CRITICALITY AND RISK ASSESSMENT FOR PIPE REHABILITATION IN THE CITY OF SANTA BARBARA SEWER SYSTEM

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ABSTRACT

Criticality and Risk Assessment for Pipe Rehabilitation in the City of

Santa Barbara Sewer System

Emilio Carmelo Rossi II

Aging sewer infrastructure is posing greater and greater risk to the health and well-being of City residents. Issues can range from pipe blockages in sewer laterals to Sanitary Sewer Overflows. This thesis develops a risk analysis method that can be used by municipalities to maintain and rehabilitate sewer assets. Risk combines the effect of Likelihood of Failure (LOF) and Consequence of Failure (COF) to perform a complete two-dimensional analysis that allows for relative comparison between different pipes in the system. The LOF rating has been equated to pipe integrity while the COF rating was related to the environmental, economic, and social consequences to pipe failure.

In order to estimate pipe integrity Closed Circuit Television (CCTV) scores from the City of Santa Barbara were used in combination with spatial and physical properties associated with each pipe. The CCTV scores were simply integer values between 0 and 5 based on the National Association of Sewer Services Company's (NASSCO) Pipeline Assessment Certification Program (PACP) results. The quantitative parameters included pipe material and age, distance from restaurants, distance from any above ground water source, pipe depth below the ground surface, pipe length, and vehicular traffic volumes. The sensitivity analysis compared the given structural integrity scores with the predicted scores based on the weighted scoring method. It isolated four out of six of the parameters tested that affected the structural integrity of sewer

pipes: material and age (45%), pipe depth (20%), Vehicular Traffic (10%), and distance from an above-ground water source (25%). A program was created in the C programming language that iteratively determined the percentage for each factor. These percentage factors are used to obtain the predicted structural integrity score for all the pipes.

Like the LOF rating, the COF rating consisted of scores between 0 and 5. The COF rating used pipe diameter, distance from commercial zones, distance from critical infrastructure, and vehicular traffic volume as parameters for quantifying the environmental, economic, and social consequences. These factors were determined from review of past literature and given approximately equal weighting when determining the COF rating values. The environmental factor, pipe diameter, was given a percentage factor of 30%; the economic factor, distance to commercial zones, was given a percentage factor of 30%; and the social concerns, distance to critical infrastructure and vehicular traffic volume were given percentage factors of 20% each.

Finally, the risk for each pipe was determined in Geographic Information Systems (GIS) by combining the predicted structural integrity score or LOF rating and COF rating value for each pipe. This generated color-coded maps that showed distinct pipes that had the most critical predicted structural integrity scores, highest consequence, and the pipes with the most risk. This process could be used by any City to create a maintenance and rehabilitation schedule and plan for future CCTV inspections.

Key Words: Closed Circuit Television (CCTV), Geographic Information Systems (GIS), Likelihood of Failure (LOF), Pipeline Assessment and Certification Program (PACP), Likelihood of Failure (LOF), Risk of Failure (ROF), Sewer Assets, Weighted Scoring System, Sensitivity Analysis

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LIST OF ABBREVIATIONS

AADTV	Average Annual Daily Traffic Volume
ACP	Asbestos Cement Pipe
APE	Actual Probability of Existence
APN	Assessor Parcel Number
ASCE	American Society of Civil Engineers
ATP	Actual Transitional Probability
Caltrans	California Department of Transportation
CC	Condition Class
CCTV	Closed Circuit Television
City	City of Santa Barbara
CMMS	Computerized Maintenance Management Software
CNRC	Canadian National Research Council
COF rating	Consequence of Failure
CR	Criticality Ranking
CS	Criticality Score
FOG	Fats, Oils, and Grease
GIS	Geographic Information Systems
GPR	Ground Penetrating Radar
GS	Given Score
I/I	Inflow and Infiltration
ICG	Internal Condition Grade

KARO	Kanalroboter-German Robotic, Automatic Inspection System
LACP	Lateral Assessment and Certification Program
LOF rating	Likelihood of Failure
MACP	Manhole Assessment and Certification Program
MCS	Monte Carlo Simulation
MSCC	Manual of Sewer Condition Classification
NASSCO	National Association of Sewer Service Companies
NRC	National Research Council
PACP	Pipeline Assessment and Certification Program
PIRAT	Pipeline Inspection Real-Time Assessment Technique
PS	Predicted Score
PVC	Polyvinyl Chloride
RCP	Reinforced Concrete Pipe
ROF rating	Risk of Failure
SP	Steel Pipe
SPE	Simulated Probability of Existence
SRM	Sewer Rehabilitation Model
SSET	Sewer Scanner and Evaluation Technology
SSO	Sanitary Sewer Overflow
STP	Simulated Transitional Probability
VCP	Vitrified Clay Pipe
WIR	Weighted Impact Rating
WRc	Water Research Center

CHAPTER 1 INTRODUCTION

America's infrastructure is in a constant decline. Methods of risk assessment allow municipalities to maintain critical infrastructure by proactively checking transportation, energy, water distribution, communications, and many other infrastructure systems. In particular, sewer infrastructure needs to be addressed because it is often overlooked as compared to other forms of critical infrastructure like energy or water distribution. This paper develops a risk assessment model that predicts the pipes most at risk with the help of the National Association of Sewer Services Company (NASSCO) assessment methods, Closed Circuit Television (CCTV), and the computer program, Geographic Information Systems (GIS). Methodology is tested using data from the City of Santa Barbara (City).

1.1 BACKGROUND

The American Society of Civil Engineers (ASCE) reports on America's deteriorating infrastructure in categories that include water and the environment, transportation, public facilities, and energy. Overall America's infrastructure received a grade of a "D+" (American Society of Civil Engineers, 2013). In particular, the wastewater system, which includes sewer pipes, received a grade of a "D". This does not look good for the present, and this looks even worse for our future. It is estimated that capital investment of a total $298 billion dollars is required over the next 20 years for upgrades and maintenance (American Society of Civil Engineers, 2013). Three quarters of this capital need address pipe-related issues while water treatment plants and stormwater needs make up the remaining quarter.

1.2 PROBLEM

Out of all the wastewater infrastructure, this paper focuses on the pipe networks that transport waste to the wastewater treatment facilities. In the past, the City has seen an increased frequency of Sanitary Sewer Overflows (SSO's). A SSO refers to an event when the contents of the sewer overflow into public streets through manholes. During the summer of 2011, Santa Barbara Channelkeeper sued the City of Santa Barbara for the increased frequency of SSO's because in 2010 there was an average of 13 spills per 100 miles of sewer pipe per year. This rate more than tripled the California average, and a well-maintained sewer system has 0-2 spills/100 miles/year (Santa Barbara Channelkeeper, 2011).

The legal consent decree filed in 2012 required action by the City in two phases (United States District Court Central Distict of California, 2012). Phase 1 required 4 main aspects:

1) Review and update the City's routine cleaning and accelerated cleaning programs, including development of standardized procedures for cleaning and for reporting maintenance activities for sewer pipes
2) Review and update the City's emergency SSO response program
3) Update the City's Computerized Maintenance Management Software (CMMS) to implement improvements to the City's asset management program
4) Link the City's CMMS to its Geographic Information Systems (GIS)

Phase 2 then required 5 additional points:

1) Develop a plan for inspecting and assessing the condition of gravity sewers
2) Develop a method for prioritizing future replacement, rehabilitation and repair projects
3) Assess the condition of the City's pump stations and force mains and make recommendations for prioritizing needed repairs
4) Review and update the City's Fats, Oils, and Greases (FOG) program

5) Update the City's current sewer system management plan

Because of these legal issues, the City increased its focus on pipe maintenance and rehabilitation using the NASSCO assessment and CCTV inspections. The data from these inspections was a vital part of the analysis presented in this paper.

1.3 SCOPE

This thesis measures risk by combining the Likelihood of Failure (LOF) and Consequence of Failure (COF) rating using a simple multiplication scheme. The simple multiplication scheme would allow for easy adoption and replication by other municipalities throughout the United States.

PACP data of CCTV inspections were used to predict the LOF rating score for each pipe. The sensitivity analysis checked 20 scenarios that predicted both the highest structural condition grade (absolute score) as well as the weighted average of the two highest structural condition grades (average score). Related to the LOF rating, the condition grade for scores between 3 and 5 was predicted by material and age (45%), pipe depth (20%), vehicular traffic volume (10%), and the distance from any above-ground water source (25%). The COF rating was then determined using 4 factors that encompass environmental, economic, and social concerns that included pipe diameter (30%), distance from Commercial zones (30%), distance from critical infrastructure (20%), and the amount of vehicular traffic flow (20%).

This paper aimed to develop a method of risk assessment for sewer pipes that can effectively address different pipe networks. The creation of a maintenance and rehabilitation schedule would be the next step in the continual assessment of sewer pipes. The City of Santa Barbara was used

as an initial test for the methodology. It effectively accomplished the goal of developing a risk assessment model as it isolated the critical factors for LOF rating. Visual maps were created in GIS that show LOF rating, COF rating, and total risk for each pipe.

1.4 PAPER OUTLINE

Chapter 2 Literature Review (Page 6)

The literature review emphasizes previously developed assessment technologies, assessment techniques, numerical analysis, and risk analysis methods. This research led to the development of the methods used in the analysis discussed in this paper.

Chapter 3 Method (Page 30)

The methods contain information on the process of the analysis performed. This includes the description of the tools used, data acquisition, sensitivity analysis, and risk analysis.

Chapter 4 Results (Page 53)

This chapter summarizes and discusses the results of the LOF rating, COF rating, and ROF rating assessments. It will go into an in-depth summary of patterns found through the results.

Chapter 5 Discussion (Page 66)

This chapter discusses the results and its possible implications. It goes into the Likelihood of Failure, Consequence of Failure, and Risk of Failure results for this thesis and Brown and Caldwell results in 2012.

Chapter 6 Conclusion (Page 71)

This section summarizes the whole paper and discusses improvements to future risk assessments.

Appendix A GIS Snapshots (Page 77)

This appendix contains three toolboxes created in GIS 10.1 used to determine the distance of sewer pipes from restaurants and water sources (river and ocean).

Appendix B Organize Program (Page 82)

This appendix contains the source code of the program that organizes the data from GIS to prepare it for the analysis process by creating 20 different text files that will be analyzed by the sensitivity analysis program in Appendix C. It is composed of one text file named “organize.c”.

Appendix C Sensitivity Analysis Program (Page 92)

This appendix contains the program that performs the sensitivity analysis on the data from the CCTV NASSCO scores which determines the best combination of factors that predicts the structural criticality score. It is composed of three text files: the main c file “sensitivity.c” and the header files “sensitivity.h” and “statistics.h”.

Appendix D GIS Maps and DataGIS Maps and Data (Page 123)

This section has GIS maps and data referenced throughout this thesis document. These figures represent the visual distribution of pipe data throughout the City of Santa Barbara Sewer System.

Appendix E Caltrans Traffic Count Data (Page 143)

Data used in the sensitivity analysis and consequence assessment for Caltrans traffic counts along Highway 101 are included in this appendix. Refer to Sections 3.3.6 and 3.4.4.

Appendix F Results (Page 147)

This appendix includes results from the analysis in this thesis. This includes tables and figures for the sensitivity analysis, Consequence of Failure (COF) results, and Risk of Failure (ROF) results.

CHAPTER 2 LITERATURE REVIEW

Due to the constant aging of sewer systems, assessments are needed to determine their current and future condition. In some form, all assessments consider Probability of Failure (also known as Likelihood of Failure(LOF)), Consequence of Failure (COF), or Risk of Failure (ROF). The most complete assessment will contain POF, COF, and ROF because it considers some form of pipe criticality and consequence assessment.

Throughout literature, many authors relate the LOF rating to the structural integrity of pipes. Pipe structural integrity is often ranked by a simple integer score between values of 0 and 5 but given a different name depending on region and sewer maintenance authority. Germany uses Condition Class (CC); the United States uses Criticality Score (CS); and Great Britain uses Criticality Rating (CR). The COF is often in monetary terms or values of life-loss, and it measures the effect of pipe failure in terms of environmental, economic, and social consequences (Moss, 2013). Risk of Failure combines both Likelihood of Failure and Consequence of Failure to provide a more accurate view of pipe prioritization for maintenance and rehabilitation as compared to the LOF or COF individually.

This section delves into the different types of assessment technologies, assessment systems, logits and age dependency of pipe deterioration, multiple regression analysis, Monte Carlo Simulations and assessment models, determination of asset residual life, and risk analyses. This chapter discusses the topics of LOF rating and COF rating individually and will finally combine these concepts to explain ROF rating.

2.1 ASSESSMENT TECHNOLOGIES

Various assessment technologies are used to check the current level of deterioration within a pipe network. Wirahadikusumah et al (1998) and Tuccillo et al (2010) consider physical, photographic, Closed Circuit Television (CCTV), and other advanced assessment techniques to check the current level of deterioration within a pipe network.

Physical inspection involves man-entry into large diameter pipes which involves numerous risks including hydrogen sulfide build up which must be ventilated to provide a safe working environment. Photographic inspection uses a remote camera to take a series of photos along the pipe section. One of the most common photographic techniques, CCTV, consists of a mounted camera that is pulled through the sewer with cables (Wirahadikusumah, Abraham, Iseley, & Prasanth, 1998).

Both photographic and CCTV inspection with video have similar disadvantages. The quality of the results depends on the skill and experience of the technician or engineer evaluating the photos or video and debris can hide serious cracks. Additionally, photography and video are better for smaller pipes because larger pipes create lighting and camera resolution issues (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). CCTV has also been expanded to include video in addition to photography and allows for every foot of pipe to be analyzed given freedom of movement. The analysis in this thesis uses CCTV data that has determined the structural integrity of the pipes.

Wirahadikusumah et al (1998) and Tuccillo et al (2010) also cited several more advanced inspection that include infrared thermography system, sonic distance measurement, and Ground Penetrating Radar (GPR). The infrared thermography system is based on the theory that energy

flows from warmer to cooler areas. Following the transfer of heat throughout the pipe section, this system efficiently inspects pipe wall integrity and bedding and void conditions by locating water leaks, voids caused by erosion, deteriorated insulation, and poor backfill (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). It includes four main subsystems: the infrared scanner head and detector, real-time microprocessor, data acquisition and analysis equipment, and image recording or retrieving devices (Wirahadikusumah, Abraham and Iseley, 1998).

The sonic distance measuring device determines the time for sound to travel from one object to a target (Wirahadikusumah, Abraham and Iseley, 1998). This method is based on the theory that different materials allow sound to travel more quickly or slowly depending on density and elasticity. It can be used in water or air, but it cannot operate in both air and water simultaneously because different instrumentation is required.

Ground Penetrating Radar (GPR) transmits electromagnetic waves into the ground to determine the change in electrical responses from subsurface materials (Wirahadikusumah, Abraham and Iseley, 1998). This method collects data on sewer structure condition, the condition of the sewer-soil interface, the condition of the surrounding soil, and void conditions surrounding the pipe (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). It transmits radio waves into the ground and is reflected back to the surface after different speeds depending on the density of the surrounding soil (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). Ground Penetrating Radar does not work well around clay soils and does not identify specific utilities (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). This method also requires substantial experience to accurately interpret results and does not yield a complete picture of sewer condition.

Autonomous and semi-autonomous sewer inspection systems include Kanalroboter (KARO), Pipeline Inspection Real-Time Assessment Technique (PIRAT), and Sewer Scanner and Evaluation Technology (SSET). KARO is the name given to a German robot that automatically detects sewer type, location, and size of defects. The robot carries 3D optical sensors, ultrasonic sensors, and microwave sensors that detect defects up to ten centimeters beyond the pipe wall (Wirahadikusumah, Abraham, Iseley, & Prasanth, 1998). These defects include but are not limited to voids in surrounding soil, cracks in the pipe, root intrusion, and joint offsets.

Australian authorities have created the PIRAT, an instrument that detects the geometric data of pipes and automatically identifies and rates each defect. It is an in-pipe vehicle that is equipped with a laser scanner for drained pipes and sonar for flooded pipes. KARO and PIRAT are both semi-autonomous can be equipped with CCTV, sonar, laser, and microwave sensor and are considered a “two-pass” system (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012). The first pass detects potential defects while the second pass confirms those defects in more detail (Tuccillo Ph.D., Jolley P.E., Martel P.E., & Boyd Ph.D. P.E., 2012).

The Sewer Scanner and Evaluation Technology (SSET) is a flexible tool that uses CCTV, a laser scanner, and gyroscope technology. It provides video record, a full circumference scanned image of the pipe, a color-coded print out of the defects, and written description of each defect. With most other methods, the operator scores the sewer pipes while the inspection equipment goes through the pipes and the engineer must verify these results. With the SSET, the operator is only responsible to ensure that equipment operates correctly, while the engineer makes maintenance and rehabilitation decisions from the automatically created defect reports.

2.2 ASSESSMENT SYSTEMS

McDonald and Zhao (2001) performed a condition and rehabilitation assessment on large diameter sewers greater than 900 mm (36 inches) based on the Canadian National Research Council (CNRC) sewer rehabilitation model that outlines the performance assessment of sewers. The paper summarizes the major impact factors in decision-making, data management, selection of rehabilitation methods, prediction of existing sewer conditions, and cost estimates. This whole process includes creating an inventory database, performing an impact assessment, prioritizing and inspecting sewer pipes, assessing pipe condition, decision-making on rehabilitation actions, rehabilitating, and determining the frequency of future inspection. This process is shown in Figure 2-1 below. It is important to note that pipes go through a constant cycle of inspection, condition assessment, and rehabilitation.

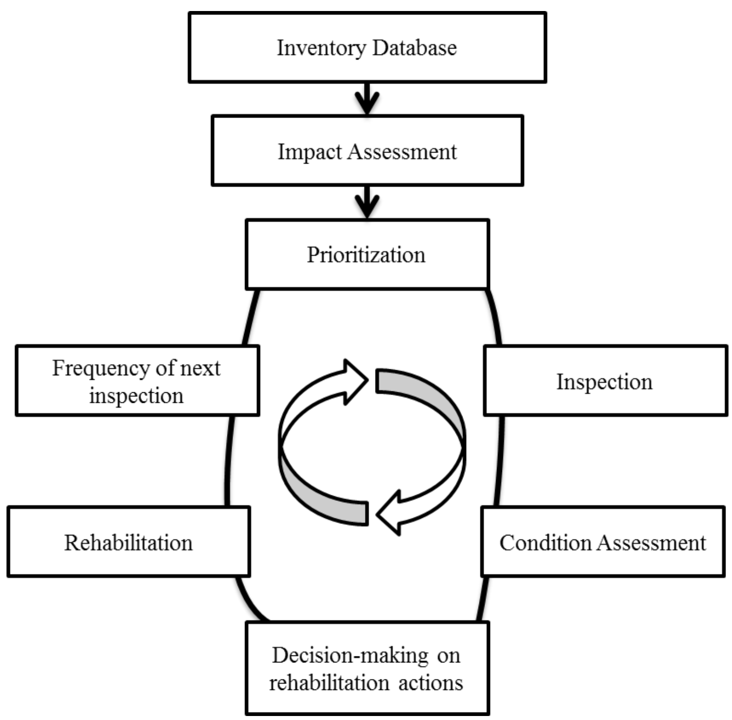


Figure 2-1 Approach for Managing Sewer Assets (McDonald & Zhao, 2001)

One of the most important aspects of the assessment is the impact prediction of the existing sewer conditions. In order to predict the existing sewer pipe conditions, six factors are important: location (f_1), type of embedment soil (f_s), burial depth (f_z), pipe diameter (f_d), functionality (f_f), and seismic zone (f_q). McDonald and Zhao (2001) calculated the Weighted Impact Rating (WIR) as shown in Equation 2-1 below.

$$WIR = (0.2)f_1 + (0.16)f_s + (0.16)f_z + (0.16)f_d + (0.16)f_f + (0.16)f_q \quad \text{Equation 2-1}$$

This equation uses factors ($f_{\text{"x"}}$) that range between values of 1 for a low degree of impact to 3 for a high degree of impact. The constants in front of the condition factor scores total to a value of one to approximate the percentage of impact. Weighted impact ratings allow municipal professionals to prioritize current inspection tasks and future inspection frequencies.

The Water Research Center (WRc) developed the first Manual of Sewer Condition Classification (MSCC) in 1980 to provide consistent assessment throughout Great Britain (National Association of Sewer Service Companies, 2010). Other regions including Australia, New Zealand, Southeast Asia, and Europe have developed WRc-based coding systems. In 2002, the WRc helped the National Association of Sewer Service Companies (NASSCO) to develop the Pipeline Assessment and Certification Program (PACP) and more recently the Manhole Assessment and Certification Program (MACP) and the Lateral Assessment and Certification Program (LACP). This was developed in the United States to provide a standard for sewer assessment because, in the past, engineers had used different adaptations of the WRc codes.

NASSCO cites six main reasons for inspection: routine operational requirements, troubleshooting, compliance with mandated programs, inspection of new or renewed sewers, the detection of Inflow and Infiltration (I/I), and capital improvement program projects. The

inspection process allows municipalities to record descriptive data, develop a Condition Rating (CR) for each line, develop rehabilitation and maintenance recommendations, and establish future inspection needs. Standardizing scoring for CCTV data with NASSCO's standard scoring techniques is beneficial because it normalizes pipe scores that accurately compare different sewer systems.

NASSCO trains municipalities in the PACP code to effectively rate the structural, operation and maintenance, and construction condition of sewer pipes, based on a scoring system between zero and five. A score of zero means that there are no defects in the pipe while a pipe with a score of five is in the worst condition with many defects. Operation and maintenance scores deal with foreign objects found in the pipe. This includes deposits, root intrusion, I/I, obstacles and obstructions, the presence of vermin, and the testing of grout connections (National Association of Sewer Service Companies, 2010). The construction condition scores are based on the methods of construction which are divided into four groups: taps, intruding seal material, direction/alignment of the sewer, and access points.

This thesis focuses on using the structural condition score, which deals with physical pipe damage, to predict the current condition of active sewer pipes. According to the PACP reference manual, the structural condition score has a total of thirteen types of defects: cracks, fractures, broken, hole, deformed, collapsed, joint, surface damage, buckling, weld failure, point repair, lining features, and brickwork (National Association of Sewer Service Companies, 2010).

2.3 LOGITS AND AGE DEPENDENCY OF PIPE DETERIORATION

Younis and Knight (2010) published two articles in the *Tunneling and Underground Space Technology* journal. Both case studies procured data from the City of Niagara Falls wastewater

infrastructure to perform sewer criticality assessments. Younis and Knight (2010) used an ordinal regression model based on cumulative logits using a generalized linear model formulation. Ordinal refers to any response where a variable is rank ordered. In the case of the sewer system assessment by Younis and Knight (2010), this refers to the Internal Condition Grade (ICG) of the pipe based on the Sewer Rehabilitation Model (SRM), in this case. Logits return values between negative infinity and positive infinity and has the input of a probability of an event occurring as shown in Equation 2-2 below. If the logit equals a value of less than or equal to zero, there is a 50% chance or less of the event occurring. If the logit equals a value of greater than or equal to zero, there is a 50% chance or more of the event occurring.

$$Logit = ln\frac{P}{1-P} \qquad \text{Equation 2-2}$$

Finally, the generalized linear model formulation combines the analysis and the given data to solve problem of the sewer assessment. They found that Reinforced Concrete Pipes (RCP) deteriorated with age, while Vitrified Clay Pipes (VCP) did not. They determined that VCP can survive indefinitely if installed properly, while RCP is prone to corrosion from hydrogen sulfide.

Younis and Knight (2010) used an ordinal regression model with continuation ratio logits to determine the estimated probability that a pipe will stay at the current ICG or will deteriorate beyond the current ICG. They again established that RCP degradation is age dependent and the probability to go to a worse ICG increases as age increases. It was shown that the conditional probability for RCP to go beyond the ICG of 3 at the age of 40 years is 60%, and increases to 90% at 80 years. However, VCP degradation is independent of age. The results showed that up to the age of 65 years, VCP had greater conditional probabilities than RCP due to poor installation practices, but as age increased, the probabilities to go beyond the current ICG stayed constant. For example, all VCP with an ICG of 4 had a probability to advance to a worse condition of 45%.

Younis and Knight only based their research on pipe material and age and did not include other variables as will be seen in other research articles in this section.

2.4 MULTIPLE REGRESSION ANALYSIS

Chughtai and Zayed (2007) assessed the structural condition of the sewer system in the City of Niagara Falls, Canada, to proactively provide cost-effective preventative maintenance and solutions based on the severity of pipe condition. They discussed that the existing condition of a sewer pipe can be divided into the structural and operational categories. Structural categories referred to the physical properties of the pipe, while the operational categories describe the "capability to meet its service requirements." Chughtaie and Zayed (2007) developed an assessment tool to predict the structural and operational condition grades of a pipe based on CCTV inspection data filtered through the WRc classification system.

Using multiple regression analysis, many different variables were considered in the prediction of the structural condition of the pipes, but the analysis resulted in seven different factors that affected the pipe degradation. These factors are separated into three categories: physical, operational, and environmental factors. The factors included diameter, length, street category, depth, age, material class, and bedding material as shown in

Equation 2-3 through Equation 2-5 below. The equations demonstrate that different factors affect the pipe materials to varying degrees. These equations are prediction models for RCP, Asbestos Cement Pipes (ACP), and Polyvinyl Chloride (PVC) pipes.

Equation 2-3 RCP Structural Condition Prediction Model

$$\frac{1}{Structural\_Condition\_Grade} = 3.94 + 0.592\frac{\log_{10} Diameter}{Length} - 0.00681e^{Street\_Category} - 3.22\log_{10} Depth - 1.6\frac{\log_{10} Age}{Concrete\_Class} + 6.92\frac{\log_{10} Depth}{Bedding\_Factor} - 5.75\frac{1}{Bedding\_Factor}$$

Equation 2-4 ACP Structural Condition Prediction Model

$$(Structural\_Condition\_Grade)^2 = 20.9 + 542\frac{\log_{10} Depth}{Length} + .207Age - 0.741Asbestos\_Cement\_Class - 14.8Diameter^{0.1}$$

Equation 2-5 PVC Pipe Structural Prediction Model

$$(0.1)^{Structural\_Condition\_Grade} = 2.25 - 0.00642Age - 1.89Length^{0.01} - 0.0302Bedding\_Factor - 0.0405Street\_Category - 0.000013(Diameter)^{0.3}(Depth)^4$$

In addition, the operational condition grade is also predicted. Pipe material, age, length, diameter, and bed slope contributed to the prediction of the operation of a pipe as shown in Equation 2-6 below. All four equations showed between 82% and 86% accuracy when applied to the given data set.

Equation 2-6 Operational Condition Prediction Model for ACP, RCP, and PVC

$$Operational\_Gade = \left(\frac{.308 + .567\left(\frac{Age}{Diam^n}\right)(Length)^{Slope}}{Age}\right)^{1/0.63}$$

2.5 MONTE CARLO SIMULATIONS AND ASSESSMENT MODELS

Monte Carlo Simulations (MCS) use many iterations and "brute-force" to solve probabilistic problems (Moss, 2013). They are often used to generate random numbers in order to obtain a specific probability distribution or for optimization. Uses for MCS will be discussed in assessment models.

With the help of MCS, Ruwanpura et al (2004) created a model to predict the Criticality Rating (CR). The CR has a range of integers between 1 and 5 from best to worst. Using the sewer network of Edmonton, Ruwanpura et al (2004) created a proactive approach to preventative sewer rehabilitation with three rule-based simulation models that predict the current CR, uses Markov Chains to predict transitional probabilities, and predicts the cost of maintenance or rehabilitation. Markov chains model the probability of a future event depending only on its current state. In this case, the probability that a pipe will degrade based on its current CR.

The first model predicts the current CR of a pipe based on pipe age, material type, and length. Using pipe age increments of 5 years, the Actual Probability of Existence (APE) is determined for each CR. Monte Carlo Simulations are then used to calculate the Simulated Probability of Existence (SPE), and the SPE are compared to the APE to determine the current CR of the pipe. A pipe is within a CR if the SPE is greater than the APE.

The second model uses Markov Chains to predict transitional probabilities of CR based on the APE. It is assumed a pipe can do one of two things: stay at the current CR or deteriorate to a higher CR. The small, 5-year age increment ensures that the pipe will not increase by more than one rating. Once the Actual Transitional Probabilities (ATP) are determined, MCS are used to

determine the Simulated Transitional Probability (STP). If the STP for a pipe to get worse is greater than the ATP for a pipe to get worse, then the model predicts the pipe will degrade.

The third model uses either the current CR from the first model or the future CR from the second model to estimate the costs of maintenance or rehabilitation. Only those pipes with a CR of four or five are in need of rehabilitation, according to the City of Edmonton. Monte Carlo Simulations use statistical, historical data to predict the cost of each rehabilitation technique based on the historic likelihood of occurrence. For this study, the cost of each rehabilitation technique has been simplified only to the length of the pipe in question. Table 2-1 shows the City of Edmonton's rehabilitation techniques and approximate historic costs as used in the MCS. This model yields an approximate cost of sewer rehabilitation with a confidence that will not exceed the cost. A confidence interval of 80% gives a 20% probability to exceed the budget. Combined, these three models would enable municipalities to effectively create a rehabilitation schedule as well as predict the associated monetary costs for sewer maintenance and rehabilitation.

Table 2-1 City of Edmonton Rehabilitation Techniques and Costs (Ruwanpura, Ariaratnam, & El-Assaly, 2004)

Method	Full reline	Spot reline	Open cut	Spot open cut	Tunnel
Percentage	67.44%	13.84%	12.69%	3.16%	2.87%
Cost/meter (Canadian $)	562.00	1812.00	1426.00	1812.00	4200.00

2.6 DETERMINATION OF RESIDUAL SERVICE LIFE FOR SEWER TYPES

Most states in Germany require yearly sewer inspections (Baur & Herz). This is a very expensive process that can be mitigated by predicting the Condition Class (CC) of pipes to determine

critical areas in the sewer system that are in need of inspection. The CC score ranges between 1 and 5 from best to worst condition. Baur and Herz (n.d.) created a method to determine transitional probabilities between pipe scores to find the residual service life of the pipes, and to schedule inspection dates based on data from the City of Dresden sewer infrastructure.

A deterioration model that predicts the service life within any single CC was used to rank the sewer pipes. The deterioration model utilized a transition function to model pipe deterioration as shown in Equation 2-7 below.

$$R(t) = (A+1)/(A+e^{B(t-C)}) \qquad \text{Equation 2-7}$$

The function, R(t), predicts the percentage of pipes that will stay in their current Condition Class from a given age, t, in years. A is the aging parameter that regulates the smoothness of transition in the function. B is a transition parameter in units of 1/year that accelerates the transition rate as B increases. C is resistance time to stay in a transition class in years. Figure 2-2 below shows the transition curves for produced from Equation 2-7 where the x-axis represents pipe age in years and the y-axis represents R(t). The “cc5 to cc4” curve reflects the steepest drop-off in transition percentage because pipes that are in the best condition at advanced ages are less likely to stay in their current condition. The “cc2 to cc1” curve reflects those pipes going into the worst CC because pipes that are already in bad condition are more likely to stay in the same condition.

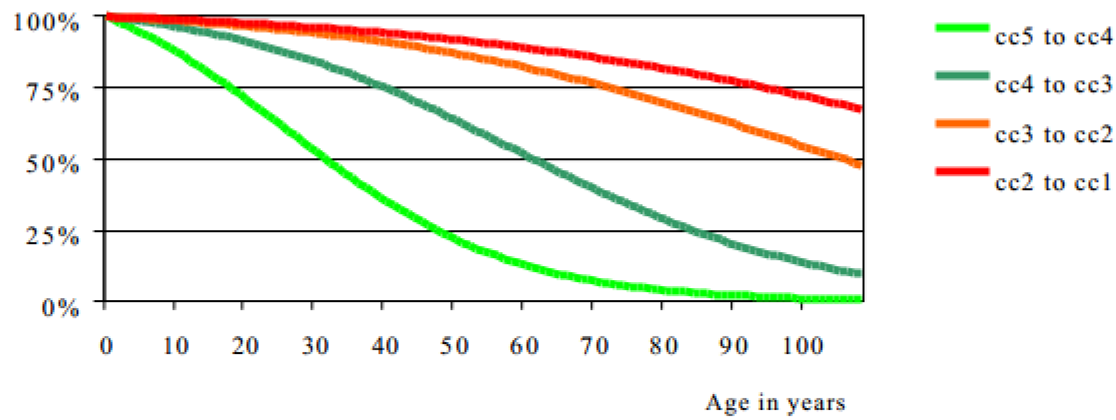


Figure 2-2 Transition Functions for the Dresden Sewer Sample (Baur & Herz)

The aging speed and residual service life can be found from the transition curves as shown in Figure 2-4 below. The residual service life refers to the number of years remaining until the sewer pipe reaches a CC of one, the worst condition rating possible with respect to the aging speed of the pipe. Once a pipe is inspected, the municipality can estimate the remaining life within a CC with Figure 2-3 by approximating the aging speed. The final step of any sewer system assessment involves the scheduling of inspection dates.

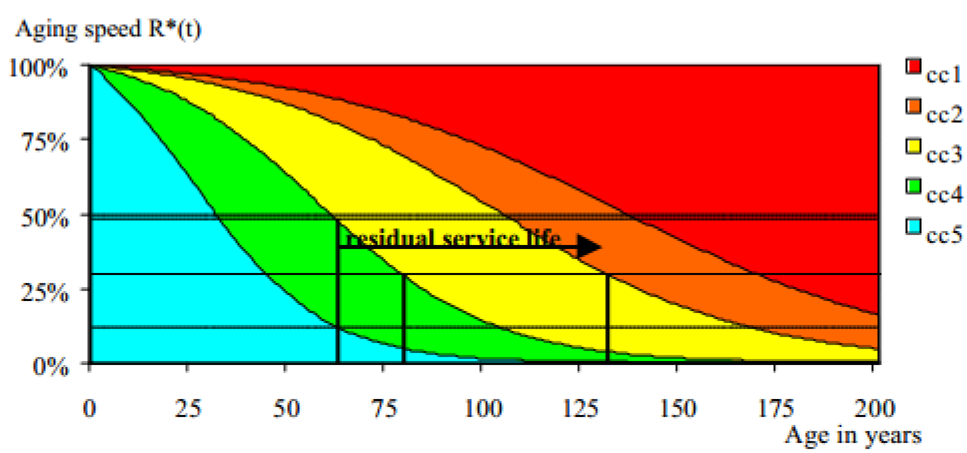


Figure 2-3 Aging Speed and Residual Service Life Estimate (Baur & Herz)

Additionally, Baur and Herz (n.d.) found that construction period, material type, function, type of pipe, pipe shape, gradient, and street category all affect the aging behavior of sewer pipes. Construction period refers to year of construction, i.e. the 1960's or 1980's. Different functions include wastewater, stormwater, or combined pipes. The type of pipe takes into account whether it is a feeder or main channel. Street categories include main streets and side streets as well as other streets in the City of Dresden. Analysis of these categories along with new inspection data will allow for better estimation of aging speed and inspection need (Baur & Herz).

2.7 RISK ANALYSIS OF SEWER ASSETS

All of the previously mentioned methods of sewer system assessment have acknowledged the failure methods and predictions of failure, but they have not considered the consequence of those failures. In an effort to perform a more complete evaluation, a risk assessment process is used to combine both the Likelihood of Failure (LOF) and the Consequence of Failure (COF). The Risk of Failure (ROF) can be simply defined as the multiplication of the LOF and COF as shown below in Equation 2-8 (Moss, 2013).

$$ROF = LOF * COF \qquad \text{Equation 2-8}$$

At its most basic form, the LOF measures the chance of a particularly defined failure to occur. The frequentist and Bayesian approaches have both been employed in previous studies to determine LOF. The frequentist approach requires a large number of data points, which is typically difficult to obtain in many real worldengineering applications. A good example that uses the frequentist approach is manufacturing engineering, where items are created in large quantities. On the other hand, the Bayesian or degree-of-belief approach does not rely on large data sets, but rather makes inferences for unique situations. This tends to be more common in areas where data is difficult and expensive to collect. The COF rating measures the effect of failure and can be

represented as a monetary, life-loss, or other defined scaling factor (Moss 2013). These consequences can include social, economic, and environmental effects in the aftermath of a pipe failure.

Nelson et al (2010) describes the process to evaluate sewer pipe and manhole condition assessment data. Their research addresses two main issues: sewer pipe prioritization and the risk-based approach to condition analysis (Nelson, Rowe, & Varghese, 2010). According to Nelson et al (2010), deterioration results from adjacent construction activities, weather, seismic ground movement, vandalism, and normal wear and tear.

The first step in a sewer system assessment is pipeline inspection to gather current condition data. Nelson et al (2010) utilized PACP data from inspections of the study's sewer system to effectively manage these assets. They collected condition data, determined the LOF and COF rating of manholes and sewer pipes, and determined the ROF. Based on the results of the assessment, four actions can result:

1) Do nothing
2) Clean and maintain
3) Structural repair
4) Rehabilitation

Next, the LOF rating and COF rating are scored. In order to obtain the LOF rating and COF rating, individual factors within both scores vary between one and five and then are summed together using a weighted scoring system similar to Equation 2-1 as stated previously.

Nelson et al (2010) determined that the LOF score is based on structural condition (40%), hydraulic capacity (40%), and maintenance factors (20%). They assigned these weighting coefficients based on professional judgement. The structural condition and maintenance scores

were determined using CCTV data analyzed using the Pipeline Assessment and Certification Program (PACP). See Section 2.2 for more information on the PACP methods. Hydraulic capacity was scored based on hydraulic analysis and predicted Inflow and Infiltration (I/I) rates. I/I refers to the amount of water that enters the pipe segment from groundwater or stormwater. Infiltration and Inflow (I/I) rates were combined to supplement the hydraulic analysis to determine the available design storm capacity within the pipe. Pipe segments that could carry larger storm events were given a less critical score (Nelson, Rowe, & Varghese, 2010).

Nelson et al (2010) also determined that the COF score is based on major users, community/environmental impact, service area, constructability, and critical crossing factors. Major users refer to hospitals, schools, and industrial areas. Community or environmental impact measures the impact associated with community health, safety, and environmental protection. Service area covers the impact of service disruption throughout a city, which was based on pipe diameter. Constructability deals with the amount of difficulty associated with replacing broken pipe segments, which was supplemented by land use, traffic, and geological data. Critical crossings encompass construction issues associated with fixing pipes across utilities, water ways, railroads, and major roadways (Nelson, Rowe, & Varghese, 2010).

In order to determine the ROF for a particular pipe, Nelson et al (2010) multiplied the LOF and COF together as previously shown in Equation 2-8. The resulting ROF can then be used by municipalities to prioritize rehabilitation efforts for their sewer system.

Salmon and Salem (2012) focused on the determination of COF and presented simple multiplication, matrix and fuzzy schemes to perform the risk analysis. In this study, the LOF values are determined from predictions or observations from sewer pipe structural degradation. The COF deals with factors that have economic, social, and environmental effects. Economic

factors included those factors that influence the operation, maintenance, and repair costs. Environmental factors referred to those issues that have the potential to affect the amount of sewage discharge and quality of aquatic life. Lastly, social factors apply to public inconveniences and traffic delays. In order to combine all these factors, a weighted scoring system was used to put more weight on factors that cause more monetary damage or appear in more than one category. Examples of each are shown below in Table 2-2 (Salmon & Salem, 2012).

Table 2-2 COF rating Categories and Examples (Salmon & Salem, 2012)

COF rating Categories	**Examples**
Economic	Pipe diameter, depth, number of laterals, building proximity, location relative to right-of-way, distance from force main, and proximity to railroad track.
Environmental	Proximity to water sources, pipe function, landslide potential, and distance from overflow locations.
Social	Roadway type, building type, distance from central business, distance from businesses, distance from recreational areas, and observations and/or public complaints.

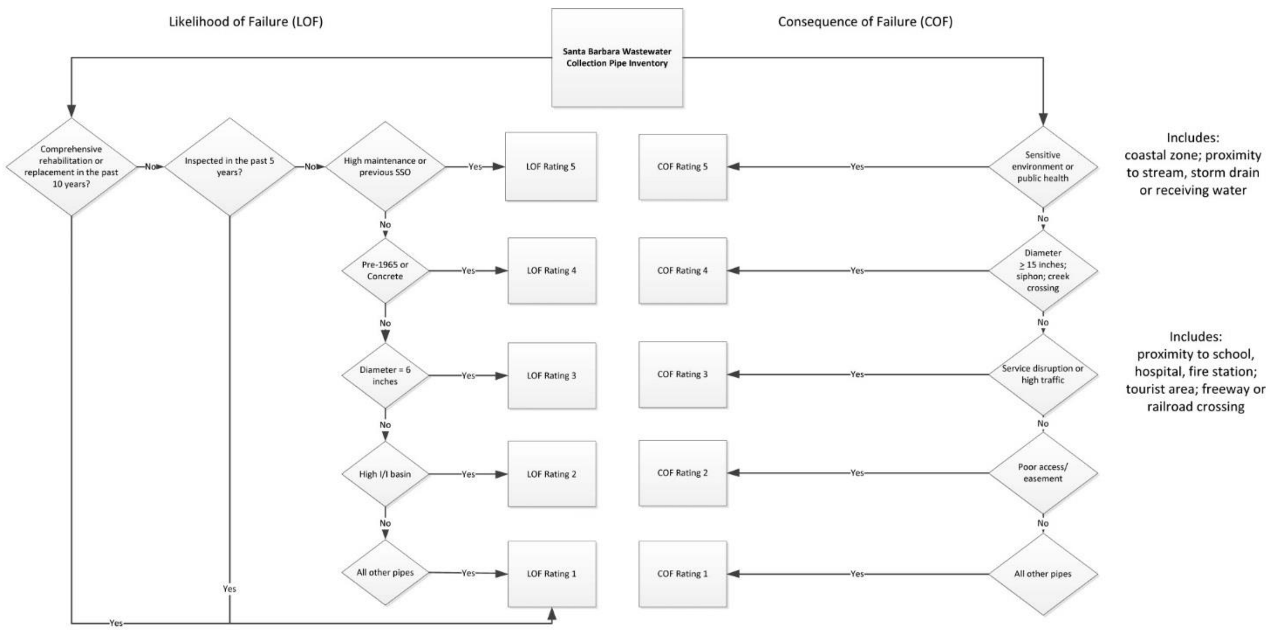
To combine both the LOF and COF scores Salmon and Salem (2012) used simple multiplication, risk matrices, and fuzzy inference systems. The multiplication scheme presented the total risk for each pipe, but could not differentiate between pipes with a small LOF and large COF from pipes with a large LOF and small COF. Risk matrices allow for different levels of risk from different combinations of LOF and COF. Fuzzy inference systems define different LOF and COF in linguistic terms and yield similar results to the risk matrices. According to Salmon and Salem (2012), fuzzy inference systems provide slightly better method compared to the matrices.

2.8 BROWN AND CALDWELL RISK ASSESSMENT

In response to the legal consent decree (Santa Barbara Channelkeeper, 2011), the City of Santa Barbara hired Brown and Caldwell to develop methodology to improve their inspection techniques. One particular aspect of the improvements created a risk assessment model to prioritize CCTV inspections. The City plans to completely inspect the entire network within ten years (Brown and Caldwell, 2012).

The risk assessment involved quantifying the LOF rating and the COF rating using a system of if-then statements as shown in Figure 2-4, on the next page. After both ratings were determined, they were multiplied together to find the risk score. A pipe with a risk score greater than or equal to 16 was included in the priority 1 inspection list. Those pipes with a priority of 1 need emergency repair and are at high risk of a Sanitary Sewer Overflow (SSO). Priorities 2 through 4 relate to decreasing levels of required maintenance. Pipes without a priority level are not in need of maintenance or repair.

The LOF rating was based on past rehabilitation or replacement and inspection, age, diameter, and Inflow and Infiltration (I/I) estimates as shown on the left half of Figure 2-4 on the next page. The COF rating was affected by sensitive environment or public health, pipe diameter, service disruption or high traffic as shown on the right half of Figure 2-4. The results of the LOF rating, COF rating, and risk score are displayed in Figure 2-5 through Figure 2-7 and were created in Geographic Information Systems (GIS). These results are used as a comparison for the results in this thesis.



Risk Score = LOF Rating x COF Rating

Risk Score ≥16: Include in Priority 1 Inspection List

Remaining pipes will be inspected by basin with the highest average basin risk score inspected first.

Figure 2-4 Risk-Based Prioritization for Initial CCTV Inspection

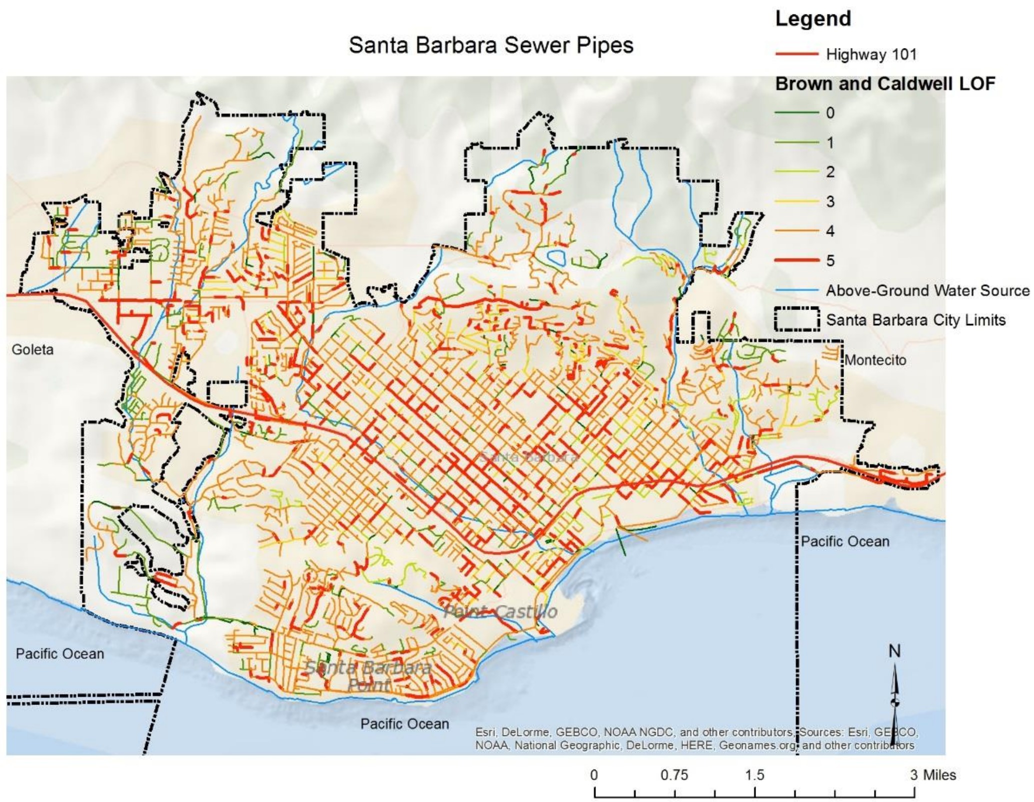


Figure 2-5 Brown and Caldwell Likelihood of Failure Results

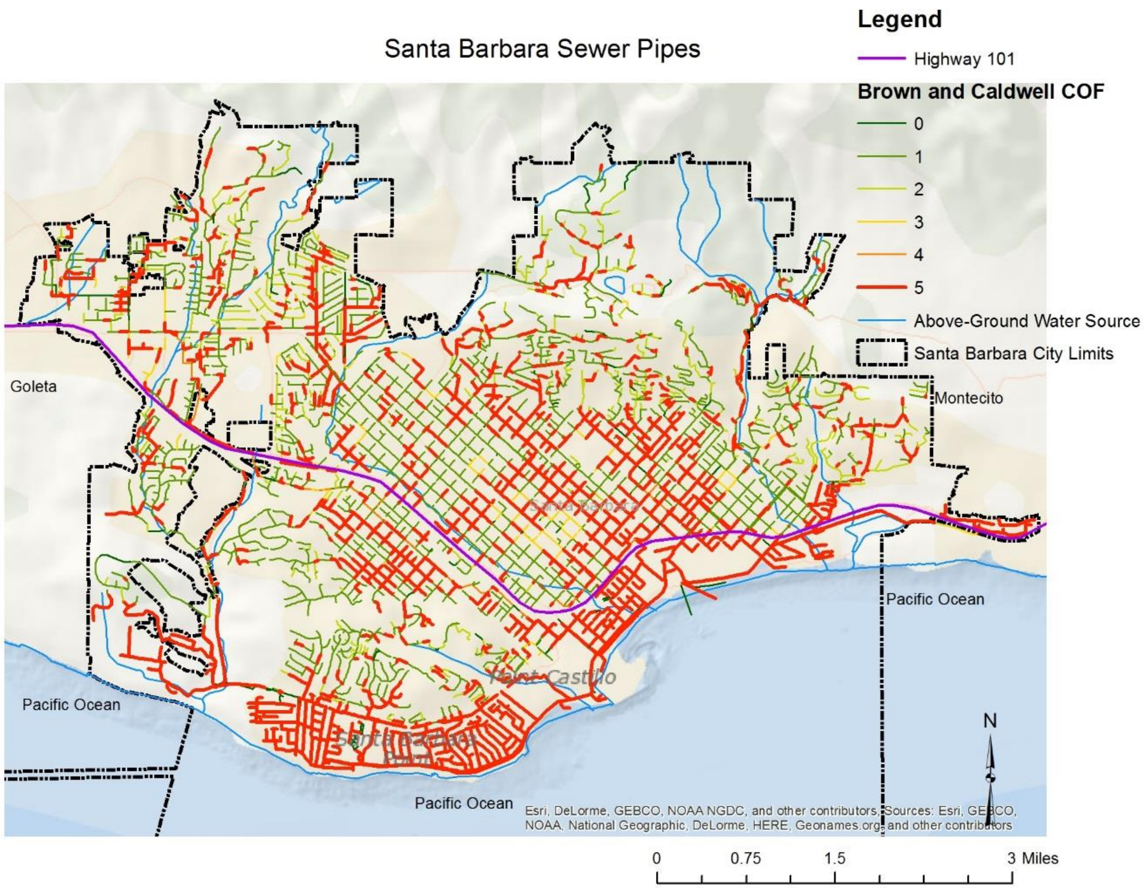


Figure 2-6 Brown and Caldwell Consequence of Failure Results

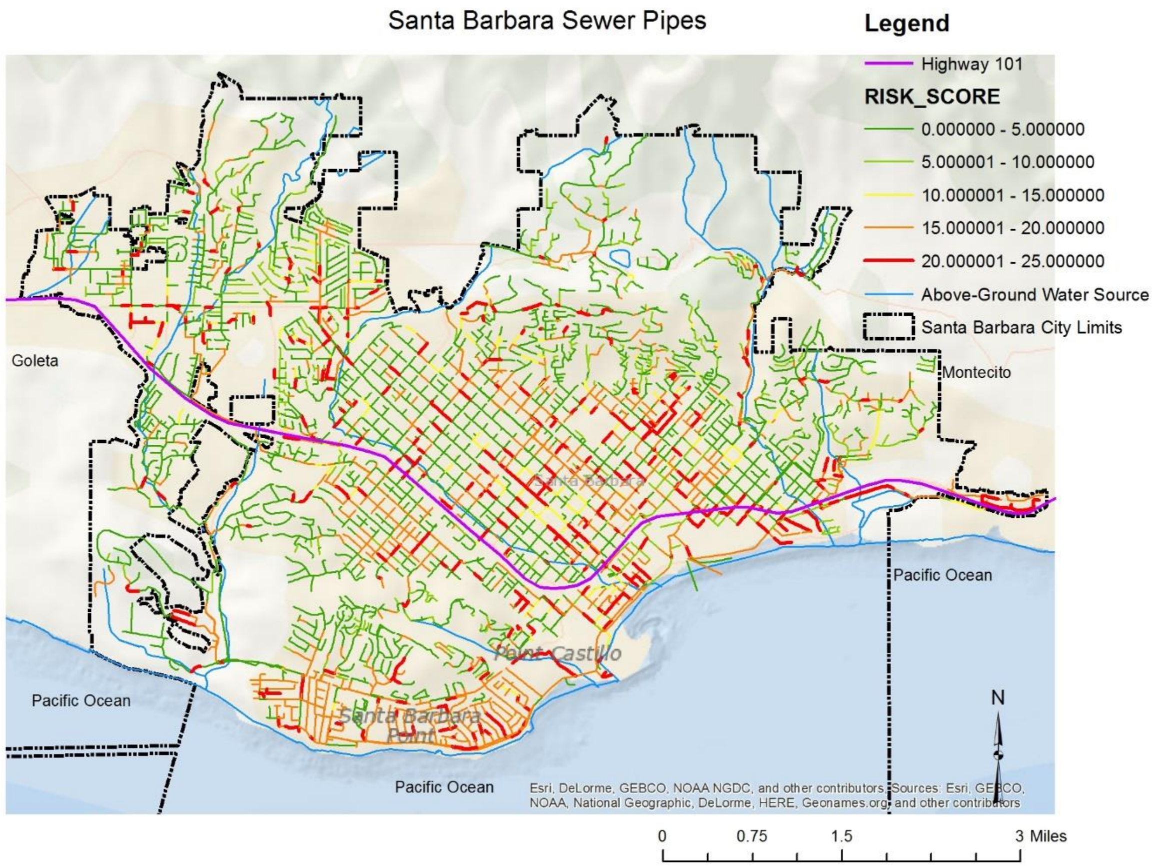


Figure 2-7 Brown and Caldwell Risk of Failure Result

CHAPTER 3 METHODOLOGY

This study develops a method that combines sewer pipe criticality assessment and consequence assessment to determine pipe risk. Ultimately, this allows pipes to be ranked based on their structural integrity, consequence, and risk in order to eventually develop a maintenance and rehabilitation schedule. This chapter is broken down into 5 main topics:

1) Tools
2) Data Acquisition
3) Sensitivity Analysis of Given Structural Integrity Score
4) Consequence Assessment
5) Risk Analysis

3.1 GENERAL SUMMARY

Risk of Failure (ROF) is composed of the Likelihood of Failure (LOF) and the Consequence of Failure (COF). For this reason, the sensitivity analysis and the COF rating assessment must be completed before the risk is calculated. The LOF rating and COF rating ratings are both based scores between 0 and 5, from best to worst condition. The LOF rating, COF rating, and ROF rating ratings were displayed in Geographic Information Systems (GIS).

This thesis uses a LOF rating that is determined from the sensitivity analysis. The sensitivity analysis uses six different factors with a weighted scoring system to predict pipe structural integrity. Using a program developed in the C-programming language, it compares the Predicted Score (PS) to the Pipeline Assessment and Certification Program (PACP) structural integrity scores for pipes with Closed Circuit Television (CCTV) data. The sensitivity analysis tested

twenty different scenarios, each with two cases. Only the scenario that best described the sewer system in the City of Santa Barbara (City) was used to calculate the LOF rating for all City pipes in GIS. The accuracy and precision of the scenarios for the sensitivity analysis also affected this choice.

The COF rating rating is made up of four factors that represent environmental, economic, and social impacts. Again, a weighted scoring scheme was used, but the weights or percentage factors for each of the four factors were based on judgement. The COF rating was calculated within GIS for all pipes.

The ROF rating rating is finally calculated by multiplying the LOF rating and COF rating ratings. Since both the LOF rating and COF rating is based on scores between 0 and 5, the ROF rating can have a range between 0 and 25. GIS displays the scores for all the pipes.

3.2 TOOLS

The analysis performed in this report involved the use of two software tools:

1) GIS
2) C-programming

GIS or Geographic Information Systems relies on collaboration to efficiently collect, organize, manage, analyze, communicate, and distribute geographic information (ESRI, 2014). It is developed by Environmental Systems Research Institute, Inc (ESRI). This software allows for analysis of spatial and numerical data with pattern recognition. One useful tool creates custom functions using “toolboxes” that allow groups of commands to be sequenced and repeated very

efficiently. This was utilized to create a tool to rapidly determine the distance of all the pipes from important locations. The toolboxes created for this project are included in Appendix A.

The data used for this project is made up of shapefiles that contain spatial data with tabular data attached to its components. Spatial objects have a geographic location on the x-y plane while tabular data refers to the information attributed to these spatial objects. This tabular data has rows and columns, like Microsoft Excel, and can include numerical data (i.e. invert elevations) or textual information (i.e. street names). Numerical data can be mathematically manipulated whereas textual information provides descriptions that differentiate between different objects.

There are many programming languages, including but not limited to C, C++, Java, and Visual Basic, that are available to create programs to execute repetitive mathematical calculations. The author specifically selected the C programming language in this thesis papeter to take advantage of prior experience. The program created in C quickly analyzed data within text files exported from GIS and was used in the sensitivity analysis of the criticality scores. The source code created for the programs in this study are presented in Appendices B and C. The files presented in the appendices have either a file extension of ".c" or ".h". The ".c" file extension designates a program written in the language of C that contains the body of the program. The ".h" file extension denotes header files that contain supplemental functions.

3.2.1 DATA ACQUISITION

The City of Santa Barbara boasts a population of approximately ninety thousand people. Out of the forty-three square miles of City area, twenty-two of those are on land and twenty-one are on water. Two hundred and fifty-three miles of sewer pipe are located within the City limits. A map of the City is located in Figure 3-1 on the next page.

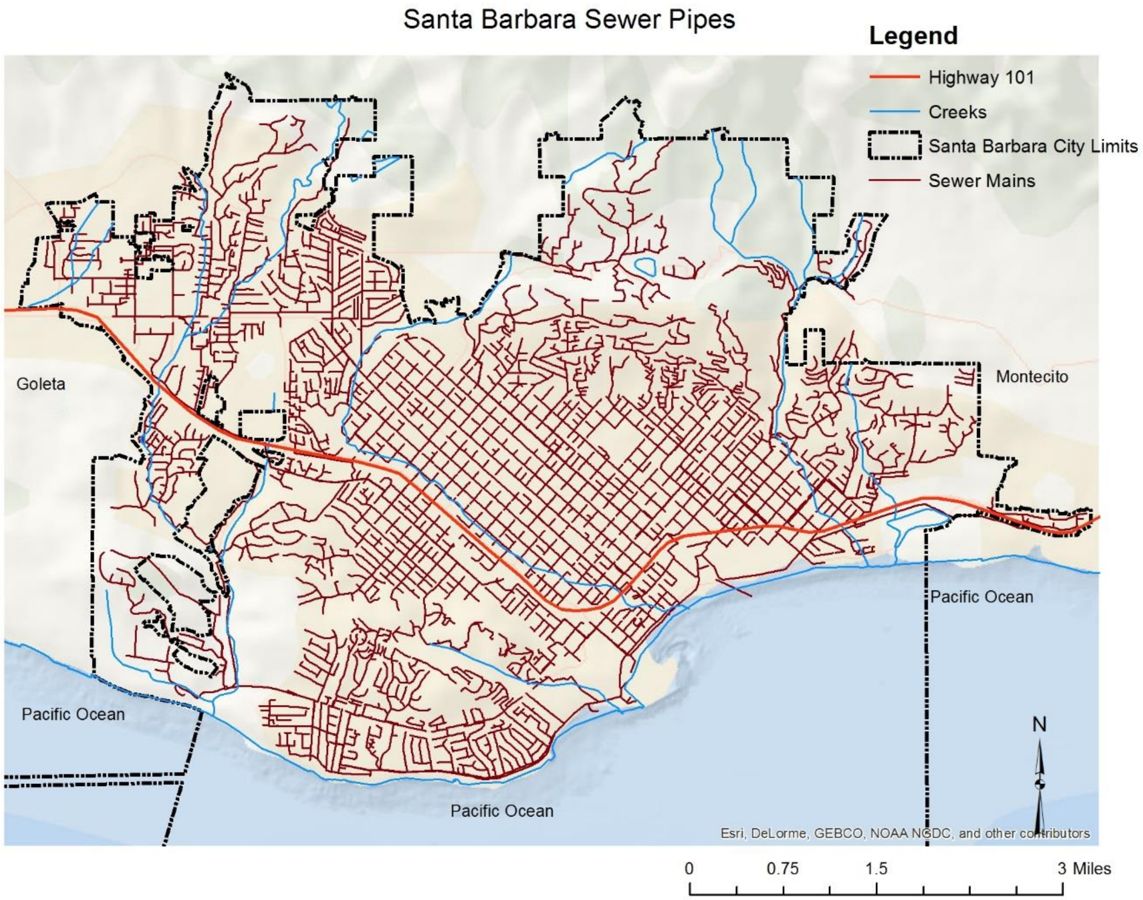


Figure 3-1 Santa Barbara Sewer Infrastructure

GIS files were acquired from the City of Santa Barbara that included sewer pipe data, restaurant locations, above ground water source locations, zoning districts, traffic counts, and critical infrastructure. Additionally, 932 valid PACP NASSCO scores from historic CCTV analysis were recorded in excel format. The breakdown of this data is discussed in the next chapter.

3.2.2 SEWER PIPE GIS FILE

The sewer pipe shapefile contains data on pipe material, length, diameter, upstream and downstream manhole names, upstream and downstream invert elevations, status, installation date, slope, and soil type. Table 3-1 below provides an example of the data from a sample pipe. This data was used throughout the criticality and consequence assessment. Figure D-1 in Appendix D highlights the available data used for the assessment.

Table 3-1 Example of Given Pipe Data

Parameter	Value
Material	VCP
Length	100 feet
Diameter	8 inches
Upstream Invert	187.78
Downstream Invert	186.17
Status	LIVE
Installation Date	1/1/1951
Slope	0
Soil Type	Clay

One problem encountered while checking the data for errors was that individual pipes did not always have information on pipe slope and invert elevations. In order to circumvent this problem, slope data was not used for the LOF rating assessment. Additionally, invert elevations were assumed for pipes with no pipe elevation data.

Pipe slope has been shown to have a profound effect on structural degradation of sewer pipes. However, the invert and rim elevations at manholes were incomplete which leads to unknown slope conditions. There are two opposing hypotheses regarding pipe slope in sewers. First, Chughtai and Zayad (2007) state that higher slopes cause higher velocities which in turn cause greater pipe erosion. Another explanation is that pipes with flatter slope will have a decreased flow velocity and subsequently reduced scour cleaning. This may lead to increased concentrations of hydrogen sulfide within the pipe, which can contribute to increased rates of pipe degradation. Equation 3-1 shows how to calculate the slope of a pipe segment given upstream and downstream invert elevations are required for all pipes to determine pipe slope.

$$\text{Slope} = \frac{\text{Invert}_{\text{up}} - \text{Invert}_{\text{down}}}{\text{Length}} \qquad \text{Equation 3-1}$$

3.2.3 RESTAURANT LOCATION GIS FILE

The restaurant location shapefile contains spatial data points. These points have information on the Assessor's Parcel Number (APN), restaurant name, street direction, street name, zip code, restaurant owner, and Fats, Oils, and Grease (FOG) interceptor installation status. The geographic location was used to determine the location of pipes relative to the restaurants throughout the City. This distance was used in the sensitivity analysis for the criticality scoring. See Figure D-2 in Appendix D for restaurant locations through the City.

3.2.4 ABOVE GROUND WATER SOURCE LOCATION GIS FILE

This GIS file contains lines that represent the location of above ground water sources including creeks, streams, and reservoirs. The boundary for the Pacific Ocean was added to model coastal

boundaries. This data was used as one of the variables for the sensitivity analsysis. See Figure D-3 in Appendix D for locations of above ground water source locations.

3.2.5 ZONING DISTRICTS GIS FILE

The zoning district shapefile consists of all the residential, agricultural, commercial, and industrial zones in the City. They were created using polygons as seen in the complete zoning map in Appendix E. The relative distance of pipes from commercial zones was used in the consequence assessment. The City of Santa Barbara zoning map is shown Figure D-4 of Appendix D.

3.2.6 TRAFFIC COUNT DATA

Traffic Count data from two sources was used. The first source was traffic counts from studies inside the City of Santa Barbara that had been saved as a GIS file. The second source was the California Department of Transportation (Caltrans), which provided traffic count data along US Highway 101 (California Department of Transportation, 2013). Both sources were combined into one GIS file to create the traffic density map discussed in both the sensitivity analysis of the criticality score and consequence assessment sections. Figure D-5 in Appendix D shows the City and Caltrans data collection locations.

3.2.7 NASSCO PACP CCTV SCORES

Reliable CCTV scores obtained from the City contained information on pipe identification, activity classification, the date of assessment, engineer who completed the analysis, maintenance score, structural score, and general notes. Pipe identification was used to import the structural score into the GIS shapefile for the City’s sewer assets.

The structural score is composed of a combination 4 numbers or letters, i.e. 544A. This score means that there were a total of 4 scores of 5 and ten scores of 4 throughout the length of the pipe. The letters that can occur in the second and fourth spot allow the rating to record more than 9 instances of a score. Also, only the top two scores are displayed with this naming convention.

The criticality scores are used to perform a sensitivity analsysis that predicts the structural integrity of pipe segments. The sensitivity analysis was done two different ways:

1) Prediction of only the higher, more critical score (Absolute)
2) Prediction of the weighted average of the top two scores (Average)

The absolute and average score for "544A" is shown below in Table 3-2.

Table 3-2 Calculation for Absolute and Average Score

	Calculation
Absolute Score	5
Average Score	[(5x4) + (4x10)] / (4+10) = 4.29

3.3 CRITICALITY SCORE SENSITIVITY ANALYSIS

Other studies of pipe criticality have assumed the factors and weights that most affect the structural deterioration or the Likelihood of Failure for pipes. These assumptions are a good place to start an assessment if inspection data is unavailable. When CCTV data is available, a sensitivity analysis allows for an accurate determination of structural deterioration or maintenance scores.

The analysis in this paper used a linear weighting method similar to the Weighted Impact Rating developed by McDonald and Zhao (2001) in Equation 2-1 to predict pipe criticality. Pipe

criticality relates to the Likelihood of Failure (LOF) as the first parameter in the risk equation. The LOF rating is based on the quantitative assessment of physical and derived factors.

The process to determine which factors affect pipe criticality or structural deterioration consists of three main steps. First, research on available data from the City of Santa Barbara was combined to create a list of testing variables. This thesis determined that six different parameters had the most influence as shown in Table 3-3 below.

Table 3-3 Testing Parameters

Number	**Factor**
1	Pipe Material and Age/Installation Date
2	Distance from Restaurants
3	Distance from any above-ground water source
4	Pipe Depth below the Ground Surface
5	Pipe Length
6	Amount of Vehicular Traffic

Second, a scoring system was created for each of these testing parameters. Each pipe was scored based on the six properties, and these results were tabulated and saved. All pipes were scored between values of zero and five similar to the PACP scores. The scoring system used throughout the analysis is described in Table 3-4 below. The scoring criteria for each of the six factors above are summarized in the next sections 3.3.1 through 3.3.7.

Table 3-4 Scoring System

Score	Condition
0	Best
1	Very Good
2	Good
3	Ok
4	Bad
5	Worst

Third, all possible weighting combinations for all six variables were tested to determine each factor's impact. The weights varied between 0.00 and 1.00. Equation 2-1 is an example of how the degree of impact and scoring factors are combined to find the "Weighted Impact Rating" (McDonald & Zhao, 2001). A weighted value of zero (0.00) means that a variable has no effect, or 0%, on the Criticality Score. On the other extreme, a weighted value of one (1.00) shows that a single factor will predict 100% of the Criticality Score. This system is explained in more depth in section 3.3.7.

3.3.1 PIPE MATERIAL AND AGE

Pipe inspection and installation dates were used to determine the age of the pipe at inspection. Pipe material service life was used to normalize the scores because pipe materials have different estimated lifespans. In general, as a pipe ages, it has a higher likelihood to be in a more critical state and will therefore be assigned a higher score. Pipe materials encountered in the dataset, associated estimated lifespan, and corresponding scores are shown in Table 3-5 below. The sources used in Table 3-5 specifically refer to sewer pipe use and take into account pipe corrosion from interaction with sewage material. See Figure D-6 in Appendix D to visually see the pipe scoring throughout the City. Figure D-7 shows the location of all pipe material.

Table 3-5 Material Scoring

Material	Estimated Lifespan (years)	Score					
		0	1	2	3	4	5
Cast Iron[1]	75-100	0-12.50	12.51-25.00	25.01-37.50	37.51-50.00	50.01-62.50	62.51-75.00
Polyvinyl Chloride[2]	70	0-11.67	11.68-23.33	23.34-35.00	35.01-46.67	46.68-58.33	58.34-70.00
Ductile Iron[2]	60	0-10.00	10.00-20.00	20.01-30.00	30.01-40.00	40.01-50.00	50.01-60.00
Reinforced Concrete[2]	65	0-10.83	10.84-21.67	21.68-32.50	32.51-43.33	43.34-54.17	54.18-65.00
Steel[2]	85	0-14.17	14.18-28.33	28.34-42.50	42.51-56.67	56.68-70.83	70.84-85.00
Polyethylene[3]	50-100	0-12.50	12.5-25.00	25.01-37.50	37.51-50.00	50.01-62.50	62.51-75.00
Vitrified Clay[4]	100	0-16.67	16.68-33.33	33.34-50.00	50.01-66.67	66.68-83.33	83.34-100.00

Estimated Lifespan in Table 3-5 sourced from [1] (PS Inspection & Property Services LLC, 2011), [2] (American Water Works Association), [3] (Connectra Fusion Technologies, LLC), and [4] (National Clay Pipe Institute).

3.3.2 DISTANCE FROM RESTAURANTS

Keener et al (2008) found evidence from sanitary sewer personnel suggesting that deposits of Fats, Oils, and Grease (FOG) form between 50 and 200 meters away from restaurants. These deposits can form blockages in as little as 30 days or up to two years and can lead to Sanitary Sewer Overflows (SSO) that result in flooding of public streets and the spread of potent odors and increased health risk. Table 3-6 shows that pipes closer to restaurants will be assigned a higher criticality score for the sensitivity analysis.

Table 3-6 Restaurant Scoring

Score	Distance (feet)
0	5,501+
1	4,401-5,500
2	3,301-4,400
3	2,201-3,300
4	1,101-2,200
5	0-1,100

Instead of following the distances as prescribed by Keener et al (2008), the breakdown for scoring was instead determined using information directly from the City of Santa Barbara. The data shows that pipes were at a maximum of 9,018 feet from any restaurant. Because the vast majority of pipes were between 0 and 5,500 feet away from restaurants, the maximum distance considered for a score of 1 was set to 5,500 feet. This yields 5 equal intervals of 1,100 feet for scores between 1 and 5. Figure D-8 in Appendix D shows the pipe scoring based on distance from restaurants.

3.3.3 DISTANCE FROM AN ABOVE-GROUND WATER BODY

Typically, the ground water elevation rises near above ground water bodies, which can lead to increased Inflow and Infiltration (I/I) for sewer pipes in close proximity to them.
Table 3-7 summarizes the scoring for the location of pipes with respect to distance from an above ground water source. The scores were divided into six equal distance intervals with those pipes closest to any water source being assigned a more critical score. A range of 889 feet for each score was used as shown in the table below because the pipes ranged between zero and 5,335 feet. Figure D-9 in Appendix D shows the scoring for the distance from an above-ground water source.

Table 3-7 Scoring of Distance from Water Source

Score	Distance (feet)
0	4,447+
1	3,558-4,446
2	2,669-3,557
3	1,779-2,668
4	890-1,778
5	0-889

3.3.4 PIPE DEPTH BELOW SURFACE

The pipe invert is a measure of the flowline elevation of a sewer pipe where it connects to its corresponding manhole. For the purpose of this investigation, the manhole rim was considered to be located at the ground elevation. Pipe depth is defined as the difference between manhole rim elevation and the invert elevation.

Pipes that are located closer to the surface are assigned a higher score due to the effects of dynamic loading from the volume of traffic from the street above. Additionally, pipes that are buried deeper are also assigned higher scores, due to increased soil pressure associated with the increased depth of cover. Not all of the pipes at the time of this analysis had data for upstream and downstream invert elvations as well as manhole rim elevations. In order to compensate for the missing data, the average depth of cover was determined. The average depth to the invert corresponded to 7.25 feet. Table 3-8 summarizes the scoring for pipe depth. See Figure D-10 in Appendix D for the GIS map for pipe depth scoring.

Table 3-8 Pipe Depth Scoring

Score	Lower Range (feet)	Upper Range (feet)
0	10.0-11.0	
1	8.5-10.0	11.0-12.5
2	7.0-8.5	12.5-14.0
3	5.5-7.0	14.0-15.5
4	4.0-5.5	15.5-17.0
5	0.0-4.0	17.0+

3.3.5 PIPE LENGTH

Pipe length refers to the length of pipe between manholes. According to Chughtai and Zayed (2007), longer pipes are more likely to be affected by bending stresses that can reduce the structural integrity of the pipe. Longer pipes are assigned a higher score as shown in Table 3-9 below. See Figure D-11 in Appendix D for pipe length scoring.

Table 3-9 Length Scoring

Score	Length (feet)
0	0-120
1	120-207
2	207-302
3	302-423
4	423-500
5	500+

3.3.6 VEHICULAR TRAFFIC

Traffic volume is important to pipe networks because streets with more traffic, which can lead to greater structural deterioration due to increased cyclical loading. Traffic counts for City streets were obtained from the City in the form of a shapefile in GIS while traffic counts for US

Highway 101 exits were obtained from the website of Division of Traffic Operations, State of California (Caltrans) and imported into to GIS. The data used to develop a traffic flow map is shown in Appendix D. Table 3-10 below shows that the LOF rating score increases as the Average Annual Daily Traffic Volume (AADTV) increases.

Table 3-10 Traffic Volume Scoring

Score	AADTV
0	0-21,931
1	21,932-43,861
2	43,862-65,792
3	65,793-87,722
4	87,723-109,653
5	109,654+

GIS was used to determine the vehicular traffic score through five main steps (see Figure D-12 through Figure D-16 in Appendix D):

1) Create a shapefile that includes City traffic data, already in GIS format, and Caltrans traffic counts along US Highway 101 within City limits. The City data contains counts inside the City while Caltrans data shows traffic counts near exits on the highway. The resulting combined shapefile contains points that have a spatial location as well as a numerical value for daily traffic counts. Additional points were interpolated on the highway between Caltrans data points at exits to develop a more accurate traffic flow map. Refer to Figure D-12.
2) Interpolate the data points in GIS by using the “Natural Neighbor” tool. This creates a raster map of traffic counts. Raster datasets characterize geographic features by dividing the area into discrete rectangular cells. In this case, each cell has a value that shows the interpolated traffic count at that location. Refer to Figure D-13.
3) Next, use the GIS “Reclassify” tool to replace the value within raster map cells with the scoring system shown in Table 3-10 above. Refer to Figure D-14.

4) Create polygons from the raster map using the "Raster to Polygon" tool in GIS. This tool creates a polygonal outline around adjacent raster cells of the same score. Refer to Figure D-15.
5) Starting with the polygons corresponding to the lowest score, zero, use "Select by Location" to select pipes within each polygon and assign the appropriate score until all pipes have been processed. It is important to note that you must assign scores from the best scenario to the worst scenario so that those pipes on the border between two different scores will receive the higher score. Refer to Figure D-16.

3.3.7 SCORING SYSTEM

In order to predict pipe scores, a weighted scoring system was used as shown below in Equation 3-2 below.

$$PS = \sum_{i=1}^{N} (\lambda_i * S_i) \qquad \text{Equation 3-2}$$

It uses a simple linear model with normalized scores between zero and five. The variable, i, refers to the factor number, corresponding to the factor number in Table 3-3. The variable, N, refers to the total number of factors from Table 3-3. This equation determines the Predicted Score (PS) by multiplying all the percentage factors (λ_i) and the corresponding scores (S_i) together, then taking their sum. Individual weights range from zero (0.00) to one (1.00) and total to one (1.00) as shown in Equation 3-3 below and correspond to the relative impact on the total PS.

$$\sum_{i=1}^{N} \lambda_i = 1 \qquad \text{Equation 3-3}$$

The sensitivity analysis has 4 main steps:

1) Determines the individual pipe scores for all the factors

2) Determines values for λ, uses the values for λ to determine the PS
3) Compares the PS of all known pipes to the given structural criticality scores
4) Goes to the next case for all λ until the best case is determined.

In order to compare the difference between the PS and Given Score (GS), the first, second, and third quartiles of the differences were calculated. The GS refers to the structural score from the CCTV assessment with PACP results as explained in Section 3.2.6. This sensitivity analysis uses the median to measures the accuracy of the differences. The median refers to the value that lies at 50% of the total data set. The difference between the first and third quartile value, the interquartile range, measures the data precision by determining the values that lie between 25% and 75% of the data. Averages and standard deviations cannot be relied on because data for the differences did not follow a normal distribution and were frequently skewed to the left or right (Wade & Koutoumanou, 2010).

The sensitivity analysis uses 20 different scenarios to thoroughly test the effect the different factors from Table 3-3 have on the pipe network. These scenarios which are shown below in Table 3-11, have two cases: absolute and average scoring methods. The scenarios include pipe data based on the given structural integrity score and material type. For example, scenario one determines the most accurate and precise relative weights (λ_i) for each of the factors for all pipes with a given structural score of zero. Scenario 19 determines the most accurate and precise important factors for VCP with scores between three through five. Scenario 19 does not include those pipes that have been scored with 2 or below.

Table 3-11 Sensitivity Analysis Scenarios

Scenario	Score	Materials
1	0	All
2	1	All
3	2	All
4	3	All
5	4	All
6	5	All
7	0	VCP
8	1	VCP
9	2	VCP
10	3	VCP
11	4	VCP
12	5	VCP
13	0-5	All
14	1-5	All
15	3-5	All
16	4-5	All
17	0-5	VCP
18	1-5	VCP
19	3-5	VCP
20	4-5	VCP

This process determines the best combination of factors that most accurately and precisely predict structural integrity of sewer pipes for a given scenario. This follows the computer code in Appendix B and Appendix C. The process is expanded below:

1) Isolate pipes that have complete PACP CCTV structural integrity scores and organize by the six different categories as shown in Table 3-3.
2) Use the scoring table found in each factor's respective section to rate each category and assign their corresponding scores (S). More factors can be included given available data.
3) Start with scenario one.
4) Assign the values for all six percentage factors (λ). Each λ must be between zero (0.00) and one (1.00) such that the total of all λ sum to one (1.00).

5) Calculate the PS for all pipes with Equation 3-2 using the current combination of λ_i and S_i.
6) For each pipe, compare the PS to the given criticality score by calculating the difference between the two values. Once all the differences have been calculated, determine the first quartile, median, and third quartile for the data.
7) Next, compare the accuracy and the precision of the current data set (from step 6) with that of the current best data set. The median, or second quartile, demonstrates the accuracy while the difference between the first and third quartiles, expresses the precision of the data. If the median is less than the current best median and the difference between the first and third quartile is also less than the current best range, the current values are saved as the best values. Additionally, the corresponding λ are saved.
8) Repeat steps four through seven until all combinations of λ have been tested. These iterated combinations of λ result in the most accurate and precise PS. Record these combinations of λ and the associated quartile values.
9) Repeat steps four through eight until all scenarios as shown in Table 3-11 have been tested.

After all 20 scenarios have been completed, record the resulting best combinations of λ and determine which cases best represents the criticality of the pipes within GIS. Those cases that are more precise and accurate are those that best represent pipe criticality. When the case that best represents the City's sewer assets is chosen, it is then applied to all the pipes within GIS to create a color-coded LOF rating map.

3.4 CONSEQUENCE ASSESSMENT

The consequence assessment is composed of four different scoring criteria. These include pipe diameter, distance from commercial zones, distance from critical infrastructure, and vehicular traffic. They make up environmental, economic, and social consequences to pipe failure.

3.4.1 PIPE DIAMETER

For this study, pipe diameter was used to approximate the flow through sewer pipes. Smaller pipes have less capacity when compared to larger pipes. If a pipe breaks and releases waste into the groundwater, larger pipes will have a greater potential environmental consequence due to its greater maximum capacity. Table 3-12 below shows the scoring breakdown for pipe diameter. Each score was simply divided into six equal intervals. See Figure D-17 in Appendix D for the pipe diameter scoring GIS map.

Table 3-12 Pipe Diameter Scoring

Score	Pipe Diameter (inches)
0	0-6
1	7-13
2	14-20
3	21-26
4	27-33
5	34-42

3.4.2 DISTANCE FROM COMMERCIAL ZONES

Cities contain various types of land use zones. Divisions include residential, agricultural, commercial, and industrial. The City of Santa Barbara has six different commercial districts that include Limited Commercial (C-1), Commercial (C-2), Limited Commercial (C-3), Commercial

Manufacturing (C-M), Restricted Commercial (C-P), and Harbor Commercial (H-C). To some extent each of these zones have stores and services that are vital to the City's continued success.

It was determined that the maximum distance of sewer pipes from any commercial zone was 6,000 feet, therefore, the scores were determined with equal intervals of 1000 feet for scores between 0 and 5. Those pipes farther away from the business sector of the City received a lower score because they would have less impact on daily business in the case of a pipe failure as shown in Table 3-13 below. See Figure D-18 in Appendix D for the GIS map for the distance from commercial zones pipe scoring.

Table 3-13 Scoring for Distance from Commercial Zones

Score	Distance (feet)
5	0-1000
4	1001-2000
3	2001-3000
2	3001-4000
1	4001-5000
0	5001+

3.4.3 DISTANCE FROM CRITICAL INFRASTRUCTURE

Distance from critical infranstructure is one of the factors that encompasses social concerns throughout the City. Here, critical infrastructure is defined as emergency services and schools. Critical emergency services are defined by Homeland Security to include law enforcement, fire and emergency services, emergency management, and emergency medical services (2014). Pipe breaks and subsequent repairs could impede the City's ability to respond to incidents. In addition, school locations were included to take into account large public meeting areas that could be negatively affected.

In order to determine locations for the critical infrastructure the City's mapping site and google maps were used to create a shapefile within GIS that included locations for the police station, fire stations, and emergency medical service providers. Table 3-14 below shows the scoring breakdown for the distance from critical infrastructure. Pipes that are closer to critical infrastructure receive a higher, more critical score. It was found that the greatest distance to any pipe was 10,000 feet and the scoring was determined based on 6 equal intervals. Refer to Figure D-19 in Appendix D for the distance from critical infrastructure scoring map.

Table 3-14 Scoring for Distance from Critical Infrastructure

Score	**Distance (feet)**
5	0-1667
4	1668-3333
3	3334-5000
2	5001-6667
1	6668-8333
0	8334+

3.4.4 VEHICULAR TRAFFIC

Traffic volume was also used for the consequence assessment. Like the distance from critical infrastructure, this is also a social concern. If a pipe needs maintenance or replacement and is located in an area of the City with much traffic, it will affect many people. Those pipes that are in areas of higher annual average daily traffic flows received a higher more critical score. The same scoring system is used as in Table 3-10. Refer to Figure D-16 in Appendix D for the vehicular traffic scoring map.

3.5 RISK ANALYSIS

The concept of risk encompasses the Likelihood of Failure (LOF) as well as the consequence of Failure (COF). As shown in Equation 2-8 in the Literature Review, it is most simply the multiplication between these two values. In the first chapter, Salmon and Salem (2012) use simple multiplication, risk matrices, and fuzzy inference systems to determine the risk of failure. For this analysis, the simplified multiplication method was used because both the LOF rating and COF rating values were saved within GIS.

The Likelihood of Failure (LOF) is often estimated in most engineering problems and requires a definition for the meaning of failure. For the analysis, it was simply defined as the predicted LOF rating since it measures the structural deterioration within a pipe. When there is greater structural deterioration and a pipe receives a more critical score, it has a higher LOF rating. These scores range from zero to a maximum of 5 as shown in

Table 3-4, which describes the scoring method used throughout all the analyses.

Usually consequence refers to some monetary loss or life loss (Moss, 2013). This is often very difficult to predict, so the Consequence of Failure (COF) value was also measured like the LOF rating ranked between values of zero and five. Equation 3-4 below is a simplified version of Equation 2-8. Equation 3-4 multiplies the LOF rating and COF rating together. GIS can then use the predicted LOF rating, COF rating, and risk score for each pipe to create maps that show the most critical pipes. It will be beneficial to review current maintenance schedules and to determine pipes that need CCTV inspection.

$$\text{Risk} = (\text{LOF}) \times (\text{COF}) \qquad \text{Equation 3-4}$$

CHAPTER 4 RESULTS

This chapter will discuss the results of the analyses described in chapter 3 and has four main responsibilities:

1) Provide statistical analysis of City data
2) Provide results of the sensitivity analysis
3) Provide results for consequence assessment
4) Provide results for risk assessment

4.1 DATA DISTRIBUTION

932 out of the 6,310 or about fifteen percent of all City of Santa Barbara (City) sewer pipes had Closed Circuit Television (CCTV) data. This data consisted of structural condition and maintenance scores as explained in Section 3.2.7 on page 36. The sensitivity analysis in this thesis focuses on using the structural condition score and physical and spatial pipe characteristics.

In general, typical samples were not collected for each of the six categories as shown in Table 3-3. More data for pipe material and age, distance from restaurants, pipe depth, and pipe length needed to be collected. Table F-1 and Table F-2 in Appendix F show that the collected data for the distance from Above-Ground Water Source and Traffic Volume have typical distributions when compared to the whole sewer network. Table F-6 shows the sample size for each pipe score.

4.1.1 PIPE MATERIAL AND AGE DATA COLLECTION

More data on PVC pipes need to be collected to obtain a more representative sample. The original collected data has only 6.01% Polyvinyl Chloride (PVC) pipes as compared to the 20.33% that is

in the whole system. Collecting additional data will increase the percentage of PVC material in the collected data and substantially decrease the percentage of Vitrified Clay Pipe material. Table 4-1 below compares the distribution of pipe material data in the total system to that of the dataset.

Table 4-1 Pipe Material Data Distribution

Pipe Material				
Type	Total Count	Total Percent	Data Count	Data Percent
CAS	50	0.63	2	0.21
DIP	26	0.25	0	0.00
PE	62	0.82	3	0.32
PVC	1304	20.33	56	6.01
RCP	20	0.16	3	0.32
SP	14	0.06	0	0.00
VCP	5008	77.62	868	93.13
Σ	6310	100.00	932	100.00

In addition to material data, more pipe age data for years between 0 and 40 years needs to be collected. This will increase the percentage of data between 0 and 40 years while decreasing the percentage of data between 80 and 120 year old pipes. See Table 4-2 on the next page.

Table 4-2 Pipe Age Data Distribution

Pipe Age				
Age (Years)	Total Count	Total Percent	Data Count	Data Percent
0-20	539	8.54	35	3.76
20-40	829	13.14	55	5.90
40-60	2144	33.98	305	32.73
60-80	946	14.99	156	16.74
80-100	1484	23.52	314	33.69
100-120	290	4.60	67	7.19
120-140	4	0.06	0	0.00
	6310	100.00	932	100.00

4.1.2 DISTANCE FROM RESTAURANTS DATA COLLECTION

Data for the distance from restaurant data needs more data in the areas with red font in order to counteract the excess data in green font in Table 4-3 below.

Table 4-3 Pipe Restaurant Distance Data Distribution

Distance from Restaurants				
Distance (ft)	Total Count	Total Percent	Data Count	Data Percent
0-1000	2266	35.91	453	48.61
1000-2000	1637	25.94	237	25.43
2000-3000	1289	20.43	138	14.81
3000-4000	713	11.30	77	8.26
4000-5000	204	3.23	16	1.72
5000-6000	78	1.24	2	0.21
6000-7000	88	1.39	9	0.97
7000-8000	22	0.35	0	0.00
8000-9000	13	0.21	0	0.00
Σ	6310	100.00	932	100.00

4.1.3 PIPE DEPTH DATA COLLECTION

As mentioned in Section 3.3.4, many of the sewer pipes were given the pipe depth value of 7.25 feet based on the average pipe depth throughout the whole City system. In order to accurately represent this parameter, manhole invert and lid elevations would need collection for the rest of the pipes. See

Table 4-4 below for the distribution of pipe depth data. Table 4-5 on the next page shows the distribution of pipe lengths in the collected City data. More data should be collected for those areas that are in red to compensate for the extra data in green.

Table 4-4 Pipe Depth Data Distribution

Pipe Depth				
Depth (ft)	Total Count	Total Percent	Data Count	Data Percent
0-5	553	8.76	178	19.10
5-10	5391	85.44	640	68.67
10-15	269	4.26	81	8.69
15-20	72	1.14	25	2.68
20-25	25	0.40	8	0.86
Σ	6310	100.00	932	100.00

Table 4-5 below shows the distribution of pipe lengths in the collected City data. More data should be collected for those areas that are in red to compensate for the extra data in green.

Table 4-5 Pipe Length Data Distribution

Pipe Length				
Length (ft)	Total Count	Total Percent	Data Count	Data Percent
0-150	2259	35.80	249	26.72
150-300	2630	41.68	396	42.49
300-450	1056	16.74	201	21.57
450-600	350	5.55	81	8.69
600-750	7	0.11	5	0.54
750-900	2	0.03	0	0.00
>900	6	0.10	0	0.00
Σ	6310	100.00	932	100.00

4.2 SENSITIVITY ANALYSIS

The criticality or sensitivity analysis determined the factors that have the most influence on the twenty different scenarios as presented in Table 3-11. Each scenario tested two cases: the absolute and average scores. The results from the sensitivity analysis are shown in Table F-3 in

Appendix F. Table F-3 shows the first, second, and third quartiles of the of the difference between the Predicted Score and the Given Score as well as the percentage factors that are associated with the each of the factors shown in Table 3-3.

Scenario #15 of the scenarios that predicts scores 3 through 5 for all materials was applied in GIS to predict the LOF rating because it predicts those pipes that are most critical (scores of 5) as well as those pipes that are in the process of deteriorating (scores of 3). This scenario predicted scores of 3-5 with a median value of 0 and an interquartile range of 1.27. The first quartile value was -0.67, and the third quartile value was 0.60. A positive value for the quartile values means that the given criticality score was over-predicted (i.e. a GS of a 3 was predicted as a 5). Scenario #18 predicted that material and age, pipe depth, traffic volume, and distance from an above-ground water source impacted the Criticality Score with percentage factors (λ) of 45%, 20%, 10%, and 25%, respectively. This combination of λ was then applied to the whole pipe network in GIS as shown in Figure 4-1 on the next page to display the LOF rating results. Figure 4-2 shows the accuracy and precision for scenarios 17 through 20 on a box and whisker plot.

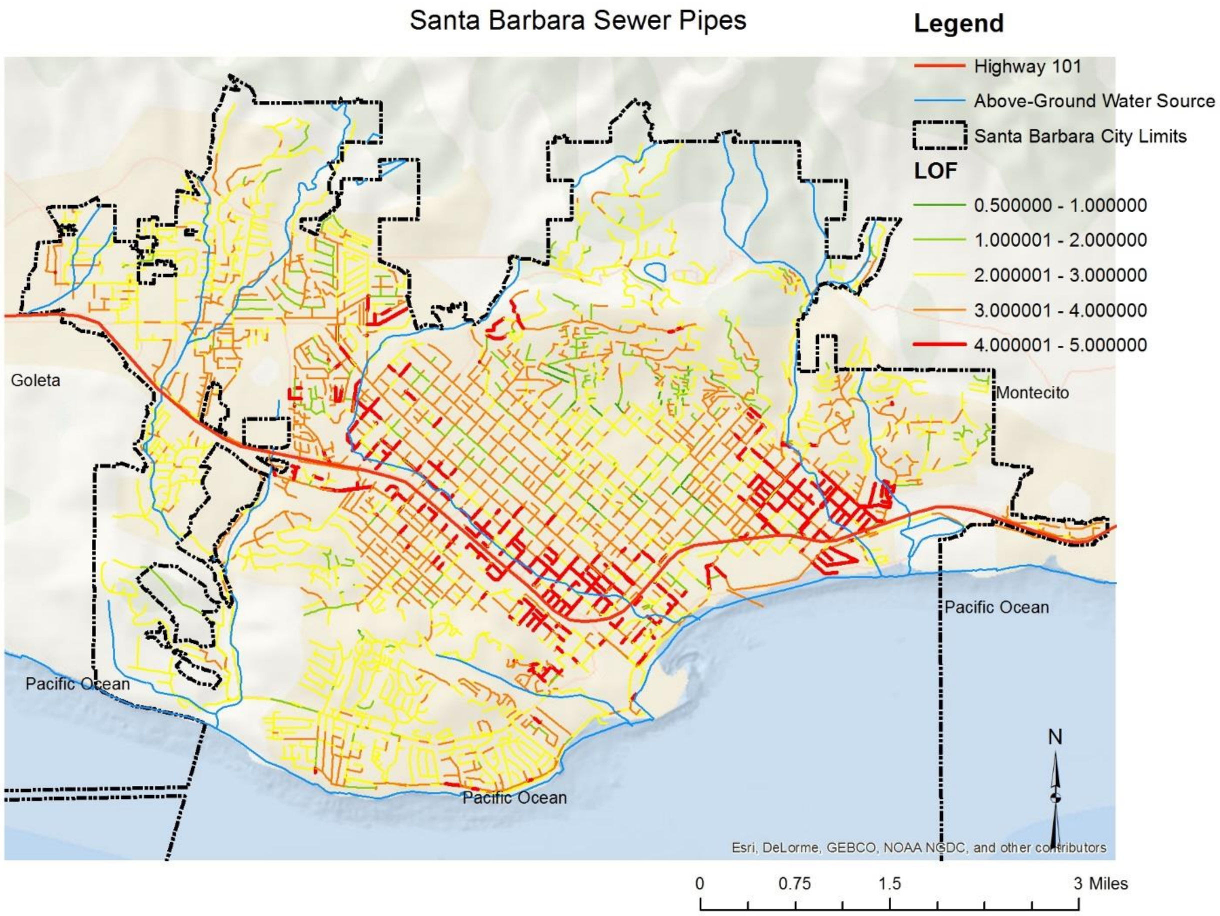


Figure 4-1 Likelihood of Failure Rating Results

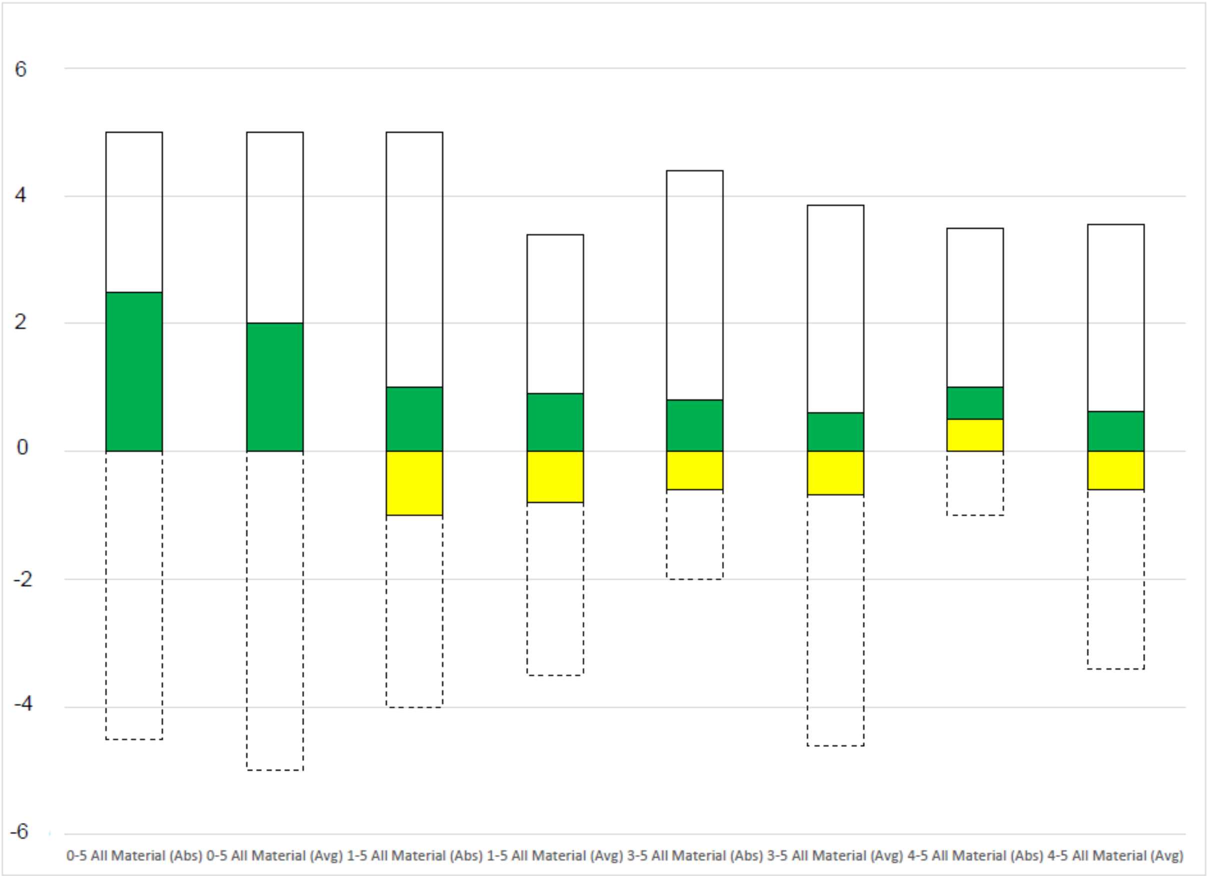


Figure 4-2 Accuracy and Precision of Sensitivity Analyses for Scenarios 13 through 16

4.2.1 MINOR RESULTS

Besides Scenario #15, the other scenarios produced results that could expand our knowledge of sewer pipe degradation. Figure F-3 in Appendix F shows scenarios 1 through 6 which predict structural integrity scores of 0 through 5, respectively for all material types. Figure F-4 shows scenarios 7 through 12 which also predict structural integrity scores of 1 through 5, respectively, but only for the Vitrified Clay Pipe material. In general, as the score increases for both the average and absolute cases, the percentage factor for the distance from restaurants decreases. Additionally, the percentage factor for material and age as well as the distance from an above-ground water source increase. Pipe depth seems to only have a minor effect on the prediction of the following scores:

1) 3 for the average score of all materials (Figure F-2)
2) 3 for the absolute score of all materials (Figure F-1)
3) 4 for the absolute score of all materials (Figure F-1)
4) 1 for the absolute score of VCP (Figure F-3)
5) 3 for the absolute score of VCP (Figure F-3)
6) 5 for the absolute score of VCP (Figure F-3)
7) 1 for the average score of VCP (Figure F-4)
8) 3 for the average score of VCP (Figure F-4)
9) 4 for the average score of VCP (Figure F-4)
10) 5 for the average score of VCP (Figure F-4)

The reason for this minor effect could be due to the fact that values were assumed for many of the pipes due to incomplete pipe inverts and manhole lid elevations. A more complete survey of pipe inverts and manhole lids would allow for a more accurate means of predicting the effect of pipe

depth and slope on the LOF rating score. Traffic volume and pipe length seemed to have an even smaller effect as seen in Figure F-1 through Figure F-4.

Figure F-5 and Figure F-6 in Appendix F show the effects of predicting combinations of factors at once. Figure F-5 shows the predictions for all materials given both the absolute and average scoring system. Figure F-6 shows the predictions for VCP given absolute and average scoring system as well. For the average cases of scenarios of 12 through 16 and scenarios 17 through 20, material and age increase in effect as the group scores become smaller and closer to 5. At the same time, the effect of the distance to any above-ground water source increases. Scenario 12 through 16 for absolute scores does not show this pattern but rather decreases from the "3-5 abs" at 80% case to "4-5 abs" case at 50% in Figure F-5. For all the cases mentioned in this paragraph, pipe depth affects 8 out of 16 cases between 15% and 30%. Additionally, scenario 14 (see Figure F-5, "1-5 Abs") is influenced by pipe depth at 50%.

In general, the sensitivity analyses show that as predicted scores get closer to 5 material and age and distance from an above-ground water source will have greater impact. At the same time the rest of the variables: traffic volume, pipe length, pipe depth, and distance from restaurants will have decreased effect on sewer pipe structural integrity or LOF rating. In order to predict the LOF rating within the City of Santa Barbara sewer system scenario 15 was used because it encompasses all materials, scores between 3 and 5, and was the most accurate and precise. The highest LOF rating values occur around Highway 101.

4.3 CONSEQUENCE ASSESSMENT

This part of the assessment uses environmental, economic, and social concerns to determine the Consequence of Failure (COF). The factors that contribute to each of these concerns are discussed in Section 3.5 and are shown below in Table 4-6 below.

Table 4-6 Consequence Factors

Concern	**Factors**	**Percentage Factor (λ)**
Environmental	Pipe diameter	0.30
Economic	Distance from Commercial Zones	0.30
Social	Distance from Critical Infrastructure	0.20
Social	Vehicular Traffic Volume	0.20

The percentage factors were assigned manually based on judgement. More emphasis was applied to social concerns because they directly affect the public. The scoring for each of the factors in Table 4-6 is explained within Section 3.5. The COF rating GIS map is shown in Figure 4-3 on the next page. The COF rating values are maximized around Highway 101.

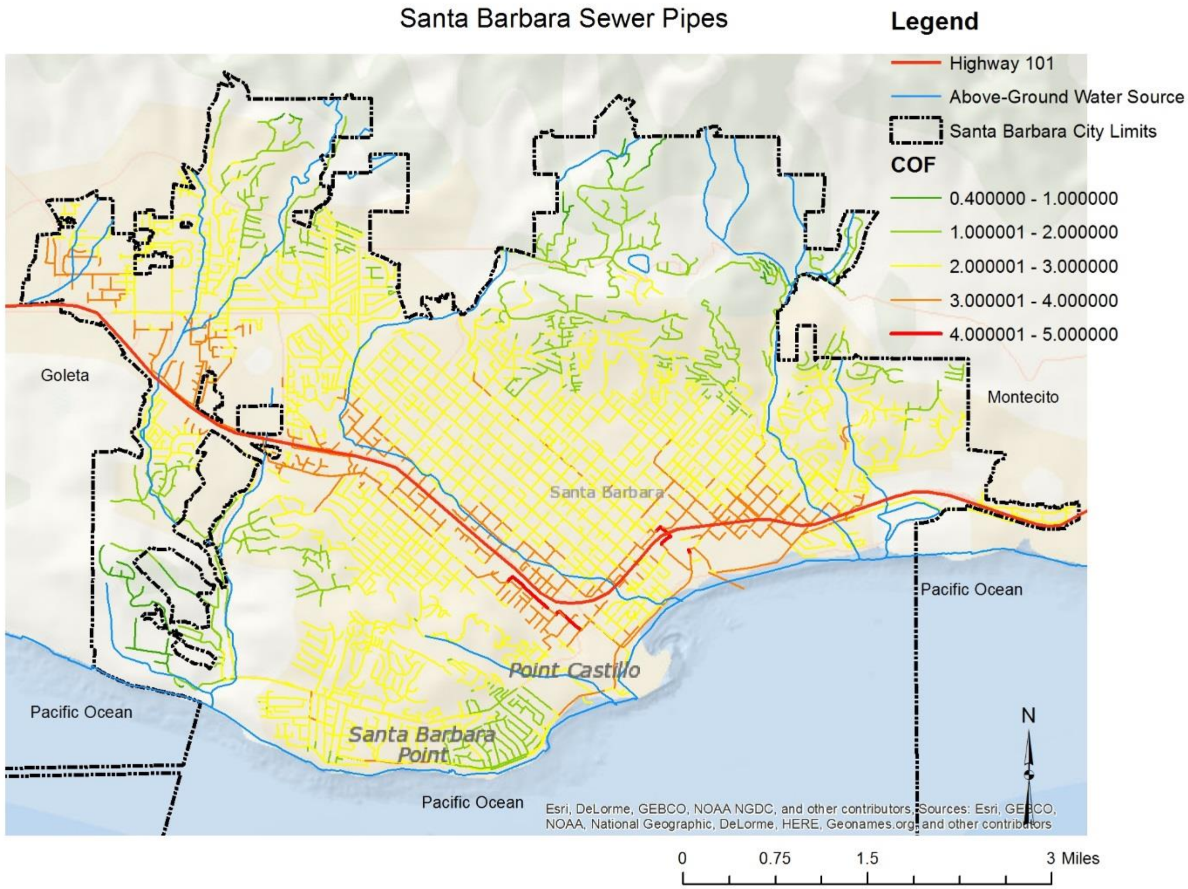


Figure 4-3 Consequence of Failure Results

4.4 RISK ASSESSMENT

In order to obtain the Risk of Failure values for each pipe, the LOF rating and COF rating were multiplied together as shown in Equation 3-4 below. With LOF rating and COF rating values between 0 and 5, the ROF rating could range between a value of 0 and 25. The GIS map in Figure 4-4 on the next page shows that ROF rating values range from 1.06 to 20. The pipe segments with the most risk are located near Highway 101.

$$\text{Risk} = (\text{LOF}) \times (\text{COF}) \qquad \text{Equation 3-4}$$

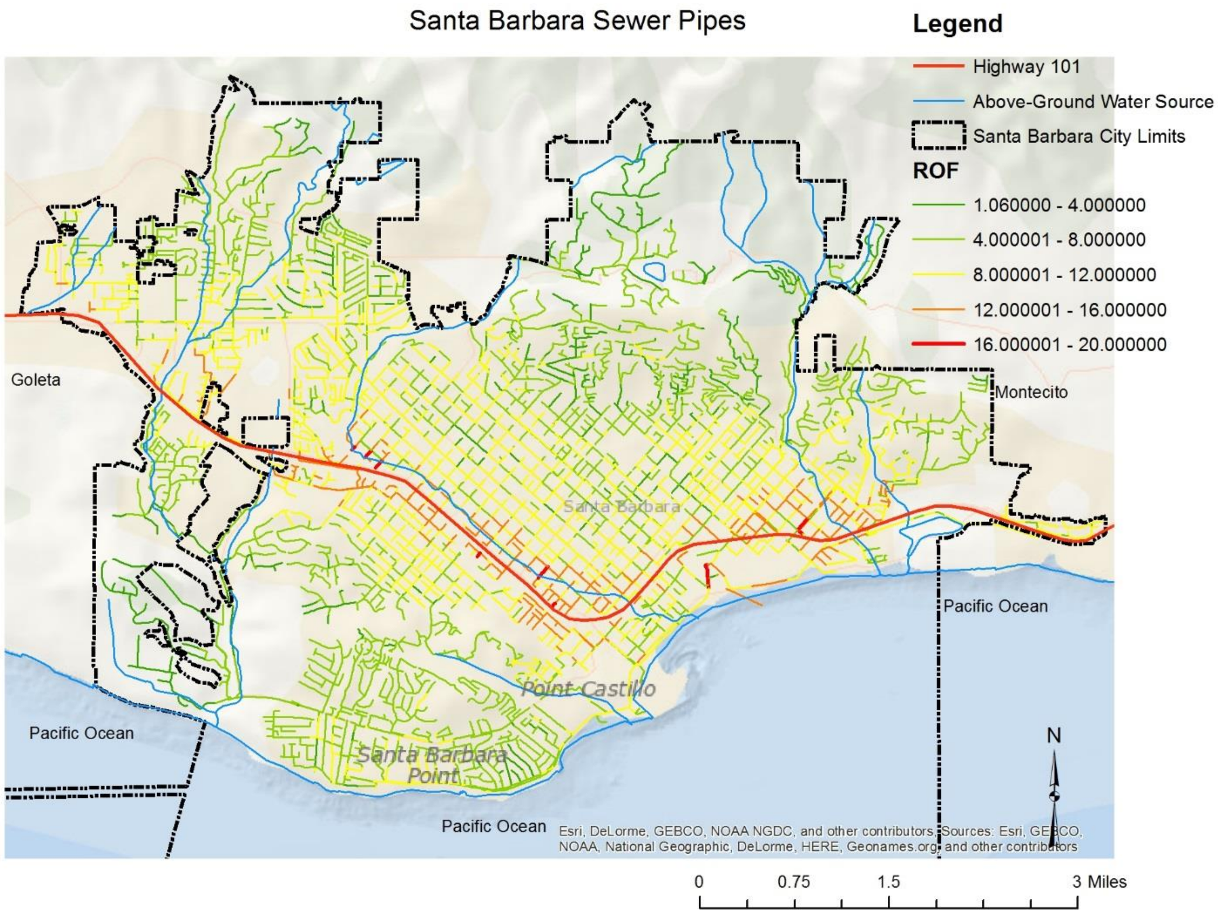


Figure 4-4 Risk of Failure Results

CHAPTER 5 DISCUSSION

The concept of risk is defined by the combination of the Likelihood of Failure (LOF) and Consequence of Failure (COF) to find the Risk of Failure (ROF). This paper uses a simple multiplication scheme to combine the LOF rating and COF rating so that it could be easily adopted and repeated by other municipalities. The LOF rating was determined using the Closed Circuit Television (CCTV) results analyzed with the Pipeline Assessment Certification Program (PACP) to perform a sensitivity analysis on important factors that can affect sewer pipe structural integrity. The COF rating for the City of Santa Barbara consider environmental, economic, and social concerns. GIS is used to display LOF rating, COF rating, and ROF rating results as displayed in Figure F-1, Figure F-2, and Figure F-3 in Appendix F, respectively.

5.1 LIKELIHOOD OF FAILURE RATING

The sensitivity analysis determined the percentage factors for material and age (45%), pipe depth (20%), vehicular traffic volume (10%), and the distance from any above-ground water source (25%) for scenario 15 from Table 3-11. As shown in the minor results in Section 4.2.1, the effect of material and age increased as the score that was predicted also increased. This supports that material and age have a 45% impact on the LOF rating. The factor with the second highest percentage factor was distance from an above-ground water source. This makes sense because the City is near the ocean and will thus have higher ground water elevations that can affect pipe degradation.

Surprisingly, pipe depth still had quite an impact on the LOF rating score with a percentage factor of 20%. Even though much of the pipe depth data was assumed, this still proves the importance

of pipe depth in the City's sewer system. Additionally, traffic volume has a percentage factor of 10% for scenario 15.

Of the sensitivity analysis completed on the 20 different scenarios, scenario 15 was selected to determine the level of service for four main reasons:

1) This scenario is applicable for all material types,
2) This scenario is both accurate and precise,
3) This scenario predicts scores of 3 through 5, and
4) Relevance to literature and theory.

Scenarios 7 through 12 and 16 through 20 assessed cases that were only applicable for Vitrified Clay Pipe. This would not be representative for the whole system while a scenario that accounts for all material types would embody the City's sewer assets.

Scenarios 1 through 6 and 7 through 12 in predict each individual score. When these are applied in GIS to the whole sewer network, it puts too much of an emphasis on the LOF rating values of 5 and there are issues with varying predictions for each pipe. In order to correct this, combinations of scores were added to the sensitivity analysis in scenarios 13 through 20.

Scenario 15 predicts scores of 3, 4, and 5 with an interquartile range of 1.27 and median of 0.00 for the difference between given and predicted scores. Predicting all three scores allows municipalities to have knowledge of pipes that are currently in the worst condition with scores of 5 as well as those pipes that are about to start to get worse with scores of 3.

Multiple authors, including McDonald and Zhao (2001), Ariatnam et al (2001), Ruwanpura et al (2004), and Baur and Herz (2002) have noted that material and age, pipe depth, vehicular traffic

volume, and ground water level. They also note other factors such as pipe length and distance from restaurants, but each sewer system is different and will have different combinations and weights for each factor.

Rather than using engineering judgement to determine the factors that affect the LOF rating score, this thesis reduces some of the engineering judgement required to perform the analysis by determining the factors that have the most effect. However, there will always be some engineering judgement involved when these pipes were scored during inspection before the sensitivity analysis.

5.2 CONSEQUENCE OF FAILURE

Salmon and Salem (2012) cited economic, environmental, and social consequence as shown in Table 2-2 in the literature review. Table 4-6 shows the consequence factors and percentage factors used to estimate the COF rating for the City pipe network which include economic, environmental, and social consequences. A weighted scoring system as shown in Equation 3-2 was also used for this part of the risk analysis. The factors of pipe diameter, distance from commercial zones, distance from critical infrastructure, and vehicular traffic volume were used because that data was available, they provide a simple COF rating value determination, and they encompass economic, environmental, and social consequences.

5.3 RISK OF FAILURE

The ROF rating used the multiplication method to combine both the LOF rating and COF rating as shown in Equation 3-4. GIS allows the user to save the LOF rating, COF rating, and ROF rating scores; compare similar LOF rating scores, and visually see the pipes most at risk. This enables municipalities to compare all three values and compare high LOF rating and low COF

rating values to low LOF rating and high COF rating values. See Figure F-3 for the ROF rating results.

The ROF rating results show that pipes with the biggest ROF rating are located near Highway 101. This follows the same pattern as the COF rating results in Figure F-2 while the LOF rating results were more distributed. Overall, the determination of the ROF rating effectively isolated the pipes most at risk.

5.4 COMPARISON TO BROWN AND CALDWELL

Brown and Caldwell performed a risk assessment of the City of Santa Barbara sewer system in 2012. Those results are shown in Appendix G with LOF rating, COF rating, and ROF rating results in Figure G-2, Figure G-3, and Figure G-4, respectively. Figure G-1 shows the process that they used to assign LOF rating and COF rating values. Their purpose was to create a maintenance and rehabilitation schedule for pipes with little previous data.

Brown and Caldwell (2012) determined that pipes were given a LOF rating value if there is high maintenance or a previous Sanitary Sewer Overflow (SSO). They then determined that age, pipe diameter, Inflow and Infiltration (I/I) were also important in determining the LOF rating score. Comparatively, this thesis uses pipe age to determine the LOF rating score. However, it does not take into account SSO or I/I data, although it does predict LOF rating scores based on current CCTV results with PACP ratings.

High COF rating values were given to those pipes in highly sensitive environments or public health. Brown and Caldwell (2012) also take into account pipe diameter, crossings, high traffic,

and poor access. This thesis uses pipe diameter, traffic volume, and distance from commercial and critical zones to take all those aspects into account.

The Brown and Caldwell (2012) LOF rating map in Figure G-2 produces more LOF rating that are more spread out when compared to Figure F-1 which shows the highest near around Highway 101. The same is true for the comparison of the COF rating and ROF rating maps in Appendices F and G. The results in this thesis show how the risk assessment could be fine-tuned with prediction of the LOF rating. Overall, the model presented in this paper provides a more complete picture of sewer pipe risk than that presented by Brown and Caldwell in 2012.

5.5 PRACTICE

Since this paper presents a simple weighted scoring method for LOF rating and COF rating, the process presented can be easily applied to any sewer system given available CCTV data with PACP ratings along with the use of Geographic Information Systems software to conduct spatial analyses. This is a step forward when compared to intuitively designed risk assessment systems because it takes into account the actual condition of pipe integrity.

CHAPTER 6 CONCLUSION AND RECOMENDATIONS

6.1 SUMMARY AND EVALUATION OF RESULTS

This project aimed to develop a risk assessment model that can effectively address different pipe networks with different spatial and physical factors. For this paper, data was acquired from the City of Santa Barbara (City) in GIS format. This data included Closed Circuit Television (CCTV) data with Pipeline Assessment Certification Program (PACP) structural integrity scores. The risk assessment combined Likelihood of Failure (LOF) and Consequence of Failure (COF) in order to calculate the Risk of Failure for each pipe in the City sewer network.

The sensitivity analysis with the weighted scoring method in Equation 3-2 with PACP pipe ratings determined that material and age (45%), pipe depth (20%), vehicular traffic volume (10%), and the distance from any above-ground water source (25%) affected the structural integrity of sewer pipes. This was applied to the GIS shapefile to obtain Figure F-1 in Appendix F. The COF rating was then determined using the same weighted scoring method to include pipe diameter (30%), distance from commercial zones (30%), distance from critical infrastructure (20%), and vehicular traffic volume (20%) to take into account environmental, economic, and social consequences of system failure. See Figure F-2 in Appendix F for the resulting GIS map. Finally, both the LOF rating and COF rating were multiplied together to obtain the ROF rating map shown in Figure F-3.

When comparing the results from the risk analysis in this thesis to the risk analysis performance by Brown and Caldwell (2012), this thesis provides a more accurate and precise method. Brown

and Caldwell focused on creating a ranking system to prioritize and plan pipe inspections. They had less data than is now available. This thesis capitalizes on the CCTV data captured because of the Brown and Caldwell risk assessment and fine-tunes their results.

6.2 RECOMMENDED AREAS FOR IMPROVEMENT AND FUTURE RESEARCH

Some slight modifications could be included to create more accurate and precise results, specifically in performing the sensitivity analysis on the structural integrity scores. More data could be collected and included for the sensitivity analysis. This data could include pipe slope, Sanitary Sewer Overflow, and Inflow and Infiltration. Additionally, it would be beneficial to use available pipe flow data to replace pipe diameter in the COF rating assessment.

Another recommendation would be to predict the LOF rating using nonlinear formulas similar to Chughtai and Zayed (2007) in section 2.4. Their analysis predicted structural integrity scores at an accuracy of 82% to 86%. This would reduce the amount of judgement involved in the analysis as it could remove the necessity for scoring factors before the sensitivity analysis. In effect actual pipe age or pipe length values could be used instead of scores between 0 and 5.

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APPENDIX A GIS SNAPSHOTS

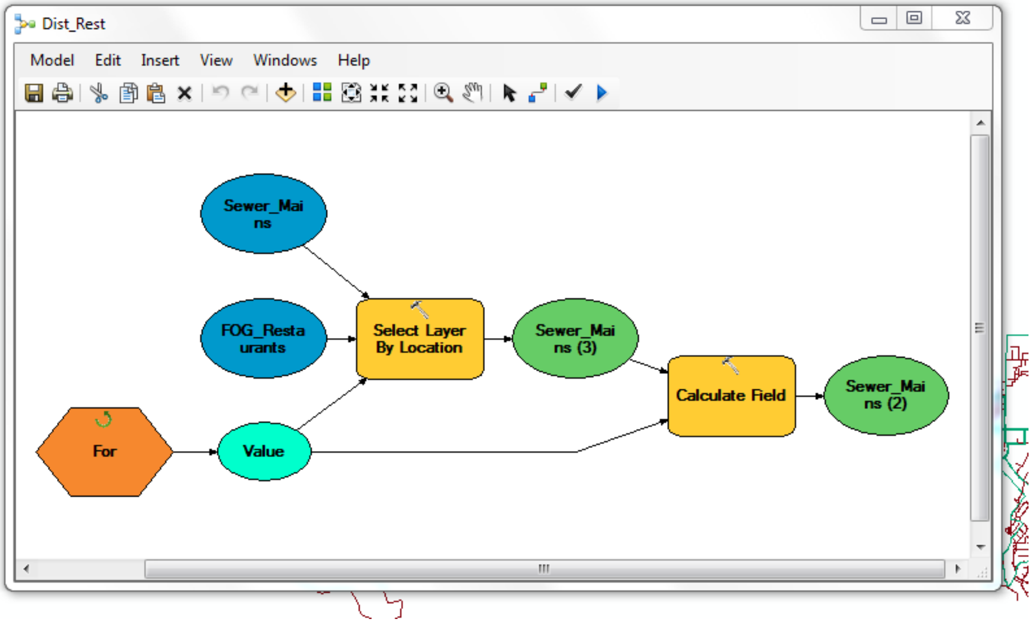


Figure A-1 Distance to Restaurant Toolbox

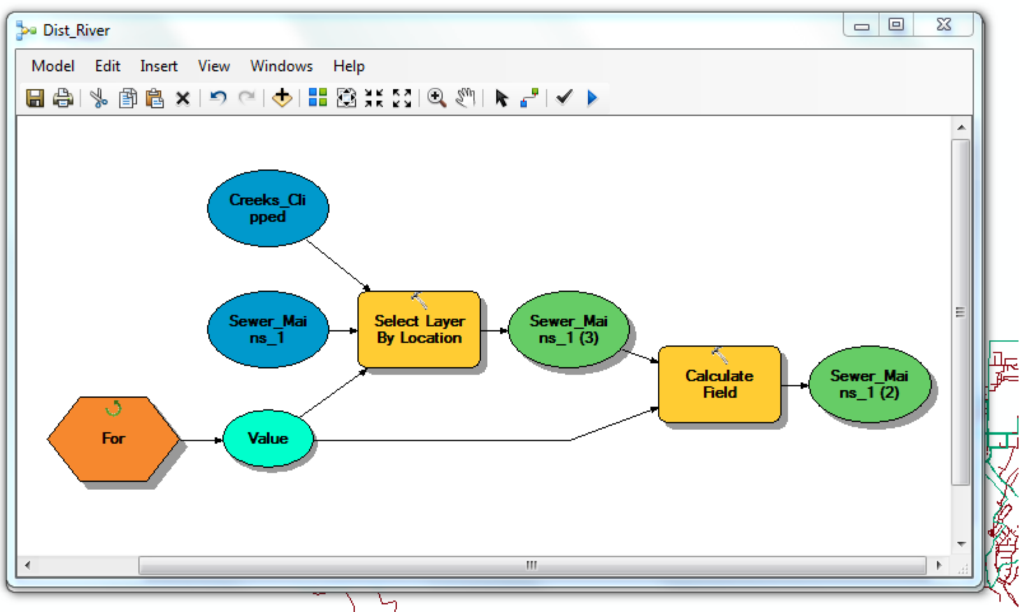


Figure A-2 Distance to Above Ground Water Source Toolbox

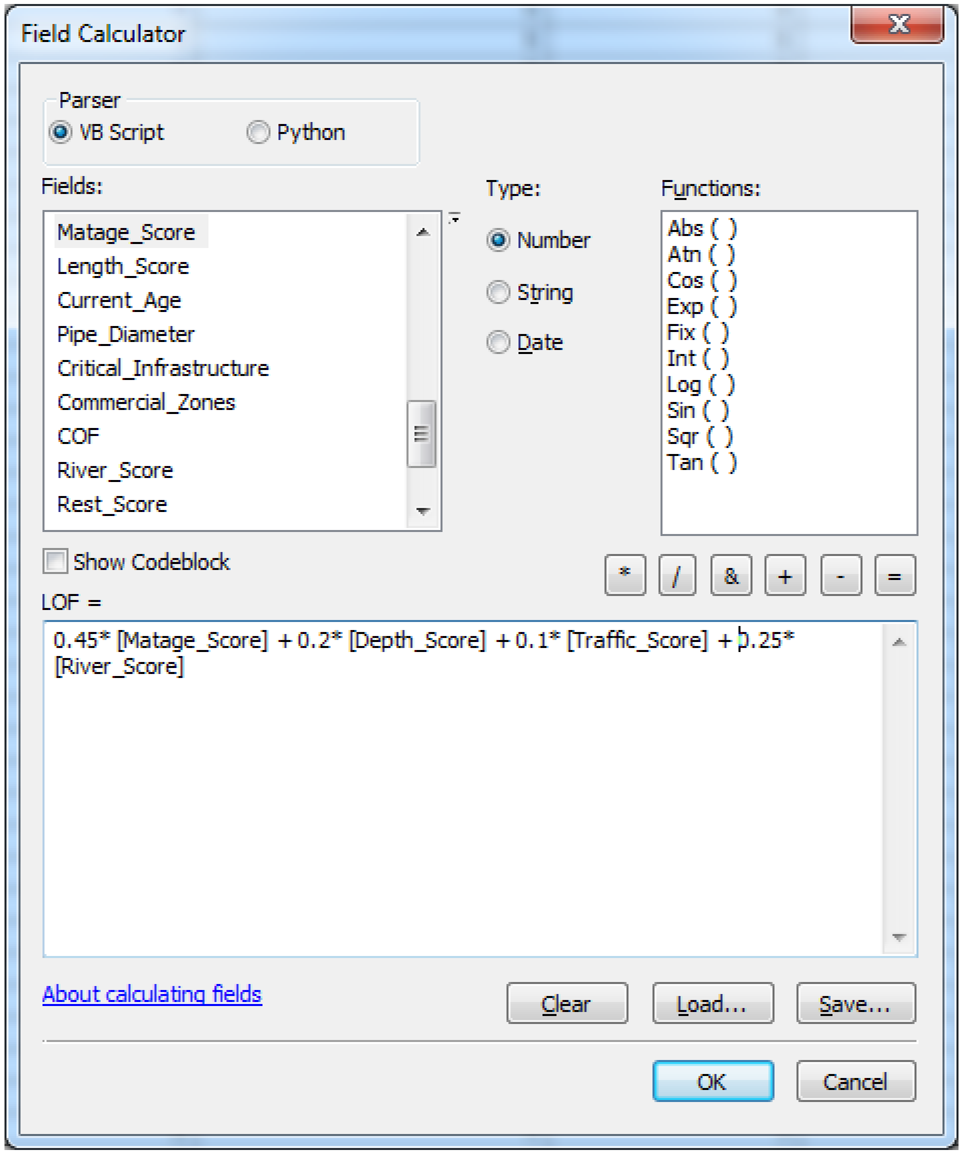


Figure A-3 LOF rating Calculation with Field Calculator

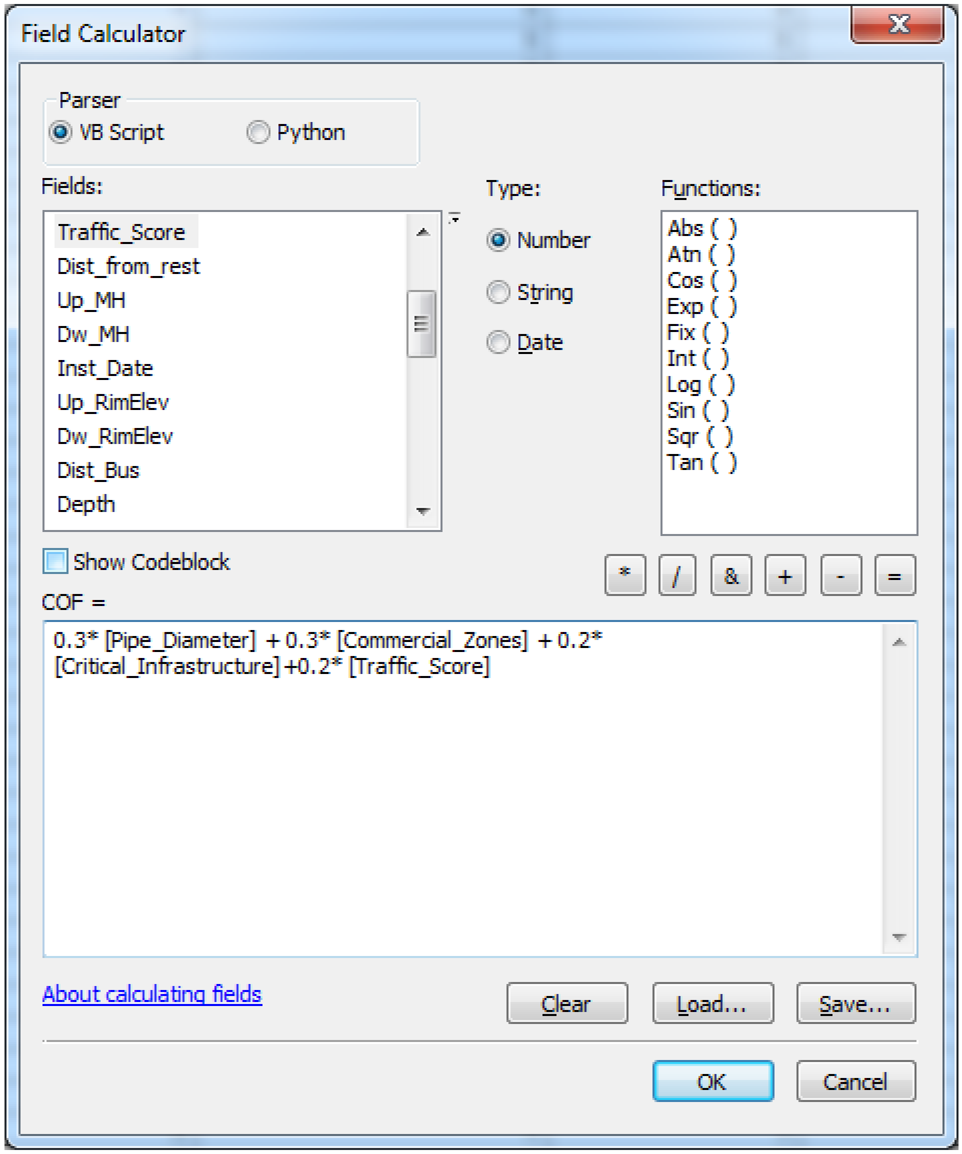


Figure A-4 COF rating Calculation with Field Calculator

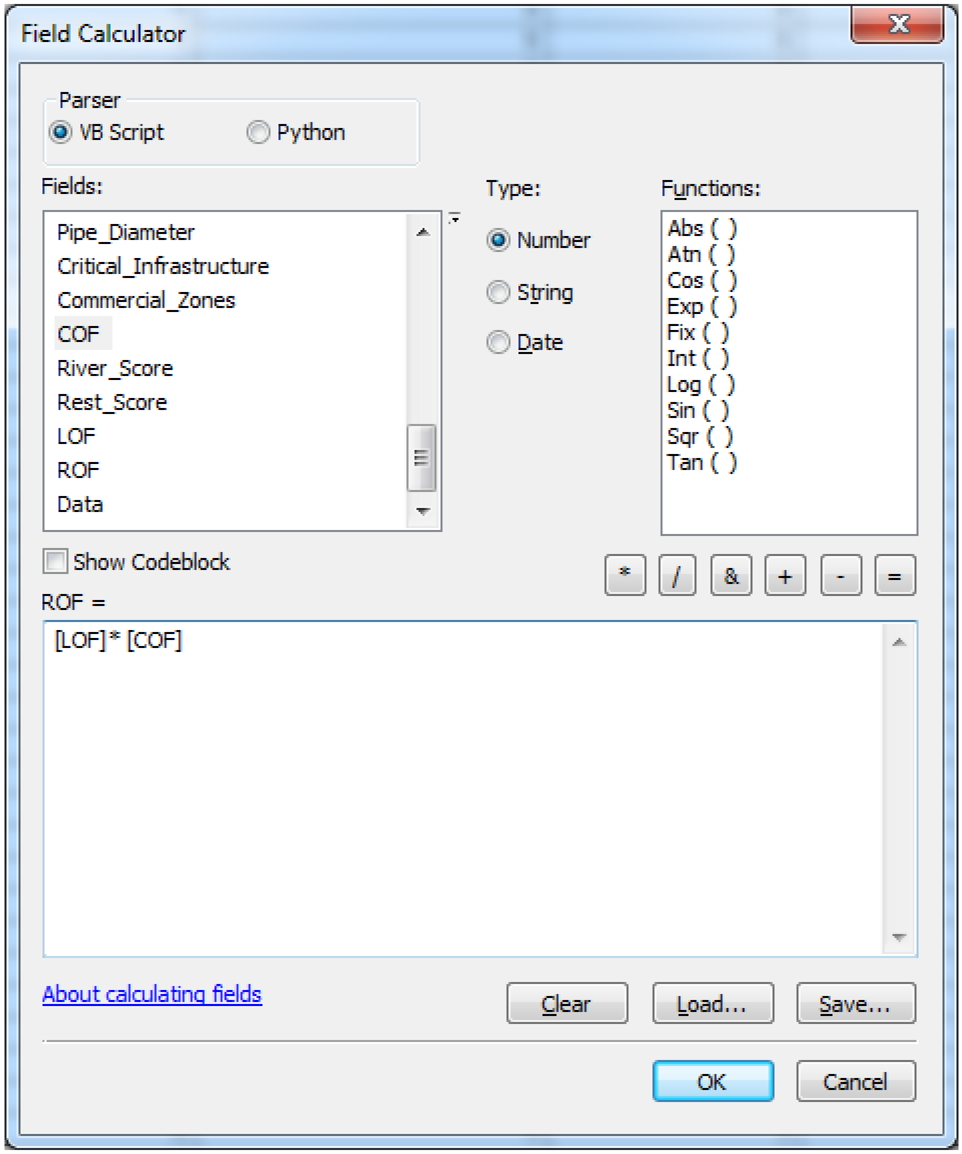


Figure A-5 ROF rating Calculation with Field Calculator

APPENDIX B ORGANIZE PROGRAM

B.1 TO COMPILE IN LINUX

gcc –o –wall organize.c organize

B.2 ORGANIZE.C

```
#include <stdio.h>

#define FNAME "Score_7.txt"

#define N 2028


/* FUNCTIONS */

void Header(FILE *fd)

{

    fprintf(fd, "OBJECTID\tMATERIAL\tTraffic_Score\t");

    fprintf(fd, "Dist_from_Rest\tDepth\tAge\tLength\tRiver\tSoil\tScore\tAvg\n");

}


void PrintToFile(FILE *fd, int objid, char *mat, int traf, int rest, float depth, float age, float lth,
int river, int soil, int score, float avg)

{

    fprintf(fd, "%d\t%s\t", objid, mat);

    fprintf(fd, "%d\t%d\t", traf, rest);

    fprintf(fd, "%.2f\t%.2f\t", depth, age);

    fprintf(fd, "%.2f\t%d\t", lth, river);

    fprintf(fd, "%d\t%d\t", soil, score);

    fprintf(fd, "%.2f\n", avg);

}


/* MAIN CODE */

int main(void)
```

```
{
	printf("Here\n");
	/* Values for reading in from file */
	FILE *finput = fopen(FNAME, "r");
	char buffer[170], material[N][4];
	int objID[N], score_traffic[N], dist_restaurant[N], score_given[N], dist_river[N],
score_soil[N];
	float depth[N], age[N], length[N], score_avg[N];
	/* Counter */
	int n;
	/* Values for Creating new files */
	FILE *f0 = fopen("Score_0.txt", "w");		//Only 0's (all materials)
	FILE *f1 = fopen("Score_1.txt", "w");		//Only 1's (all materials)
	FILE *f2 = fopen("Score_2.txt", "w");		//Only 2's (all materials)
	FILE *f3 = fopen("Score_3.txt", "w");		//Only 3's (all materials)
	FILE *f4 = fopen("Score_4.txt", "w");		//Only 4's (all materials)
	FILE *f5 = fopen("Score_5.txt", "w");		//Only 5's (all materials)
	FILE *f6 = fopen("Score_6.txt", "w");		//1's through 5's (all materials)
	FILE *f8 = fopen("Score_8.txt", "w");		//0's through 5's (VCP)
	FILE *f9 = fopen("Score_9.txt", "w");		//1's through 5's (VCP)
	FILE *f10 = fopen("Score_10.txt", "w");	//Only 0's (VCP)
	FILE *f11 = fopen("Score_11.txt", "w");	//Only 1's (VCP)
	FILE *f12 = fopen("Score_12.txt", "w");	//Only 2's (VCP)
	FILE *f13 = fopen("Score_13.txt", "w");	//Only 3's (VCP)
	FILE *f14 = fopen("Score_14.txt", "w");	//Only 4's (VCP)
	FILE *f15 = fopen("Score_15.txt", "w");	//Only 5's (VCP)
```

```
FILE *f16 = fopen("Score_16.txt", "w");     //4's and 5's (VCP)
FILE *f17 = fopen("Score_17.txt", "w");     //3's through 5's (VCP)
FILE *f18 = fopen("Score_18.txt", "w");     //4's and 5's (all materials)
FILE *f19 = fopen("Score_19.txt", "w");     //3's through 5's (all materials)


/* Read Values from file */
if (finput == NULL)
{
    printf("%s does not exist", FNAME);
}
else
{
    fgets(buffer, sizeof(buffer), finput);
    for (n = 0; n < N; n++)
    {
    fscanf(finput, "%d %s", &objID[n], material[n]);
    fscanf(finput, "%d %d", &score_traffic[n], &dist_restaurant[n]);
    fscanf(finput, "%f %f", &depth[n], &age[n]);
    fscanf(finput, "%f %d", &length[n], &dist_river[n]);
    fscanf(finput, "%d %d", &score_soil[n], &score_given[n]);
    fscanf(finput, "%f", &score_avg[n]);
    }


    Header(f0);
    Header(f1);
    Header(f2);
```

```
Header(f3);
Header(f4);
Header(f5);
Header(f6);
Header(f8);
Header(f9);
Header(f10);
Header(f11);
Header(f12);
Header(f13);
Header(f14);
Header(f15);
Header(f16);
Header(f17);
Header(f18);
Header(f19);

for (n = 0; n < N; n++)
{
    if (score_given[n] == 0)
        PrintToFile(f0, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

    else if (score_given[n] == 1)
        PrintToFile(f1, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
```

```
else if (score_given[n] == 2)
    PrintToFile(f2, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

else if (score_given[n] == 3)
    PrintToFile(f3, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

else if (score_given[n] == 4)
    PrintToFile(f4, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

else
    PrintToFile(f5, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

if (score_given[n] >= 1)
    PrintToFile(f6, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

if (score_given[n] >= 4)
    PrintToFile(f18, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

if (score_given[n] >= 3)
```

```
PrintToFile(f19, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

if (strcmp(material[n], "VCP") == 0)
{
    PrintToFile(f8, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

    if (score_given[n] >= 1)
        PrintToFile(f9, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

    if (score_given[n] == 0)
        PrintToFile(f10, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
    else if (score_given[n] == 1)
        PrintToFile(f11, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
    else if (score_given[n] == 2)
        PrintToFile(f12, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
    else if (score_given[n] == 3)
        PrintToFile(f13, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
    else if (score_given[n] == 4)
```

```
                PrintToFile(f14, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
            else
                PrintToFile(f15, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);

            if (score_given[n] >= 4)
                PrintToFile(f16, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);


            if (score_given[n] >= 3)
                PrintToFile(f17, objID[n], material[n], score_traffic[n], dist_restaurant[n],
depth[n], age[n], length[n], dist_river[n], score_soil[n], score_given[n], score_avg[n]);
        }
    }
    fclose(f0);
    fclose(f1);
    fclose(f2);
    fclose(f3);
    fclose(f4);
    fclose(f5);
    fclose(f6);
    fclose(f7);
    fclose(f8);
    fclose(f9);
```

```
        fclose(f10);
        fclose(f11);
        fclose(f12);
        fclose(f13);
        fclose(f14);
        fclose(f15);
        fclose(f16);
        fclose(f17);
        fclose(f18);
        fclose(f19);
        fclose(finput);
    }
    return 0;
}
```

APPENDIX C SENSITIVITY ANALYSIS PROGRAM

C.1 TO COMPILE

gcc –o –wall sensitivity.c sensitivity

C.2 SENSITIVITY.C

```
#include "analysis.h"


int main(void)

{

    printf("Just 0's (all materials)\n");

    Analyze(N0, 0);


    printf("Just 1's (all materials)\n");

    Analyze(N0, 1);


    printf("Just 2's (all materials)\n");

    Analyze(N2, 2);


    printf("Just 3's (all materials)\n");

    Analyze(N3, 3);


    printf("Just 4's (all materials)\n");

    Analyze(N4, 4);


    printf("Just 5's (all materials)\n");

    Analyze(N5, 5);


    printf("1's through 5's (all materials)\n");

    Analyze(N6, 6);
```

```
printf("0's through 5's (all materials)\n");
Analyze(N7, 7);

printf("0's through 5's (VCP)\n");
Analyze(N8, 8);

printf("1's through 5's (VCP)\n");
Analyze(N9, 9);

printf("Just 0's (VCP)\n");
Analyze(N10, 10);

printf("Just 1's (VCP)\n");
Analyze(N11, 11);

printf("Just 2's (VCP)\n");
Analyze(N12, 12);

printf("Just 3's (VCP)\n");
Analyze(N13, 13);

printf("Just 4's (VCP)\n");
Analyze(N14, 14);

printf("Just 5's (VCP)\n");
```

```
    Analyze(N15, 15);

    printf("4's and 5's (all materials)\n");
    Analyze(N16, 16);

    printf("3's thorugh 5's (all materials)\n");
    Analyze(N17, 17);

    printf("4's and 5's (VCP)\n");
    Analyze(N18, 18);

    printf("3's through 5's (VCP)\n");
    Analyze(N19, 19);

    return 0;
}
```

C.3 SENSITIVITY.H

```
#include <stdio.h>

#include <string.h>

#include <stdlib.h>

#include "statistics.h"


#define N0 984

#define N1 184

#define N2 201

#define N3 234

#define N4 214

#define N5 211

#define N6 1044

#define N7 2028

#define N8 1802

#define N9 1001

#define N10 801

#define N11 176

#define N12 193

#define N13 220

#define N14 208

#define N15 204

#define N16 412

#define N17 632

#define N18 425
```

```
#define N19 659


#define MAX (float)1
#define NUM_BUCKETS (float)40


/*------------------------------------------------*/
/*   This function TempValue returns the
   corresponding float value */
float TempValue(int x, FILE *ftest)
{
      float value;


      if (x == 0)
            value = 0;
      else
            value = (float)x*MAX/NUM_BUCKETS;


//    fprintf(ftest, "%f\n", value);


      return value;
}


/*------------------------------------------------*/
/*   This funciton scores all the materials by
age. Those pipes that are older receive
a more critical score */
```

```
int MaterialAgeScore(char material[4], float age)
{
  int score;
/* CAS == Cast Iron -> max = 100 -----
  PVC == Polyvinyl Chloride -> max = 70 -----
  DIP == Ductile Iron Pipe -> max = 60
  PE == Polyethylene -> max = 75 -----
  VCP == Vitrified Clay Pipe -> max = 100 -----
  SP == Steel Pipe -> max = 95 -----
  RCP == Reinforced Concrete Pipe -> max = 75 -----*/

    if (strcmp(material, "CAS") == 0 || strcmp(material, "VCP") == 0)
    {
        if (age <= 20)
            score = 1;
        else if (age <= 40)
            score = 2;
        else if (age <= 60)
            score = 3;
        else if (age <= 80)
            score = 4;
        else
            score = 5;
    }
    else if (strcmp(material, "PVC") == 0)
    {
```

```
    if (age <= 14)
         score = 1;
    else if (age <= 28)
        score = 2;
    else if (age <= 42)
        score = 3;
    else if (age <= 56)
        score = 4;
    else
        score = 5;
}
else if (strcmp(material, "SP") == 0)
{
    if (age <= 19)
        score = 1;
    else if (age <= 38)
        score = 2;
    else if (age <= 57)
        score = 3;
    else if (age <= 76)
        score = 4;
    else
        score = 5;
}
else if (strcmp(material, "RCP") == 0 || strcmp(material, "PE") == 0)
{
```

```
    if (age <= 15)
        score = 1;
    else if (age <= 30)
        score = 2;
    else if (age <= 45)
        score = 3;
    else if (age <= 60)
        score = 4;
    else
        score = 5;
}
else if (strcmp(material, "DIP") == 0)
{
    if (age <= 12)
        score = 1;
    else if (age <= 24)
        score = 2;
    else if (age <= 36)
        score = 3;
    else if (age <= 48)
        score = 4;
    else
        score = 5;
}
else
{
```

```
        if (age <= 10)
            score = 1;
        else if (age <= 20)
            score = 2;
        else if (age <= 30)
            score = 3;
        else if (age <= 40)
            score = 4;
        else
            score = 5;
    }
    return score;
}


/*--------------------------------------------*/
/*  This function returns the score for depth.
    Those pipes that are deeper and closer to the
    surface have higher, more critical scores */
int DepthScore(float depth)
{
    if (depth <= 4 || depth >= 17)
        return 5;
    else if (depth <= 5.5 || depth >= 15.5)
        return 4;
    else if (depth <= 7 || depth >= 14)
        return 3;
```

```
    else if (depth <= 8.5 || depth >=12.5)
        return 2;
    else
        return 1;
}
/*-------------------------------------------*/
/*  This function returns the score for distance
    from the restaurants. Those pipes closer to
    the restaurant receive a more critical score */
int RestaurantScore(int distance)
{
    if (distance >= 350)
        return 1;
    else if (distance >= 250)
        return 2;
    else if (distance >= 150)
        return 3;
    else if (distance >= 50)
        return 4;
    else
        return 5;
}
/*-------------------------------------------*/
/*`This function returns the score the length
    of the pipe. Those pipes that are longer, will
    receive a greater, more critical score. */
```

```
int LengthScore(float length)
{
    if (length <= 120)
        return 1;
    else if (length <= 207)
        return 2;
    else if (length <= 302)
        return 3;
    else if (length <= 423)
        return 4;
    else
        return 5;
}
/*-------------------------------------------*/
/*  This function returns the score for the
    distance from a river. Those pipes closer to
    the river, receive a greater, more critical
    score. */
int RiverScore(int distance)
{
    if (distance <= 25)
        return 5;
    else if (distance <= 50)
        return 4;
    else if (distance <= 75)
        return 3;
```

```
    else if (distance <= 100)
        return 2;
    else
        return 1;
}
/*---------------------------------------------*/
/* This function checks to see the best combination
   and returns the best combination */
IQR BestRange(IQR best, IQR check)
{
    if (check.q2 <= best.q2 && check.q3 < best.q3)
    {
        best.a = check.a;
        best.b = check.b;
        best.c = check.c;
        best.d = check.d;
        best.e = check.e;
        best.f = check.f;
        best.g = check.g;
        best.q1 = check.q1;
        best.q2 = check.q2;
        best.q3 = check.q3;
    }
    return best;
}
```

```
/*-------------------------------------------*/
/*  This function returns the best combination
    of values for the sensitivity analysis. */
void Analyze(int max, int i)
{
    // Variables for reading in from file
    char buffer[190], material[max][4];
    int objID[max], score_traffic[max], dist_restaurant[max], score_given[max], dist_river[max],
score_soil[max];
    float depth[max], age[max], length[max], score_avg[max];
    // Variables for initial analysis
    int intA, intB, intC, intD, intE, intF, intG;
    float score_final[max], difference_abs[max], difference_avg[max];
    float bufA, bufB, bufC, bufD, bufE, bufF, bufG;
    // Variables for average and standard deviation
    // max_value refers to average+stdev
    float average, stdev, max_value;
    char filename[125], fileread[15];
    // Variables for Analysis
    int score_matage[max], score_restaurant[max], score_depth[max], score_length[max],
score_river[max];
    // Variables for Statistical Analysis
    // 50 chosen because it is way bigger than anything that can be calculated
    // makes sure that the first iteration of data takes the variables below
    IQR bestRange_abs, bestRange_avg, range, range_abs, range_avg;
    // Variable for counter
```

```
int n, max_count, current_count = 1;

FILE *ftest = fopen("test.txt", "w");

// Initialize range
range.a = 0;
range.b = 0;
range.c = 0;
range.d = 0;
range.e = 0;
range.f = 0;
range.g = 0;
range.q1 = 0;
range.q2 = 50;
range.q3 = 50;
// Initialize bestRange_abs
bestRange_abs.q1 = 0;
bestRange_abs.q2 = 50;
bestRange_abs.q3 = 50;
// Initialize bestRange_avg
bestRange_avg.q1 = 0;
bestRange_avg.q2 = 50;
bestRange_avg.q3 = 50;

// This is for counting to see how far the analysis is
if (NUM_BUCKETS == 10)
```

```
        max_count = 8008;
    else if (NUM_BUCKETS == 20)
        max_count = 230230;
    else if (NUM_BUCKETS == 30)
        max_count = 1947792;
    else if (NUM_BUCKETS == 40)
        max_count = 9366819;
    else // NUM_BUCKETS == 50
        max_count = 32468436;

    sprintf(fileread, "Score_%d.txt", i);
    FILE *fread = fopen(fileread, "r");

    if (fread == NULL)
    {
        printf("Could not find Score_%d.txt\n", i);
    }
    else
    {
    printf("Found %s\n", fileread);
    /* Read in values from file */
    /* Skip first line */
    fgets(buffer, sizeof(buffer), fread);

    for (n = 0; n < max; n++)
    {
```

```
        fscanf(fread, "%d %s", &objID[n], material[n]);
        fscanf(fread, "%d %d", &score_traffic[n], &dist_restaurant[n]);
        fscanf(fread, "%f %f", &depth[n], &age[n]);
        fscanf(fread, "%f %d", &length[n], &dist_river[n]);
        fscanf(fread, "%d %d", &score_soil[n], &score_given[n]);
        fscanf(fread, "%f", &score_avg[n]);
        // Score pipes here
        score_matage[n] = MaterialAgeScore(material[n], age[n]);
        score_restaurant[n] = RestaurantScore(dist_restaurant[n]);
        score_depth[n] = DepthScore(depth[n]);
        score_length[n] = LengthScore(length[n]);
        score_river[n] = RiverScore(dist_river[n]);
    }

    fclose(fread);

    for (intA = 0; intA <= NUM_BUCKETS; intA++)
    {
        range.a = TempValue(intA, ftest);

        for (intB = 0; intB <= (NUM_BUCKETS - intA); intB++)
        {
          range.b = TempValue(intB, ftest);

          for (intC = 0; intC <= (NUM_BUCKETS - intA - intB); intC++)
          {
```

```
range.c = TempValue(intC, ftest);

for (intD = 0; intD <= (NUM_BUCKETS - intA - intB - intC); intD++)
{
    range.d = TempValue(intD, ftest);

    for (intE = 0; intE <= (NUM_BUCKETS - intA - intB - intC - intD); intE++)
    {
        range.e = TempValue(intE, ftest);

        for (intF = 0; intF <= (NUM_BUCKETS - intA - intB - intC - intD - intE);
intF++)
        {
            range.f = TempValue(intF, ftest);
            intG = NUM_BUCKETS - intA - intB - intC - intD - intE - intF;
            range.g = TempValue(intG, ftest);

            // Status Bar
            printf("\r%d/%d", current_count++, max_count);
            // Analysis Here //
            for (n = 0; n < max; n++)
            {
                bufA = range.a*(float)score_matage[n];
                bufB = range.b*(float)score_restaurant[n];
                bufC = range.c*(float)score_depth[n];
                bufD = range.d*(float)score_length[n];
```

```
                bufE = range.e*(float)score_traffic[n];
                bufF = range.f*(float)score_river[n];
                bufG = range.g*(float)score_soil[n];

                score_final[n] = bufA + bufB + bufC + bufD + bufE + bufF + bufG;
                difference_abs[n] = (float)score_given[n] - score_final[n];
                difference_avg[n] = (float)score_avg[n] - score_final[n];

                if (difference_abs[n] < 0)
                    difference_abs[n] = (-1)*difference_abs[n];

                if (difference_avg[n] < 0)
                    difference_avg[n] = (-1)*difference_avg[n];

            }

            range_abs = InterQuartileRange(difference_abs, max, range);
            range_avg = InterQuartileRange(difference_avg, max, range);

            // Check the ranges
            bestRange_abs = BestRange(bestRange_abs, range_abs);
            bestRange_avg = BestRange(bestRange_avg, range_avg);
            }
        }
    }
}
```

```
    }
}
// ABSOLUTE SCORES
// Create File Name for Absolute Scores
// Rescore Pipes
for (n = 0; n < max; n++)
{
    bufA = bestRange_abs.a*(float)score_matage[n];
    bufB = bestRange_abs.b*(float)score_restaurant[n];
    bufC = bestRange_abs.c*(float)score_depth[n];
    bufD = bestRange_abs.d*(float)score_length[n];
    bufE = bestRange_abs.e*(float)score_traffic[n];
    bufF = bestRange_abs.f*(float)score_river[n];
    bufG = bestRange_abs.g*(float)score_soil[n];

    score_final[n] = bufA + bufB + bufC + bufD + bufE + bufF + bufG;
    difference_abs[n] = (float)score_given[n] - score_final[n];
}

bestRange_abs = InterQuartileRange(difference_abs, max, bestRange_abs);



sprintf(filename,/home/emilio/Desktop/Results_%d/Abs%%:%.5f,%.5f,%.5f,%.3f,%.3f,%.3f,
%.3f,%.3f,%.3f,%.3f.txt", i, bestRange_abs.q1, bestRange_abs.q2, bestRange_abs.q3,
bestRange_abs.a, bestRange_abs.b, bestRange_abs.c, bestRange_abs.d, bestRange_abs.e,
bestRange_abs.f, bestRange_abs.g);
```

```
FILE *f_abs = fopen(filename, "w");

    if (f_abs == NULL)
        printf("Error with %s\n", filename);

for (n = 0; n < max; n++)
{
    // Print Values into text file
    fprintf(f_abs, "%d\t%d\t", objID[n], score_matage[n]);
    fprintf(f_abs, "%d\t%d\t", score_restaurant[n], score_depth[n]);
    fprintf(f_abs, "%d\t%d\t", score_length[n], score_traffic[n]);
    fprintf(f_abs, "%d\t%d\t", score_river[n], score_soil[n]);
    fprintf(f_abs, "%d\t%.2f\t", score_given[n], score_final[n]);
    fprintf(f_abs, "%.2f\t", score_avg[n]);
    fprintf(f_abs, "%.2f\n", difference_abs[n]);
}

fclose(f_abs);

    // This is now for the Average Scores
    for (n = 0; n < max; n++)
    {
        bufA = bestRange_avg.a*(float)score_matage[n];
        bufB = bestRange_avg.b*(float)score_restaurant[n];
        bufC = bestRange_avg.c*(float)score_depth[n];
```

```
        bufD = bestRange_avg.d*(float)score_length[n];
        bufE = bestRange_avg.e*(float)score_traffic[n];
        bufF = bestRange_avg.f*(float)score_river[n];
        bufG = bestRange_avg.g*(float)score_soil[n];

        score_final[n] = bufA + bufB + bufC + bufD + bufE + bufF + bufG;
        difference_avg[n] = (float)score_avg[n] - score_final[n];
    }

    bestRange_avg = InterQuartileRange(difference_avg, max, bestRange_avg);



  sprintf(filename,"/home/emilio/Desktop/Results_%d/Avg%%:%.5f,%.5f,%.5f,%.3f,%.3f,%.3
f,%.3f,%.3f,%.3f,%.3f.txt", i,     bestRange_avg.q1, bestRange_avg.q2, bestRange_avg.q3,
bestRange_avg.a, bestRange_avg.b, bestRange_avg.c, bestRange_avg.d, bestRange_avg.e,
bestRange_avg.f, bestRange_avg.g);

    FILE *f_avg = fopen(filename, "w");

    if (f_avg == NULL)
        printf("Error with %s\n", filename);


    for (n = 0; n < max; n++)
    {
        // Print Values into text file
```

```
			fprintf(f_avg, "%d\t%d\t", objID[n], score_matage[n]);
			fprintf(f_avg, "%d\t%d\t", score_restaurant[n], score_depth[n]);
			fprintf(f_avg, "%d\t%d\t", score_length[n], score_traffic[n]);
			fprintf(f_avg, "%d\t%d\t", score_river[n], score_soil[n]);
			fprintf(f_avg, "%d\t%.2f\t", score_given[n], score_final[n]);
			fprintf(f_avg, "%.2f\t", score_avg[n]);
			fprintf(f_avg, "%.2f\n", difference_avg[n]);
		}

		fclose(f_avg);
		printf("\n");
	}
}
```

C.4 STATISTICS.H

```
#include <stdio.h>

#include <math.h>


typedef struct

{

    float a, b, c, d, e, f, g;

    float q1, q2, q3;

}   IQR;


/*------------------------------------------*/


int IsOdd(value)

{

    if (value % 2 == 0)

        return 0; //It is even odd==false

    else

        return 1; //It is odd odd==true

}

/*------------------------------------------*/

void BubbleSort(float *values, int max)

{

    int i, j;

    float temp;
```

```
    for (i = 0; i < (max - 1); i++)
    {
        for (j = 0; j < (max - i - 1); j++)
        {
            if (values[j] > values[j + 1])
            {
                temp = values[j];
                values[j] = values[j + 1];
                values[j + 1] = temp;
            }
        }
    }
}
/*---------------------------------------------*/
void MergeSortedHalves(float *values, int left, int middle, int right)
{
    int length = right - left + 1;
    float temp[length];
    int index1, index2, index;

    index1 = left; // first element of first half
    index2 = middle + 1; // first element of second half
    index = 0; // Beginning of temp array

    while (index1 <= middle && index2 <= right)
    {
```

```
            if (values[index1] < values[index2])
                  temp[index++] = values[index1++];
            else
                  temp[index++] = values[index2++];
      }

      if (index1 <= middle)
      {
            while (index1 <= middle)
            temp[index++] = values[index1++];
      }
      else
      {
            while (index2 <= right)
                  temp[index++] = values[index2++];
   }

   index1 = left;

   for (index = 0; index < length; index++)
      values[index1++] = temp[index];
}
/*------------------------------------------*/
void MergeSort(float *values, int first, int last)
{
      int middle;
```

```
    if (first < last)
    {
        middle = (first + last)/2;
        MergeSort(values, first, middle);
        MergeSort(values, middle + 1, last);
        MergeSortedHalves(values, first, middle, last);
    }
    else
    {
        ; // Does nothing
    }
}
/*---------------------------------------------*/
IQR InterQuartileRange(float *values, int max, IQR range)
{
    int i;
    float sort[max];

    // Copy all values to the sorted value
    for (i = 0; i < max; i++)
    {
        sort[i] = values[i];
    }

    // Sort Values
```

```
MergeSort(sort, 0, max - 1);


// Calculate Median (q2), 1st quartile (q1), 3rd quartile (q3)
if (max % 2 == 0)
{
    range.q2 = (sort[max/2] + sort[max/2 - 1])/2.0;

    if (IsOdd(max/2) == 0) //IsOdd == False
    {
        range.q1 = (sort[max/4] + sort[max/4 - 1])/2.0;
        range.q3 = (sort[max*3/4] + sort[max*3/4 - 1])/2.0;
    }
    else //IsOdd(max/2) == 1 (True)
    {
        range.q1 = sort[max/4];
        range.q3 = sort[max*3/4];
    }
}
else
{
    range.q2 = sort[max/2];

    if (IsOdd(max/2) == 0) //IsOdd == False
    {
        range.q1 = (sort[max/4] + sort[max/4 - 1])/2.0;
        range.q3 = (sort[max*3/4] + sort[max*3/4 + 1])/2.0;
```

```
        }
        else //IsOdd(max/2) == 1 (True)
        {
            range.q1 = sort[max/4];
            range.q3 = sort[max*3/4];
        }
    }
    return range;
}
/*-------------------------------------------*/
float Average(float *values, int max)
{
    float sum = 0;
    int n;

    for (n = 0; n < max; n++)
    {
        sum = sum + values[n];
    }

    return (sum/max);
}
/*-------------------------------------------*/
float StandardDeviation(float *values, float avg, int max)
{
    float sum = 0; // sum of (xi - mean)^2
```

```
    int n;

    for (n = 0; n < max; n++)
    {
        sum = sum + ((values[n] - avg)*(values[n] - avg));
    }

    return sqrtf(sum/(float)max);
}
/*-------------------------------------------*/
```

APPENDIX D GIS MAPS AND DATA

Figure D-1 Available Data

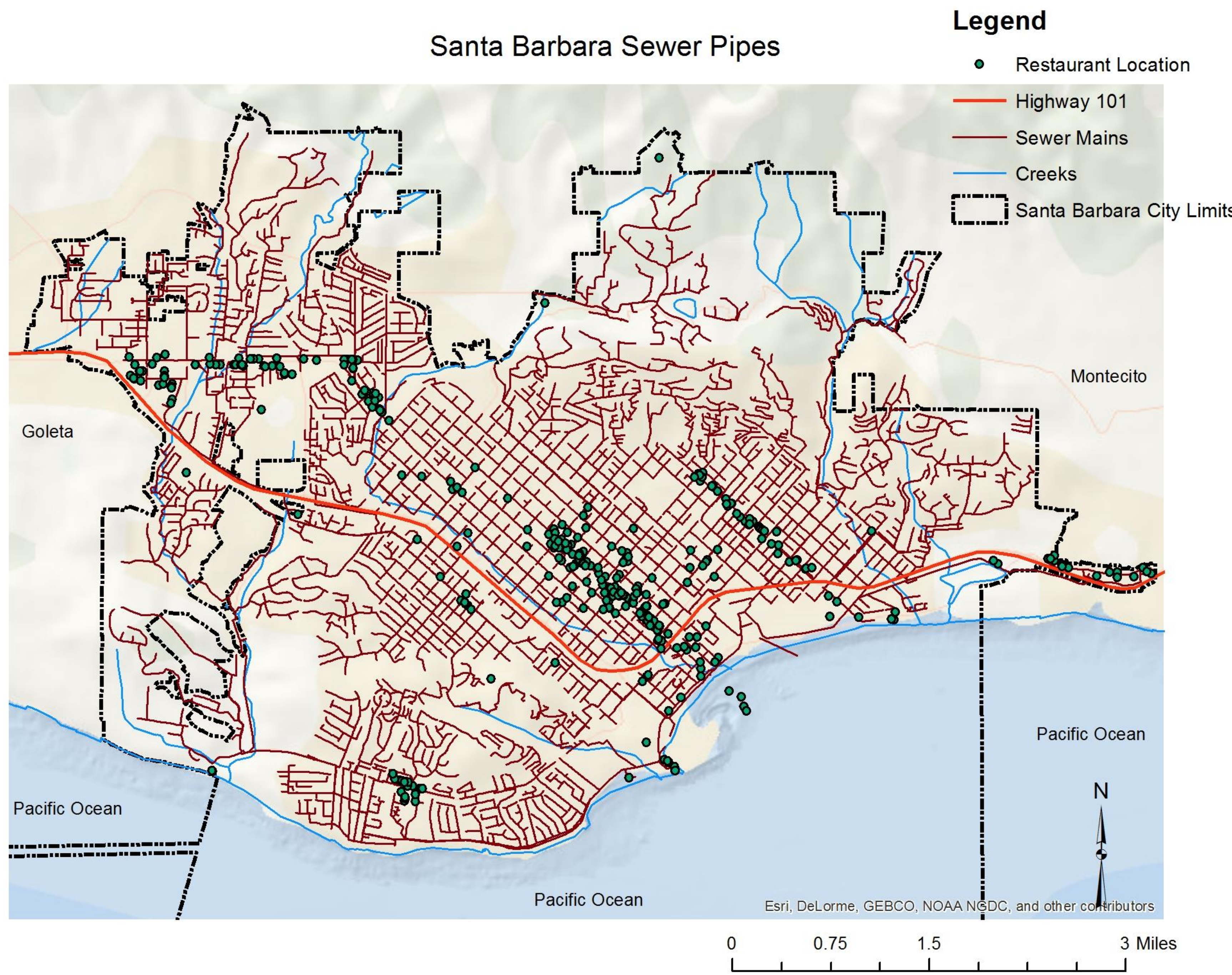


Figure D-2 Restaurant Locations

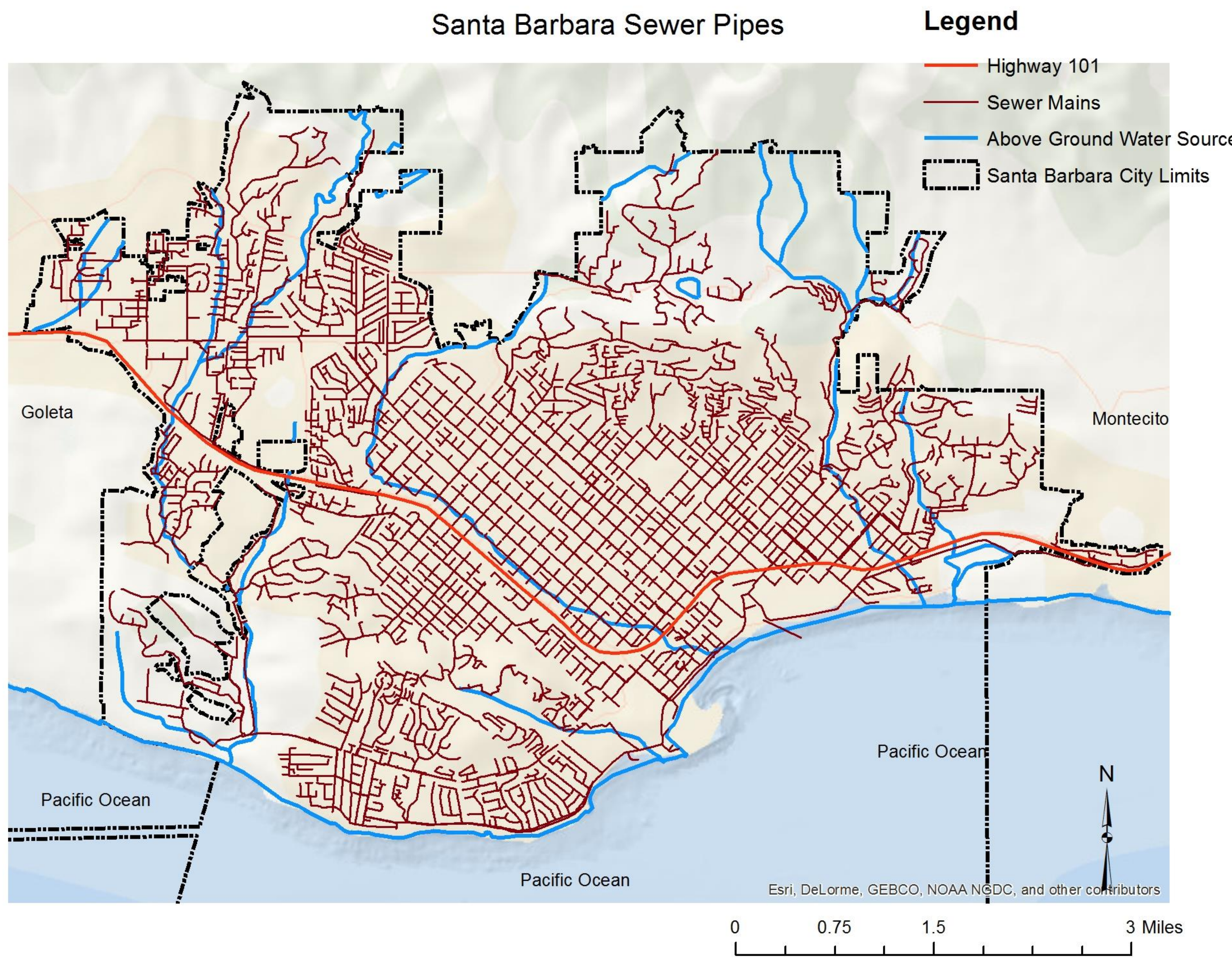


Figure D-3 Above-Ground Water Source

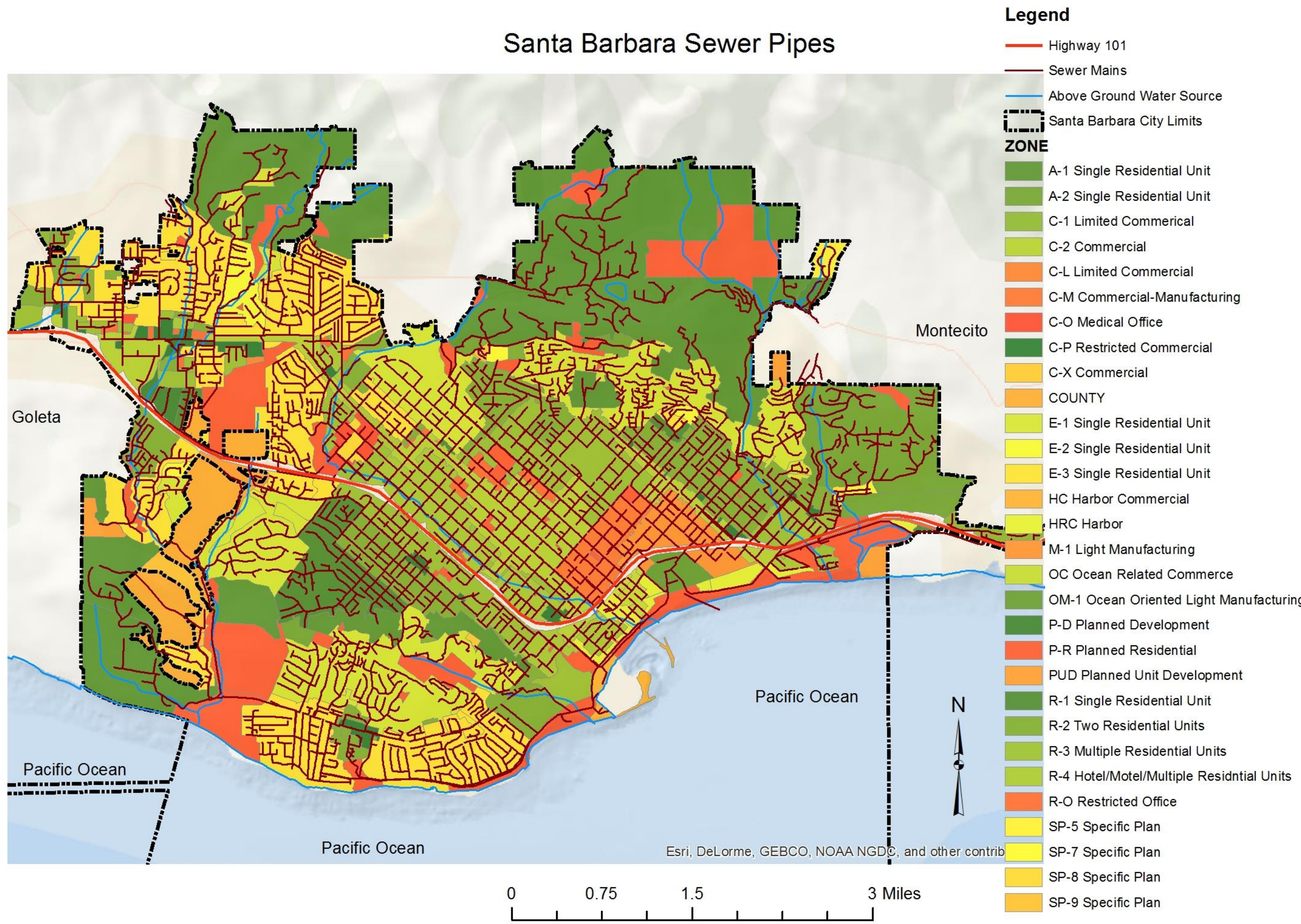


Figure D-4 City of Santa Barbara Zoning Map

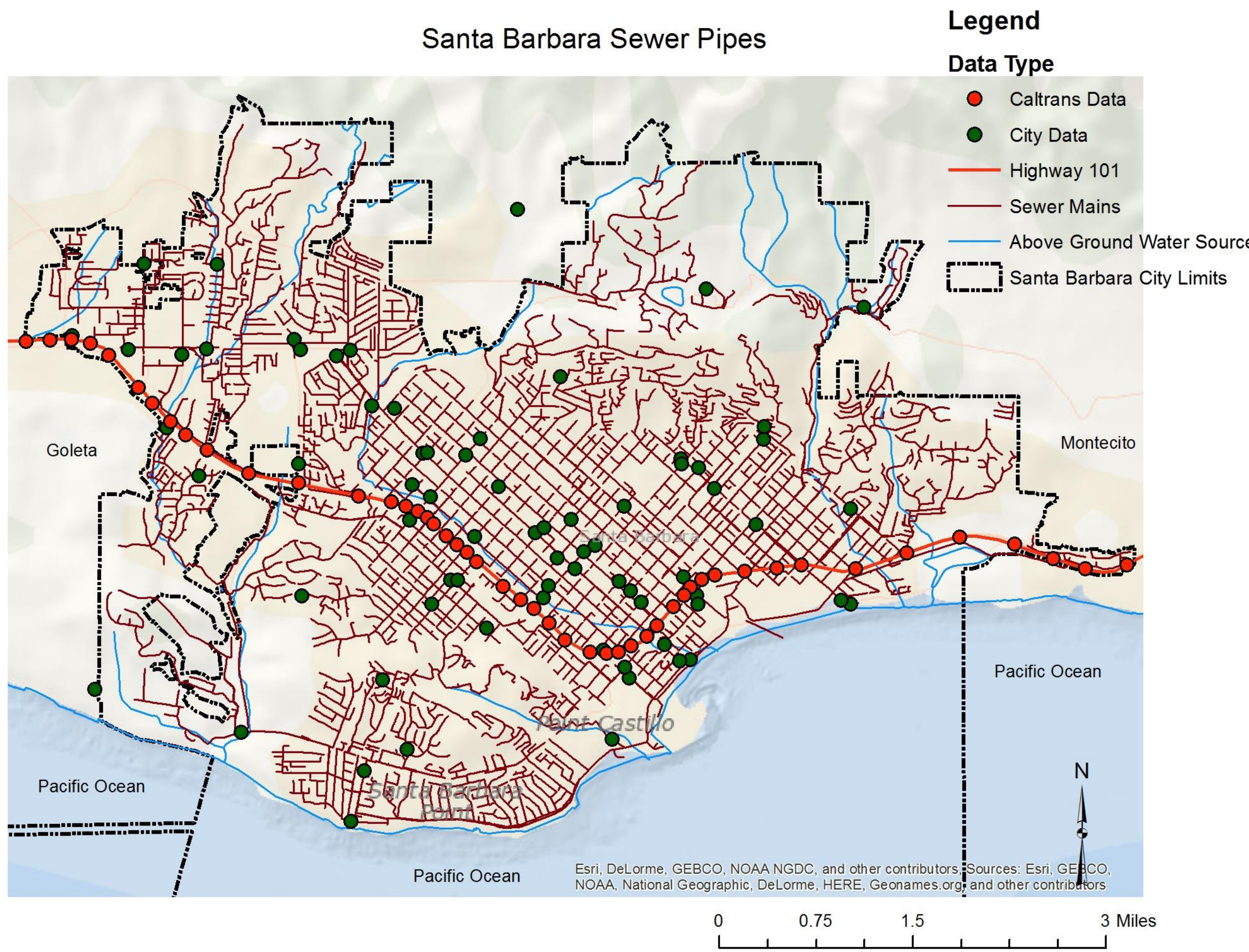


Figure D-5 City and Caltrans Data Collection Locations

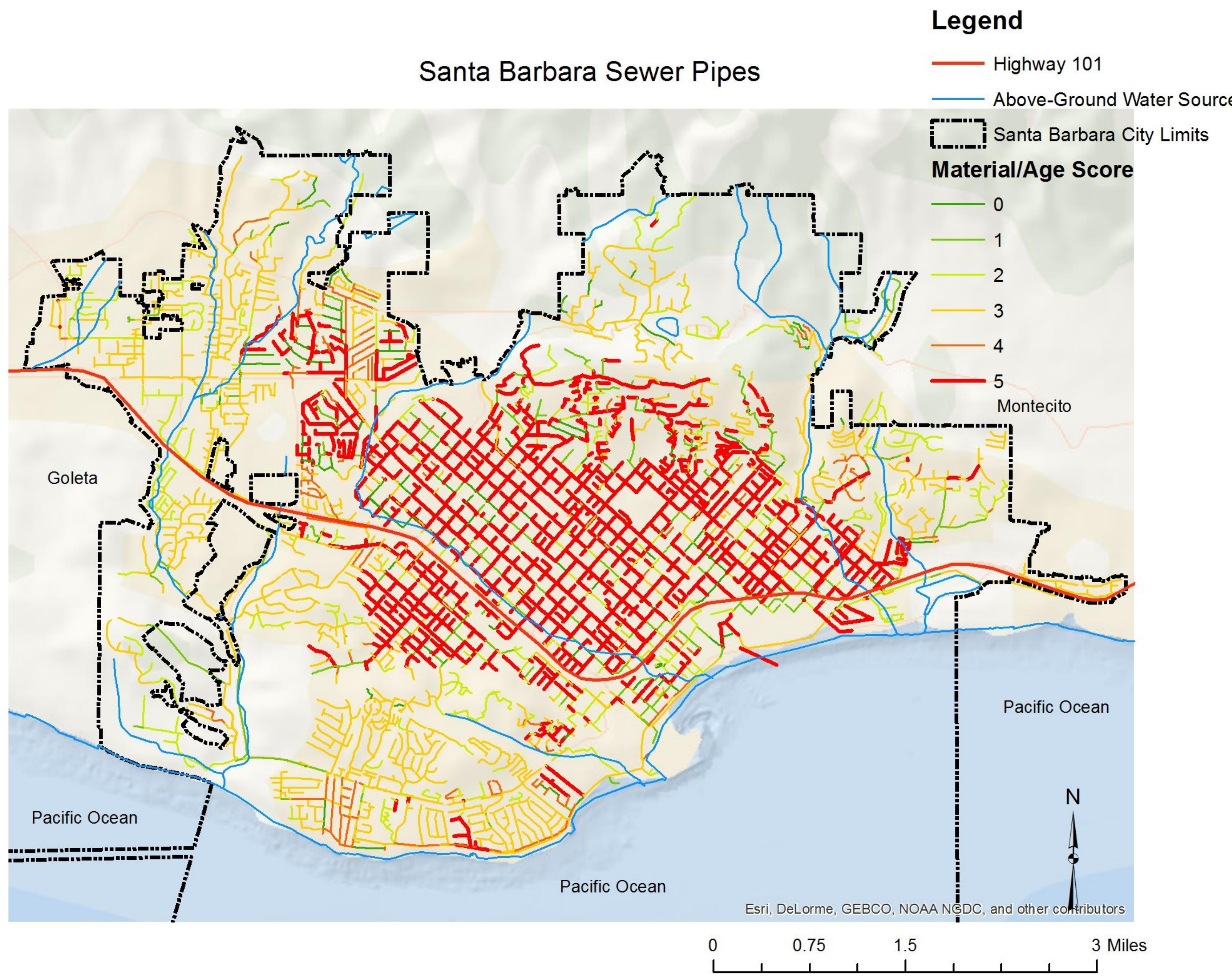


Figure D-6 Pipe Material and Age Scoring

Figure D-7 Pipe Material

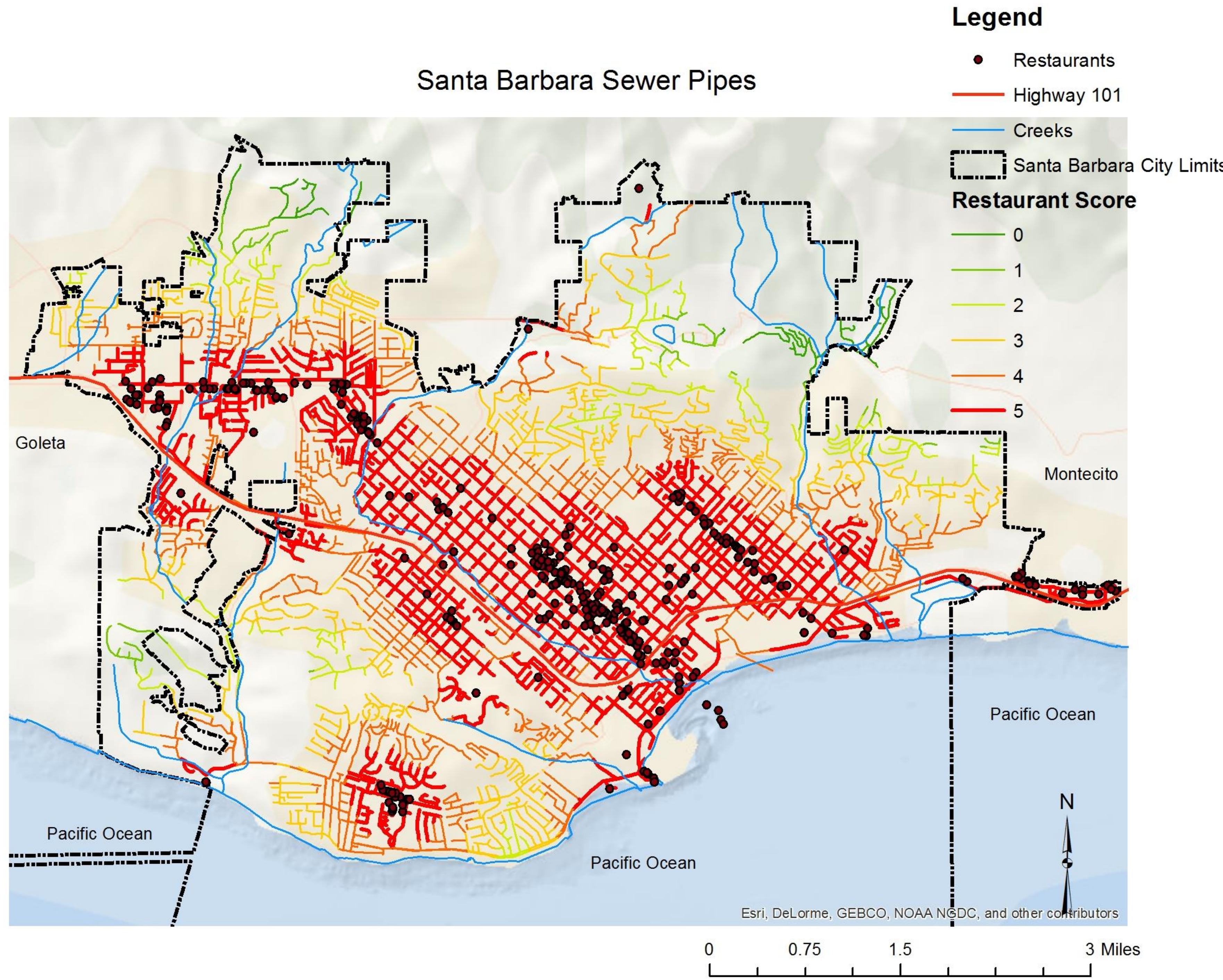


Figure D-8 Restaurant Scoring

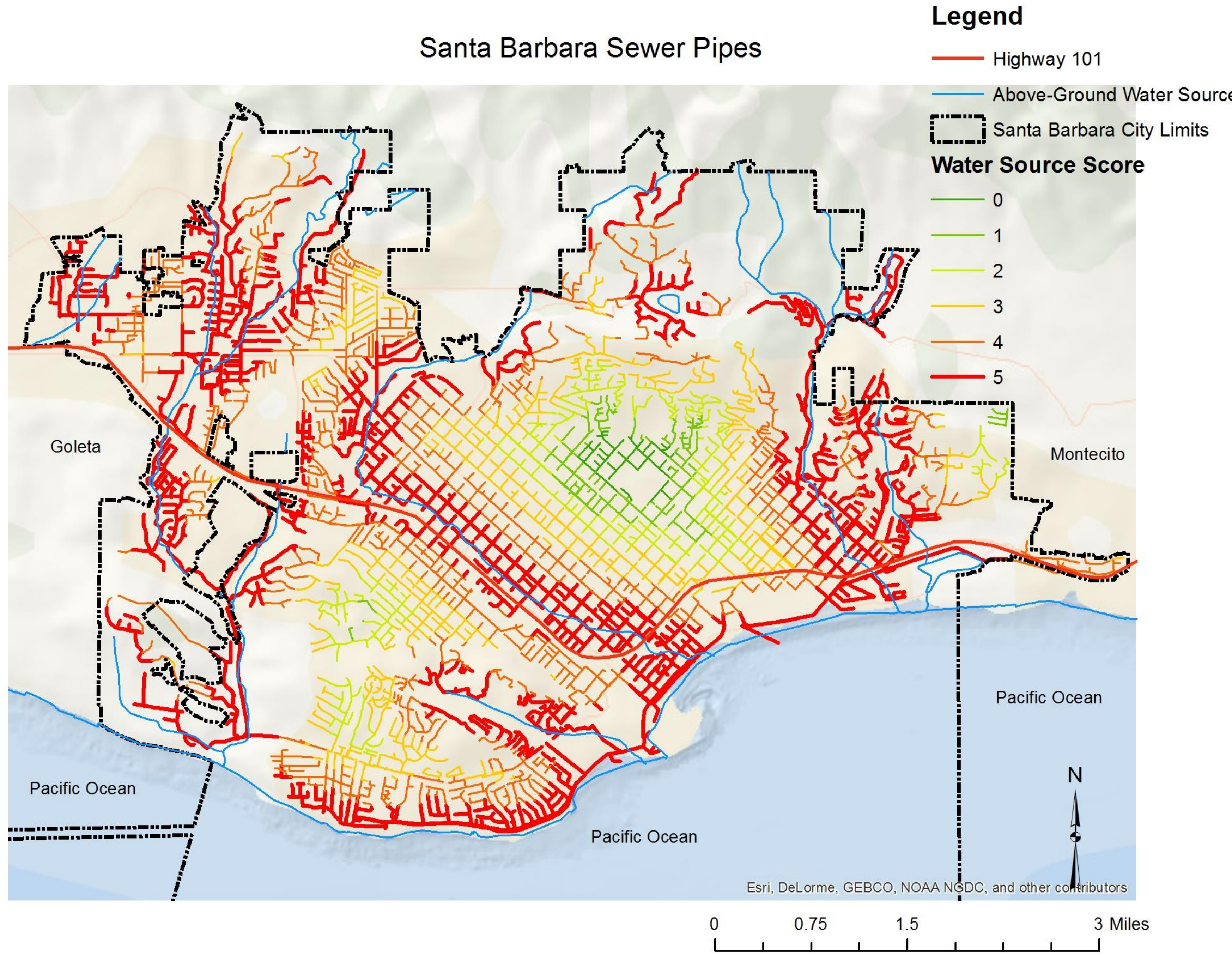


Figure D-9 Distance from Above-Ground Water Source Scoring

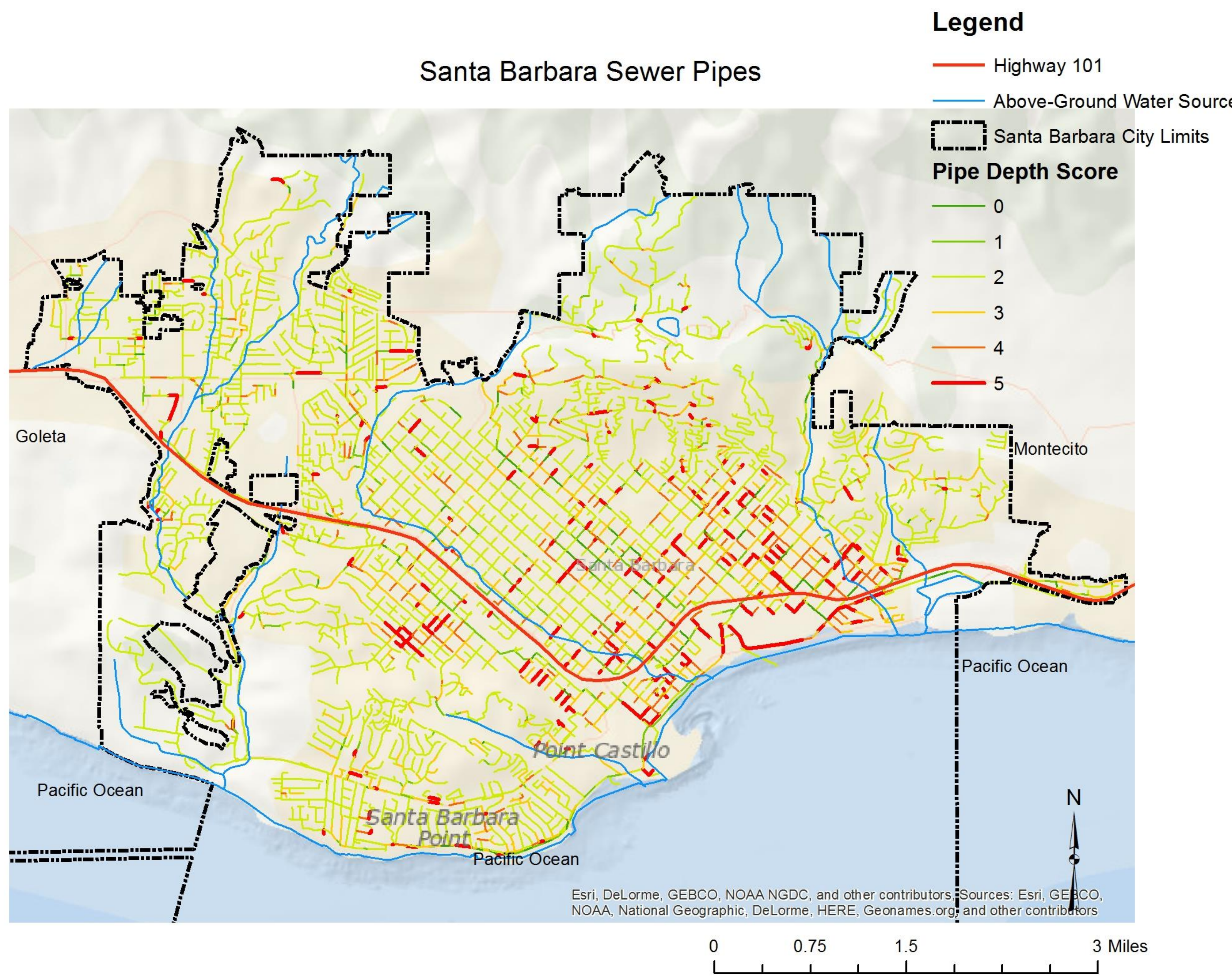


Figure D-10 Pipe Depth Scoring

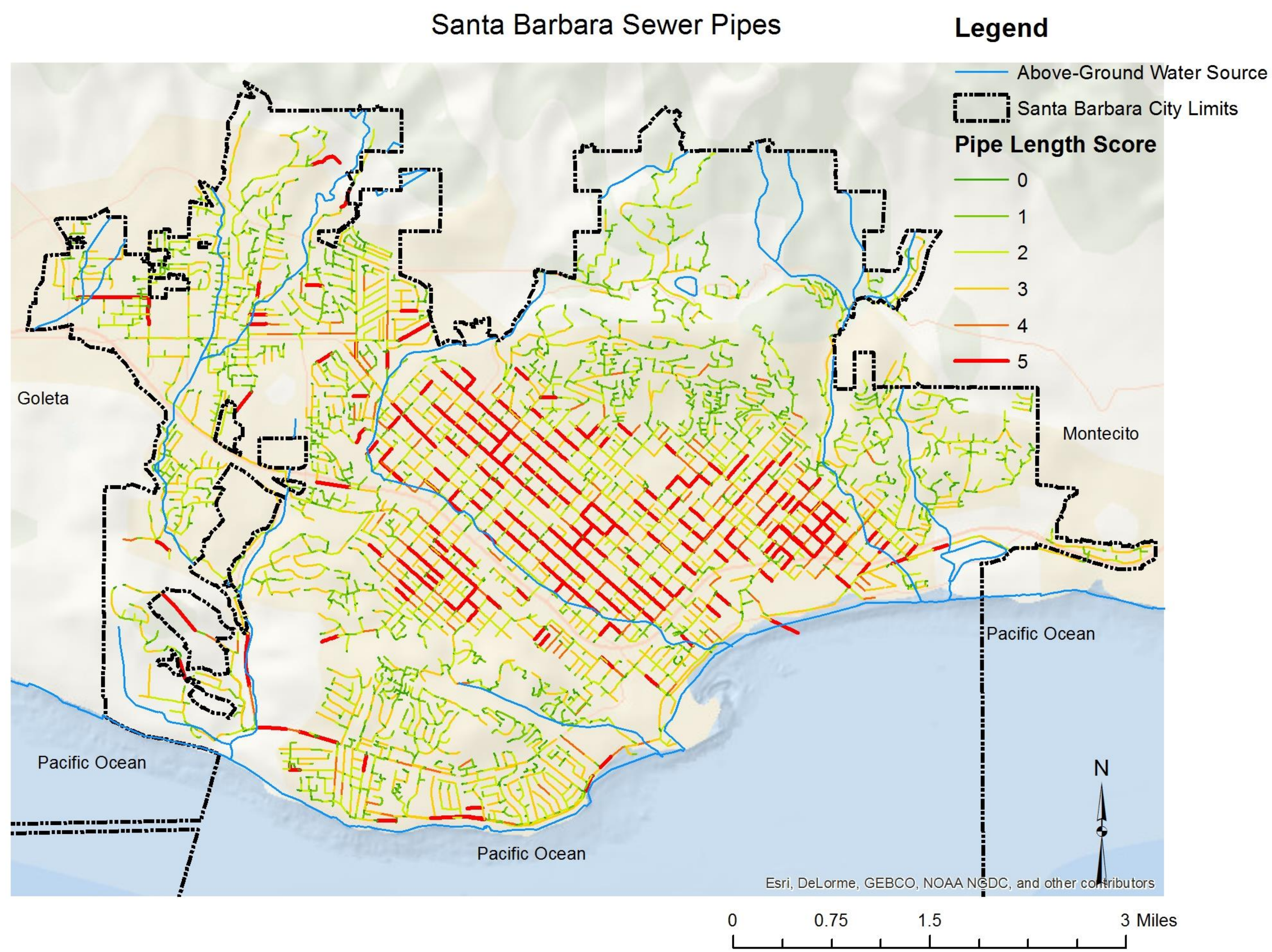


Figure D-11 Pipe Length Scoring

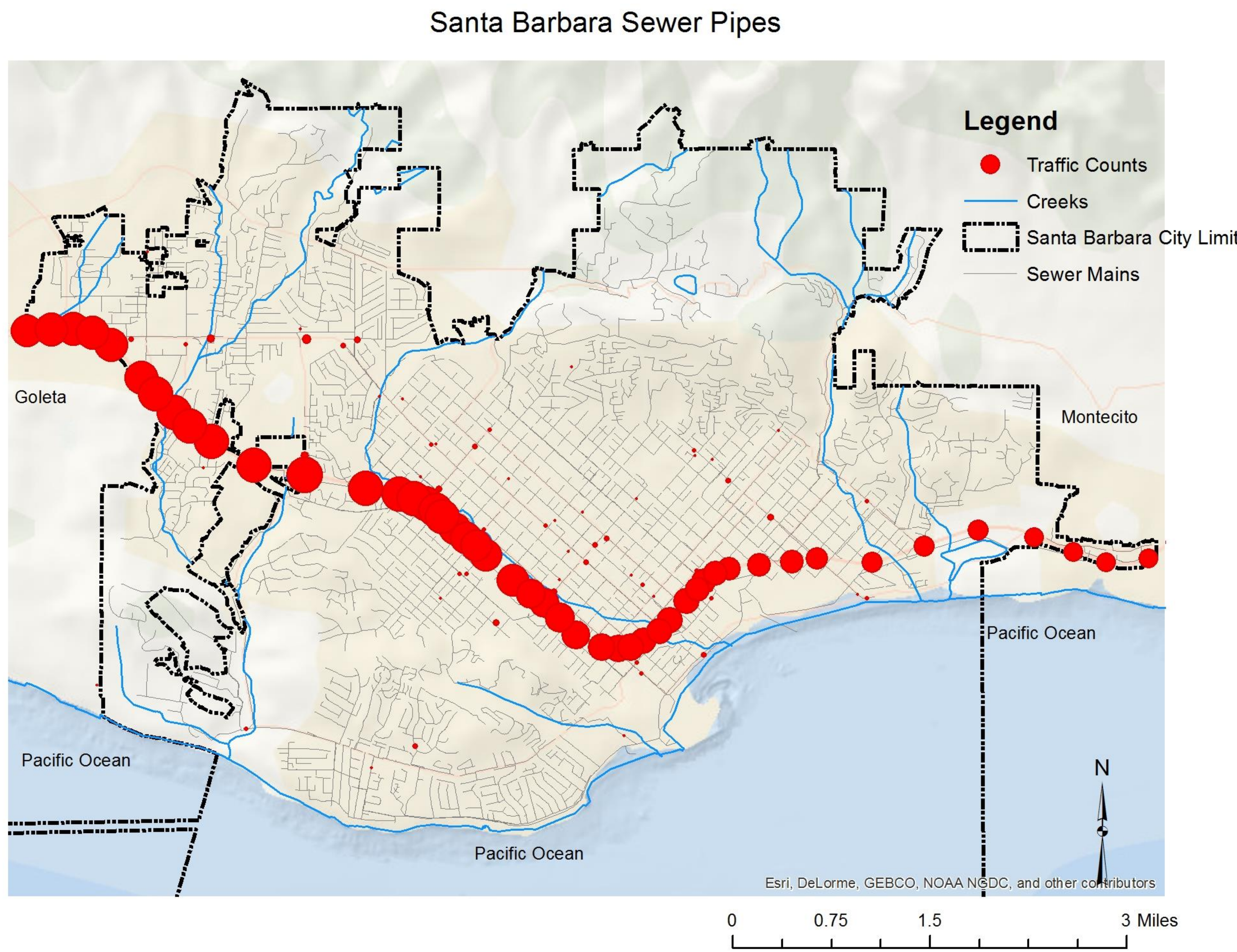


Figure D-12 Step One for Vehicular Traffic Data – Data

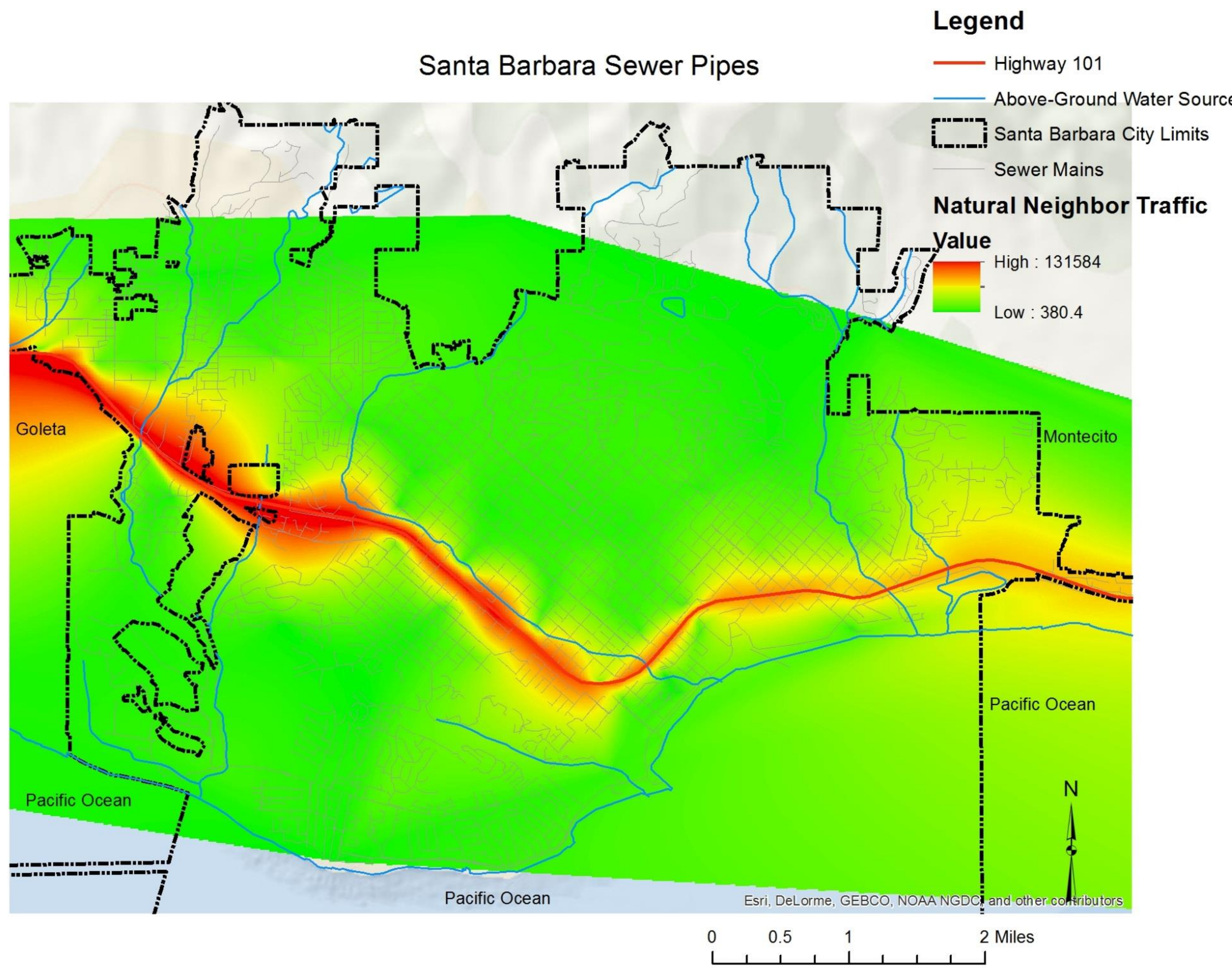


Figure D-13 Step Two for Vehicular Traffic Data – Natural Neighbor Tool

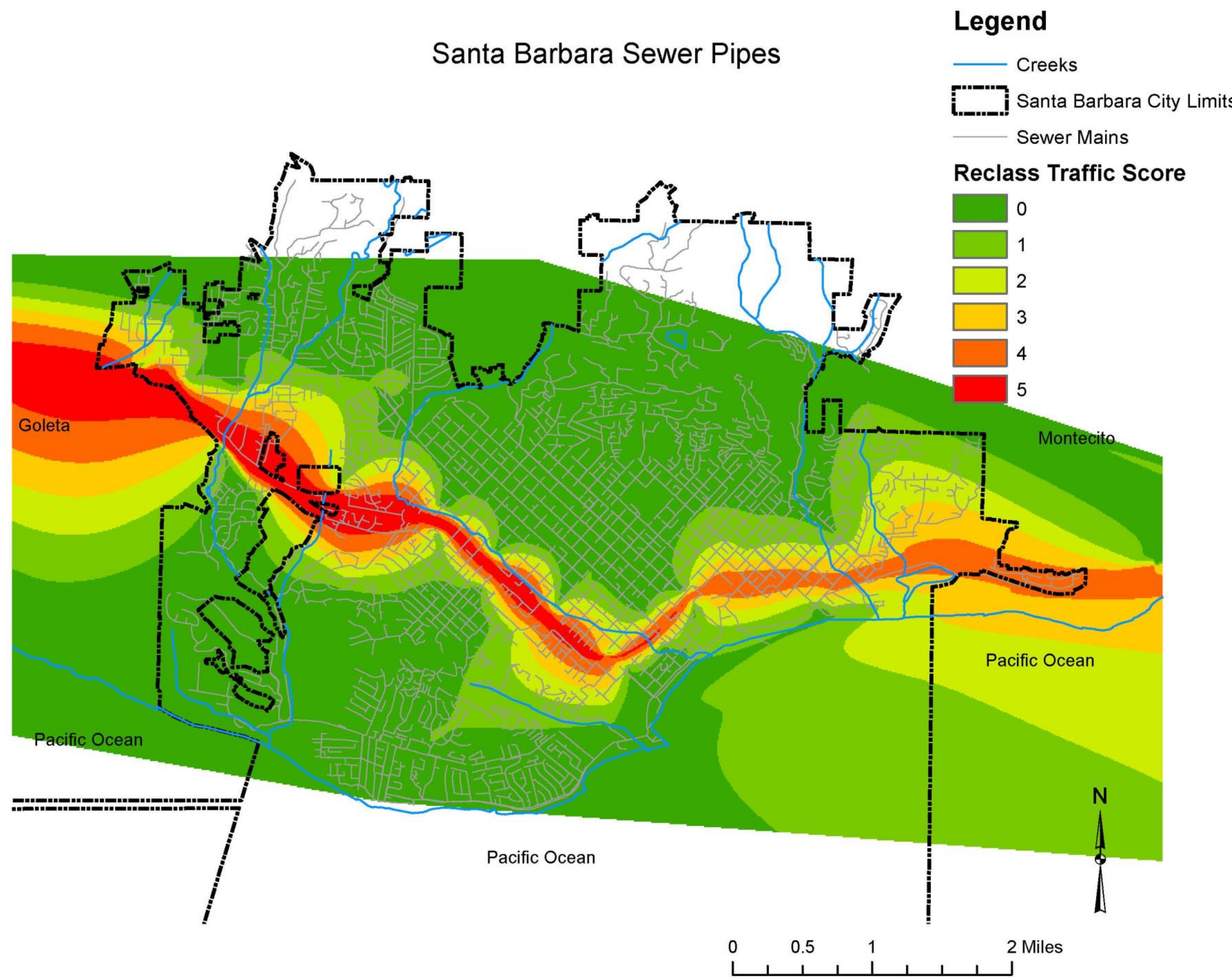


Figure D-14 Step Three for Vehicular Traffic Data – Reclassify Tool

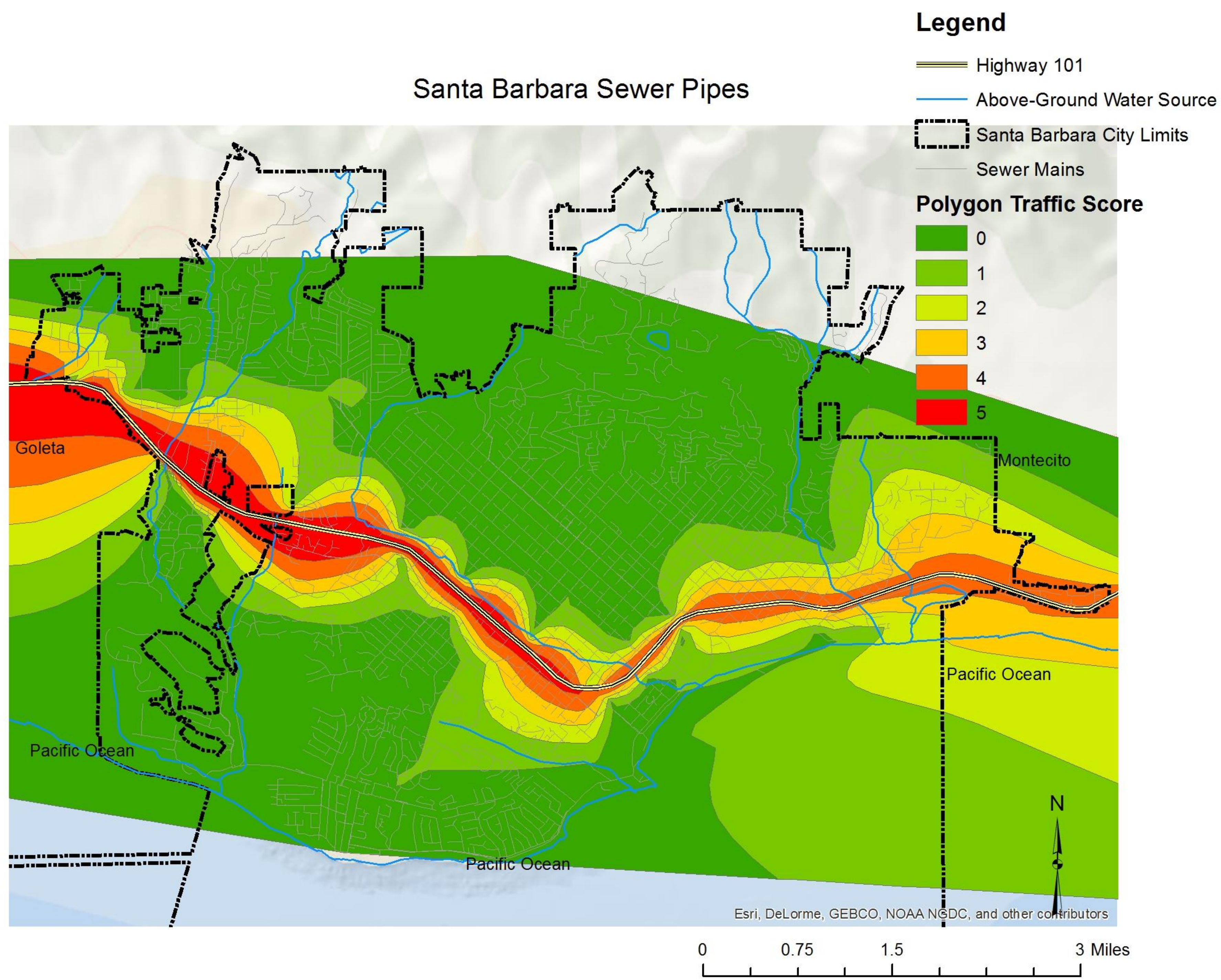


Figure D-15 Step Four for Vehicular Traffic Data – Raster to Polygon Tool

Figure D-16 Step Four for Vehicular Traffic Data – Scoring with Select by Location

Figure D-17 Pipe Diameter Scoring

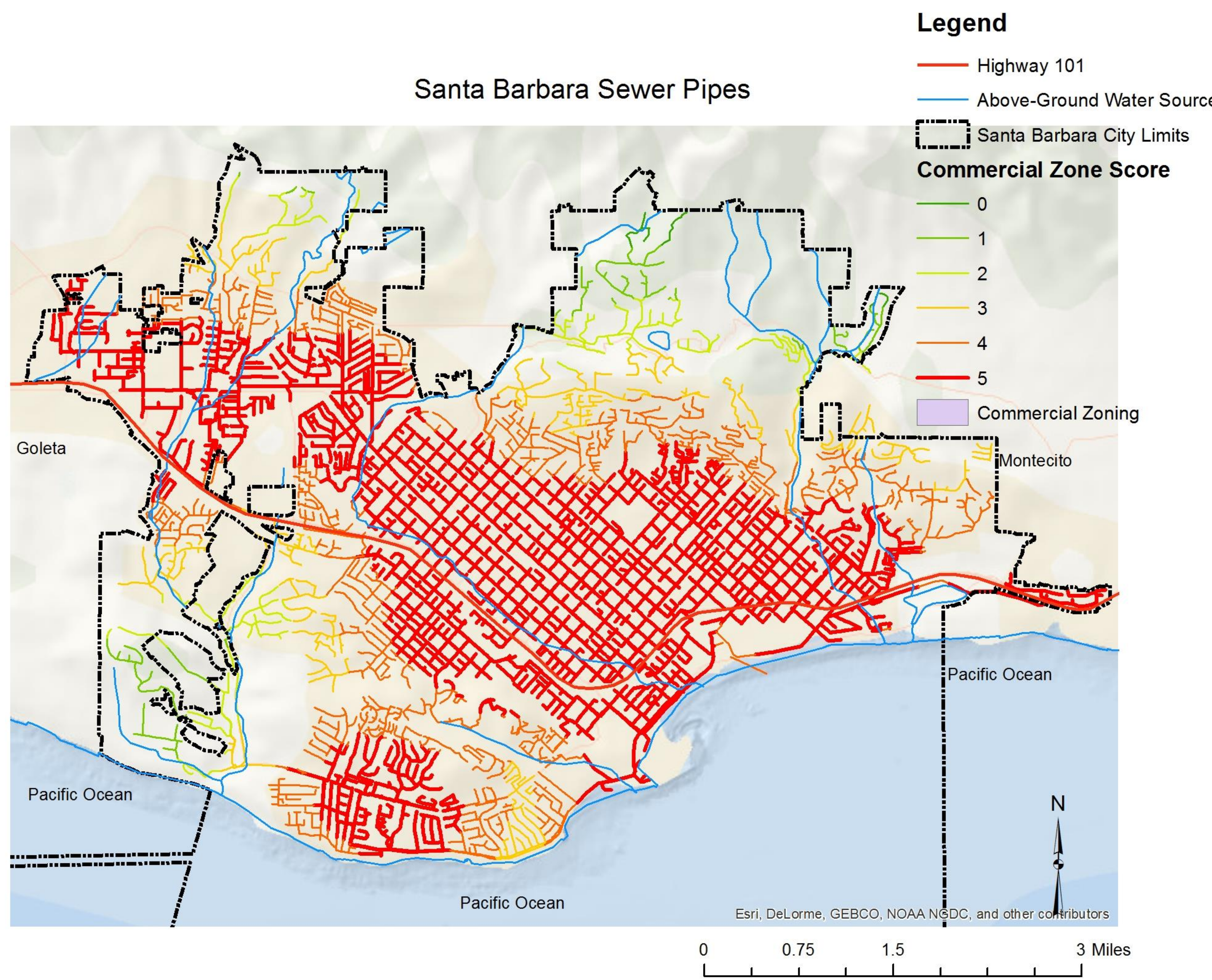


Figure D-18 Commercial Zone Scoring

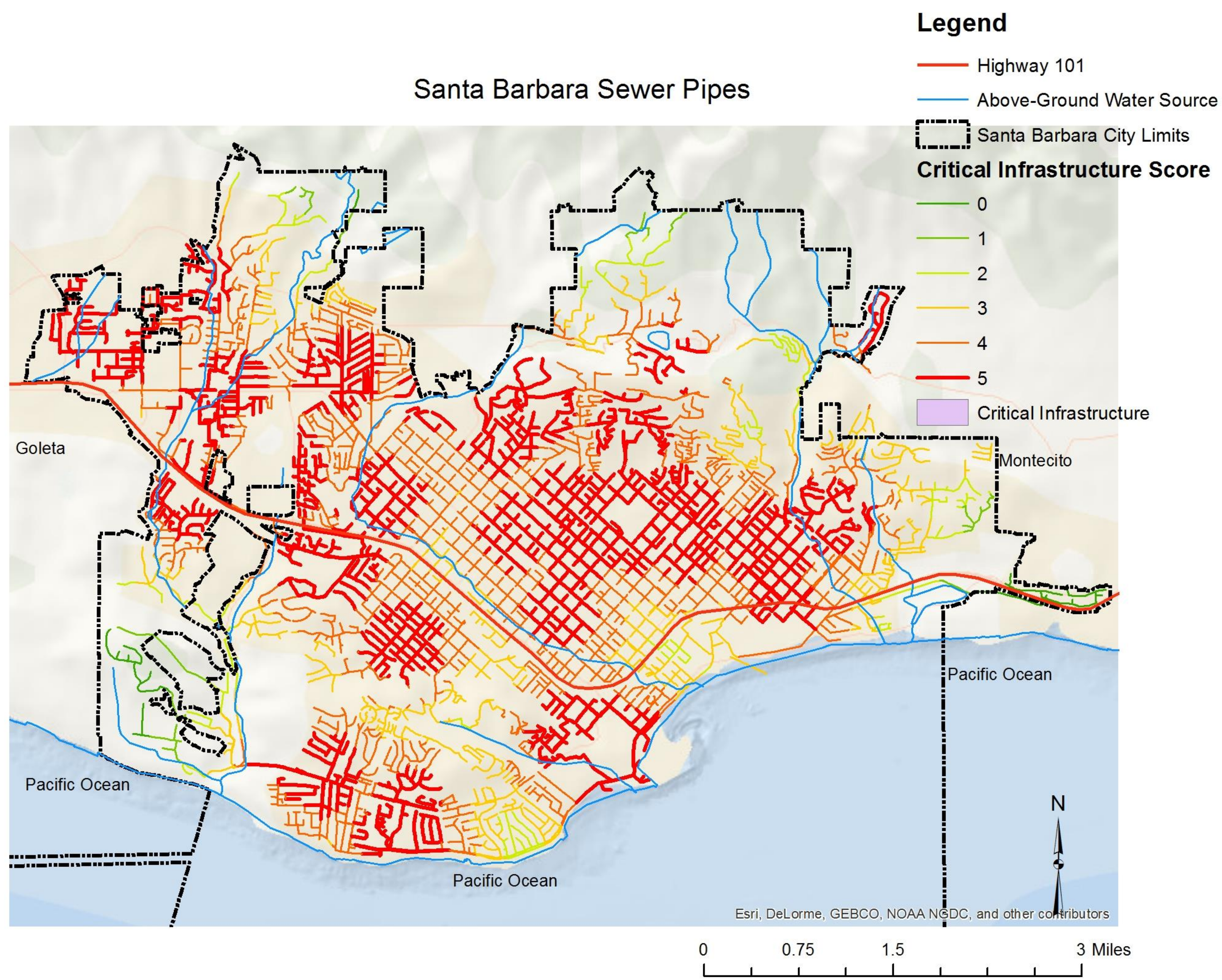


Figure D-19 Critical Zone Scoring

APPENDIX E CALTRANS TRAFFIC COUNT DATA

Route	County		Postmile	Description	Back Peak Hour	Back Peak Month	Back AADT	Ahead Peak Hour	Ahead Peak AADT	Ahead AADT
101	VEN		26.39	VENTURA, JCT. RTE. 126	7400	95000	89000	9900	129000	119000
101	VEN		28.452	VENTURA, SEAWARD AVENUE	9900	129000	119000	10100	125000	117000
101	VEN		29.45	VENTURA, VISTA DEL MAR DRIVE	10100	125000	117000	10000	121000	113000
101	VEN		30.147	VENTURA, CALIFORNIA STREET	10000	121000	113000	8300	98000	91000
101	VEN		30.906	VENTURA, JCT. RTE. 33	8300	98000	91000	5800	78000	70000
101	VEN	R	32.7	SOLIMAR BEACH, SOUTH JCT. RTE. 1	5800	78000	70000	5700	74000	66000
101	VEN	R	38.976	SEACLIFF, NORTH JCT. RTE. 1	5700	74000	66000	5900	76000	67000
101	VEN	R	43.622	VENTURA/SANTA BARBARA COUNTY LINE	5800	74000	66000			
101	SB	R	0	VENTURA/SANTA BARBARA COUNTY LINE				5800	74000	66000
101	SB	R	0.634	JCT. RTE. 150 EAST	5700	70000	61000	5800	71000	64000
101	SB		1.622	EL RINCON	5800	71000	64000	6000	70000	66500
101	SB		2.64	CARPINTERIA, CASITAS PASS ROAD	6000	70000	66500	6000	66000	60600
101	SB		3.059	CARPINTERIA, LINDEN AVENUE	6000	66000	60600	6300	71000	65400
101	SB		3.773	CARPINTERIA, SANTA MONICA ROAD	6300	71000	65400	6100	67000	61600
101	SB	R	5.283	SOUTH PADARO LANE	6300	68000	63300	6300	68000	62700
101	SB	R	7.138	PADARO LANE	6300	68000	62700	6300	69000	62900
101	SB	R	8.264	EVANS AVENUE	6300	69000	62900	5400	66000	64000
101	SB		9.003	MONTECITO, SHEFFIELD DRIVE	5400	66000	64000	6600	71000	65700
101	SB		10.023	SAN YSIDRO ROAD	6600	71000	65700	7100	77000	71100
101	SB		10.536	OLIVE MILL ROAD	7100	77000	71100	6600	72000	66100
101	SB		11.407	SANTA BARBARA, JCT. RTE. 225 WEST	6500	71000	65200	7400	84000	76800
101	SB		12.754	SANTA BARBARA, JCT. RTE. 144	7500	84000	78000	8000	93000	85300
101	SB		13.485	SANTA BARBARA, GARDEN STREET	8000	93000	85300	8600	102000	94300

101	SB	R	14.187	SANTA BARBARA, CASTILLO STREET	8600	102000	94300	9500	108000	103000
101	SB	R	14.758	SANTA BARBARA, CARRILLO STREET	9500	108000	103000	9900	123000	117000
101	SB	R	15.733	SANTA BARBARA, MISSION STREET	9900	123000	117000	11000	139000	133000
101	SB		16.552	SANTA BARBARA, JCT. RTE. 225 SOUTHEAST	11000	139000	133000	11000	137000	132000
101	SB		17.784	LA CUMBRE ROAD	11000	134000	128000	11300	134000	127000
101	SB		18.364	JCT. RTE. 154	11200	133000	127000	11500	124000	118000
101	SB		18.924	EL SUENO ROAD	11500	124000	118000	11000	129000	119000
101	SB		20.062	TURNPIKE ROAD	11000	129000	119000	11000	125000	115000
Route	County		Postmile	Description	Back Peak Hour	Back Peak Month	Back AADT	Ahead Peak Hour	Ahead Peak AADT	Ahead AADT
101	SB		21.414	JCT. RTE. 217 SOUTH	11000	125000	115000	8900	83000	79400
101	SB		22.533	FAIRVIEW AVENUE	8900	83000	79400	7100	78000	71000
101	SB		23.711	LOS CARNEROS ROAD	7100	78000	71000	5900	69000	65000
101	SB		24.762	STORKE ROAD	5900	69000	65000	4000	41000	35400
101	SB		26.907	HOLLISTER AVENUE	4000	41000	35400	4000	38000	31500
101	SB		33.852	EL CAPITAN BEACH STATE PARK	4000	38000	31000	4000	32000	30200
101	SB	R	48.847	LAS CRUCES, JCT. RTE. 1 NORTHWEST	3100	35000	30100	3000	28000	23700
101	SB	R	56.463	SANTA ROSA ROAD	3000	28000	23700	3000	27000	22900
101	SB	R	57.117	BUELLTON, JCT. RTE. 246	3000	27000	22900	2500	24000	21200
101	SB	R	57.552	NORTH BUELLTON	2500	24000	21200	2500	27000	23400
101	SB		62.671	ZACA, JCT. RTE. 154 EAST	2500	27000	23400	3100	33000	30400
101	SB		70.921	LOS ALAMOS, JCT. RTE. 135 NORTHWEST	3100	33000	30400	3200	33000	28800
101	SB		82.183	SANTA MARIA, CLARK AVENUE	3200	33000	29600	4000	47000	40700
101	SB		84.336	SOUTH SANTA MARIA	4000	47000	40700	5000	53000	47000
101	SB		86.588	BETTERAVIA ROAD	5000	53000	47600	6000	66000	59800
101	SB		87.603	EAST STOWELL ROAD	6000	66000	59800	6500	72000	65000

101	SB		88.601	SANTA MARIA, JCT. RTE. 166 WEST	6500	72000	65000	6000	67000	61800
101	SB		89.693	SANTA MARIA, DONOVAN ROAD	6000	67000	61800	5800	63000	58000
101	SB		90.749	JCT. RTE. 135 SOUTH	5800	63000	58000	6200	70000	64100
101	SB		90.988	SANTA BARBARA/SAN LUIS OBISPO COUNTY LINE	6200	70000	64100			

APPENDIX F RESULTS

Table F-1 Above-Ground Water Source Data Distribution

Distance from Above-Ground Water Source				
Distance (ft)	Total Count	Total Percent	Data Count	Data Percent
0-750	2201	34.88	307	32.94
750-1500	1692	26.81	229	24.57
1500-2250	1074	17.02	178	19.10
2250-3000	634	10.05	108	11.59
3000-3750	441	6.99	60	6.44
3750-4500	203	3.22	43	4.61
4500-5250	64	1.01	7	0.75
5250-6000	1	0.02	0	0.00
Σ	6310	100.00	932	100.00

Table F-2 Traffic Volume Data Distribution

Traffic Volume				
AADTV (cars/day)	Total Count	Total Percent	Data Count	Data Percent
0-21931	3717	58.91	474	50.86
21931-43861	1158	18.35	173	18.56
43861-65792	524	8.30	85	9.12
65792-87722	380	6.02	94	10.09
87722-109653	333	5.28	77	8.26
>109653	198	3.14	29	3.11
Σ	6310	100.00	932	100.00

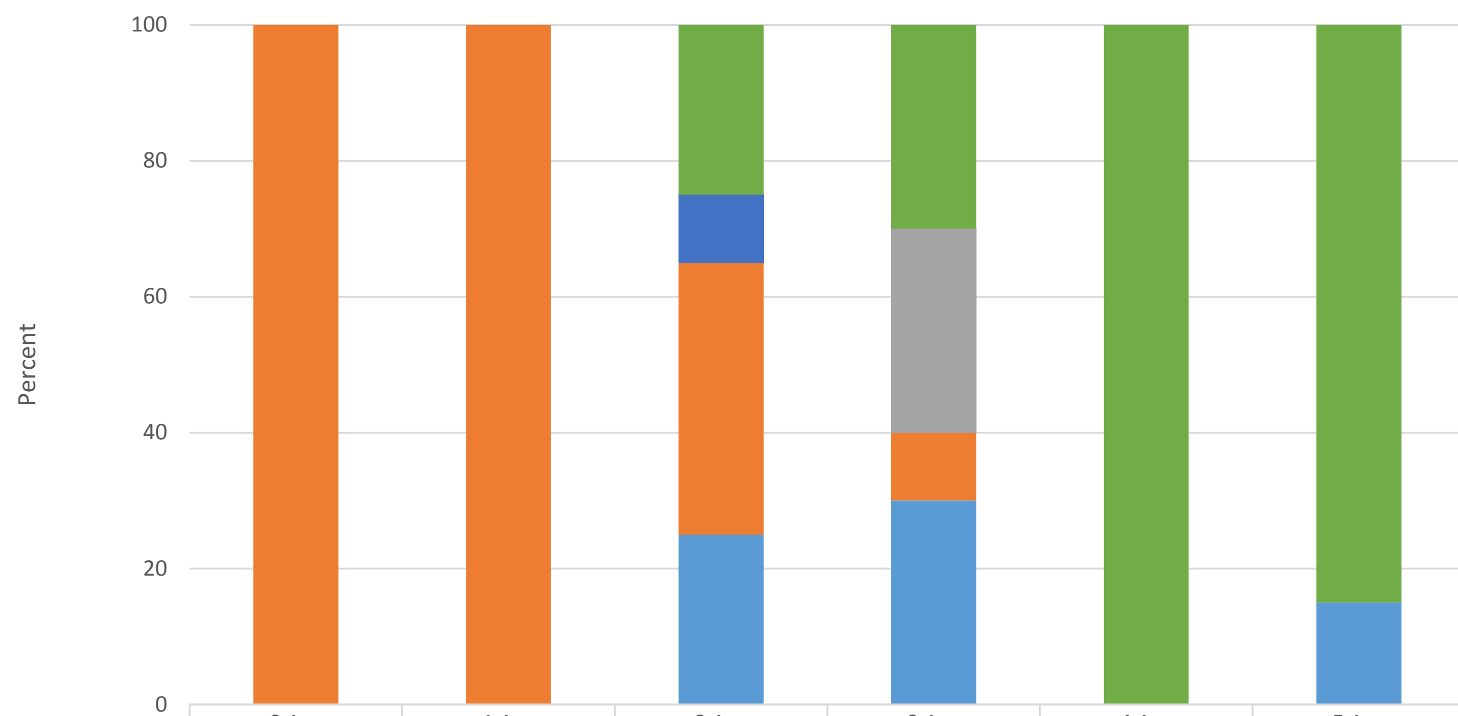
Table F-3 Criticality Sensitivity Results

Trial	Scores	Material	Type	1Q	2Q	3Q	Range	Material/Age	Restaurant	Depth	Length	Traffic	River	Minimum	Maximum
0	0	All	Abs	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	0.00
0	0	All	Avg	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	0.00
1	1	All	Abs	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	1.00
1	1	All	Avg	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	1.00
2	2	All	Abs	-0.25	0.00	0.25	0.50	0.25	0.40	0.00	0.00	0.10	0.25	-1.55	1.50
2	2	All	Avg	-0.54	0.00	0.25	0.79	0.25	0.50	0.00	0.00	0.00	0.25	-2.15	1.50
3	3	All	Abs	-0.30	0.00	0.30	0.60	0.30	0.10	0.30	0.00	0.00	0.30	-1.40	2.10
3	3	All	Avg	-0.50	0.00	0.50	1.00	0.20	0.10	0.20	0.30	0.00	0.20	-3.10	2.00
4	4	All	Abs	-1.00	0.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	1.00	-1.00	4.00
4	4	All	Avg	-0.40	0.00	0.55	0.95	0.40	0.00	0.10	0.00	0.15	0.35	-2.75	3.05
5	5	All	Abs	0.30	0.85	1.70	1.40	0.30	0.15	0.00	0.00	0.00	0.00	0.00	0.00
5	5	All	Avg	-0.45	0.09	0.90	1.35	0.55	0.00	0.00	0.00	0.00	0.45	-2.75	3.65
6	1-5	All	Abs	-1.00	0.00	1.00	2.00	0.00	0.00	0.50	0.00	0.00	0.50	-4.00	5.00
6	1-5	All	Avg	-0.80	0.00	0.90	1.70	0.20	0.00	0.30	0.30	0.10	0.10	-3.50	3.40
7	0-5	All	Abs	0.00	0.00	2.50	2.50	0.00	0.25	0.00	0.00	0.75	0.00	-4.50	5.00
7	0-5	All	Avg	0.00	0.00	2.00	2.00	0.00	0.00	0.00	0.00	1.00	0.00	-5.00	5.00
8	0-5	VCP	Abs	-0.60	0.00	2.10	2.70	0.00	0.30	0.30	0.00	0.40	0.00	-3.50	5.00
8	0-5	VCP	Avg	0.00	0.00	2.08	2.08	0.00	0.00	0.00	0.00	1.00	0.00	-5.00	5.00
9	1-5	VCP	Abs	-1.00	0.00	1.00	2.00	0.25	0.00	0.25	0.25	0.00	0.25	-3.75	3.25
9	1-5	VCP	Avg	-0.75	0.00	0.92	1.67	0.25	0.00	0.25	0.50	0.00	0.00	-3.75	4.00
10	0	VCP	Abs	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	0.00
10	0	VCP	Avg	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-4.00	0.00
11	1	VCP	Abs	-0.10	0.00	0.20	0.30	0.10	0.70	0.10	0.00	0.00	0.10	-2.30	0.60
11	1	VCP	Avg	-0.10	0.00	0.20	0.30	0.10	0.70	0.10	0.00	0.00	0.10	-2.30	0.60
12	2	VCP	Abs	-0.25	0.00	0.25	0.50	0.25	0.45	0.00	0.00	0.05	0.25	-1.65	1.25
12	2	VCP	Avg	-0.58	0.00	0.25	0.83	0.25	0.50	0.00	0.00	0.00	0.25	-2.15	1.25
13	3	VCP	Abs	-0.25	0.00	0.35	0.60	0.35	0.20	0.10	0.00	0.00	0.35	-1.40	2.45
13	3	VCP	Avg	-0.55	0.00	0.40	0.95	0.30	0.00	0.25	0.00	0.25	0.20	-4.25	2.30
14	4	VCP	Abs	-1.00	0.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00	1.00	-1.00	4.00
14	4	VCP	Avg	-0.43	0.00	0.55	0.98	0.35	0.05	0.15	0.05	0.05	0.35	-3.00	2.25
15	5	VCP	Abs	0.40	0.85	1.75	1.35	0.70	0.00	0.05	0.00	0.00	0.25	0.00	4.15
15	5	VCP	Avg	-0.36	0.08	0.95	1.31	0.60	0.00	0.05	0.00	0.00	0.35	-2.70	3.85
16	4-5	All	Abs	0.00	0.50	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.50	-1.00	3.50
16	4-5	All	Avg	-0.59	0.00	0.63	1.22	0.45	0.00	0.20	0.00	0.00	0.35	-3.40	3.55
17	3-5	All	Abs	-0.60	0.00	0.80	1.40	0.80	0.00	0.00	0.00	0.00	0.20	-2.00	4.40
17	3-5	All	Avg	-0.67	0.00	0.60	1.27	0.45	0.00	0.20	0.00	0.10	0.25	-4.60	3.85
18	4-5	VCP	Abs	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	-1.00	5.00

18	4-5	VCP	Avg	-0.64	0.00	0.60	1.24	0.45	0.00	0.15	0.00	0.00	0.40	-3.30	3.50
19	3-5	VCP	Abs	-0.50	0.00	1.00	1.50	0.50	0.00	0.00	0.00	0.00	0.50	-2.00	3.50
19	3-5	VCP	Avg	-0.65	0.00	0.65	1.30	0.35	0.05	0.15	0.00	0.05	0.40	-4.50	3.30

Table F-4 Sample Size for Each Score

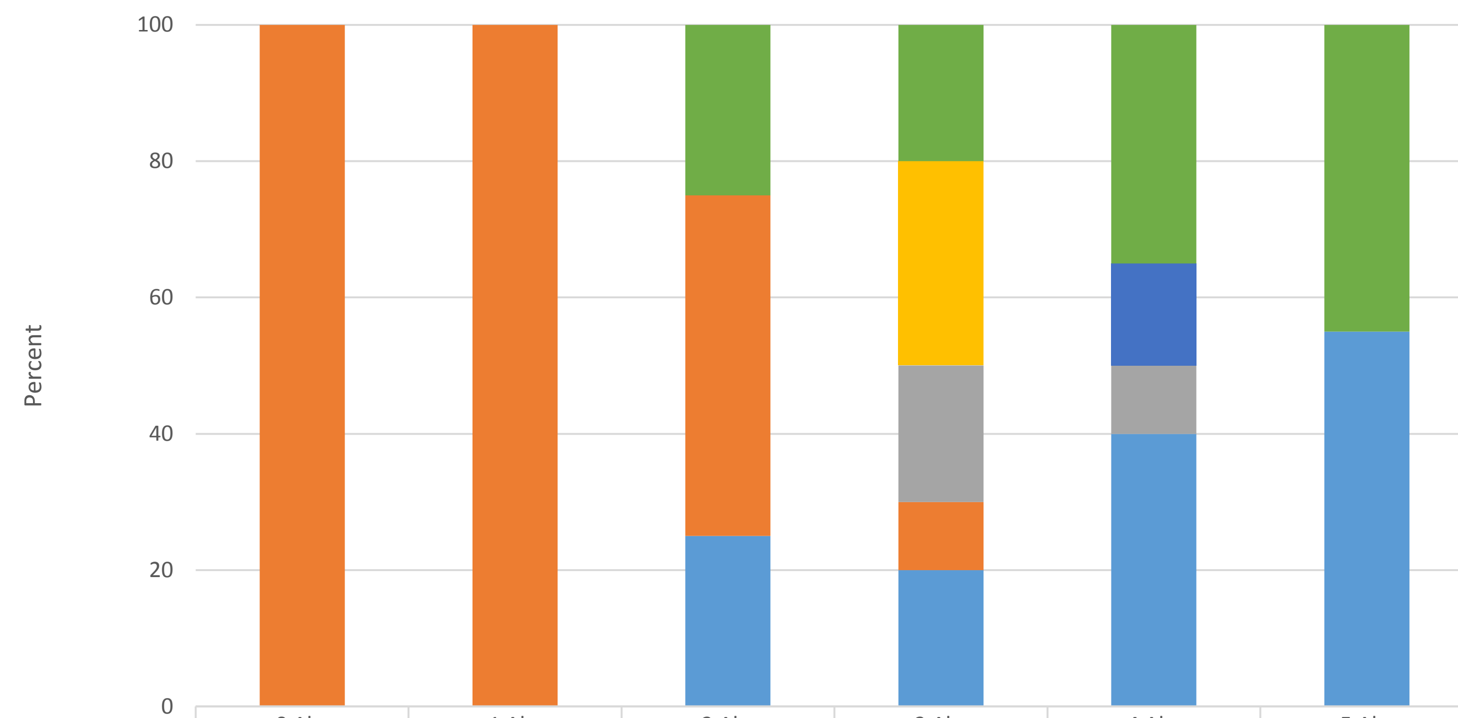
Score	**Material**	**Number of Samples**
0	All	203
	VCP	116
1	All	33
	VCP	27
2	All	118
	VCP	80
3	All	144
	VCP	91
4	All	203
	VCP	146
5	All	234
	VCP	170
0-5	All	935
	VCP	630
1-5	All	723
	VCP	514
3-5	All	581
	VCP	407
4-5	All	437
	VCP	316



	0 Avg	1 Avg	2 Avg	3 Avg	4 Avg	5 Avg
Water Source	0	0	25	30	100	85
Traffic	0	0	10	0	0	0
Pipe Length	0	0	0	0	0	0
Pipe Depth	0	0	0	30	0	0
Restaurant	100	100	40	10	0	0
Material/Age	0	0	25	30	0	15

Score

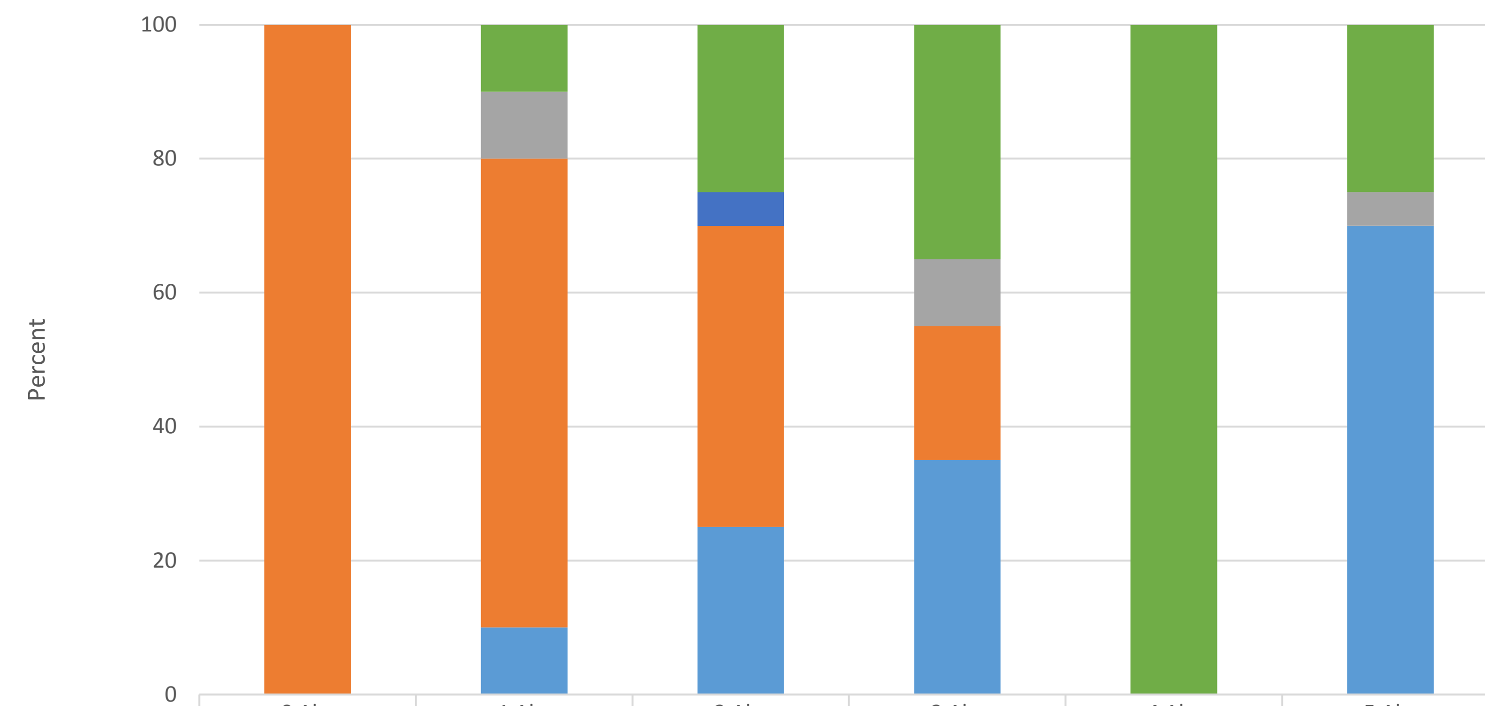
Figure F-1 Results for Scenario #1 through #6 for Absolute Scores



	0 Abs	1 Abs	2 Abs	3 Abs	4 Abs	5 Abs
Water Source	0	0	25	20	35	45
Traffic	0	0	0	0	15	0
Pipe Length	0	0	0	30	0	0
Pipe Depth	0	0	0	20	10	0
Restaurant	100	100	50	10	0	0
Material/Age	0	0	25	20	40	55

Score

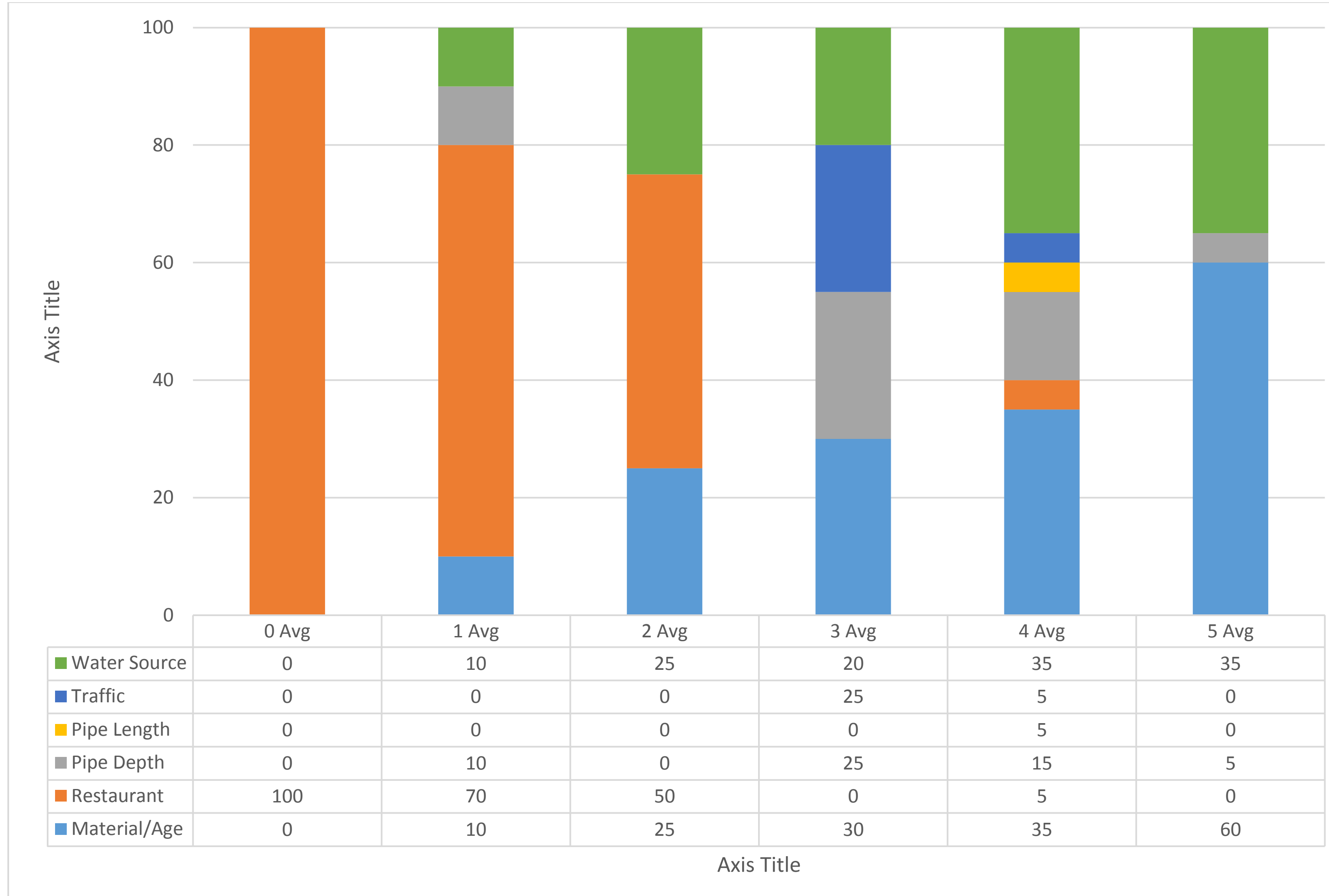
Figure F-2 Results for Scenario #1 through #6 for Average Scores



	0 Abs	1 Abs	2 Abs	3 Abs	4 Abs	5 Abs
Water Source	0	10	25	35	100	25
Traffic	0	0	5	0	0	0
Pipe Length	0	0	0	0	0	0
Pipe Depth	0	10	0	10	0	5
Restaurant	100	70	45	20	0	0
Material/Age	0	10	25	35	0	70

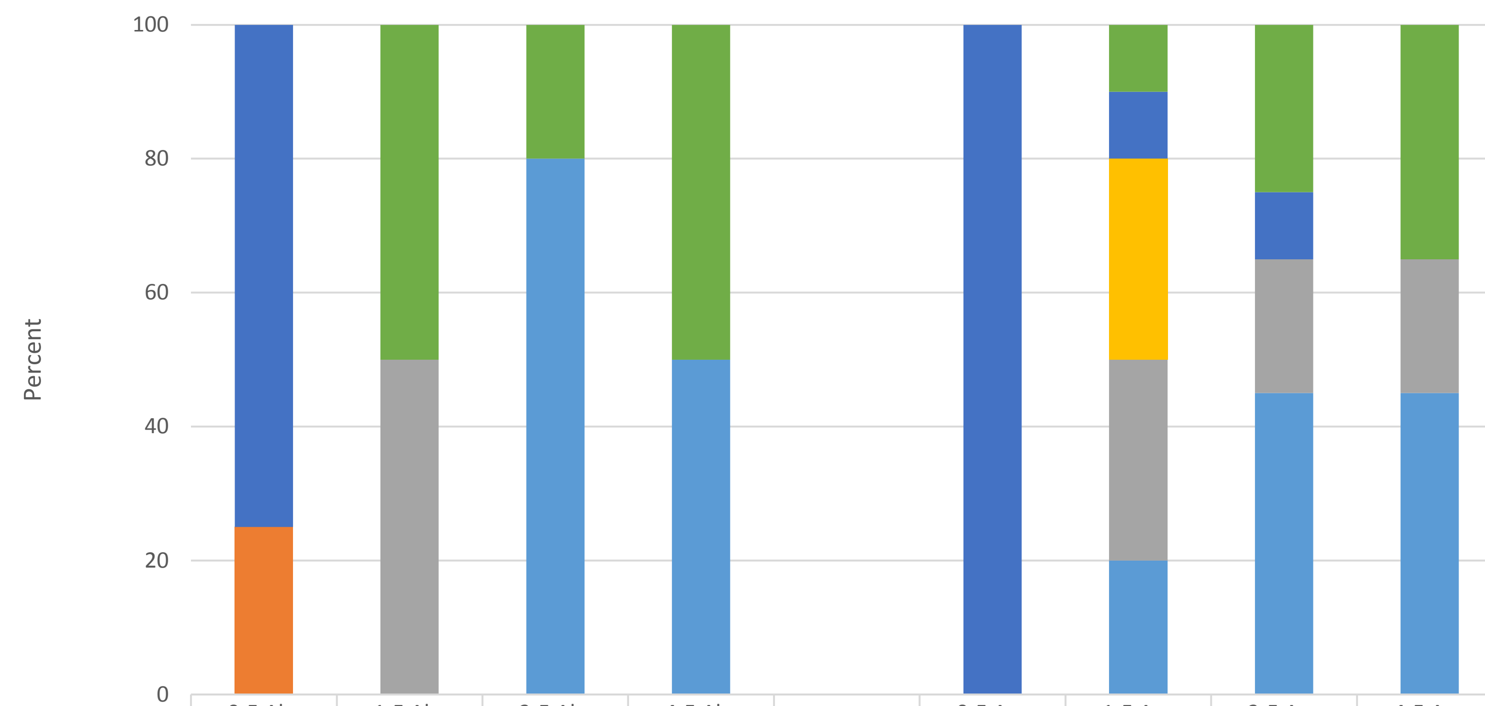
Score

Figure F-3 Results for Scenario #7 through #12 for Absolute Scores



	0 Avg	1 Avg	2 Avg	3 Avg	4 Avg	5 Avg
Water Source	0	10	25	20	35	35
Traffic	0	0	0	25	5	0
Pipe Length	0	0	0	0	5	0
Pipe Depth	0	10	0	25	15	5
Restaurant	100	70	50	0	5	0
Material/Age	0	10	25	30	35	60

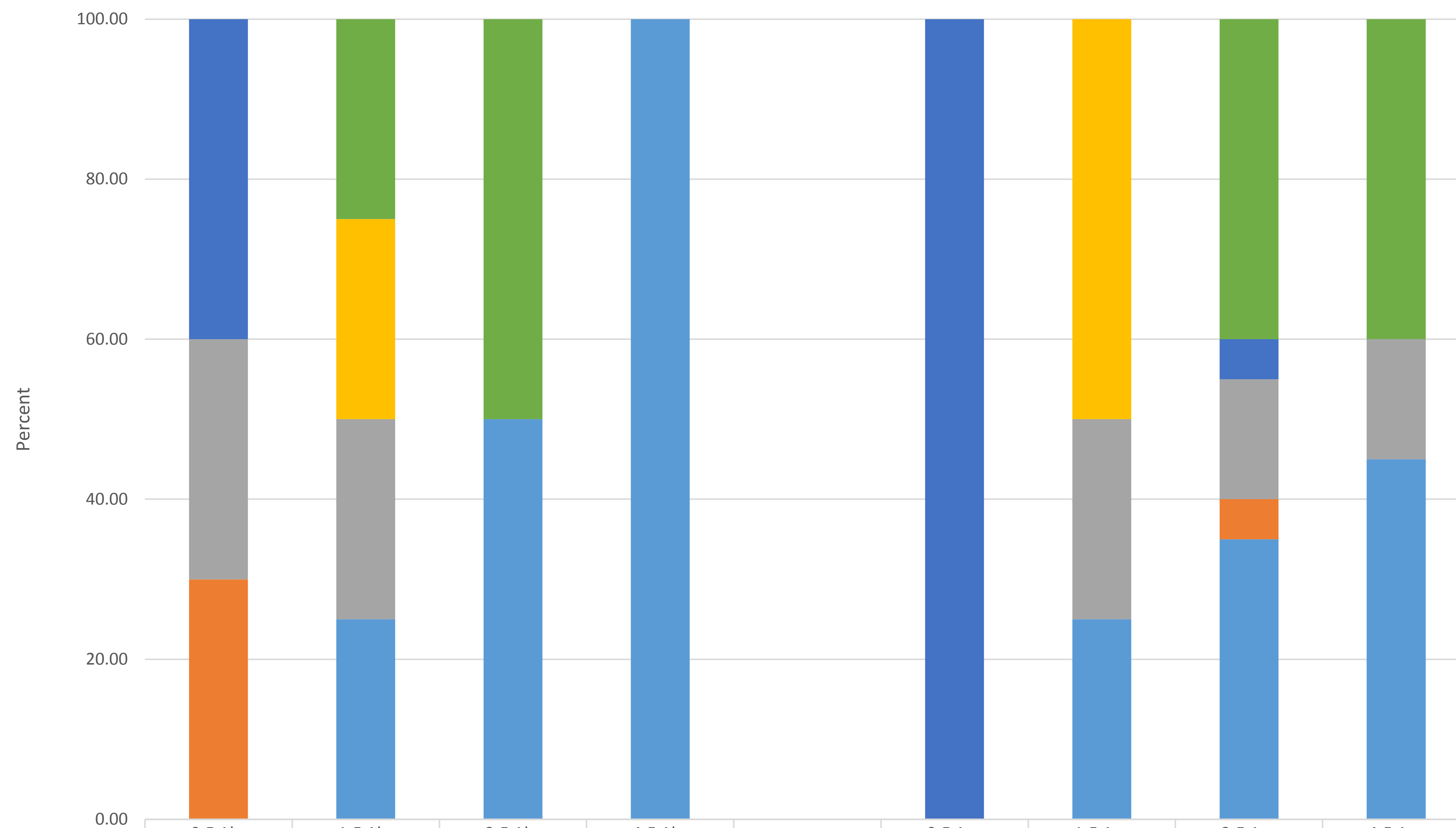
Figure F-4 Results for Scenario #7 through #12 for Average Scores



	0-5 Abs	1-5 Abs	3-5 Abs	4-5 Abs		0-5 Avg	1-5 Avg	3-5 Avg	4-5 Avg
River	0	50	20	50		0	10	25	35
Traffic	75	0	0	0		100	10	10	0
Pipe Length	0	0	0	0		0	30	0	0
Pipe Depth	0	50	0	0		0	30	20	20
Restaurant	25	0	0	0		0	0	0	0
Material/Age	0	0	80	50		0	20	45	45

Score

Figure F-5 Results for Scenario #13 through #16 for Absolute and Average Scores



	0-5 Abs	1-5 Abs	3-5 Abs	4-5 Abs		0-5 Avg	1-5 Avg	3-5 Avg	4-5 Avg
River	0.00	25.00	50.00	0.00		0.00	0.00	40.00	40.00
Traffic	40.00	0.00	0.00	0.00		100.00	0.00	5.00	0.00
Pipe Length	0.00	25.00	0.00	0.00		0.00	50.00	0.00	0.00
Pipe Depth	30.00	25.00	0.00	0.00		0.00	25.00	15.00	15.00
Restaurant	30.00	0.00	0.00	0.00		0.00	0.00	5.00	0.00
Material/Age	0.00	25.00	50.00	100.00		0.00	25.00	35.00	45.00

Score

Figure F-6 Results for Scenario #17 through #20 for Absolute and Average Scores

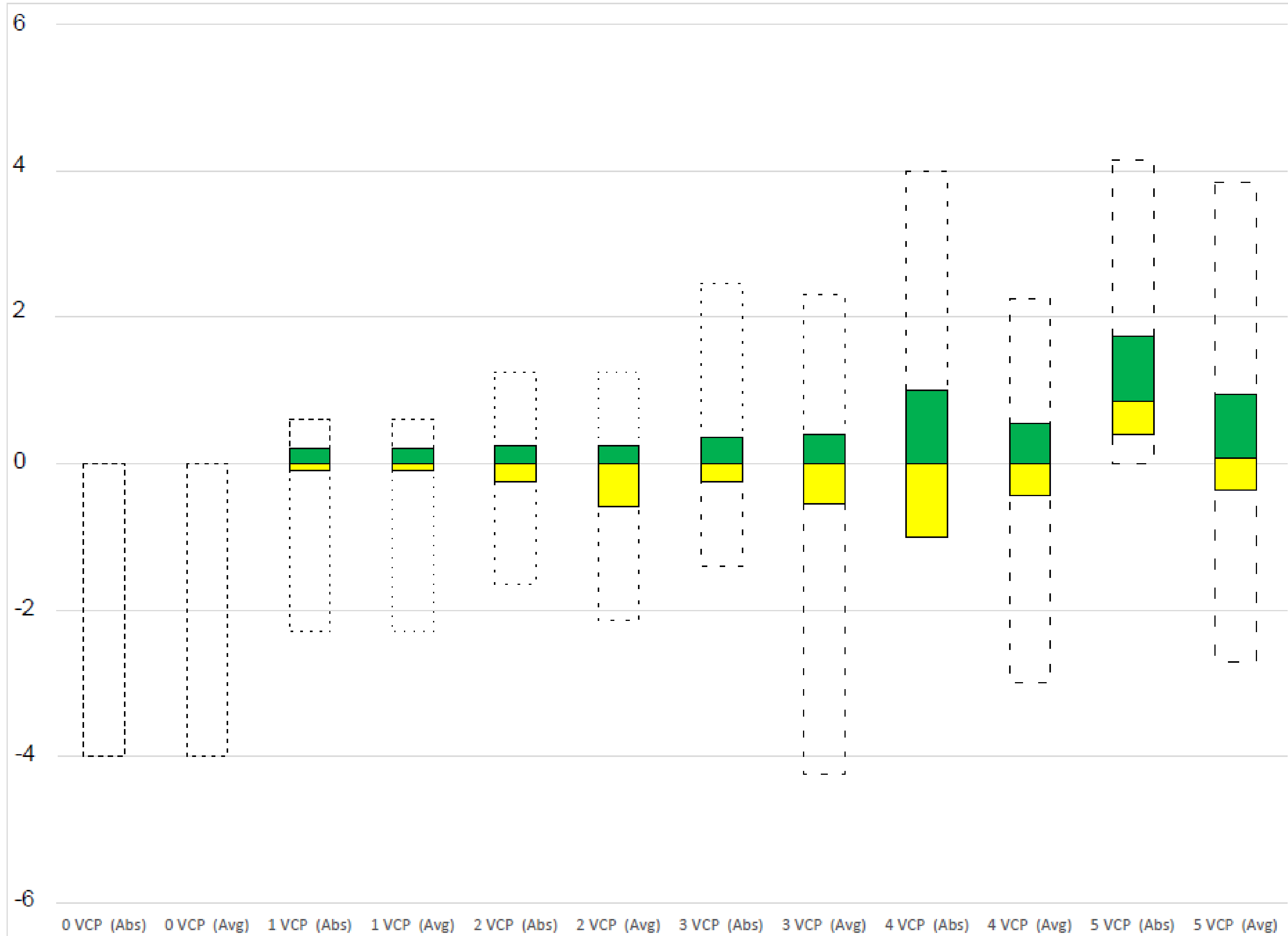


Figure F-7 Accuracy and Precision of Sensitivity Analyses for Scenarios 7 through 12

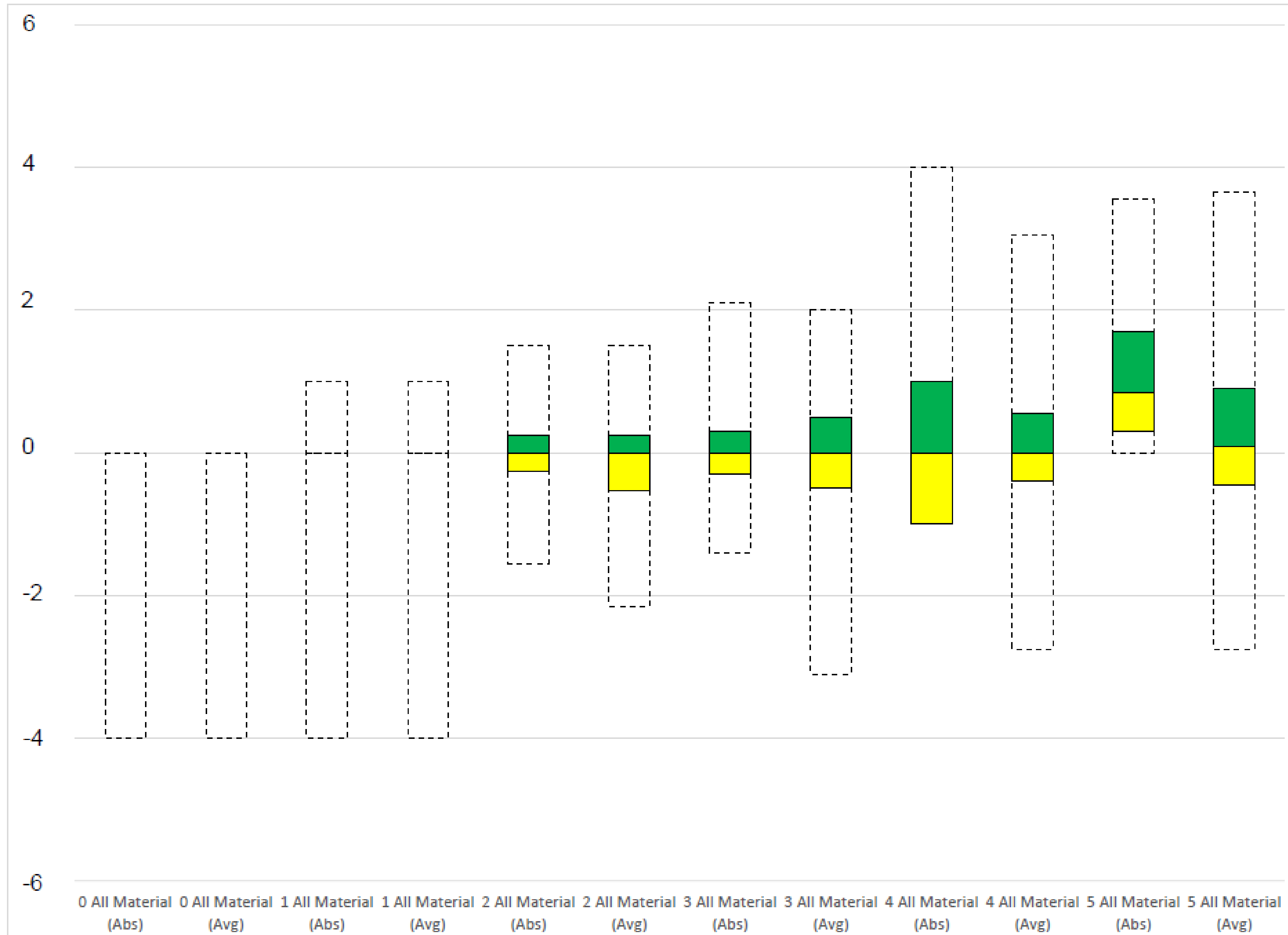


Figure F-8 Accuracy and Precision of Sensitivity Analyses for Scenarios 1 through 6

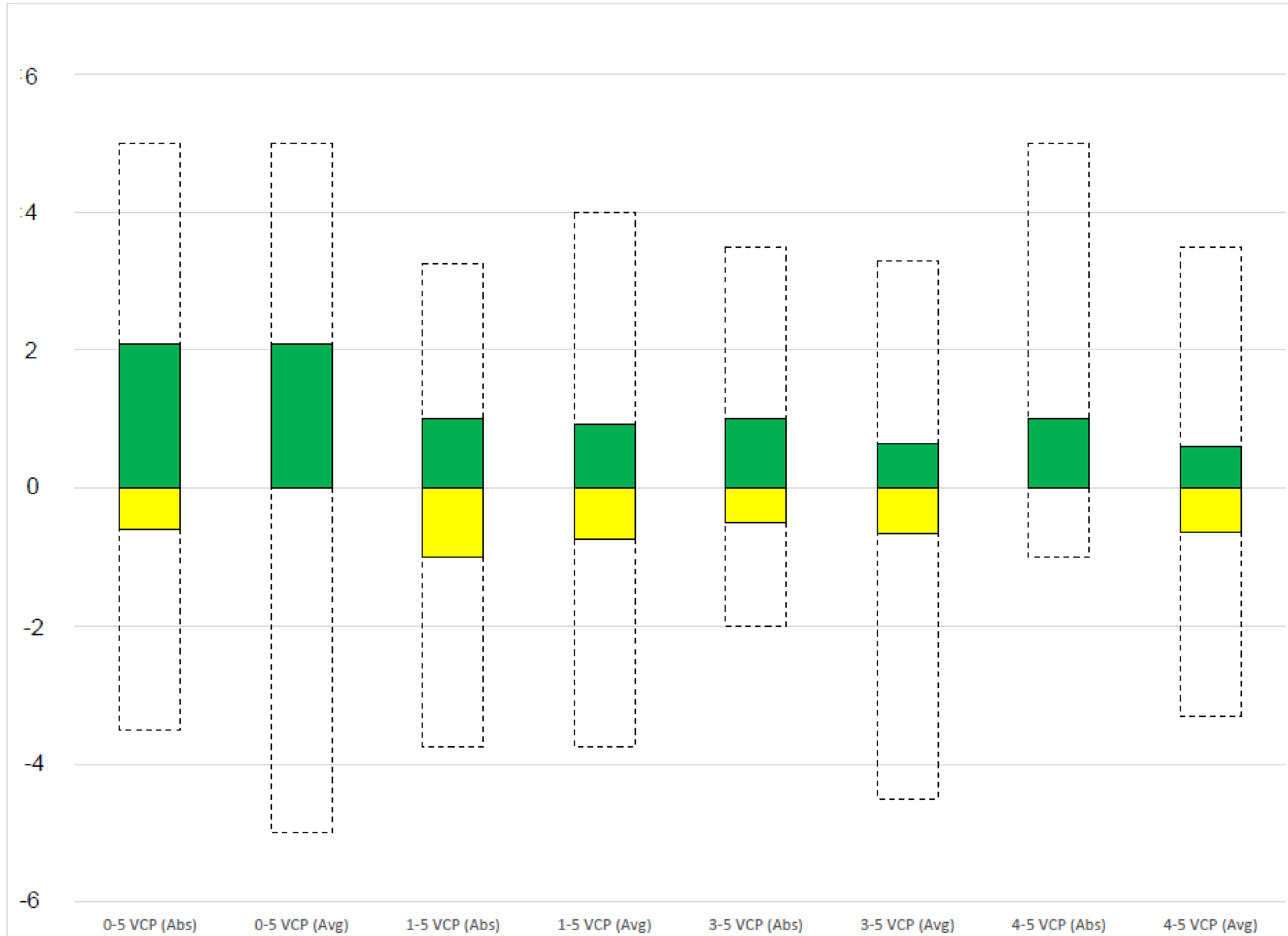


Figure F-9 Accuracy and Precision of Sensitivity Analyses for Scenarios 17 through 20