a secondary criterion, however, based on the results from this study, it is recommended that the age criterion should be replaced with one of the statistically based models used in this study.

The three statistically based models all slightly vary. The 2019 model, which includes both the corrosive soil data and average daily traffic volume data, is considered the most accurate because of the extra data. Table 6.1 shows that the RUL does not change significantly between the 2019 model and complex, but the traffic impact scores differ significantly. This shows that the corrosive soil data did not significantly influence the results, however, using average daily traffic volume instead of street classification for the traffic impact score resulted in the changes in the overall results between the two models. Therefore, if a municipality places a high value on the impact to traffic from water main failures, it is recommended that the complex model be modified to include the average daily traffic volume instead of street classification.

The results for all four models for the entire City for each scenario are displayed in Tables 6.2-6.4. Smaller variations of results between these models are amplified with a bigger water distribution system. This can be seen when comparing results from only the downtown pressure zone and results from the entire city which are shown in Appendix C. The advantage of the simplified model is that it requires little data and is a more simple calculation. This can save a

municipality money especially if data necessary for the complex models are unavailable. When there is a lack of data, the simple model is preferred because of the small difference in results between the simple model and the two complex models on a small scale. However, it is recommended that larger municipalities use the complex model that uses average daily traffic volume to calculate for the traffic impact score because the difference in results become more significant with an increasing number of pipes. Additionally, the complex model consistently has a smaller number of pipes in the critical risk category, which will save the municipality money from replacing or rehabilitating pipes that would have been in the critical risk category in the simple model.

Table 6.1 Comparison of Statistically Based Models for Downtown Pressure Zone

All Pipes	Given Age (years)	Average ASL (years)	Average NY (years)	Average NY 2019 (years)	Average RUL 2019 (years)	Average RUL Simplified (years)	Average RUL Complex (years)	Average Traffic Volume Impact Score (-)	Average Traffic Impact Score (-)
Present Scenario	41.14	92.78	90.42	90.44	49.30	51.63	49.28	1.20	1.16
Future Scenario	57.03	92.78	90.42	90.44	33.44	35.78	33.43	1.42	1.16
Low ASL Scenario	41.14	54.81	52.46	52.47	11.34	13.67	11.32	1.20	1.16

Table 6.2 Present Scenario Risk of Failure Category Comparison for Entire City

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	553	619	1098	560
High	388	362	3097	377
Moderate	648	639	0	647
Low	11268	11237	8662	11273

Table 6.3 Future Scenario Risk of Failure Category Comparison for Entire City

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	789	843	2223	738
High	662	614	5280	680
Moderate	1460	1244	0	1457
Low	9947	10156	5354	9982

Table 6.4 Low ASL Scenario Risk of Failure Category Comparison for Entire City

Risk of Failure Category	2019	Simplified	Age-Related	Complex
Critical	1205	1130	1098	1223
High	1230	866	3097	1223
Moderate	3173	2060	0	3162
Low	7250	8801	8662	7249

6.2 Reliability of Data

All of the data used in this study was either obtained from the 2015 San Luis Obispo Water Distribution System Master Plan or directly from the City of San Luis Obispo itself. The shapefile obtained from the city included installation dates that were compared to the range of common installation years for various water main materials provided by AWWA (2011). The installation dates provided by the city matched the range of typical installation years from the AWWA (2011), which confirmed the accuracy of the data.

Any values that were unknowns were assumed to be the worst-case scenario or in the case of the anticipated service life were run under a sensitivity analysis scenario. The internal pipe pressures were assumed to be at the maximum value for each respective pressure zone because the WaterCAD model did not provide pressure information at the pipes themselves but at the nodes in the system. Additionally, the peak hour demand flow rate was used for all pressure zones because the WaterCAD model only provided flow rates at the nodes in the system and not the pipes themselves.

It is highly recommended that data be collected accurately and is continuously updated because unreliable data could significantly impact the results of the models. Unreliable data would decrease the value of the prediction models analyzed in this study as a tool to determine a cost-effective water main rehabilitation/ replacement schedule.

6.3 Recommendation for Improvement and Further Research

Time constraints, academic resources, and an unfamiliarity with the San Luis Obispo's potable water system resulted in assumptions that could be improved upon further study. The roads that did not have average daily traffic data from the city were assumed to have a traffic

impact score of 1. This may not be true and further data collected could improve the accuracy of the model because average daily traffic volume did significantly impact the results of this study. Further improvement for cost of pipe replacement, accuracy of area covered by industrial and residential developments, flow rates in each pipe, and internal pressure for each pipe may have significant impacts to the results of this study.

Another recommendation would be to run a sensitivity analysis on each parameter in the statistically complex model to see which parameters can be removed without significantly affected the results of the model. This could be beneficial for municipalities interested in obtaining accurate results at a cheaper cost.

It is recommended to use computer programs such as ArcMap, Excel, or other programs to perform the calculations necessary for these models. These calculations can be tedious and time consuming without such programs. Additionally, these computer programs can be updated in an efficient manner as updated data becomes available. ArcMap is also a great tool for not only collecting data, but visually representing results. The visually represented data can show how pipes are in relation to each other, which can make it easier for the municipality to plan projects for pipes in the same location.

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Appendix A: Present Scenario Sample Excel Calculations

Pipe ID	Material	Present Year	Installation Year	T (-)	Age (Years)	ASL (years)	std ASL	ASL Output (years)	NY_CS (years)	Complex NY (years)	Diameter (in)	Length (ft)
6295	PVC	2019	1982	0.3	37	100	16.67	100.13	94.15	93.55	8	199.4
6296	PVC	2019	1982	0.3	37	100	16.67	100.07	94.15	94.07	8	23.8
6299	DI	2019	1982	0.8	37	100	8.33	99.93	100.79	99.87	8	304.8
6307	PVC	2019	1982	0.3	37	100	16.67	100.14	93.47	93.45	6	7.1
6308	PVC	2019	1982	0.3	37	100	16.67	99.95	94.15	93.96	8	62.9
6309	PVC	2019	1982	0.3	37	100	16.67	100.09	94.15	94.01	8	46.6
6322	PVC	2019	1982	0.3	37	100	16.67	99.88	94.15	94.00	8	48

Pressure Zone	Demand (GPM)	Pressure (psi)	Soil Type	LH (ft)	Land Use	% Industrial	% Residential	Pipe Cost Per Linear Foot ($/foot)	Pipe Cost ($)
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	185	$36,889
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	185	$4,403
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	215	$65,532
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	170	$1,207
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	185	$11,637
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	185	$8,621
Downtown	3354	93	Non-Corrosive	0	Commercial	4	96	185	$8,880

Street	Cross Streets	Average Daily Traffic Volume	Traffic Class	Critical Customer	Cost Impact Score	Flow Rate Impact Score	Traffic Impact Score	Traffic Volume Impact Score	Critical Customer Score	Consequence Score	Consequence Score 2019
Walnut	Osos-Santa Rosa	3471	Collector	Police Facility	3	5	3	2	0	11	10
Walnut	Osos-Santa Rosa	3471	Collector	Police Facility	1	5	3	2	0	9	8
Walnut	Chorro-Osos	2266	Local	School	4	5	1	2	3	13	14
Walnut	Osos-Santa Rosa	3471	Collector	Police Facility	1	5	3	2	0	9	8
Walnut	Osos-Santa Rosa	3471	Collector	Police Facility	2	5	3	2	0	10	9
Walnut	Osos-Santa Rosa	3471	Collector	Police Facility	1	5	3	2	0	9	8
Walnut	Santa Rosa-Toro	8741	Collector	Police Facility	1	5	3	5	0	9	11

NY 2019 Output (years)	NY Output (years)	RUL 2019 (years)	Adjusted RUL 2019 (years)	Simplified RUL 2019 (years)	Complex RUL (years)	2019 PF	Simplified PF	Complex PF	2019 RF	Simplfied RF	Complex RF	Risk Cat 2019	Risk Cat Simp	Risk Cat Age	Risk Cat Complex
94.28	94.22	57.28	57.28	57.22	63.13	57.22	1	1	1	10	11	11	Low Risk	Low Risk	Low Risk	Low Risk
94.22	94.21	57.22	57.22	57.21	63.07	57.21	1	1	1	8	9	9	Low Risk	Low Risk	Low Risk	Low Risk
100.71	100.62	63.71	63.71	63.71	62.93	63.62	1	1	1	14	13	13	Low Risk	Low Risk	Low Risk	Low Risk
93.61	93.61	56.61	56.61	56.61	63.14	56.61	1	1	1	8	9	9	Low Risk	Low Risk	Low Risk	Low Risk
94.09	94.08	57.09	57.09	57.09	62.95	57.08	1	1	1	9	10	10	Low Risk	Low Risk	Low Risk	Low Risk
94.23	94.22	57.23	57.23	57.23	63.09	57.22	1	1	1	8	9	9	Low Risk	Low Risk	Low Risk	Low Risk
94.02	94.01	57.02	57.02	57.02	62.88	57.01	1	1	1	11	9	9	Low Risk	Low Risk	Low Risk	Low Risk

```vba
Sub RUL_CALC()

'Select Input values by specifying a range
    Dim Pipematrix As Variant

    Sheet23.Activate
     Range("A1").Select
      Range(Selection, Selection.End(xlDown)).Select
      Range(Selection, Selection.End(xlToRight)).Select
    Pipematrix = Selection.Value
    MsgBox ("Number of Rows:" & vbNewLine & vbNewLine & _
Selection.Rows.Count)
    MsgBox ("Number of Columns:" & vbNewLine & vbNewLine & _
Selection.Columns.Count)

   'Enter the number of Rows and Columns
    Const Rows = 12858
    Const Columns = 57

   'Clear the current values from Risk Analysis Sheet
    Sheet23.Activate
        Range("AN2:AQ13000").ClearContents
        Range("AS2:AS13000").ClearContents
        Range("J2:J13000").ClearContents
        Range("M2:M13000").ClearContents
        MsgBox ("Output values cleared")
    Sheet23.Activate

   'Define Variables Needed for MonteCarlo Simulation

   'RowCounter, ColCounter, and i are to iterate each equation 10,000
times
    Dim RowCounter As Integer
    Dim ColCounter As Integer
    Dim i As Integer

   'The mean and standard deviation variables are the output of one
iteration
   'The sum of mean and sum of standard deviation variables are the
summation of 10,000 iterations
    Dim meanAge(Rows, Columns) As Variant
    Dim stdAge(Rows, Columns) As Variant
    Dim summeanAge(Rows, Columns) As Variant
    Dim sumstdAge(Rows, Columns) As Variant
    Dim meanASL(Rows, Columns) As Variant
    Dim stdASL(Rows, Columns) As Variant
    Dim summeanASL(Rows, Columns) As Variant
    Dim sumstdASL(Rows, Columns) As Variant
    Dim meanNY(Rows, Columns) As Variant
    Dim stdNY(Rows, Columns) As Variant
    Dim summeanNY(Rows, Columns) As Variant
    Dim sumstdNY(Rows, Columns) As Variant
    Dim meanNY_CS(Rows, Columns) As Variant
    Dim stdNY_CS(Rows, Columns) As Variant
    Dim summeanNY_CS(Rows, Columns) As Variant
    Dim sumstdNY_CS(Rows, Columns) As Variant
```

```vba
    Dim meanRULSimple(Rows, Columns) As Variant
    Dim stdRULSimple(Rows, Columns) As Variant
    Dim sumstdRULSimple(Rows, Columns) As Variant
    Dim summeanRULSimple(Rows, Columns) As Variant
    Dim meanRULComplex(Rows, Columns) As Variant
    Dim summeanRULComplex(Rows, Columns) As Variant
    Dim stdRULComplex(Rows, Columns) As Variant
    Dim sumstdRULComplex(Rows, Columns) As Variant
    Dim meanRUL_CS(Rows, Columns) As Variant
    Dim summeanRUL_CS(Rows, Columns) As Variant
    Dim stdRUL_CS(Rows, Columns) As Variant
    Dim sumstdRUL_CS(Rows, Columns) As Variant

'Identify the Column for each input value

'Present Year
    Const present_year = 3

'Installation Year(IY)
    Const mean_IY = 5

'Standard Deviation of Installation Year
    Const std_IY = 7

'Given Installation Year
    Const Given_IY = 6

'Age
    Const Age = 9

'Anticipated Service Life (ASL)
    Const mean_ASL = 11

'Standard Deviation of Anticipated Service Life
    Const std_ASL = 12

'Number of years until first failure (NY)
    Const NY = 15

'Number of years until first failure with corrosive soil data
(NY_CS)
    Const NY_CS = 14

'Diameter
    Const D = 16

'Length of Pipe in Highly Corrosive Soil
    Const LH = 22

'Length of Pipe
    Const L = 17

'Pressure
    Const P = 20

'Pipe Material Parameter
    Const T = 8
```

```vba
'Percent Overlain by Industrial Cover
    Const IC = 24

'Percent Overlain by Residential Cover
    Const RC = 25

'Clark et al (1982) Regression Parameters

'Diameter Parameter
    Const x2 = 0.338

'Pressure Parameter
    Const x3 = -0.022

'Industrial Cover Parameter
    Const x4 = -0.265

'Residential Cover Parameter
    Const x5 = -0.0983

'CorrosAge Soil Length Parameter
    Const x6 = -0.0003

'PipeMaterial Parameter
    Const x7 = 13.28


'Compute calculations for each pipe with 10,000 iterations
    For RowCounter = 2 To Rows
     ColCounter = 1
        For i = 1 To 10000

'Calculate the mean and sum of mean for Age
    On Error GoTo meanAgeError
    meanAge(RowCounter, ColCounter) = Pipematrix(RowCounter,
present_year) - Application.WorksheetFunction.Norm_Inv(Rnd(),
Pipematrix(RowCounter, mean_IY), Pipematrix(RowCounter, std_IY))
        summeanAge(RowCounter, ColCounter) = summeanAge(RowCounter,
ColCounter) + meanAge(RowCounter, ColCounter)
    On Error GoTo 0

'Calculate the mean and sum of mean for ASL
    On Error GoTo meanASLError
    meanASL(RowCounter, ColCounter) =
Application.WorksheetFunction.Norm_Inv(Rnd(), Pipematrix(RowCounter,
mean_ASL), Pipematrix(RowCounter, std_ASL))
        summeanASL(RowCounter, ColCounter) = summeanASL(RowCounter,
ColCounter) + meanASL(RowCounter, ColCounter)
    On Error GoTo 0

'Calculate the mean and sum of mean for NY
    meanNY(RowCounter, ColCounter) = meanASL(RowCounter,
ColCounter) + x2 * Pipematrix(RowCounter, D) + x3 *
Pipematrix(RowCounter, P) + x4 * Pipematrix(RowCounter, IC) + x5 *
Pipematrix(RowCounter, RC) + x6 * Pipematrix(RowCounter, L) + x7 *
Pipematrix(RowCounter, T)
```

```vb
        summeanNY(RowCounter, ColCounter) = summeanNY(RowCounter,
ColCounter) + meanNY(RowCounter, ColCounter)

    'Calculate the mean and sum of mean for NY with Corrosive Soil Data
        meanNY_CS(RowCounter, ColCounter) = meanASL(RowCounter,
ColCounter) + x2 * Pipematrix(RowCounter, D) + x3 *
Pipematrix(RowCounter, P) + x4 * Pipematrix(RowCounter, IC) + x5 *
Pipematrix(RowCounter, RC) + x6 * Pipematrix(RowCounter, LH) + x7 *
Pipematrix(RowCounter, T)
        summeanNY_CS(RowCounter, ColCounter) = summeanNY_CS(RowCounter,
ColCounter) + meanNY_CS(RowCounter, ColCounter)

    'Calculate the mean and sum of mean for RUL (Simplified)
        meanRULSimple(RowCounter, ColCounter) = meanASL(RowCounter,
ColCounter) - Pipematrix(RowCounter, Age)
        summeanRULSimple(RowCounter, ColCounter) =
summeanRULSimple(RowCounter, ColCounter) + meanRULSimple(RowCounter,
ColCounter)

    'Calculate the mean and sum of mean for RUL (Complex)
        meanRULComplex(RowCounter, ColCounter) = meanNY(RowCounter,
ColCounter) - Pipematrix(RowCounter, Age)
        summeanRULComplex(RowCounter, ColCounter) =
summeanRULComplex(RowCounter, ColCounter) + meanRULComplex(RowCounter,
ColCounter)

    'Calculate the mean and sum of mean for RUL_CS (CS)
        meanRUL_CS(RowCounter, ColCounter) = meanNY_CS(RowCounter,
ColCounter) - Pipematrix(RowCounter, Age)
        summeanRUL_CS(RowCounter, ColCounter) =
summeanRUL_CS(RowCounter, ColCounter) + meanRUL_CS(RowCounter,
ColCounter)

    'A single iteration has been completed, move onto next iteration
        Next i

    'Calculate the Mean Age
        meanAge(RowCounter, ColCounter) = summeanAge(RowCounter,
ColCounter) / 10000

    'Calculate the Mean ASL
        meanASL(RowCounter, ColCounter) = summeanASL(RowCounter,
ColCounter) / 10000

    'Calculate the Mean NY
        meanNY(RowCounter, ColCounter) = summeanNY(RowCounter,
ColCounter) / 10000

    'Caclculate the Mean NY_CS
        meanNY_CS(RowCounter, ColCounter) = summeanNY_CS(RowCounter,
ColCounter) / 10000

    'Calculate the Mean RUL (Simplified)
        meanRULSimple(RowCounter, ColCounter) =
(summeanRULSimple(RowCounter, ColCounter)) / 10000

    'Calculate the Mean RUL (Complex)
```

```vba
        meanRULComplex(RowCounter, ColCounter) =
(summeanRULComplex(RowCounter, ColCounter)) / 10000

    'Calculate the Mean RUL_CS
        meanRUL_CS(RowCounter, ColCounter) = (summeanRUL_CS(RowCounter,
ColCounter)) / 10000

    'Output results into Risk Analysis Sheet
        Sheet23.Cells(RowCounter, 10).Value = meanAge(RowCounter,
ColCounter)
        Sheet23.Cells(RowCounter, 13).Value = meanASL(RowCounter,
ColCounter)
        Sheet23.Cells(RowCounter, 41).Value = meanNY(RowCounter,
ColCounter)
        Sheet23.Cells(RowCounter, 40).Value = meanNY_CS(RowCounter,
ColCounter)
        Sheet23.Cells(RowCounter, 43).Value = meanRULSimple(RowCounter,
ColCounter)
        Sheet23.Cells(RowCounter, 45).Value =
meanRULComplex(RowCounter, ColCounter)
        Sheet23.Cells(RowCounter, 42).Value = meanRUL_CS(RowCounter,
ColCounter)

    'All 10,000 iterations have been completed, move onto next pipe
        Next RowCounter

    Sheet23.Activate

    MsgBox ("Calculation Complete")

    Exit Sub

    'Error handling statement for Error 1004. This error occurs when
Excel cannot access the worksheetfunction (occurs once each time the
application is run)
meanAgeError:
    Select Case Err.Number
    Case 1004
        meanAge(RowCounter, ColCounter) = Pipematrix(RowCounter,
present_year) - Application.WorksheetFunction.Norm_Inv(Rnd(),
Pipematrix(RowCounter, mean_IY), Pipematrix(RowCounter, std_IY))
        Case Else
    End Select
    Resume Next

  Exit Sub

    'Error handling statement for Error 1004. This error occurs when
Excel cannot access the worksheetfunction (occurs once each time the
application is run)
meanASLError:
    Select Case Err.Number
        Case 1004
            meanASL(RowCounter, ColCounter) =
Application.WorksheetFunction.Norm_Inv(Rnd(), Pipematrix(RowCounter,
mean_ASL), Pipematrix(RowCounter, std_ASL))
        Case Else
```

```
        End Select
        Resume Next

End Sub
```
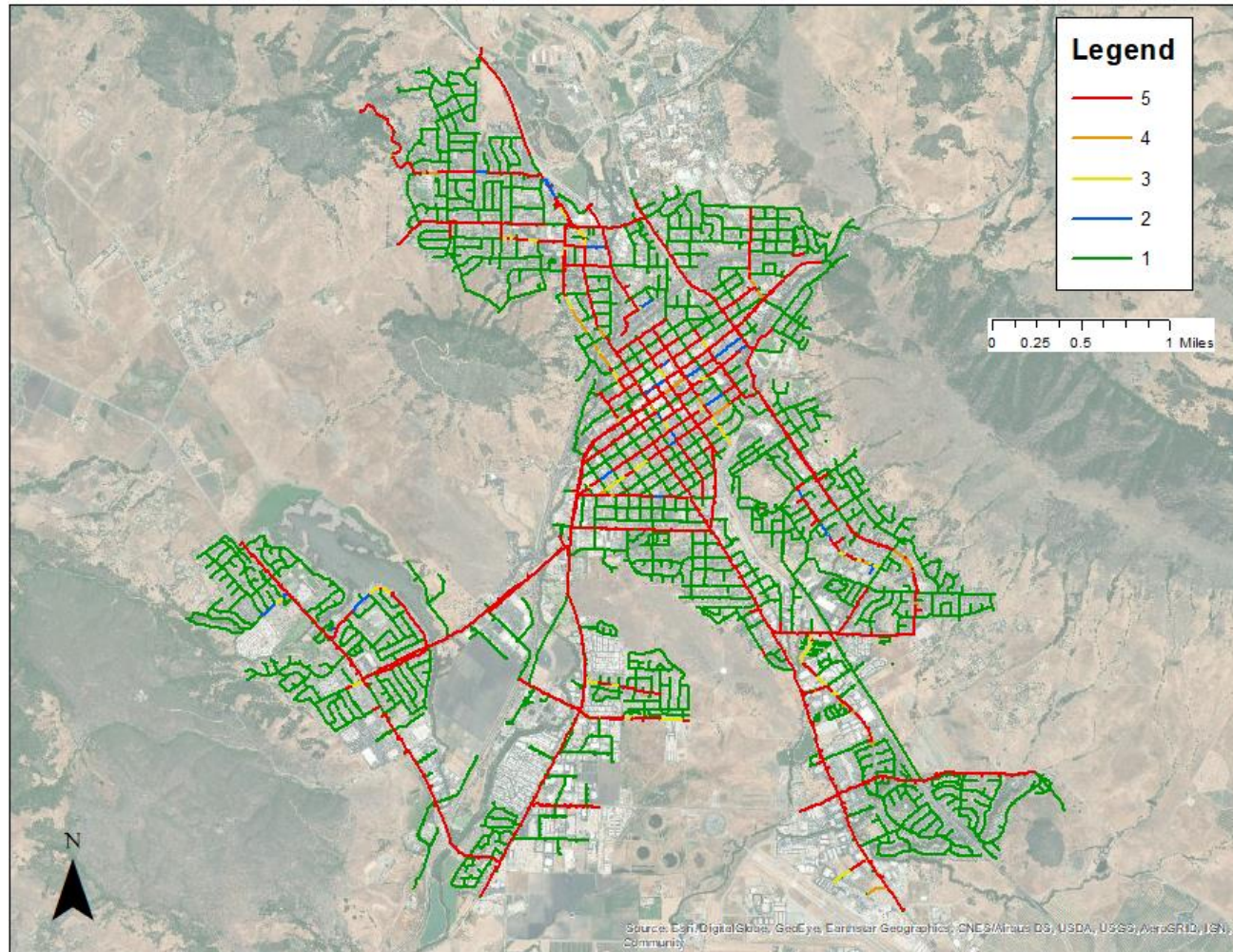
Figure C.1 Future Average Daily Volume Impact Score Categories
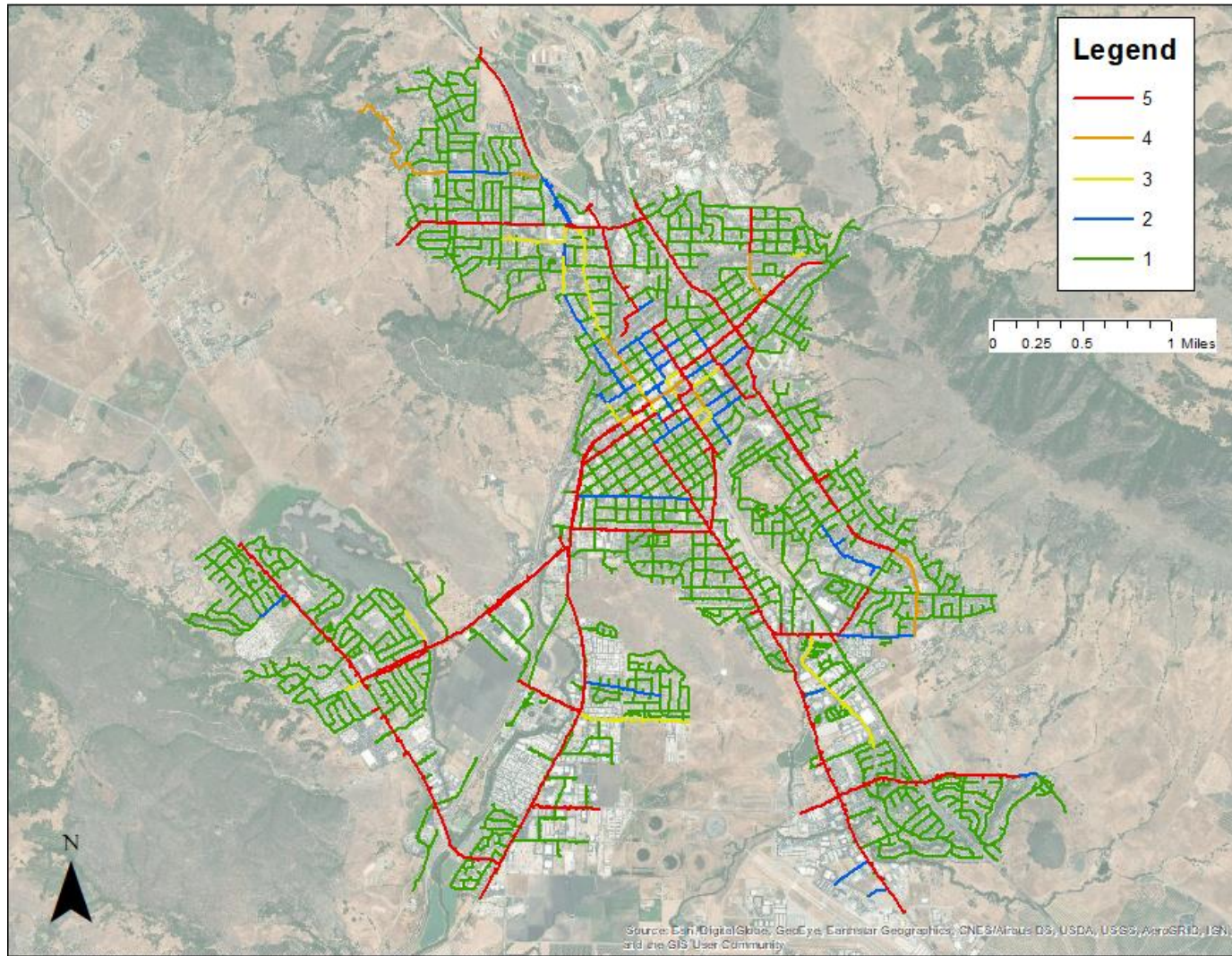
Figure C.2 Current Average Daily Traffic Volume Impact Score Categories
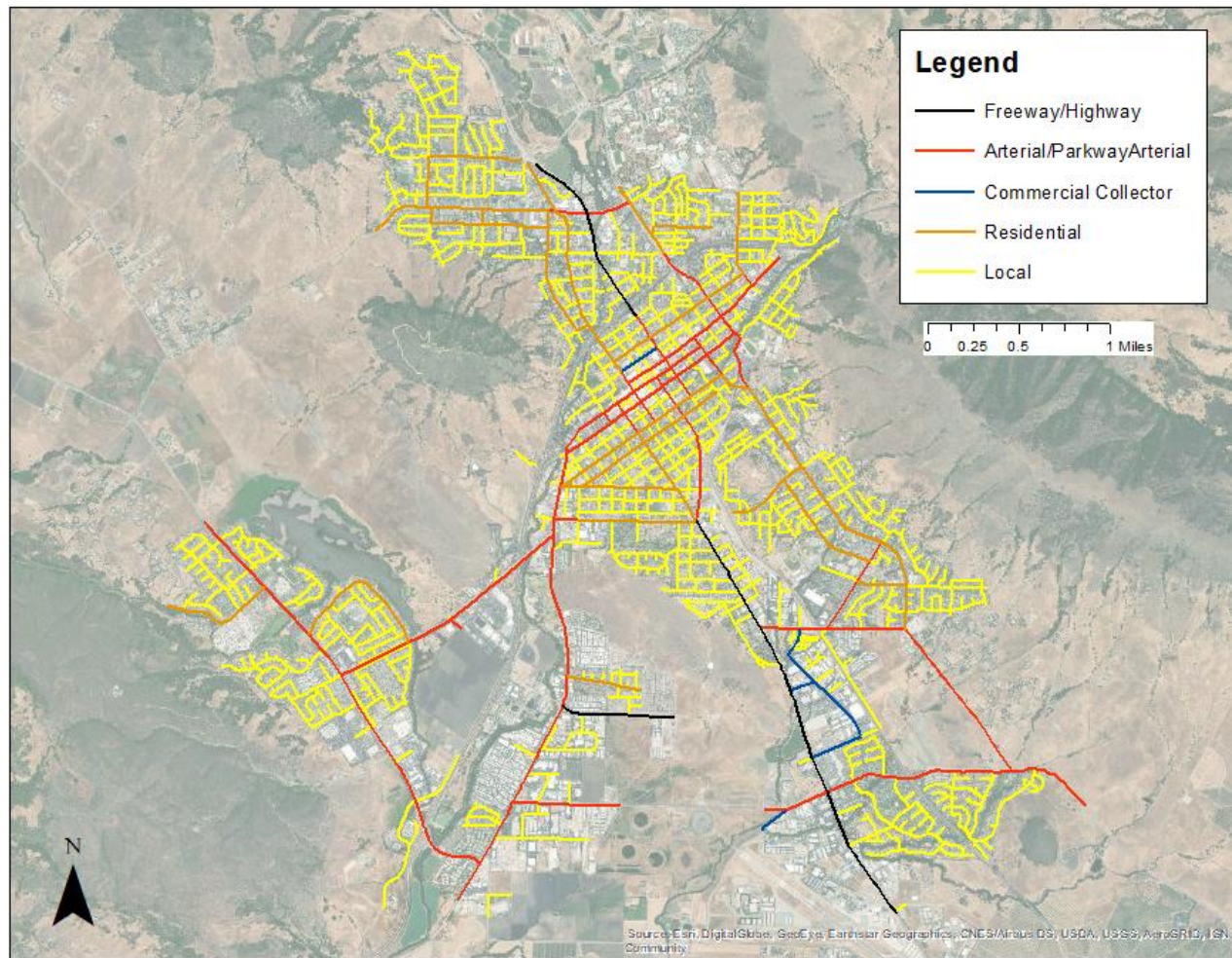
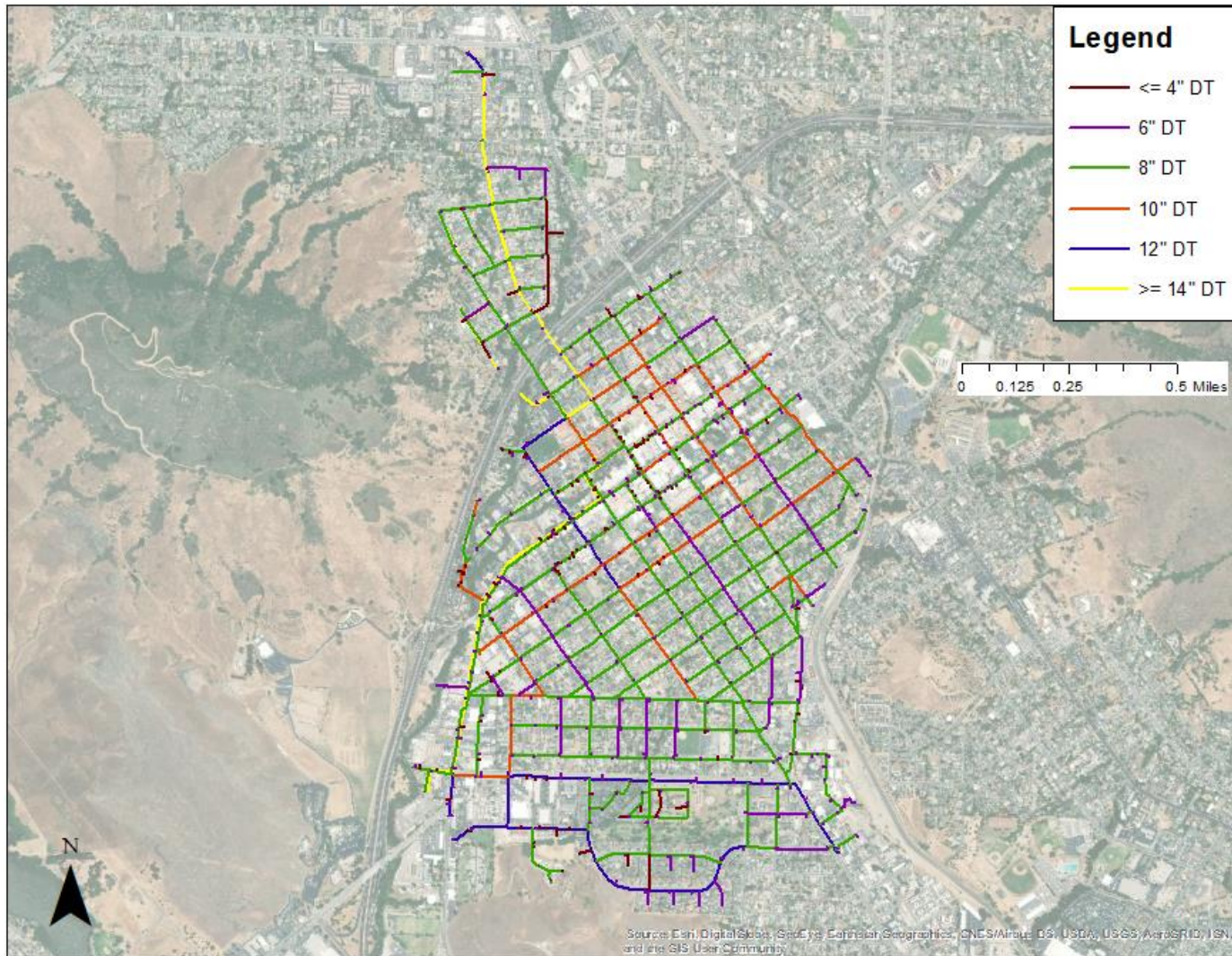**Figure C.4** Current Street Classifications in San Luis Obispo

85

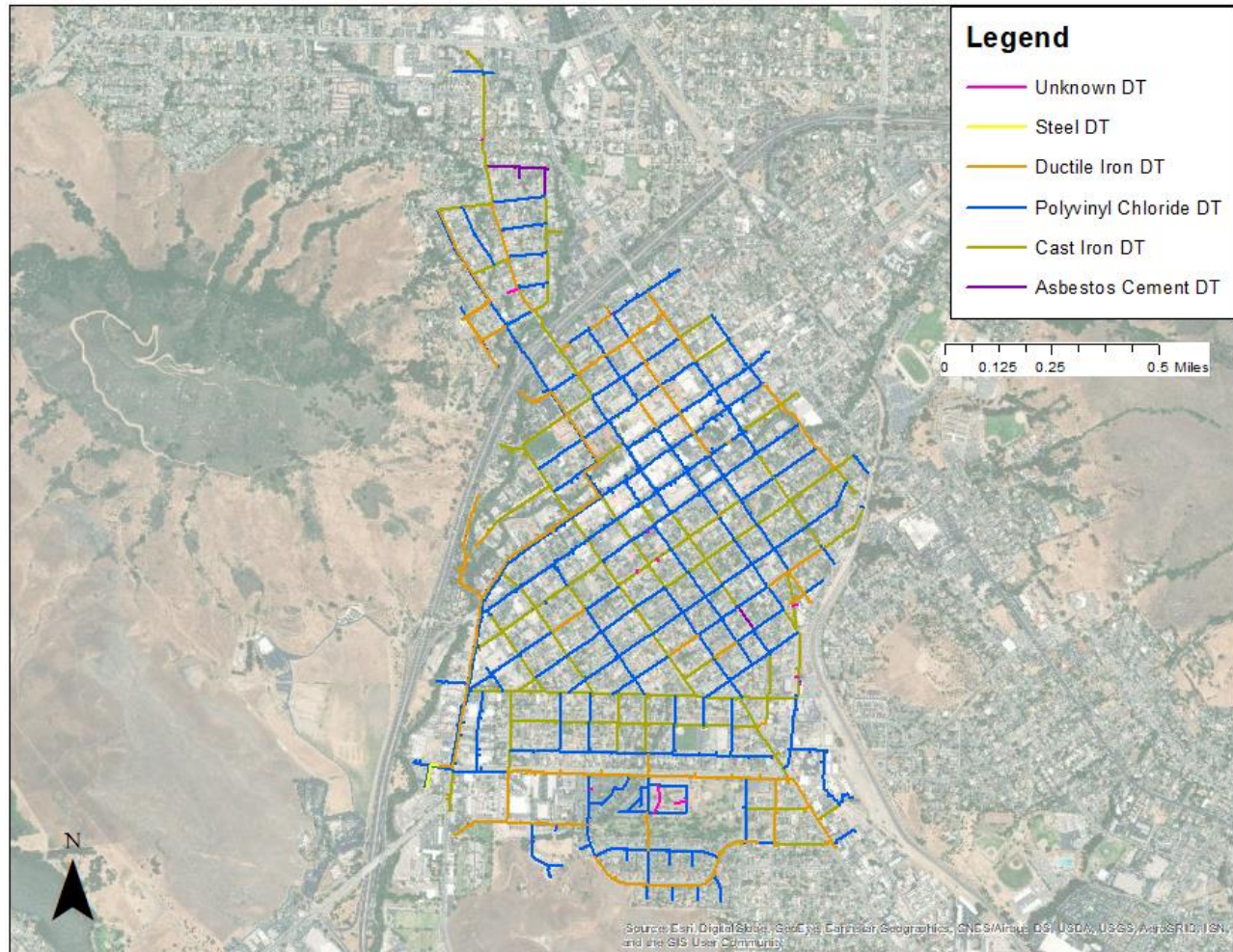**Figure C.3** Pipe Sizes in Downtown Pressure Zone

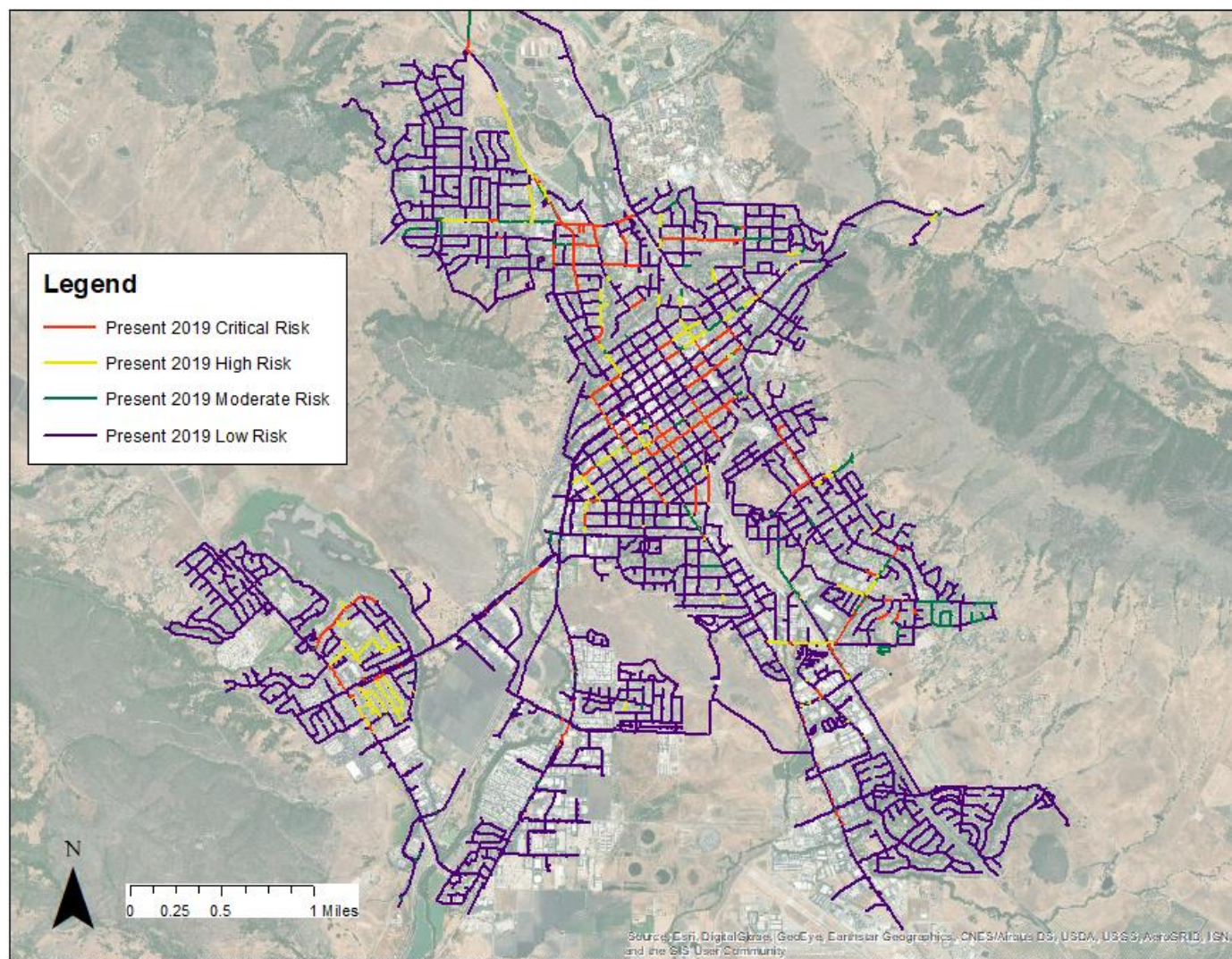**Figure C.5** Pipe Material Downtown Pressure Zone
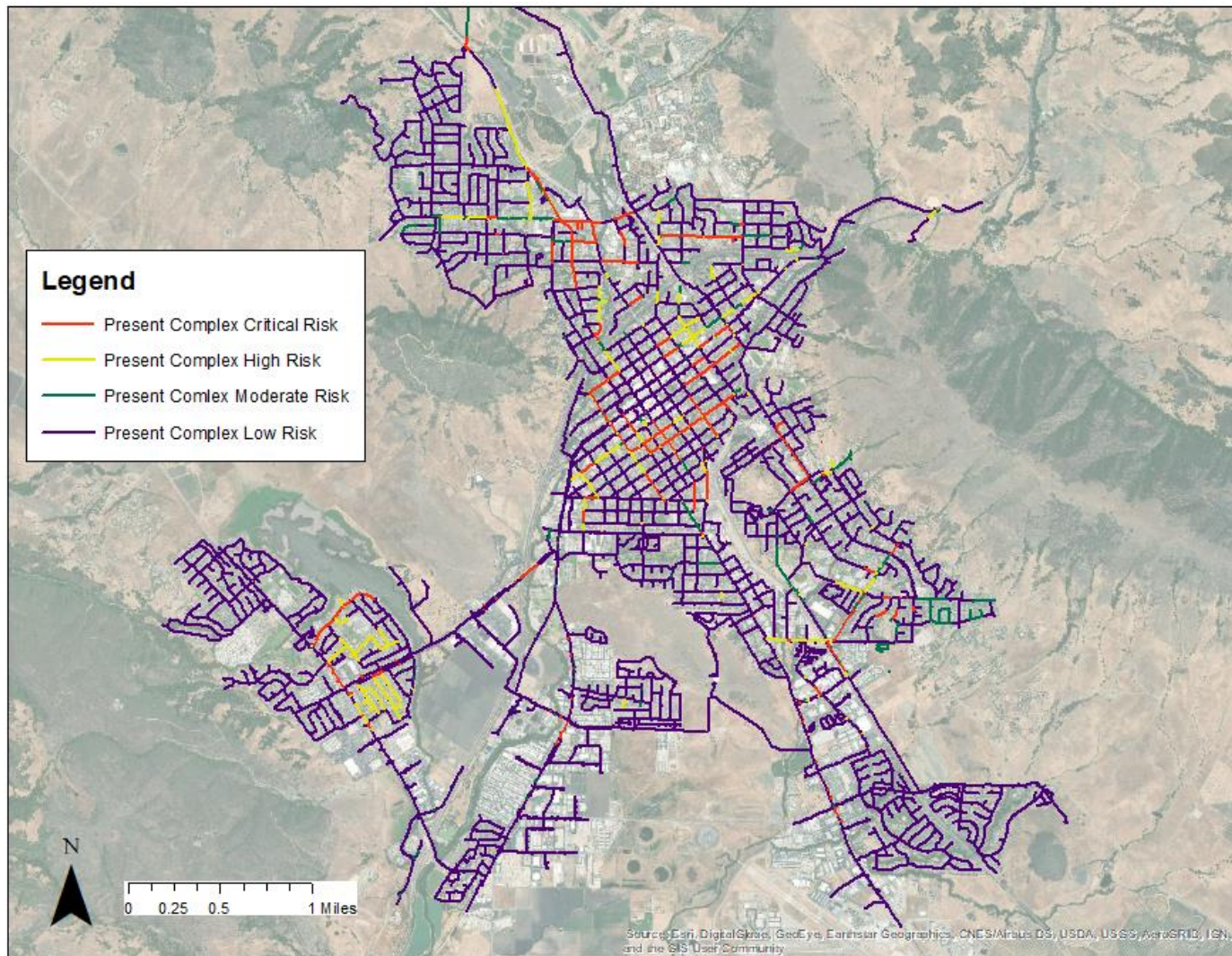
Figure C.5 Present Scenario 2019 Model
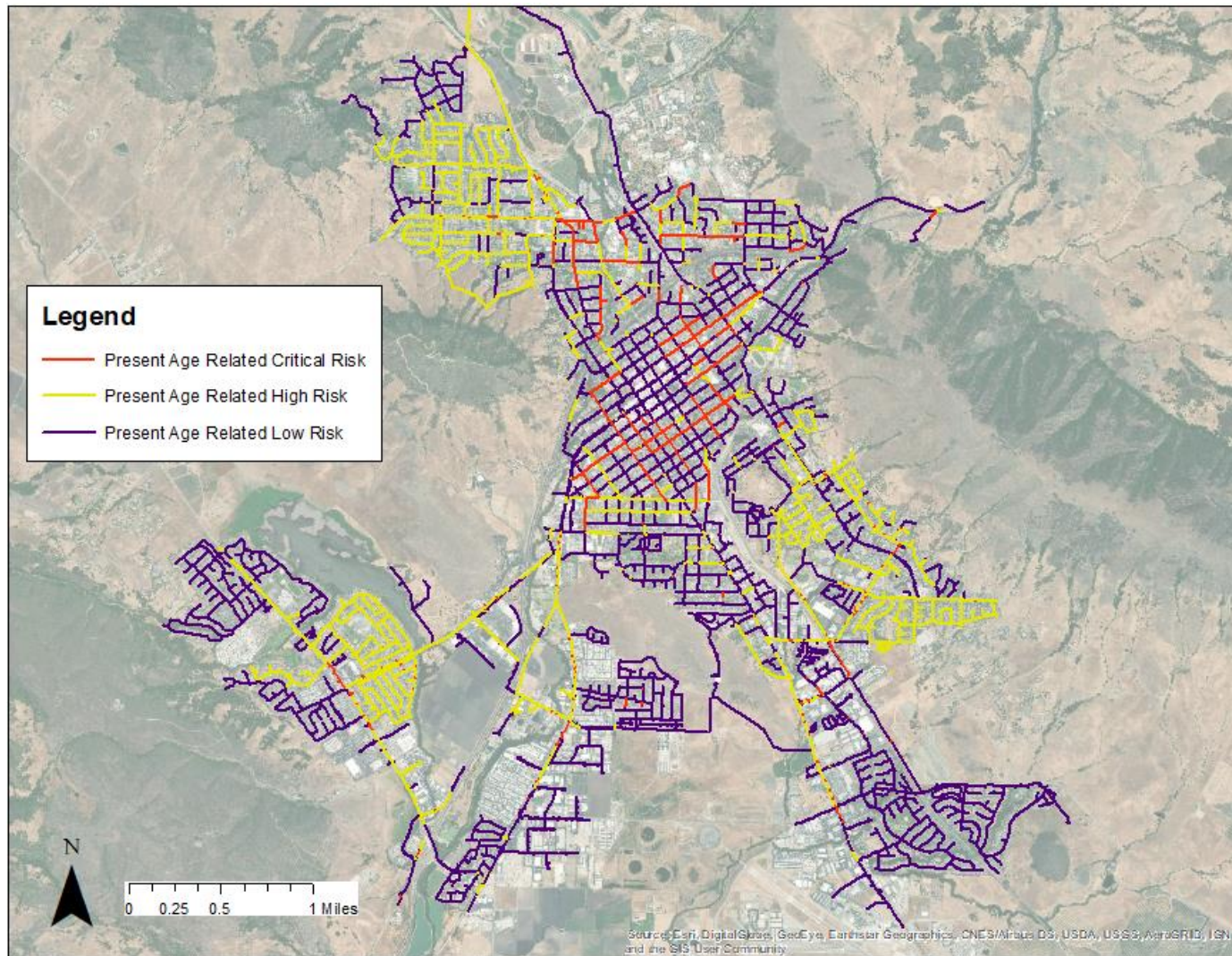
Figure C.6 Present Scenario Complex Model

Figure C.7 Present Scenario Age-Based Model
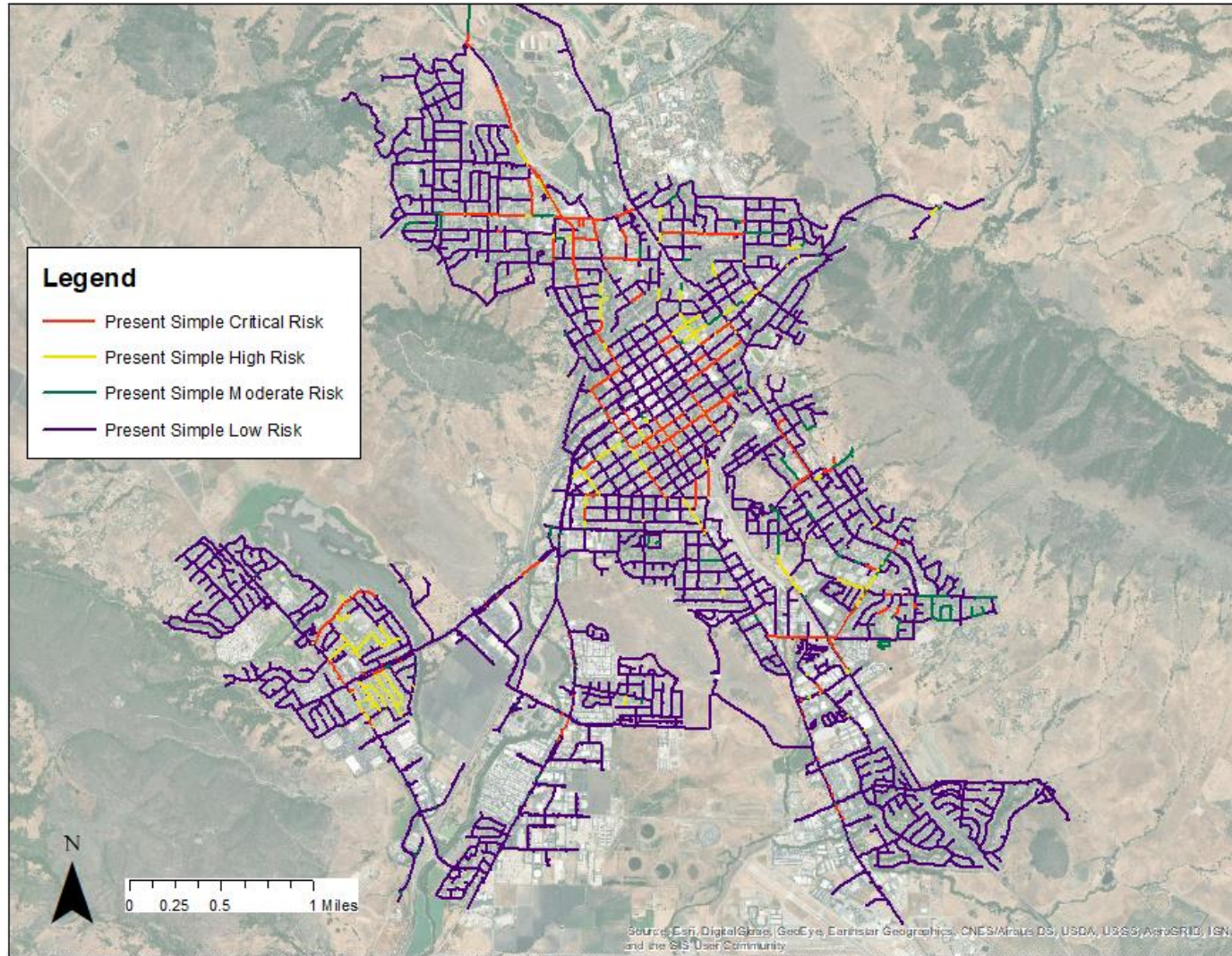
Figure C.8 Present Scenario Simple Model
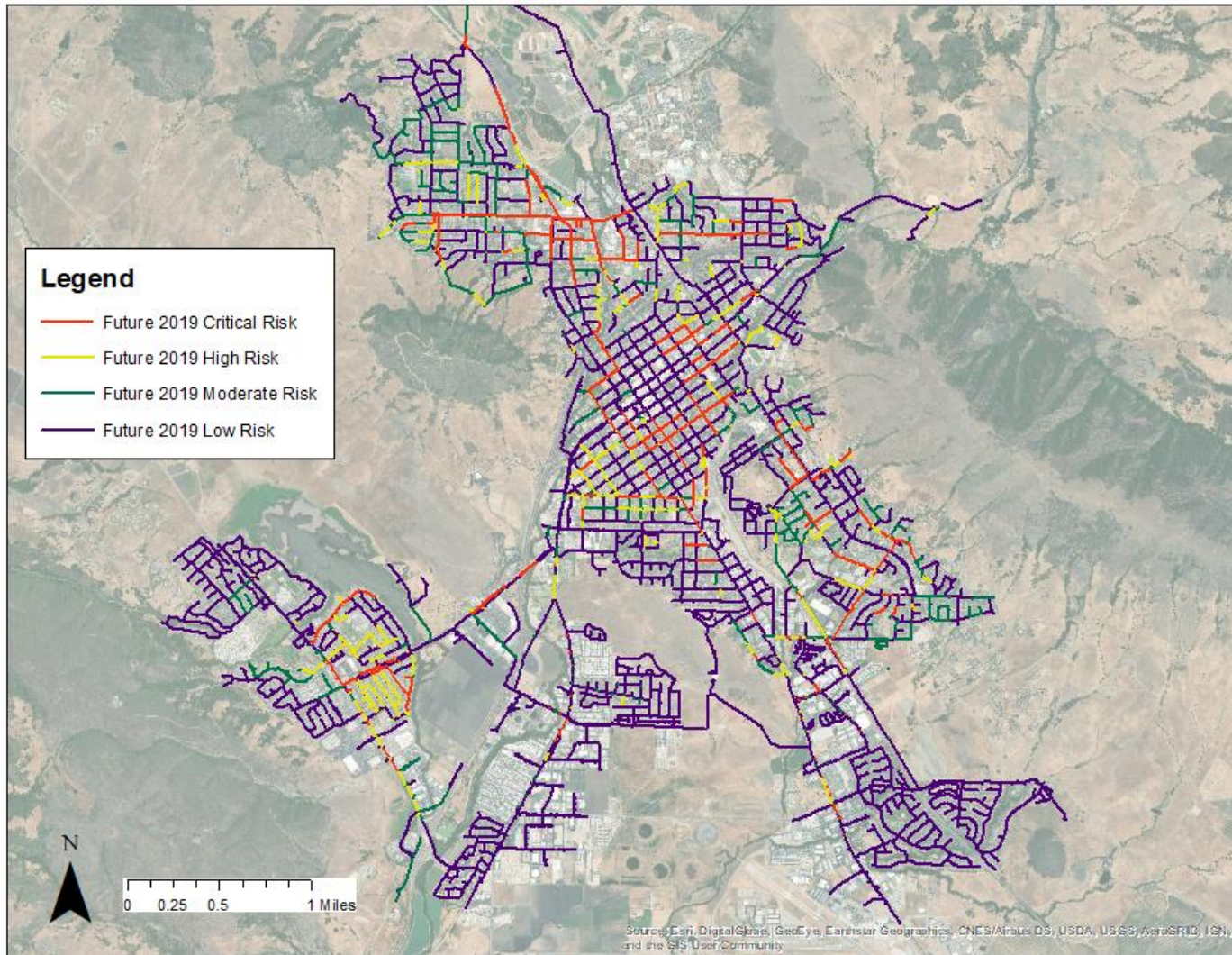
Figure C.9 Future Scenario 2019 Model
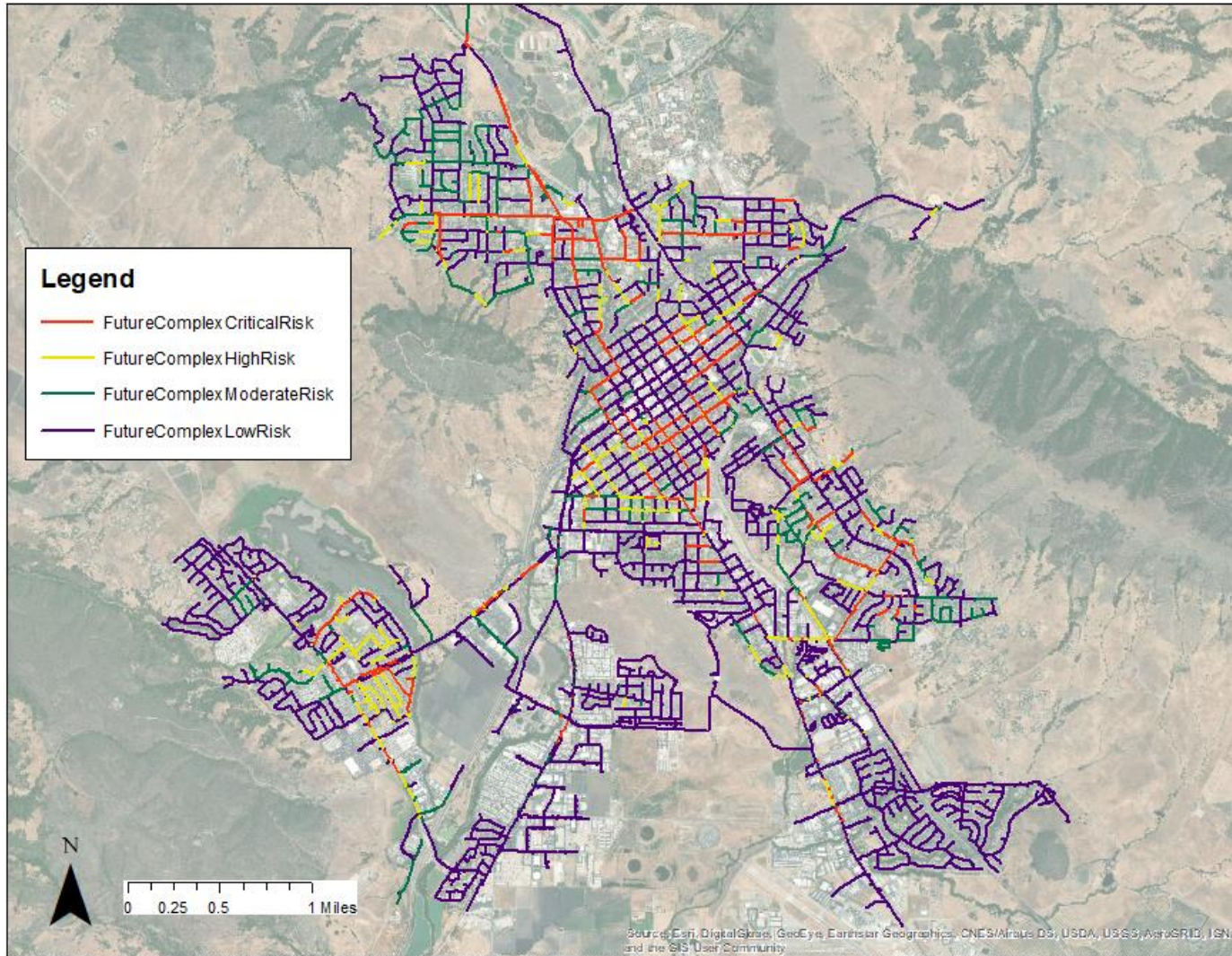
Figure C.10 Future Scenario Complex Model
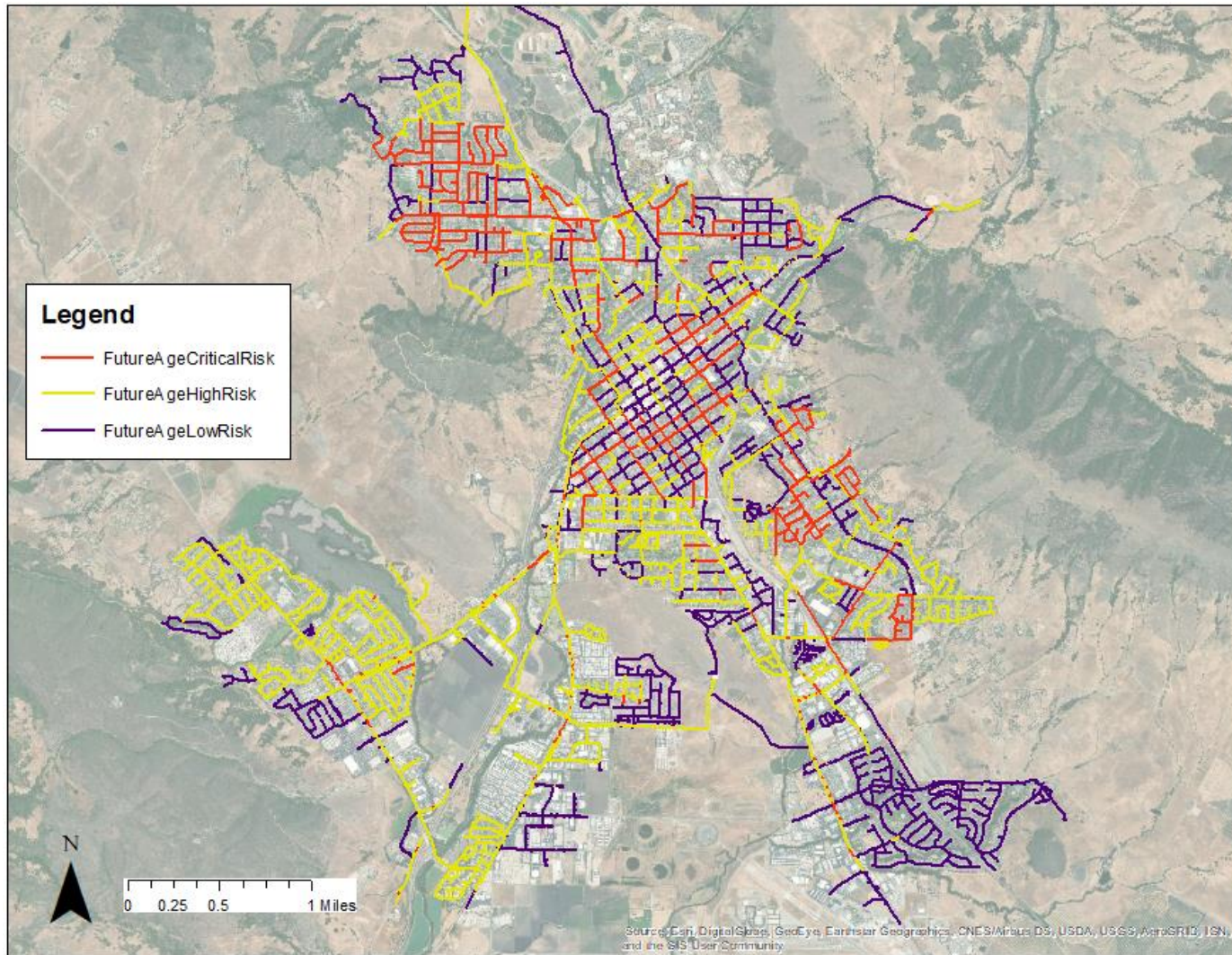
Figure C.11 Future Scenario Age-Based Model
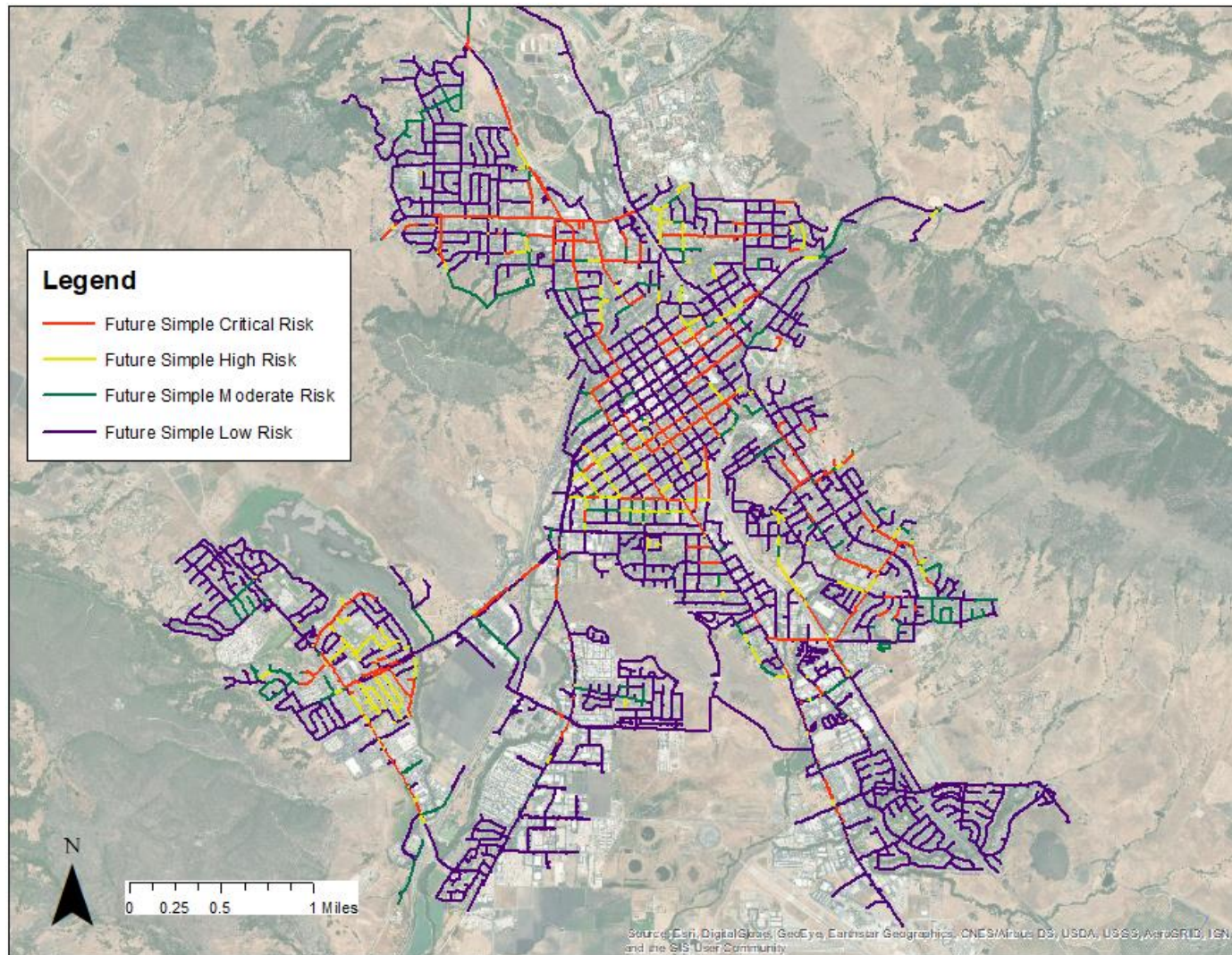
Figure C.12 Future Scenario Simple Model
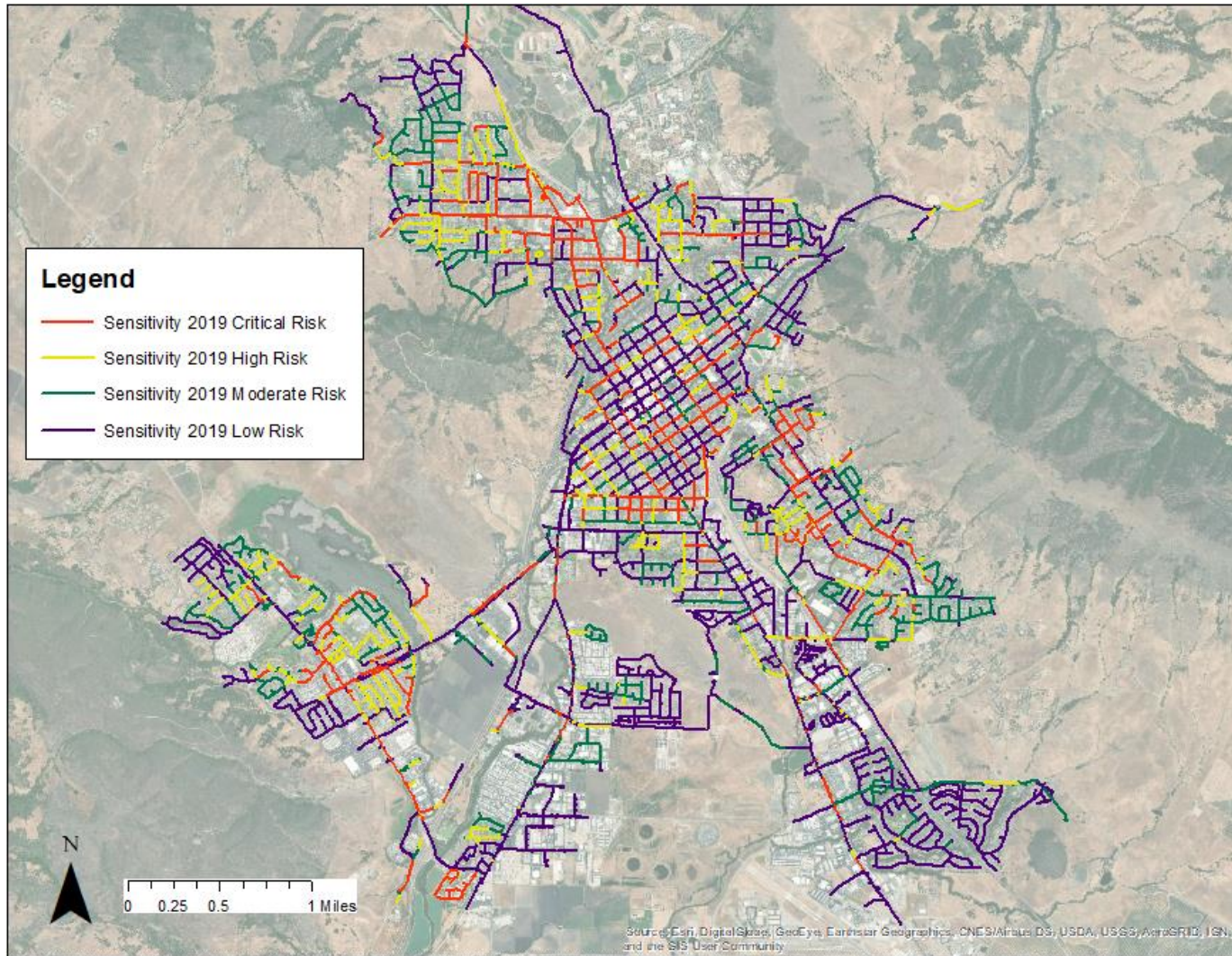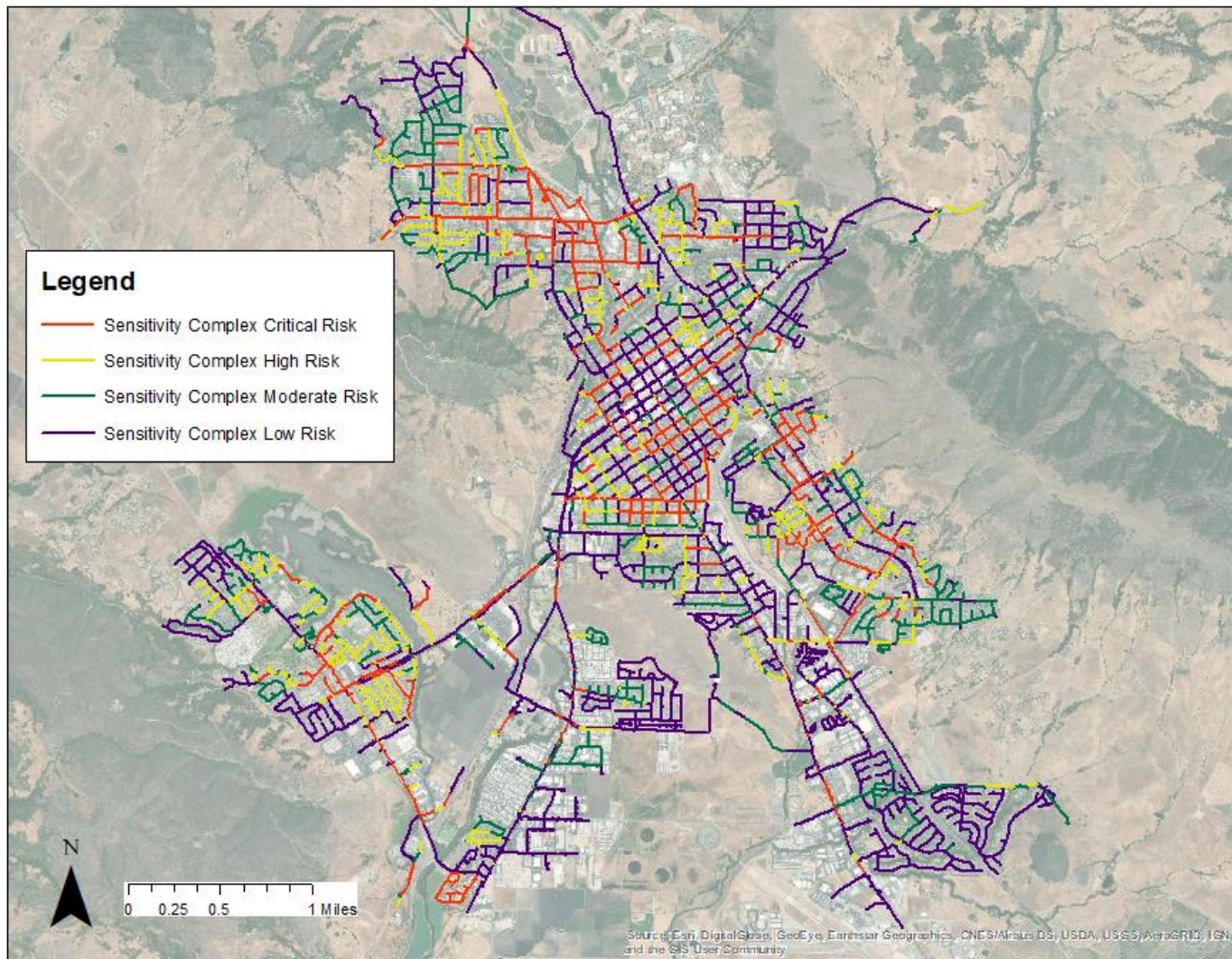
Figure C.13 Low ASL Scenario 2019 Model

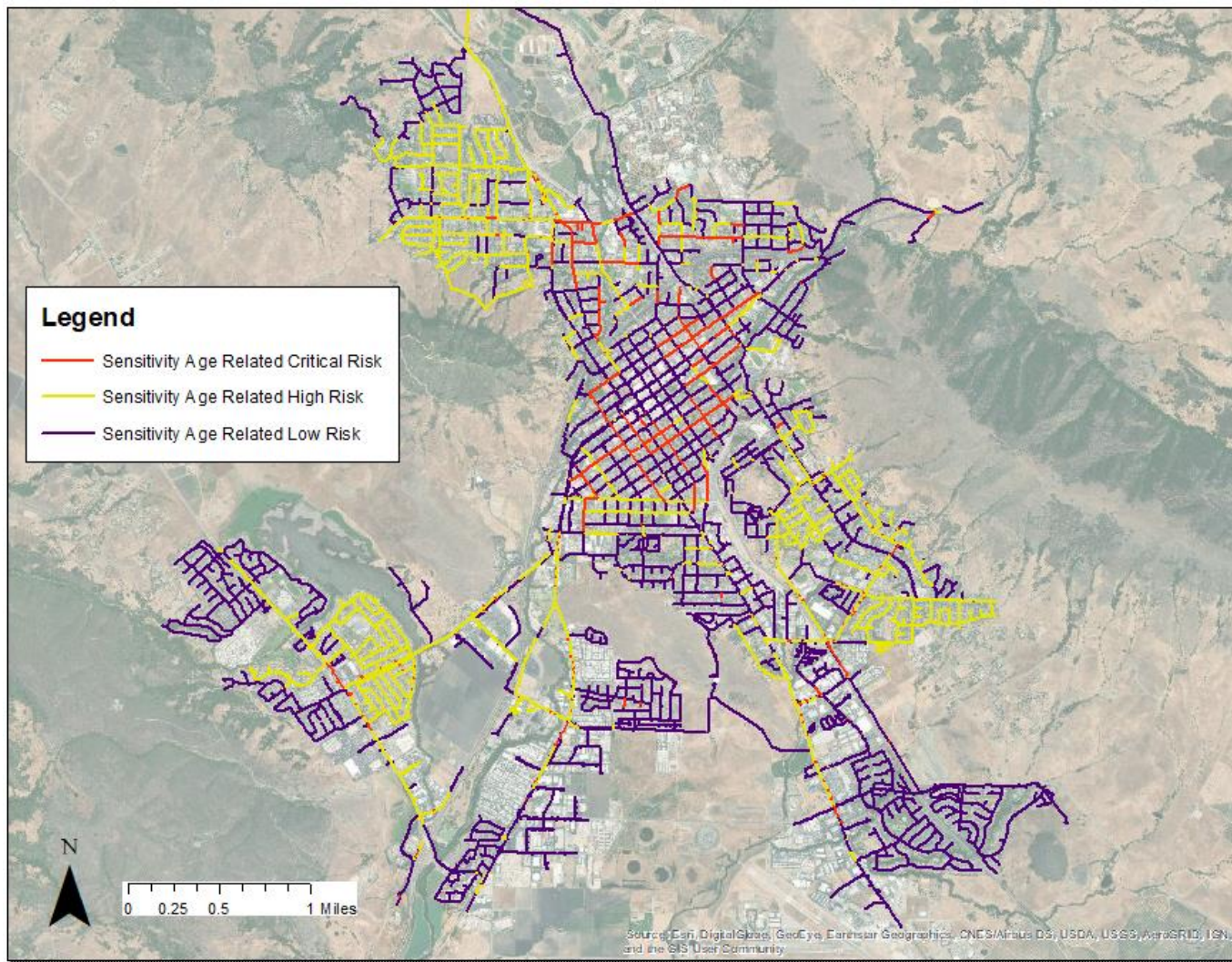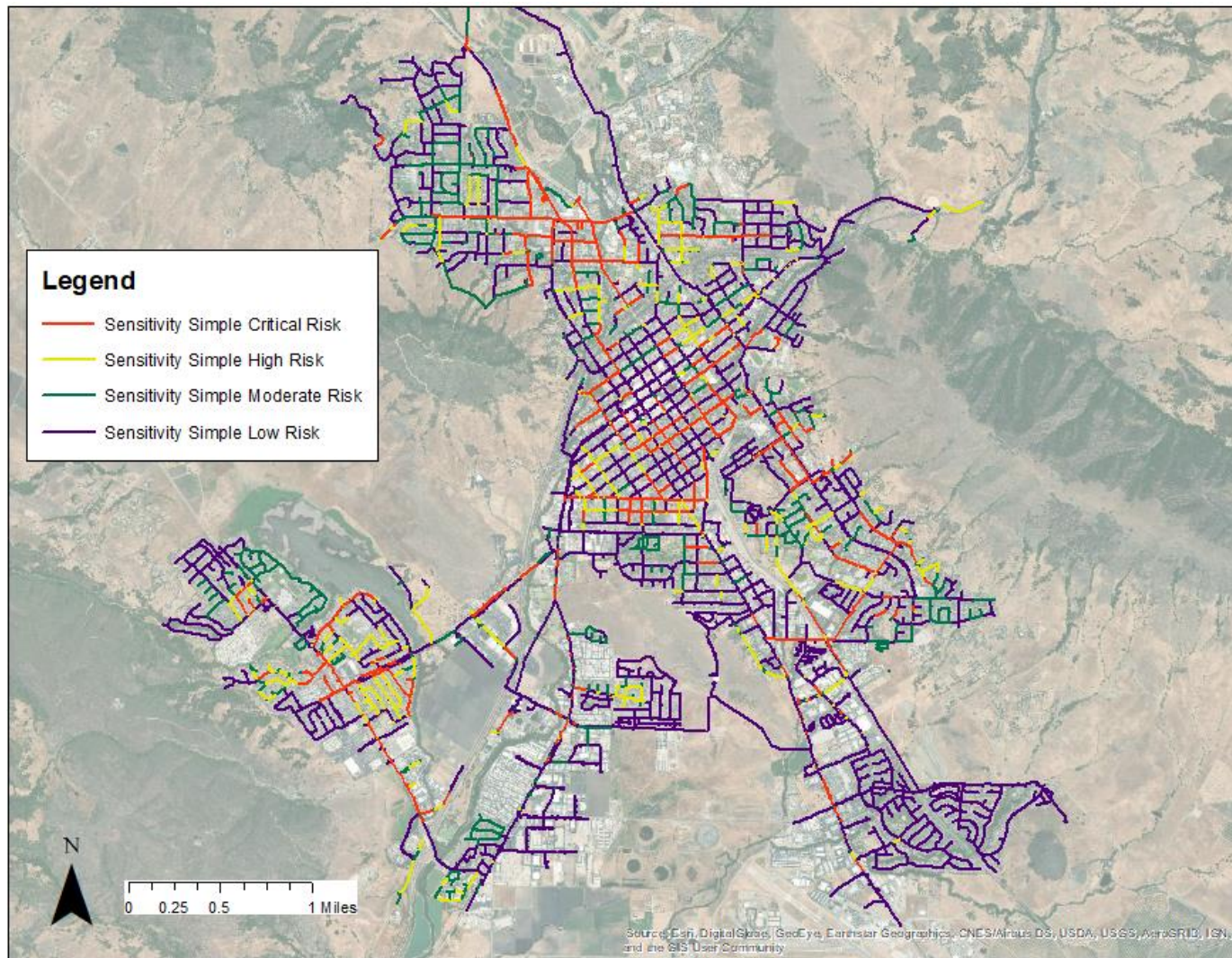**Figure C.14** Low ASL Scenario Complex Model

Figure C.15 Low ASL Scenario Age-Based Model

Figure C.16 Low ASL Scenario Simple Model