Development of a Novel Performance Index and a Performance Prediction Model for Metallic Drinking Water Pipelines

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Abstract

Previous authors have developed many different types of water pipe condition and failure models using the various methodologies available. Contrary, current utilities are struggling to maintain their current water infrastructure system, due to the lack of effective prediction tools at hand. The gap between the methodologies available in academic research and the tools available to current water utilities needs to be addressed. This paper presents a fuzzy inference prediction model used to forecast the performance rating of individual drinking water pipeline sections (node to node) in which utilities can easily apply to their drinking water infrastructure system.

Prior to the development of a prediction model, a through literature and current practice review is completed detailing and summarizing all the available mathematical models. Following, an infrastructure overview is presented detailing the various pipe materials, lifecycle and failure modes and mechanisms. A data structure is also detailed which lists all parameters that affect the condition and/or performance of a pipeline. All of these tools are successfully used to develop a fuzzy inference performance model.

The fuzzy inference performance model is considered novel in that it considers close to 30 pipe parameters. Moreover, the performance model is applied using the Western Virginia Water Authority (WVWA) and the Washington Suburban Sanitary Commission (WSSC) databases to evaluate and verify the predicting results. Lab testing of several pipe samples is also used to evaluate the model. The testing consists of a ring bearing test which is used to calculate the rupture modulus of the pipe. Comparing the original vs. the current rupture modulus can determine the remaining strength of the pipe. The remaining strength can then be used to assess the performance results predicted by the fuzzy inference model.

Further a framework is set forth which utilizes the model's predicted performance ratings to develop deterioration curves which can be used as a tool to forecast and plan future inspection, repair, rehabilitation and replacement of water pipelines. The deterioration model is made up of a Markov chain approach coupled with a non-optimization technique.

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1 Introduction

“New solutions are needed to what amounts to nearly a trillion dollars in critical water and wastewater investments over the next two decades. Not meeting the investment needs of the next 20 years risks reversing the public health, environmental, and economic gains of the last three decades” (WIN 2000). Most cities and towns started building drinking water and collection systems over 100 years ago and many of these systems have not received adequate upgrades, maintenance, repair and rehabilitation over time (USEPA 2005).

Today, municipal governments are facing an infrastructure crisis requiring costly renewal beyond their capacity. There has been a steady decline in the state of our water infrastructure over the past two decades and a growing concern is that these facilities may be inadequate for current requirements and projected future growth (USEPA 2005). Funding for these needs is limited, and a deferred maintenance, out-of-sight, out-of-mind philosophy still prevails in many regions.

Recently, for example, the American Society of Civil Engineers (ASCE) in its 2009 assessment of the nation’s infrastructure assigned the grade “D-” (ASCE 2009). It is estimated that the cost of replacing all water mains in the U.S. would run to $348 billion (Engineers 2000). Although the federal government has spent more than $71 billion on water treatment programs since 1973, the nation’s 19,000 water systems still face enormous infrastructure funding needs in the next 20 years to replace pipes and other constructed facilities that have exceeded their design life (Engineers 2000). With billions of dollars being spent yearly for water infrastructure, the systems face a shortfall of at least $21 billion annually to replace aging facilities and comply with existing and future federal regulations (WIN 2000).

Monetary investment alone will not resolve this dilemma; it must be met with a new approach to sustainable water infrastructure engineering and management. There is a critical disconnect between the methodological remedies for infrastructure renewal problems and the current sequential or isolated manner of renewal analysis and execution. These disconnect manifests are in need for a holistic systems perspective. New tools are needed to provide the intellectual support for utility assets decisions necessary to sustain economic growth, environmental quality and improved societal health.

1.1 Motivation for the Proposed Research and Problem Statement

A report on global water resources states “water needs to rise up the totem pole of political discourse” in which governments need to address the booming water demand or face grave human, environmental and economic consequences (Walzer 2009). This article also commented on the report “Charting Our Water Future,” which discusses that in 20 years the water demand will be 40% higher than it is today and more than 50% higher in rapidly developing countries (Group 2009).

The amount of water lost through leaky pipes due to deteriorated water distribution networks is a concern due to its impact on the water pipe system and environment (Seica 2004). As stated in the “Facts, Center for Advancement of Trenchless Technologies from Waterloo, Ontario,” of all water produced, approximately 25% of it is lost or unaccounted for in the distribution system. These losses are due to leaks and water pipeline breaks. It was found that a reduction of water losses from 25% to 10% would result in a savings of approximately $380 million per year (Baker 1997).

Countries are also faced with the increasing economic pressures to satisfy the requirements of regulatory compliance. For example in the U.S. the Environmental Protection Agency (EPA) implemented the Safe Drinking Water Act (SDWA) which protects the public health by regulating the nation’s public drinking water supply. Amendments have been made through the years which have enhanced the law recognizing the source of water protection, operator training, funding for water system improvements and public information as all important components of providing safe drinking water to the public. Today, many water authorities are looking beyond the traditional maintenance programs for their water distribution system and are implementing proactive strategies (De Silva et al. 2006).

From the increasing water demand and regulatory compliance to the accumulation of damage and gradual degradation of components the water infrastructure system is in need of critical attention (Dehghan et al. 2008). Water utilities have found that the “do nothing until a system component fails” is not the best option since ultimately this method increases the costs and affects customer satisfaction and the environment (Loganathan 2002).

Drinking water plays a critical role in every aspect of civilization: agriculture, industry, economy, environment, recreation, transportation, culture and health. While clean water conditions remain an elusive luxury in many parts of the world, we, as Americans, take them for granted. Much of America’s drinking water infrastructure; however, is old and deteriorating. A crisis looms as our demands on these systems increase. The costs associated with renewal of these eroding systems are staggering.

In particular, one of the key focuses of water pipe infrastructure assets are on metallic material pipelines due to their vast presence as a result to their wide acceptance and availability during the bulk installation of the water infrastructure systems. Overall, the miles of pipe installed within the U.S. for large water distribution systems totals roughly around 600,000 miles (AWWA 2005). Previous studies have gone further in classifying the total miles of pipeline installed by pipe material. A diagram illustrating the miles of pipeline per pipe material type is seen in Table 1. As shown, roughly 60 to 70% of the U.S. water infrastructure is made up of ferrous materials. The remaining percentage constitutes asbestos cement, pre-stressed concrete, glass reinforced pipe, polyethylene, polyvinyl chloride and other materials.

Table 1: Water Network by Pipe Material (Adapted from EPA Report-Condition Assessment of Ferrous Water Transmission and Distribution Systems (Thomson 2009))

Source of Data	Water Industry Database (a)		Water://Stats 1996 Distribution Survey (b)		Water://Stats 2002 Distribution Survey (c)	
Utilities Responded/Surveyed	1,097/3,000		898/3,200		337/3,000	
Response Rate	37%		28%		11%	
Pipe Material	Miles Installed	Percent of Total	Miles Installed	Percent of Total	Miles Installed	Percent of Total
Cast Iron	341,175	39.6	155,038	41.3	71,472	35.4
Ductile Iron	189,115	21.9	81,119	21.6	45,004	22.3
Steel	34,047	3.9	16,415	4.4	7,821	3.9
Asbestos Cement	136,196	15.8	56,360	15	30,484	15.1
Pre-Stressed Concrete	23,584	2.7	15,921	4.2	4,774	2.4
Glass Reinforced Plastic	665	0.08	422	0.1	NA	NA
Polyethylene	3,349	0.4	1,318	0.4	1,377	0.7
Polyvinyl Chloride	114,152	13.2	42,125	11.2	29,835	14.8
Others/Unknown	20,169	2.3	6,719	1.8	11,391	5.6

Not Available (NA), (a) (AWWARF 1992), (b) (AWWARF 1996), (c) (AWWA 2004)

Overall, our water infrastructure network is in dire need of new tools to provide the intellectual support for water infrastructure decisions necessary to sustain economic growth, environmental quality and improved societal health. Our current water infrastructure is declining at an alarming rate and priority must be given to these assets that are in critical condition. Developing an efficient prediction model can provide a fast and reliable decision-making tool that is needed to handle the large volume of deteriorating buried pipeline infrastructure systems, particularly drinking water pipelines, which pose serious threats to the environment if they fail.

1.2 Research Goals

The research goals to be addressed are:

1. To develop a novel fuzzy inference model for drinking water pipeline performance prediction.
2. To provide a framework for deterioration prediction to determine the remaining physical life of drinking water pipelines.

1.3 Research Objectives

Accurate prediction of water pipe structural and functional deterioration plays an essential role in the utility asset management process and capital investment planning. A key to implementing an asset management strategy is a comprehensive understanding of asset condition and performance and how asset condition and performance changes over time. The primary objective of this research is therefore to develop a novel performance index for drinking water pipelines. Secondly, a framework is set forth for the development of deterioration curves for predicting the remaining physical life of drinking water pipe assets. Specifically, the water pipe performance model will be designed to specifically analyze metallic material pipelines since they entail the majority of installed drinking water pipelines in the U.S. as shown in Table 1. Overall, this research aims to provide an integrated view of the entire metallic pipe infrastructure process.

Performance assessment and deterioration modeling are rapidly becoming an increasing part of life-cycle asset management activities in the U.S. In this research a total-systems approach will be taken for the development of a deterioration model for predicting the remaining physical life of metallic water pipes. The proposed research will focus on defining the following objectives:

1. Summarizing the literature and current practice related to condition curves and failure models.
2. Identifying critical parameters and collecting all relevant data related in determining the performance of a drinking water infrastructure system.
3. Developing a fuzzy inference model for predicting the performance of individual drinking water pipeline sections (node to node).
4. Evaluating the developed performance index using artificial, field and lab data.
5. Providing a framework for deterioration prediction to determine the remaining physical life of water pipeline assets.

A comprehensive literature review on the variety of condition and failure models will aid in understanding the various types of mathematical models which are currently available. This background coupled with a current practice review can help to identify the gap between the models found in literature and water utility asset management practices.

In developing a performance index it is important to understand the lifecycle and various failure modes and mechanisms for each particular pipe material. Parameters which may lead to these failures can affect a pipeline whether they are physical pipe properties, the external environment or operational factors. Within this dissertation a section highlighting the different lifecycles and specific failure modes and mechanisms will be presented for each pipe material type. An extensive list of all parameters which influence the pipes' performance level are also included in a data structure.

Through extensive analysis and assessment of existing methodologies in determining the condition and/or failure of a water pipeline and the evaluation of the current utility practice, a drinking water performance index for metallic pipelines will be developed based on the fuzzy inference methodology. Overall, implementation of the fuzzy inference methodology incorporates engineering judgment in order to predict infrastructure deterioration where data is scarce, cause-effect knowledge is imprecise and observations and model criteria are expressed in vague or "fuzzy" terms (Burn 2009). To demonstrate the capabilities of the fuzzy inference method, a weighted factor performance model will also be developed.

Water infrastructure is a complex system that is comprised of many variables that can have an effect on the overall condition and/or performance of the pipe. Considering the extensive variables, the methodology selected needs to be able to account for a large amount of data. In particular, the fuzzy logic methodology is capable of handling any number of input and output variables. This methodology also has the ability to allow users to essentially model parameters in separate modules before combining them into a single performance index which can help target areas contributing to low output values.

The main concept of fuzzy logic is that it is made up of memberships that have a continuous grade that can account for the uncertainty in an event. With the current understanding of our water infrastructure and how the parameters affect the pipe, it is not appropriate to measure the performance of a pipeline using a binary set theory, such as the weighted factor method, in which the member either belongs to a set or does not. Currently our water infrastructure knowledge can be vague in terms of how various parameters affect a pipe, especially when evaluating differing pipe materials. Researchers and utility personnel typically only have an inclination of certain boundaries the role of the parameter may take on. With imprecise categories, the vagueness and ambiguity of the parameters can be efficiently managed utilizing the fuzzy logic membership functions.

Currently the water infrastructure data available from water utilities is very limited and many fields are unpopulated due to the difficulty in obtaining data owing to its physical underground location and poor historical records. However, many variables can be derived indirectly, downloaded through online databases and/or quantified using an educated guess. Since fuzzy logic approximates the variables into membership functions the imprecise data can be handled since it avoids abrupt changes from one discrete output state to another when the input is changed only marginally (Sivanandam et al. 2007). Therefore, inconsistency in the data can still be accounted for utilizing the fuzzy logic methodology.

Fuzzy logic also has the ability to describe systems linguistically through if-then rule statements (Sivanandam et al. 2007). Application of the rule statements allows for utility and expert knowledge and interrelationships between parameters to be modeled which is improbable utilizing various other methods such as the weighted factor. Incorporating utility and expert knowledge can prove to be very valuable as much of this comprehension of the infrastructure system is not documented.

Overall, with the uncertainties and imprecision in utility data due to lack of a historical database and ambiguity in the effect of pipe parameters have in determining the condition and/or performance, a method needs to be employed that can account for these impediments. Current utility and expert knowledge is also crucial as much of our infrastructure is just starting to see the major effects of pipeline deterioration. The use of the continuous membership functions and rule statements within the fuzzy logic methodology demonstrates to be well suited in generating water pipeline performance values.

A solid evaluation process for the performance index is necessary to illustrate that the model developed is substantial and can be applied universally. By testing the various limits of the model and applying it to a utility database a confidence level can be achieved. Furthermore, lab testing is presented to relate the remaining structural capacity to the performance level predicted.

Subsequent to the development of the drinking water pipe performance index, deterioration curves are developed to model the lifespan of pipeline assets. Specifically, the deterioration curves are generated utilizing a Markov chain methodology which is a discrete-time stochastic process. Within this probability theory, the stochastic process has the Markov property if the conditional probability distribution of future states of the process, given the present state and all past states, depends only upon the current state and not on any past states. The expected value method will be utilized for the estimation of the transition probabilities.

1.4 Organization of the Dissertation

The dissertation is organized in the following manner:

Chapter 2: Literature Review - This chapter presents a thorough literature review on water pipe condition/failure models which highlights over 50 articles published over the past 10 years. Also highlighted is a current practice review which aids in gauging the gaps between the available mathematical models and current utility practice. Finally this chapter concludes with the contribution of the proposed research and how the proposed work is differentiated from previous work.

Chapter 3: Water Pipeline Performance Data - This chapter provides a brief overview of the predominately used water pipeline materials. A comprehensive list of the water pipe's lifecycle and failure modes and mechanisms is presented along with a comprehensive data structure listing all the parameters that can affect the performance level of a water pipeline.

Chapter 4: Development of a Water Pipeline Performance Index – This chapter provides the methodology for the weighted factor and fuzzy inference models in the development of a novel water pipe performance index for metallic pipelines. The resultant performance scale along with a reliability index is presented. Results from pilot study are used to evaluate the performance index.

Chapter 5: Water Pipeline Performance Index Evaluation & Framework for Deterioration Prediction – This chapter provides methods used to assess and ensure that the developed performance index and its implementation to a real world database are correct. This is done through the evaluation of artificial, field and lab data. Also, a framework is provided that utilizes the predicted pipe performance results to aid in the development of a pipe deterioration prediction model.

Chapter 6: Conclusions and Limitations - This chapter will assess the overall research and list the limitations of the developed models.

Chapter 7: Future Recommendations – The concluding chapter will provide recommendations for future model development.

2 Literature Review

Data and reports on reasons for pipe failure began to appear after the 1940s. After the 1960s, changes in pipe materials and methods added to the complexity of the prediction problem. In the last three decades, only a few research teams have reported on main break causes and prediction. Most reports present analytical ideas, but lack databases of actual break records. A number of different mathematical functions have been fit to main break data, but the datasets lack the integrity needed to yield consistent results.

This chapter presents the theoretical background on the different types of condition curves along with a state-of-the-technology literature review and current practice review on condition curves and failure models in order to gauge the gap between the models found in literature and the ones found in today's current water utility practice. The state-of-the-technology literature review provides a comprehensive overview of research work carried out since the year 2000 to develop failure and deterioration models for water pipes. The state-of-the-technology current practice review provides a comprehensive overview of several current utility practices related to failure and deterioration models for water pipes. Nine utilities in the U.S., Australia and Canada with significant activities of water pipe infrastructure management participated within the study in order to gauge today's current water utility asset management practices. The chapter concludes with a section discussing the body of knowledge that will be affected by this research and how the proposed research is differentiated from previous work.

2.1 Theoretical Background

It is very difficult and perhaps impossible to establish a universal, reliable performance deterioration curve for use in all regions. Types of deterioration models available for predicting the condition and performance of water pipes can be grouped into the following six categories: deterministic, statistical, probabilistic and advanced mathematical models which consists of artificial neural networks (ANN), fuzzy logic and heuristic. The input parameters and output results of pipe deterioration models are heavily dependent on the type of methodology chosen. Each type of deterioration model is summarized in the following subheadings.

2.1.1 **Deterministic Model Approach**

Deterministic models are commonly used in instances where the relationships between components are certain. There are two different approaches in which a deterministic model may be developed: empirical and mechanistic. The empirical approach, in deterministic modeling, relates failure rates to the attributes of the asset. This approach is only applied to cohorts of pipes. The mechanistic approach, on the other hand, predicts the service lifetimes of individual assets. Specifically, the means of degradation and failure modes and mechanisms of the asset is well understood when considering this approach (Urquhart 2010).

Deterministic Model Approach:

- The majority of the existing deterministic-based models may be classified as structural or functional performance models and primary response models.
- It can predict an average single value of a dependent variable.
- It can be broken down into two categories: mechanistic and empirical based on which dependent and independent variables are included in the models and how their relationship is established.
- Most of the existing prediction models have been developed through regression analysis, combined mechanistic-empirical analysis and opinions from experienced engineers.
- The problem with deterministic-oriented prediction models is that the applicability of each individual model is restricted to a specific location.

2.1.2 **Statistical Model Approach**

Statistical modeling is commonly used to predict the lifetime or failure time of infrastructure (Lawless 1982). Specifically, statistics are utilized to developed a model from observed data in order to serve as a tool or mechanism to describe the data (Hahn and Shapiro 1994). The statistical methodology is typically applied to asset cohorts that have recorded historical failure or condition data. Applicability is limited when considering newer assets or assets with an insufficient historical database.

Statistical Model Approach:

- In regression models, the dependent variable of pipe condition or other indicators is related to one or more independent variables such as soil, thickness, load, etc.
- Pipe infrastructure data are required to predict the future condition.
- Condition of pipe ranking is required to predict future condition.
- Applied to homogenous groups of pipe infrastructure systems.
- One of the common features among different types of statistical models is that they are all based on a large number of long-term observed field data and processed through regression analysis.
- In many cases, the regression-based approach is not suitable for modeling the actual deterioration process of pipe infrastructure since the sampling data used in the regression analysis suffers from various limitations, such as pipe structure, loading and environmental variables.

2.1.3 **Probabilistic Model Approach**

Probabilistic modeling analyzes the probability or relative frequency of an event occurring (Creighton 1994). The likelihood of these occurrences is practical to describe the failure of an asset. Specifically, the probability of an event to occur is denoted by a 1; while the probability of an event which cannot occur is 0. All other probabilities must lie within the [0-1] interval (Mitrani 1998). Condition data and asset attribute information is required in modeling the probability of failure.

Probabilistic Model Approach:

- Predicts a distribution and range of values for dependent variables, such as pipe condition state vectors.
- Commonly utilized in pavement, bridge and other infrastructure network management concerning repair, rehabilitation and replacement (R,R,&R) priority programming.
- The model is based on extensive data.

2.1.4 **Artificial Neural Network Model Approach**

Artificial Neural Networks (ANN) is a method used to model the deterioration or failure of a pipe infrastructure. A neural network is comprised of interconnected processing elements often referred to as “neurons” that work together to provide a result. Each element is relatively simple in nature, but can become very complex when interconnecting multiple networks (Landau and Taylor 1998). When properly trained, the ANN model mimics the functioning of the human brain through pattern recognition and generalization capabilities (Lingireddy and Brion 2005). Overall, this methodology provides a useful tool for modeling asset deterioration or failure due to its nonlinearity, adaptivity and learning capabilities (Haykin 1994).

Artificial Neural Network Model Approach:

- The immense capabilities of the human brain in processing information and making decisions, even under very complex circumstances and under uncertain environments, have inspired researchers to mimic the computational abilities in ANN.
- The topology corresponds to the ordering and organizing of the nodes from the input layer to the output layer of the network. In fact, the way the nodes and the interconnections are arranged within the layers of a given ANN determines its topology. The choice for using a given topology is mainly depends on the type of problem.
- Increased levels of skill and training are required to develop these complex networks and subsequently train these networks; otherwise, it will be a “black-box” approach.
- Quality labeled data are required for supervised training and predicting the future condition.

2.1.5 Fuzzy Logic Model Approach

Fuzzy logic is a mathematical method used to deal with systems provided with inexact information or uncertainty. Variables are assigned a degree of membership on a continuous interval [0, 1] and are subjected to approximate reasoning in a way the human brain functions (Sivanandam et al. 2007). Fuzzy methods are recognized to handle systems that are subjected to uncertainties, ambiguities and contradictions. In general, this nonlinear model provides an expert rule based system capable of imitating the human thought process (Siler and Buckley 2005).

Fuzzy Logic Model Approach:

- Applied to a number of areas of infrastructure management, such as bridges, highways, oil and gas pipelines and water pipe networks.
- Challenges exist in constructing fuzzy rule sets, selecting membership functions and determining the defuzzification process.
- This technique implements expert opinions.
- Used for systems that are subject to uncertainties, ambiguities and contradictions.

2.1.6 Heuristic Model Approach

The heuristic models are more common for infrastructure problems that are not well understood. The model produces sub-optimal solutions and is developed through subjective opinion from experienced field engineers and experts.

Heuristic Model Approach:

- Method to illustrate failure risks with limited or no pipe data.
- This technique is a structured way of capturing expert opinions.

2.2 Review of Articles

Pipe infrastructure asset management normally requires significant levels of models and data to predict the condition and performance of pipe systems. Deterioration models for predicting condition and performance of water pipes can be grouped into the following six categories: deterministic, statistical, physical, ANN, fuzzy logic and heuristic. This section provides a comprehensive overview of recent research work carried out over the past 10 years to develop failure and deterioration models for water pipes. Altogether, more than 50 articles were reviewed in their entirety. This report complements the papers and reports by Kleiner and Rajani (2001) and Rajani and Kleiner (2001) which reviewed articles published before 2000.

2.2.1 **Deterministic Models**

There are 13 articles published regarding the use of deterministic models for water pipe condition/performance assessment and prediction modeling. A summary of deterministic models is shown in Table 2.

Description: Rajani and Kleiner (2001) provided a comprehensive review of the structural deterioration of water mains using physically based models published until the year 2000. The article was aimed at providing a review of articles that use deterministic models but also includes probabilistic models that deal with uncertainties in defining the deterioration and failure processes.

Table 2: Deterministic Models

References	Article Title	Prediction Type
Rajani & Kleiner (2001)	Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models	Review of Deterministic Models
Rajani & Makar (2000)	A Methodology to Estimate Remaining Life of Grey Cast Iron Water Mains	Remaining Service Life
Rajani et al. (2000)	Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life	Remaining Service Life
Deb et al. (2002)	Prioritizing Water Main Replacement & Rehabilitation	Prioritizing Replacement
Babovic et al. (2002)	A Data Mining Approach to Modeling of Water Supply Assets	Risks of Pipe Burst
LU et al. (2003)	Lifetime Prediction for ABS Pipes Subjected to Combined Pressure & Deflection Loading	Lifetime Prediction
Farshad (2004)	Two New Criteria for the Service Life Prediction of Plastic Pipes	Service Life Prediction
Seica & Packer (2006)	Simplified Numerical Method to Evaluate the Mechanical Strength of Cast Iron Water Pipes	Strength
Seica & Packer (2004)	Finite Element Evaluation of the Remaining Mechanical Strength of Deteriorated Cast Iron Pipes	Strength
Kim et al. (2007)	Assessment of Residual Tensile Strength of Cast Iron Pipes	Residual Life
Davis et al. (2008)	Fracture Prediction in Tough Polyethylene Pipes Using Measured Craze Strength	Time to Failure
Burn et al. (2009)	Risk Analysis for Pipeline Assets-The Use of Models for Failure Prediction in Plastics Pipelines	Lifetime
Davis et al. (2009)	Long Term Performance Prediction for PE Pipes	Lifetime

Model Description: Rajani and Makar (2000) presented a methodology that estimates the remaining service life of grey cast iron (CI) water mains by evaluating how corrosion pits affect the structural capacity of a pipe. The residual resistance capacity, anticipated corrosion rates and corrosion pit measurements are evaluated in order to predict when the factor of safety (FS) will fall below a minimum requirement. The FS is correlated with the remaining service lifetime, which can be used to schedule appropriate maintenance and the replacement of water mains. This methodology and case study is also presented within the article "Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life" (Rajani et al. 2000).

The proposed methodology establishes a base condition and an iterative procedure to estimate the remaining service life of pipe segments. Both one-time and multiple-time corrosion pit measurements are evaluated utilizing either direct or indirect measurements. An estimate of the corrosion rate is based on type of CI, the pipe loading and the operational and environmental conditions. The pit producing the shortest remaining service life within the pipe segment is the principal factor in determining the priority for repair or replacement.

A case study was presented to validate the proposed methodology. Results from the one-time measurements, illustrating the FS vs. the remaining service life with two diameter sizes, showed that smaller diameter pipes are more likely to suffer breaks earlier than larger diameter pipes, since the size of the corrosion pits significantly influences the structural resistance of water mains. The multiple-time measurements were evaluated using a plot of dimensionless vertical load vs. the dimensionless internal pressure, illustrating how the stress states for each corrosion pit move towards the ultimate failure envelope from one inspection to another over time. It was recommended that further analysis should be performed to validate the proposed methodology in order to identify model limitations.

Data Requirements: This methodology analyzes specific pipe sections from samples to determine the structural resistance capacity and the residual tensile strength. Characteristics collected for the pipe, soil, and operating conditions consists of pipe diameter, thickness, manufactured year, age, backfill material, native soil, trench depth to crown, backfill weight density, pipe laying condition, load factor dependent on laying condition, pressure, surge pressure allowance, water temperature, frost load factor, impact traffic factor, wheel load, traffic reduction factor, bursting tensile strength, tensile strength, ring rupture modulus and fracture toughness. Parameters used to describe the corrosion model include soil pH and soil resistivity.

Model Description: Deb et al. (2002) presented a mechanistic model based on analyzing the growth of corrosion pits on CI pipes, the resultant loss of wall thickness and the reduction in pipe strength over time. The mechanistic model presented four main objectives: (1) estimate the residual strength of the pipe , (2) determine maximum loads to which the mains are exposed, (3) determine a SF for each pipe and (4) prioritize water mains for replacement based on the calculated SF for individual pipes. The SF is calculated by taking the residual strength of the pipe as a function of remaining pipe wall thickness divided by the maximum stress subject to the pipe.

The model developed within this project was tested with the Regional Municipality of Ottawa-Carleton's (RMOC) database; however, the results were not verified or analyzed for their statistical significance. Soil type was recognized as the predominate factor that could predict the SF for pipes. This methodology primarily focuses on the external corrosion occurring from corrosive soil; therefore, internal corrosion and corrosion due to stray currents are not considered. This method is not meant to be used as a predictor of water main breaks.

Data Requirements: This methodology analyzes specific pipe sections from samples to relate the pipe wall thickness to the modulus of rupture, tensile strength, ring modulus and fracture toughness. The SF's were calculated based on ring stress, hoop stress, tensile stress, bending stress, combined ring and hoop stress and combined tensile and bending stress. Model data inputs consisted of pipe identification, region, soil class, material type, analysis year, pipe type, diameter, year installed, length, traffic type, working pressure, depth, pavement type and beam span.

Model Description: Babovic et al. (2002) presented scoring models and Bayesian networks which are advanced data mining methods that are used in the modeling of water supply assets to determine the risks of pipe bursts. The primary purpose of risk assessment models is to incorporate each factor that is responsible for an increased risk of pipe failure. In modeling pipe behavior, scoring models present similarities or associations between inputs and outputs. Each case is assigned a score or value and is then grouped by the same or similar scores. The number of cases in where a pipe burst occurred or did not occur is counted. The measure of the quality of a score through grouping is quantified by using the coefficient of concordance (CoC). Bayesian networks use the concept of deterministic modeling but take into account the uncertainties. A Bayesian network is modeled by constructing a graphic model of arcs pointing to random variables that illustrate probabilistic dependence of variables affecting other variables.

Both of the advanced data mining methods presented in this report are applied using a Copenhagen Water case study. Burst rates in different classes of pipes were analyzed. A sensitivity analysis concluded that the number of previous bursts was the main predictor in this study. In comparing scoring models to Bayesian networks, the CoC concluded that scoring models provided a lower maximum burst risk but were able to classify a higher number of cases correctly. A limitation of scoring models is that they are driven entirely by data; while, Bayesian networks apply theoretical knowledge in addition to data. If the model is data driven, the model is solely based on the quality of the data used. This study is only an introduction to asset management; therefore, both the scoring models and Bayesian networks need to be further investigated to provide a reliable model.

Data Requirements: Variables included within the scoring model are pipe installation year, pipe age, number of bursts, number of houses where the pipe starts and ends, pipe diameter, length, material and the traffic frequency. The Bayesian network model estimates the history of the pipe along with three limited state functions, including hoop stress limit state, shear stress limit state and fatigue limit state. Variables included in the Bayesian network included pipe depth, installation method, pipe material, mean diameter, thickness, age, age of last burst event, previous repairs, rainfall, temperature and soil type.

Model Description: Lu et al. (2003) presented a linear fracture mechanics approach for the determination of pipe lifetime prediction. This approach is specifically used in order to analyze brittle failure initiating from flaws located at the surface of acrylonitrile-butadiene-styrene (ABS) plastic pipes. The model proposed utilizes a linear fracture mechanics approach for the determination of a pipe lifetime. Within this methodology, stress intensity factors are established and are associated with pressure, deflection and residual stress that are combined to determine the net total stress at the opening of a flaw.

Having established the stress intensity factors (SIFs), an algorithm to predict pipe lifetime is utilized. A time marching loop is then used to simulate crack growth until the SIF developed by the structure is equal to the current fracture toughness of the ABS material. Additional fracture mechanics approaches using fracture toughness and stress rupture lifetime is used to validate the lifetime prediction method.

A pipe section was utilized to verify the results, and it was concluded that the predicted failure times were in agreement with experimental results. In every instance, the fracture toughness was exceeded before the crack propagated through the pipe wall. Factors controlling pipe lifetime were also singled out and evaluated: soil deflection and initial flaw size, fracture toughness and slow crack growth resistance, and residual stress. Some areas of improvement stated within this article included examination into the crack tip process zone, numerically computed SIFs, flaws in service, point loads and fatigue and pipeline networks.

Data Requirements: Parameters describing the slow crack growth were determined from a logarithmic plot obtained from a "C ring" test by means of a pipe sample. The fracture mechanics approach in the determination of a pipeline lifetime considered factors such as pipe wall thickness, diameter and internal pressure.

Model Description: Farshad (2004) proposed two new criteria for the service life prediction of single layer and multilayer plastic pipelines under pressure: the ultimate strain extrapolation method (USEM) and the distortion energy extrapolation method (DEEM). The process of both methodologies includes performing internal hydrostatic pressure tests, creep tests to determine the creep modulus and calculation of the hoop stress. The USEM and DEEM is then determined by relating the creep modulus and the calculated hoop strain with the strain and distortion energy. Following a regression analysis is applied to determine the long term failure strain as a function of time.

Sample data from a PVC-U pipe was included within this study to verify the proposed methods. Overall, three regression models were employed based on stress, strain and energy. Results were analyzed by comparing a classical standard extrapolation method (SEM) with the ultimate strain and energy methods. In all cases, the independent model was in agreement with the modified SEM analyses. Conclusions proposed that the USEM appeared to be suitable for brittle and fiber-reinforced materials that fail due to an ultimate strained state rather than applicability of maximum stress. The DEEM is suggested to be applicable to a broader range of material types.

Data Requirements: A pipe sample was utilized to relate the various models to one another. The USEM method analyzes strain, including variables such as hoop stress and the time-dependent creep modulus, while the DEEM method analyzed the distortion energy based on Poisson’s ratio, creep modulus in reference to time and the stress at failure.

Model Description: Seica and Packer (2006) examined a numerical strength evaluation method that is able to predict the strength of CI pipes as a result of longitudinal bending. The main use of this method is implemented with CI pipes that experience no corrosion and/or uniform corrosion. The proposed section analysis method evaluates the cross section of the pipe, which is divided into a number of horizontal strips. Overall, this method uses a “smear” approach to calculate for the corrosion pits by using a fictitious pipe wall thickness based on the amount of material lost due to corrosion. Using the section analyses method, linear and non-linear finite element analyses were performed that were purposely employed in order to compare and verify the resulting failure loads. This finite element evaluation is also presented within the article “Finite Element Evaluation of the Remaining Mechanical Strength of Deteriorated Cast Iron Pipes” (Seica 2004).

Six CI pipes were utilized in this study to estimate the bending strength under a four-point bending load condition. In a comparison of the section analyses to the finite element method, it was shown that the nonlinear section analysis provided similar results to the finite element analysis, which was in contrast to the linear analysis. In certain cases, it was illustrated that the section analysis method in comparison to the finite element method tended to overestimate the strength of pipes that had deep and/or localized corrosion pits and pipes with internal defects. As this method uses a smear approach, the analysis method is not accurate for pipes that have deep and/or localized corrosion pits and pipes with internal defects.

Data Requirements: CI pipe samples were tested to estimate the bending strengths. Variables included within this study are external pipe diameter, pipe wall thickness in terms of tension and compression, total number of strips used in the cross section, tensile stress and strain and external and internal radius that are used to determine the shift of the neutral axis. Stress and strain relationships were analyzed for compression and tension.

Model Description: Kim et al. (2007) developed prediction models for CI pipes using the assessment of residual tensile strength based on pit characteristics and fracture toughness. Samples of CI pipes were used to measure the degree of deterioration of pipes, including defects such as corrosion and pitting, and to analyze fracture toughness, the installation environment and water qualities. The tensile strength approach uses statistical analysis between mechanical intensity and geometric characteristics of corrosion pitting, while the fracture toughness approach is applied with a SF in order to assess the structural stability of the pipe.

Results illustrated that the proposed models using tensile strength and fracture toughness of CI pipes successfully estimated the residual life of water pipes. Analysis of the results proposed that the determination of fracture toughness may be more reliable than considering only the pit depth.

Data Requirements: Sample specimens of CI pipes were utilized to assess tensile strengths and fracture toughness's. Pit characteristics of tensile specimens include nominal diameter, specimen width, gross thickness, average pit depth, net metallic thickness, gross area and net metallic area. Tensile strengths were computed utilizing the breaking loads and area, while the fracture toughness was calculated based on nominal stress, length of notch and geometric factor by the specimen shape.

Model Description: Davis et al. (2008) examined fracture prediction in tough polyethylene (PE) pipes using measured craze strength from circumferentially deep-notched tensile (CDNT) tests. This study used an empirical method to predict the time to failure for PE pipes under pressure and deflection loads. The craze strength is related to the reference stress by the calculation of a craze stress using the CDNT test. The reference stress employed within this model utilizes the current load and the rigid-plastic collapse load of the component, as well as yield stress. The craze stress versus the failure time data is then used to predict the time to crack initiation.

The predicted model vs. actual observations was compared utilizing five types of PE pipes. Overall, this craze model tended to slightly underestimate the time to failure of the specimens compared to the actual craze stress failure time. Further analysis included quantifying the effect of additional constraints, such as pressure/deflection tests. Additionally, the model only predicted via craze failure initiation of the time to crack and did not account for the time following (i.e., the crack growth to failure).

Data Requirements: Sample specimens were required and needed to be remolded accordingly for the CDNT tests. Variables for the specimens consisted of outer diameter, thickness, pressure, deflection, initial crack length, actual failure time and predicted failure time.

Model Description: Burn et al. (2009) also examined three approaches that can be used to analyze plastic pipelines to determine the lifetime of the material: linear elastic fracture mechanics (LEFM), elastic plastic fracture mechanics (EPFM) and craze mechanics theory. Based on these values, Broberg's assessment criteria was used to allow the proper selection of one of the three lifetime prediction methodologies. The LEFM theory evaluates the fracture process by taking into account the SIF and the toughness of the pipe material. The EPFM theory accounts for the non-linearity in material deformation and for crack blunting that can occur prior to crack initiation. The final theory described within this article used craze mechanics to calculate the stress within a material. This methodology and case study is also presented within the article "Long-Term Performance Prediction for PE Pipes" (Davis 2009).

These theories were applied to six plastic pipe materials. In order to validate Broberg's criteria selection for the materials using the EPFM theory, each crack tip was evaluated by plotting the J-integral vs. the crack growth. Overall, the J-R curves were very close to the theoretical blunting line, indicating that crack growth is related to crack tip blunting. Therefore, the EPFM theory was not applicable. It was shown that the newer PE materials can form a large craze zone at the crack tip where LEFM and EPFM theories are not applicable and thus, the craze mechanics theory must be applied. Further analysis of this method may be necessary to obtain validated results in terms of an appropriate defect size and failure time with respect to the level of heat stabilizer.

Data Requirements: Coupon samples of PVC and PE pipes are utilized in determining crack growth rates on applied SIFs and time dependent craze strengths.

Summary of Deterministic Models

As this literature review illustrates, there are two types of deterministic models: empirical and mechanical. The key difference is that the mechanical models are primarily developed to predict the service lifetime of individual assets, while empirical models predict failure rates of networks. The limitation in using deterministic models is that the applicability of each individual model is restricted to a certain location and related factors. In general, deterministic models are unreliable in ascertaining pipe behavior under various environmental conditions and in quantifying the factors or parameters that affect the rate of pipe deterioration. Empirical models are only applied to homogenous groups of assets, while mechanistic models are normally applied to individual assets (Burn 2009).

The deterministic models presented in this report primarily entailed the use of laboratory tests and sample specimens to acquire the information needed. These techniques are difficult to implement in an entire water pipe system, and samples provided would only represent a certain section of the pipe. As a result of laboratory testing, special tests are needed to determine the different properties of varying materials. However, many of the methods proposed within the articles can only be used for one type of pipe material. The deterministic methods are simple in nature and are not able to account for such complexity as non-uniform corrosion in metal pipes or various environmental and operational stresses. It should be noted that very few pipe parameters are often utilized within this type of analysis. Overall, deterministic models are very site-specific and an entire system can only be generalized if the conditions remain the same throughout the site.

2.2.2 **Statistical Models**

There are 14 articles published on the use of statistical models for water pipe condition/performance assessment and prediction modeling. A summary of the statistical models is shown in Table 3.

Description: Kleiner and Rajani (2001) provided a comprehensive review of the structural deterioration of water mains using statistical models. These models utilized historical data based on past inspections and failures to quantify structural deterioration in water pipes. This article provides a thorough review of how these models evolved. Models reviewed are published from 1980 until 1999.

Table 3: Statistical Models

References	Article Title	Prediction Type
Kleiner & Rajani (2001)	Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models	Review of Statistical Models
Le Gat & Eisenbeis (2000)	Using Maintenance Records to Forecast Failures in Water Networks	Failure Rates
Park & Loganathan (2002)	Methodology for Economically Optimal Replacement of Pipes in Water Distribution Systems: 2 Applications	Optimal Replacement
Loganathan et al. (2002)	Threshold Break Rate for Pipeline Replacement in Water Distribution Systems	Optimal Replacement
Pelletier et al. (2003)	Modeling Water Pipe Breaks-Three Case Studies	Break Rates
Vanrenterghem-Raven (2007)	Risk Factors of Structural Degradation of an Urban Water Distribution System	Break Rates
Poulton et al. (2007)	The Impact of Pipe Segment Length on Break Predictions in Water Distribution Systems	Break Rates
Kleiner & Rajani (2008)	Prioritizing Individual Water Mains for Renewal	Break Rates
Berardi et al. (2008)	Pipe Deterioration Models for Water Distribution Systems	Failure Rates
Savic (2009)	The Use of Data-Driven Methodologies for Prediction of Water and Wastewater Asset Failures	Failure Rates
Wang et al. (2009)	Prediction Models for Annual Break Rates of Water Mains	Break Rates
Wood & Lence (2009)	Using Water Main Break Data to Improve Asset Management for Small and Medium Utilities: District of Maple Ridge, B. C.	Break Rates
Wang et al. (2010)	An Assessment Model of Water Pipe Condition Using Bayesian Inference	Deterioration Rates
Xu et al. (2011)	Pipe Break Prediction Based on Evolutionary Data-Driven Methods with Brief Recorded Data	Break Rates

Model Description: Le Gat and Eisenbeis (2000) presented the use of maintenance records to forecast failures in water networks based on statistical survival analysis for various pipe materials. The maintenance records used within this study are modeled from various utilities that have short- and long-term records. To calculate the number of failures in the pipes based on the statistical survival analysis, the Weibull Proportional Hazard Model (WPHM) was applied in the model to predict the times to failure. The survival function, S, was applied and took into account the components that affect the pipe with relation to time to failure. The failure time corresponding to the given survival probability is determined. The Monte Carlo simulation is used to aid in the prediction of the number of failures.

Using maintenance records, this paper presents two case studies, Charente-Maritime and Lausanne, which are used to compare the forecasted to the observed failures. The Charente-Maritime study predicted results that coincided with the observed number of pipe failures. In the case of the Lausanne study; however, the model underestimated every forecasted failure. The underestimated forecasted failures from the latter study are due to the increased pipe degradation observed within their site, missing environmental factors and inadequate records of failures. A section devoted to training and testing of the data was not presented.

Data Requirements: Factors that were analyzed within a Charente-Maritime case study were pipe length, age of the pipe, pipe diameter, type of pipe assembling, soil type, level of traffic and the supply methods such as gravity and pumping. The Lausanne case study, on the other hand, included such variables as the pipe length, diameter, material, pressure and age of the pipe. In order to evaluate each of these case studies, each utility was separated based on the type of pipe material. Within the types of pipes, groups were then formed depending on the number of previous failures (NOPF) (i.e., no previous failures or one or more previous failures).

Model Description: Park and Loganathan (2002) presented a methodology using threshold break rates in conjunction with failure prediction models in order to determine the optimal replacement of pipes in water distribution systems. These models consist of exponential, linear break rate and the Weibull form of Rate of Occurrence of Failure (ROCOF). Several examples were provided illustrating the use of a ROCOF in the break history of a pipe to determine optimal replacement times. Furthermore, the authors analyzed the optimal threshold break rate as a function of the pipe diameter in conjunction with replacement and repair costs. Practical usage of the threshold break rate is also presented within this article. A similar article presenting this methodology and examples are presented in the article “Threshold Break Rate for Pipeline Replacement in Water Distribution Systems” (Loganathan 2002).

Optimal replacement time expressions were obtained by setting the threshold break rate equal to the projected pipe break rates from the failure prediction models. Results obtained from three examples verified the accuracy and equivalence of the relationships. The cost data analysis also provided practical tables that recognized the relationship between the threshold break rate and the pipe diameter.

Data Requirements: Parameters utilized within the article are the number of breaks per 1,000 feet of pipe, base year for the analysis, growth rate coefficient, annual interest rate, repair cost of a break and replacement cost for the entire length of a pipe.

Model Description: Pelletier et al. (2003) assessed the deterioration rate of water pipes utilizing a modeling approach based on survival analysis with characteristics of the pipe and breakage history. The goal is to apply a pipe break model that estimates the present and future structural states of water pipes. The proposed model is used with minimal data while focusing on the number of previous breaks as the main issue. The model proposed employs two distributions for different break orders, utilizing a calibration strategy based on maximizing a likelihood function that extends the use of survival analysis. The distributions include Weibull, used for the first break order, and the exponential distribution to describe the behavior of subsequent breaks. Three statistical functions were used to represent the two distributions: survival function, probability density function and the hazard function. Overall, the Weibull/exponential model was applied, associating the risk of failure with subsequent breaks.

Three case studies from the Quebec municipalities of Chicoutimi, Gatineau and Saint-Georges were utilized to analyze the proposed model. The survival function was first plotted as a function of time in years for each of the three municipalities. Data were based on the Weibull distribution of the pipe failure from installation to first break. The results illustrated that pipes laid after 1960 have a higher risk of failure in comparison to pipes laid prior to 1960. This discrepancy may be explained by differing installation methods and material quality. Pipe replacement scenarios were also analyzed, which illustrated increases in annual pipe breaks for utilities with and without replacement scenarios. Ongoing research will seek to evaluate the impact of different risk factors such as pipe diameters and types of materials on the probability of break occurrence. A limitation of this model is that it does not consider other pipe deterioration methods such as corrosion, and only predicts the variability in the annual number of pipe breaks due to the natural gaining of pipes.

Data Requirements: Collected data variables consisted of pipe diameter, length, type of material, year of installation, type of soil and land used above the pipe.

Model Description: Vanrenterghem-Raven (2007) evaluated a proportional hazard model (PHM) to identify risk factors that affect the failure of urban water pipes to forecast the number of pipe breaks. Some concerns in applying this PHM to an urban environment is the presence of a vast number of relevant environmental factors that can lead to failure, the high left truncation of the data and erratic factors that may be specifically related to urban areas. The PHM is a statistical method that is used for renewable processes. The methodology utilizes a hazard rate function modeled with a WPHM to calculate the number of expected breaks per pipe. This proposed methodology is utilized through a Monte Carlo simulation. The significance of the risk factors were also identified by running a PHM one variable at a time along with data fitted to the PHM model to assess the significance of the risk factors.

This model was applied to a municipality in the urban area of Long Island City in New York. The statistical significance of every variable included within this study was determined, along with the expected number of breaks. Mixed results were concluded when comparing the expected number of breaks to observed breaks. This methodology does not consider the correlation between breaks and leaks due to other critical factors such as flow and pressure. The incorporation of these factors can ultimately increase the potential of the model since only structural degradation was included. A section devoted to training and testing of the data was not presented.

Data Requirements: Pipe variables used within this research included pipe length, diameter, material and age, and environmental factors including traffic, subway, location (intersection or block), water zones and highway. The combined effects of subway and highway, subway and water, intersection and length, and intersection and traffic were also evaluated. The pipe material was classified into subpopulations concerning steel and non-steel materials.

Model Description: Poulton et al. (2007) evaluated the impact of pipe segment length on break predictions in water distribution systems. A statistical model utilizing the linearly extended Yule process (LEYP) was presented that implements break predictions for each segment. Calculations using LEYP are performed based on an intensity function that depends on the age of the segment considered, the number of previous events and the vector of covariates. The described intensity function includes the influence of previous events in a form derived from the LEYP process, the influence of age in the form of the Weibull model and the influence of the covariates represented in the Cox proportional hazards model.

A case study was conducted to verify the statistical model with data collected from Veolia Water in France. During the method evaluation, it was found that the case study data included sandwiched pipes and segments made of different material than the original pipe placed there to support hydraulic equipment or to make repairs. In order to ensure consistent results, all sandwiched pipes and segments were eliminated and replaced using a concatenation process. Results illustrated that the model is not sensitive to short pipe segments. Furthermore, the concatenation process seemed to weaken the model's ability to identify pipe break risk. A section devoted to training and testing of the data was not presented.

Data Requirements: Parameters necessary for the proposed model included pipe diameter, length, installation year, identification of pipe concerned, date of intervention and type of incident. Desirable variables included such factors as joint type, reason for incident for pipe intervention data, soil type, soil surface type, traffic level and water pressure.

Model Description: Kleiner and Rajani (2008) examined the use of a non-homogenous Poisson model by evaluating pipe parameters that affect a water pipe. Overall, this statistical analysis considers three classes of parameters: pipe dependent, time dependent and pipe and time dependent. Several stages are also involved with validation of the model. First, the model must be trained via a process that involves use of the maximum likelihood method with a Lipschitz Global Optimizer (LGO) algorithm. The next step in testing is to validate the model, which involves forecasting the number of breaks in a validation period. Finally, the forecasted and observed failures are compared.

A case study utilizing data from a water utility in Canada is presented to verify the statistical model. The training period yielded quality results and concluded that the model was appropriate based on the goodness-of-fit test. Results showed that the model must analyze the covariates at group and pipe levels to avoid the inference that all covariates have the same impact on pipes. The proposed methodology was trained and validated accordingly.

Data Requirements: Parameters included within this study were pipe material, diameter, installation year, length, climate, X-Y coordinates of pipe nodes break date and break type.

Model Description: Berardi et al. (2008) proposed the application of performance indicators to model pipe deterioration using evolutionary polynomial regression (EPR). These performance indicators are incorporated into pipe deterioration models to determine projected failure rates. EPR is separated into two main stages: search for the best model structures using an integer coded genetic algorithm (GA) and parameter estimation for an assumed model structure using the least squares (LS) method. Overall, the EPR employs a multi-objective search to determine models that best relate to the optimal trade-off. Once the EPR is operated, each mathematical model or formula represents a point on the Pareto optimal trade-off curve of possible models. This methodology and case study were also presented within the article “The Use of Data Driven Methodologies for Prediction of Water and Wastewater Asset Failure” (Savic 2009).

The EPR models cannot be directly used to calculate the failure rate for individual pipes; therefore, two approaches are presented for establishing individual pipe criticality. The first approach develops a general failure model that can be used within any decision support framework. The alternative approach presented within this article is implemented by a specific multi-objective approach for pipe rehabilitation/replacement planning. The case study presented within this article contains asset information and failure records from a United Kingdom (UK) water distribution system. In order to validate the results, the model consisted of a pre-processing and a modeling phase. Overall, the EPR model successfully highlighted essential variables utilizing the case study data; however, the case study was not used to validate the failure rate calculations. A section devoted to the training and testing of data was not presented.

Data Requirements: Pipe assets included within this study are pipe age, diameter, length and number of properties.

Model Description: Wang et al. (2009) examined the development of deterioration models in order to predict the annual break rates of water mains considering material type. Overall, the methodology consisted of evaluating the best subset regressions, which led to determining the best possible relationship between the breakage rates and the independent variables of pipe age, size and length. Five multiple regression models were developed illustrating statistical analysis of different pipe material types. Linear and curvilinear relationships were considered in order to determine the most appropriate fit. The significance of each regression model was verified using the “F-test” and “t-test”.

A case study utilizing a Canadian municipality is presented to verify the proposed regression models. A sensitivity analysis of the developed models was conducted to evaluate how the annual break rates affected the independent variables. The first analysis consisted of evaluating the annual break rate vs. the pipe length, concluding that the pipes had a decreasing trend in annual break rate as the lengths of the pipes became longer. Another analysis included within this study was the annual break rate vs. pipe age, which showed that the annual break rates increase with age. Limitations of the developed model include that it is unable to predict when the next failure will occur in an individual pipe and it does not account for previous pipe repairs, cathodic protection and soil conditions. A section devoted to the training and testing of data was not presented.

Data Requirements: The data parameters included within these models were pipe material, diameter, length, year of installation, depth and break records.

Model Description: Wood and Lence (2009) utilized break data to forecast future break rates within subgroups consisting of pipe material, diameter, age and surface material. Two statistical deterministic equations were developed for each group of pipes: time-linear equations and time-exponential equations. Accuracy of the derived equations was calculated as the percent error of model predictions in comparison to the cumulative breaks in a one year time period.

Analyses showed varying break rates within the various subgroups. With the exception of CI, the pipe material groups such as asbestos cement (AC) and ductile iron (DI) had more accurate results utilizing the time-linear models than the time-exponential models. When analyzing factors individually or combining the sub factors, results showed mixed results in the accuracy to predict break rates.

Data Requirements: Past pipe break data was utilized in order to predict future breaks in varying sub groups. Sub groups were based on pipe material, diameter, age and surface material, such as, asphalt, concrete, gravel or grass.

Model Description: Wang et al. (2010) proposed a model which utilizes Bayesian inference to calculate pipe factor weights using pipe deterioration rates and various pipe factor. The relative influence of each factor on model performance was evaluated. Factors with the smallest influence on pipe condition were eliminated. The analysis used three measures of fit to test and compare the model results: Deviance Information Criterion (DIC), coefficient of determination and standard error.

Results were modeled by comparing the deterioration rates of the observed and Bayesian model. Analyses showed that pipe age and diameter had the most influence in determining the pipe condition. The factors including the number of road lanes, trench depth and electric recharge were eliminated from the final analysis due to their less significant weights in determining pipe condition. There was no significant difference among the models measurements of fit suggesting the models are within good agreement.

Data Requirements: Pipe deterioration rates were based on factors including outer corrosion, crack, pin hole, inner corrosion and Hazen-Williams C value. Model factors included pipe diameter, pressure head, age, trench depth, number of road lanes, inner coating, outer coating, electric recharge, bedding condition, soil condition and pipe material.

Model Description: Xu et al. (2011) developed two data-driven techniques, Genetic Programming (GP) and Evolutionary Polynomial Regression (EPR) to predict pipe breaks. Genetic programming is an algorithm-based methodology; while, EPR is a hybrid data-driven technique that incorporates a regression based on a numerical regression techniques which has the searching power of GP.

A pipe break data set from a water distribution system in Beijing was applied to the developed models. Specifically, homogenous groups based on pipe diameter and year of installation were analyzed. Earlier breaks were applied to develop the model, while the later breaks were utilized to validate the model. Both the GP and EPR models predicted similar results to the recorded number of breaks when fitting the total number of breaks for the earlier time period. When using the GP and EPR equations to predict future breaks, the developed models proved to underestimate the total number of pipe breaks. Authors attributed this underestimation due to the improved detection capability and construction.

Data Requirements: The input parameters for both the GP and EPR methods were pipe diameter, age and length.

Summary of Statistical Models

Statistical modeling entails the use of statistics to serve as a tool or mechanism to describe observed data. This overall approach was primarily developed due to the lack of fundamental science related to physical mechanisms that lead to pipe failure, which was required for deterministic models and availability of failure data. There are several types of statistical models available; however, a common feature is the basis on a large number of long term observed field data and processing through regression analysis. Usually, this approach is only applied to homogenous groups or cohorts of assets (Burn 2009). The statistical models use historical data related to water pipe failure to identify patterns. These models are broadly classified into Regression, Markov-chain, Bayesian and others.

The statistical models primarily entailed the use of maintenance records and failure data to forecast the number of pipe failures; however, historical maintenance records may be difficult to retrieve. This method is successful in modeling all types of pipe materials. Articles also provided methods in prioritizing pipe parameters and describing the role or factor they play in pipe deterioration. One article also described replacement scenarios implemented by different rates. Limitations of statistical models include selection of the proper model and finding a reliable historical database. To increase the validity of the results, several statistical models can be utilized. All statistical models presented in literature do not predict the condition of water pipes but pipe failure breaks. In addition, many of the models do not have a section devoted to training or testing of the data. Having a training and testing set would allow for a valid robust model that is generalized and able to predict future failure rates in different geographical locations. Another limitation is the regression-based approach. This approach often is not suitable for modeling the actual deterioration processes of a pipe since the sampling data frequently suffers from various limitations and selected examples. Consideration must be given to the pipe parameters that are utilized within the method. In most cases, only several parameters are analyzed, which may lead to variability in the number of predicted failures.

2.2.3 **Probabilistic Models**

There are seven articles published on the use of probabilistic models for water pipe condition/performance assessment and prediction modeling. A summary of the probabilistic models is shown in Table 4.

Table 4: Probabilistic Models

References	Article Title	Prediction Type
De Silva et al. (2006)	Condition Assessment and Probabilistic Analysis to Estimate Failure Rates in Buried Metallic Pipelines	Failure Rates
Davis et al. (2007)	A Physical Probabilistic Model to Predict Failure Rates in Buried PVC Pipelines	Failure Rates
Dehghan et al. (2008a)	Probabilistic Failure Prediction for Deteriorating Pipelines: Nonparametric Approach	Failure Rates
Dehghan et al. (2008b)	Statistical Analysis of Structural Failures of Water Pipes	Failure Rates
Davis et al. (2008)	Failure Prediction and Optimal Scheduling of Replacements in Asbestos Cement Water Pipes	Lifetime
Davis & Marlow (2008)	Quantifying Economic Lifetime for Asset Management of Large Diameter Pipelines	Lifetime
Moglia et al. (2008)	Strong Exploration of a Cast Iron Pipe Failure Model	Failure Rates

Model Description: DeSilva et al. (2006) presented a condition assessment and probabilistic analysis to estimate failure rates in metallic pipelines. Since many pipelines have limited historical failure records, condition assessment data is used to quantify the level of deterioration and to estimate the probability of failure of an entire pipeline over time. Given samples, a two-parameter Weibull probability distribution function was applied to estimate the maximum corrosion rate. The distributions are then extrapolated to describe the distribution over a larger target area and converted to equivalent approximate normal distribution functions. A Level II first-order-second-moment (FOSM) analysis is then combined with condition assessment data to determine the probability of failure. This model assumes that a binomial probability process can be used to calculate the expected failure rate of a pipeline.

A case study illustrating several sections of a buried mild steel pipe subjected to external surface corrosion was used to verify the value of the analysis. The remaining wall thickness of the pipe at each test point was conducted through various condition assessment techniques. Overall, the binomial probability process yielded results illustrating the relationship between failure rate and elapsed time. The model correctly verified that certain sections of pipe were located in a more corrosive soil than other pipe sections. This methodology proposes only analyzing selective sections for condition assessment of a pipe to represent the failure of the entire pipeline.

Data Requirements: This methodology proposes only analyzing selective pipe sections for condition assessment to represent the failure of the entire pipeline. The probabilistic failure models take into consideration of such factors as maximum applied stress (external and temperature contraction loads), critical stress required for failure related to external (soil characteristics and aeration) and internal (water quality and lining quality) galvanic corrosion, internal pressure, pipe wall thickness and radius of the pipe.

Model Description: Davis et al. (2007) evaluated developing a physical probabilistic model to predict failure rates in polyvinylchloride (PVC) pipelines. Due to limited failure data for PVC pipelines, this methodology proposes the evaluation of internal defects to determine the failure rates. The time to brittle fracture for pipes with internal defects resulting from internal pressure, soil deflection and residual stress is first determined by the LEFM theory. The defect sizes are then modeled as a stochastic variable and applied to a two-parameter Weibull distribution. The lifetime probability distribution is then approximated by a Monte Carlo simulation. Failure rates are estimated by a Weibull hazard function.

The predicted failure rates from the proposed failure model were compared with the failure data from 17 UK water utilities. A graph comparing the Monte Carlo simulation and the Weibull hazard function resulted in quality conformity between the two. From extracting failure history, including pipe length, the effect on age of average failure rates was determined. The comparison between predicted failure rates and observed failure rates were plotted, which showed the predicted curves compare favorably with the actual failure data. A limitation to utilizing Monte Carlo simulation is that results will change due to the random generation of data.

Data Requirements: Samples are required to determine the fracture properties of the pipe material. Parameters that are used to develop the Monte Carlo simulation included the number of segments in the pipeline, pipe segment length, total simulated time, incremental time period, material short-term fracture toughness, slow crack growth parameters, inherent defect size Weibull scale parameters, material short-term Young's modulus, visco-elastic parameter for reduction in Young's modulus, material short-term yield strength, visco-elastic parameter for reduction in yield strength, outer and inner pipe radius, maximum internal pressure in each segment, soil cover depth, soil unit weight, soil modulus, surface load and residual hoop stress acting at the pipe inner surface.

Model Description: Dehghan et al. (2008) proposed a nonparametric approach for the probabilistic failure prediction for deteriorating pipelines throughout various time intervals. The nonparametric approach takes into consideration pipe factors that are non-stationary in nature while the parametric approach does not. The idea of using a parametric approach may lead to inaccurate predictions since it cannot account for changes in the failure patterns over time. Utilizing the nonparametric approach, a maximum likelihood method estimates the failure probability of pipes in order to estimate the number of failures during a time period and its confidence intervals. The model is not intended for the prediction of a single component failure or systems where performance is sensitive to the behavior of a single component.

The technique provided was verified through the use of data from water pipes in western suburbs of Melbourne, Australia, and also with a simple averaging technique used to forecast the number of failures. Overall, the predicted number of failures based on the proposed method and a simple averaging method were compared to the true number of failures. Results concluded that the predicted number of failures using the proposed model closely resembled the observed number of failures. However, the predicted number of failures given by the simple averaging technique did not resemble values of the observed failures.

Data Requirements: This model relies heavily on the history of pipe failure data. Water mains were analyzed by groups that considered their material type, size and location.

Model Description: Dehghan et al. (2008) presented a parametric model using a probabilistic measure for pipe failure rates called likelihood of number of failures (LNF). These LNF values are derived from lifetime models that are empirically computed using a pipe failure database which is then compared to the theoretical failure rate. Since the theoretical failure rates are time-invariant, the authors further examine the stationarity of the pipe failure rates in practice, since the parametric model results are only valid if the pipes' failure rate is a stationary random process.

To evaluate the non-stationary pipe failure rates a case study was presented which analyzed the effect of rainfall in relation to the failure rate. The case study consists of an area covered with expansive clay soils which is believed to be the cause of many pipe fractures; therefore, the rainfall data is particularly analyzed to be the influencing factor. To analyze this assumption, the empirical failure rates were estimated and compared to the rainfall data. Results illustrated that when the rainfall was significantly above or below average for the season, there was a noticeable increase in the number of failures that demonstrates the failure process is non-stationary, suggesting that evaluating the failure rates or inter-failure times is invalid. Conclusions suggested that all parameters need to be updated to account for the time-varying nature of pipe failure processes or to develop a non-parametric approach that can efficiently analyze the non-stationary pipe failure process.

Data Requirements: Parameters used for the parametric pipe lifetime models considered the pipe material, size and geographical location.

Model Description: Davis et al. (2008) described a failure prediction method for AC water pipes using a physical probabilistic failure model. The physical probabilistic failure model is specifically designed to evaluate AC pipes under internal and external loads. The proposed probabilistic model implied the use of residual tensile strength to determine the degradation rate of a pipe; however, evaluation of this model found that the degradation rates varied significantly. A Weibull distribution was then utilized to develop a degradation rate, but when modeling the pipe lifetime data, the predicted data strayed from the data produced by Weibull distribution. An alternative method, Herz distribution, was finally used to model the uncertainty of the lifetime of a pipe which utilizes an empirical cumulative probability distribution.

A case study was utilized in where the AC water pipeline was subjected to both pressure and external loading. A graph illustrating the cumulative lifetime probability vs. the predicted service lifetime was plotted which showed the similarity between the empirical service lifetime distribution based on the Monte Carlo simulation with 1,500 trials and the fitted Herz distribution. A renewal rate was also presented through evaluating a hazard function. The tensile strengths used in this article were obtained from previous research and when calculating the degradation rate, one should take into consideration the changes in manufacturing methods.

Data Requirements: Attributes for the case study consisted of pipe diameter, wall thickness, installation year, internal pressure, burial depth, unit weight of the surrounding soil, live surface load from traffic and degradation rate. Degradation rates were determined by evaluating residual tensile strengths from small pipe coupons.

Model Description: Davis and Marlow (2008) looked at developing a physical probabilistic failure model utilizing condition assessment to determine the lifetime of CI pipelines. Specifically, a case study of a large diameter pipeline located in urban Australia was used to verify the proposed method. Due to the pipes' critical nature, historical failure data is not available and condition assessment techniques must be used to determine the remaining lifetime. The proposed method evaluates only several segments of the pipeline in order to determine corrosion rates. To model this variation, a two-parameter Weibull probability distribution function was used. A probability distribution function accounting for the variation in the pipe corrosion rate is implemented with a physical model to predict pipe failure due to internal pressure and external loading. This physical probabilistic model is then applied to a Monte Carlo simulation before being fitted again to another two-parameter Weibull distribution to model the variation in the predicted lifetime of the pipe. A hazard function is also generated to represent the probability that pipe assets will fail over time.

Graphs illustrating the failure time probability distribution and the hazard function for the CI mains indicated approximate failure times and the economic lifetime of a pipeline. A limitation within this study is that the model generated only illustrates pipes restricted to internal pressure and in-plane bending; therefore, the resulting failure mode is only shown with a longitudinal fracture, which is just one type of a failure mode. Other failure modes such as circumferential fractures are not considered.

Data Requirements: A pipe sample was analyzed to determine the corrosion rate of the system. The proposed model utilized factors such as internal pressure, mean diameter, external loads from soil and surface loads, original pipe wall thickness, pipe age, maximum corrosion rate and tensile strength of a un-corroded pipe.

Model Description: Moglia et al. (2008) looked at the strong exploration of a CI pipe failure model utilizing fracture mechanics of the pipe failure process. The first model generated is simple, which allows strong explorations of additional model assumptions. Throughout numerous assumptions, the model improved drastically. An elementary method, FOSM, was initially used but proved to yield inaccurate results. A new approach to the model evaluates the nominal tensile strength of pipes, which can determine the maximum corrosion defect. To account for the uncertainty or randomness within the data, a Weibull distribution is utilized adding stochasticity to the corrosion rate. The proposed model calculates failure rates based on historical data using a random Poisson statistical process. The maximum likelihood estimator used within Poisson distribution is used to calculate the failure rate of the historical data sets.

A case study was employed utilizing small diameter reticulation mains. By modeling various assumptions into the simulated model, the predicted and observed failure rates yielded similar results. Only failure modes by corrosion or combined corrosion and fractures are included within the observed data model. The authors recommend that the model should be tested with additional data sets. A section devoted to the training and testing of the data was not presented. This model will probably not be able to predict the failure rates for another area since the methodology used is not generalized.

Data Requirements: To determine maximum corrosion defects, pipe samples were evaluated for their tensile stress. Input variables within the model included pipe wall thickness, pipe construction year, pipe mean diameter, failure observation year, internal pressure, external load, soil load, failure exposure, corrosion rate, pipe age, pipe length, number of observed failures and the tensile strength of the pipe wall.

Summary of Probabilistic Models

Probabilistic modeling entails the use of statistical analysis to analyze the probability or relative frequency of an event occurring. Also, in contrast to purely statistical approaches, physical models are based on the actual degradation and failure processes that occur in service. Specifically, physical probabilistic models are developed where historical failure data is unavailable. These models predict the failure probability for a single asset or the failure rates for a network. One method primarily used to predict a distribution and range of values for dependent variables is the Monte Carlo simulation (Burn 2009).

The probabilistic models primarily entailed the prediction of failure rates for databases that have very little information. Specifically, parameters are analyzed that affect the performance of a pipe rather than evaluating the previous pipe failure history. Techniques used to predict pipe failure rates within the articles presented were condition assessment techniques, fracture mechanics, estimation of internal defects and the estimation of the likelihood of the number of failures. In many of the articles, the condition assessment of a pipe is only analyzed for a pipe section and not the entire pipeline. All probabilistic models presented predict the failure of a water pipe and not the condition of a pipe. No assurance is given to a utility manager to apply these methods since there is no generalization of the models and all fit the model by making assumptions. The methods used must be realistic and close to a real scenario. Simulations such as Monte Carlo can be questioned in how one would generate the random numbers. A limitation with using probabilistic models is the technique used to determine the failure rates. Since there are many techniques that can be used to predict the actual degradation and failure process of a pipe system, different conclusions will arise. Also, all asset types and loading conditions must be applied in order for the model to apply for an entire pipe network.

2.2.4 **Artificial Neural Networks**

There are six articles published on the use of ANN for water pipe condition/performance assessment and prediction modeling. A summary of the ANN is shown in Table 5.

Table 5: Artificial Neural Networks

References	Article Title	Prediction Type
Christodoulou et al. (2004)	A Risk Analysis Framework for Evaluating Structural Degradation of Water Mains in Urban Settings, Using Neurofuzzy Systems and Statistical Modeling Techniques	Pipe Failure
Al-Barqawi & Zayed (2006)	Condition Rating Model for Underground Infrastructure Sustainable Water Mains	Condition Rating
Achim et al. (2007)	Prediction of Water Pipe Asset Life Using Neural Networks	Pipe Failure
Geem et al. (2007)	Trenchless Water Pipe Condition Assessment Using Artificial Neural Network	Condition Rating
Amaitik & Amaitik (2008)	Development of PCCP Wire Breaks Prediction Model Using Artificial Neural Networks	PCCP Wire Breaks
Lijuan et al. (2012)	Leakage Prediction Model Based on RBF Neural Network	Leakage Time & Number

Model Description: Christodoulou et al. (2004) examined the structural degradation of water mains in an urban setting using statistical modeling techniques from parametric and non-parametric analyses. To identify pipe risk factors and their relevance to main breaks, an ANN is applied that utilizes a back propagation algorithm. Outputs of the network consisted of the days to failure (lifecycle) for each pipe segment and the outcome of the observation (i.e., break or non-break). Both outputs were utilized for pattern recognition and ranking relevant weights for risk factors. Parametric methods, Poisson regression and multi-model regression analysis were used to define the break data in terms of days to failure for the relevant risk factors. The non-parametric method used within this study was the Kaplan-Meier product limit estimator.

Kernel smoothing was applied to the multidimensional regression model and the Kaplan-Meier survival analysis model. This kernel smoothing entails using a joint probability density function that is estimated by illustrating a series of estimators based on known kernels or known density functions. Within this specific study, Epanechnikov kernels used for bounded datasets were applied.

The parametric and non-parametric models presented within this article efficiently modeled a New York City historical database by identifying break data in terms of days to failure and the hazard rate in relation to time to failure. Two graphs were plotted that illustrated the multi-dimensional regression and the Kaplan-Meier survival analysis. All of the models utilized within this article reinforced results found in previous studies that concluded the number of pipe breaks, material and pipe diameter present high risk factors that can affect the pipe. The ANN also successfully identified risk factors and ranked them in respect to relative importance utilizing pattern recognition and incomplete datasets. A section devoted to the training and testing of data was not presented. This article seems to try and fit the specific data; therefore, the methodology used is not generalized and cannot predict failure rates for another area in the future.

Data Requirements: The ANN seems like it is used as a “black box” given that no description was provided about the creation of the neural network. Parameters collected included data at the time of the break event (previous breaks, material, diameter and length) and areas affected by the aftermath (traffic, subway, highway and intersection block).

Model Description: Al-Barqawi and Zayed (2006) developed a condition rating model to assess the rehabilitation priority for water mains using an ANN. The ANN uses a back propagation algorithm analyzing environmental, physical and operational factors to determine the water main condition. The output variable consists of a condition rating scale from 0 to 10 with 0 representing a critical condition and 10 representing an excellent condition.

Data from municipalities in New Brunswick, Quebec and Ontario, Canada were used for training and testing the data set. The results from the ANN model were compared with the validated data set and it was concluded that the model predicted the water main condition rating within the reasonable margin. Breakage rate and age were shown to have the highest effect on the condition rating. An inverse relation between the condition rating and breakage rates was shown for most water main types.

Data Requirements: The ANN seems like it is used as a “black box” given that no description was provided about the creation of the neural network. The water main condition was based on type of soil, type of road surface, pipe cover, pipe diameter, pipe material, pipe age, number of breaks and the Hazen Williams C-Factor.

Model Description: Achim et al. (2007) presented a multi-layer perceptron neural network (MLP NN) to predict pipeline failure in terms of failures/km/year. The overview of the paper presents an Australian water company seeking to improve their capability to predict failures by utilizing an ANN. In the past, the water company predicted failures using two statistical models based on past failure histories and the age of the pipe: shifted time power model (STPM) and shifted time exponential model (STEM). However, these models predict a relatively low correlation between the actual and predicted amount of failures. The MLP NN topology within this article consisted of an input layer with six nodes, two hidden layers with eight nodes each, and an output layer with one node. Several techniques were used to cross-validate the models, including bootstrapping and random sampling.

Through data processing it was shown any exclusion of a variable reduced the predictive capability of the NN. In conclusion, NNs are useful for modeling complex problems with relatively less effort and these models can handle the combined effects of a large number of input variables. Future analysis for this model consists of incorporating time-dependent factors within the analysis, such as climatic factors and corrosion, along with additional supplementary factors to influence asset performance. In relation to the water company's statistical methods, the NNs unmistakably outperformed the STPM and STEM models in terms of predicting pipe failures. A section devoted to the training and testing of data was presented; however, results discussing/illustrating this stage were not provided.

Data Requirements: The ANN seems like it is used as a "black box" given that no description was provided about the creation of the neural network. Input variables included in the analysis were pipe diameter, year of construction, age, length and geographic coordinates.

Model Description: Geem et al. (2007) considered an ANN to assess the water pipe condition without excavating. They compared the ANN to a multi-layer perceptron (MLP) model in relationship to the real score condition. The proposed ANN utilized the MLP model with a back-propagation algorithm, while an overall pipe condition index was derived for the output layer based on five factors: outer corrosion, crack, pin hole, inner corrosion and Hazen Willams C value. Overall, the models were trained and verified utilizing separate pipe records.

The model developed was applied to a case study in South Korea. The ANN model generated a higher determination coefficient than the multiple linear regression (MLR) model in terms of the statistical correlation between observed and computed data. Overall, the results showed that the proposed ANN model takes into consideration the high nonlinearity that pipe data possess whereas the MLR model failed to consider the nonlinearity in real world data with respect to interpolation or extrapolation. All factors incorporated within the model were an adequate representation of a pipe condition. In future applications, the incorporation of more pipe data will increase the reliability of the model. It was also mentioned that the back-propagation technique could be replaced with a meta-heuristic technique.

Data Requirements: The ANN seems like it is used as a "black box" given that no description was provided about the creation of the neural network. Parameters included in the input layer of the ANN were pipe material, diameter, pressure head, inner coating, outer coating, electric recharge, bedding condition, age, trench depth, soil condition and the number of road lanes used.

Model Description: Amaitik and Amaitik (2008) examined the Great Man-made River Authority (GMRA) located in Africa, which experienced several pipe ruptures due to pre-stressed concrete cylinder pipe (PCCP) wire breaks. Shortly after these ruptures, a cathodic protection system was adopted for the entire network of pipes. A model using the ANN method was then developed in order to predict PCCP wire breaks and to provide utility authorities adequate information to monitor, inspect and rehabilitate their pipeline network.

The data analyzed special and standard pipes in relation to the installment of cathodic protection. The proposed ANN model did consist of training and testing phases. Results of the analysis were compared to a MLR model to quantify/verify the validity of the proposed model. When analyzing the actual vs. predicted number of breaks for the proposed ANN and the MLR model, it was shown that the ANN predicted PCCP wire breaks more efficiently than the MLR model. Analysis of the results also illustrated a pattern in the wire break predictions of the specialized and standard pipes. For example, the specialized pipes have a very low rate of failure when compared to standard pipes.

Data Requirements: The ANN seems like it is used as a "black box" given that no description was provided about the creation of the neural network. A multitude of records were utilized within this paper which may increase the system performance reliability. This model consisted of nine parameters that affected the deterioration process of the PCCP: monitoring period, pipe age, soil resistivity, design pressure, design soil density, design soil cover, type of pre-stressing wire wrap, wire diameter and wire pitch. The variables utilized are independently presented, which may not always be the case since there sometimes exists a cumulative effect of the variables.

*Model Descriptio*n*:* Lijuan et al. (2002) proposed a Radial Basis Function (RBF) neural network to forecast pipe leakage in water distribution networks. The RBF is a Gaussian function that is based on a forward network composed for an input, hidden and output layer. Two prediction models are presented: leakage time and leakage trend. The leakage time prediction model estimates each pipe leakage time pertaining to the laying parameters per pipe; while the leakage trend model utilizes the leakage time series to predict the future leakage number.

A leakage data set from a city of north China which included records such as leakage time, location, pipe diameter, material, leakage reason, leakage parts and maintenance and repairs records was utilized to evaluate the models. Results from the leakage time model presented the actual leakage date vs. the forecasted leakage date. The relative error between these two values was less than 10% which is considered a useful model. The leakage trend model results compared the actual vs. the predicted number of leaks. The maximum predicted error was 13% which also proved to be a good estimate. A section devoted to the training and testing of data was presented; however, results discussing/illustrating this stage were not provided.

Data Requirements: The ANN seems like it is used as a "black box" given that no description was provided about the creation of the neural network. Parameters included in the input layer neurons were pipe type, size, pressure, temperature, road surface properties and pipe buried depths.

Summary of ANN

ANN modeling entails the use of all variables that influence the service life of a pipe. Due to its highly complex, nonlinear and parallel computer composition, the ANN is primarily inspired by the way information in a biological nervous system is processed. The input information and the predicted outputs are linked with the use of functional relationships. This approach can be used to develop an individual asset or a network (Burn 2009).

The statistical models included very few parameters considering the robust nature of ANNs. Overall, each parameter analyzed can increase the system performance reliability, including time-dependent factors. Parameters can also be applied a weight, which is a method in prioritizing the actual amplitude each factor plays on the overall condition of the water pipe to conclude a defined output. The method can also be utilized to represent any type of pipe material. A limitation to the ANNs is that the authors seem to use it as a "black box," which means that no description was provided on the creation of the neural network. It should be noted that a section devoted to training or testing of the data was not presented in several of the articles. Without this phase, the data is fitted, and therefore; the methodology used is not generalized and cannot predict future failure rates for another area. It was shown in the articles that ANN models are extremely capable of taking into consideration a higher degree of nonlinearity and unmistakably outperformed other models such as STPM, STEM and MLR. Since this model is primarily based on actual data parameters, a limitation may be the lack of data utilities possess. This model approach also requires an increased level of skill and training in order to develop these complex networks as well as train them.

2.2.5 **Fuzzy Logic**

Nine articles have been published on the use of fuzzy logic modeling for water pipe condition/performance assessment and prediction modeling. A summary of the fuzzy logic models is shown in Table 6.

Table 6: Fuzzy Logic Models

References	Article Title	Prediction Type
Kleiner et al. (2005)	Risk Management of Large Diameter Water Transmission Mains	Deterioration Rates
Kleiner et al. (2004)	Modeling Failure Risk in Buried Pipes Using Fuzzy Markov Deterioration Process	Deterioration Rates
Makropoulos & Butler (2005)	A Neurofuzzy Spatial Decision Support System for Pipe Replacement Prioritisation	Vulnerability Rates
Najjaran et al. (2006)	Fuzzy Expert System to Assess Corrosion of Cast/Ductile Iron Pipes from Backfill Properties	Deterioration Rates
Najjaran et al. (2004)	A Fuzzy Expert System for Deterioration Modeling of Buried Metallic Pipes	Deterioration Rates
Sadiq et al. (2004)	Fuzzy-Based Method to Evaluate Soil Corrosivity for Prediction of Water Main Deterioration	Deterioration Rates
Rajani & Tesfamariam (2007)	Estimating Time to Failure of Cast-Iron Water Mains	Failure Rates
Rajani & Tesfamariam (2005)	Estimating Time to Failure of Ageing Cast Iron Water Mains Under Uncertainties	Failure Rates
Tesfamariam et al. (2006)	Possibilistic Approach for Consideration of Uncertainties to Estimate Structural Capacity of Ageing Cast Iron Water Mains	Failure Rates
Fares & Zayed (2010)	Hierarchical Fuzzy Expert System for Risk of Failure of Water Mains	Risk of Failure

Model Description: Kleiner et al. (2005) proposed a fuzzy Markov deterioration process to predict the future condition of a CI and DI pipe and PCCP. This model consists of a two stage process. The first step utilizes a fuzzy rule-based algorithm to determine the deterioration rate at a specific stage in life and condition state. Specifically, triangular fuzzy numbers are utilized defined by vertices of the triangle which represent ranges of the variables age, condition state or deterioration rate. Fuzzy rule-based modeling is used to represent the means of fuzzy "if-then" rules. The rule set for this specific example is *if* the pipe age is "A" *and* the pipe condition state is "C" *then* the deterioration rate is "D" at any given time.

Determination of the condition state of the asset in the next time step is then calculated from the present condition state and the deterioration rate in where the deterioration rate matrix takes on the traditional Markov deterioration process. The authors also go further by identifying risk levels over the life of a pipe using a fuzzy possibility of failure and the failure consequences.

This methodology is also presented within the article “Modeling Failure Risk in Buried Pipes Using Fuzzy Markov Deterioration Process” (Kleiner et al. 2004).

Due to limited data observations for asset condition, this model was not validated. No reasoning was provided why the specific membership function was selected. The fuzzy sets and techniques did help incorporate the imprecision and subjectivity of the data.

Data Requirements: This methodology requires parameters such as the age of pipe and the condition state. The condition state is assessed on limited characteristics particular to the pipe material type which include CI and DI pipe-external coating, external pipe barrel/bell, inner lining/surface and joint; or PCCP-mortar coating, pre-stressed wire, concrete core, pipe geometry and joint. To validate the model, two consecutive observations from the asset condition need to be readily available.

Model Description: Makropoulos and Butler (2005) developed a neurofuzzy system to predict the water pipe leakage vulnerability. This model includes a fuzzy inference system that is combined with a neural network back-propagation algorithm which is employed to train the model. The specific back-propagation is also known as the steepest descent method.

Input-output pairs are utilized to train the neuro-fuzzy system, which in this instance was water main burst records. The burst records together with their characteristics can be used to measure the probability of failure of a pipe with a specific characteristic. This data cannot be directly used within the neurofuzzy training system; therefore, a tool to pre-process the data was developed based on Bayesian statistics. This Bayesian statistics module is capable of accepting data in vector form which is used in the Bayes’ formula to calculate the probability of an instance occurring.

Overall, the calculated Bayesian probability of failure with each characteristic is utilized in the neurofuzzy system to link specific characteristics with the suitability for pipe replacement. The cumulative effect of the various pipe characteristics in relation to the final calculated pipe vulnerability is computed using the Ordered Weighted Averaging (OWA) and Spatial Ordered Weighted Averaging (SOWA).

The model was trained using the data from two water distribution networks with analyzing each network with and without training the fuzzy inference system. A graph illustrating the percent of actual bursts included in the set vs. the vulnerability ratings was provided. Results indicated that the training procedure increased the overall model performance. It is important to realize that some pipe bursts may not be in relation to the characteristics evaluated. In addition, the OWA and SOWA techniques must be used to determine the cumulative effect characteristics have on the pipes, since the Bayesian probability models only imply independent variables and not the interdependency of the characteristics.

Data Requirements: The inputs required to run the model include soil type, pipe age, pipe density, street type, diameter, maximum pressure and pipe material.

Model Description: Najjaran et al. (2006) evaluates a fuzzy expert system for the deterioration modeling of buried metallic pipes based on surrounding soil properties. This model consists of a subjective and an objective part. Two expert systems were proposed for the fusion of the subjective and objective models. The first structure consists of a fuzzy subjective and objective model which directly determines the deterioration rate using soil properties. The other method consists of a fuzzy subjective model to determine the corrosivity potential (CoP) of given soil samples and then the regression objective model uses the field data which relates the CoP to deterioration rates. Specifically, the fuzzy knowledge base was determined through 5 input variables which are based from the 10-point scoring method that is commonly used to predict the soil CoP. The 10-point scoring method was first introduced by the Cast Iron Pipe Research Association (CIPRA) and is now utilized by the Ductile Iron Pipe Research Association (DIPRA). This methodology is also presented within the articles “A Fuzzy Expert System for Deterioration Modeling of Buried Metallic Pipes” (Najjaran et al. 2004) and “Fuzzy-Based Method to Evaluate Soil Corrosivity for Prediction of Water Main Deterioration” (Sadiq et al. 2004).

A series of soil samples were used in the validation of the proposed fuzzy logic expert system. A graph illustrating the relationship between the deterioration rate (DR) and CoP was provided. The fuzzy expert system yields reasonable data; however, data scatter exists which can be a result from not tuning the model through field data or not considering a dominant factor in which influences the CoP and DR.

Data Requirements: The input variables utilized from a soil sample include the soil resistivity, soil pH, percent of clay fines, soil redox potential and soil sulfide. The soil properties, pipe age and maximum pit depth are used to train the models.

Model Description: Rajani and Tesfamariam (2007) presented a possibilistic approach for the consideration of uncertainties to estimate the structural capacity of aging CI water mains. The model is an analytical model called Winkler type pipe-soil interaction (WPSI), which is based on a possibilistic approach that uses the remaining pipe wall thickness to determine the current structural FS. The WPSI model determines the stresses, strains and displacements at any place along a jointed pipe. To account for the uncertainties within the input parameters, a fuzzy set theory using triangular fuzzy numbers (TFN) is applied allowing approximate reasoning. The calculated FS is also a TFN that can be implied as a possibility distribution. The uncertainty is described using two measures: Π, which is the possibility, and N, which is necessity. The possibility of failure utilizing the framework is classified in terms of an FS, and the failure should lie between the measures of N and Π. This methodology is also presented within the articles "Estimating Time to Failure of Ageing Cast Iron Water Mains under Uncertainties" (Rajani and Tesfamariam 2005) and "Possibilistic Approach for Consideration of Uncertainties to Estimate Structural Capacity of Aging Cast Iron Water Mains" (Tesfamariam et al. 2006).

The application and verification of the method is illustrated through a case study in Calgary, Canada. Several locations along the pipeline were identified to illustrate how the input parameters affected the pipe. The input parameters of remaining wall thickness, residual strength and fracture toughness were positively correlated with the FS. Results of the sensitivity analysis also suggested that large diameter mains are strongly affected by external loads while small diameters are strongly affected due to the level of bedding lost. The analysis concludes that the use of corrosion control in terms of pit growth can be the most effective way to decrease the failure rate of metal pipes. Also, evaluating the possibility and necessity in relation to failure consequences can provide levels of risk for a pipe. It should be noted that this method analyzes the FS primarily based on the remaining pipe wall thickness; therefore, only pipes that experience corrosion can be utilized.

Data Requirements: Pipe samples are required to determine the pipes elastic modulus, tensile strength, ring modulus of rupture, bursting tensile strength, Poisson's ratio and fracture toughness. Other input parameters consists of pipe nominal diameter, wall thickness, pipe length, thermal coefficient, soil unit weight, trench depth and width, unsupported length, earth load and traffic load, water pressure, transient water pressure, remaining wall thickness and temperature difference.

Model Description: Fares and Zayed (2010) developed a hierarchical fuzzy expert system to determine the risk of failure of water mains. This system consists of 16 risk-of-failure factors within four main categories (environmental, physical, operational and post failure). Using the Mamdani rule system, the impact of the factors based on the four categories is first determined. The crisp observation of each of the four models is then again analyzed using fuzzy to determine the risk of failure. The risk of failure output scale ranges from 0 to 10, where 0 is the least risky condition and 10 is the riskiest condition.

A case study was applied which classified specific pipe segments based on their risk condition level. Particular pipe characteristics such as diameter and material were also highlighted by illustrating statistics for the total count and length for pipes classified as fair and risky. Results concluded that small diameter and CI pipes contribute most to network risk.

Data Requirements: Factors include type of soil, average daily traffic, water table level, pipe diameter, material, age, protection method, breakage rate, hydraulic factor, water quality, leakage rate, cost of repair, damage to surrounding, loss of production, traffic disruption and type of serviced area.

Summary of Fuzzy Logic Models

Fuzzy logic modeling entails the use of fuzzy logic-based techniques that possess the ability to incorporate engineering judgment to predict infrastructure deterioration. This type of model is often used where data is scarce, cause-effect knowledge is imprecise and observations and model criteria are expressed in vague or “fuzzy” terms (Burn 2009).

The fuzzy logic models present knowledge-based approaches. Each of the methods seemed very intense and cumbersome. The membership function primarily used within the articles was the TFN. One article stated TFNs were used for simplicity purposes. As evidenced in the case studies, fewer pipe parameters were analyzed in comparison to the artificial intelligence model ANN. Two of the methods did analyze the remaining pipe wall thickness in which only deterioration rates of metal pipes could be determined. The main limitation for fuzzy logic models is the challenges that exist in constructing a fuzzy rule set, selecting a membership function and determining a defuzzification process.

2.2.6 **Heuristic**

Five articles have been published on the use of heuristic modeling for water pipe condition/performance assessment and prediction modeling. A summary of the heuristic models is shown in Table 7.

Table 7: Heuristic Models

References	Article Title	Prediction Type
Kleiner & Rajani (1999)	Using Limited Data to Assess Future Needs	Break Rates
Watson et al. (2004)	Bayesian-Based Pipe Failure Model	Failure Rates
Al-Barqawi & Zayed (2006)	Assessment Model of Water Main Conditions	Condition Rating
Al-Barqawi & Zayed (2008)	Infrastructure Management: Integrated AHP/ANN Model to Evaluate Municipal Water Mains' Performance	Condition Rating
Zhou et al. (2009)	Development of a Fuzzy Based Pipe Condition Assessment Model Using PROMETHEE	Condition Rating

Model Description: Kleiner and Rajani (1999) presented a five-step methodology to assess the future needs of water pipes using limited data. This methodology provides a way for utilities that have limited break history data to budget for future pipe replacement. The five steps included within this methodology comprise of: (1) gathering data in relation to homogeneous groups used to predict future breaks where data is insufficient, (2) establishment of group breakage rate patterns to predict future breakage rates, (3) use of projected breakage rates to determine the economic life of water mains, (4) examination of probabilistic scenarios of water main life and (5) determination of the investments required to replace water mains. Breakage patterns are identified using an exponential relationship and are based on water main structural breaks, which did not include leaks discovered by specialized programs. Due to the absence of data, a heuristic procedure was used to apply three probability distributions to the group data: Gumbel, Weibull and Herz distribution. An analysis of variance (ANOVA) procedure was utilized to identify significant variants.

Verification of the model took place through a case study. The development of a heuristic procedure applied to three probability distributions was highlighted in a plot representing the replacement rate vs. year. It was found that the replacement age in the first 30 years was very similar between all distributions; however, the distributions began to predict dissimilar rates thereafter. The ANOVA procedure verified that pipe vintage, soil type and operating pressure was critical in predicting breakage rates. This methodology should only be used for financial planning and is not intended to be used for a water main renewal plan. This methodology is only used to identify a specific cohort and not individual pipe sections.

Data Requirements: Parameters and homogenous cohorts consisted of vintage, soil type, diameter, region, length, operating pressure, road type, surface condition, foundation state, car traffic loading and bus traffic loading.

Model Description: Watson et al. (2004) presented a Bayesian methodology that combines engineering knowledge with recorded failure data to establish failure rates. This hierarchical model works to combine information from various sources of data while assuming similarity between parameters. The model assumes the failure rates of each pipe are from the same distribution called hyperprior. The pooling of the data dramatically improves the accuracy of the failure rates and can be seen as assumptions that pipes are identical as well as different. This hyperprior then determines how the individual failure information updates affect other similar pipes in a network. For example, a "tight" hyperprior with small variance implies that pipes are similar, while a "loose" hyperprior with large variance implies that pipes are different.

To validate the methodology, breaks were generated for two random pipes assuming a constant failure rate. The simulation results compared the failure rates vs. time, which illustrated the Bayesian model in comparison with the natural estimation that assumed a Poisson distribution. In the first 25 years, it was shown that the Bayesian model provided a better estimate of the failure rate than through the Poisson distribution. After the 25-year period, it was shown that the Bayesian model converged to the natural estimate of the failure rate.

Data Requirements: This methodology uses engineering knowledge combined with previously recorded failure data.

Model Description: Al-Barqawi and Zayed (2006) proposed a condition assessment model utilizing the analytic hierarchy process (AHP). The AHP consists of quantifying the effect of qualitative factors with regards to expert knowledge. The AHP application presented within the article consists of an eight step process. The factors which affect the condition of a water main are first acknowledged by setting up a hierarchy. Pair-wise comparison matrices are then developed for the main and sub-factors along with assigning priorities and establishing a priority vector. A consistency analysis is then used to verify the consistency of the pair-wise comparison matrix so that the weights can be considered. Priority weights are considered along with assigned attribute effects for each sub-factor. The condition assessment value is finally determined which mathematically combines the different priority matrices with the efficiency rate score for each criterion.

A case study was utilized to determine the condition of water mains using the AHP. The condition assessment values ranged from 10 to 0 illustrating an excellent to critical pipe condition. The validation process proved that the model provides acceptable results. Pipe age was said to have the highest effect on the condition assessment ratings.

Data Requirements: Factors considered within this AHP consist of type of soil, type of traffic/road, type of service, ground water level, pipe diameter, pipe material, pipe age, breakage rate, Hazen Williams C-Factor, cathodic protection and operational pressure.

Model Description: Al-Barqawi and Zayed (2008) developed an integrated model utilizing an AHP and ANN. The AHP is first utilized to assign weights and assess the current condition of a water main based on physical, environmental and operational factors. Since the AHP cannot deal with incomplete and missing data points, an ANN, which is trained with the available data set that accounts for missing points utilizing pattern recognition, is used. The ANN model utilizes a back propagation algorithm. The output condition rating ranged from a score of 10 to 0 illustrating excellent to critical pipe condition.

A case study utilizing three different municipalities in Canada was used to assess the results. Graphs illustrated the inverse relationship between pipe condition rating and age. Validation of the results proved the effectiveness of the model in predicting water main condition ratings when comparing the predicted versus actual ratings. This methodology was also presented as a web-based condition rating tool.

Data Requirements: Factors included within this AHP/ANN model consists of type of pipe, pipe diameter, pipe age, type of soil, ground water table level, type of service, average daily traffic, type of road, type of service, number of breaks, Hazen-William coefficient, cathodic protection and operational pressure.

Model Description: Zhou et al. (2009) presented a pipe condition rank method using fuzzy PROMETHEE II. PROMETHEE is an outranking method that constructs an outranking relation for a particular criterion/indictor and uses this relation to give ranks to each pipe. The model processes first-level and second-level pipe condition indicators and then generates a pipe condition index or ranking for each pipe. The weight of each indicator is fuzzy and is generated using the AHP; while the preference function is obtained through expert experience and knowledge.

The model was applied to eight pipe samples. Results ranked each of the eight pipes by the highest to lowest breakage risk. The interval size between adjacently ranked pipes indicated whether or not the ranking position was affected by changes in weights used. For example, the smaller the interval the more likely the rankings are affected by the subjective weights.

Data Requirements: The first level condition indicators include physical indicators, load, external corrosion and historical breakage. The second level condition indicators include pipe diameter, pipe age, pipe length, buried depth, water pressure, impact strength and maximum pressure.

Summary of Heuristic Models

The heuristic models illustrate how methodologies incorporate engineering knowledge rather than data parameters that affect a pipe to determine failure rates. One limitation of using engineering knowledge is the inconsistency in expert judgments from individual to individual and/or lack of experience in the personnel in making the judgments. This procedure may be a reliable method to illustrate failure risks with limited or no pipe data; however, employment of this methodology is limited due to its simplicity and the fact that any type of pipe material can be analyzed. This technique is a structured way of capturing expert opinions. Overall, utilities can use heuristic models as a first step in the determination of failure rates if no other mathematical model is available.

2.3 Current Water Utility Practice

A comprehensive overview of current utility practices related to failure and deterioration models for water pipes can help gauge the understanding between available mathematical models and current utility practice in predicting water pipe condition/performance and failure. In order to determine current practices, nine utilities in the U.S., Australia and Canada with significant activities of water pipe infrastructure management were contacted to participate in a survey. The type of information requested within the survey included: types of inspection and condition assessment techniques used; prioritization of inspection, maintenance and R,R&R; type of condition deterioration prediction; methods used to generate condition curves; factors included within the condition curves; software used; associated costs in generating condition curves; and type of pipe condition and/or performance index. Information from the survey assisted in targeting the most appropriate condition curves and deterioration modeling currently available.

It is seen from this current practice review that the inspection and condition assessment techniques utilized are dependent on the type of pipe material and differ significantly throughout the utilities. The prioritization, inspection, maintenance, R,R&R for water pipes also varies throughout utilities and is dependent on factors that include pipe material type, age, diameter, purpose of pipe and critical/non-critical. Within the utility current practice, utilities often utilize a condition rating index (CRI) that evaluates the existing water main condition by rating the pipe on a scale from excellent to an inferior quality condition. Performance measures can also be utilized to provide qualitative and/or quantitative information needed to measure the extent to which a utility is achieving its intended outcomes. Throughout the nine surveyed utilities, approximately half of them utilize some sort of condition index or ranking system to prioritize water pipes; while, only one utility utilized performance measures which were based on planned interruption, performance measures for main breaks and customer satisfaction. A diagram illustrating the various utilities inspection methods, condition indices, performance measures and models are shown in Table 8.

The exact deterioration or failure model utilized by utilities varies significantly. Generally, each utility utilizes a type of long-term economic forecast model which is a tool designed to help the utility estimate the “economic life” of assets to support planning for the maintenance and replacement of water pipe aiding to the total lifecycle cost analysis. Types of long-term economic forecast models presented through the survey consisted of Nessie Curves, Wave Rider Model, KANEW and the Computed Aided Rehabilitation of Water Networks (CARE-W) which has a Long-Term Planning (LTP) tool to estimate the long term investment needs.

Table 8: Summary of Utility Inspection, Condition Index/Performance Measures and Models

Utility	Inspection Methods	Condition Index(Ranking)/ Performance Measures (Y-Yes, N-No)	Models
A	Cathodic Protection Program, Pipe Sampling, Leak Detection, Uni-Directional Flushing Program, Water Main Internal Lining Program, Valve and Hydrant Replacement Program, Neighborhood Program, and Hydroscope	Y/Y	1.Reactive Renewal Program
			2.Proactive Renewal Program
			3.Hydraulic Model
B	Non-Invasive Technology, Cathodic Protection, Forensic, Sahara, Smart Ball, and Echologics Acoustic Wave Technology	N/N	1.Computer Aided Rehabilitation of Water Networks (CARE-W)
			2.Linearly Extended Yule Process (LEYP)
C	Hazen Williams C-Factor Test and Corrosion Monitoring Stations	Y/N	1.Nessie Curve (Long-Term Economic Forecast)
			2.Pipe Prioritization Replacement Model
			3.Hydraulic Model
D	Spot Checks	N/N	1.Wave Rider (Long-Term Economic Forecast)
			2.Water Main Replacement Model
E	Linear Polarization Resistance, Magnetic Flux Leakage, Ultrasonic’s	Y/N	1.KANEW (Long-Term Capital Investment Forecast Tool)
			2.PARMS-PRIORITY (Water Main Prediction Model)
F	Internal Visual/Sounding Inspection, Electromagnetic Inspection, Sonic/Ultrasonic Pulse Echo, Sahara, Smart Ball, Leakfinder RT, Acoustic Fiber Optics, and Electrochemical Potential Survey	Y/N	1.Nessie Curve (Long-Term Economic Forecasting Model)
			2.UMP Condition Rating System
G	X	X	1.Hansen Asset Management System
H	X	X	1.Pipe Evaluation Model (PEM)
I	X	X	1.Point System

X - Unavailable

Many of these utilities also utilized some form of pipe condition/failure curve or prioritization model in order to predict individual pipe failure. The input parameters utilized to develop these curves or prioritization model do vary significantly and are dependent on the type of model and utility objectives. For example, a Canadian utility developed a proactive water main renewal program to analyze area and candidate criteria rankings for water pipes. The area criteria rankings are based from condition/material/maintenance history components, hydraulic components and water quality components; while the candidate criteria rankings are based on components such as condition/break history, demographic, hydraulic, water quality and economies of scale. Each component is separated into several categories which are given a rank of 0 to 5 and are then applied to a weighting scheme. The final score is based on the total number of points which is then classified into ranks.

The CARE-W software is also used by a utility that includes fundamental instruments for estimating the current and future conditions of water networks. Tools utilized from the program consist of the Annual Rehabilitation Plan (ARP) from which annual rehabilitation projects are selected and ranked and the Linearly Extended Yule Process (LEYP) tool which analyzes break data to predict future break rates. Another software program called PARMS-PRIORITY is utilized by an Australian utility. This program predicts the condition of water pipelines based on risk calculation, failure prediction, cost assessment, data exploration and scenario evaluation.

A Weibull distribution model based on recent leak history of a particular pipe compared to the risk cost of failure and repair against the replacement cost was also utilized by a utility for water main replacement. Specifically, this model determines if individual water pipes are near or at the end of their economic life by comparing the annual cost of a new pipe to the marginal risk cost of the existing pipe. Another utility prioritizes pipe replacement projects utilizing a point system based on the number of breaks, life expectancy and maintenance costs. A similar point system was also developed that comprises a combination of the age of the water main and its break frequency where points are assigned based on year of installation and number of pipe breaks. Pipes with seven or more points require referral.

A Pipe Evaluation Model (PEM) was also presented that is a comprehensive planning and decision support tool designed to assess priorities for the replacement and rehabilitation of water pipes. The model consists of assessment factors that are applied to different weighting schemes to allow for the utility to adjust their model for annual priorities. Assessment factors include physical (size, material type and age); geographical (soil, corrosion, field samples, paving and redevelopment); hydraulic (Hazen Williams C-factor, fire flow and operational pressure); maintenance (breaks and leak rates) and quality of service/reliability (discolored water and outage rate).

Another utility developed a water pipe condition rating system that establishes a baseline condition rating for water pipes utilizing condition assessment protocol. The rating system includes six parameters that aid in determining further inspections of pipes: land use, repair history, operational needs, known manufacturing defects, last inspected and pipe diameter. Each risk factor has a defined set of rating factors per a specific description of the risk factor. An empirical formula utilizing the six parameters is used to define the risk value. Pipes with risk values of approximately 80 are considered to be at risk, while a risk value of more than 100 is to be at an increased risk.

Overall, many utilities feel confident about their condition prediction and/or failure models; however, they do not consider evaluation and validation of their models a priority. Utilities do endure exceptionally different costs associated to their utility in relation to programs, software, models, condition assessment, etc. The software and programs utilized by each utility vary based on their needs and budget. Most of the utilities have some form of geographical information system (GIS) database that stores their water pipe infrastructure data. In conclusion, utilities are willing to use a robust condition prediction or deterioration model if it is available and piloted at various water utilities.

2.4 Global Research Organizations

Organizations worldwide have conducted research projects to help improve the predictability of critical water mains. Some of the national and international organizations include the United States Environmental Protection Agency (USEPA), American Water Works Association (AWWA), Water Research Foundation (WaterRF), Commonwealth Scientific and Industrial Research Organisation (CSIRO), National Research Council (NRC) Canada and the United Kingdom Water Industry Research (UKWIR). Many of these organizations collaborate to develop scientific achievements in the water pipe industry. These collaborations are prominent since they allow organizations to learn from one other and share information for the common good.

Organizational research efforts have led to significant undertakings with projects including the development of various software programs which focus on pipe failure forecasting, current condition and strategic planning techniques. Along with their variable focus, each technique varies in their data needs, skills required and degree of sophistication (WERF 2000). A list of these software programs is shown in Table 9.

Table 9: Condition Assessment and Planning Techniques (Adopted from WERF (2000))

Technique	Focus	Data needs	Skills Required	Degree of sophistication	Commercialized
FailNet-Stat	Failure Forecasting	High (Asset and Failure Data)	High	High	Research in Europe
WRc Trunk Main Structural Condition	Current Condition / Remaining Life	Moderate	High	Basic	Available as Manual
CARE -W	Strategic Planning with Rehab Planning	Dependent on Tools Used	High	High	Yes in Europe & U.S.
KANEW	Strategic Tool for Replacing	High (Comprehensive Data)	High	High	Available through AWWARF
PARMS-Planning	Decision Support for Asset Renewal	High (Asset and Failure Data)	High	High	Produced by CSIRO, Australia
PARMS-PRIORITY	Decision Support for Asset Renewal	High (Asset and Failure Data/ Future Costs)	High	High	Produced by CSIRO, Australia
PIREP	Decision Support System for Rehab Planning	High (Asset and Failure Data)	High	High	No (Under Development)
SCRAPS	Bayesian Logic Structure	Moderate	High	Basic	Available through WERF
UtilNets	Reliability Support System	Very High (Asset and Failure Data)	High	High	Prototype Stage
D-WARP	Long Term Planning using Asset Failure Curves	High (Asset and Failure Data)	High	High	Produced by NRC, Canada
W-PIPER	Engineering, Design and Maintenance	Moderate	Medium	Medium	Produced by US Army Corps of Engineers
AQUA-WertMin 4.0	Forecasts the Deterioration of Pipe Condition & Rehabiliation Needs	High (Condition & Asset Data)	High	High	Developed in Germany
EPAREL	Failure Probability	High (Asset & Failure Data)	High	High	Developed by the Norwegian Research Institute

2.5 Critical Review

Pipe infrastructure asset management normally requires the collection of a wide range of data and a model to predict the condition and performance of pipe systems. Models for predicting the condition and performance of water pipes are typically considered as deterministic, statistical, probabilistic, ANN, fuzzy inference and heuristic. The capabilities and limitations of each model type are summarized below.

Deterministic models often utilize laboratory tests and sample specimens to acquire the necessary information needed so that relationships between components are certain. The applicability of a deterministic model is therefore restricted to a certain location and cannot be used under various environmental conditions. Deterministic models are based on limited parameters. Physical or mechanistic-based models and empirical models are few examples of deterministic models. Empirical models can only be applied to homogenous groups of assets, while mechanistic models are normally applied to individual assets. Empirical deterministic models could be applied to pipes that have adequate and reliable historical water pipeline failure data.

Statistical models primarily forecast the number of pipe failures with the use of maintenance records and failure data. In recent years, many authors have used statistical models to predict pipe failure. Typically, only select data parameters are used to determine failure rates; therefore, methods are often applied in prioritizing the pipe parameters. This approach is usually only applied to homogenous groups or cohorts of assets. Statistical models could be applied to pipes that have an adequate and reliable time-dependent historical database; however, applicability of statistical models is limited when considering newer pipes or cases with insufficient historical and/or time-dependent data.

Physical probabilistic models entail the use of statistical analysis, especially when historical failure or inspection data is limited or unavailable. These models specifically analyze the affect parameters have on pipe performance rather than evaluating the previous pipe failure history. These models can predict the probability of failure for a single asset or for a network. Usually, they are applied to pipes where the process of deterioration and factors for failure are well understood.

Artificial Neural Networks determine pipe deterioration rates utilizing all variables that influence the service life of a pipe. Each analyzed parameter can increase the system performance reliability. Parameters can be prioritized by applying weights and learning algorithms. An increase level of skill is involved in developing these complex networks. Data pre-processing, training and testing methods for selecting appropriate network are required. This approach can be used to develop a model for an individual asset or entire network.

Fuzzy logic models specifically incorporate engineering judgment and professional experience in order to predict infrastructure deterioration process. This type of model is often used where data is scarce, cause-effect knowledge is imprecise and observations and model criteria are expressed in vague or “fuzzy” terms. An increased level of skill is required in constructing the rule set and deciding the defuzzification process for the final output. The fuzzy logic based approach for pipe deterioration modeling is an essential mechanism to incorporate professional opinions and expert knowledge.

Heuristic models are scarce and limited in nature, but can illustrate how methodologies incorporate engineering knowledge in the determination of failure rates. A limitation of using engineering knowledge is inconsistency in the expert judgments from individual to individual and/or lack of personnel experience in making the judgments. However, model capabilities can be improved by considering additional expert knowledge and opinions.

From the current practice review it is shown that many of the water utilities have taken a step forward in developing predictive models. However, the models developed lack robustness and reliability compared to the numerous models found in published literature. In comparison, many of the models found in literature are relatively complicated for the average utility to apply to their own water infrastructure system. Additional research is required to improve, evaluate, and validate the deterioration prediction models to aid in bridging the gap between the models found in literature and the current utility practice. Overall, this state of the technology review is a key component which can provide readers, water utilities and research organizations options to achieve coordinated outcomes for the future.

2.6 Conclusions

Highlighted below are the conclusions of the methodologies for predicting the condition/performance of water pipes based on the literature and current practice reviews previously presented within this report. Overall, there are significant challenges associated with predicting the remaining economic life of water pipe infrastructure system.

- A multitude of parameters influence the condition and performance of water pipe infrastructure.
- A number of mathematical models have been proposed in the literature and few utilities have developed models and/or methods to manage water pipes.

- There are gaps between available mathematical models and current utility practice in predicting water pipe condition/performance and failure.
- There are limitations in model capabilities and/or complexity in analysis and validating these models.
- Limitations of model capabilities are not in mathematics, but in lack of fundamental understanding of pipe performance based on environmental factors.
- There is an inadequate understanding of pipe failure mode and mechanism.
- There is a lack of historical database and standard data collection and analysis protocols.
- There is no clear definition of pipe failure, some utilities consider water pipe break as a failure while other utilities consider a water pipe burst/rupture as a failure.
- There is a lack of standard definition when it comes to such terms as condition curve, deterioration curve, failure curve, performance curve, etc.
- To achieve improved pipe management, utilities would like to know the following:
    - What kind of condition information is necessary?
    - At what level of detail data (temporal and spatial) should data be collected?
    - What level of accuracy is acceptable?
    - How to evaluate and validate condition assessment technology?
    - How to analyze and validate deterioration models?

2.7 Recommendations

Highlighted below are the recommendations of the methodologies for predicting the condition/performance of water pipes based on the literature and current practice reviews presented within this paper. Overall, there is a need for reliable deterioration model(s) to be developed and piloted at various utilities. There are several recommendations to be made related to improving the practice of water pipe infrastructure asset management.

- Identify critical parameters that affect water pipe performance based on pipe material, diameter, joint type, external and internal environmental factors, etc.
- Data is critical to managing pipe infrastructure effectively. At a minimum, a pipe inventory and current information about pipe condition are essential.
- There is an urgent need for the standardization of definitions and protocols to collect, manage and analyze data related to the pipe infrastructure system.
- Improve quality, quantity and accessibility of condition/performance assessment data.
- Develop reliable and cost-effective technologies for condition/performance assessment.
- Generate long-term performance data through accelerated testing.
- Develop and/or modify existing models to better predict pipe condition/performance.
- Significant uncertainties exist in existing models, and while it may not be possible to eliminate them, they should be evaluated.

- It is important to pilot existing and/or new models at various utilities for practical use and adoption.
- A reliable pipe condition/performance deterioration model would greatly assist utilities.
- Additional research is needed as to how to design more efficient and cost-effective data collection strategies and how to extract information from existing datasets.
- New technologies with potential for improving the pipe condition/performance assessment process continue to emerge, and utilities need help evaluating them.
- Engineering practices and research continues to change rapidly, and utilities need to integrate the increasing body of knowledge.
- Utilities must develop in-house programs which will help them to prioritize R,R&R of water pipes for individual pipe segments.
- Emphasis must be placed on the statistical analysis and validation of models developed.
- Utilities need to develop and implement robust condition indices and performance measures regarding their water pipe infrastructure system.

2.8 Contribution of the Proposed Research to the Current Literature and Body of Knowledge

Performance assessment and deterioration modeling have become a critical aspect in life-cycle asset management. In general, a well-structured management program increases the confidence of decision making in regards to asset risk assessment, life-cycle costing, energy management and renewal options with associated costs. The proposed research aims at developing a performance index for metallic pipelines and the prediction of pipeline deterioration curves. Overall, these approaches lead to making confident asset management decisions.

There have been many proposed methodologies in assessing or predicting the condition or failure of water pipelines; however, the literature review revealed only few pipe condition or failure models that have been developed utilizing the fuzzy inference methodology. After considering the limited historical database and logistics of the pipeline infrastructure system, the fuzzy inference methodology was chosen for construction of the performance model.

The proposed research is believed to be more comprehensive than the fuzzy logic reports previously presented in this report. This is because the previous models mainly focus on only identifying a certain pipe characteristic or influencing factor that can lead to pipeline failure and not a range of factors that influence pipeline performance. For example, Najjaran et al. (2006) assesses the pipe condition by relating soil properties to the CoP which mimics the existing DIPRA 10-point scoring method and Rajani and Tesfamariam (2007) uses the WPSI model and possibilistic approach to estimate the structural capacity of aging CI water mains by determining the remaining pipe wall thickness due to corrosion. Particularly, the proposed research defines pipe performance through structural, characteristic, external and functional properties in terms of life expectancy, structural condition, break rate, internal condition, external stress and external corrosion. By evaluating each of these categories, key problem areas, as it relates to the pipe performance, can be identified.

Due to the restrictions of the previously proposed fuzzy inference methodologies, very few parameters are considered. The proposed performance model includes a broad range of parameters giving this model the reliability and consistency in determining the overall pipe performance rating. Other key restrictions, to previous fuzzy prediction models, includes that one model requires knowledge of the current structural condition, which is rarely available, and two models entail expensive and vigorous testing in the gathering of sufficient data.

The proposed research will contribute to the overall drinking water pipeline body of knowledge through the development of a data structure, pipeline performance index and comprehensive index evaluation process. Specifically, in developing the proposed research, the pipeline lifecycle, failure modes and mechanisms and data structure will be identified. All of these concepts are crucial in identifying key pipeline deterioration criteria and understanding the lifetime of a water pipe in order to develop a performance index. The proposed data structure and performance model will encourage water utilities to collect and document additional pipeline parameters during the installation, inspection and R,R&R process. An extensive evaluation process of the fuzzy inference performance model is also included. Previously many of the authors have lacked an acceptable means of evaluating their developed algorithm. By assessing a broad range of artificial, field and lab data, this evaluation process proves to be exceptional when compared to previously published models. Lastly, a future framework is set forth that utilizes the predicted performance ratings in the development of deterioration curves. These deterioration curves are specifically forecasted for individual subsets which can be used for determining further inspection and the R,R&R of pipelines.

3 Water Pipeline Performance Data

Water pipe is the main component in a drinking water distribution system. Most buried pipeline networks in the past have been installed using open trench construction methods which typically consist of placing pipes on a bedded material and then backfilling. Today, many pipeline networks are installed utilizing trenchless methods. Studies have shown that the structural performance and behavior of the buried pipe is dependent on type of soil, construction sequence, compaction control, surface loads and the type of pipe material utilized (Heger 1985; Serpente 1993; Rajani 1996; Boot 1998; Davies 1999; Makar 2000).

The pipelines that are used in the municipal water system consist of varying pipe material types. Specific application of a material type is dependent on the location and design purposes of the pipe to be installed. Consideration should be given to the pipe materials advantages, disadvantages and failure modes. For example, rigid pipe is designed to resist external loads by its inherent strength, whereas flexible pipe relies on the capacity of the surrounding soil to carry the load and provide stability. All types of pipe can perform well, but the conditions for satisfactory long-term performance vary. Furthermore, the performance criteria are different for the different types of pipe: the severity of cracking is the main performance criterion for rigid concrete pipe, whereas the degree of deflection is the main performance criterion for flexible pipe. For the purpose of analysis or design or both, it is necessary to develop a complete understanding of the failure modes and mechanisms of buried pipe infrastructure systems.

Many parameters affect the water pipe infrastructure systems. Examples of these parameters are physical factors such as pipe diameter, age, material and environmental factors such as soil properties and external loading. Effects of these parameters in relation to a particular pipe material type may lead to failures such as cracks, fractures and holes which in turn lead to a leaky pipe. Also, the effects of one parameter may amplify the effects of another. Figure 1 shows examples of some of these parameters which affect pipe deterioration in both short-term and long-term.

To develop a standard data structure, it is essential that the life cycle and failure modes and mechanisms of a pipe are thoroughly understood. Knowing the various life phases of a pipe aids in the development of a pipe data structure by giving one an understanding of when potential failures can occur at each stage. Furthermore, a comprehensive understanding of the various types of pipe failure modes and mechanisms aids in a complete list of potential factors or attributes of a pipe which affect the performance of a pipeline. Each of the factors playing a role in affecting the pipe condition is classified into separate groups based on their characteristics. Moreover, each parameter is prioritized based on parameter importance level in determining the overall pipe performance. A complement study pertaining to wastewater pipes was previously published by Sinha et al. (2008).

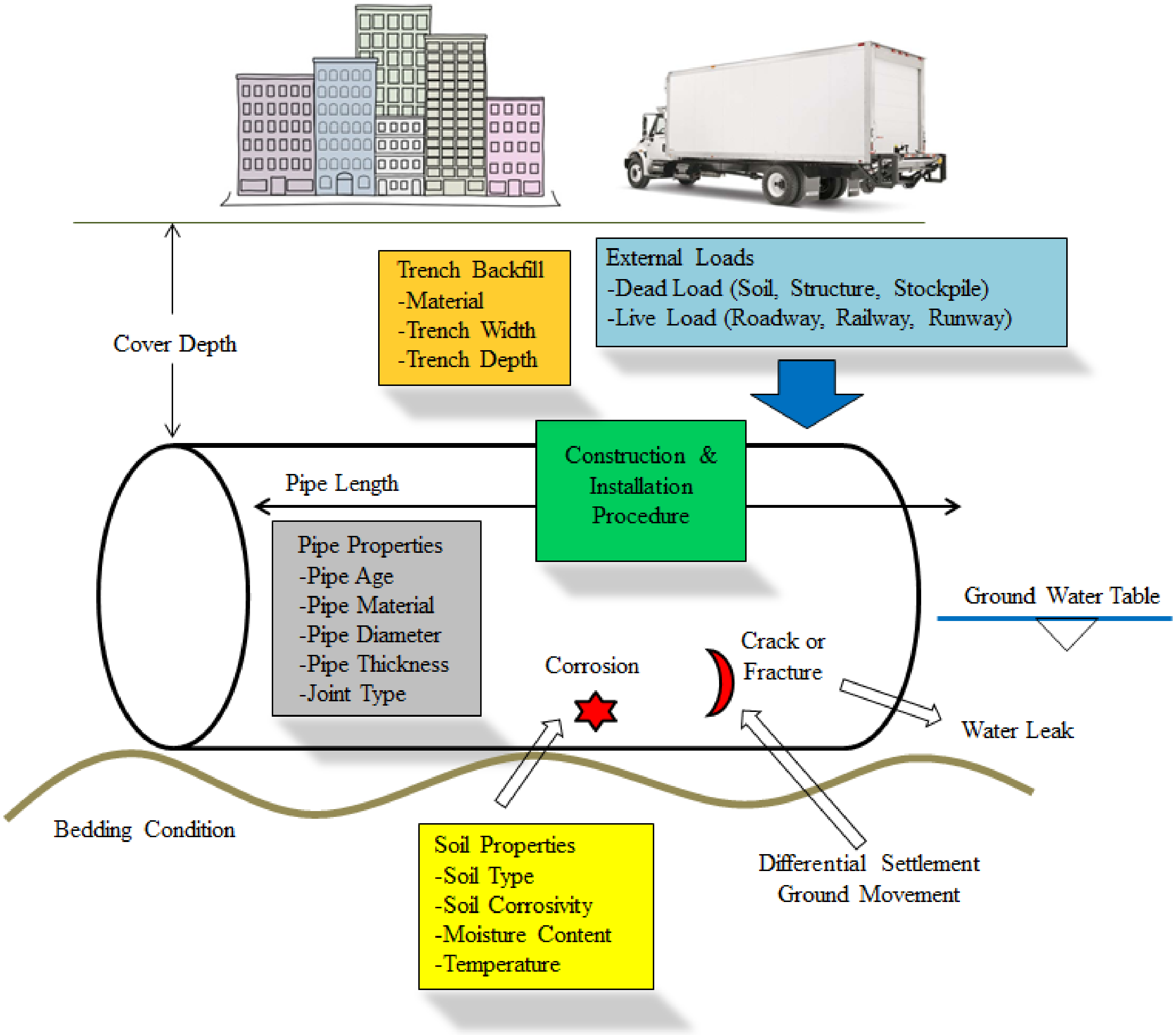


Figure 1: Factors Affecting the Condition and Performance of Buried Water Pipes

3.1 Water Pipe Materials

Various types of water pipeline materials have been installed over the past century. Each pipe material is characteristically designed for certain applications and provides their own advantages. The design and installation of a specific pipe type should be taken into consideration and only used where properly fit. For example, a ferrous pipeline should not be utilized in an area where there are stray currents present unless proper precautions have been taken such as installing cathodic protection. Not providing cathodic protection for this particular installation may lead to severe pipe corrosion and failure of the pipe. The following paragraphs give an overview of the most predominantly utilized water pipeline materials over the past 100 years.

Cast Iron Water Pipe

Around the 1900's grey CI pipes were introduced into the market and were produced by casting molten iron in vertical sand molds. The disadvantage of the cast in place CI pipes was the lack of a uniform thickness due to the misalignment of the central core mold; therefore, spun grey iron pipes were introduced around the 1930s and were widespread till 1960. This process included pouring molten CI into cylindrical molds that were made out of metal and sand lined, which rotated at high speeds. The centrifugal force formed the pipe walls (Reed 2006).

CI water pipes were predominately installed before the introduction of DI and thermoplastic materials. Today CI is no longer used; however, many water utilities still have a very high percentage of pit or spun CI pipeline. The main advantage of CI was its low cost. Disadvantages include that they are structurally weak and are subjected to internal corrosion that can lead to water quality problems. Also, age is not a good indicator of its structural condition since the older pit CI pipes have thicker walls than the later spun CI pipes (Reed 2006).

Ductile Iron Water Pipe

In 1955, DI pipe was introduced to the pipeline construction industry to replace CI due to its additional strength, toughness and ductility. DI differs from CI as it is in graphite form which is spheroidal, while CI takes on a flake form. A cement mortar is normally used for lining purposes (Reed 2006).

DI water pipes are primarily used where there are heavy traffic loads, the ground is subject to movement and subsidence and where there is contaminated land. The primary advantages of using DI is its high strength and toughness, resistance to pressure fatigue, well established methods of repair and impermeability to organic contaminants. Also, imported bedding is not required. Disadvantages include that they require protection against internal and external corrosion, there is a potential rise in pH when conveying soft waters, corrosion protection systems are at risk in certain soils, they are susceptible to impact and accidental damage and they are susceptible to attack by stray currents. Caution should be used where there are aggressive waters and where there runs a risk of stray current interference (Reed 2006).

Polyethylene Pipes

In the 1950's, PE pipes were introduced. More modern materials then became available from 1980 to 1990. One material that became available in the early 1980's was medium density polyethylene (MDPE) which was used over earlier low density polyethylene (LDPE) and high density polyethylene (HDPE) due to improved weld ability and resistance to crack growths. It should be noted that PE pipes are the same type of polymer (plastomers) as PVC pipes (Reed 2006).

PE pipes are primarily used in low to medium stress applications and where the ground is subject to movement and subsidence. The main advantages of using PE pipes is their corrosion resistance; flexibility; toughness; ability to absorb impact loads, vibration and ground movement; suitability for narrow trenching and trenchless applications; suitability for rehabilitation; ability to be welded to form a leak free end load resistance system and that they are lightweight. Disadvantages include that they are susceptible to permeation or degradation by certain organic contaminants, selected or imported bedding is required, dependent on stable support from ground to resist deformation, susceptible to UV degradation and run the risk of floatation. Caution should be used where there is contaminated land (Reed 2006). To help provide stability against UV degradation, PE pipes are typically impregnated with carbon black.

Polyvinyl Chloride Water Pipes

PVC pipe was introduced for water distribution markets in the 1950's. Polyvinyl chloride is a synthetic polymer which is a large molecule made up of many smaller units used to create a long chain. These chains and organic connections are obtained through processing of natural products or through synthesis of primary materials from oil, gas or coal. Each of these chains is made up of monomers which contain carbon and hydrogen as well as other elements such as oxygen, nitrogen, chlorine or fluorine (Reed 2006). During pipe manufacturing plasticizers are also often added to make the PVC pipes more ductile.

PVC pipes are primarily used in most low stress applications. The advantages of using PVC are their corrosion resistance, high resistance to chemical attack and the fact that they are lightweight. Disadvantages include that they are susceptible to permeation or degradation by certain organic contaminants, susceptible to point loading and impact damage, certain grades are susceptible to UV degradation, run the risk of fracture in contaminated land, selected or imported bedding is required, dependent on stable support from ground to resist deformation, requires care in handling and runs the risk of floatation. Caution should be used where there is contaminated land, surge conditions and where the ground is subject to movement and subsidence (Reed 2006).

Pre-Stressed Concrete Cylinder Water Pipes

In 1942, PCCP were first developed in the U.S. There are two types of PCCP: lined PCCP, where the concrete core is lined with a steel cylinder and embedded PCCP, where the steel cylinder is embedded within a concrete core. Specifically the concrete core is place by a centrifugal process, radial compaction or by vertical casting. Once cured, the pipe is wrapped with high strength wire which has a stress of 75% of the minimum specified tensile strength. Thick cement slurry then embeds the wire and is finished with a dense mortar coating (Reed 2006).

PCCP pipes are primarily used in heavy trafficked roads, contaminated organic land and where the ground is subject to movement. The advantages of using PCCP are their resistance to corrosion, high beam strength and rigidity and are impermeable to organic contaminants. Also, a high degree of compaction is not required. Disadvantages include that they are very heavy and are vulnerable to chemical attack from certain soils and waters. Caution should be used where there are aggressive soils and waters (Reed 2006).

Asbestos Cement Pipes

Asbestos cement (AC) pipes were first introduced in the 1930's and were an alternative to CI pipe from 1950 to 1960. The manufacturing then ceased in the UK in 1986 and was banned in many states of the U.S. in the 1990's. The production of AC pipes consisted of cement slurry containing approximately 2% by weight of chrysotile (white asbestos) fibers and Portland cement. The mixture was fed into layers onto the outer surface of a smooth rotating mandrel and consolidated by pressure. The pipe was then matured under water for several days where it was trimmed to the appropriate length (Reed 2006).

AC pipes were primarily used in heavy trafficked areas, contaminated land (organic) and where the ground was subject to minor movement. Advantages of using AC pipes were their strength and rigidity, ability to withstand fluctuating pressure and surges and their corrosion resistance to most soils and waters. Imported bedding was not required. Disadvantages include that they are susceptible to impact and accidental damage and they are vulnerable to chemical attack by certain soils and waters (Reed 2006).

3.2 Life Cycle

In order to understand the various types of pipe failures, it is important to first consider the pipes' lifecycle. Specifically, the lifecycle of a pipeline infrastructure system consists of the design and manufacturing, transportation and construction, and operation and maintenance phases. All R,R&R are considered as external influences that will also affect the life cycle of the infrastructure system. These infrastructure systems exhibit a common behavior which is known as the bathtub theory. This bathtub theory is a function of the probability of failure with time. The name "bathtub" comes from the line commonly produced by the probability curve (Farshad 2006). A representation of the bathtub theory as related to the failure probability of piping systems is seen in Figure 2.

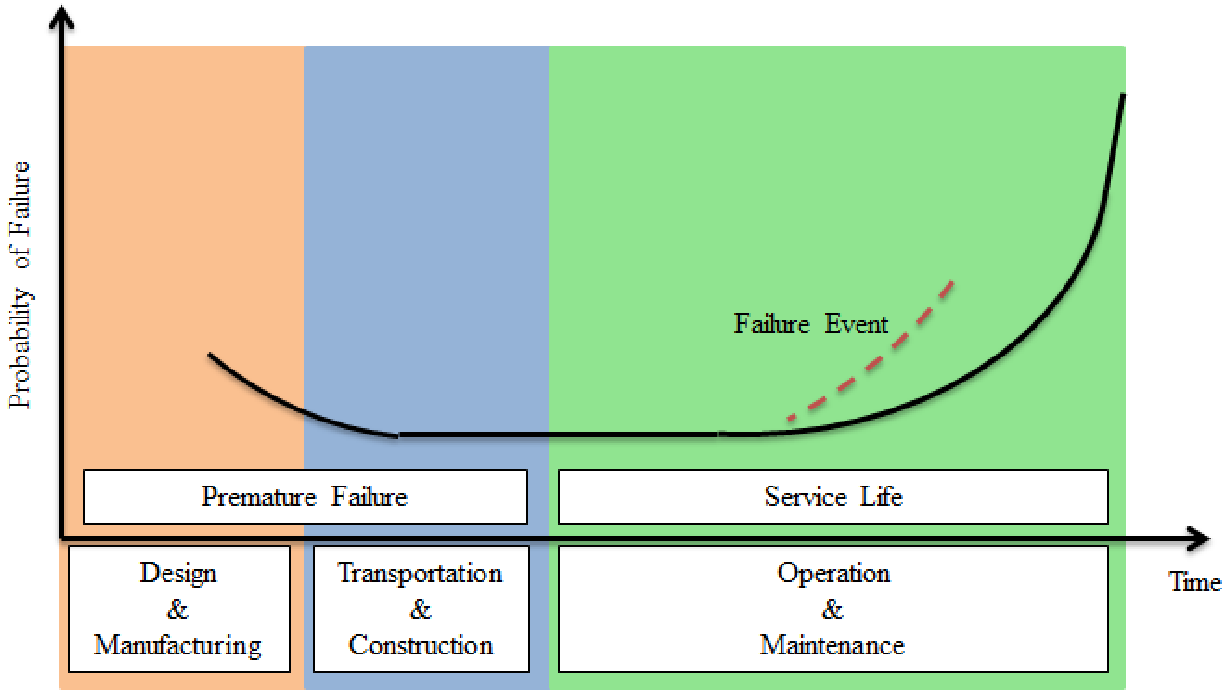


Figure 2: Bathtub Theory

The bathtub theory illustrates that the water pipe may not be in perfect condition when placed and installed in the ground. Some defects and damage may have taken place during the design and manufacturing processes which ultimately lowers the quality of the overall product. Some causes of failure which can occur during the design and manufacturing stages are poor design, poor project planning, dimensioning, observation and quality control, manufacturing defects and storage. The construction process may also have a permanent effect on pipe failure; examples include failure due to transit, human error and poor workmanship. Careless or improper construction processes may also lower the performance of the pipe. Throughout years of service, operation and maintenance will also affect the pipe performance through various failure causes such as mechanical, thermal, chemical, biological, external interferences, natural catastrophes, inappropriate services and maintenance. A table illustrating the complete life cycle of a pipeline is seen in Table 10 (Boot 1998; Makar 2000; Makar 2001; Moser 2001; Garcia 2002; Kellagher 2002; NASSCO 2003; NRC-CNRC 2003; Burn 2005; Kleiner et al. 2005; Najafi 2005; Cassa 2006; Grigg 2007; Le Gouellec 2007; Thomson 2007).

Table 10: Life Cycle of a Water Pipeline

Design	***Poor Design***
	Connection, Vertical Connection, Thrust Restraint, Pipe Wall Thickness, Special Applications, (Mechanical Vulnerable Material-CI,PCCP,AC), (Coating, Corrosion Control-CI,DI) , (Chemical Vulnerable Material-CI,DI,PCCP,AC), (Organic Substance Control-PE,PVC)
	Poor Project Planning
	Improper Connection, Time Limited Design, Poor Assumptions of Environment, Internal Pressure, Temperature, (Under-Design for Load-CI, PE, PVC)
	Dimensioning
Manufacture	***Manufacturing Defects***
	Pipe Wall Thickness, Inclusions of Unintended Structures, Surface Defects, Poor Fabrication, (Porosity due to Air Pockets-CI,PE,PVC,PCCP,AC), (Cheap Composite Material-PE,PVC), (Substandard Material-CI,PCCP,AC), (Unspecified Material Content-CI)
	Storage
	Time, Tall Stacks, (Excessive Heat-PE,PVC)
	Observation & Quality Control
Construction	***Transit***
	External Damage, Change in Dimension, (Coating Damage-CI,DI)
	Human Error
	Third Party Damage
	Poor Workmanship
	Improper Connections, Pipe Bedding, Poor Backfilling Material, Impact Damage, (Lining Issues-CI,DI,PCCP), (External Coating-CI,DI)
	Observation & Quality Control
Operation & Maintenance	***Mechanical***
	Material Properties, Hydraulic Factors
	Thermal
	Temperature Failures
	Biological
	Microbiologically Influenced Corrosion
	External Interference
	Movement of Soil, Tensile & Compression Failures
	Internal Interference
	Fatigue
	Natural Catastrophe
	Inappropriate Service/Maintenance
R,R&R	***Design Error***
	Manufacturing Error
	Construction Error
	Operation & Maintenance Error

3.3 Failure Modes and Mechanisms

The failure process in buried pipes is much more complex than expected. At the most basic level pipe failures are caused by applied forces exceeding the residual strength of the pipe material. In general, the forces applied to buried pipe can be considered as five groups: those produced by internal pressure; bending forces; crushing forces; soil movement induced tensile forces and temperature induced expansive forces. The proper repair of failures depends on knowing the causes and selecting the appropriate repair procedures that take these causes into account; otherwise, the repair may only be temporary. Developing a list of the particular failure modes and mechanisms examines the durability and performance of buried pipes and will help municipal and utility engineers to understand the effects of various factors and to determine the best pipe material for specific site conditions.

Failure modes of water pipes are defined as each type of failure which occurs within the pipe. The failure mechanism is an event which causes the pipe to reach one or multiple strength and serviceability limit states (Farshad 2006). Limit states are defined into two states: ultimate limit state and serviceability limit state. The ultimate limit state defines a condition at which the strength of the pipe is reached. An example of this state would be a pipe burst. The serviceability limit state defines a condition at which a particular function of the pipe is no longer fulfilled. Examples of this state may be large deformations, a loss of water tightness and buckling (Farshad 2006).

A complete list of the various failure modes and mechanisms of pipe materials were developed based on a thorough literature review and working closely with the various pipe associations and are shown in Table 11 (Boot 1998; Makar 2000; Makar 2001; Moser 2001; Garcia 2002; Kellagher 2002; NASSCO 2003; NRC-CNRC 2003; Burn 2005; Kleiner et al. 2005; Najafi 2005; Cassa 2006; Grigg 2007; Le Gouellec 2007; Thomson 2007). As shown some failure modes can be found in all material types such as cracking (crack line visible on the surface and not physically opened) and fractures (crack that has visibly opened); however, other failure modes are more specific to a particular pipe type or classification. For example, “buckling” is only considered a failure mode in PE and PVC pipes due to the materials ductility in comparison to more rigid material types such as DI and PCCP. Also the failure of the “lining” will only be seen in material pipe types such as CI, DI, PCCP and AC since these pipes typically are lined at the beginning or sometime throughout their lifetime to improve overall pipe quality.

Table 11: Failure Modes and Mechanisms

Failure Mode		**Failure Mechanism**	**Material**
Cracking	Circumferential	Bending moments applied to the pipe and soil movements which produce tensile forces on pipe	All
	Longitudinal	Internal water pressure, crushing forces acting on the pipe, and/or compressive forces along the pipe	
	Spiral	Pressure surges and/or combination of bending forces and internal pressure	
	Mixed	Combination of stresses that cause longitudinal and circumferential cracking	
	Ring	Axial tension, bending, traffic load, settlement, uplift, production, fatigue, residual stresses, temperature, and frost	PE, PVC
	Axial	Internal pressure, bending, traffic load, production, residual stresses, and frost	
	Irregular	Environmental such as chemical (plasiticizers), UV and stress cracking	
	RCP	Dynamic loading at low temperatures	
Fracture	Circumferential	Bending moments applied to the pipe and soil movements which produce tensile forces on pipe	All
	Longitudinal	Internal water pressure, crushing forces acting on the pipe, and/or compressive forces along the pipe	
	Spiral	Pressure surges and/or combination of bending moments and internal pressure	
	Mixed	Combination of stresses that cause longitudinal and circumferential cracking	
Buckling	Axial	External pressure, axial compression, temperatures, fire, and interventions	PE, PVC
	Transverse/ Ring	External pressure, axial compression, production, residual stresses, high temperatures, fire, and interventions	
	Non-Symmetric	Longitudinal bending and brazier effect	
	Longitudinal	Axial compression and thermal effects	

Table 11: Failure Modes and Mechanisms Cont.

Failure Mode		Failure Mechanism	Material
Leakage/Burst	Snap Through/2-Sided	External pressure	PE, PVC
	Burst	Internal/external pressure,axial tension/compression,bending,traffic load,settlement,uplift,production,impact,vibration,fatigue,fire, frost,abrasion,chemicals, biological,interventions	
	Blown Section	Propagating brittle fracture bifurcates and then rejoins the original crack path	
	Tapping Band	Occurs during tapping	
	Perforation	Stress intensity factor doesn't exceed the material fracture toughness before the crack tranverses the full wall thickness	
	Pinhole	External point load, impact, and third party damage	
	Blowout Holes	Pipe is thinned and water pressure blows out the remaining	CI, DI, PCCP, RC, AC
Blisters/Voids	Voids	Production and chemicals	PE, PVC
	External Blister	Production, impact, fatigue, UV radiation, frost, chemicals, and abrasion	
	Internal Blister	Production, fatigue, chemicals, and abrasion	
	Blazes	Osmosis	
	Delamination	Internal pressure, external pressure, axial compression, production, impact, fatigue, UV radiation, frost, chemicals, and abrasion	

Table 11: Failure Modes and Mechanisms Cont.

Failure Mode		Failure Mechanism	Material
Surface Damage	Roughness Increased/ Agg.Visible/ Projecting/ Missing	Hydrogen Sulfide attack or other mechanical or chemical erosion	PCCP, AC
	Wires Visible/ Projecting/ Broken	Hydrogen Sulfide attack or other mechanical or chemical erosion	PCCP
	Surface Spalling	Movement of pipe, a chipped pipe, or the expansion action of corroded reinforcement	PCCP
	Corrosion	Chemicals Attack	CI, DI
	Tuberculation	Corrosion built up due to low flow velocities	All
	Deterioration/ Disintegration	Total breakage, collapse, fire damage, and disintegration	PE, PVC
	Change in Color	Production, high temperatures, UV radiation, frost, chemicals, biological, and interventions	
	Abrasion/ Erosion	Interventions, flow velocity, internal pressure, production, chemicals	
Crazing	Through/ External/ Internal	Internal pressure, axial tension, bending, settlement, uplift, fatigue, chemicals, and residual stresses	PE, PVC
Lining Failure	Detached	Poor installation and maintenance damage	CI, DI, PCCP, AC
	Blistered	Improper installation and defective material	
	Buckled	Poor installation and defective material	
	Wrinkled	Excess material on the inside radius	
Joint Failure	Loss of Tightness	Improper installation, pull out, differential settlement, defective material, rubber gasket is damaged, poor adhesion, degradation, corrosion, and axial deflection	All
	Broken	Differential settlement, external pressure, degradation, thermal expansion, corrosion, and cracking	

3.4 Data Structure

Understanding of the pipes' lifecycle and classifications of their varying failure modes and mechanisms helps one to identify the parameters that affect the pipes overall quality, condition and/or performance. Collecting and analyzing these separate pipe parameters leads to a data structure which are used as inputs to develop a condition or performance index and deterioration prediction model that helps to aid in the asset management decision making process of prioritizing inspection, R,R&R, planning operation and maintenance, developing capital improvement programs and making high level decisions. The parameters of a pipeline can be categorized into five classes based on their characteristics: physical/structural, operational/functional, environmental, financial and others. These classes are presented in Figure 3.

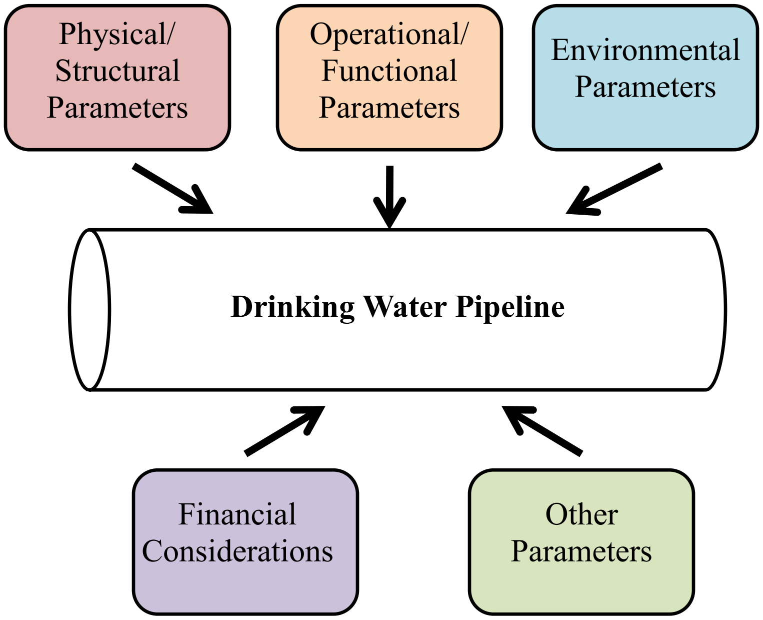


Figure 3: Classification of Pipe Parameters

Gathering of this data for each of the pipe parameters can be overwhelming especially for smaller cities and townships due to lack of a historical database and available tools and workforce; therefore, a Bronze, Silver and Gold data structure was developed based on a thorough analysis of the pipe failure modes and mechanisms and in collaboration with various pipe associations and water utilities to help prioritize essential parameters that can be used in performance prediction. The main distinction between these three data structures are the number of parameters a utility should collect. It is important to recognize that some parameters may be more influential to certain utilities in performance prediction than others. For example tidal influences typically only influence utilities which are located along the ocean while this is not a factor in many of the utilities located midland.

Currently, many utilities do not have a strong database which consists of the wide-ranging pipe qualities, features or characteristics. Without these parameters it is difficult for water utilities to prioritize inspection, R,R&R and even budget for the upcoming years. The goal in developing these separate data structures is to encourage water utilities to start collecting and improving their existing database. Means of collecting data include direct record, derived, downloaded or educated guess; however, gathering the data using methods such as deriving, downloading and by an educated guess may lower the overall reliability of the data.

Thorough analysis along with a complete understanding of the water pipes lifecycle and various failure modes and mechanisms help to develop a list comprising of each parameter that affects a pipes' performance level. Overall, this list contains of over 100 parameters which makes up the standard data structure. Specifically, each parameter is classified based on the category of a parameter and is constructed into a Bronze, Silver and Gold data structure as a result of the priority or overall role a parameter plays in determining the pipes' performance. The selections of parameters which make up each data structure were based on various discussions with pipe associations and utility managers.

The Bronze, Silver and Gold data structure is illustrated in Table 12 listing each pipe parameter under its particular pipe classification as shown in Figure 3 (Black&Veatch 1999; USEPA 1999; Rajani et al. 2000; Kathula 2001; Makar 2001; Baptista 2002; Deb et al. 2002; Garcia 2002; Kellagher 2002; Mays 2002; Stone et al. 2002; UKWIR 2002; NASSCO 2003; Szeliga 2003; Heastad 2004; NRC-CNRC 2004; Najafi 2005; Royer 2005; Saegrov 2005; Al-Barqawi and Zayed 2006; Mehta 2006; Chughtai 2007; Elsayegh 2007; Le Gouellec 2007; Starling 2007).

Bronze Data Structure

The Bronze data structure is for utilities which are small and do not have a lot of man-hours due to a smaller workforce. This structure is highlighted by the white cells in Table 12 which consists of 25 parameters that are considered the most valuable and attainable in terms of asset management. Parameters included in this data structure consisted of critical parameters classifying the pipe such as material type, age, depth, location, design life, soil type, live and dead loads, operational pressure, pipe records, service type, financial costs and a few others. Most of these parameters should be easily located in a utility database and records.

Silver Data Structure

The Silver data structure is for utilities which are larger than Bronze utilities; however, still may not have a large team specialized in the asset management of water pipelines. This structure consists of the Bronze data structure along with 25 additional parameters which are highlighted by the light grey cells in Table 12. Parameters included in this data structure consist of physical parameters which describe the pipes' characteristics further such as joint type, lining, cathodic protection and external coating; environmental parameters that include factors which can affect corrosivity and loading levels of a pipe such as groundwater table, stray currents, flooding and bedding condition; and operational parameters that further describe the function of the pipe such as flow velocity, pressure surges and pressure limitations.

Gold Data Structure

The Gold data structure is for the utilities which represent some of the largest cities within the U.S. and already have their own team devoted to the continuation and improvement to their asset management strategy. This structure includes the Bronze and Silver data structure along with all other existing pipe parameters which are highlighted by the darker grey cells in Table 12. Overall, the Gold data structure represents all parameters defined which consists of over 100 factors. Some of these parameters such as soil disturbance, average closeness to trees and other failing utilities may be difficult to attain while others such as dissolved oxygen content and alkalinity are vaguely understood in terms of how their affect determines the pipe performance level.

3.5 Data Collection Protocol

Data collection of each parameter is costly and time consuming. Sources of where a parameter can be located include utility records, construction specification, hydraulic model, product standards, pipe sample geotechnical records, aerial photography, customer complaints, other testing and through an online database. Table 13 illustrates each water pipe parameter and its collection source by the Bronze, Silver and Gold Data Structure.

Table 12: Water Pipe Data Structure

Physical/Structural Parameters	**Environmental Parameters**	**Operational/Functional Parameters**
Node Identification Number	Land Cover	Operational Pressure
Node Length	Soil Type	Pipe Renewal Record
Material Type	Water Source	Pipe Failure Record
Nominal Diameter	Dead Load	Water Quality Violations
Age	Live Load	O&M Practices
Depth	Climate - Temperature	Consumption
Location	Soil Corrosivity	Service Type
Design Life	Groundwater Table	Pressure Limitations
Joint Type	Bedding Condition	Water Temperature
Lining	Stray Currents	Water Flow Velocity
Cathodic Protection	Frost Penetration	Pressure Surges
Vintage	Soil Moisture Content	Pipe Inspection Record
Wall Thickness	Flooding	Leakage Amount
Installation	Soil pH	Pressure Complaints
External Coating	Trench Backfill	Discolored Water
Wire Type (PCCP only)	Soil Resistivity	Leakage Allowance
Thrust Restraint	Extreme Events	Water pH
Pipe Section Length	Non-Uniform Bedding	Hydraulic Capacity
Manufacture/Class/Date	Topography	Backflow Potential
Material Quality	Groundwater Corrosivity	Fire Flows
Dissimilar Metals	Compliance	Water Pumps
Degradation of Pipe Material	Soil Disturbance	Connection Density
Trench Width	Runoff Rate	Service Connections
Valve Type	Rainfall/Precipitation	Main Connections
Absorption Capacity	Slope of Land	Service Interruptions
Financial Considerations	Tidal Influences	Hydrant Density
Capital Cost	Catchment Area (Watershed)	Valve Density
Annual Operation Cost	Seismic Activity	Node Elevation
Annual Maintenance Cost	Average Closeness to trees	Node Hydraulic
Annual Rehabilitation Cost	Wet/Dry Cycles	Backlog of Maintenance
Installed & Replacement Cost	Soil Sulfides	Hydrant Information
Annual Energy Cost	Soil Redox Potential	Valve Information
Depreciated Value	Failing Utilities	Wire Breaks (PCCP only)
Benefit/Cost	Winter Salt Intrusion	Water Corrosivity
Consequence/Risk of Failure	Other Utility Failure	Water Age
	Other Parameters	Presence of Tuberculation
	Third Party Damage	Water Alkalinity
	Other Information	Dissolved Oxygen Content
		Water Source
		Hazen Williams C Factor

**Data Structure Class-Bronze (White); Silver (White and Light Grey); Gold (White, Light Grey and Dark Grey)*

Table 13: Parameter Sources

	Parameter	**Sources**
Physical/Structural	Node Identification Number	Utility Records
	Node Length	Utility Records, Construction Specification
	Material Type	Utility Records, Construction Specification, Pipe Sample
	Nominal Diameter	Utility Records, Construction Specification, Product Standards, Pipe Sample
	Age	Utility Records, Construction Specification
	Depth	Utility Records, Construction Specification, Other Testing
	Location	Utility Records, Construction Specification, Other Testing
	Design Life	Utility Records, Product Standards
Environmental	Land Cover	Utility Records, Construction Specification, Aerial Photography, Online Database
	Soil Type	Utility Records, Geotechnical Records, Other Testing, Online Database
	Water Source	Utility Records
	Dead Load	Utility Records, Construction Specification, Aerial Photography
	Live Load	Utility Records, Other Testing
Operational/ Functional	Operational Pressure	Utility Records, Hydraulic Model, Other Testing
	Pipe Renewal Record	Utility Records
	Pipe Failure Record	Utility Records
	Water Quality Violations	Utility Records, Other Testing
	O&M Practices	Utility Records
	Consumption	Utility Records
	Service Type	Utility Records, Construction Specification, Hydraulic Model
Financial	Capital Cost	Utility Records
	Annual Operation Cost	Utility Records
	Annual Maintenance Cost	Utility Records
	Annual Rehabilitation Cost	Utility Records
	Installed & Replacement Cost	Utility Records
Physical/Structural	Joint Type	Utility Records, Construction Specification, Product Standards
	Lining	Utility Records, Construction Specification, Product Standards, Pipe Sample
	Cathodic Protection	Utility Records, Construction Specification
	Vintage	Utility Records, Construction Specification, Product Standards
	Wall Thickness	Utility Records, Construction Specification, Product Standards, Pipe Sample
	Installation	Utility Records, Construction Specification
	External Coating	Utility Records, Construction Specification, Product Standards, Pipe Sample
	Wire Type (PCCP Only)	Utility Records, Product Standards

**Data Structure Class-Bronze (White); Silver (White and Light Grey); Gold (White, Light Grey and Dark Grey)*

Table 13: Parameter Sources Cont.

	Parameter	**Sources**
Environmental	Climate-Temperature	Utility Records, Online Database
	Soil Corrosivity	Utility Records, Geotechnical Records, Other Testing
	Groundwater Table	Utility Records, Geotechnical Records, Other Testing, Online Database
	Bedding Condition	Utility Records, Construction Specification, Other Testing
	Stray Currents	Utility Records, Construction Specification, Geotechnical Records, Other Testing
	Frost Penetration	Utility Records, Other Testing, Online Database
	Soil Moisture Content	Utility Records, Geotechnical Records, Other Testing
	Flooding	Utility Records, Aerial Photography, Online Database
Operational/Functional	Pressure Limitations	Utility Records, Product Standards
	Water Temperature	Utility Records, Other Testing
	Water Flow Velocity	Utility Records, Hydraulic Model, Other Testing
	Pressure Surges	Utility Records, Hydraulic Model
	Pipe Inspection Record	Utility Records
	Leakage Amount	Utility Records, Hydraulic Model, Other Testing
	Pressure Complaints	Utility Records, Customer Complaints
	Discolored Water	Utility Records, Customer Complaints, Other Testing
	Leakage Allowance	Utility Records
Physical/Structural	Thrust Restraint	Utility Records, Construction Specification, Other Testing
	Pipe Section Length	Utility Records, Construction Specification, Product Standards
	Manufacture/Class/Date	Utility Records, Construction Specification
	Material Quality	Utility Records, Construction Specification, Product Standards, Pipe Sample
	Dissimilar Metals	Utility Records, Construction Specification
	Degradation of Pipe Material	Utility Records, Product Standards, Pipe Sample, Other Testing
	Trench Width	Utility Records, Construction Specification, Other Testing
	Valve Type	Utility Records, Construction Specification
	Absorption Capacity	Utility Records, Product Standards, Other Testing
Environmental	Soil pH	Utility Records, Geotechnical Records, Other Testing
	Trench Backfill	Utility Records, Construction Specification, Other Testing
	Soil Resistivity	Utility Records, Geotechnical Records, Other Testing
	Extreme Events	Utility Records, Online Database
	Non-Uniform Bedding	Utility Records, Construction Specification, Other Testing
	Topography	Utility Records, Construction Specification, Aerial Photography, Online Database
	Groundwater Corrosivity	Utility Records, Other Testing
	Compliance	Utility Records, Other Testing
	Soil Disturbance	Utility Records
	Runoff Rate	Utility Records, Other Testing
	Rainfall/Precipitation	Utility Records, Other Testing, Online Database
	Slope of Land	Utility Records, Construction Specification, Aerial Photography, Online Database
	Tidal Influences	Utility Records, Aerial Photography, Other Testing, Online Database

**Data Structure Class-Bronze (White); Silver (White and Light Grey); Gold (White, Light Grey and Dark Grey)*

Table 13: Parameter Sources Cont.

	Parameter	**Sources**
Environmental	Catchment Area (Watershed)	Utility Records
	Seismic Activity	Utility Records, Online Database
	Average Closeness to Trees	Utility Records, Aerial Photography
	Wet/Dry Cycles	Utility Records, Online Database
	Soil Sulfides	Utility Records, Geotechnical Records, Other Testing
	Soil Redox Potential	Utility Records, Geotechnical Records, Other Testing
	Failing Utilities	Utility Records, Other Testing
	Winter Salt Intrusion	Utility Records, Geotechnical Records, Aerial Photography, Other Testing
	Other Utility Failure	Utility Records, Other Testing
Operational/Functional	Water pH	Utility Records, Other Testing
	Hydraulic Capacity	Utility Records, Product Standards
	Backflow Potential	Utility Records, Hydraulic Model
	Fire Flows	Utility Records, Other Testing
	Water Pumps	Utility Records, Construction Specification, Product Standards
	Connection Density	Utility Records, Construction Specification, Hydraulic Model
	Service Connections	Utility Records, Construction Specification, Hydraulic Model
	Main Connections	Utility Records, Construction Specification, Hydraulic Model
	Service Interruptions	Utility Records, Customer Complaints
	Hydrant Density	Utility Records, Construction Specification, Hydraulic Model
	Valve Density	Utility Records, Construction Specification, Hydraulic Model
	Node Elevation	Utility Records, Construction Specification, Hydraulic Model
	Node Hydraulic	Utility Records, Construction Specification, Hydraulic Model
	Backlog of Maintenance	Utility Records
	Hydrant Information	Utility Records, Product Standards
	Valve Information	Utility Records, Product Standards
	Wire Breaks (PCCP Only)	Utility Records, Other Testing
	Water Corrosivity	Utility Records, Other Testing
	Water Age	Utility Records, Hydraulic Model
	Presence of Tuberculation	Utility Records, Other Testing
	Water Alkalinity	Utility Records, Other Testing
	Dissolved Oxygen Content	Utility Records, Other Testing
	Water Source	Utility Records
	Hazen Williams C Factor	Utility Records, Hydraulic Model
Financial	Annual Energy Cost	Utility Records
	Depreciated Value	Utility Records
	Benefit/Cost	Utility Records
	Consequence/Risk of Failure	Utility Records
Other	Third Party Damage	Utility Records
	Other Information	Utility Records

**Data Structure Class-Bronze (White); Silver (White and Light Grey); Gold (White, Light Grey and Dark Grey)*

4 Development of a Water Pipeline Performance Index

Pipeline performance assessment is crucial in determining the overall performance of individual pipe assets and identifying key areas of infrastructure in need of future inspection and R,R&R. With a complete understanding of the infrastructures lifecycle, failure modes and mechanisms and data structure, an index is developed to predict the overall performance of individual metallic water pipelines.

4.1 Methodology of the Pipeline Performance Index

This section provides the theoretical background of the methods, weighted factor and fuzzy inference, used to develop the water pipe performance index.

4.1.1 **Weighted Factor**

The weighted factor methodology provides a technique capable of combining qualitative and quantitative factors (Kumar 2009). In particular, each factor or parameter is assigned a score and is allocated a weight based on its relative importance. The weighted factor equation is shown as

$$y = (\alpha \cdot x_1) + (\beta \cdot x_2) + (\gamma \cdot x_3) \ldots \tag{1}$$

where,

y is the performance index
α, β, γ… are the weights
x1, x2, x3… are the parameter scores

4.1.2 **Fuzzy Inference**

The notion of fuzzy sets classified with a continuum of grades of membership was first introduced in 1965 by Zadeh (1965). Unlike the binary set theory that can only describe crisp events, the theory of fuzzy logic is based on graded memberships that can account for uncertainty in events (Mohandas). In particular, the membership functions define the fuzzy logic system allowing for the capability of modeling imprecise data and vague statements. Fuzzy logic also allows for representation of interrelationships between input parameters and can incorporate the use of expert judgments.

The two most acknowledged types of fuzzy inference methods are the Mamdani and Sugeno. The Mamdani method was first introduced in 1975 by Mamdani and Assilian (1975), while the

Sugeno method was introduced in 1985 by Sugeno (1985). The Mamdani and Sugeno inference methods separate themselves from one another by the way the output membership function is defined. Specifically, the output membership function utilizing the Mamdani method is expected to be in fuzzy sets while the Sugeno output membership function must be linear or constant (Sivanandam et al. 2007). Within this research, the Mamdani fuzzy inference method was chosen over the Sugeno method since the fuzzy sets can account for the uncertainties and imprecision of input data. The Mamdani method also has widespread acceptance.

Fuzzy logic is not limited to the number of inputs and outputs; however, the greater number makes the analysis process more complex. The fuzzy logic system is defined by membership functions that are formulized through insights of a category structure found in the "real world". These membership functions are then subjected to fuzzy if-then rules created through expert knowledge. Through aggregation of the truncated output functions and defuzzification, a resultant single output value is calculated. Overall the fuzzy logic methodology consists of

1. Defining the input variables through membership functions.
2. Determining and applying the logical operations.
3. Finding the consequence of each rule considering the weight and output function.
4. Aggregation of the consequences.
5. Defuzzification of the output distribution into a single value.

A diagram illustrating the fuzzy process can be seen in Figure 4. Each of these steps is further defined in the following sections.

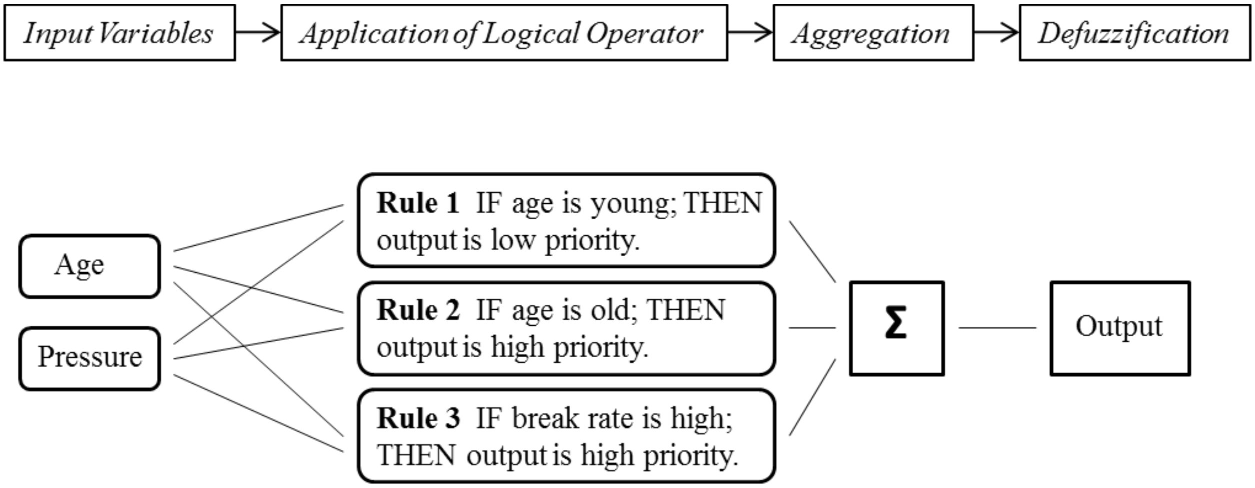


Figure 4: Fuzzy Logic Process

4.1.2.1 Input Variables & Membership Functions

Binary or classic sets are also known as “crisp sets” since they have a value of 1 or 0 depending on whether the member belongs to a set or does not. Conversely fuzzy sets can possess a continuum grade of membership that can have values varying between 0 and 1 (Mohandas).

Let *A* represent the fuzzy set in the universe of discourse X and *x* be an element within X. By definition the membership function $\mu_A(x)$ of fuzzy set *A* is a function of

$$\mu_A\colon X \rightarrow [0,1] \tag{2}$$

where,
μ_A is a characteristic function for set A
X is the universe of discourse

The membership degree for any element *x* in *X* can then be described by

$$\mu_A(x) \in [0,1] \tag{3}$$

where,
$\mu_A(x)$ is the membership function of fuzzy set A

The fuzzy set *A* is then expressed as

$$A = \{(x, \mu_A(x)) \mid x \in X\} \tag{4}$$

where,
x is an element within X

A membership function is a line or curve that defines how each point in the input space is mapped to the degree of membership. The membership function can represent fuzzy concepts such as “young” or “old”, “small” or “large”, etc. There are several types of membership functions which include triangular-shaped, trapezoidal-shaped, Gaussian-shaped, generalized bell-shaped, sigmoidally-shaped, s-shaped, z-shaped and Π-shaped. For this research, the triangular-shaped membership function was selected due to its widely accepted use and simplicity. Choosing the other available membership functions would have led to the difficulty in defining the curvature of each line. With the available degree of reasoning as regards to the role the input parameter plays in determination of the resultant output, utilizing the curve functions is unreasonable due to the lack of accuracy.

The triangular-shaped membership function is represented by a set of three points that form a triangle. The degree of membership can be defined for each input and output variable. An example of the triangular-shaped membership function can be seen in Figure 5.

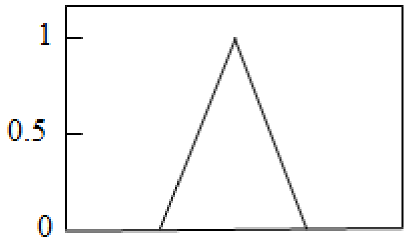


Figure 5: Triangular-Shaped Membership Function

4.1.2.2 Logical Operations & Rule Statements

Input variables that have been fuzzified are subjected to linguistic statements developed through engineering judgments. These statements are if-then rules that are developed to illustrate the input relationship with the output. An example of an if-then rule statement showing the relationship between *Input 1* and *Output 1* is

"IF input 1 is A, THEN output 1 is B."

Fuzzy logic also has the capability of modeling the interrelationships between parameters using Boolean logic operators AND, OR, and NOT. An example of a rule statement modeling the interrelationship between *Input 1* and *Input 2* utilizing the AND operator is

"IF input 1 is A AND input 2 is B THEN output 1 is C."

These operators are also defined as the minimum, maximum and complement operations. A diagram illustrating how the fuzzy inference links with the logical operations is shown in Figure 6. Along with defining each if-then rule statement, weights are assigned to each rule to prioritize the significance of the if-then statement as it pertains to the output.

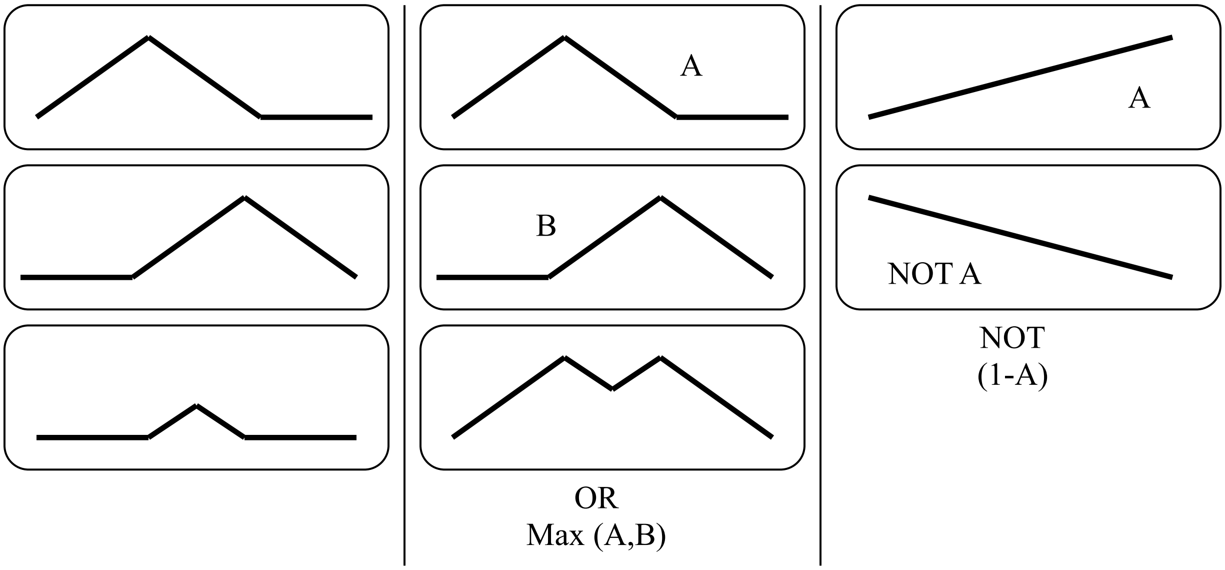


Figure 6: Logical Operations (Adapted from Matlab Fuzzy Logic Toolbox User Guide 2010)

4.1.2.3 Consequence & Aggregation

The resultant consequence of each rule statement is determined by the evaluating the fuzzified inputs in respect to each rule and the rule strength. Based on these controls, the output function for each rule is truncated. Following the consequence, aggregation is concluded by combining each rules truncated fuzzy set output into a single fuzzy set. These fuzzy output sets can be aggregated into a single fuzzy set utilizing the maximum, probabilistic OR (algebraic sum) or summation (sum of each rules output set) operator. The effect each aggregation operator has on the consequence is shown in Figure 7. Unlike the maximum operator that only accounts for the maximum value of the resulting truncated membership function; the summation operator was chosen within this research since it represents all truncated values from the output membership function.

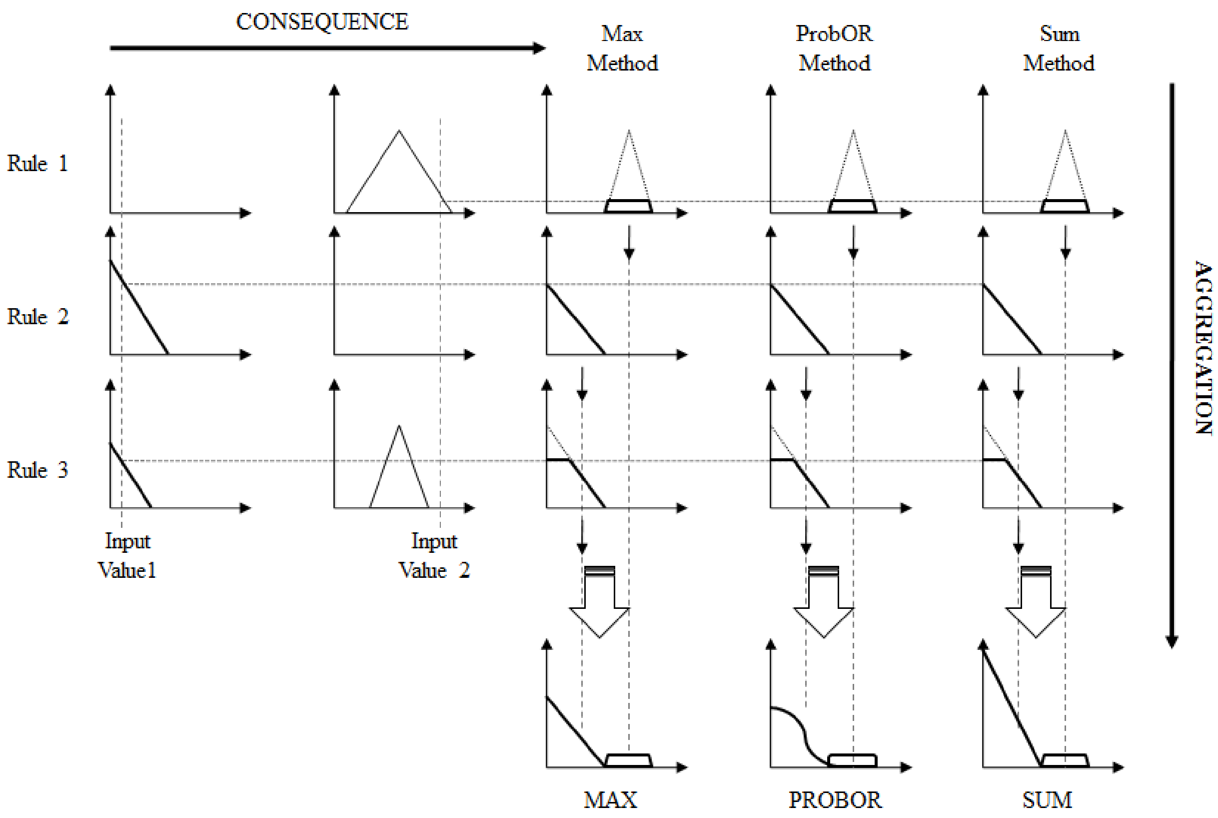


Figure 7: Consequence and Aggregation

4.1.2.4 Defuzzification

Using the Mamdani fuzzy inference method, the aggregate output fuzzy set is defuzzified into a single output value. Several techniques can be used for defuzzification: centroid, bisector, mean value of maximum (MOM), smallest value of maximum (SOM) and largest value of maximum (LOM).

The centroid technique returns the center of the area beneath the curve; while the bisector technique divides the region into two sub-regions of equal area. The MOM, SOM, and LOM techniques give the mean, smallest and largest value of the maximum value of the aggregated output membership function. Since the MOM technique returns the mean maximum value assumed by the aggregate membership function, this technique was selected for this research allowing for a perfect "excellent" score when all inputs were most favorable and vice versa for a "very poor" score. Methods such as the centroid and bisector technique will only come close to and will never fall on the highest or lowest possible score.

4.2 Model Development

The water pipe performance model is specifically designed to analyze metallic material pipelines since they entail the majority of installed water pipelines in the U.S. as shown in Table 1. It is important in analyzing these material types to take into consideration specific parameters directly affecting the chemical make-up of the pipe. For example, pipe corrosion is often a failure mode related to metallic materials. Factors such as cathodic protection, stray currents, dissimilar materials, pipe coating, and soil corrosivity are just some of the factors that can help control and/or justify the level of pipe corrosion.

The performance level of a pipeline not only considers the current condition of the pipeline but also how the pipeline is functioning given the pipelines characteristics and internal and external environments. How the pipe characteristics react to the surrounding environment will relate directly to the rate of corrosion and various failure modes due to implicit stress. With that said, it is important when analyzing metallic pipeline performance to consider the current condition of the pipeline, internal stress, external stress, internal corrosion and external corrosion.

As documented in the review of literature and current practice, there is a great disconnect between the two when it comes to tools used to evaluate the condition and predict pipe failure. Most of the previous models developed are primarily based on academic exercises that consider few parameters and are not successfully validated using a current utility database. To address this concern, the performance index will be unlike any of the other models presented in the literature review as it is developed based on working closely with various utilities. Many additional parameters will also be considered which is unfounded in other published models. The developed performance index coupled with a solid evaluation process will prove to be a successful model which can be used by current utilities as an effective tool to evaluate the performance of their current drinking water infrastructure.

Before a value of pipe performance can be assigned to a particular pipe section several steps must take place.

1. Select the methodology
2. Collect and organize all input parameters per required unit
3. Input parameters per pipe section
4. Run model to determine performance results
5. Analyze performance rating in terms of prioritizing future inspection and R,R&R

4.2.1 **Model Layout**

Based on the parameter characteristics, the performance model consists of analyzing four modules: current pipe integrity, internal condition, external stress and external corrosion. Internal corrosion was not considered within the performance model due to inconsistent and/or varying effects parameters were found to have on internal corrosion (McNeill 2000). Several indices, such as the Langelier and Larson Index, have previously been developed to correlate the corrosion rate; however, no index has been proven to be the "cure all, end all" in regards to water corrosivity (Benson 2011). Instead the Hazen Williams C factor was used as an indirect measurement of internal corrosion. It should be noted that the developed performance model is specifically for non-scaling drinking water.

Each of the four modules is classified based on a number of parameters. The layout of the fuzzy logic model is shown in Figure 8. In particular, by analyzing separate modules the utility will be able to define problem areas resulting in low performance values.

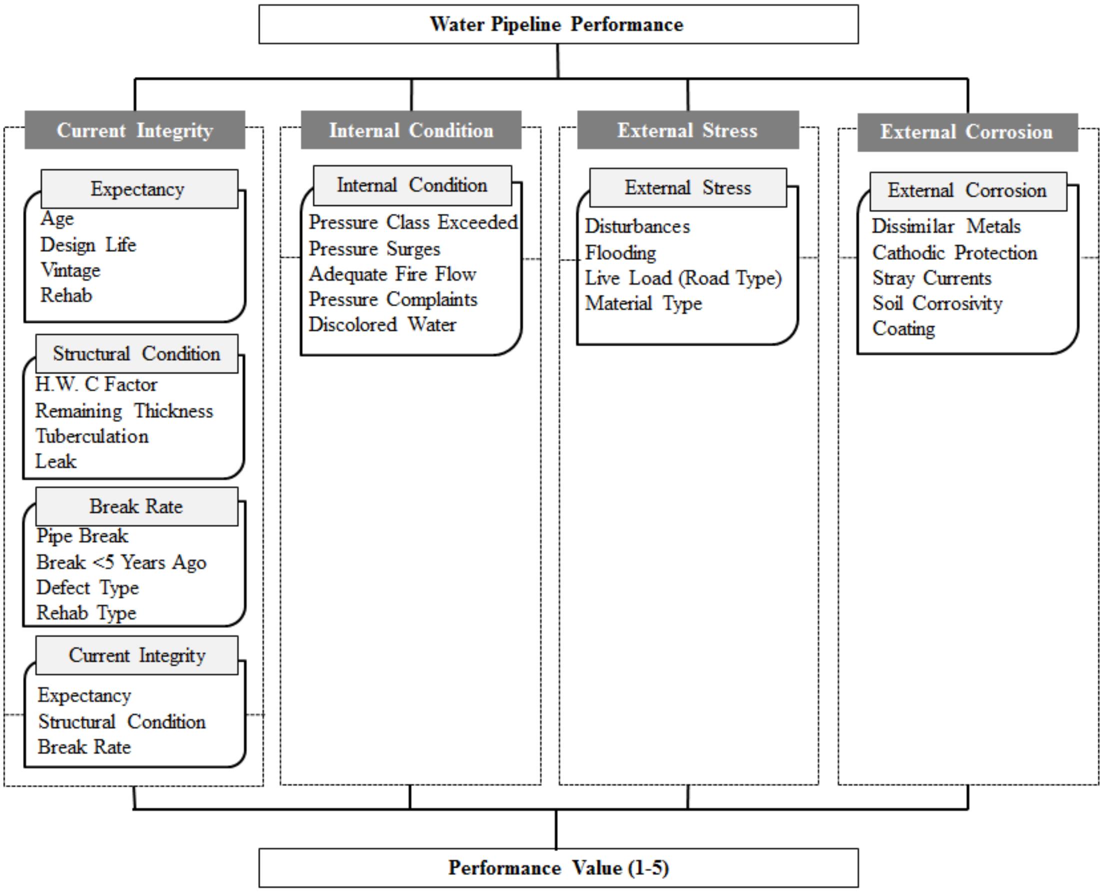


Figure 8: Model Layout

4.2.2 **Parameters**

Pipe performance parameters were selected based on literature, meetings with various pipe associations and utilities and utility questionnaires. Altogether, 27 parameters were chosen due to their profound influence on the overall evaluation of pipeline performance and are shown in Table 14. A brief summary of how each parameter listed above can affect the overall performance of the water pipe is described in the following paragraphs.

Table 14: Model Parameters

Adequate Fire Flow	Dissimilar Metals	Pressure Complaints
Age	Disturbances	Pressure Surges
Break <5 Years Ago	Flooding	Rehab
Cathodic Protection	Hazen Williams C Factor	Rehab Type
Coating	Leak	Remaining Thickness
Defect Type	Live Load (Road Type)	Soil Corrosivity
Design Life	Material Type	Stray Currents
Diameter	Pipe Break	Tuberculation
Discolored Water	Pressure Class Exceeded	Vintage

Adequate Fire Flow-The rate of water flow at a particular pressure and time duration must be adequate for fire suppression efforts. *Source:* Fire flows are determined through testing of the fire hydrants or are found within the utility records.

Age- Age is the length of time since the asset was installed. The age of a pipeline may or may not be a strong indicator of pipeline deterioration and is a function of the material type and other factors. Typically, it is assumed that older pipes may have increased pipe stresses due to deterioration with age. *Source:* The age is determined based on the installation year found in a Geographical Information System (GIS) or in the construction specifications.

Break <5 Years Ago- Recent pipe breaks are often considered more precarious than past pipe breaks. *Source:* The year of the pipe break is found within the utility records.

Cathodic Protection-Cathodic protection is a technique used to control the corrosion of a metal surface by adjusting the electric potential of a pipe. The most common protection method is the sacrificial anode method which uses galvanic anodes of zinc and magnesium. In the presence of stray currents, these active metals oxidize more easily that lead to corrosion of the sacrificial anodes and not of the protected metal. The active materials must oxidize almost completely before the less active metal will corrode. *Source:* Construction specifications and other utility records document if cathodic protection is present.

Coating-An external coating is an approach used to provide protection of the pipeline from external corrosion. If properly applied, a coating provides resistance to soil corrosivity, hazards of pipeline transportation and water penetration or absorption. This coating is only applied during the manufacturing process (AWWA 2004). *Source:* Documents such as construction specifications and other utility records record whether an external coating is present. Assessing product standards and pipe sampling are also other methods of determining if the pipeline has an external coating.

Defect Type- The pipe defect type is a factor that aids in assessing the pipe condition. *Source:* The defect type is found within the utility records.

Design Life-The design life is the period of time that the pipe is expected to operationally function. A high design life indicates a longer life expectancy; however, other influencing parameters may reduce the expected life. In contrast, the pipe can also be functional past the design life. *Source:* The design life is determined by product standards or is found within the utility records that include a GIS.

Diameter-The diameter of a pipeline is typically classified by the nominal or outside diameter rather than the inside diameter. Small diameter pipelines are more susceptible to beam failure than larger pipe diameters. In relation to pipe capacity, smaller diameters lead to increased fluid velocity, but reduced water pressure downfield. Smaller diameter pipelines with the same fluid flow also have a greater loss of pressure. *Source:* The diameter of a pipeline is determined through pipe sampling or standards or is found in the construction specifications or other utility records such as a GIS.

Discolored Water-Discolored water is caused when sediment within the water pipeline is disturbed or suspended in the water due to an increase in the flow rate. (See Flow Velocity) The discoloration may be a factor of old or corroded pipelines. *Source:* Customer complaints determine whether discolored water is present. These instances are found in the utility records.

Dissimilar Metals-When dissimilar metals are connected and are exposed to an electrolyte, galvanic corrosion will occur since the metals have different properties. The galvanic difference within the metals causes one metal (anode) to release electrons to another metal (cathode). The metal that discharges the electron can result in pipeline corrosion; while the metal accepting the electron is protected from corrosion (AWWA 2004). *Source:* Dissimilar metal connections are found in the construction specifications or other utility records that include a GIS.

Disturbances-Third party disturbances to the pipeline can lead to direct or indirect damage. For example construction disturbances due to excavation can lead to direct damage which results in the equipment physically breaking the pipe or indirect damage due to soil movement close to the pipe. Disturbances in the pipe bedding or alignment can lead to beam failure if the pipe is not adequately supported and/or the pipe depth is not sufficient (Smith 2000). *Source:* If disturbances were documented they would be found in the utility records.

Flooding-Flooding can impact the pipe and soil equilibrium causing the pipe to collapse or float out of alignment. Aggressive waters and/or constant water in contact with the pipe can increase the external corrosion rate (ASCE 2009). *Source:* Flooding is determined through aerial photography or is found within the utility records or on an online weather database.

Hazen Williams C Factor-The Hazen Williams C factor is the roughness coefficient of the inside of a pipe based on an equation evaluating the pressure drop due to friction as it relates to the pipe diameter and flow rate. Low C Factors indicate older pipes and poor internal conditions. *Source:* The Hazen Williams C factor is determined through use of a hydraulic model or is documented in utility records.

Leak-Leaks may lead to pipe bedding erosion, increased soil moisture and/or result in increased pipe stresses. A leaking pipe is a strong indicator of potential fracture, pinhole and/or joint failure. *Source:* The presence of a pipe leak is determined through acoustic testing, a hydraulic model or is documented in the utility records.

Live Load-Live loading from traffic causes compressive forces on the pipe wall. This downward pressure is a factor of the pipe depth, soil type, type of pavement (rigid or flexible) and the type of vehicles. Excessive crushing forces lead to longitudinal cracks on the pipe wall. Bending stresses are also present within the pipe if the pipeline is not evenly supported. Excessive bending stress leads to circumferential cracking (Smith 2000). *Source:* The live load is determined by evaluating ADT records. Utilizing a GIS the proximity of the road to the pipeline can be assessed.

Material Type-The metallurgy of the pipe material type can dictate the resilience of strength and also the resistance to corrosion. Different pipe material types are designed for various service types and vary in design life, thickness, diameter, etc. *Source:* The pipe material type is determined through pipe sampling or is found in the construction specifications or other utility records that include a GIS.

Pipe Break- A break in the water pipe leads to leaks. *Source:* The break rate is found within the utility records.

Pressure Class Exceeded-An operational pressure exceeding the designed pressure class results in increased pipe wall stresses which may lead to possible pipe breaks. *Source:* A hydraulic model is a source to determine if the pressure class is exceeded.

Pressure Complaints-Customer complaints regarding low or no water pressure may indicate possible water main breaks. Fluctuations in the operational pressure can change the acting stresses on the pipe wall. (See Operational Pressure) *Source:* Low or high pressure is determined through customer complaints or is found within the utility records.

Pressure Surges- A pressure surge is a sudden change, often short, increase in pressure as a result of a greater rate change of fluid velocity. This dynamic pressure can result in increased pipe stresses. These surges occur when the velocity or pressure changes due to the closing of a valve or the starting/stopping of a pump (ASCE 1992). *Source:* Pressure surges are determined through a hydraulic model or are found within the utility records.

Rehab- The internal surface of a pipe can be covered by a coating to improve resistance from tuberculation and corrosion. This lining is applied during the manufacturing period or installed to an existing pipe. Common types of lining consist of cement and epoxy coatings. *Source:* Documents such as construction specifications and other utility records record whether an internal coating is present. Assessing product standards and pipe sampling are also other methods of determining if the pipeline has an internal coating.

Rehab Type-The pipe rehabilitation type is a factor in determining the pipe condition. *Source:* The rehabilitation type is found within the utility records.

Remaining Thickness- Corrosion dictates the remaining wall thickness. *Source:* The remaining wall thickness is determined through testing or is found in utility records.

Soil Corrosivity-Soil corrosivity cannot be directly measured and is a function of several soil properties such as soil redox potential, soil pH, soil resistivity, soil sulfides, moisture content, etc. (Kleiner 2010). The corrosivity level of the soil can result in metallic corrosion of the pipeline. *Source:* The corrosivity of the soil is determined by soil testing that includes soil resistivity, soil sulfides, soil pH, soil redox potential and moisture content or is found in the geotechnical records or other utility records.

Stray Currents-Stray currents are caused by a local direct current (DC) flowing through the earth. These stray currents can be present if the pipe is nearby a transportation system such as a railway or if other utilities are close to the pipe. Often these stray electrical currents can cause electrolytic corrosion in metal pipelines if they are not properly protected. Cathodic protection is the most common protection method of metal pipelines as a result of stray currents. *Source:* The presence of stray currents is determined through testing or is found in the geotechnical records, construction specifications or other utility records.

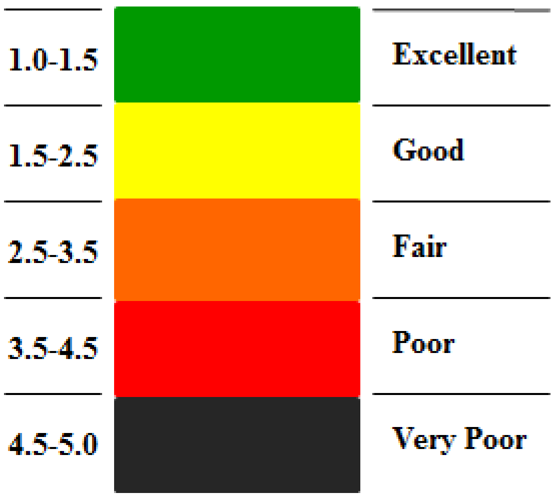
Tuberculation-Tuberculation is the formation or development of small mounds of corrosion products inside a pipe. This buildup increases the roughness of the inside of the pipe, increasing the resistance to water flow and decreasing the C factor of the pipe. *Source:* The presence of tuberculation is determined by pipe sampling and other testing.

Vintage-The pipe vintage can determine the metallurgy, uniformity, thickness, pressure class and available diameters of the various pipe materials. For example, CI pipe was initially pit cast; however, through the years this casting method was changed to centrifugally spun cast. These variances due to pipe vintage can control the resiliency of the pipe material. *Source:* The pipe vintage is determined by product standards or is found in the construction specifications or other utility records.

4.2.3 **Performance Scale**

The performance index will provide the ability to quantitatively measure the pipe performance of individual pipe segments and the prioritization between other segments. Past condition indexes for wastewater pipes and within the pavement area of transportation commonly rate their infrastructure based on scales of 1-5, 1-7 and 1-100. Specifically, NASSCO developed a standard condition rating system for gravity feed sewers which is based on a 1-5 scale (NASSCO 2003); however, to-date a standard condition rating system for pressurized pipelines does not exist. With that said a water pipeline performance index was developed based on the current wastewater condition scale presented by NASSCO.

Numerically, the scale ranges from values of one to five with 1.0 to 1.5 representing the pipe performance is excellent or near excellent and 4.5 to 5.0 meaning the pipe is in a very poor condition or possibly failed. Pipe ratings of 1.5 to 2.5, 2.5 to 3.5 and 3.5 to 4.5 represents the pipe performance is good, fair and poor. The color coded performance index is shown in Figure 9.



1.0-1.5	🟩	Excellent
1.5-2.5	🟨	Good
2.5-3.5	🟧	Fair
3.5-4.5	🟥	Poor
4.5-5.0	⬛	Very Poor

Figure 9: Water Pipeline Performance Index

4.2.4 **Reliability Index**

A reliability scale was developed to forecast the overall confidence of the drinking water pipe performance index. Many water utilities across the U.S. have little information regarding the logistics of their water pipelines; however, many of these pipe parameters can be easily derived or downloaded from existing sources. For those parameters not easily attainable, an educated guess can be specified.

The reliability percentage of the overall drinking water pipe performance score is calculated using a parameter reliability scale as shown in Table 15. Specifically, each parameter used to determine the pipe performance level is given a value representing the parameter reliability based on whether the data was direct, derived indirectly, was an educated guess, or there was no data available. The reliability levels are classified on a value ranging between 0 to 5, with 0 representing the least reliable data and 5 being the most reliable data. The reliability score can be determined through Equation 5.

Table 15: Index Reliability Scale

Parameter Reliability	**Value**
Direct Record	5
Derived Indirectly	4
Educated Guess (High Confidence)	3
Educated Guess (Normal Confidence)	2
Educated Guess (Low Confidence)	1
No Data	0

$$I_r(\%) = \frac{\sum_{i=1}^{n} R_i}{n*5} * 100 \qquad (5)$$

where;
$I_r(\%)$ is the index reliability percentage
R_i is the parameter reliability score
n is the number of parameters

4.3 Weighted Factor Performance Model

The weighted factor model is setup to analyze each of the four modules: current integrity, internal condition, external stress and external corrosion. Each module resultant value is then combined to determine the overall pipe performance level. Specifically, each of the parameters in each module is assigned a score and applied a weight based on the relative importance of the parameter pertaining to the module. Scores assigned to each parameter value range on a scale of 1 “Excellent” to 5 “Very Poor”. The ranges for each parameter using the weighted factor methodology are shown in Tables 16-19.

Weights assigned to each parameter in each module are developed based on a questionnaire provided to each utility. The weights will vary from one utility to another based on the utilities questionnaire feedback. The questionnaire is composed of rating the significance of each parameter on a one to five scale in determining the category values, with a value of one representing “most importance;” while a value of five represents “least importance”. The resultant pipe performance level will be calculated by assuming equal weights for each of the four modules. The questionnaire developed for this research is shown in Appendix A.

Table 16: Current Integrity Weighted Factor Parameter Ranges

			Parameter	Unit	Range
Current Integrity			Age	*year*	(1)-0-25; (2)-26-50; (3)-51-75; (4)-76-100; (5)-101-130
			Design Life	*year*	(1)-101-130; (2)-76-100; (3)-51-75; (4)-26-50; (5)-0-25
			Vintage	*year*	(1)-1800-1920; (2)-1991-2012; (3)-1971-1990; (4)-1921-1945; (5)-1946-1970
			Rehab	*yes/no*	(1)-Yes; (5)-No
	Pipe Diameter	1" to 4"	Hazen Williams C Factor	*c factor*	(1)-90-140; (2)-80-89; (3)-70-79; (4)-55-69; (5)-<54
		5" to 8"	Hazen Williams C Factor	*c factor*	(1)-95-140; (2)-85-94; (3)-75-84; (4)-70-74; (5)-<69
		9" to 12"	Hazen Williams C Factor	*c factor*	(1)-105-140; (2)-90-104; (3)-80-89; (4)-75-79; (5)-<74
		>12"	Hazen Williams C Factor	*c factor*	(1)-105-140; (2)-95-104; (3)-85-94; (4)-75-84; (5)-<74
			Remaining Thickness	*percent*	(1)-95-100; (2)-85-94; (3)-65-84; (4)-45-64; (5)-<44
			Tuberculation	*percent of pipe area*	(1)-0-5; (2)-6-15; (3)-16-35; (4)-36-55; (5)-56-100
			Leak	*yes/no*	(1)-No; (5)-Yes
			Pipe Break	*yes/no*	(1)-No; (5)-Yes
			Break <5 Years Ago	*yes/no*	(1)-No; (5)-Yes
			Defect Type	*type*	(1)-N/A; (2)-Joint; (3)-Circular or Spiral Crack/Fracture; (4)-Multiple Cracks/Fractures; (5)-Hole
			Rehab Type	*type*	(1)-N/A; (2)-Section; (3)-Segment; (5)-None

Table 17: Internal Condition Weighted Factor Parameter Ranges

	Parameter	**Unit**	**Range**
Internal Condition	Pressure Class Exceeded	*occasion*	(1)-Never; (2)-Rarely; (3)-Occasionally; (4)-Often; (5)-Always
	Pressure Surges	*occasion*	(1)-Never; (2)-Rarely; (3)-Occasionally; (4)-Often; (5)-Always
	Adequate Fire Flow	*yes/no*	(1)-Yes; (5)-No
	Pressure Complaints	*yes/no*	(1)-No; (5)-Yes
	Discolored Water	*yes/no*	(1)-No; (5)-Yes

Table 18: External Stress Weighted Factor Parameter Ranges

	Parameter	**Unit**	**Range**
External Stress	Disturbances	*yes/no*	(1)-No; (5)-Yes
	Flooding	*occasion*	(1)-Never; (3)-Occasionally; (5)-Often
	Live Load	*type*	(1)-Unpaved; (2)-Non-National Highway System; (3)-National Highway System; (4)-Interstate; (5)-Railroad/Airport
	Material Type	*type*	(1)-Ductile Iron; (2)-Cast Iron; (3)-Copper; (4)-Galvanized Steel

Table 19: External Corrosion Weighted Factor Parameter Ranges

	Parameter	**Unit**	**Range**
External Corrosion	Dissimilar Metals	*yes/no*	(1)-No; (5)-Yes
	Cathodic Protection	*yes/no*	(1)-Yes; (5)-No
	Stray Currents	*yes/no*	(1)-No; (5)-Yes
	Soil Corrosivity	*level*	(1)-Low; (2)-Low-Moderate; (3)-Moderate;(4)-Moderate-High; (5)-High
	Coating	*yes/no*	(1)-Yes/Efficient; (5)-Yes/Non-Efficient or No

4.4 Fuzzy Inference Performance Model

The fuzzy inference performance model is made up of 8 separate fuzzy inference modules: life expectancy, structural condition, break rate, current integrity, internal condition, external stress, external corrosion and performance. Specifically, each of these modules has their own separate input variables with corresponding membership functions, rules and defuzzified output having a 1 "Excellent" to 5 "Very Poor" performance value. Each module is combined through three phases: Phase 1 consists of three fuzzy models: life expectancy, structural condition and break rate; Phase 2 consists of four fuzzy models: current integrity, internal condition, external stress and external condition; and Phase 3 consist of the performance model. A table illustrating detailing each of the three phases with input and output variables is seen in Table 20.

Table 20: Fuzzy Inference Phases

Phase	Model	Input Variables	Output Variables
1	1	Age, Design Life, Vintage, Rehab	Life Expectancy
1	2	Hazen Williams C Factor, Remaining Wall Thickness, Tuberculation, Leak	Structural Condition
1	3	Pipe Break, Break <5 Years Ago, Defect Type, Rehab Type	Break Rate
2	4	Life Expectancy, Structural Condition, Break Rate	Current Integrity
2	5	Operational Pressure, Pressure Surges, Adequate Fire Flow, Pressure Complaints, Discolored Water	Internal Condition
2	6	Disturbances, Flooding, Live Load (Road Type), Material Type	External Stress
2	7	Dissimilar Metals, Cathodic Protection, Stray Currents, Soil Corrosivity, Coating	External Corrosion
3	8	Life Expectancy, Internal Condition, External Stress, External Corrosion	Performance

The modules are linked by using the prior phases modules defuzzified output values. For example the defuzzified outputs from each of the Phase 1 models (Life Expectancy, Structural Condition, and Break Rate) are used as the inputs for the Current Integrity fuzzy inference model. Phase 2 consists of analyzing four modules (Current Integrity, Internal Condition, External Stress and External Condition) and their defuzzified outputs are used for the inputs for the final Performance fuzzy inference model. A figure illustrating this process with each of the three phases and modules is seen in Figure 10.

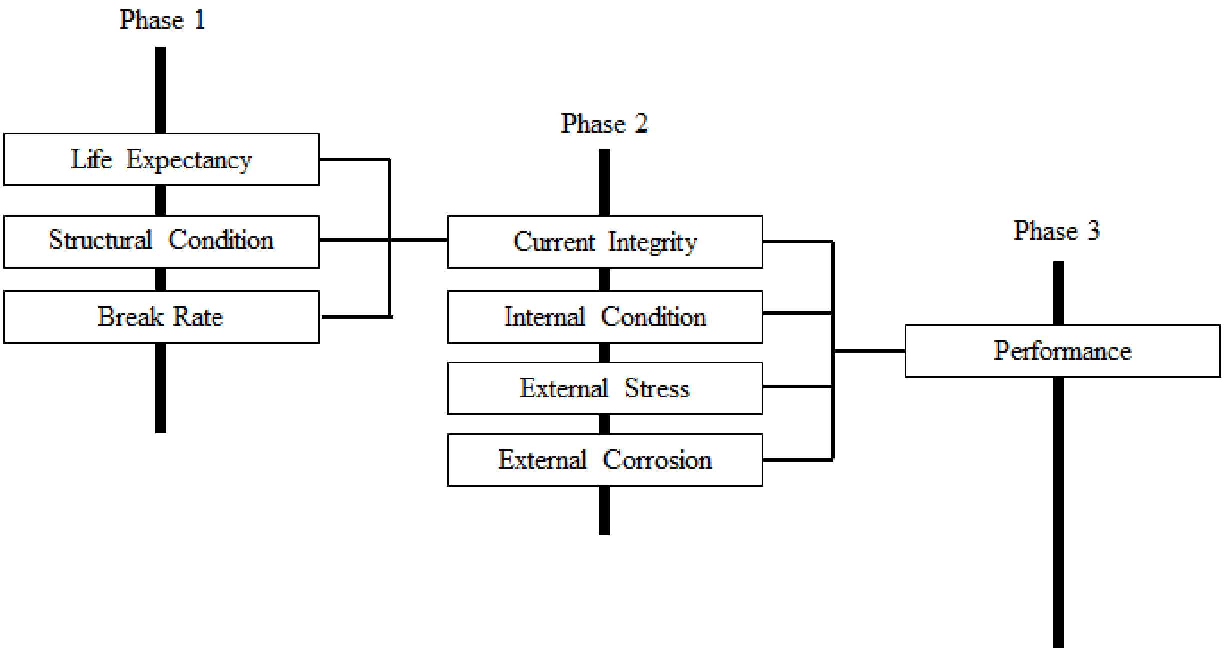


Figure 10: Phase 1, 2 and 3

4.4.1 **Development of Input & Output Membership Functions**

One of the most difficult steps within the fuzzy inference method is construction of the membership functions. Due to limited water utility historical databases, the construction of the membership functions is restricted to expert-driven techniques rather than data-driven techniques that often include statistical methods. Specifically, the expert-driven techniques attempt to capture expert knowledge from industry professionals.

4.4.1.1 Phase 1 & 2 Membership Functions

Phases 1 and 2 of the fuzzy inference model consist of evaluating each module category and module itself. The input and output membership functions for both of these phases were formulated based on a heuristic methodology. A benefit of utilizing the heuristic method includes the ability to select the shapes of the membership functions based on previous experience and rules of thumb. Incorporating utility and expert knowledge can prove to be very valuable as much of the comprehension of the infrastructure system is not documented. Even though utility personnel are very knowledgeable regarding their particular water infrastructure, systems can be drastically different from one utility to another. As a result, the membership functions and rules were formulated through rules of thumb, literature and expert knowledge from various pipe associations and utilities in order to get an overall perspective of parameters and their relationship to the pipe performance level. The generated membership functions were then validated by numerous professionals including engineers from various utilities, consultants, pipe associations and condition assessment companies.

The majority of the parameters and membership ranges will be similar when applying this model to various utilities. Variations of the parameter ranges may result due to distinctions in the utilities historical database and/or utility geographic location. For example, the pipe defect type may be based on the types of failure modes seen within a particular utility. A summary of the input and output variables, membership ranges and linguistic terms for Phase 1 and 2 is presented in Tables 21-27. Diagrams of the membership functions for each input variable and resultant outputs is shown in Appendix B.

4.4.1.2 Phase 3 Membership Functions

In Phase 3 of the fuzzy inference model, the final pipe performance output is determined using the defuzzified outputs from the models in Phase 2 (Current Integrity, Internal Condition, External Stress and External Corrosion) as shown in Table 28. Each of the four input membership functions, shown in Appendix B, was constructed through rules of thumb and expert opinion and was validated by numerous professionals. In contrast, the resultant performance output membership function was formulated using the Delphi method, which is a technique used to obtain the judgment of a select group of experts (Dalkey 1963). This method consists of selecting a panel of experts to participate in two or more rounds of structured surveys until a consensus is reached. After each round, the facilitator provides an anonymous summary of the previous survey results for use in the subsequent rounds, encouraging participants to consider revising their response based on the opinions of the other panel members to decrease response variability (Hallowell 2010).

The Delphi method was initially developed in the 1950s by the RAND Corporation for the U.S. Air Force (Dalkey 1963). Since then, several researchers in the field of construction engineering and management have relied on this method as a tool to collect a consensus of expert opinions in where traditional methods such as surveys, interviews and brainstorming techniques are unsuccessful (Hallowell 2010). Examples of previous Delphi method applications within the construction field include studies of the economic impact assessment of roadway funding (Robinson 1991), delivery methods on design performance in multifamily housing projects (Hyun 2008) and the fire safety system evaluation for public assemble buildings (Shields 1990). This method was also employed to develop membership functions in previous fuzzy inference models (Elbarkouky 2010).

The application of the Delphi method to construct the final performance output membership function consisted of two rounds of structured surveys. The first round of the Delphi method solicited the opinions of 8 experts within the pipeline infrastructure management field. Experts were kept anonymous to avoid the influence of dominant panel members (Hallowell 2010). Each expert was provided with a survey asking to *"Select the range of elements (xi) which represent the "Excellent, Good, Fair, Poor and Very Poor" pipe performance level."* It was acknowledged that each term was assumed to have a triangular shape with a peak located at the numerical rating that represents it respected performance level. A total of five different responses were collected after round one of the Delphi method as shown in Figure 11.

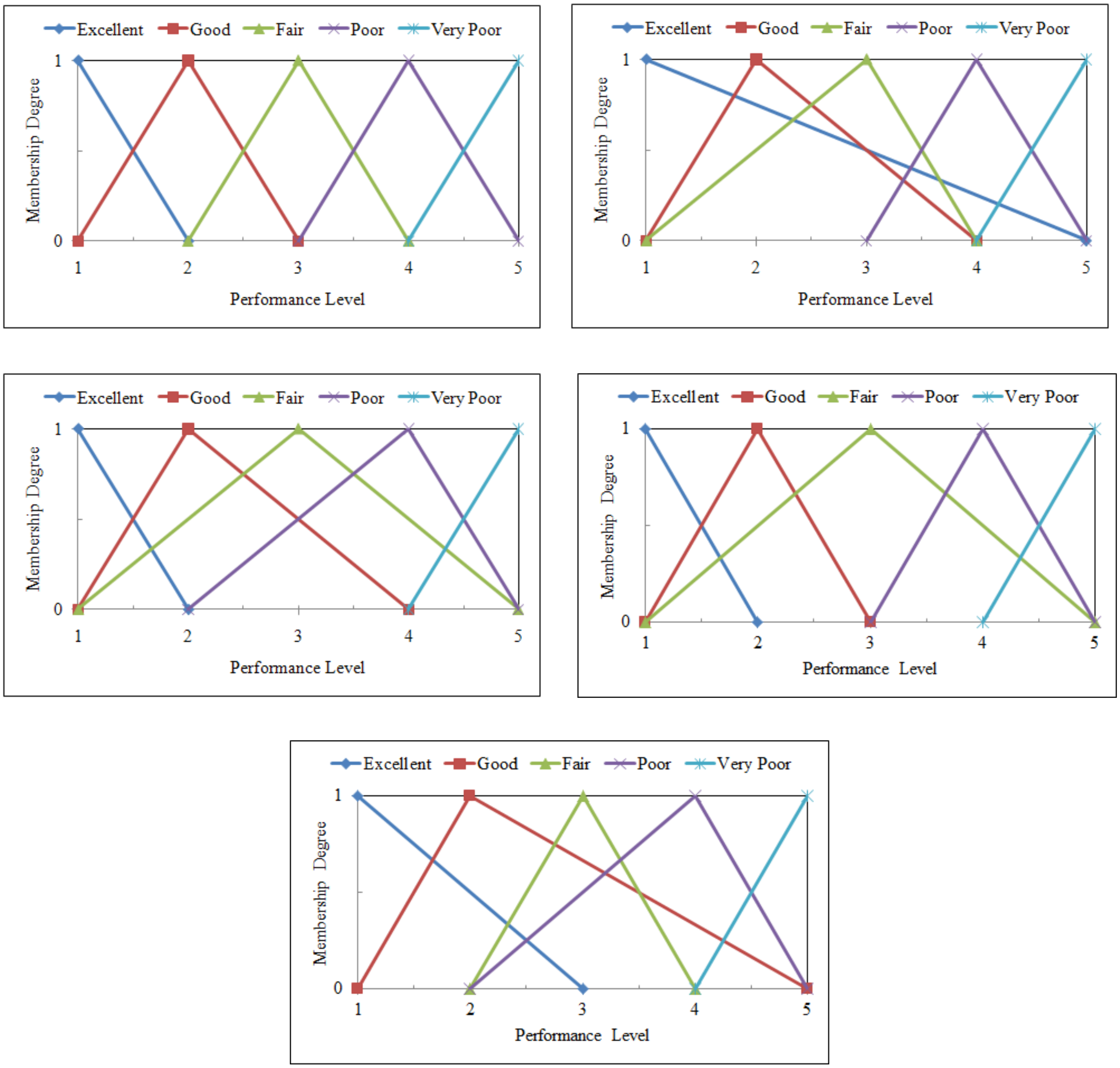


Figure 11: Round 1 Delphi Results

The summarized results of the first round were sent back to the experts along with two additional rules to consider in formulating the resultant membership function. The additional rules posed in round two of the Delphi method suggested that “*The membership function should be evenly proportioned due to the logistics of the scale,”* and *“The legs of the membership function should overlap to a certain extent to represent the fuzziness of the linguistic terms.”* Specifically, in this round, experts were asked to consider revising their answer based on the previous responses and the additional two rules in order to achieve a group consensus. A total of six experts participated in round two, out of the initial eight experts. The frequency of their responses per each side of the performance membership function was determined and is shown in Figure 12.

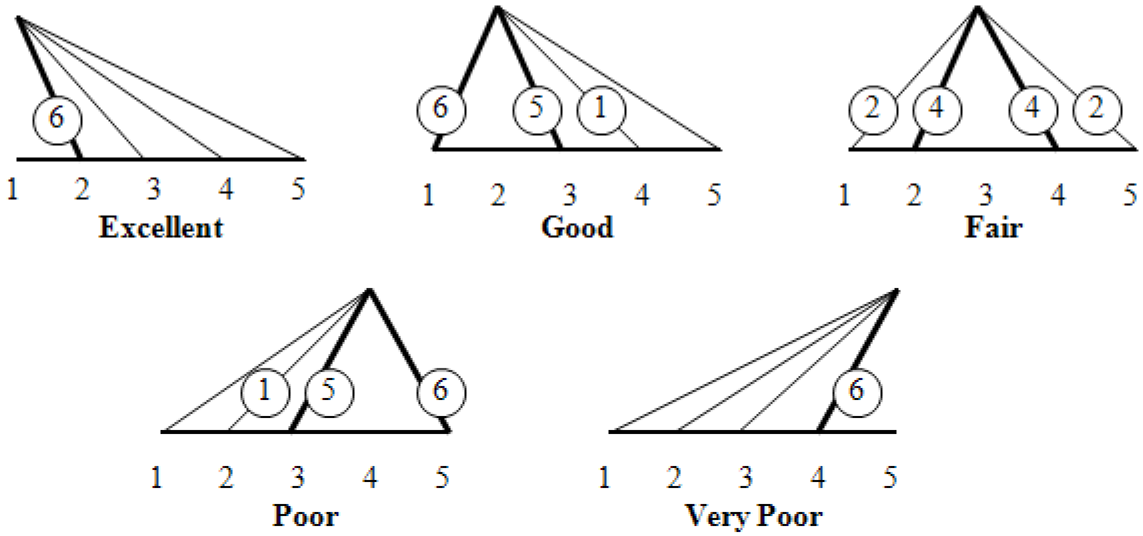


Figure 12: Round 2 Delphi Method

After evaluating the round two results and observing a consensus in the formation of the performance membership function, no further rounds deemed necessary. The final resultant performance output membership function based on the Delphi method is shown in Figure 13.

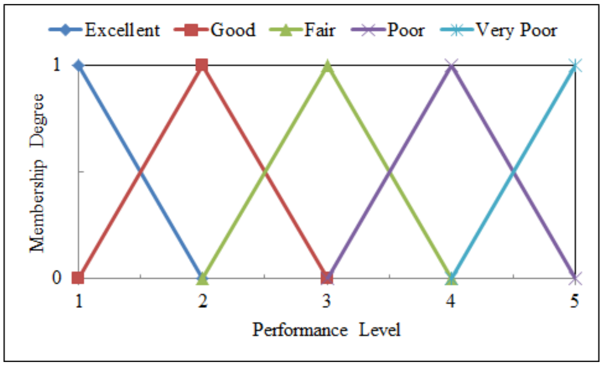


Figure 13: Final Performance Level Output Membership Function from the Delphi Method

4.4.2 Development of If-Then Rule Statements

The rule base for each inference system was also developed on the heuristic expert-driven technique. Each rule reflects on the general rule of thumb and expert knowledge from various professionals including engineers from various utilities, consultants, pipe associations and condition assessment companies. The rules generated for the fuzzy inference model will be the same in applying this model to various utilities; however, discrepancies may arise under special circumstances. In these special cases, a new or change in the rule set would be necessary.

Every parameter within each fuzzy logic model is combined using Boolean logic. By combining each of the parameters with the Boolean logic operator “and”, key parameters are able to control the output. For example, consider the external corrosion fuzzy model which combines the parameters dissimilar metals, cathodic protection, stray currents, soil corrosivity and coating. A high soil corrosivity level will poorly affect the external corrosion module; however, if a satisfactory external coating is present than the module will not be affected by the soil corrosivity level which is a “real life” scenario. A complete list of the fuzzy inference if-then rule statements are shown in Appendix C. Altogether 1,528 if-then rule statements make up each of the three phases of the fuzzy inference system.

Table 21: Fuzzy Inference Model Membership Ranges – Life Expectancy Module (Phase 1/Module 1)

	Input Variables	**Membership Function Ranges**	**Linguistic Terms**
Life Expectancy	Age	(0-30), (25-55), (50-80), (75-105), (100-130) years	Very Young, Young, Middle Aged, Old and Very Old
	Design Life	(0-30), (25-55), (50-80), (75-105), (100-130) years	Very Inferior, Inferior, Moderate, Superior, Very Superior
	Vintage	(1800-1930), (1910-1950), (1940-1980), (1970-2000), (1995-2012) year	Excellent, Poor, Very Poor, Fair, Good
	Rehab	Yes, No	Desirable, Undesirable
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	Life Expectancy	Values are continuous with a range of 1 to 5	Very High, High, Moderate, Low and Very Low

Table 22: Fuzzy Inference Model Membership Ranges – Structural Condition Module (Phase 1/Module 2)

Structural Condition			**Input Variables**	**Membership Function Ranges**	**Linguistic Terms**
	Pipe Diameter	**< 4"**	Hazen Williams C Factor	(0-56), (51-71), (66-81), (76-91), (86-140) C Value	Very Low, Low, Moderate, High and Very High
		5" to 8"	Hazen Williams C Factor	(0-71), (66-76), (71-86), (81-96), (91-140) C Value	Very Low, Low, Moderate, High and Very High
		9" to 12"	Hazen Williams C Factor	(0-76), (71-81), (76-91), (86-106), (101-140) C Value	Very Low, Low, Moderate, High and Very High
		> 12"	Hazen Williams C Factor	(0-76), (71-86), (81-96), (91-106), (101-140) C Value	Very Low, Low, Moderate, High and Very High
			Remaining Thickness	(0-45), (35-65), (55-85), (80-95), (90-100) Percent	Very Low, Low, Moderate, High, Very High
			Tuberculation	None, Light, Moderate, Heavy, Extreme	Preferable, Desirable, Mediocre, Least Desirable and Undesirable
			Leak	Yes, No	Undesirable, Desirable
			Output Variable	**Membership Function Ranges**	**Linguistic Terms**
			Structural Condition	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor

Table 23: Fuzzy Inference Model Membership Ranges – Break Rate Module (Phase 1/Module 3)

	Input Variables	**Membership Function Ranges**	**Linguistic Terms**
Break Rate	Pipe Break	Yes, No	Undesirable, Desirable
	Break <5 Year Ago	Yes, No	Undesirable, Desirable
	Defect Type	N/A, Joint, Circular or Spiral Crack/Fracture, Multiple Cracks/Fracture, Hole	N/A, Mild, Moderate, Severe, Extreme
	Rehab Type	N/A, Section, Segment, None	Preferable, Desirable, Mediocre, Least Desirable
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	Break Rate	Values are continuous with a range of 1 to 5	N/A, Low, Moderate, High and Very High

Table 24: Fuzzy Inference Model Membership Ranges – Current Integrity Module (Phase 2/Module 4)

Current Integrity	**Input Variables**	**Membership Function Ranges**	**Linguistic Terms**
	Life Expectancy	Values are continuous with a range of 1 to 5	Very High, High, Moderate, Low and Very Low
	Structural Condition	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor
	Break Rate	Values are continuous with a range of 1 to 5	N/A, Low, Moderate, High and Very High
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	Current Integrity	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor

Table 25: Fuzzy Inference Model Membership Ranges – Internal Condition Module (Phase 2/Module 5)

Internal Condition	**Input Variables**	**Membership Function Ranges**	**Linguistic Terms**
	Pressure Class Exceeded	Never, Rarely, Occasionally, Often, Always	Preferable, Desirable, Mediocre, Least Desirable and Undesirable
	Pressure Surges	Never, Rarely, Occasionally, Often, Always	Very Low, Low, Moderate, High and Very High
	Adequate Fire Flow	Yes, No	Desirable, Undesirable
	Pressure Complaints	Yes, No	Undesirable, Desirable
	Discolored Water	Yes, No	Undesirable, Desirable
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	Internal Stress	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor, Very Poor

Table 26: Fuzzy Inference Model Membership Ranges – External Stress Module (Phase 2/Module 6)

	Input Variables	**Membership Function Ranges**	**Linguistic Terms**
External Stress	Disturbances	Yes, No	Undesirable and Desirable
	Flooding	Never, Occasionally, Often	Desirable, Mediocre, Least Desirable
	Live Load (Road Type)	Unpaved, Non-National Highway System, National Highway System, Interstate, Railroad/Airport	Very Light, Light, Moderate, Heavy and Very Heavy
	Material Type	Ductile Iron, Cast Iron, Steel/Galvanized Steel, Copper	Preferable, Desirable, Mediocre, Least Desirable and Undesirable
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	External Stress	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor, Very Poor

Table 27: Fuzzy Inference Model Membership Ranges – External Corrosion Module (Phase 2/Module 7)

External Corrosion	**Input Variables**	**Membership Function Ranges**	**Linguistic Terms**
	Dissimilar Metals	Yes, No	Undesirable and Desirable
	Cathodic Protection	Yes, No	Desirable and Undesirable
	Stray Currents	Yes, No	Undesirable and Desirable
	Soil Corrosivity	Low, Moderate, High	Low, Moderate, High
	Coating	Yes/Efficient, Yes/Non-Efficient or No	Desirable and Undesirable
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	External Corrosion	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor, Very Poor

Table 28: Fuzzy Inference Model Membership Ranges – Performance Module (Phase 3/Module 8)

Performance	**Input Variables**	**Membership Function Ranges**	**Linguistic Terms**
	Current Integrity	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor
	Internal Condition	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor
	External Stress	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor
	External Corrosion	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor
	Output Variable	**Membership Function Ranges**	**Linguistic Terms**
	Performance	Values are continuous with a range of 1 to 5	Excellent, Good, Fair, Poor and Very Poor

4.5 Performance Index Results

Implementation of the drinking water pipe performance index is essential in identifying the overall competence of the developed models. To evaluate the value of the previously developed pipe performance index, a case study utilizing real utility data from the Western Virginia Water Authority (WVWA) is applied. In particular, the WVWA serves roughly 23 million gallons of drinking water per day to approximately 158,000 people (WVWA 2009). With over 1,000 miles of water pipes, WVWA works in supplying potable drinking water to the city of Roanoke, Roanoke County and parts of Franklin County in the state of Virginia.

In particular, this case study involved analyzing a specific zone of water pipelines named “Gravity” which consisted of over 14,000 water pipe sections (node to node). The data collected by the utility consisted of the pipe sections age, design life, vintage, rehab (lining), diameter, pipe break, break <5 years ago, defect type, rehab/rehabilitation type, fire flow, road type, material type, dissimilar metals, cathodic protection, coating and location.

With the various tools, technology and sources available, several other parameters were derived for use in determining the pipe performance: Hazen Williams C factor and soil corrosivity. The Hazen Williams C factor was determined through “C” factor tables based on the pipe material type, age and diameter. Soil information attained from the U.S. Department of Agriculture Soil Survey Geographic (SSURGO) database allowed classification of soil types to be specified to individual pipelines. Specifically, a report on each soil type classified the soil corrosivity level per metallic corrosion.

Data for other parameters were based on high, medium and low educated guesses provided by the head infrastructure asset manager of the WVWA. These parameters consisted of leak, the occurrences of exceeding the water pressure class, occasion of pressure surges, pressure complaints, discolored water, disturbances, flooding and the presence of stray currents. Also, the managers at WVWA decided that all galvanized pipes were determined to have a 50 year design life and a Hazen Williams C factor of 50 due to findings of sufficient encrustation and deposits during this time period.

Parameters that were unable to be derived or provided with an educated guess were assumed to be in perfect condition. These parameters consisted of the remaining thickness and the percent tuberculation. A summary table illustrating the WVWA parameter collection type is listed in Table 29.

Table 29: WVWA Parameter Collection Type

Parameter	**Collection Type**
Age	*Direct Record*
Design Life	*Direct Record*
Vintage	*Direct Record*
Rehab	*Educated Guess (High Confidence)*
C Factor	*Derived (Based on Age, Diameter, Material Type)*
Remaining Thickness	*No Data*
Tuberculation	*No Data*
Leak	*Direct Record*
Break	*Direct Record*
Break <5 Year Ago	*Direct Record*
Defect Type	*Direct Record*
Rehab/Rehabilitation Type	*Direct Record*
Pressure Class Exceeded	*Educated Guess (High Confidence)*
Pressure Surges	*Educated Guess (High Confidence)*
Adequate Fire Flows	*Direct Record*
Pressure Complaints	*Educated Guess (High Confidence)*
Discolored Water	*Educated Guess (High Confidence)*
Disturbances	*Educated Guess (High Confidence)*
Flooding	*Educated Guess (High Confidence)*
Live Load (Road Type)	*Direct Record*
Material Type	*Direct Record*
Dissimilar Metals	*Direct Record*
Cathodic Protection	*Direct Record*
Stray Currents	*Educated Guess (High Confidence)*
Soil Corrosivity	*Derived (Downloaded from SSURGO)*
Coating	*Direct Record*

4.5.1 **Weighted Factor Model Results**

Weights assigned to each parameter for the weighted factor model were developed based on the questionnaire provided to WVWA which evaluated the significance of each parameter. The weights per parameter were summed to equal one for each of the four modules (current integrity, internal condition, external stress and external condition) and are provided in Table 30.

Table 30: WVWA Weights

Module	Parameter	Weights
Current Integrity	Age	0.06
	Design Life	0.09
	Vintage	0.09
	Rehab (Lining)	0.09
	Hazen Williams C Factor	0.04
	Remaining Thickness	0.09
	Tuberculation	0.09
	Leak	0.12
	Pipe Break	0.12
	Break <5 Years Ago	0.09
	Defect Type	0.06
	R/R Type	0.06
Internal Condition	Pressure Class Exceeded	0.23
	Pressure Surges	0.26
	Adequate Fire Flow	0.19
	Pressure Complaints	0.16
	Discolored Water	0.16
External Stress	Disturbances	0.40
	Flooding	0.20
	Live Load	0.20
	Material Type	0.20
External Corrosion	Dissimilar Metals	0.22
	Cathodic Protection	0.17
	Stray Currents	0.17
	Soil Corrosivity	0.22
	Coating	0.22
Performance	Current Integrity	0.25
	Internal Stress	0.25
	External Stress	0.25
	External Corrosion	0.25

The performance results obtained from the weighted factor model for the "Gravity Zone" in WVWA are shown in Figure 14. The majority of the pipes have a "Good" performance level. There were also a few segments classified as having an "Excellent" or a "Fair" performance level.

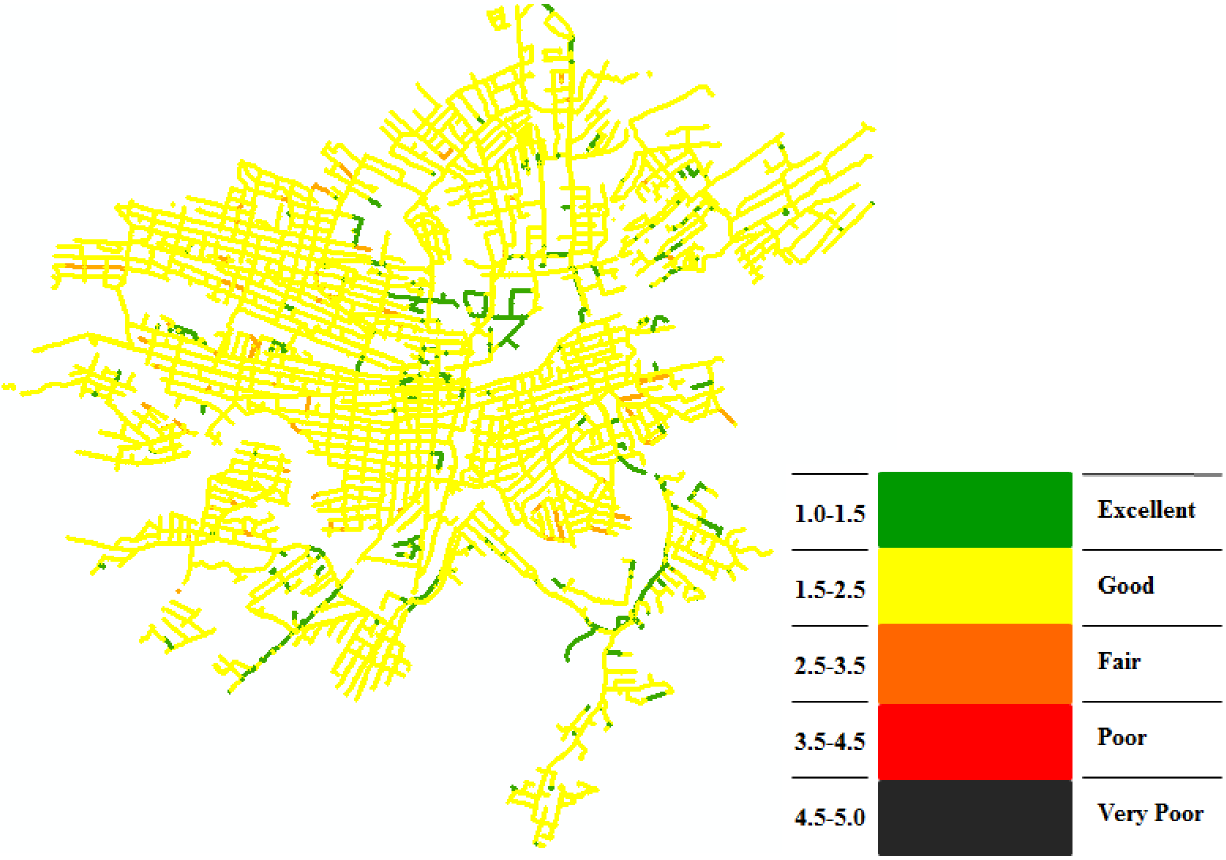


Figure 14: WVWA Weighted Factor Performance Index Results

4.5.2 **Fuzzy Inference Model Results**

The performance results obtained from the fuzzy inference model for the "Gravity Zone" in WVWA are shown in Figure 15. Performance results from the fuzzy inference model ranged from an "Excellent" to a "Very Poor" performance rating. Percentages of each range included 9% "Excellent", 18% "Good", 49% "Fair", 11% "Poor" and 13% "Very Poor".

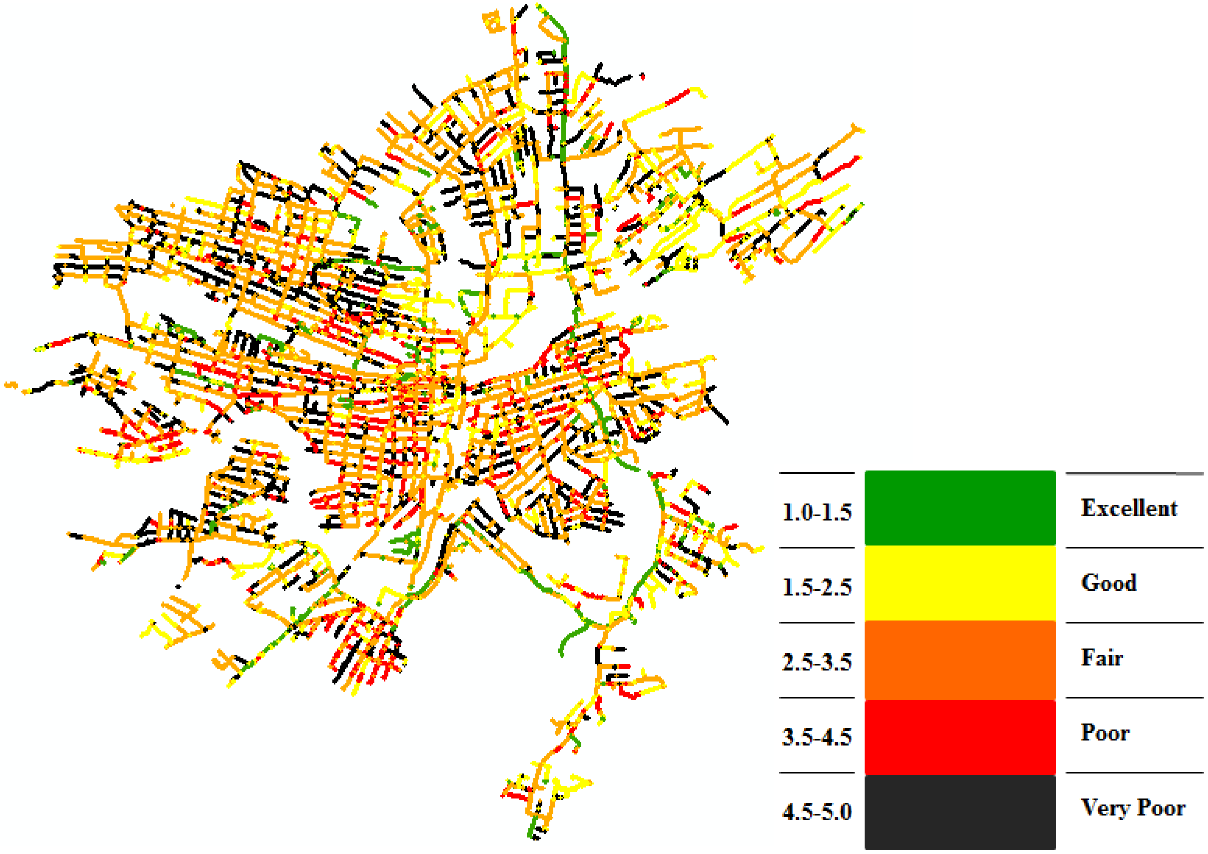


Figure 15: WVWA Fuzzy Inference Performance Index Results

The reliability of both the weighted factor and fuzzy inference performance index was calculated based on the individual parameter reliability as shown in Table 31. The WVWA performance index for both the weighted factor and fuzzy inference model has an 80% reliability level.

Table 31: WVWA Performance Index Parameter Reliability

Parameter	Parameter Reliability
Age	5
Design Life	5
Vintage	5
Rehab (Lining)	5
Hazen Williams C Factor	4
Remaining Thickness	0
Tuberculation	0
Leak	3
Pipe Break	5
Break <5 Years Ago	5
Defect Type	5
Rehab/Rehabilitation Type	5
Pressure Class Exceeded	3
Pressure Surges	3
Adequate Fire Flow	5
Pressure Complaints	3
Discolored Water	3
Disturbances	3
Flooding	3
Live Load (Road Type)	5
Material Type	5
Dissimilar Metals	5
Cathodic Protection	5
Stray Currents	3
Soil Corrosivity	4
Coating	5
Performance Index Reliability	80%

To evaluate the benefits of modeling pipe performance with the fuzzy inference theory over the weighted factor methodology, module and the resultant performance index results were compared for three pipe samples (A, B and C). The parameters of each sample and outputs are shown in Table 32. Relating the weighted factor and fuzzy inference module (current integrity, internal condition, external stress and external corrosion) resultants with the overall performance output, it is shown that the weighted factor methodology essentially “averages” each module result. In contrast, the fuzzy inference method uses the most critical module value (closest to 5) to impact the resultant which is owed to the interrelationships of the fuzzy inference if/then rule statements. The following examples show the benefits of the fuzzy inference model over the weighted factor model by specifically evaluating the parameters pipe break, age vs. design life and external coating vs. metallic corrosion.

Recent pipe breaks often connote a higher potential of future breaks within the same pipe segment. Specifically, the fuzzy inference method considers a previous pipe break a critical parameter in determining the fuzzy inference break rate value. This is also shown in the weighted factor method in which the parameter pipe break is given a “high” weight in the calculation of the current integrity module. Considering *Pipe A* in relationship to the pipe break, the fuzzy inference break rate module value is 5.00 “Very Poor” which combined with the life expectancy and structural condition output owed to a fuzzy inference current integrity module value of 4.78 “Very Poor”. Contrary, the weighted factor current integrity module value is 3.02 “Fair”. As shown in the current integrity results, the fuzzy inference methodology is able to interpret the significant of the parameter pipe break in the overall resultant, while the weighted factor methodology cannot.

Benefits of the fuzzy inference interrelationships using the if/then rule statements are also observed when evaluating the design life vs. age. Using the fuzzy inference if/then rule statements, interrelationships were formed stating that if the pipes age is beyond the design life, than the current integrity of the pipe is “Very Poor”. As shown in *Pipe B*, the age of the pipe is 88, while the design life is only 50 years. Using the fuzzy inference methodology, the if/then rule statements resulted in a fuzzy inference life expectancy output of 4.40 “Poor” which combined with the structural condition and break rate output owed to a fuzzy inference current integrity output of 4.56 “Very Poor”. In contrast, the weighted factor current integrity output is 2.24 “Good”. Results concluded that the fuzzy inference methodology is capable of determining the interrelationships of parameters.

Lastly, the benefit of evaluating the external coating vs. metallic corrosion using the fuzzy inference over the weighted factor methodology was challenged. In considering the fuzzy inference methodology, no matter the severity in the parameters owing to metallic corrosion (dissimilar metals, stray currents and soil corrosivity); if a coating is present and is effective, than the external corrosion module has a 1 "Excellent" value. In comparison, if there is no coating present or if the coating is "non-effective", than the resultant fuzzy inference external corrosion module value will reflect the other parameter values owing to external corrosion. Contrary, the weighted factor model in not able to interpret these interrelationships and each parameter is applied a specific weight. As shown in *Pipe C*, there is a presence of dissimilar metals, no cathodic protection is installed, no stray currents are present and there appears to be a high soil corrosivity level; however, there is an effective coating applied to the pipe. Overall, the external corrosion rating using the fuzzy inference method is 1 "Excellent" due to the effective coating present which prohibits corrosion due to the dissimilar metals and a high soil corrosivity level. The weighted factor method is not capable of interpreting these interrelationships and predicted a value of 3.44 "Fair". These conclusive results show the significant benefit of using the fuzzy inference methodology when evaluating the external coating vs. metallic corrosion.

Comparative results of the fuzzy inference vs. the weighted factor methodology analyzing previous pipe breaks, the design life vs. age and the external coating vs. metallic corrosion showed that the fuzzy inference model is capable of analyzing a complex drinking water pipe system. Specifically, the advantages of the fuzzy inference over the weighted factor methodology lies in the defined membership functions and if/then rule statements. Based on the fuzzy inference model capabilities along with the comparison of the fuzzy inference and weighted factor methodologies, only the fuzzy inference model and results are further evaluated. Particularly, the weighted factor methodology served as a tool to illustrate the ability the fuzzy inference model has when examined under extreme circumstances. Overall, the weighted factor methodology proved to be unsatisfactory in complex water infrastructure systems.

Table 32: WVWA Weighted Factor vs. Fuzzy Logic Sample Results

Parameter	***Unit***	**Pipe A**	**Pipe B**	**Pipe C**
Age	*year*	34	88	7
Design Life	*year*	75	50	75
Vintage	*year*	1976	1922	2003
Rehab (Lining)	*yes/no*	No	No	No
C Factor	*c factor*	90	50	125
Remaining Thickness	*percent*	100	100	100
Tuberculation	*level*	None	None	None
Leak	*yes/no*	No	No	No
Pipe Break	*yes/no*	Yes	No	No
Breaks <5 Years Ago	*yes/no*	Yes	No	No
Defect Type	*type*	Extreme	N/A	N/A
R/R Type	*type*	Segment	N/A	N/A
Pressure Class Exceeded	*occasion*	No	No	No
Pressure Surges	*occasion*	No	No	No
Adequate Fire Flow	*yes/no*	Yes	Yes	Yes
Pressure Complaints	*yes/no*	No	No	No
Discolored Water	*yes/no*	No	No	No
Disturbances	*yes/no*	No	No	No
Flooding	*occasion*	Never	Never	Never
Live Load	*road type*	Non-NHS	Non-NHS	Non-NHS
Material Type	*type*	DI	Galvanized	DI
Dissimilar Metals	*yes/no*	No	Yes	Yes
Cathodic Protection	*yes/no*	No	No	No
Stray Currents	*yes/no*	No	No	No
Soil Corrosivity	*level*	Moderate	Low	High
Coating	*yes/no*	No	No	Yes
Life Expectancy Output	*Fuzzy Logic*	2.44	4.40	1.46
Structural Condition Output	*Fuzzy Logic*	2.00	4.56	1.18
Break Rate Output	*Fuzzy Logic*	5.00	1.00	1.00
Current Integrity Output	*Weighted Factor*	3.02	2.24	1.63
	Fuzzy Logic	4.78	4.56	1.32
Internal Condition Output	*Weighted Factor*	1.00	1.00	1.00
	Fuzzy Logic	1.00	1.00	1.00
External Stress Output	*Weighted Factor*	1.20	2.00	1.20
	Fuzzy Logic	1.00	3.00	1.00
External Corrosion Output	*Weighted Factor*	2.12	3.44	3.44
	Fuzzy Logic	1.00	3.00	1.00
Performance Output	*Weighted Factor*	1.84	2.17	1.82
	Fuzzy Logic	4.76	4.56	1.32

5 Water Pipeline Performance Index Evaluation & Framework for Deterioration Prediction

Researchers have proposed different models in order to help predict the condition/performance and failure of water pipelines but do not provide a sufficient evaluation process to understand whether or not the model is predicting a reasonable value in respect to the actual value found in the field. Specifically, evaluation ensures that the model and its implementation are correct. Striving to provide a substantial evaluation process can acquire significant credibility of the model. Overall, the performance index evaluation will help to measure the robustness of the developed performance model through testing of the algorithm.

With the development of the performance index model, subsequently, the performance index can be modeled over time. In detail, a framework for deterioration prediction is presented which utilizes a Markov chain approach in the development of deterioration curves. Evaluation of the developed pipe deterioration curves can assist in optimizing the best time for future pipe inspection and selection of the suitable R,R&R technique.

5.1 Performance Index Evaluation

Considerable research has been conducted in evaluating the reliability and robustness of models in other fields of science and engineering. Bayarri et al. (2005) proposed a framework for the evaluation of computer models. Their evaluation framework includes six procedures: 1) specification of inputs and parameters with associated uncertainties or ranges; 2) determination of evaluation criteria; 3) data collection and experiment design; 4) model approximations for the output; 5) output analysis comparing the computer output with field data; and 6) use of results from step 5 to improve the model and to utilize the validated model for the validation of future models. Other methods researchers used to evaluate and validate their model included: Liu et al. (2011) who used multiple attribute group decision making problems to evaluate the security of the computer network; Farley et al. (2010) used field data to validate the methodology for burst and leak detection and location; Nassif et al. (2003) used measured stresses in the experiment and compared those with the computer simulation results to validate their dynamic model for bridges subject to moving trucks; and Kim and Leet (2007) validated a model for evaluating learning management systems, based on a survey of experts regarding validation items.

In this dissertation, evaluation of the developed performance index consists of analyzing the data on three different approaches: artificial, field and lab test data. Model evaluation based on artificial data analyzes input test data by three bands of values, which classify the best, moderate and worst case values. The rationale of this approach is done through artificially controlling the input of the model to verify the model output. For example, when all the best values for each parameter are entered, the model should ideally give the best output. Similarly, if all the moderate or worse values of each parameter are adopted, the model shall indicate the moderate and worst pipe performance. Next, model evaluation based on field data assesses the reasonability of the model using real utility data and also compares the develop performance model against an existing water utility's condition model. The credibility is further checked by expert opinion of fellow utility engineers. Lastly, evaluating the model based on lab testing relates the remaining strength of the pipe to a performance rating which is compared to the performance rating found through the fuzzy inference model.

Limitations of these evaluation approaches include:

Artificial Data

- This test data evaluation method is most suitable for cases where there are a large number of input parameters. In the case of models with fewer parameters, the Monte Carlo simulation can be run in order to obtain their statistical behavior of the model.

Field Data

- If the utility database is limited, the "best" possible values will be implemented in the model for the missing variables. In this case, these input values and their effect on the model would not be evaluated which could underestimate the severity of the pipe performance.
- Some input variables may be constant in all the pipes due to same condition throughout the network. In this case, the effect of the parameters variation is not seen.
- Every model output is dependent on the methodology utilized and input parameters.

Lab Test Data

- Lab testing is very expensive and is limited per available funds.
- Sample specimens are only representative of the pipe sample tested.
- Lab testing is similar to the loading condition found when the pipe is in service, but they are not exactly the same.

5.1.1 **Evaluation Based on Artificial Data**

Artificial data was initially used to aid in the development of the fuzzy inference performance model. Specifically, input data was fed into the model to review the expected outputs. Glitches within the model were then addressed through the addition of new parameters, changes in the defined membership functions and the review of the if/then rule statements. Utilities and other experts within the field were also encouraged to implement sample input values into the model and to review the output to give additional feedback.

To assess the reliability and robustness of the model, evaluation of the fuzzy inference model began by testing artificial or "imaginary" input values based on three bands to represent the best, moderate and worst case scenarios. This method is used because by artificially controlling the inputs the outputs can easily be compared. When all the best values are entered the model should ideally give the best output and this holds true also for the other two cases. Overall, these input data bands observed whether or not the output fell within the corresponding range. In each band several parameters were also changed individually to observe the model sensitivity per critical parameters. Specifically, the model challenges the pipes according to their diameter which is divided into four ranges of 1-4, 5-8, 9-12, and >12 inches. Several points were observed during test data evaluation which is summarized below.

1. The model performed well when analyzing input data by the three band scenarios (i.e. when the best input parameter values were entered in the model the output reflected with the best condition ranges. Similar results were found for the other two bands.)

2. The most influential or sensitive parameters observed during the evaluation process were the Hazen William C factor, pipe break and external coating.

    a. When the Hazen William C factor was changed from 85 to 75 while analyzing the best possible case band of 1 to 4 inch diameter model, the models performance index changed from 2 "Good" to a 3 "Fair" performance state. This is due to the fact that this parameter largely influences the current integrity module. Similar observations were also noticed in the cases of the other three pipe diameter ranges.

    b. Pipe break also influenced the model in a reasonable manner. For example if a moderate pipe break was present less than five years ago and the pipe segment was repaired, the break rate was changed from 1 "Excellent" to a 3 "Fair" performance level from when the pipe was not previously broken.

    c. The most sensitive parameter in this model is external coating. This is due to that when all the parameters responsible for external corrosion are severe but there is an external coating on the pipe, the final output of the external corrosion is 1 “Excellent” performance. However, when a value corresponding to no external coating is inducted in the model with all other external corrosion values severe, then the output of external corrosion module results in a performance of 5 “Very Poor”.

3. The Hazen William C factor influences the model non-linearly. (Depending on the diameter of the pipe, C factor values below 60 to 80 give the worst performance values.)
4. In the best case scenarios, the overall performance gives resultant values close to or exactly 1 “Excellent” performance.

5. In the worst case scenarios, the overall performance gives resultant values close to or exactly 5 “Very Poor” performance.

5.1.2 **Evaluation Based on Field Data**

Utility engineering evaluation and assessment of field data in relation to the predicted pipe performance is fundamental as the model is specifically developed for utilities to implement to their current water infrastructure. Currently, many utilities are reliant on field personnel to determine future inspection and R,R&R of their water infrastructure. These utilities are in need of a method to analyze the performance of drinking water pipelines before their field staff retires and the knowledge of their water infrastructure system is lost.

The performance model was evaluated utilizing field data from the WVWA and the Washington Suburban Sanitary Commission (WSSC) to analyze the robustness of the model when applied in real case scenarios. Specifically, field data from the WVWA was input into the fuzzy inference performance model in where expert opinion verified the resultants. The output from the performance model using field data from WSSC was also compared similarly with expert opinion, but also included comparison to their existing condition model score.

5.1.2.1 Western Virginia Water Authority (WVWA)

The WVWA does not use a condition model to determine future inspection and R,R&R of their water infrastructure but however relies on field personnel. During the development process of the performance model, field technicians from the WVWA provided critical engineering knowledge in relation to parameters and their effect on pipeline performance as seen in the field. Utility engineers and management also provided valuable model feedback.

Implementation of the performance model to WVWA data analyzed 14,000 pipe sections as previously presented. Of those pipe sections assessed by the fuzzy inference methodology, a sample size representing this population was further evaluated. Given a 95% confidence level and 5% margin of error, a total of 375 random pipe sections were chosen (Krejcie 1970). Each of these pipe samples, their parameters and resultant fuzzy inference module outputs are shown in Appendix D.

In analysis of this data set, the overall performance value was largely dependent on three factors: Hazen Williams C factor, pipe break and the external coating on the pipes. Contrary to the traditional assumption that pipe age determines the overall lifetime of a pipeline, it is revealed that the pipe age is not directly related to the performance rating. The following is several graphs which represent the pipe age, Hazen Williams C factor and pipe break in relation to the pipe performance. The external coating on the pipes is also shown in relation to the predicted output corrosion module. Due to the limited WVWA database, some parameters and their effects on the fuzzy inference performance model could not be tested. These parameters included remaining wall thickness and percent of tuberculation.

Age

The pipe age in the utility pipe database is one of the many factors in determining the overall performance predicted by the model based on engineering judgment. The plot of pipe performance vs. pipe age, as shown in Figure 16, illustrates that the pipe age is not directly related in determining the overall pipe performance value. This graph does however show how pipe age in combination with other parameters can predict the resulting performance rating. As shown in Figure 16, the following analysis will evaluate young (triangles), middle aged (ovals) and old (rectangle) pipes in relation to the varying performance ratings of excellent (green), good (yellow), fair (orange), poor (red) and very poor (black).

The green triangle represents some of the youngest pipes that have an “Excellent” performance rating due to favorable conditions. Next, the yellow triangle also represents young pipes but with a “Good” performance rating. These young pipes are less than excellent due to the fact that no external coating is present and the soil has a moderate corrosivity level. The orange triangle illustrates young pipes with a “Fair” performance level. Parameters owing to this “Fair” performance rating are dissimilar metals, no cathodic protection, moderate soil corrosivity and no external coating. In several cases, illustrated by the black triangle, the performance of the pipe was “Very Poor” regardless of the young age which was mainly attributed to a recent pipe break.

Evaluating the middle aged pipes, the orange oval highlights pipes with favorable conditions with the exception of the pipe’s vintage. In particular, the middle aged pipes are less than excellent due to a poor vintage era which resulted in the reduced pipe thickness mainly attributed to WWII. The red oval highlights the middle aged pipelines with a “Poor” performance rating. Mainly, these pipes are galvanized steel that have a low design life and an unfavorable vintage. In particular, pipe materials such as galvanized steel and copper have a much lower design life than CI and DI pipes. The middle aged pipes with the “Very Poor” performance rating, shown by the black oval, are pipes with recent pipe breaks and an unfavorable vintage.

It is shown that some of the oldest pipes have a “Fair” performance rating represented by the orange rectangle. This “Fair” performance rating is due to the pipes quality vintage combined with favorable conditions. The red rectangle represents older galvanized pipes with a “Poor” performance rating. Again, these pipe materials have a very low design life which attributes to the lower performance rating. Lastly, the black rectangle illustrates the oldest pipes that have a “Very Poor” performance rating. These “Very Poor” performance ratings are due to recent pipe breaks. Points not highlighted in this graph can also be described by a variance of parameters.

Overall, this graph illustrates that the pipe performance is not directly related to the pipe age and that other factors can dominate the resulting performance rating. In conclusion, typically utilities want to replace pipelines based just on age; however, many older pipes are still in good to fair condition due to their superior quality coupled with favorable conditions. Contrary, there are particular instances in where the pipe can fail during its earliest years due to poor installation and design. Based on these conclusions, the parameter “age” is not considered a critical factor in determining the final performance rating.

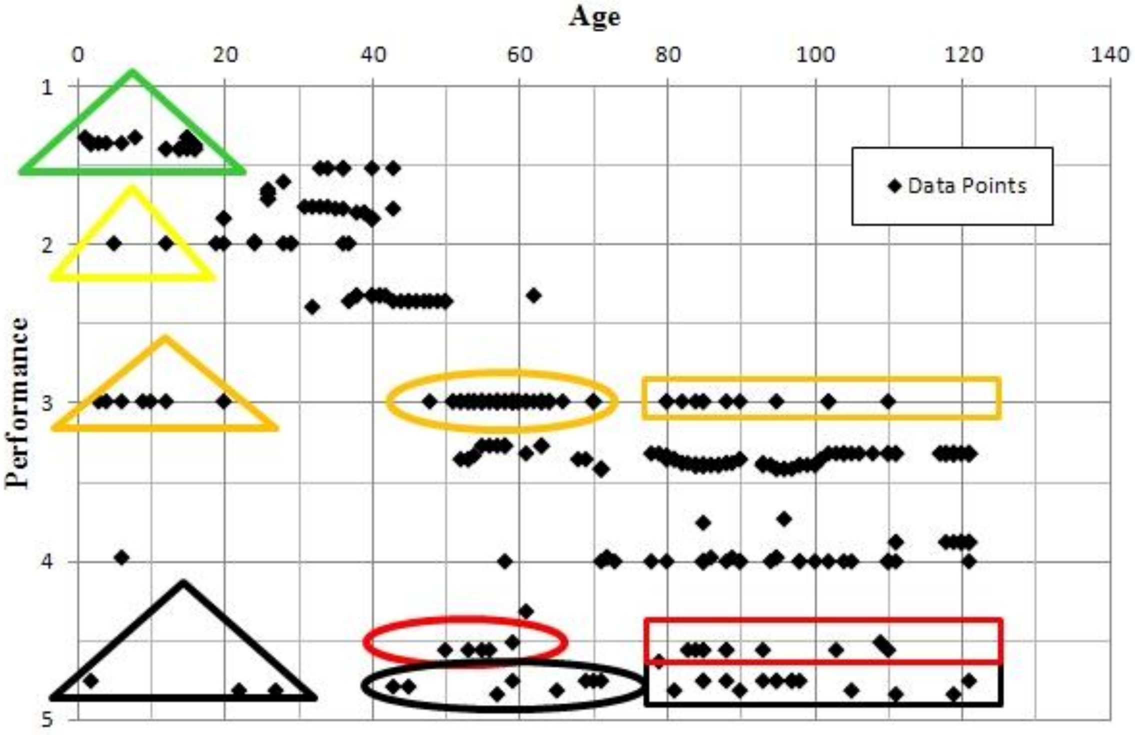


Figure 16: Performance vs. Age

Hazen Williams C Factor

The plot of pipe performance vs. the Hazen Williams C factor, as shown in Figure 17, illustrates that the pipe performance is dependent upon the C factor. The Hazen Williams C factor is the roughness coefficient of the inside of a pipe based on an equation evaluating the pressure drop due to friction as it relates to the pipe diameter and flow rate. Low C factors indicate older pipes and poor internal conditions. Also, the smaller the diameter pipe is said to have a lower Hazen Williams C factor than a larger diameter pipe of the same age which also contributes to a poorer performance value. Although the relationship of pipe performance vs. the Hazen Williams C factor is not a linear, it is shown that the C factor largely influences the resulting performance value.

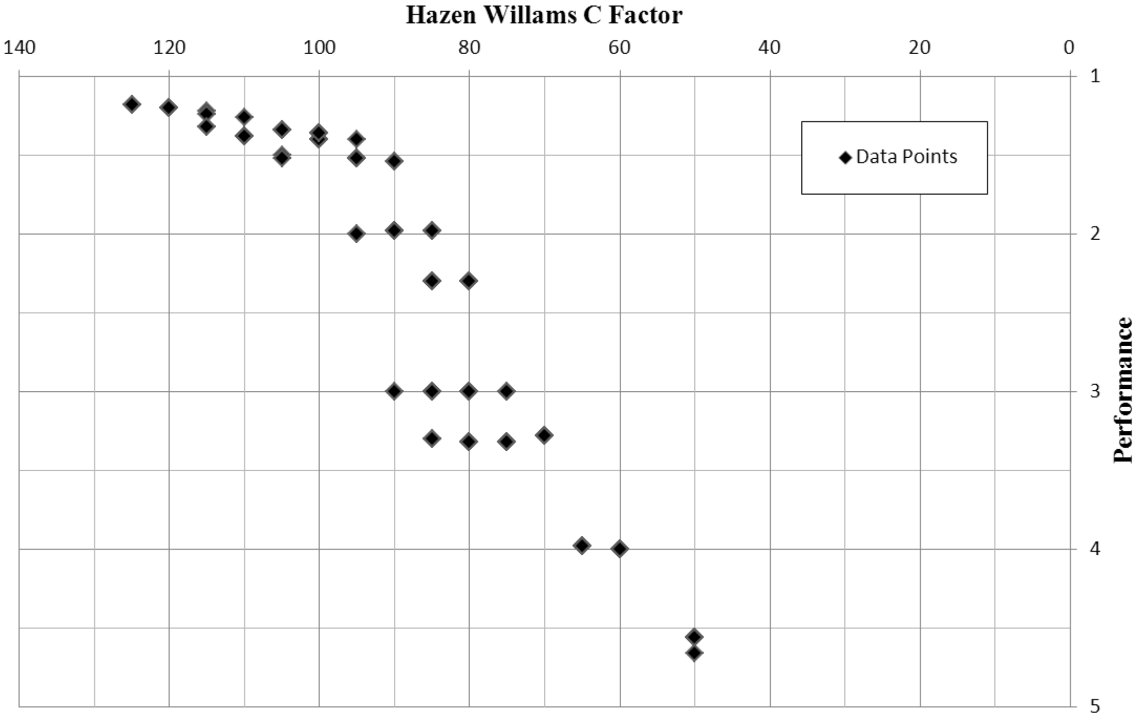


Figure 17: Performance vs. Hazen Williams C Factor

Pipe Break

Pipe break is a very important parameter in the model as it reflects on how the pipe is performing underground with varying influencing parameters. A pipe with previous breaks indicates to a utility that a problem exists in where further inspection and evaluation need to take place in order to prevent future adversities. Results illustrated in the plot of pipe performance vs. pipe break, as seen in Figure 18, show that pipe sections with previous breaks have poorer performance ratings. As previously mentioned, if pipe break is "no" than it is represented though a value of "5"; while, "yes" is denoted by a value of "1". Again, the pipe segment is characterized based on "node" to "node"; therefore, if there is a break in just a section of the segment, the entire pipe segment will reflect the pipe break performance level.

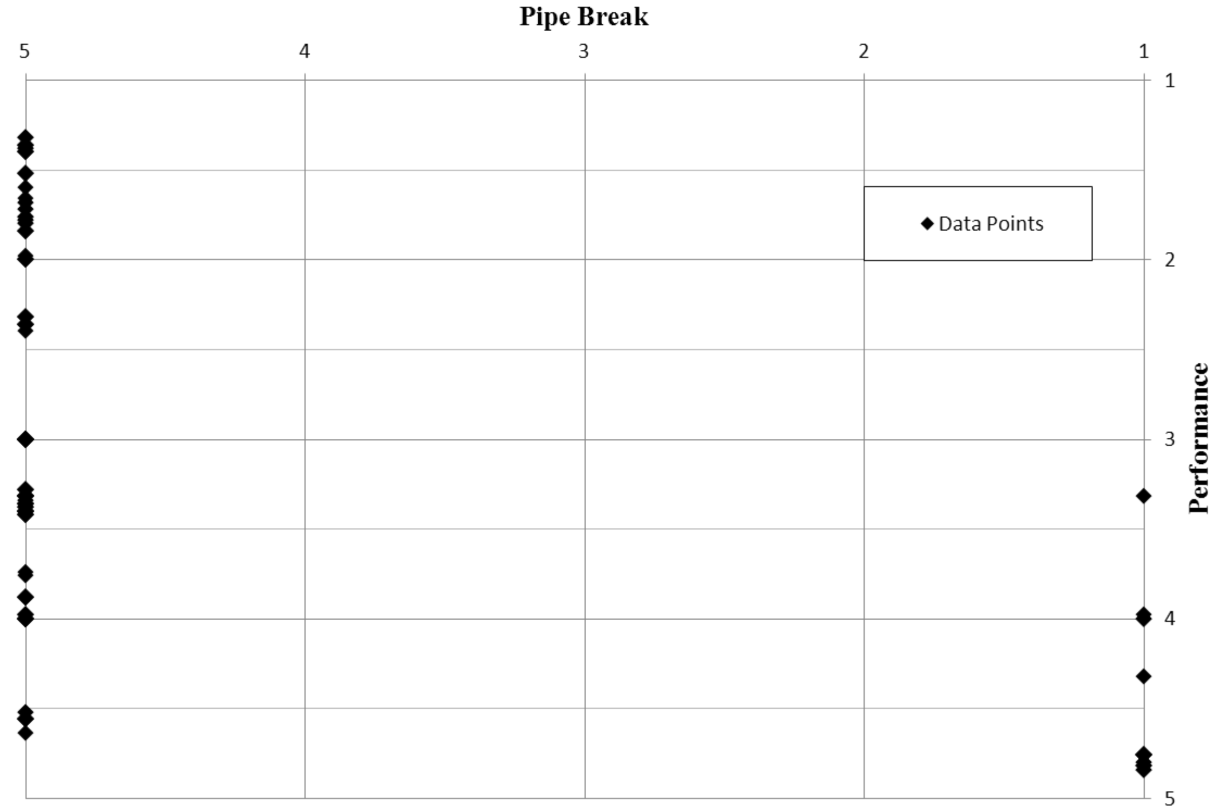


Figure 18: Performance vs. Pipe Break

External Coating

In this model the external coating of the pipe is a major factor in deciding the value of the external corrosion module as shown in Figure 19. This factor was also shown to be critical in determining the overall performance when analyzing the artificial data. In all the cases where the pipes were applied an external coating, considering all other external corrosion factors, the external corrosion rating is 1 “Excellent”. However, when an external coating was not present, and unfavorable corrosion parameters were present, the external corrosion rating was less than “Excellent”. As previously mentioned, a “yes” external coating value is represented by a “1” while a “no” external coating value is denoted by a value of “5”.

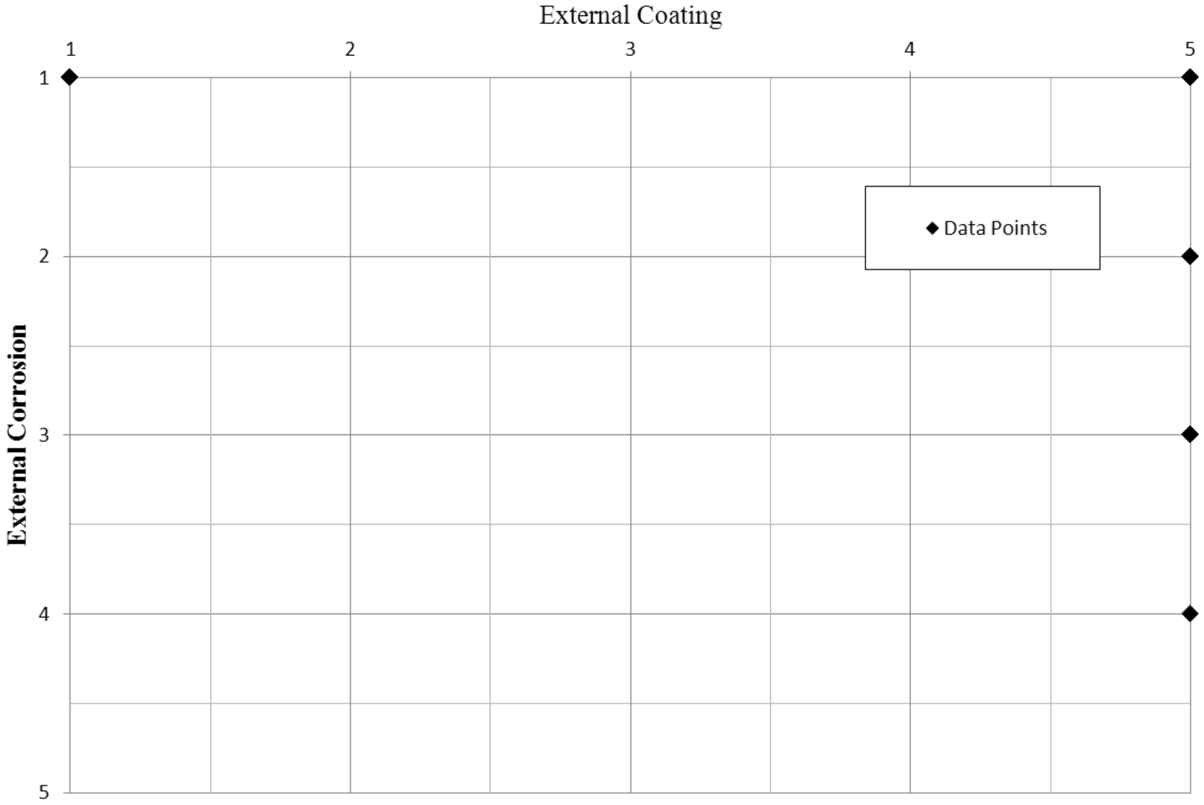


Figure 19: External Corrosion vs. External Coating

Implementation of the prediction model with the WVWA has led to positive support of the performance index. The utility engineers and management staff have provided their confidence in the developed model. As a result, WVWA has motivated their field staff to collect more data during routine valve replacements and pipe installations because they see the benefit of collecting data to feed the fuzzy inference predictive model.

5.1.2.2 Washington Suburban Sanitary Commission (WSSC)

The WSSC is one of the utility leaders in the evaluation of water infrastructure and has a special team devoted to the testing and analysis of their current infrastructure. In addition, WSSC has a superior asset management plan which includes an existing condition model. This WSSC condition model was used to compare the results of the developed fuzzy inference performance model based on similar inputs. Their previous studies and practices were recorded and crucial water infrastructure knowledge was reflected in the developed performance model from various meetings with their utility engineers and management staff.

With servicing a population of 1.8 million, WSSC is the 8th largest water and wastewater facility in the U.S. and has a service area of 1,000 square miles which includes Montgomery and Prince George's counties in Maryland. WSSC's existing condition model based on engineering judgment is comprised of an age and corrosion based score which includes parameters such as material type, diameter, length, construction year, rehabilitation date, number of breaks, break type, lining, break date, discolored water, water leak, fire hydrant issue, valve leak, low pressure, fire flows, proximity of break, aggressive soil, cathodic protection, wrap, wall thickness, and soil corrosion rates. The output values of the WSSC condition model range from 1 "Excellent" to 5 "Very Poor" which is similar to the performance scale developed in this paper. Overall, testing the fuzzy inference model against another existing condition model can illustrate the versatility of the developed index as it can be utilized with any number of water utilities to successfully predict the performance of water pipelines.

A total of 27 pipe samples from WSSC were evaluated by the fuzzy inference and condition model. The list of the WSSC pipe samples and the fuzzy inference parameters are shown in Table 33. Parameters provided by direct record included age, vintage, rehab (lining), thickness, tuberculation, leak, pipe break, break <5 years ago, defect type, rehab/rehabilitation type, adequate fire flows, pressure complaints, discolored water, live load (road type), material type, cathodic protection, soil corrosivity and external coating. Product standards were utilized to determine the design life and the Hazen Williams C factor was derived using the age, diameter and material type. An educated guess was specified to parameters including pressure class exceeded, pressure surges, disturbances, flooding, dissimilar metals and stray currents. Overall, the performance index model reliability level utilizing WSSC data has an 89% reliability level.

Fuzzy inference and WSSC's condition model scores for each of these pipe samples are compared in Table 34. Specifically, this table lists the output fuzzy inference values for the four modules which make up the performance index module and the fuzzy inference performance output value and rating. Also included is a list of parameters which are contributing to the specific fuzzy inference module output. Lastly, the WSSC condition score calculated by utility's existing model is listed.

Evaluating Pipe 1, the final performance index value for the fuzzy inference model predicted a "Fair" performance rating of 3.38. Parameters owing to this performance rating included structural condition module parameters Hazen Williams C factor and thickness and break rate module parameters pipe break, break history and defect type. The fuzzy inference model performance rating for this particular pipe sample was compared to the WSSC condition model score of 3.57. Overall, the fuzzy inference model predicted a 0.19 value below the WSSC model.

In comparing all the fuzzy inference and condition model scores, 75% of the samples performance/condition outputs were within a 0.5 score of the other. A graph illustrating the fuzzy inference performance model results vs. the WSSC condition model results are shown in Figure 20. There are five pipe samples (Pipe 11, 20, 21, 23 and 26) in which the fuzzy inference performance index value is greater than 1.0 away from the WSSC condition score.

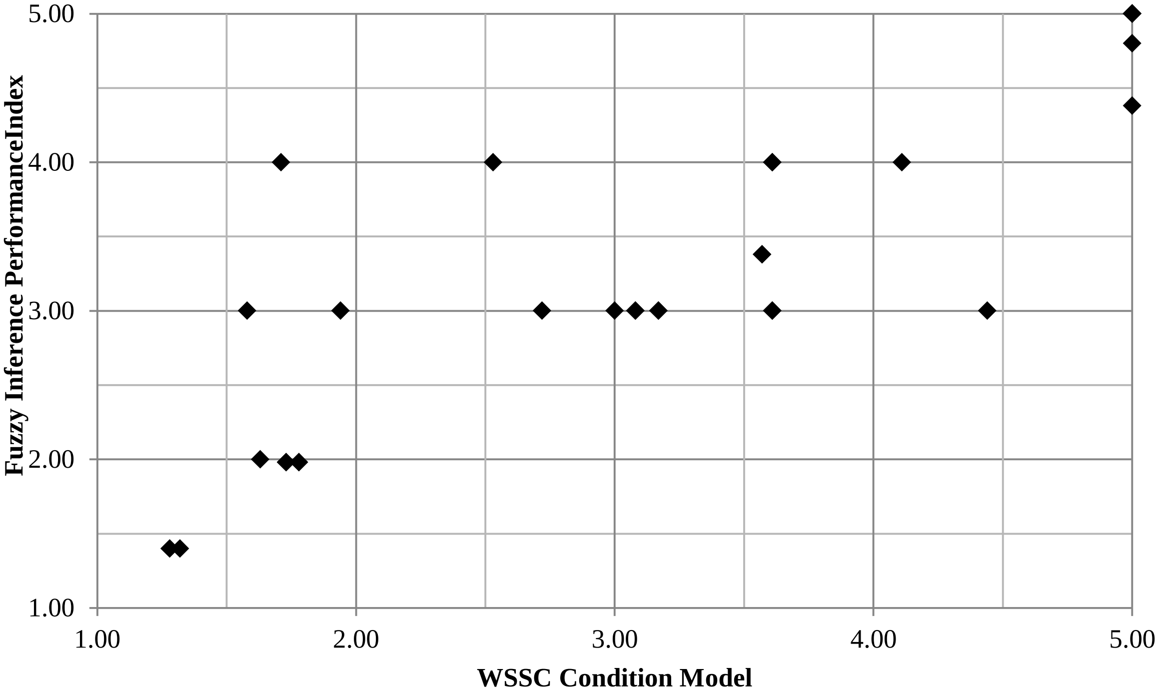


Figure 20: Fuzzy Inference Performance Index vs. WSSC Condition Model

Further evaluating Pipe 20 and Pipe 21, the fuzzy inference performance index value for both samples is 4.0 which is a “Poor” performance rating; while the WSSC condition model predicted scores of 2.53 and 1.71. When discussing the results of both models with WSSC, it was concluded that the WSSC condition score model was under predicting, in which the scores should be much higher as a result to the high tuberculation levels found within both pipes. The other sample, Pipe 23, had a fuzzy inference performance index value of 3.0 which is a “Fair” performance rating; while the WSSC condition model predicted a score of 4.44. Discussion of this pipe sample concluded that the WSSC condition model was over predicting, in which the condition score should be lower since this pipe only has minor graphitization. Pipe samples 11 and 26 had a fuzzy inference performance index value of 3.0 which is a “Fair” performance rating; while the WSSC condition model predicted scores of 1.94 and 1.58. The reason for the higher performance rating with the fuzzy inference model was due to previous breaks within the last 5 years.

Considering the differing methodology and techniques used to construct each of the models and varying input parameters, the fuzzy inference model proves to be a successful model in determining the drinking water pipe performance. Furthermore, the fuzzy inference performance model predicted more accurate results than the comparative existing WSSC condition score. This holds truth since the fuzzy inference performance model is coupled with membership functions and if/then rule statements capturing engineering knowledge than just a simple weighted and rule based methodology generated by one expert opinion. In addition, the fuzzy inference model has more parameters to predict the drinking water pipe performance than the WSSC condition model, which include factors such as the Hazen Williams C factor, tuberculation, pressure surges, flooding and dissimilar metals.

After further evaluation of the fuzzy inference model results, WSSC completed additional testing to verify the model’s compared. Based on this analysis, WSSC has stated that they would like to further investigate a fuzzy inference model to predict the condition and/or performance of their pipelines, than use of their existing age and corrosion based model. In conclusion, WSSC has great confidence in the developed fuzzy performance model and its capabilities.

Table 33: WSSC Pipe Samples

Parameter	***Units***	**Pipe 1**	**Pipe 2**	**Pipe 3**	**Pipe 4**	**Pipe 5**	**Pipe 6**	**Pipe 7**	**Pipe 8**	**Pipe 9**	**Pipe 10**
Diameter	*inch*	8	6	6	6	8	8	8	10	10	8
Age	*year*	97	80	75	73	73	56	56	56	56	56
Design Life	*year*	100	100	100	100	100	75	75	75	75	75
Vintage	*year*	1915	1932	1937	1939	1939	1956	1956	1956	1956	1956
Rehab (Lining)	*yes/no*	Yes	No	Yes	No	No	No	No	Yes	Yes	No
Hazen Williams C Factor	*c factor*	75	75	140	75	75	80	80	140	140	80
Remaining Thickness	*percent*	83	81	85	83	84	82	82	94	94	82
Tuberculation	*level*	None	Heavy	None	Heavy	None	Moderate	Moderate	None	None	Moderate
Leak	*yes/no*	No	No	No	No	No	No	No	No	No	No
Pipe Break	*yes/no*	Yes	No	Yes	Yes	Yes	Yes	No	No	No	Yes
Break <5 Years Ago	*yes/no*	Yes	No	Yes	No	Yes	No	No	No	No	No
Defect Classification	*type*	Moderate	N/A	Moderate	Moderate	Severe	Moderate	N/A	N/A	N/A	Moderate
Type of R/R	*type*	Segment	N/A	Segment	Segment	Segment	Segment	N/A	N/A	N/A	Segment
Pressure Class Exceeded	*occasion*	No	No	No	No	No	No	No	No	No	No
Pressure Surges	*occasion*	No	No	No	No	No	No	No	No	No	No
Adequate Fire Flow	*yes/no*	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	*yes/no*	No	No	No	No	No	No	No	No	No	No
Discolored Water	*yes/no*	No	No	No	No	No	No	No	No	No	No
Disturbances	*yes/no*	No	No	No	No	No	No	No	No	No	No
Flooding	*occasion*	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable
Live Load	*road type*	Moderate	Moderate	Light	Light	Light	Light	Light	Light	Moderate	Light
Material Type	*yes/no*	CI	CI	CI	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	*yes/no*	No	No	No	No	No	No	No	No	No	No
Cathodic Protection	*yes/no*	No	No	No	No	No	No	No	No	No	No
Stray Currents	*yes/no*	No	No	No	No	No	No	No	No	No	No
Soil Corrosivity	*level*	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Coating	*yes/no*	No	No	No	No	No	No	No	No	No	No

Table 33: WSSC Pipe Samples Cont.

Parameter	***Units***	**Pipe 11**	**Pipe 12**	**Pipe 13**	**Pipe 14**	**Pipe 15**	**Pipe 16**	**Pipe 17**	**Pipe 18**	**Pipe 19**	**Pipe 20**
Diameter	*inch*	8	8	8	6	6	6	6	10	10	8
Age	*year*	55	55	55	54	54	54	54	53	53	53
Design Life	*year*	75	75	75	75	75	75	75	75	75	75
Vintage	*year*	1957	1957	1957	1958	1958	1958	1958	1959	1959	1959
Rehab (Lining)	*yes/no*	Yes	Yes	Yes	No	No	No	No	Yes	Yes	No
Hazen Williams C Factor	*c factor*	140	140	140	80	80	80	80	140	140	140
Remaining Thickness	*percent*	86	86	86	82	82	82	82	94	94	83
Tuberculation	*level*	None	None	None	Heavy	Heavy	Heavy	Moderate	None	None	Heavy
Leak	*yes/no*	No	No	No	No	No	No	No	No	No	No
Pipe Break	*yes/no*	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes
Break <5 Years Ago	*yes/no*	Yes	Yes	No	No	No	Yes	No	No	No	No
Defect Classification	*type*	Moderate	Severe	N/A	Moderate	Moderate	Severe	Moderate	N/A	N/A	Moderate
Type of R/R	*type*	Segment	Segment	N/A	Segment	Segment	Segment	Segment	N/A	N/A	Segment
Pressure Class Exceeded	*occasion*	No	No	No	No	No	No	No	No	No	No
Pressure Surges	*occasion*	No	No	No	No	No	No	No	No	No	No
Adequate Fire Flow	*yes/no*	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes
Pressure Complaints	*yes/no*	No	No	No	No	No	No	No	No	No	No
Discolored Water	*yes/no*	No	No	No	No	No	No	No	No	No	No
Disturbances	*yes/no*	No	No	No	No	No	No	No	No	No	No
Flooding	*occasion*	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable
Live Load	*road type*	Light	Light	Light	Light	Light	Light	Moderate	Light	Light	Light
Material Type	*yes/no*	CI	CI	CI	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	*yes/no*	No	No	No	No	No	No	No	No	No	No
Cathodic Protection	*yes/no*	No	No	No	No	No	No	No	No	No	No
Stray Currents	*yes/no*	No	No	No	No	No	No	No	No	No	No
Soil Corrosivity	*level*	Low	Low	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Coating	*yes/no*	No	No	No	No	No	No	No	No	No	No

Table 33: WSSC Pipe Samples Cont.

Parameter	***Units***	**Pipe 21**	**Pipe 22**	**Pipe 23**	**Pipe 24**	**Pipe 25**	**Pipe 26**	**Pipe 27**
Diameter	*inch*	8	8	8	8	6	6	8
Age	*year*	52	52	49	49	47	47	47
Design Life	*year*	75	75	75	75	75	75	75
Vintage	*year*	1960	1960	1963	1963	1965	1965	1965
Rehab (Lining)	*yes/no*	No	No	No	No	Yes	Yes	Yes
Hazen Williams C Factor	*c factor*	140	80	90	90	140	140	140
Remaining Thickness	*percent*	84	84	84	84	94	94	94
Tuberculation	*level*	Heavy	Heavy	Moderate	Moderate	None	None	None
Leak	*yes/no*	No	No	No	No	No	No	No
Pipe Break	*yes/no*	No	Yes	Yes	No	No	Yes	No
Break <5 Years Ago	*yes/no*	No	No	No	No	No	Yes	No
Defect Classification	*type*	N/A	Moderate	Moderate	N/A	N/A	Moderate	N/A
Type of R/R	*type*	N/A	Segment	Segment	N/A	N/A	Segment	N/A
Pressure Class Exceeded	*occasion*	No	No	No	No	No	No	No
Pressure Surges	*occasion*	No	No	No	No	No	No	No
Adequate Fire Flow	*yes/no*	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	*yes/no*	No	No	No	No	No	No	No
Discolored Water	*yes/no*	No	No	No	No	No	No	No
Disturbances	*yes/no*	No	No	No	No	No	No	No
Flooding	*occasion*	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable
Live Load	*road type*	Light	Light	Light	Light	Light	Light	Light
Material Type	*yes/no*	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	*yes/no*	No	No	No	No	No	No	No
Cathodic Protection	*yes/no*	No	No	No	No	No	No	No
Stray Currents	*yes/no*	No	No	No	No	No	No	No
Soil Corrosivity	*level*	Moderate	Moderate	Low	High	Low	Low	Low
Coating	*yes/no*	No	No	No	No	No	No	No

Table 34: Fuzzy Inference vs. WSSC Condition Model

Sample	Fuzzy Current Integrity Output	Fuzzy Internal Condition Output	Fuzzy External Stress Output	Fuzzy External Corrosion Output	Fuzzy Inference Performance Output	Fuzzy Inference Performance Rating	Why the Fuzzy Rating?	WSSC Condition Score
Pipe 1	3.38	1.00	2.00	1.00	3.38	Fair	Structural Condition (C Factor, Remaining Thickness) Break Rate (Break, Break History, Defect Type)	3.57
Pipe 2	3.98	5.00	2.00	2.00	5.00	Very Poor	Internal Condition (Fire Flow)	5.00
Pipe 3	3.00	1.00	1.00	2.00	3.00	Fair	Break Rate (Break, Break History, Defect Type)	3.17
Pipe 4	4.00	5.00	1.00	2.00	5.00	Very Poor	Structural Condition (Tuberculation) Internal Condition (Fire Flow)	5.00
Pipe 5	4.38	1.00	1.00	2.00	4.38	Poor	Break Rate (Break, Break History, Defect Type)	5.00
Pipe 6	3.00	1.00	1.00	2.00	3.00	Fair	Life Expectancy Structural Condition (C Factor, Remaining Thickness, Tuberculation)	3.08
Pipe 7	3.00	1.00	1.00	2.00	3.00	Fair	Life Expectancy Structural Condition (C Factor, Remaining Thickness, Tuberculation)	2.72
Pipe 8	1.40	1.00	1.00	2.00	1.98	Good	External Corrosion (Soil Corrosivity)	1.78
Pipe 9	1.40	1.00	2.00	2.00	1.98	Good	External Corrosion (Soil Corrosivity) External Stress (Live Load)	1.78
Pipe 10	3.00	1.00	1.00	2.00	3.00	Fair	Life Expectancy Structural Condition (C Factor, Remaining Thickness, Tuberculation)	3.61
Pipe 11	3.00	1.00	1.00	1.00	3.00	Fair	Break Rate (Break, Break History, Defect Type)	1.94
Pipe 12	4.00	1.00	1.00	1.00	4.00	Poor	Break Rate (Break, Break History, Defect Type)	3.61
Pipe 13	2.00	1.00	1.00	1.00	2.00	Good	Structural Condition (Remaining Thickness)	1.63
Pipe 14	4.00	5.00	1.00	2.00	5.00	Very Poor	Structural Condition (Tuberculation) Internal Condition (Fire Flow)	5.00

Table 34: Fuzzy Inference vs. WSSC Condition Model Cont.

Sample	Fuzzy Current Integrity Output	Fuzzy Internal Condition Output	Fuzzy External Stress Output	Fuzzy External Corrosion Output	Fuzzy Inference Performance Output	Fuzzy Inference Performance Rating	Why the Fuzzy Rating?	WSSC Condition Score
Pipe 15	4.00	5.00	1.00	2.00	5.00	Very Poor	Structural Condition (Tuberculation) Internal Condition (Fire Flow)	5.00
Pipe 16	4.60	5.00	1.00	2.00	4.80	Very Poor	Structural Condition (Tuberculation) Break Rate (Break, Break History, Defect Type) Internal Condition (Fire Flow)	5.00
Pipe 17	3.00	5.00	2.00	2.00	5.00	Very Poor	Internal Condition (Fire Flow)	5.00
Pipe 18	1.40	1.00	1.00	2.00	1.98	Good	External Corrosion (Soil Corrosivity)	1.73
Pipe 19	1.40	1.00	1.00	2.00	1.98	Good	External Corrosion (Soil Corrosivity)	1.73
Pipe 20	4.00	1.00	1.00	2.00	4.00	Poor	Structural Condition (Remaining Thickness, Tuberculation)	2.53
Pipe 21	4.00	1.00	1.00	2.00	4.00	Poor	Structural Condition (Remaining Thickness, Tuberculation)	1.71
Pipe 22	4.00	1.00	1.00	2.00	4.00	Poor	Structural Condition (C Factor, Remaining Thickness, Tuberculation)	4.11
Pipe 23	3.00	1.00	1.00	1.00	3.00	Fair	Structural Condition (C Factor, Remaining Thickness, Tuberculation)	4.44
Pipe 24	3.00	1.00	1.00	3.00	3.00	Fair	Structural Condition (C Factor, Remaining Thickness, Tuberculation)	3.00
Pipe 25	1.40	1.00	1.00	1.00	1.40	Good	Life Expectancy	1.32
Pipe 26	3.00	1.00	1.00	1.00	3.00	Fair	Break Rate (Break, Break History, Defect Type)	1.58
Pipe 27	1.40	1.00	1.00	1.00	1.40	Good	Life Expectancy	1.28

5.1.3 **Evaluation Based on Lab Test Data**

Testing based on artificial data and real utility field data successfully assessed the robustness of the developed fuzzy inference performance model; however, the model parameters are not entirely holistic in how they are quantified and truth beholds whether or not the model is predicting actual water pipe performance values found in the field. In order to assess a "real life" scenario, extracted samples were collected from the field and tested in the laboratory. The purpose of lab testing is to compare the remaining strength of the pipe with the predicted fuzzy inference performance value which analyzes the pipe before it is dug up. With the consideration of close to 30 pipe parameters, the fuzzy inference performance model does not consider obvious factors including crack and fractures; therefore, relating the models results to the remaining strength of the pipe with use of lab tests can help in strengthening the overall confidence level the model has when predicting pipe performance. Specifically, the WVWA provided several pipe samples which were acquired through valve replacement and are considered a good representation of the pipe segment. Overall, determining the materials mechanical properties is essential in analyzing the remaining structural state of the pipe.

There are two main loads which act on a buried pressurized pipe: internal and external. The internal loading is typically simulated in the lab using a bursting tensile test in which both ends of the pipe segment is capped and water pressure is applied till the pipe fails. This bursting tensile test can provide information on the tensile strength of the pipe. In contrast, the pipe strength for the external loading is examined using a ring bearing test for the rupture modulus which shows the resistance of the pipe due to the bending stresses.

The ring bearing test was chosen to assess the remaining strength of the pipe due to the simplicity of the test and monetary constraints. In particular, the tensile test requires that the samples be molded into "dog bone" specimens which are very costly. Limited to only the ring bearing test, the results will be constrained to only evaluating the stress demonstrated externally.

With use of the ring bearing test, the rupture modulus is calculated by

$$R = 0.954\frac{W\,(d+t_{avg})}{l_r {t_{ave}}^2} \tag{6}$$

where,

R is the rupture modulus (psi)
W is the breaking load (lbs)
d is the average inside diameter (in)
t_{avg} is the average thickness of the pipe (in)
l_r is the length of the ring (in)

Pipe standards can provide the original rupture modulus prior to installation of the pipe. By extracting a sample of the pipe and using the ring bearing test to determine the breaking load, the current rupture modulus can be calculated. Comparison of the original vs. the current rupture modulus determines the remaining strength of the pipe. The remaining strength can then be related to the current pipe condition. The percent of strength remaining categorized per pipe condition is shown in Table 35.

Table 35: Remaining Strength vs. Pipe Condition

Strength Remaining	**Condition Score**
100-90%	Excellent
90-75%	Good
50-75%	Fair
50-25%	Poor
25-0%	Very Poor

WVWA Testing

The testing procedure (ASA 1962; ASA 1962) requires that each of the pipe samples be cut to the length of 1.5 times its nominal diameter prior to testing. To represent the actual working condition, the sample is not cleaned prior to the test. The sample is then loaded in compression till failure between two bearing plates using a two-point loading system. Please note that standards require a three-point loading system using a “V” shaped steel board, but this was too costly. The ring was also fitted with a linear varying displacement transducer (LVDT).

The samples utilized for testing consisted of four 6” CI, 1” galvanized and a 2” galvanized pipe, which were exhumed from the WVWA utility during routine valve replacement. Testing of the CI pipelines consisted of loading the pipe sample to failure and using the maximum load which was applied during failure to calculate the rupture of modulus. Specifically, pipe 1 and 2 are from the same pipe segment but two different sections. One section is free from all cracks and fractures; while, the other one has a crack already developed. This scenario is the same for pipe 3 and 4. The two galvanized pipes were also tested; however, due to the physical characteristics of this material, the samples failed to rupture. DI and galvanized pipes are both flexible materials in which this specific test is not applicable since the pipe will fail to crack and/or fracture under loading. On the contrary, CI is a very brittle material, in which the ring bearing test is capable of calculating the rupture of modulus. A table illustrating each of the pipe samples and their parameters are shown in Table 36.

Table 36: WVWA Lab Testing Samples

Parameters	***Unit***	**Pipe 1**	**Pipe 2**	**Pipe 3**	**Pipe 4**	**Pipe 5**	**Pipe 6**
Diameter	*in*	6	6	6	6	1	2
Age	*year*	121	121	121	121	62	55
Design Life	*year*	120	120	120	120	50	50
Vintage	*year*	1891	1891	1891	1891	1950	1957
Rehab (Lining)	*yes/no*	No	No	No	No	No	No
C Factor	*c factor*	75	75	75	75	50	50
Remaining Thickness	*percent*	100	100	100	100	50	100
Tuberculation	*level*	None	None	None	None	Moderate	Light
Leak	*yes/no*	No	No	No	No	Yes	No
Pipe Break	*yes/no*	Yes	Yes	Yes	Yes	Yes	Yes
Break <5 Years Ago	*yes/no*	Yes	Yes	Yes	Yes	Yes	Yes
Defect Type	*type*	N/A	Severe	N/A	Severe	Extreme	Mild
R/R	*type*	N/A	None	N/A	None	None	Segment
Pressure Class Exceeded	*occasion*	Never	Never	Never	Never	Never	Never
Pressure Surges	*occasion*	Never	Never	Never	Never	Never	Never
Adequate Fire Flow	*yes/no*	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	*yes/no*	No	No	No	No	No	No
Discolored Water	*yes/no*	No	No	No	No	No	No
Disturbances	*yes/no*	No	No	No	No	No	No
Flooding	*occasion*	Never	Never	Never	Never	Never	Never
Live Load	*road type*	NonNHS	NonNHS	NonNHS	NonNHS	NonNHS	NonNHS
Material Type	*type*	CI	CI	CI	CI	GAL	GAL
Dissimilar Metals	*yes/no*	No	No	No	No	No	No
Cathodic Protection	*yes/no*	No	No	No	No	No	No
Stray Currents	*yes/no*	No	No	No	No	No	No
Soil Corrosivity	*level*	Moderate	Moderate	Moderate	Moderate	Low	Low
Coating	*yes/no*	No	No	No	No	No	No

Results

The calculated modulus of rupture for each test was compared to its original modulus of rupture to determine the remaining strength. As documented by Seica, M. et al (2002), the original modulus of rupture for the 6” CI main, roughly 90 years old, is 34,954 psi. The American Standards Association (ASA) standards (ASA 1962; ASA 1962) did not start publishing the rupture modulus for CI pipelines until 1962; therefore, since the CI test samples are 121 years old, the original modulus of rupture was taken from Seica.

Results of the calculated rupture modulus, remaining strength and condition score found through lab testing can be compared to the performance rating calculated by the fuzzy inference prediction model. Overall, the condition score found through lab testing should be close to the performance rating found through the fuzzy inference model. A table showing the test and model results are shown in Table 37. Also, before and after photos of the test specimens are shown in Figure 21.

Table 37: Lab Test and Fuzzy Inference Model Results

Pipe	Rupture Modulus (psi)	Remaining Strength (%)	Condition Score	Fuzzy Inference Performance Value	Fuzzy Inference Performance Rating
1	23,901	68	Fair	3.32	Fair
2	6,900	20	Very Poor	4.88	Very Poor
3	22,191	63	Fair	3.32	Fair
4	12,955	37	Poor	4.88	Very Poor
5	---	---	---	4.78	Very Poor
6	---	---	---	4.56	Very Poor

The calculated rupture modulus results from the ring bearing test show that the remaining strength of pipe 1 is 68% which is correlated with a “Fair” condition score; while the fuzzy inference performance model predicted a 3.32 value corresponding to a “Fair” performance rating. Specifically, the fuzzy inference performance rating is the value predicted based on age and other factors before the pipe is extracted; while the condition score found through the rupture modulus is the actual physical remaining strength of the pipe.

Evaluating the other cracked section of the initial pipe segment, pipe 2, it is shown that the remaining strength of the pipe is 20% which is correlated to a “Very Poor” condition score; while the fuzzy inference performance model predicted the cracked pipe segment to be a value of

4.88 corresponding to a “Very Poor” performance rating. Pipes 1 and 2 are very similar to pipes 3 and 4 as the remaining strength of pipe 3 is 63% a “Fair” condition score in comparison to a predicted 3.32 value which is a “Fair” performance rating and pipe 4 has a remaining strength of 37% which is a “Poor” condition score in comparison to the predicted 4.88 value of “Very Poor” performance. These results illustrate that the fuzzy inference performance model results are consistent with the pipes modulus of rupture and is capable of predicting realistic performance ratings.

Contrary to the CI pipe samples, the rupture modulus results for the galvanized pipe samples 5 and 6 were not obtained due to the physical characteristics of the pipe. By physically evaluating pipe 5, a hole in the pipe wall was visible which was most likely due to corrosion. Therefore, it can be said that based on a visual inspection this pipe is failed or “Very Poor”. The fuzzy inference performance value for pipe 5 was 4.78 which is also a “Very Poor” rating, showing the performance index is predicting values highly correlated to the actual pipe condition. Pipe 6 on the other hand did not show forms of corrosion or reduced wall thickness. The fuzzy inference performance value for this sample was 4.56 having a “Very Poor” rating. The performance rating of pipe 6 is representative of the actual condition considering the age of the pipe is past the design life and the pipe has a Hazen Williams C factor of 50. From the picture in Figure 21 it is also shown that the pipe has mild tuberculation.

The ring bearing test illustrates that the calculated rupture modulus can be related to the remaining physical strength of the pipe. Results determined that the condition score predicted from the remaining pipe strength were in good relation to the performance ratings predicted by the fuzzy inference model. As illustrated, the ring bearing test is only applicable for brittle materials such as CI pipes and cannot be used to test more flexible pipes such as DI and galvanized pipes. Since a large portion of the buried water pipeline infrastructure is CI pipes, it is concluded that this test justified the testing of only CI pipes. Due to the limited samples and money constraints, testing was limited to a small sample size and the ring bearing test. In the future, more samples, varying tests and differing pipe materials should be tested to evaluate every performance level; however, this may be difficult as utilities typically only remove pipe that is in “Poor” or “Very Poor” condition. Also, since DI was one of the most recent installed material types, samples may be challenging to obtain since many DI pipes are still in “Excellent” and “Good” condition.

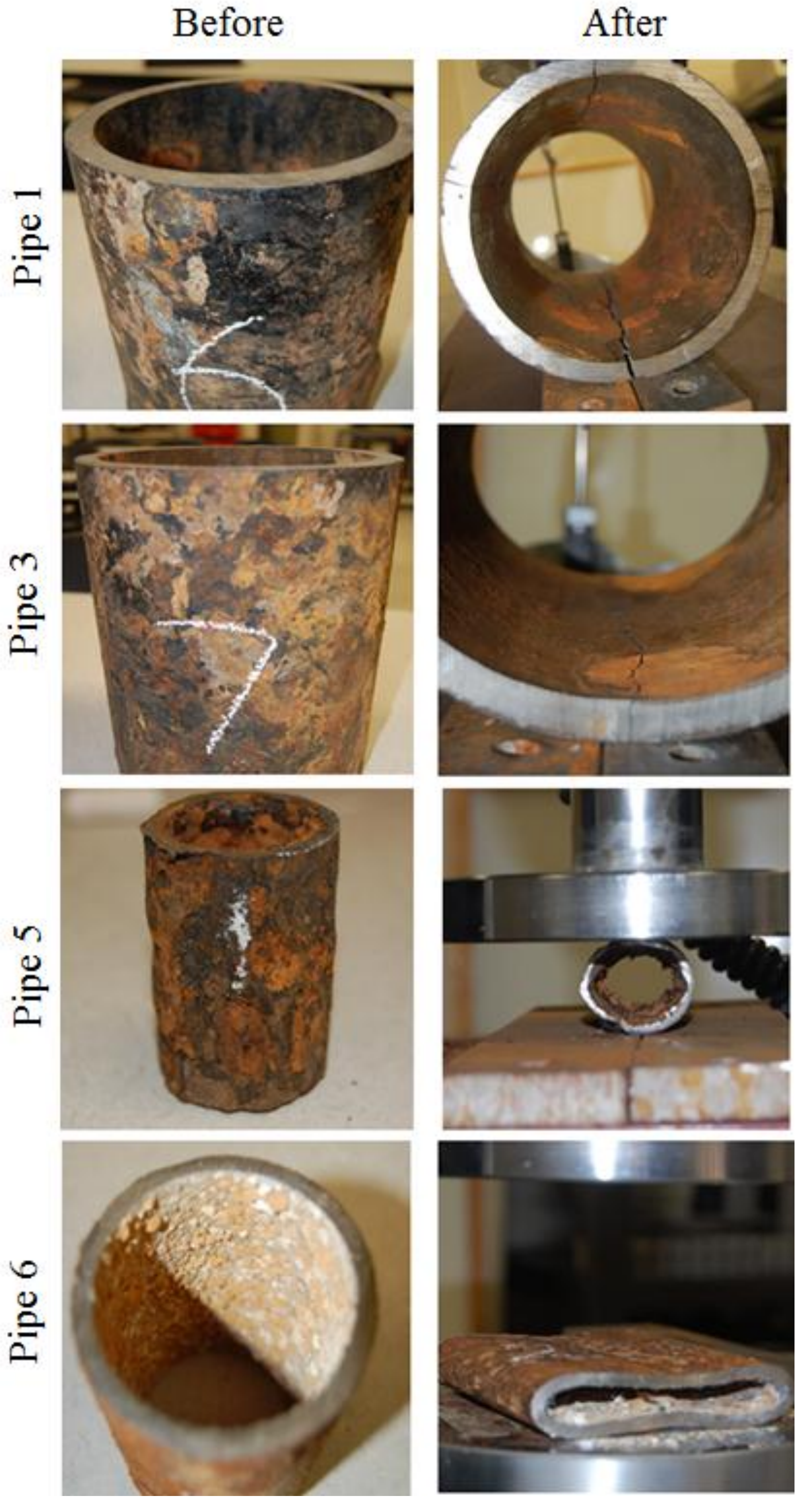


Figure 21: Lab Specimens

5.1.4 **Evaluation Summary**

The evaluation process consisted of analyzing artificial, field and laboratory data. Artificial data was specifically used in the model development stages to see if the models output was relational to the inputs provided. This evaluation based on artificial data provided the initial level of confidence of the developed model and determined the most influential parameters controlling the pipe performance rating. During this time utility and expert opinions also assisted in providing critical engineering judgment in the development of the model.

Utility field data was then used to evaluate the model which gave utilities a confidence in applying the model to their own database. It was shown that in order for a utility to adopt the fuzzy inference performance model one needs to

1. Collect and organize all input parameters per required unit
2. Input parameters per pipe section
3. Run model to determine performance results
4. Analyze performance rating in terms of prioritizing future inspection and R,R&R

Comparison of the existing utility condition model also provided a sense of reliability that the developed fuzzy inference performance model has over previously existing models. The field data evaluation provided utilities with the level of confidence that the fuzzy inference model has in predicting the pipe performance. Specifically, the field implementation has led to the utilities collecting more data during field installation and R,R&R and evaluating the fuzzy inference model as their future pipe performance prediction tool.

Lastly, limited lab testing was used to strengthen the model by relating the predicted performance rating to the remaining physical pipe strength. In detail, a ring bearing test was used to determine the rupture modulus of the extracted samples. The lab analysis concluded to be of good practice; however, a much more thorough lab analysis is needed in order to validate the model. Specifically a large range of diameter sizes, materials and varying condition states should be presented. By evaluating pipes with differing condition states, the engineering judgment used to correlate the remaining strength found through the rupture modulus to the condition score can be further refined. Various other testing methods should also be evaluated, which can determine properties such as the stress due to internal pressure which is found through tensile testing.

Overall, evaluating the performance prediction model based on three different levels of data has illustrated the reliability of the developed model. Due to monetary and time constraints it is impossible to physically dig up every pipe to determine its condition. As a result models are used to evaluate the pipe performance based on the existing utility database. There are many models used in condition evaluation and prediction, risk analysis and renewal prioritization of drinking water pipelines; however, most of these models have accuracy and reliability problems. Previous models also do not consider an extensive amount of parameters and are used to only evaluate the pipe condition; however, in order to achieve a valued performance model all determining factors must be considered which measures the pipe performance level. Specifically, parameters included in this model which assess the pipe performance level include previous breaks, break year, break defect type, break rehab type, adequate fire flows, discolored water issues and pressure complaints. Overall, this research has led to the ground foundation for pipe performance data collection, a fuzzy inference model incorporating a large array of input data variables and a solid ground for future performance model validation. Specifically, any future condition/performance model can build from the evaluation provided in this research to validate their model.

In conclusion, utilities will use this developed performance model based on that it includes an extensive amount of parameters, utilizes simple if/then rule statement that utility personnel can appreciate, is practical for establishing an asset management plan and it has been previously applied to real-life scenarios. The evaluation framework also proved the accuracy of the developed performance model which provided a confidence level to utilities. Overall, utilities which acquire this model will be able to identify potential problem areas in where future inspection needs to take place in order to assess the correct R,R&R method.

5.2 Water Pipeline Deterioration Prediction

Accurate prediction of pipeline deterioration is essential in estimating the pipeline performance over time, as it plays a significant role in asset management and investment planning. Utilizing the pipeline performance values generated through the performance index presented in the previous chapter, the estimation of pipeline deterioration curves for various subgroups can be forecasted. Specifically, a Markov Chain approach is presented to aid in the prediction of the deterioration curves. This approach has been widely accepted in predicting the deterioration of various infrastructure assets such as pavements (Butt 1987; Carnahan 1987), bridges (Jiang 1988) and sewer systems (Wirahadikusumah 2001; Baik 2003; Sinha 2007; Park 2009).

5.2.1 Markov Chain-Based Deterioration Model

A Markov chain is a stochastic process that was initially documented in 1906 by A. Markov (Ching 2006). A stochastic process is said to characterize a Markov chain, if the random process takes on a Markov property which is the conditional probability that any future event is dependent only on the current state and is independent of all past states. The Markovian property is expressed as

$$P(X_{t+1} = i_{t+1} | X_t = i_t, X_{t-1} = i_{t-1}, \dots, X_1 = i_1,\ X_0 = i_0) = P(X_{t+1} = i_{t+1} | X_t = i_t) \qquad (7)$$

where,
i_t is the state at time *t*
P is the conditional probability

The probability that state *i* at time (*t)* will change to state *j* at time *(t+1)* is termed a transition probability expressed as

$$P(X_{t+1} = j | X_t = i) = p_{ij} \qquad (8)$$

where,
i, j are states
t is time
p_{ij} is the transition probability

The term *transition* is coined when the asset performance moves from state *i*, during one period, to state *j*, during the next period. As formerly presented, a water pipeline asset can have one of five performance levels or in this case “states”. The theory of transition from one state to another and possible transition probabilities for each of the five states is shown in Figure 22. In this case, each state can have a total of five transition probabilities consisting of the probability of staying in the same state, probability of changing from one state to the next state or the probability of skipping numerous states.

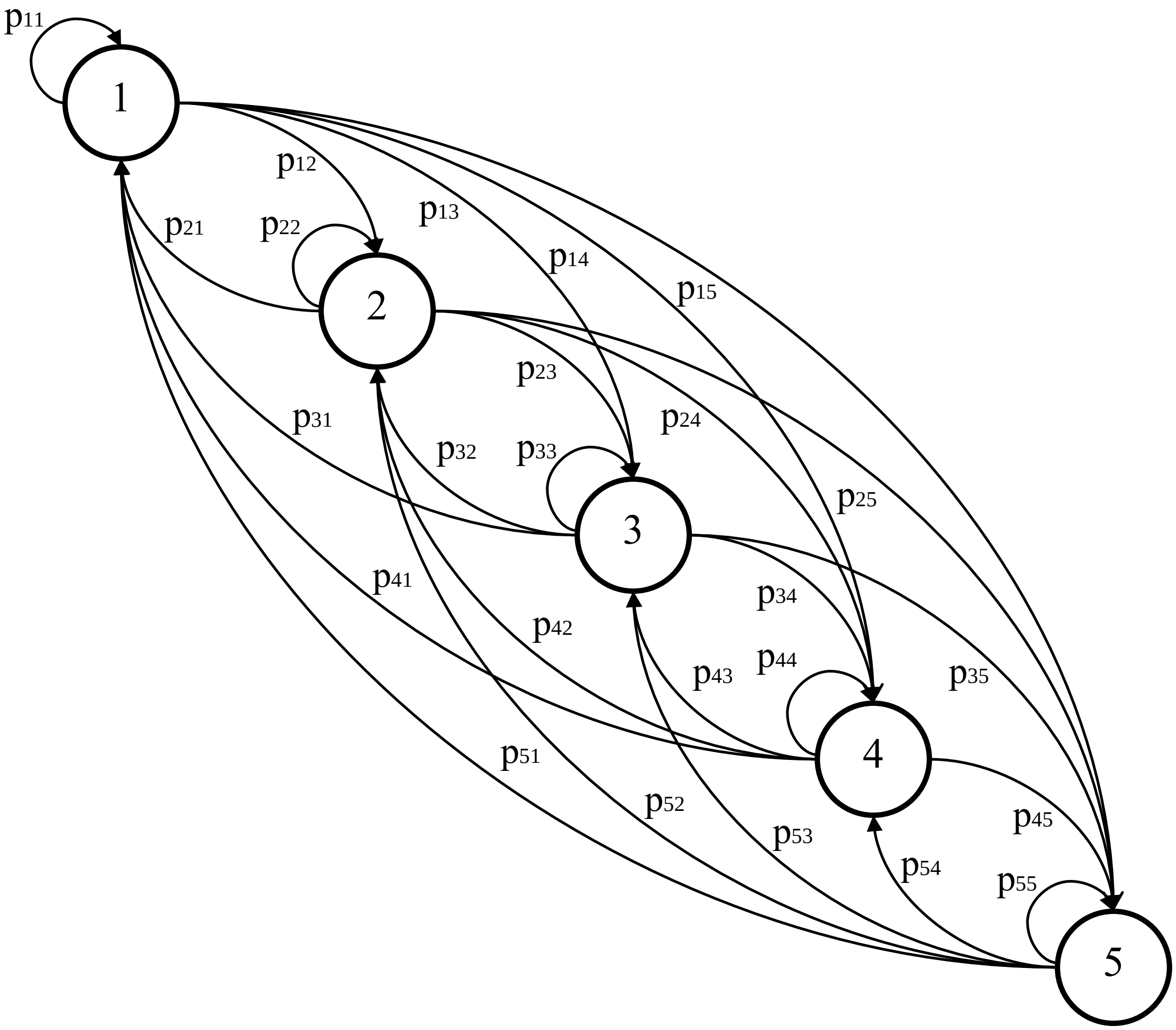


Figure 22: Markov Chain Model

Transition probabilities are often represented in the form of an *m x m* matrix. The probability that the assets performance will move from state *i* to state *j* is expressed in transition probability matrix as

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdot\cdot & p_{1m} \\ p_{21} & p_{22} & \cdot\cdot & p_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m1} & p_{m2} & \cdot\cdot & p_{mm} \end{bmatrix} \tag{9}$$

$$\sum_{j=1}^{m} P_{ij} = 1, for\ i = 1, 2, \dots, m \tag{10}$$

where,
m is the number of performance states
p_{ij} is the transition probability from state *i* to state *j*
P is the transition probability matrix

The probability that state *i* will move to state *j* after *n* periods is represented by $p_{ij}{}^{(n)}$ or the *n*-step transition probability. Based on the Chapman-Kolmogorov equation, the *n*-step transition probability matrix is

$$P^{(n)} = \underbrace{P \times P \times \dots \times P}_{n\ times} \tag{11}$$

where,
n is the number of transitions
P is the transition probability matrix
$P^{(n)}$ is the n-step transition probability matrix

5.2.2 **Transition Probability Estimation**

A nonlinear optimization base approach was proposed in the estimation of the transition probabilities. Theoretically, the estimation of the transition probability matrix is determined by minimizing the sum of the absolute difference between the expected values forecasted by regression analysis and the theoretical value determined by the Markov chain model. Previous authors have also used this technique to formulate the transition probabilities of Markov models such as in pavements (Butt 1987; Carnahan 1987), bridges (Jiang 1988) and sewer systems (Wirahadikusumah 2001; Baik 2003; Sinha 2007; Park 2009).

In developing deterioration curves, it is imperative to select several subgroups of data in order to evaluate the effects of various factors, such as pipe material, diameter, soil corrosivity, etc., have on the overall pipe performance. Subsequently, each subgroup is fitted utilizing regression analysis to determine the relationship between the performance rating and age. Estimates of the Markov chain transition probabilities for each subgroup is then determined through a nonlinear optimization technique. To avoid the assumption that the deterioration of infrastructure assets has a constant transition period over its life span, a zoning concept is introduced in where the life of the asset is defined by several zones. Overall, the nonlinear optimization technique used in the estimation of the transition probabilities of the Markov chain model is

$$Minimize \sum_{t=1}^{N} |Y(t) - E(t, P)| \tag{12}$$

Subject to $0 \leq p_{ij} \leq 1$; $i, j = 1, 2, \ldots, m$

where,
N is the number of transition periods in a zone
t is the age of the asset
Y(t) is average performance rating at age *t* determined by regression analysis
E(t, P) is the expected value of the performance at time *t* based on Markov chain model
p_{ij} is the transition probability from state *i* to state *j*
m is the number of performance states

In detail, the expected performance value based on the Markov chain model, *E(t, P)*, is

$$E(t,P) = Q^{(n)}S^T = Q^{(0)}P^{(n)}S^T \tag{13}$$

where,
$Q^{(0)}$ is the initial performance vector at stage 0
$Q^{(n)}$ is the performance vector at stage n
$P^{(n)}$ is the probability matrix after n transitions
S^T is the transpose of the performance rating vector S

5.2.3 **Deterioration Prediction Results**

To illustrate the use of the Markovian based deterioration model, WVWA performance ratings developed from the fuzzy inference model were utilized. The data set was divided into subsets based on the location of the pipe, pipe material type, diameter, live load and soil corrosivity level. In order to establish the relationship between the performance rating and the age of the pipe, regression analyses were performed per data set. The first example considers 3" CI pipe within the WVWA zone titled "Gravity" located under a non-NHS with a low soil corrosivity level. The estimated relationship between the performance rating and age based on regression analysis for a 3" CI pipe in this particular area is

$$Y(t) = \exp(1.13868 + 0.00929t) - 1.89939 \tag{14}$$

where,
t = age

The regression model given forms the basis for the estimation of the transition probabilities of the Markov chain based deterioration model. The transitions are specifically represented by a 5 x 5 probability matrix, representing the one of five performance states. To account for the tendency that older water mains deteriorate at a faster rate than newer mains, a zoning concept is applied (Wirahadikusumah 2001). A zone is a period of time that is assumed to produce a constant transition probability, which in this case study was considered as a five year zone. An added advantage of the zoning concept makes for the complex computation to be reasonably manageable.

The transition probabilities are estimated using a nonlinear optimization technique. The function given in Equation 12 essentially minimizes the sum of the absolute difference of the expected values between the regression model and the Markov chain model. Using this nonlinear optimization technique, the first zone is expressed as

$$\begin{aligned}
&Minimize\left|e^{1.13868+0.00929*1}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(1)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*2}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(2)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*3}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(3)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*4}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(4)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*5}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}[1\ 2\ 3\ 4\ 5]^T\right|
\end{aligned} \qquad (15)$$

The transition probabilities for the second zone are estimated by substituting the first zone transition probabilities, $Q_o P_1^{(5)}$, for the initial state vector, Q_1.

$$\begin{aligned}
&Minimize\left|e^{1.13868+0.00929*6}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}P_2^{(1)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*7}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}P_2^{(2)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*8}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}P_2^{(3)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*9}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}P_2^{(4)}[1\ 2\ 3\ 4\ 5]^T\right|+\\
&Minimize\left|e^{1.13868+0.00929*10}-1.89939-[1\ 0\ 0\ 0\ 0]P_1^{(5)}P_2^{(5)}[1\ 2\ 3\ 4\ 5]^T\right|
\end{aligned} \qquad (16)$$

Optimizing the nonlinear equation for each zone, transition probabilities are estimated as shown in Table 38.

Table 38: 3” CI Transition Probabilities

Zone	***P***	P_{11}	P_{22}	P_{33}	P_{44}	P_{55}
1	P_{1} (1)	0.9008	1.0000	1.0000	0.0000	1.0000
2	P_{2} (1)	1.0000	0.9632	0.4694	0.0000	1.0000
3	P_{3} (1)	0.7217	1.0000	1.0000	0.0000	1.0000
4	P_{4} (1)	1.0000	0.9956	0.4884	0.0000	1.0000
5	P_{5} (1)	0.1041	0.9988	0.9946	0.0000	1.0000
6	P_{6} (1)	0.0013	0.9501	1.0000	0.0000	1.0000
7	P_{7} (1)	0.0000	0.9327	1.0000	1.0000	1.0000
8	P_{8} (1)	0.0000	0.8596	1.0000	0.8929	1.0000
9	P_{9} (1)	0.0000	0.7639	1.0000	1.0000	1.0000
10	P_{10} (1)	0.0000	1.0000	0.8025	1.0000	1.0000
11	P_{11} (1)	0.0000	0.0000	0.9055	1.0000	1.0000
12	P_{12} (1)	0.0000	0.0000	0.9034	1.0000	1.0000
13	P_{13} (1)	0.0000	0.0000	0.7350	1.0000	1.0000
14	P_{14} (1)	0.0000	0.0000	1.0000	0.7266	1.0000
15	P_{15} (1)	0.0000	0.0000	0.0000	0.8835	1.0000
16	P_{16} (1)	0.0000	0.0000	0.0000	0.8354	1.0000
17	P_{17} (1)	0.0000	0.0000	0.0000	0.5491	1.0000
18	P_{18} (1)	0.0000	0.0000	0.0000	0.0000	1.0000

Based on the calculated transition probabilities, the Markov chain model predicts that the expected useful life of the 3” CI pipe from the WVWA “Gravity” zone under a non-NHS with a low soil corrosivity level is 90 years as shown by the deterioration curve in Figure 23. As illustrated the deterioration rate is low at the beginning of the useful life and then increases as the pipe ages. Please note that this curve is not developed based on time dependent data.

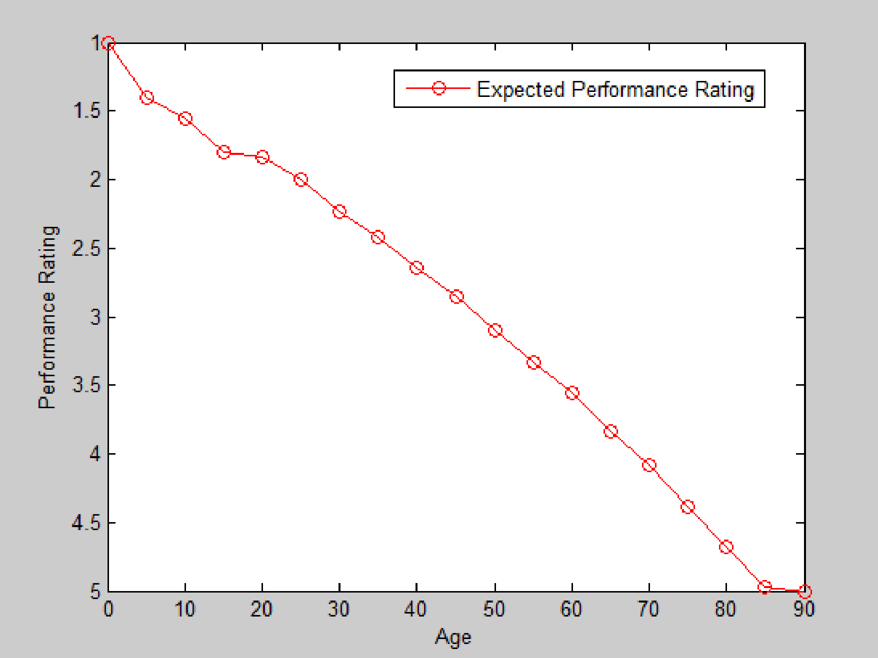


Figure 23: Markov Deterioration Curve for 3” CI Pipe

Considering that no rehabilitation of this pipe has taken place, the expected performance for the 3” CI water mains in the WVWA “Gravity” zone under a non-NHS with a low corrosivity level after 25 years is estimated as

$$
\begin{aligned}
\text{25 Year Expected Performance} &= [1\ 0\ 0\ 0\ 0]P_4^{(5)}P_5^{(5)}[1\ 2\ 3\ 4\ 5]^T \\
&= [1.22E^{-5}\ 0.990\ \ 0.004\ 1.82E^{-5}\ 1.76E^{-5}][1\ 2\ 3\ 4\ 5]^T \\
&= \ 2.0045 \qquad (17)
\end{aligned}
$$

where,

$P_4^{(5)}$ is the transition probability after 20 years

$P_5^{(5)}$ is the transition probability after 25 years

The 3” CI water pipeline performance value after 25 years is expected to drop to about 2. The probability of the performance level 2 is 0.990. The probability of this water pipeline dropping to a performance level of 3, 4 and 5 are 0.004, 1.82E-05, 1.76E-05, which are almost close to zero is unlikely. It is also infeasible for the pipeline condition to increase to 1, whose probability is 1.22E-05. Similarly, performance values at different years can be calculated.

In order to compare the deterioration curves of various subgroups, a second example considered 16” DI pipe within the WVWA zone titled “Gravity” also located under a non-NHS with a low to moderate soil corrosivity level. The estimated relationship between the performance rating and age based on regression analysis for a 16” DI pipe in this particular area is

$$Y(t) = \exp(0.22081 + 0.01354t) - 0.08677 \tag{18}$$

where,
t = age

Using this estimated relationship based on regression analysis, the transition probabilities utilizing the non-linear optimization technique are estimated for the 16” DI pipe as shown in Table 39. Unlike the 3” CI water mains which predicted a lifetime of 90 years, the Markov chain model based on the estimated transition probabilities predicts the expected useful life of the 16” DI pipe is 110 years, as shown by the deterioration curve in Figure 24. Due to the inherent makeup of the material, CI pipes typically have a shorter lifespan than DI pipes. Furthermore, larger diameter pipelines have a greater cross sectional area than smaller diameter pipelines which make the pipes less susceptible to radial loading from various traffic loads or disturbances leading to a greater life expectancy.

Table 39: 16” DI Transition Probabilities

Zone	***P***	***P11***	***P22***	***P33***	***P44***	***P55***
1	***P1 (1)***	0.9368	1.0000	1.0000	0.0000	1.0000
2	***P2 (1)***	1.0000	0.9739	0.4711	0.0000	1.0000
3	***P3 (1)***	0.8725	1.0000	1.0000	0.0000	1.0000
4	***P4 (1)***	1.0000	0.9895	0.4756	0.0000	1.0000
5	***P5 (1)***	0.7269	1.0000	1.0000	0.0000	1.0000
6	***P6 (1)***	1.0000	1.0000	1.0000	0.0000	1.0000
7	***P7 (1)***	0.1892	1.0000	1.0000	1.0000	1.0000
8	***P8 (1)***	0.0196	0.9966	0.2844	0.0708	1.0000
9	***P9 (1)***	0.0000	0.9601	1.0000	1.0000	1.0000
10	***P10 (1)***	0.0000	0.9408	1.0000	1.0000	1.0000
11	***P11 (1)***	0.0000	0.8920	1.0000	1.0000	1.0000
12	***P12 (1)***	0.0000	0.8221	1.0000	0.9670	1.0000
13	***P13 (1)***	0.0000	0.7052	1.0000	1.0000	1.0000
14	***P14 (1)***	0.0000	0.3644	0.9816	0.6240	1.0000
15	***P15 (1)***	0.0000	0.0422	0.9258	1.0000	1.0000
16	***P16 (1)***	0.0000	0.0000	0.8681	1.0000	1.0000
17	***P17 (1)***	0.0000	0.0000	0.7257	1.0000	1.0000
18	***P18 (1)***	0.0000	0.0000	0.2748	0.9772	1.0000
19	***P19 (1)***	0.0000	0.0000	0.0000	0.9002	1.0000
20	***P20 (1)***	0.0000	0.0000	0.0000	0.7810	1.0000
21	***P21 (1)***	0.0000	0.0000	0.0000	0.3133	1.0000
22	***P22 (1)***	0.0000	0.0000	0.0000	0.0000	1.0000

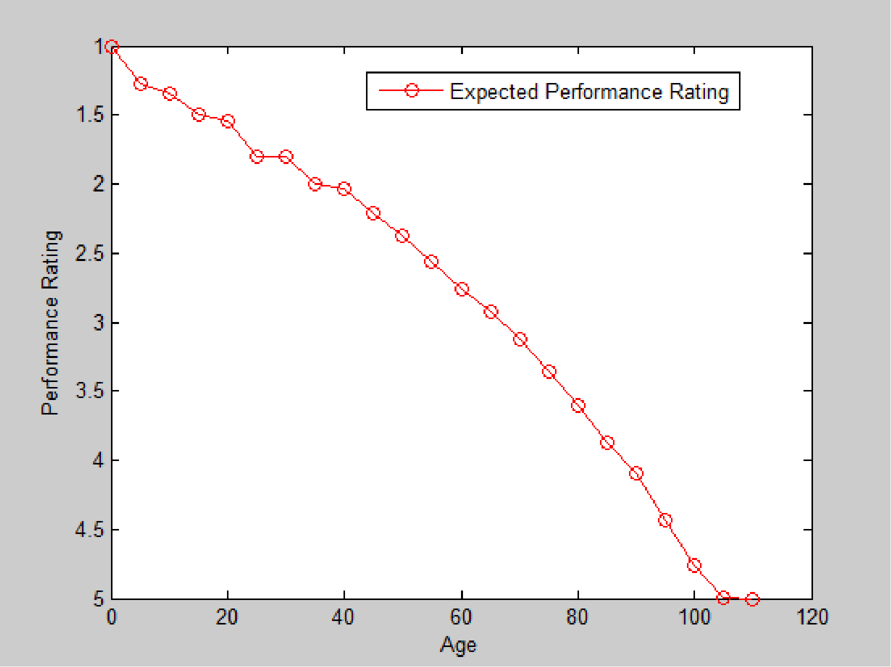


Figure 24: Markov Deterioration Curve for 16” DI Pipe

Evaluation of the predicted deterioration curve can be compared to real life utility scenarios to aid in scheduling future pipe interventions and the selection of the best R,R&R technique given the situation. The above deterioration curves illustrate the degradation of the pipe with age, if no repair or rehabilitation takes place. If no future R,R&R of the pipe is scheduled the pipe will run to failure in where replacement of the pipeline is the only option. In many instances, for example large diameter pipelines, optimizing the correct time for R,R&R of a pipeline is cheaper than letting the pipe run to failure. Also in most cases the larger diameter pipes cannot be run to failure due to their greater risk of consequence if pipe failure occurs. In these special instances utilities can optimize a time when future R,R&R should be scheduled as well as chose the best R,R&R technique.

As illustrated in Figures 23 and 24, the deterioration curves were specifically developed and estimated based on 3” CI pipes under a non-NHS with a low soil corrosivity level and 16” DI pipes under a non-NHS with a low to moderate soil corrosivity level for the WVWA zone classified as “Gravity”. This same process is applicable to be utilized to determine further deterioration curves for the various other subgroups created. Other subgroups may consist of analyzing the effect of various material types, vintage, diameter, soil corrosivity, locations, etc. Each subgroup will yield different transition probabilities and a deterioration curve based on the previously established Equation 12.

Assessing the water pipeline deterioration curves is essential in gauging the performance of these underground systems. This specific methodology has been widely utilized to estimate the deterioration of other infrastructure types such as sewers, bridges and pavements. Further analysis would determine the deterioration characterization of the various other subsets within this infrastructure system. Comparison of these curves can aid in the understanding of the various pipe attributes and their environment in relation of how the performance rating will change with age. Overall, future model verification and validation of these deterioration curves is essential to be of aid in scheduling future pipe interventions and selection of the best R,R&R technique.

6 Conclusions and Limitations

The conclusions and limitations of the fuzzy inference performance model and Markov chain deterioration model are summarized in the following paragraphs.

6.1 Conclusions

A performance model based on a fuzzy inference methodology was developed in this study for the performance estimation of metallic drinking water infrastructure assets for non-scaling water. Overall, there are significant challenges associated with predicting the remaining economic life of water pipeline infrastructure system which include the methodology used to develop a pipeline prediction model and the parameters considered. A number of mathematical models were reviewed in the literature; however, there were gaps between available mathematical models and current utility practice in predicting water pipe condition and failure. Limitations in the previous model capabilities and complexity in analysis led to selecting the fuzzy inference methodology.

In the development of the fuzzy inference performance model, the evaluation of the various pipe material types, life cycle and failure modes and mechanisms were identified. Also a data structure entailing over 100 pipe parameters which affect the overall pipe performance was detailed. Overall, a fundamental understanding of drinking water pipeline infrastructure systems was accomplished which led to the development of a weighted factor and fuzzy inference model to prioritize and predict the performance of drinking water pipelines. Particularly, the weighted factor methodology was an introductory model which was limited to binary sets; while the fuzzy inference methodology allowed for the incorporation of engineering judgment in fuzzy sets to predict infrastructure performance with the limited historical database. Infrastructure systems were also described linguistically, with the fuzzy inference methodology, through if-then rule statements which enabled significant parameters to be interpreted in the overall resultant. Challenges existed in constructing a fuzzy rule set, selecting a membership function and determining the defuzzification process.

An extensive evaluation process of the developed fuzzy inference performance index included analysis of artificial, field and lab data. In particular, the artificial evaluation process helped to develop the fuzzy inference performance prediction model through sample data input. The outputs were then analyzed to determine if further model refinement was needed. This process also allowed for utility and expert opinions to be acquired. The fuzzy inference performance model was then piloted utilizing the WVWA and WSSC utilities, illustrating the applicability of the model to current utility practice. An existing WSSC condition model score was also used to compare the resultant fuzzy inference performance output value. Lastly, the evaluation process successfully compared the modulus of rupture laboratory test results to the predicted performance value.

Overall, the evaluation process proved that the developed fuzzy inference performance index provides a user friendly prediction model in which utilities can confidently apply to their own water infrastructure system. In order to validate the model, a much more thorough lab analysis evaluating the various pipe material types, differing performance levels and testing methods needs to be established. The main limitation of using a performance model exists in the reliability of the input data. If the input data going into the model is sub-satisfactory, the capability of successful model predictability goes down.

Furthermore, a Markov chain based deterioration model was presented that provided a method used in characterizing the overall lifetime of a water main through deterioration curves. The deterioration curves are not based on time dependent data, but rather a Markov chain methodology coupled with a non-linear optimization technique. Specifically, the performance index results calculated by the fuzzy inference model were grouped in subsets and regression analysis was performed to determine the relationship between the performance rating and age. The estimation of the transition probabilities were then determined by minimizing the sum of the absolute difference between the expected values forecasted by regression analysis and the theoretical value determined by the Markov chain model. In conclusion, these deterioration curve assessments can be essential in gauging and predicting the future performance of various subsets of underground systems.

Overall, a fuzzy inference performance model and Markov based-deterioration curves were successfully developed to aid in evaluation of our current drinking water infrastructure systems. The combination of the fuzzy inference performance model and the Markov chain based deterioration model can be utilized to help utilities estimate the overall lifetime of their infrastructure. In addition, these models can be incorporated with an infrastructure management plan to help prioritize the future inspection and R,R&R of water mains.

6.2 Limitations

Highlighted below are the limitations of the developed fuzzy inference performance model and the Markov chain based deterioration model.

- The model can only predict the performance of metallic pipelines.
- The parameters considered are limited to the range of data available.
- The performance model can only predict the overall performance as good as the reliability of input data going into the model.

- The way data or parameters are characterized may vary from utility to another.
- Critical parameters, pertaining to the utility geographic location is not taken into consideration. An example is tidal influences in coastal areas.
- The performance model does not consider parameters owing to internal corrosion.
- The performance model is developed only for non-scaling drinking water.
- Qualitative parameters force whole numbers in the fuzzy inference methodology and therefore provide limited variability in the output.
- Similar input values, in the fuzzy inference model, acquired throughout the infrastructure system cannot predict output variability.
- All parameters must be given an input value, even if the parameter value is not known.
- The fuzzy inference model is not capable of learning with time.
- The fuzzy inference performance model can only predict the overall performance based on the relationship of the parameters inputs with their outputs which is governed by engineering knowledge.
- The Markov deterioration curve is dependent on the performance rating predicted from the fuzzy inference model; therefore, the reliability of the deterioration curve is only as good as the data used to determine the performance rating.
- The Markov deterioration curves are not based on time dependent data.
- Deterioration curves are governed by the number of pipe sections within a particular defined subset.
- Deterioration curves are only an estimation of a defined subset and may not resemble each pipe section exactly due to varying installation methods and other inhibiting factors which play a role in the pipe performance.

7 Future Recommendations

The main focus of this research was to develop a fuzzy inference performance index and a deterioration prediction model that can be utilized for future pipeline asset management. Further evaluation and validation of the developed models will lead to advanced performance and deterioration estimation. Although there are limitations to the developed model, this research has laid a ground foundation and has paved the way for future advanced models and validation.

Currently, the developed performance index is for metallic pipelines only, which include DI, CI, steel/galvanized steel and copper pipelines. However, other material types such as PCCP, AC, PVC and PE are also installed and are functioning in today's current infrastructure. In future development models, every material type should be considered.

One of the limitations of the current developed model is the number and complexity of the input parameters considered. Specifically, the parameters in this research were limited to a range of data available. Effects of critical parameters, such as tidal influences in coastal areas, were not investigated due to the lack of variability in the utility datasets which was relied on for the development of this model. The way data and/or parameters are characterized varies between utilities and this variability creates limitations while considering these parameters.

A nationwide standardized database should be established prior to the development of future models. This national standardized database would aid researchers to better understand water pipeline performance in several ways. In detail, the database would advance the knowledge of pipeline performance data aggregation from multiple data sources. This database would not only be helpful to standardize and accumulate the performance parameters from various water utilities, but also could be utilized to acquire valuable data from other spatial datasets such as soil properties, water table, loading, geology and land cover. This national database would be used to analyze and visualize the accumulated data for further improving the understanding of the state of buried water pipeline infrastructure, its failure rates, the general effectiveness of corrosion control measures and other key parameters for the development of future models.

Eventually, with enough data accumulation, the limitations produced by the lack of time dependent data could be minimized. The actual time dependent data can be acquired from different sources and the gaps in the data can be filled by analyzing the standardized data further. This time dependent data analysis will aid in defining additional parameters and the incorporation of more detailed parameters for future models. In addition, an internal corrosion module should be included and specific parameter ranges promoting internal corrosion shall be incorporated. Specifically, the time dependent data pertaining to external and internal corrosion shall be used to define additional parameters for future models. Moreover, the effectiveness of the coatings used for corrosion mitigation should be investigated with time dependent data.

Parameters already considered for this research should be augmented by quantifying the qualitative parameters. Specifically, the qualitative parameters in this research forced whole numbers in the fuzzy inference methodology and therefore provided limited variability in the output. By quantifying these parameters, the resolution of the models would advance which will improve the overall output performance predictions. Any additional parameters considered for future models shall be quantified as well to overcome this limitation.

The current model is verified and validated to some extent to document the accuracy and correctness of the model. Future models shall incorporate improved and standardized procedures to verify and validate the proposed model. The future evaluation efforts should rely on more enhanced laboratory tests to establish the estimation of the condition of the aged pipes. Furthermore, the future models shall be evaluated by testing pipes in all ranges of the performance index and varying pipe material types.

Although the current research developed selected deterioration prediction curves utilizing the Markov chain process, these curves should be significantly improved for practical use. The categorization of the pipes or subgroups in which this research created the deterioration models shall be further investigated and improved. Other mathematical techniques should be considered that might be more suitable for the nature of the problem and the datasets used to develop future models. These future deterioration prediction curves should also be verified and validated for aid in developing a future asset management plan.

Finally, the future models should contain some elements aiding to the utilities decision support system for prioritizing future inspection and R,R&R. The performance prediction model developed in this research can be used for network level decision support for drinking water utilities, but it does not provide a decision support system for prioritizing inspection and R,R&R. Future models shall improve by operating on a lower level asset management decision support system, such as through project selection or project levels. Overall, developed models operating in these lower levels will provide prioritization of inspection and R,R&R by their nature. Several modules of prioritization or optimization modules can also be added to the future models to acquire these goals.

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Appendix A: Utility Questionnaire

Table A.1 Utility Questionnaire

Significance of the Parameter in Determining Current Pipe Performance based on the Modules ***Current Integrity, Internal Condition, External Stress and External Corrosion*** (Circle One)

(1) Least Importance; (2) Less Importance; (3) Moderate Importance;

(4) Importance; (5) Most Importance

Current Integrity	**Life Expectancy**					
	Age	1	2	3	4	5
	Design Life	1	2	3	4	5
	Vintage	1	2	3	4	5
	Rehab (Lining)	1	2	3	4	5
	Structural Condition					
	Hazen Williams C Factor	1	2	3	4	5
	Remaining Thickness	1	2	3	4	5
	Tuberculation	1	2	3	4	5
	Leak	1	2	3	4	5
	Break Rate					
	Pipe Break	1	2	3	4	5
	Break <5 Years Ago	1	2	3	4	5
	Defect Type	1	2	3	4	5
	Rehab Type	1	2	3	4	5
Internal Condition	**Internal Condition**					
	Pressure Class Exceeded	1	2	3	4	5
	Pressure Surges	1	2	3	4	5
	Adequate Fire Flow	1	2	3	4	5
	Pressure Complaints	1	2	3	4	5
	Discolored Water	1	2	3	4	5
External Stress	**External Stress**					
	Disturbances	1	2	3	4	5
	Flooding	1	2	3	4	5
	Live Load	1	2	3	4	5
	Material Type	1	2	3	4	5
External Corrosion	**External Corrosion**					
	Dissimilar Metals	1	2	3	4	5
	Cathodic Protection	1	2	3	4	5
	Stray Currents	1	2	3	4	5
	Soil Corrosivity	1	2	3	4	5
	Coating	1	2	3	4	5
Performance	**Overall Performance**					
	Current Integrity	1	2	3	4	5
	Internal Condition	1	2	3	4	5
	External Stress	1	2	3	4	5
	External Corrosion	1	2	3	4	5

Appendix B: Fuzzy Inference Input & Output Membership Functions

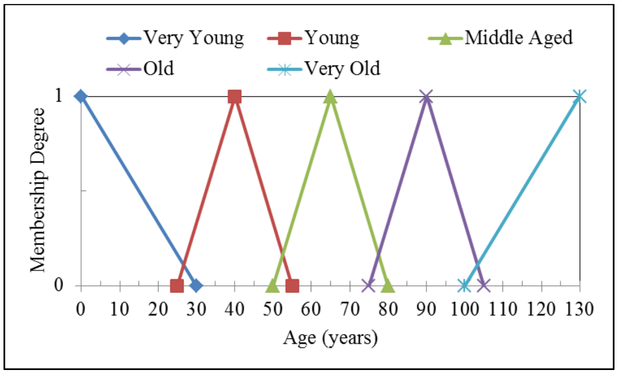

Figure B.1 Age Input Membership Function (Kleiner 2005; Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

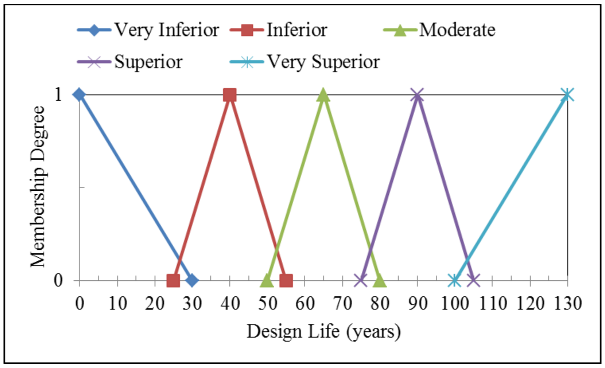

Figure B.2 Design Life Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

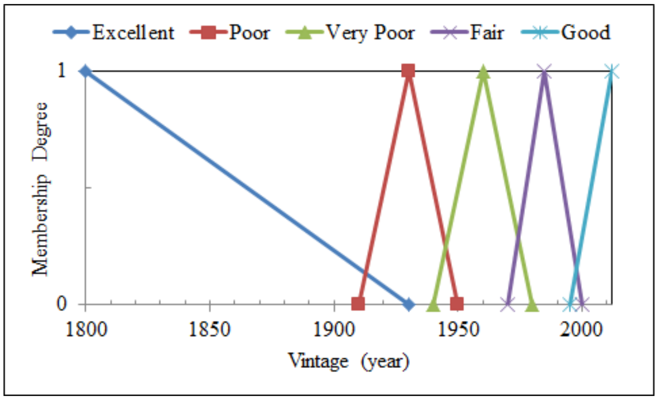

Figure B.3 Vintage Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

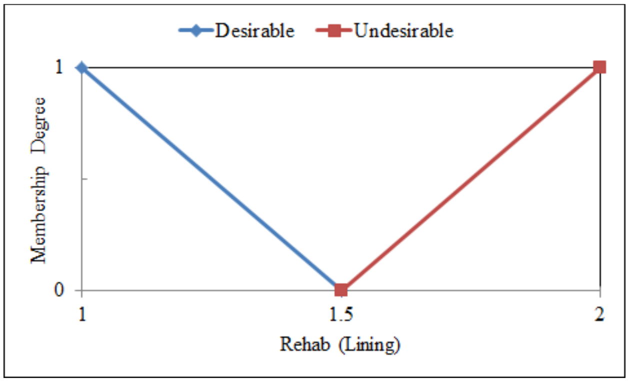

Figure B.4 Rehab (Lining) Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

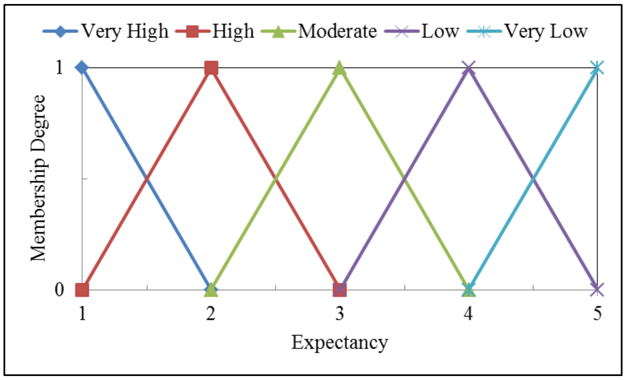

Figure B.5 Expectancy Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

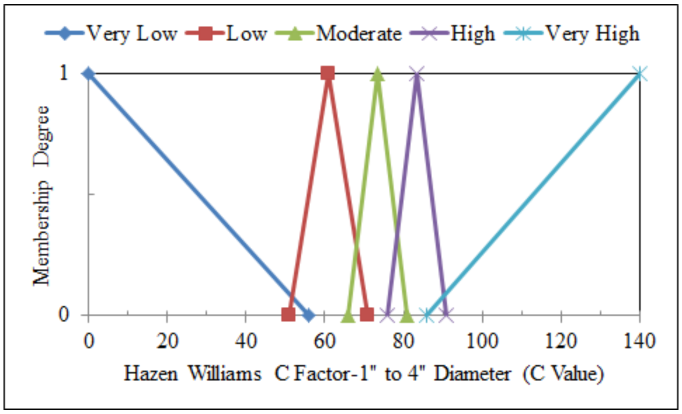

Figure B.6 Hazen Williams C Factor Input Membership Function-1” to 4” Diameter (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

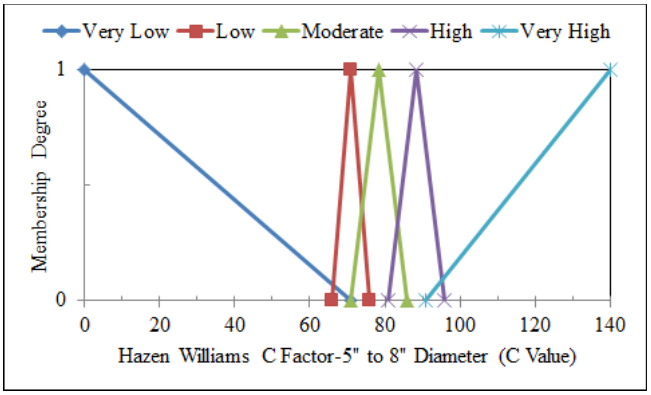

Figure B.7 Hazen Williams C Factor Input Membership Function-5” to 8” Diameter (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

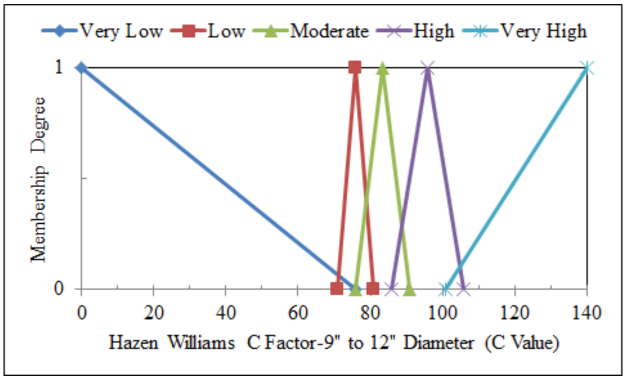

Figure B.8 Hazen Williams C Factor Input Membership Function-9” to 12” Diameter (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

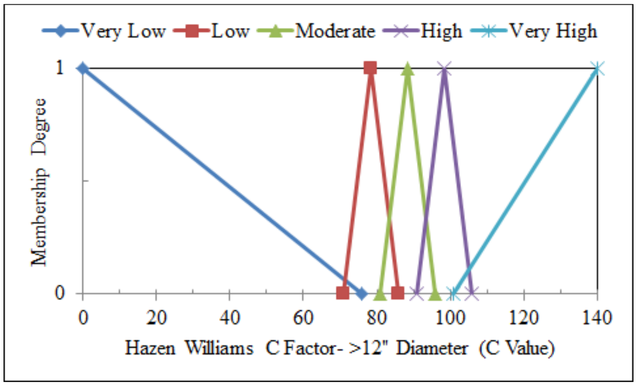

Figure B.9 Hazen Williams C Factor Input Membership Function- >12” Diameter (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

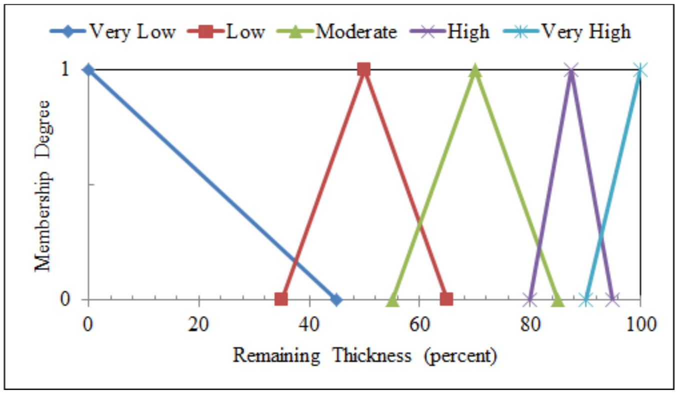

Figure B.10 Remaining Thickness Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

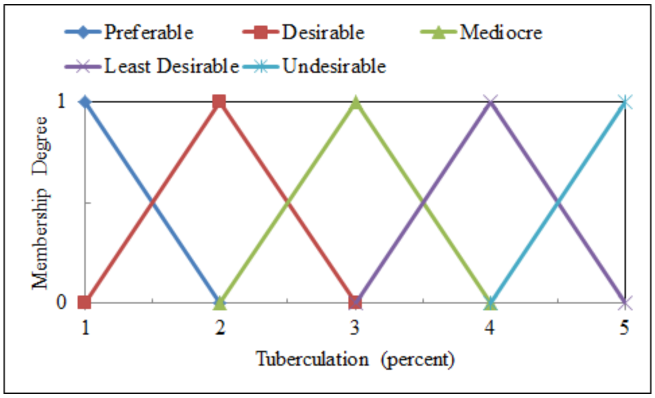

Figure B.11 Tuberculation Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

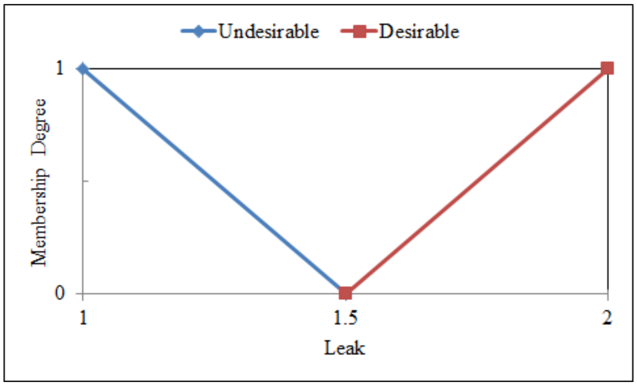

Figure B.12 Leak Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

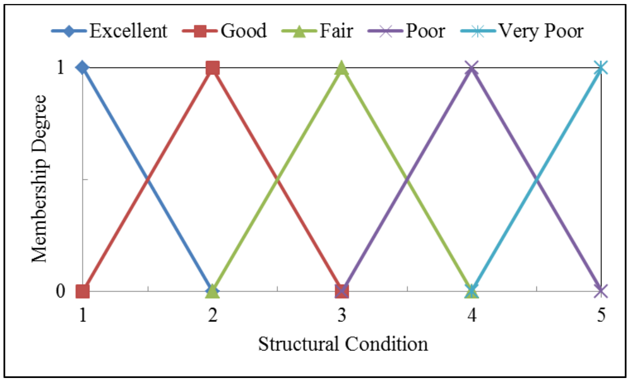

Figure B.13 Structural Condition Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

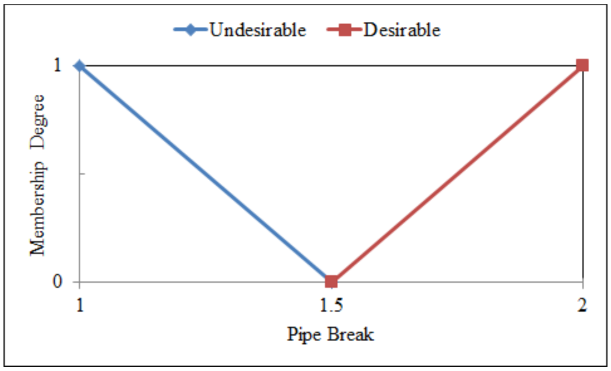

Figure B.14 Pipe Break Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

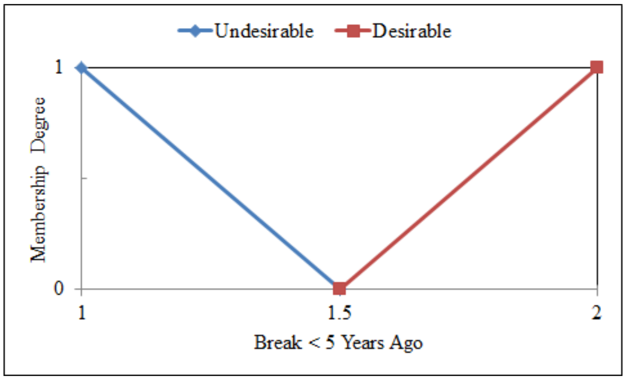

Figure B.15 Break <5 Years Ago Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

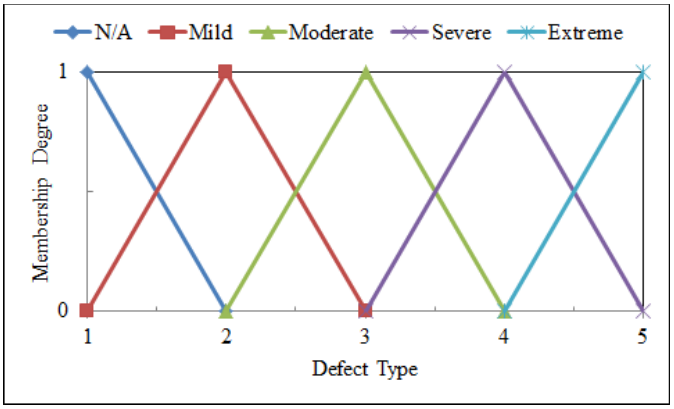

Figure B.16 Defect Type Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

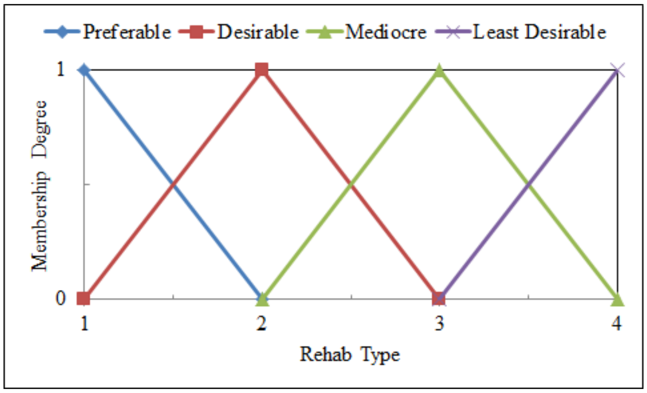

Figure B.17 Rehab Type Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

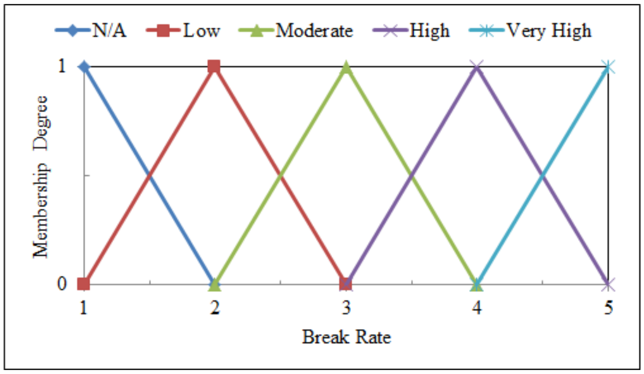

Figure B.18 Break Rate Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

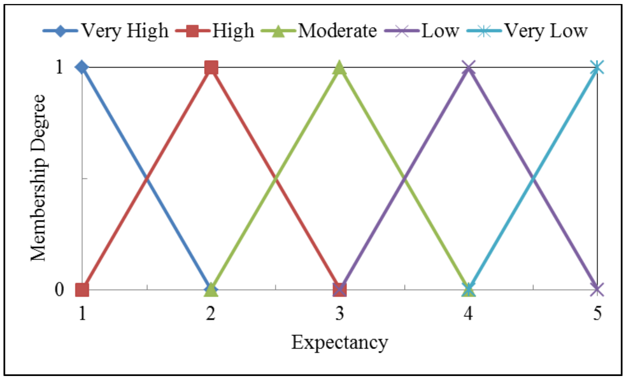

Figure B.19 Expectancy Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

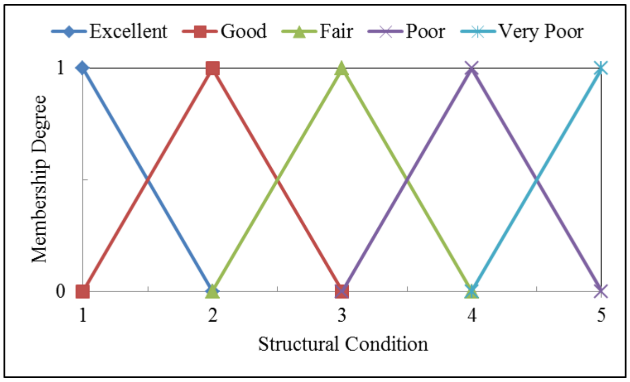

Figure B.20 Structural Condition Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

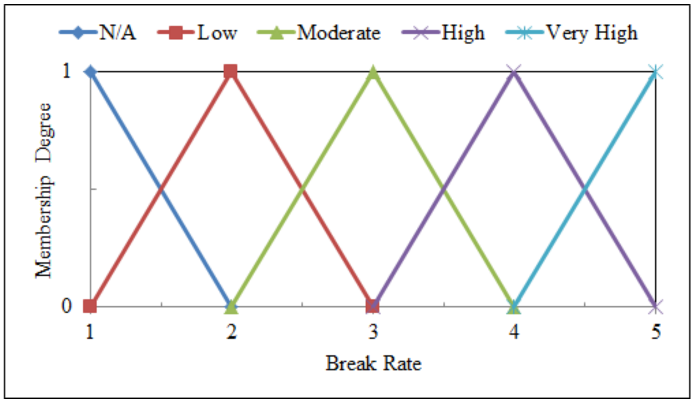

Figure B.21 Break Rate Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

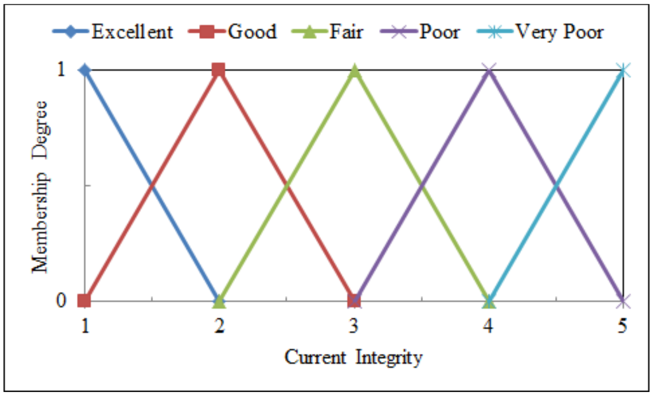

Figure B.22 Current Integrity Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

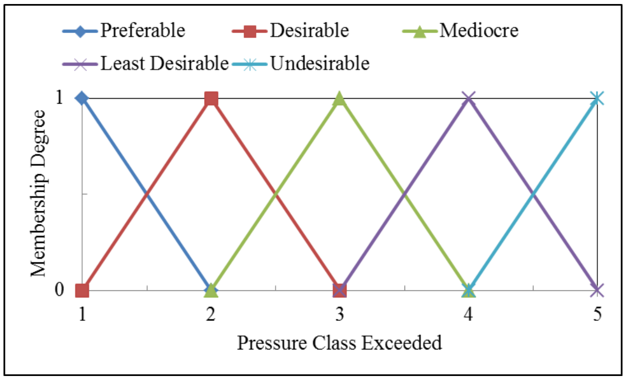

Figure B.23 Pressure Class Exceeded Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

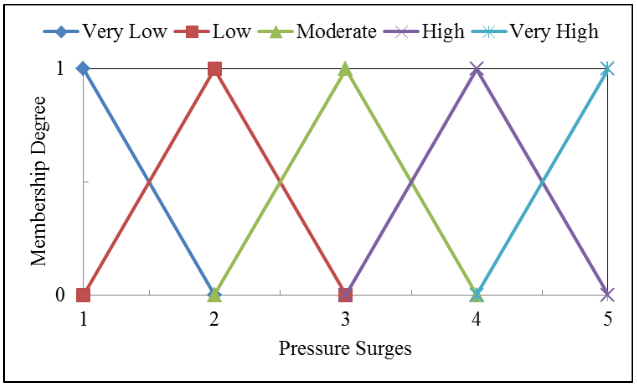

Figure B.24 Pressure Surges Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

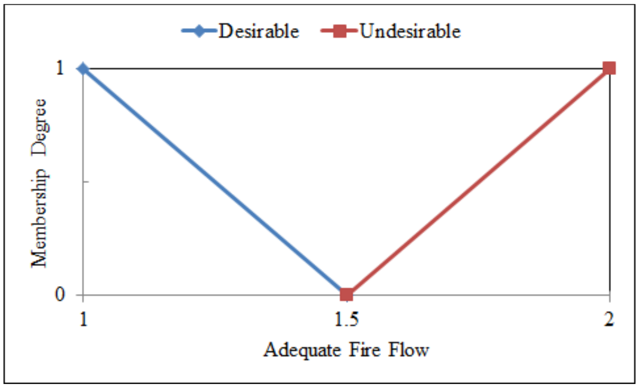

Figure B.25 Adequate Fire Flows Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

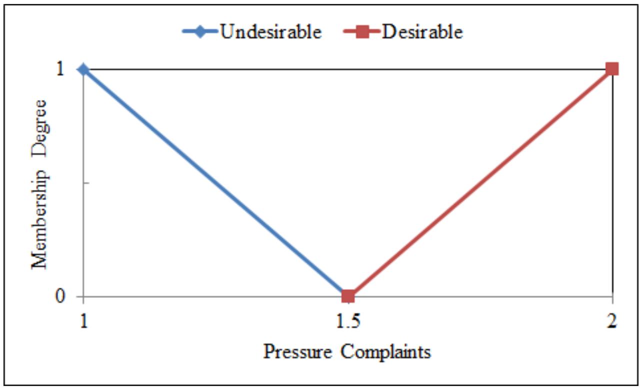

Figure B.26 Pressure Complaints Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

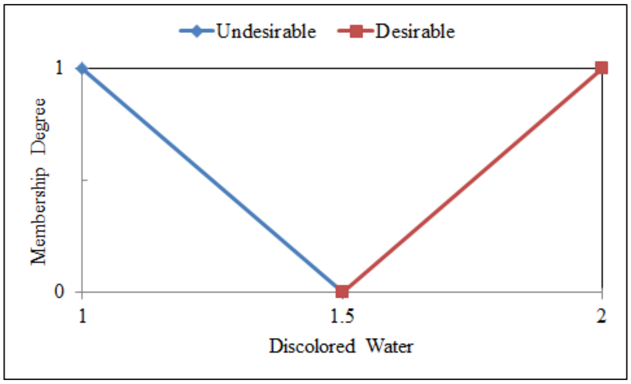

Figure B.27 Discolored Water Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

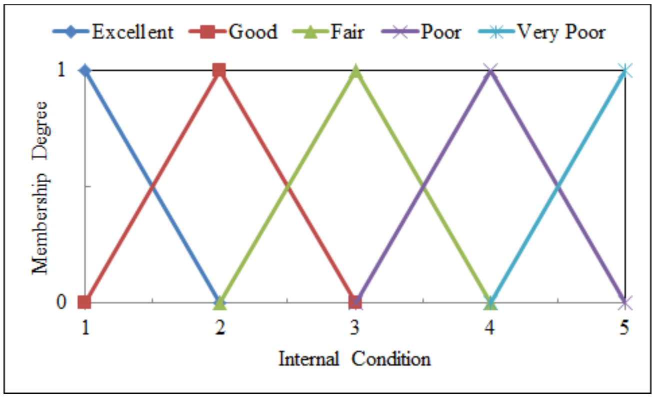

Figure B.28 Internal Condition Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

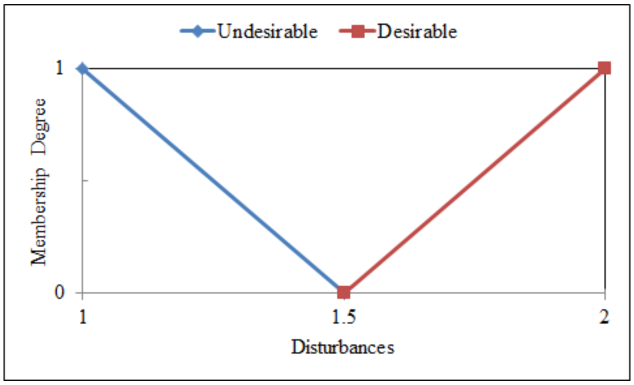

Figure B.29 Disturbances Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

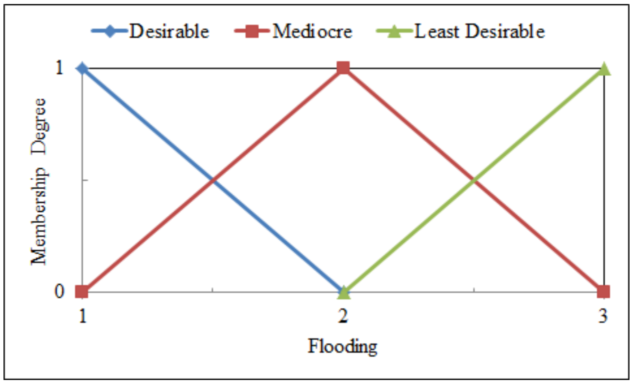

Figure B.30 Flooding Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

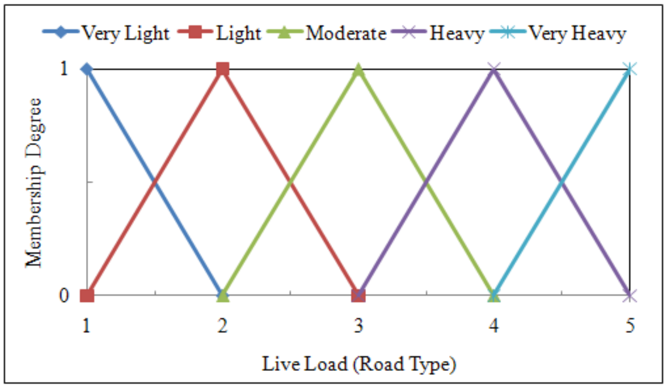

Figure B.31 Live Load (Road Type) Input Membership Function (Moser 1990; Slater 1996; Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011; PENNDOT 2011)

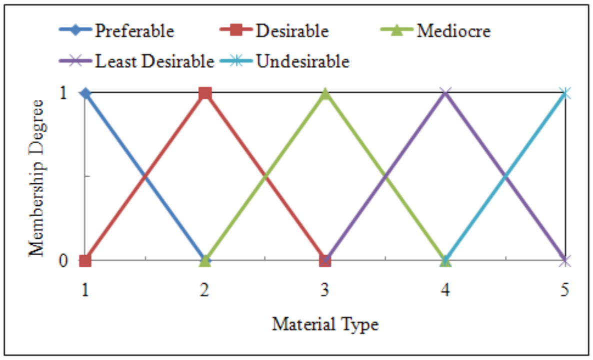

Figure B.32 Material Type Input Membership Function (ANSI/AWWA 1975; ANSI/AWWA 2009; ASTM 2009; ANSI/ASTM 2010; Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

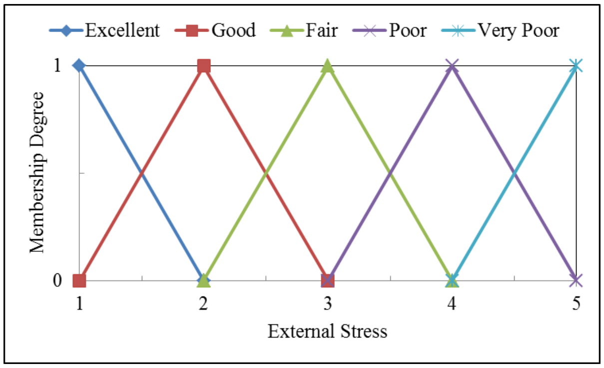

Figure B.33 External Stress Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

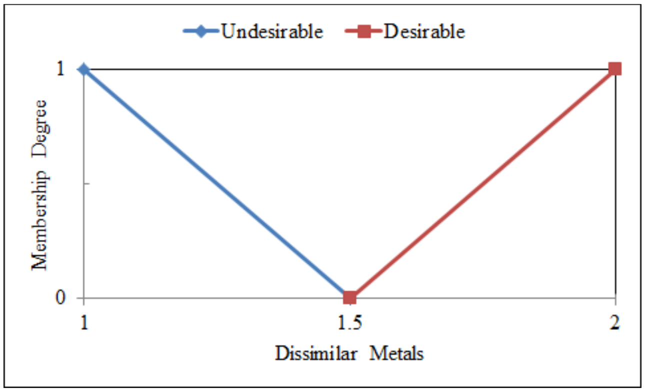

Figure B.34 Dissimilar Metals Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

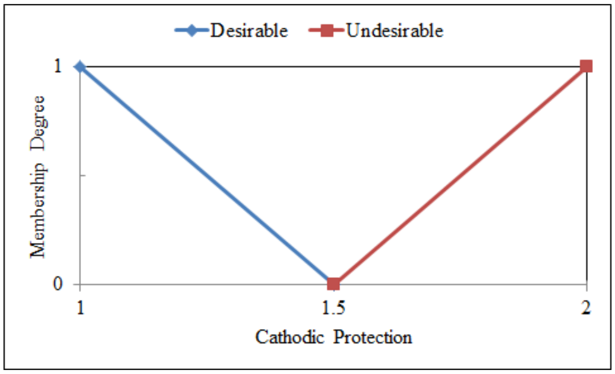

Figure B.35 Cathodic Protection Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

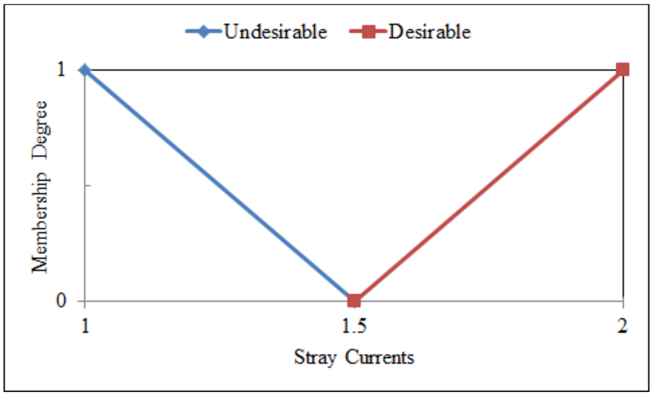

Figure B.36 Stray Currents Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

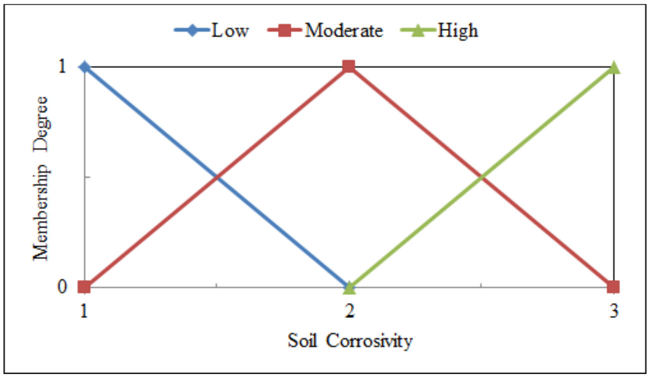

Figure B.37 Soil Corrosivity Input Membership Function (Staff 2008; Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

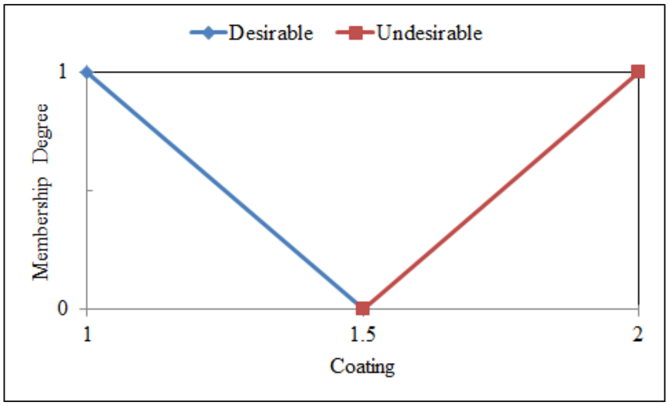

Figure B.38 Coating Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

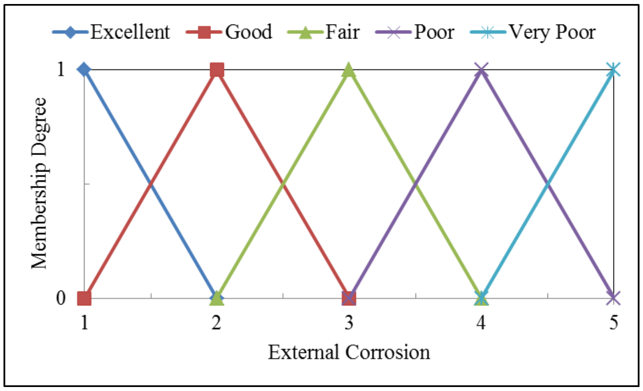

Figure B.39 External Corrosion Output Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

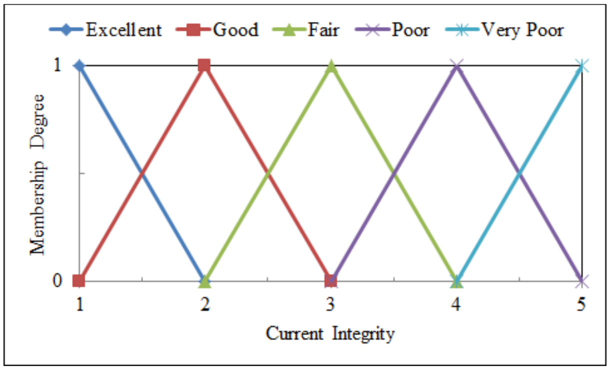

Figure B.40 Current Integrity Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

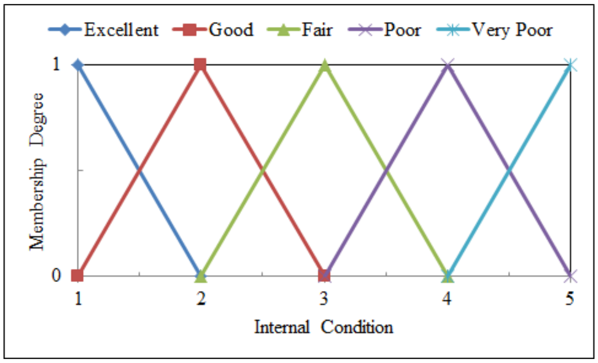

Figure B.41 Internal Condition Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

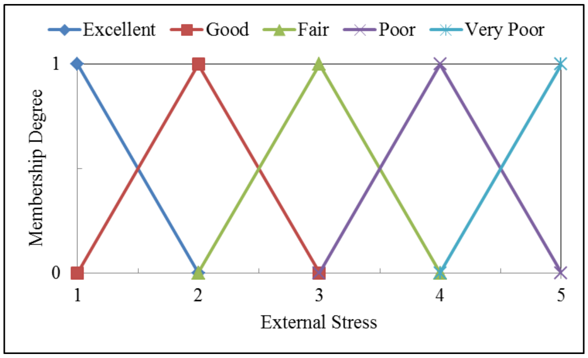

Figure B.42 External Stress Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

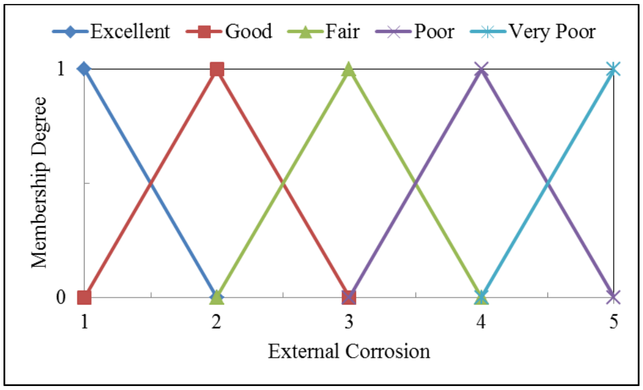

Figure B.43 External Corrosion Input Membership Function (Authority 2010/2011; Blacksburg 2010/2011; Commission 2010/2011)

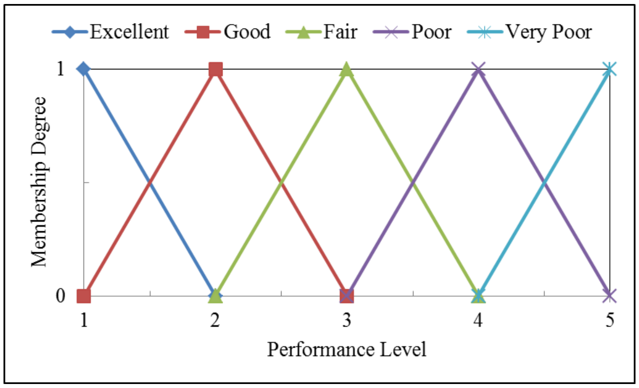

Figure B.44 Performance Output Membership Function

Appendix C: Fuzzy Inference If/Then Rule Statements

Table C.1 Fuzzy Inference Expectancy Module If/Then Rule Statements

1	***If***	Age is	Very Young	and	Design Life is	Very Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
2	***If***	Age is	Very Young	and	Design Life is	Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
3	***If***	Age is	Very Young	and	Design Life is	Moderate	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
4	***If***	Age is	Very Young	and	Design Life is	Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
5	***If***	Age is	Very Young	and	Design Life is	Very Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
6	***If***	Age is	Young	and	Design Life is	Very Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
7	***If***	Age is	Young	and	Design Life is	Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
8	***If***	Age is	Young	and	Design Life is	Moderate	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
9	***If***	Age is	Young	and	Design Life is	Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
10	***If***	Age is	Young	and	Design Life is	Very Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
11	***If***	Age is	Middle Aged	and	Design Life is	Very Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
12	***If***	Age is	Middle Aged	and	Design Life is	Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
13	***If***	Age is	Middle Aged	and	Design Life is	Moderate	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
14	***If***	Age is	Middle Aged	and	Design Life is	Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
15	***If***	Age is	Middle Aged	and	Design Life is	Very Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
16	***If***	Age is	Old	and	Design Life is	Very Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
17	***If***	Age is	Old	and	Design Life is	Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
18	***If***	Age is	Old	and	Design Life is	Moderate	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
19	***If***	Age is	Old	and	Design Life is	Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
20	***If***	Age is	Old	and	Design Life is	Very Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
21	***If***	Age is	Very Old	and	Design Life is	Very Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
22	***If***	Age is	Very Old	and	Design Life is	Inferior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
23	***If***	Age is	Very Old	and	Design Life is	Moderate	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
24	***If***	Age is	Very Old	and	Design Life is	Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High
25	***If***	Age is	Very Old	and	Design Life is	Very Superior	and	Rehab (Lining) is	Yes	***then***	Expectancy is	Very High

Table C.1 Fuzzy Inference Expectancy Module If/Then Rule Statements Cont.

26	***If***	Age is	Very Young	and	Design Life is	Very Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Moderate
27	***If***	Age is	Very Young	and	Design Life is	Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	High
28	***If***	Age is	Very Young	and	Design Life is	Moderate	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
29	***If***	Age is	Very Young	and	Design Life is	Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
30	***If***	Age is	Very Young	and	Design Life is	Very Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
31	***If***	Age is	Young	and	Design Life is	Very Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Low
32	***If***	Age is	Young	and	Design Life is	Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Moderate
33	***If***	Age is	Young	and	Design Life is	Moderate	and	Rehab (Lining) is	No	***then***	Expectancy is	High
34	***If***	Age is	Young	and	Design Life is	Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
35	***If***	Age is	Young	and	Design Life is	Very Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
36	***If***	Age is	Middle Aged	and	Design Life is	Very Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
37	***If***	Age is	Middle Aged	and	Design Life is	Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Low
38	***If***	Age is	Middle Aged	and	Design Life is	Moderate	and	Rehab (Lining) is	No	***then***	Expectancy is	Moderate
39	***If***	Age is	Middle Aged	and	Design Life is	Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	High
40	***If***	Age is	Middle Aged	and	Design Life is	Very Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very High
41	***If***	Age is	Old	and	Design Life is	Very Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
42	***If***	Age is	Old	and	Design Life is	Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
43	***If***	Age is	Old	and	Design Life is	Moderate	and	Rehab (Lining) is	No	***then***	Expectancy is	Low
44	***If***	Age is	Old	and	Design Life is	Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Moderate
45	***If***	Age is	Old	and	Design Life is	Very Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	High
46	***If***	Age is	Very Old	and	Design Life is	Very Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
47	***If***	Age is	Very Old	and	Design Life is	Inferior	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
48	***If***	Age is	Very Old	and	Design Life is	Moderate	and	Rehab (Lining) is	No	***then***	Expectancy is	Very Low
49	***If***	Age is	Very Old	and	Design Life is	Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Low
50	***If***	Age is	Very Old	and	Design Life is	Very Superior	and	Rehab (Lining) is	No	***then***	Expectancy is	Moderate

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements

1	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
2	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
3	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
4	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
5	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
6	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
7	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
8	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
9	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
10	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
11	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
12	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
13	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
14	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
15	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
16	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
17	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
18	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
19	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
20	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
21	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
22	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
23	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
24	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
25	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

26	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
27	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
28	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
29	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
30	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
31	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
32	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
33	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
34	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
35	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
36	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
37	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
38	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
39	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
40	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
41	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
42	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
43	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
44	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
45	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
46	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
47	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
48	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
49	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
50	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

51	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
52	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
53	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
54	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
55	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
56	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
57	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
58	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
59	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
60	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
61	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
62	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
63	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
64	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
65	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
66	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
67	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
68	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
69	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
70	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
71	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
72	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
73	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
74	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
75	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

76	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
77	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
78	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
79	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
80	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
81	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
82	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
83	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
84	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
85	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
86	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
87	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
88	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
89	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
90	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
91	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
92	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
93	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
94	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
95	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
96	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
97	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
98	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
99	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
100	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

101	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
102	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
103	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
104	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
105	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
106	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
107	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
108	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
109	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
110	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
111	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
112	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
113	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
114	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
115	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
116	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
117	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
118	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
119	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
120	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor
121	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	Yes	***then***	SC is	Very Poor
122	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	Yes	***then***	SC is	Very Poor
123	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	Yes	***then***	SC is	Very Poor
124	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	Yes	***then***	SC is	Very Poor
125	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	Yes	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

126	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
127	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
128	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
129	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
130	***If***	HWCF is	Very Low	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
131	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
132	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
133	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
134	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
135	***If***	HWCF is	Very Low	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
136	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
137	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
138	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
139	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
140	***If***	HWCF is	Very Low	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
141	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
142	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
143	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
144	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
145	***If***	HWCF is	Very Low	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
146	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
147	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
148	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
149	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
150	***If***	HWCF is	Very Low	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

151	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
152	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
153	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
154	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
155	***If***	HWCF is	Low	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
156	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
157	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
158	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
159	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
160	***If***	HWCF is	Low	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
161	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
162	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
163	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
164	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
165	***If***	HWCF is	Low	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
166	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
167	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
168	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
169	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
170	***If***	HWCF is	Low	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
171	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
172	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
173	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
174	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
175	***If***	HWCF is	Low	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

176	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
177	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
178	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
179	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
180	***If***	HWCF is	Moderate	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
181	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
182	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
183	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
184	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
185	***If***	HWCF is	Moderate	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
186	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Fair
187	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Fair
188	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
189	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
190	***If***	HWCF is	Moderate	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
191	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Fair
192	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Fair
193	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
194	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
195	***If***	HWCF is	Moderate	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
196	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Fair
197	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Fair
198	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
199	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
200	***If***	HWCF is	Moderate	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

201	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
202	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
203	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
204	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
205	***If***	HWCF is	High	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
206	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
207	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
208	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
209	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
210	***If***	HWCF is	High	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
211	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Fair
212	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Fair
213	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
214	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
215	***If***	HWCF is	High	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
216	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Good
217	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Good
218	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
219	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
220	***If***	HWCF is	High	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
221	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Good
222	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Good
223	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
224	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
225	***If***	HWCF is	High	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.2 Fuzzy Inference Structural Condition Module If/Then Rule Statements Cont.

226	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Very Poor
227	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Very Poor
228	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Very Poor
229	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Very Poor
230	***If***	HWCF is	Very High	***and***	RT is	Very Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
231	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Poor
232	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Poor
233	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Poor
234	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
235	***If***	HWCF is	Very High	***and***	RT is	Low	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
236	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Fair
237	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Fair
238	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
239	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
240	***If***	HWCF is	Very High	***and***	RT is	Moderate	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
241	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Good
242	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Good
243	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
244	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
245	***If***	HWCF is	Very High	***and***	RT is	High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor
246	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	None	***and***	Leak is	No	***then***	SC is	Excellent
247	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Light	***and***	Leak is	No	***then***	SC is	Good
248	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Moderate	***and***	Leak is	No	***then***	SC is	Fair
249	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Heavy	***and***	Leak is	No	***then***	SC is	Poor
250	***If***	HWCF is	Very High	***and***	RT is	Very High	***and***	T is	Extreme	***and***	Leak is	No	***then***	SC is	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (RT), Tuberculation (T) and Structural Condition (SC)

Table C.3 Fuzzy Inference Break Rate Module If/Then Rule Statements

1	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	N/A	***then***	Break Rate is	N/A
2	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	Segment	***then***	Break Rate is	N/A
3	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	Section	***then***	Break Rate is	N/A
4	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	None	***then***	Break Rate is	N/A
5	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	N/A	***then***	Break Rate is	N/A
6	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	Segment	***then***	Break Rate is	Low
7	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	Section	***then***	Break Rate is	Moderate
8	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	None	***then***	Break Rate is	Very High
9	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	N/A	***then***	Break Rate is	N/A
10	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	Segment	***then***	Break Rate is	Low
11	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	Section	***then***	Break Rate is	High
12	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	None	***then***	Break Rate is	Very High
13	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	N/A	***then***	Break Rate is	N/A
14	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	Segment	***then***	Break Rate is	Low
15	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	Section	***then***	Break Rate is	High
16	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	None	***then***	Break Rate is	Very High
17	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	N/A	***then***	Break Rate is	N/A
18	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	Segment	***then***	Break Rate is	Low
19	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	Section	***then***	Break Rate is	Very High
20	***If***	P Break is	Yes	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	None	***then***	Break Rate is	Very High
21	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	N/A	***then***	Break Rate is	N/A
22	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	Segment	***then***	Break Rate is	N/A
23	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	Section	***then***	Break Rate is	N/A
24	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	None	***then***	Break Rate is	N/A
25	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	N/A	***then***	Break Rate is	N/A

Pipe Break (P Break), Break <5 Years Ago (B<5), Defect Type (D Type), Rehab Type (R Type)

Table C.3 Fuzzy Inference Break Rate Module If/Then Rule Statements Cont.

26	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	Segment	***then***	Break Rate is	Low
27	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	Section	***then***	Break Rate is	Low
28	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	None	***then***	Break Rate is	High
29	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	N/A	***then***	Break Rate is	N/A
30	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	Segment	***then***	Break Rate is	Low
31	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	Section	***then***	Break Rate is	Low
32	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	None	***then***	Break Rate is	High
33	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	N/A	***then***	Break Rate is	N/A
34	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	Segment	***then***	Break Rate is	Low
35	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	Section	***then***	Break Rate is	Moderate
36	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	None	***then***	Break Rate is	Very High
37	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	N/A	***then***	Break Rate is	N/A
38	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	Segment	***then***	Break Rate is	Low
39	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	Section	***then***	Break Rate is	High
40	***If***	P Break is	Yes	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	None	***then***	Break Rate is	Very High
41	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	N/A	***then***	Break Rate is	N/A
42	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	Segment	***then***	Break Rate is	N/A
43	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	Section	***then***	Break Rate is	N/A
44	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	N/A	***and***	R Type is	None	***then***	Break Rate is	N/A
45	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	N/A	***then***	Break Rate is	N/A
46	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	Segment	***then***	Break Rate is	N/A
47	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	Section	***then***	Break Rate is	N/A
48	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Mild	***and***	R Type is	None	***then***	Break Rate is	N/A
49	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	N/A	***then***	Break Rate is	N/A
50	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	Segment	***then***	Break Rate is	N/A

Pipe Break (P Break), Break <5 Years Ago (B<5), Defect Type (D Type), Rehab Type (R Type)

Table C.3 Fuzzy Inference Break Rate Module If/Then Rule Statements Cont.

51	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	Section	***then***	Break Rate is	N/A
52	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Moderate	***and***	R Type is	None	***then***	Break Rate is	N/A
53	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	N/A	***then***	Break Rate is	N/A
54	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	Segment	***then***	Break Rate is	N/A
55	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	Section	***then***	Break Rate is	N/A
56	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Severe	***and***	R Type is	None	***then***	Break Rate is	N/A
57	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	N/A	***then***	Break Rate is	N/A
58	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	Segment	***then***	Break Rate is	N/A
59	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	Section	***then***	Break Rate is	N/A
60	***If***	P Break is	No	***and***	B<5 is	Yes	***and***	D Type is	Extreme	***and***	R Type is	None	***then***	Break Rate is	N/A
61	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	N/A	***then***	Break Rate is	N/A
62	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	Segment	***then***	Break Rate is	N/A
63	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	Section	***then***	Break Rate is	N/A
64	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	N/A	***and***	R Type is	None	***then***	Break Rate is	N/A
65	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	N/A	***then***	Break Rate is	N/A
66	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	Segment	***then***	Break Rate is	N/A
67	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	Section	***then***	Break Rate is	N/A
68	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Mild	***and***	R Type is	None	***then***	Break Rate is	N/A
69	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	N/A	***then***	Break Rate is	N/A
70	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	Segment	***then***	Break Rate is	N/A
71	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	Section	***then***	Break Rate is	N/A
72	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Moderate	***and***	R Type is	None	***then***	Break Rate is	N/A
73	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	N/A	***then***	Break Rate is	N/A
74	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	Segment	***then***	Break Rate is	N/A
75	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	Section	***then***	Break Rate is	N/A

Pipe Break (P Break), Break <5 Years Ago (B<5), Defect Type (D Type), Rehab Type (R Type)

Table C.3 Fuzzy Inference Break Rate Module If/Then Rule Statements Cont.

76	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Severe	***and***	R Type is	None	***then***	Break Rate is	N/A
77	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	N/A	***then***	Break Rate is	N/A
78	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	Segment	***then***	Break Rate is	N/A
79	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	Section	***then***	Break Rate is	N/A
80	***If***	P Break is	No	***and***	B<5 is	No	***and***	D Type is	Extreme	***and***	R Type is	None	***then***	Break Rate is	N/A

Pipe Break (P Break), Break <5 Years Ago (B<5), Defect Type (D Type), Rehab Type (R Type)

Table C.4 Fuzzy Inference Current Integrity Module If/Then Rule Statements

1	***If***	Expectancy is	Very High	***and***	SC is	Excellent	***and***	Break Rate is	N/A	***then***	CI is	Excellent
2	***If***	Expectancy is	Very High	***and***	SC is	Excellent	***and***	Break Rate is	Low	***then***	CI is	Good
3	***If***	Expectancy is	Very High	***and***	SC is	Excellent	***and***	Break Rate is	Moderate	***then***	CI is	Fair
4	***If***	Expectancy is	Very High	***and***	SC is	Excellent	***and***	Break Rate is	High	***then***	CI is	Poor
5	***If***	Expectancy is	Very High	***and***	SC is	Excellent	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
6	***If***	Expectancy is	Very High	***and***	SC is	Good	***and***	Break Rate is	N/A	***then***	CI is	Good
7	***If***	Expectancy is	Very High	***and***	SC is	Good	***and***	Break Rate is	Low	***then***	CI is	Good
8	***If***	Expectancy is	Very High	***and***	SC is	Good	***and***	Break Rate is	Moderate	***then***	CI is	Fair
9	***If***	Expectancy is	Very High	***and***	SC is	Good	***and***	Break Rate is	High	***then***	CI is	Poor
10	***If***	Expectancy is	Very High	***and***	SC is	Good	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
11	***If***	Expectancy is	Very High	***and***	SC is	Fair	***and***	Break Rate is	N/A	***then***	CI is	Fair
12	***If***	Expectancy is	Very High	***and***	SC is	Fair	***and***	Break Rate is	Low	***then***	CI is	Fair
13	***If***	Expectancy is	Very High	***and***	SC is	Fair	***and***	Break Rate is	Moderate	***then***	CI is	Fair
14	***If***	Expectancy is	Very High	***and***	SC is	Fair	***and***	Break Rate is	High	***then***	CI is	Poor
15	***If***	Expectancy is	Very High	***and***	SC is	Fair	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
16	***If***	Expectancy is	Very High	***and***	SC is	Poor	***and***	Break Rate is	N/A	***then***	CI is	Poor
17	***If***	Expectancy is	Very High	***and***	SC is	Poor	***and***	Break Rate is	Low	***then***	CI is	Poor
18	***If***	Expectancy is	Very High	***and***	SC is	Poor	***and***	Break Rate is	Moderate	***then***	CI is	Poor
19	***If***	Expectancy is	Very High	***and***	SC is	Poor	***and***	Break Rate is	High	***then***	CI is	Poor
20	***If***	Expectancy is	Very High	***and***	SC is	Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
21	***If***	Expectancy is	Very High	***and***	SC is	Very Poor	***and***	Break Rate is	N/A	***then***	CI is	Very Poor
22	***If***	Expectancy is	Very High	***and***	SC is	Very Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
23	***If***	Expectancy is	Very High	***and***	SC is	Very Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
24	***If***	Expectancy is	Very High	***and***	SC is	Very Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
25	***If***	Expectancy is	Very High	***and***	SC is	Very Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor

Structural Condition (SC), Current Integrity (CI)

Table C.4 Fuzzy Inference Current Integrity Module If/Then Rule Statements Cont.

26	***If***	Expectancy is	High	***and***	SC is	Excellent	***and***	Break Rate is	N/A	***then***	CI is	Excellent
27	***If***	Expectancy is	High	***and***	SC is	Excellent	***and***	Break Rate is	Low	***then***	CI is	Good
28	***If***	Expectancy is	High	***and***	SC is	Excellent	***and***	Break Rate is	Moderate	***then***	CI is	Fair
29	***If***	Expectancy is	High	***and***	SC is	Excellent	***and***	Break Rate is	High	***then***	CI is	Poor
30	***If***	Expectancy is	High	***and***	SC is	Excellent	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
31	***If***	Expectancy is	High	***and***	SC is	Good	***and***	Break Rate is	N/A	***then***	CI is	Good
32	***If***	Expectancy is	High	***and***	SC is	Good	***and***	Break Rate is	Low	***then***	CI is	Good
33	***If***	Expectancy is	High	***and***	SC is	Good	***and***	Break Rate is	Moderate	***then***	CI is	Fair
34	***If***	Expectancy is	High	***and***	SC is	Good	***and***	Break Rate is	High	***then***	CI is	Poor
35	***If***	Expectancy is	High	***and***	SC is	Good	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
36	***If***	Expectancy is	High	***and***	SC is	Fair	***and***	Break Rate is	N/A	***then***	CI is	Fair
37	***If***	Expectancy is	High	***and***	SC is	Fair	***and***	Break Rate is	Low	***then***	CI is	Fair
38	***If***	Expectancy is	High	***and***	SC is	Fair	***and***	Break Rate is	Moderate	***then***	CI is	Fair
39	***If***	Expectancy is	High	***and***	SC is	Fair	***and***	Break Rate is	High	***then***	CI is	Poor
40	***If***	Expectancy is	High	***and***	SC is	Fair	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
41	***If***	Expectancy is	High	***and***	SC is	Poor	***and***	Break Rate is	N/A	***then***	CI is	Poor
42	***If***	Expectancy is	High	***and***	SC is	Poor	***and***	Break Rate is	Low	***then***	CI is	Poor
43	***If***	Expectancy is	High	***and***	SC is	Poor	***and***	Break Rate is	Moderate	***then***	CI is	Poor
44	***If***	Expectancy is	High	***and***	SC is	Poor	***and***	Break Rate is	High	***then***	CI is	Poor
45	***If***	Expectancy is	High	***and***	SC is	Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
46	***If***	Expectancy is	High	***and***	SC is	Very Poor	***and***	Break Rate is	N/A	***then***	CI is	Very Poor
47	***If***	Expectancy is	High	***and***	SC is	Very Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
48	***If***	Expectancy is	High	***and***	SC is	Very Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
49	***If***	Expectancy is	High	***and***	SC is	Very Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
50	***If***	Expectancy is	High	***and***	SC is	Very Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor

Structural Condition (SC), Current Integrity (CI)

Table C.4 Fuzzy Inference Current Integrity Module If/Then Rule Statements Cont.

51	***If***	Expectancy is	Moderate	***and***	SC is	Excellent	***and***	Break Rate is	N/A	***then***	CI is	Good
52	***If***	Expectancy is	Moderate	***and***	SC is	Excellent	***and***	Break Rate is	Low	***then***	CI is	Good
53	***If***	Expectancy is	Moderate	***and***	SC is	Excellent	***and***	Break Rate is	Moderate	***then***	CI is	Fair
54	***If***	Expectancy is	Moderate	***and***	SC is	Excellent	***and***	Break Rate is	High	***then***	CI is	Poor
55	***If***	Expectancy is	Moderate	***and***	SC is	Excellent	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
56	***If***	Expectancy is	Moderate	***and***	SC is	Good	***and***	Break Rate is	N/A	***then***	CI is	Good
57	***If***	Expectancy is	Moderate	***and***	SC is	Good	***and***	Break Rate is	Low	***then***	CI is	Good
58	***If***	Expectancy is	Moderate	***and***	SC is	Good	***and***	Break Rate is	Moderate	***then***	CI is	Fair
59	***If***	Expectancy is	Moderate	***and***	SC is	Good	***and***	Break Rate is	High	***then***	CI is	Poor
60	***If***	Expectancy is	Moderate	***and***	SC is	Good	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
61	***If***	Expectancy is	Moderate	***and***	SC is	Fair	***and***	Break Rate is	N/A	***then***	CI is	Fair
62	***If***	Expectancy is	Moderate	***and***	SC is	Fair	***and***	Break Rate is	Low	***then***	CI is	Fair
63	***If***	Expectancy is	Moderate	***and***	SC is	Fair	***and***	Break Rate is	Moderate	***then***	CI is	Fair
64	***If***	Expectancy is	Moderate	***and***	SC is	Fair	***and***	Break Rate is	High	***then***	CI is	Poor
65	***If***	Expectancy is	Moderate	***and***	SC is	Fair	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
66	***If***	Expectancy is	Moderate	***and***	SC is	Poor	***and***	Break Rate is	N/A	***then***	CI is	Poor
67	***If***	Expectancy is	Moderate	***and***	SC is	Poor	***and***	Break Rate is	Low	***then***	CI is	Poor
68	***If***	Expectancy is	Moderate	***and***	SC is	Poor	***and***	Break Rate is	Moderate	***then***	CI is	Poor
69	***If***	Expectancy is	Moderate	***and***	SC is	Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
70	***If***	Expectancy is	Moderate	***and***	SC is	Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
71	***If***	Expectancy is	Moderate	***and***	SC is	Very Poor	***and***	Break Rate is	N/A	***then***	CI is	Very Poor
72	***If***	Expectancy is	Moderate	***and***	SC is	Very Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
73	***If***	Expectancy is	Moderate	***and***	SC is	Very Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
74	***If***	Expectancy is	Moderate	***and***	SC is	Very Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
75	***If***	Expectancy is	Moderate	***and***	SC is	Very Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor

Structural Condition (SC), Current Integrity (CI)

Table C.4 Fuzzy Inference Current Integrity Module If/Then Rule Statements Cont.

76	***If***	Expectancy is	Low	***and***	SC is	Excellent	***and***	Break Rate is	N/A	***then***	CI is	Good
77	***If***	Expectancy is	Low	***and***	SC is	Excellent	***and***	Break Rate is	Low	***then***	CI is	Fair
78	***If***	Expectancy is	Low	***and***	SC is	Excellent	***and***	Break Rate is	Moderate	***then***	CI is	Fair
79	***If***	Expectancy is	Low	***and***	SC is	Excellent	***and***	Break Rate is	High	***then***	CI is	Poor
80	***If***	Expectancy is	Low	***and***	SC is	Excellent	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
81	***If***	Expectancy is	Low	***and***	SC is	Good	***and***	Break Rate is	N/A	***then***	CI is	Fair
82	***If***	Expectancy is	Low	***and***	SC is	Good	***and***	Break Rate is	Low	***then***	CI is	Fair
83	***If***	Expectancy is	Low	***and***	SC is	Good	***and***	Break Rate is	Moderate	***then***	CI is	Poor
84	***If***	Expectancy is	Low	***and***	SC is	Good	***and***	Break Rate is	High	***then***	CI is	Poor
85	***If***	Expectancy is	Low	***and***	SC is	Good	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
86	***If***	Expectancy is	Low	***and***	SC is	Fair	***and***	Break Rate is	N/A	***then***	CI is	Fair
87	***If***	Expectancy is	Low	***and***	SC is	Fair	***and***	Break Rate is	Low	***then***	CI is	Poor
88	***If***	Expectancy is	Low	***and***	SC is	Fair	***and***	Break Rate is	Moderate	***then***	CI is	Poor
89	***If***	Expectancy is	Low	***and***	SC is	Fair	***and***	Break Rate is	High	***then***	CI is	Very Poor
90	***If***	Expectancy is	Low	***and***	SC is	Fair	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
91	***If***	Expectancy is	Low	***and***	SC is	Poor	***and***	Break Rate is	N/A	***then***	CI is	Poor
92	***If***	Expectancy is	Low	***and***	SC is	Poor	***and***	Break Rate is	Low	***then***	CI is	Poor
93	***If***	Expectancy is	Low	***and***	SC is	Poor	***and***	Break Rate is	Moderate	***then***	CI is	Poor
94	***If***	Expectancy is	Low	***and***	SC is	Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
95	***If***	Expectancy is	Low	***and***	SC is	Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
96	***If***	Expectancy is	Low	***and***	SC is	Very Poor	***and***	Break Rate is	N/A	***then***	CI is	Very Poor
97	***If***	Expectancy is	Low	***and***	SC is	Very Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
98	***If***	Expectancy is	Low	***and***	SC is	Very Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
99	***If***	Expectancy is	Low	***and***	SC is	Very Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
100	***If***	Expectancy is	Low	***and***	SC is	Very Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor

Structural Condition (SC), Current Integrity (CI)

Table C.4 Fuzzy Inference Current Integrity Module If/Then Rule Statements Cont.

101	***If***	Expectancy is	Very Low	***and***	SC is	Excellent	***and***	Break Rate is	N/A	***then***	CI is	Fair
102	***If***	Expectancy is	Very Low	***and***	SC is	Excellent	***and***	Break Rate is	Low	***then***	CI is	Fair
103	***If***	Expectancy is	Very Low	***and***	SC is	Excellent	***and***	Break Rate is	Moderate	***then***	CI is	Fair
104	***If***	Expectancy is	Very Low	***and***	SC is	Excellent	***and***	Break Rate is	High	***then***	CI is	Poor
105	***If***	Expectancy is	Very Low	***and***	SC is	Excellent	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
106	***If***	Expectancy is	Very Low	***and***	SC is	Good	***and***	Break Rate is	N/A	***then***	CI is	Fair
107	***If***	Expectancy is	Very Low	***and***	SC is	Good	***and***	Break Rate is	Low	***then***	CI is	Fair
108	***If***	Expectancy is	Very Low	***and***	SC is	Good	***and***	Break Rate is	Moderate	***then***	CI is	Poor
109	***If***	Expectancy is	Very Low	***and***	SC is	Good	***and***	Break Rate is	High	***then***	CI is	Very Poor
110	***If***	Expectancy is	Very Low	***and***	SC is	Good	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
111	***If***	Expectancy is	Very Low	***and***	SC is	Fair	***and***	Break Rate is	N/A	***then***	CI is	Fair
112	***If***	Expectancy is	Very Low	***and***	SC is	Fair	***and***	Break Rate is	Low	***then***	CI is	Poor
113	***If***	Expectancy is	Very Low	***and***	SC is	Fair	***and***	Break Rate is	Moderate	***then***	CI is	Poor
114	***If***	Expectancy is	Very Low	***and***	SC is	Fair	***and***	Break Rate is	High	***then***	CI is	Very Poor
115	***If***	Expectancy is	Very Low	***and***	SC is	Fair	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
116	***If***	Expectancy is	Very Low	***and***	SC is	Poor	***and***	Break Rate is	N/A	***then***	CI is	Poor
117	***If***	Expectancy is	Very Low	***and***	SC is	Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
118	***If***	Expectancy is	Very Low	***and***	SC is	Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
119	***If***	Expectancy is	Very Low	***and***	SC is	Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
120	***If***	Expectancy is	Very Low	***and***	SC is	Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor
121	***If***	Expectancy is	Very Low	***and***	SC is	Very Poor	***and***	Break Rate is	N/A	***then***	CI is	Very Poor
122	***If***	Expectancy is	Very Low	***and***	SC is	Very Poor	***and***	Break Rate is	Low	***then***	CI is	Very Poor
123	***If***	Expectancy is	Very Low	***and***	SC is	Very Poor	***and***	Break Rate is	Moderate	***then***	CI is	Very Poor
124	***If***	Expectancy is	Very Low	***and***	SC is	Very Poor	***and***	Break Rate is	High	***then***	CI is	Very Poor
125	***If***	Expectancy is	Very Low	***and***	SC is	Very Poor	***and***	Break Rate is	Very High	***then***	CI is	Very Poor

Structural Condition (SC), Current Integrity (CI)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements

1	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
2	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
3	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
4	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
5	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
6	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
7	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
8	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
9	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
10	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
11	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
12	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
13	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
14	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
15	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
16	***If***	PCE is	Least Desirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
17	***If***	PCE is	Least Desirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
18	***If***	PCE is	Least Desirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
19	***If***	PCE is	Least Desirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
20	***If***	PCE is	Least Desirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
21	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
22	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
23	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
24	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor
25	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

26	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
27	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
28	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
29	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
30	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
31	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
32	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
33	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
34	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
35	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
36	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
37	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
38	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
39	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
40	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
41	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
42	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
43	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
44	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
45	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
46	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
47	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
48	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
49	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor
50	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	Yes	***then***	IC is	V.Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

51	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
52	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
53	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
54	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
55	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
56	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
57	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
58	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
59	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
60	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
61	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
62	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
63	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
64	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
65	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
66	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
67	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
68	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
69	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
70	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
71	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
72	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
73	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
74	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor
75	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

76	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
77	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
78	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
79	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
80	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
81	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
82	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
83	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
84	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
85	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
86	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
87	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
88	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
89	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
90	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
91	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
92	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
93	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
94	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
95	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
96	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
97	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
98	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
99	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor
100	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	Yes	***then***	IC is	V.Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

101	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
102	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
103	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
104	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
105	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
106	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
107	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
108	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
109	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
110	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
111	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
112	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
113	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
114	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
115	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
116	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
117	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
118	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
119	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
120	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
121	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
122	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
123	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
124	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor
125	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	Yes	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

126	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
127	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
128	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
129	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
130	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
131	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
132	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
133	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
134	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
135	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
136	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
137	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
138	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
139	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
140	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
141	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
142	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
143	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
144	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
145	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
146	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
147	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
148	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
149	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor
150	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	Yes	***and***	DW is	No	***then***	IC is	V.Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

151	***If***	PCE is	Preferable	***and***	PS is	VeryLow	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Excellent
152	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Good
153	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Fair
154	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
155	***If***	PCE is	Preferable	***and***	PS is	VeryHigh	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
156	***If***	PCE is	Desirable	***and***	PS is	VeryLow	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Good
157	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Good
158	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Fair
159	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
160	***If***	PCE is	Desirable	***and***	PS is	VeryHigh	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
161	***If***	PCE is	Mediocre	***and***	PS is	VeryLow	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Fair
162	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Fair
163	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Fair
164	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
165	***If***	PCE is	Mediocre	***and***	PS is	VeryHigh	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
166	***If***	PCE is	LeastDesirable	***and***	PS is	VeryLow	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
167	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
168	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
169	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	Poor
170	***If***	PCE is	LeastDesirable	***and***	PS is	VeryHigh	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
171	***If***	PCE is	Undesirable	***and***	PS is	VeryLow	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
172	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
173	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
174	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor
175	***If***	PCE is	Undesirable	***and***	PS is	VeryHigh	***and***	AFF is	Yes	***and***	PC is	No	***and***	DWis	No	***then***	IC is	V.Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.5 Fuzzy Inference Internal Condition Module If/Then Rule Statements Cont.

176	***If***	PCE is	Preferable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
177	***If***	PCE is	Preferable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
178	***If***	PCE is	Preferable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
179	***If***	PCE is	Preferable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
180	***If***	PCE is	Preferable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
181	***If***	PCE is	Desirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
182	***If***	PCE is	Desirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
183	***If***	PCE is	Desirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
184	***If***	PCE is	Desirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
185	***If***	PCE is	Desirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
186	***If***	PCE is	Mediocre	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
187	***If***	PCE is	Mediocre	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
188	***If***	PCE is	Mediocre	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
189	***If***	PCE is	Mediocre	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
190	***If***	PCE is	Mediocre	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
191	***If***	PCE is	LeastDesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
192	***If***	PCE is	LeastDesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
193	***If***	PCE is	LeastDesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
194	***If***	PCE is	LeastDesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
195	***If***	PCE is	LeastDesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
196	***If***	PCE is	Undesirable	***and***	PS is	Very Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
197	***If***	PCE is	Undesirable	***and***	PS is	Low	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
198	***If***	PCE is	Undesirable	***and***	PS is	Moderate	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
199	***If***	PCE is	Undesirable	***and***	PS is	High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor
200	***If***	PCE is	Undesirable	***and***	PS is	Very High	***and***	AFF is	No	***and***	PC is	No	***and***	DW is	No	***then***	IC is	V.Poor

Pressure Class Exceeded (PCE), Pressure Surges (PS), Adequate Fire Flow (AFF), Pressure Complaints (PC), Discolored Water (DW), Internal Condition (IC)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements

1	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Excellent
2	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Excellent
3	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Excellent
4	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Least Desirable	***then***	ES is	Excellent
5	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Good
6	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Excellent
7	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Excellent
8	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Excellent
9	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Least Desirable	***then***	ES is	Good
10	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Fair
11	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Excellent
12	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Good
13	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Good
14	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Least Desirable	***then***	ES is	Fair
15	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Poor
16	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Good
17	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Fair
18	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Fair
19	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Least Desirable	***then***	ES is	Poor
20	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
21	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Preferable	***then***	ES is	Fair
22	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Desirable	***then***	ES is	Fair
23	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Mediocre	***then***	ES is	Poor
24	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
25	***If***	D is	Desirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements Cont.

26	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Good
27	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Good
28	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Good
29	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Least Desirable	***then***	ES is	Fair
30	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Fair
31	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Good
32	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Good
33	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Fair
34	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Least Desirable	***then***	ES is	Fair
35	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Poor
36	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Good
37	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Fair
38	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Fair
39	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Least Desirable	***then***	ES is	Poor
40	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Poor
41	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Fair
42	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Fair
43	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Poor
44	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Least Desirable	***then***	ES is	Poor
45	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
46	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Preferable	***then***	ES is	Fair
47	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Desirable	***then***	ES is	Poor
48	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
49	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
50	***If***	D is	Desirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements Cont.

51	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Poor
52	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Poor
53	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Poor
54	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
55	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Very Poor
56	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Poor
57	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Poor
58	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Poor
59	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
60	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Very Poor
61	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Poor
62	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Poor
63	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Poor
64	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
65	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Very Poor
66	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Poor
67	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Very Poor
68	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
69	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
70	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
71	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Heavy	***and***	MT is	Preferable	***then***	ES is	Poor
72	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Heavy	***and***	MT is	Desirable	***then***	ES is	Very Poor
73	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
74	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
75	***If***	D is	Desirable	***and***	F is	Undesirable	***and***	LL is	Very Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements Cont.

76	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Fair
77	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Fair
78	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Fair
79	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Least Desirable	***then***	ES is	Fair
80	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Fair
81	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Fair
82	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Fair
83	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Fair
84	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Least Desirable	***then***	ES is	Fair
85	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Fair
86	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Fair
87	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Fair
88	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Poor
89	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Least Desirable	***then***	ES is	Poor
90	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Very Poor
91	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Fair
92	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Fair
93	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Poor
94	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
95	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
96	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Preferable	***then***	ES is	Fair
97	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Desirable	***then***	ES is	Poor
98	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
99	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
100	***If***	D is	Undesirable	***and***	F is	Desirable	***and***	LL is	Very Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements Cont.

101	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Fair
102	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Fair
103	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Fair
104	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Least Desirable	***then***	ES is	Poor
105	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Poor
106	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Fair
107	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Fair
108	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Poor
109	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Least Desirable	***then***	ES is	Poor
110	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Very Poor
111	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Fair
112	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Poor
113	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Poor
114	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
115	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Very Poor
116	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Poor
117	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Poor
118	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
119	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
120	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
121	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Preferable	***then***	ES is	Poor
122	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Desirable	***then***	ES is	Very Poor
123	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
124	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Least Desirable	***then***	ES is	Very Poor
125	***If***	D is	Undesirable	***and***	F is	Mediocre	***and***	LL is	Very Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.6 Fuzzy Inference External Stress Module If/Then Rule Statements Cont.

126	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Preferable	***then***	ES is	Very Poor
127	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Desirable	***then***	ES is	Very Poor
128	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Mediocre	***then***	ES is	Very Poor
129	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	LeastDesirable	***then***	ES is	Very Poor
130	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Very Light	***and***	MT is	Undesirable	***then***	ES is	Very Poor
131	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Preferable	***then***	ES is	Very Poor
132	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Desirable	***then***	ES is	Very Poor
133	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Mediocre	***then***	ES is	Very Poor
134	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	LeastDesirable	***then***	ES is	Very Poor
135	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Light	***and***	MT is	Undesirable	***then***	ES is	Very Poor
136	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Preferable	***then***	ES is	Very Poor
137	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Desirable	***then***	ES is	Very Poor
138	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Mediocre	***then***	ES is	Very Poor
139	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	LeastDesirable	***then***	ES is	Very Poor
140	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Moderate	***and***	MT is	Undesirable	***then***	ES is	Very Poor
141	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Preferable	***then***	ES is	Very Poor
142	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Desirable	***then***	ES is	Very Poor
143	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
144	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	LeastDesirable	***then***	ES is	Very Poor
145	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	Heavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor
146	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	VeryHeavy	***and***	MT is	Preferable	***then***	ES is	Very Poor
147	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	VeryHeavy	***and***	MT is	Desirable	***then***	ES is	Very Poor
148	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	VeryHeavy	***and***	MT is	Mediocre	***then***	ES is	Very Poor
149	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	VeryHeavy	***and***	MT is	LeastDesirable	***then***	ES is	Very Poor
150	***If***	D is	Undesirable	***and***	F is	Undesirable	***and***	LL is	VeryHeavy	***and***	MT is	Undesirable	***then***	ES is	Very Poor

Disturbances (D), Flooding (F), Live Load-Road Type (LL), Material Type (MT), External Stress (ES)

Table C.7 Fuzzy Inference External Corrosion Module If/Then Rule Statements

1	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
2	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Good
3	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
4	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Fair
5	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
6	***If***	DM is	D	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
7	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
8	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Good
9	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
10	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Fair
11	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
12	***If***	DM is	D	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
13	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
14	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Good
15	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
16	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Fair
17	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
18	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
19	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
20	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Poor
21	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
22	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Very Poor
23	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
24	***If***	DM is	D	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
25	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent

Dissimilar Metals (DM), Cathodic Protection (CP), Stray Currents (STC), Soil Corrosivity (SC), Coating (C), External Corrosion (EC), Desirable (D), Undesirable (UD)

Table C.7 Fuzzy Inference External Corrosion Module If/Then Rule Statements Cont.

26	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Fair
27	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
28	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Poor
29	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
30	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	D	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
31	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
32	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Fair
33	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
34	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Poor
35	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
36	***If***	DM is	UD	***and***	CP is	D	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
37	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
38	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Fair
39	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
40	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Poor
41	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
42	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	D	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor
43	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	D	***then***	EC is	Excellent
44	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Low	***and***	C is	UD	***then***	EC is	Very Poor
45	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	D	***then***	EC is	Excellent
46	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	Mod	***and***	C is	UD	***then***	EC is	Very Poor
47	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	D	***then***	EC is	Excellent
48	***If***	DM is	UD	***and***	CP is	UD	***and***	STC is	UD	***and***	SCo is	High	***and***	C is	UD	***then***	EC is	Very Poor

Dissimilar Metals (DM), Cathodic Protection (CP), Stray Currents (STC), Soil Corrosivity (SC), Coating (C), External Corrosion (EC), Desirable (D), Undesirable (UD)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements

1	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Excellent
2	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Good
3	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
4	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
5	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
6	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Good
7	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Good
8	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
9	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
10	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
11	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
12	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
13	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
14	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
15	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
16	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
17	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
18	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
19	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
20	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
21	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
22	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
23	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
24	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
25	***If***	CI is	Excellent	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

26	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Good
27	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Good
28	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
29	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
30	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
31	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Good
32	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Good
33	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
34	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
35	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
36	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
37	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
38	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
39	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
40	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
41	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
42	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
43	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
44	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
45	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
46	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
47	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
48	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
49	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
50	***If***	CI is	Excellent	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

51	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Fair
52	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Fair
53	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
54	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
55	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
56	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Fair
57	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Fair
58	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
59	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
60	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
61	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
62	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
63	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
64	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
65	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
66	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
67	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
68	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
69	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
70	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
71	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
72	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
73	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
74	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
75	***If***	CI is	Excellent	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

76	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
77	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
78	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
79	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
80	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
81	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
82	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
83	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
84	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
85	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
86	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
87	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
88	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
89	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
90	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
91	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
92	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
93	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
94	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
95	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
96	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
97	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
98	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
99	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
100	***If***	CI is	Excellent	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

101	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
102	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
103	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
104	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
105	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
106	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
107	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
108	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
109	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
110	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
111	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
112	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
113	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
114	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
115	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
116	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
117	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
118	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
119	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
120	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
121	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
122	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
123	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
124	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
125	***If***	CI is	Excellent	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

126	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Good
127	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Good
128	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
129	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
130	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
131	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Good
132	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Good
133	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
134	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
135	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
136	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
137	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
138	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
139	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
140	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
141	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
142	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
143	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
144	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
145	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
146	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
147	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
148	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
149	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
150	***If***	CI is	Good	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

151	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Good
152	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Good
153	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
154	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
155	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
156	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Good
157	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Good
158	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
159	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
160	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
161	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
162	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
163	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
164	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
165	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
166	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
167	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
168	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
169	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
170	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
171	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
172	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
173	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
174	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
175	***If***	CI is	Good	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

176	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Fair
177	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Fair
178	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
179	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
180	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
181	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Fair
182	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Fair
183	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
184	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
185	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
186	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
187	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
188	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
189	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
190	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
191	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
192	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
193	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
194	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
195	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
196	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
197	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
198	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
199	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
200	***If***	CI is	Good	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

201	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
202	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
203	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
204	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
205	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
206	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
207	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
208	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
209	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
210	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
211	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
212	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
213	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
214	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
215	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
216	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
217	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
218	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
219	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
220	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
221	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
222	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
223	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
224	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
225	***If***	CI is	Good	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

226	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
227	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
228	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
229	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
230	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
231	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
232	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
233	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
234	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
235	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
236	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
237	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
238	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
239	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
240	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
241	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
242	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
243	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
244	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
245	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
246	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
247	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
248	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
249	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
250	***If***	CI is	Good	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

251	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Fair
252	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Fair
253	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
254	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
255	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
256	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Fair
257	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Fair
258	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
259	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
260	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
261	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
262	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
263	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
264	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
265	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
266	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
267	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
268	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
269	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
270	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
271	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
272	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
273	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
274	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
275	***If***	CI is	Fair	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

276	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Fair
277	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Fair
278	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
279	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
280	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
281	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Fair
282	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Fair
283	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
284	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
285	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
286	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
287	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
288	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
289	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
290	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
291	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
292	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
293	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
294	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
295	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
296	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
297	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
298	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
299	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
300	***If***	CI is	Fair	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

301	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Fair
302	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Fair
303	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Fair
304	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
305	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
306	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Fair
307	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Fair
308	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Fair
309	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
310	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
311	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Fair
312	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Fair
313	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Fair
314	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
315	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
316	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
317	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
318	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
319	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
320	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
321	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
322	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
323	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
324	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
325	***If***	CI is	Fair	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

326	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
327	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
328	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
329	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
330	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
331	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
332	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
333	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
334	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
335	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
336	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
337	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
338	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
339	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
340	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
341	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
342	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
343	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
344	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
345	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
346	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
347	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
348	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
349	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
350	***If***	CI is	Fair	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

351	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
352	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
353	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
354	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
355	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
356	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
357	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
358	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
359	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
360	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
361	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
362	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
363	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
364	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
365	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
366	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
367	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
368	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
369	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
370	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
371	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
372	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
373	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
374	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
375	***If***	CI is	Fair	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

376	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
377	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
378	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
379	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
380	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
381	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
382	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
383	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
384	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
385	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
386	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
387	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
388	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
389	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
390	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
391	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
392	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
393	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
394	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
395	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
396	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
397	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
398	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
399	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
400	***If***	CI is	Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

401	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
402	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
403	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
404	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
405	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
406	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
407	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
408	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
409	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
410	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
411	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
412	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
413	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
414	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
415	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
416	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
417	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
418	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
419	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
420	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
421	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
422	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
423	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
424	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
425	***If***	CI is	Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

426	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
427	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
428	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
429	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
430	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
431	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
432	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
433	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
434	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
435	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
436	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
437	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
438	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
439	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
440	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
441	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
442	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
443	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
444	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
445	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
446	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
447	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
448	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
449	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
450	***If***	CI is	Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

451	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Poor
452	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Poor
453	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Poor
454	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Poor
455	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
456	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Poor
457	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Poor
458	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Poor
459	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Poor
460	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
461	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Poor
462	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Poor
463	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Poor
464	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Poor
465	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
466	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Poor
467	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Poor
468	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Poor
469	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Poor
470	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
471	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
472	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
473	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
474	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
475	***If***	CI is	Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

476	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
477	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
478	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
479	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
480	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
481	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
482	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
483	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
484	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
485	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
486	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
487	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
488	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
489	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
490	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
491	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
492	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
493	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
494	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
495	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
496	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
497	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
498	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
499	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
500	***If***	CI is	Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

501	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
502	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
503	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
504	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
505	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
506	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
507	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
508	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
509	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
510	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
511	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
512	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
513	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
514	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
515	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
516	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
517	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
518	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
519	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
520	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
521	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
522	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
523	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
524	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
525	***If***	CI is	Very Poor	***and***	IC is	Excellent	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

526	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
527	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
528	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
529	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
530	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
531	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
532	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
533	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
534	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
535	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
536	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
537	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
538	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
539	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
540	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
541	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
542	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
543	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
544	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
545	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
546	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
547	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
548	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
549	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
550	***If***	CI is	Very Poor	***and***	IC is	Good	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

551	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
552	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
553	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
554	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
555	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
556	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
557	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
558	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
559	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
560	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
561	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
562	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
563	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
564	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
565	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
566	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
567	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
568	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
569	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
570	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
571	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
572	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
573	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
574	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
575	***If***	CI is	Very Poor	***and***	IC is	Fair	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

576	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
577	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
578	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
579	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
580	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
581	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
582	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
583	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
584	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
585	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
586	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
587	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
588	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
589	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
590	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
591	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
592	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
593	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
594	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
595	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
596	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
597	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
598	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
599	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
600	***If***	CI is	Very Poor	***and***	IC is	Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Table C.8 Fuzzy Inference Performance Module If/Then Rule Statements Cont.

601	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Excellent	***then***	P is	Very Poor
602	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Good	***then***	P is	Very Poor
603	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Fair	***then***	P is	Very Poor
604	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Poor	***then***	P is	Very Poor
605	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Excellent	***and***	EC is	Very Poor	***then***	P is	Very Poor
606	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Excellent	***then***	P is	Very Poor
607	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Good	***then***	P is	Very Poor
608	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Fair	***then***	P is	Very Poor
609	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Poor	***then***	P is	Very Poor
610	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Good	***and***	EC is	Very Poor	***then***	P is	Very Poor
611	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Excellent	***then***	P is	Very Poor
612	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Good	***then***	P is	Very Poor
613	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Fair	***then***	P is	Very Poor
614	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Poor	***then***	P is	Very Poor
615	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Fair	***and***	EC is	Very Poor	***then***	P is	Very Poor
616	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
617	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Good	***then***	P is	Very Poor
618	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Fair	***then***	P is	Very Poor
619	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Poor	***then***	P is	Very Poor
620	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor
621	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Excellent	***then***	P is	Very Poor
622	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Good	***then***	P is	Very Poor
623	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Fair	***then***	P is	Very Poor
624	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Poor	***then***	P is	Very Poor
625	***If***	CI is	Very Poor	***and***	IC is	Very Poor	***and***	ES is	Very Poor	***and***	EC is	Very Poor	***then***	P is	Very Poor

Current Integrity (CI), Internal Condition (IC), External Stress (ES), External Condition (EC), Performance (P)

Appendix D: Field Data Evaluation

Table D.1 Field Data Samples

Sample	**Pipe 1**	**Pipe 2**	**Pipe 3**	**Pipe 4**	**Pipe 5**	**Pipe 6**	**Pipe 7**
Diameter (in)	10	16	1	12	1	6	12
Age (yr)	104	80	56	36	85	60	88
Design Life (yr)	120	100	50	75	100	75	100
Vintage (yr)	1906	1930	1954	1974	1925	1950	1922
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	85	50	95	65	80	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	Galvanized	DI	DI	CI	CI
Dissimilar Metals	Yes	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	Low	Moderate	Moderate	Low
Coating	No	No	No	Yes	Yes	No	No
L Expectancy Output	1.26	3.62	4.54	2.42	3.56	2.98	3.58
S Condition Output	3.32	3.30	4.56	2.00	3.98	3.00	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.32	3.34	4.56	2.00	3.76	3.00	3.38
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	3.00	1.00	1.00	1.00	2.00
E Corrosion Output	3.00	1.00	2.00	1.00	1.00	2.00	1.00
Performance Output	**3.32**	**3.34**	**4.56**	**2.00**	**3.76**	**3.00**	**3.38**
Performance Rating	Fair	Fair	Very Poor	Good	Poor	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 8**	**Pipe 9**	**Pipe 10**	**Pipe 11**	**Pipe 12**	**Pipe 13**	**Pipe 14**
Diameter (in)	1	6	12	6	1	1.5	6
Age (yr)	55	39	85	84	95	88	43
Design Life (yr)	75	75	100	100	100	50	75
Vintage (yr)	1955	1971	1925	1926	1915	1922	1967
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	100	90	80	75	60	50	90
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	Yes	No	No	No	No
Break <5 Years Ago	No	No	Yes	No	No	No	No
Defect Type	N/A	N/A	Extreme	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	Segment	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	NHS	Non-NHS	NHS	NHS
Material Type	Copper	DI	CI	CI	CI	Galvanized	DI
Dissimilar Metals	Yes	No	No	No	No	Yes	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate
Coating	No	Yes	No	No	No	No	Yes
L Expectancy Output	3.00	2.36	3.56	3.56	3.52	4.40	2.40
S Condition Output	1.36	1.98	3.32	3.32	4.00	4.56	1.98
Break Rate Output	1.00	1.00	5.00	1.00	1.00	1.00	1.00
C Integrity Output	1.98	1.80	4.78	3.40	3.98	4.56	1.78
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	3.00	1.00	2.00	2.00	1.00	4.00	1.00
E Corrosion Output	3.00	1.00	1.00	1.00	2.00	3.00	1.00
Performance Output	**3.00**	**1.80**	**4.76**	**3.40**	**3.98**	**4.56**	**1.78**
Performance Rating	Fair	Good	Very Poor	Fair	Poor	Very Poor	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 15**	**Pipe 16**	**Pipe 17**	**Pipe 18**	**Pipe 19**	**Pipe 20**	**Pipe 21**
Diameter (in)	2	6	1	2	2	1	6
Age (yr)	41	84	22	83	59	88	96
Design Life (yr)	75	100	75	50	50	100	100
Vintage (yr)	1969	1926	1988	1927	1951	1922	1914
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	75	100	50	50	60	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	Yes	No	Yes	No	No
Break <5 Years Ago	No	No	Yes	No	Yes	No	No
Defect Type	N/A	N/A	Extreme	N/A	Extreme	N/A	N/A
Rehab Type	N/A	N/A	Segment	N/A	Segment	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	CI	Copper	Galvanized	Galvanized	CI	CI
Dissimilar Metals	No	Yes	Yes	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Low	Moderate	Moderate	High	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.36	3.56	3.00	4.42	3.48	3.58	3.50
S Condition Output	2.30	3.32	1.36	4.56	4.56	4.00	3.32
Break Rate Output	1.00	1.00	5.00	1.00	5.00	1.00	1.00
C Integrity Output	2.32	3.40	4.82	4.56	4.78	4.00	3.42
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	2.00	3.00	3.00	1.00	1.00
E Corrosion Output	2.00	3.00	3.00	3.00	2.00	3.00	2.00
Performance Output	**2.32**	**3.40**	**4.82**	**4.56**	**4.76**	**4.00**	**3.42**
Performance Rating	Good	Fair	Very Poor	Very Poor	Very Poor	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 22**	**Pipe 23**	**Pipe 24**	**Pipe 25**	**Pipe 26**	**Pipe 27**	**Pipe 28**
Diameter (in)	8	1	6	2	6	6	1
Age (yr)	36	9	40	84	35	47	88
Design Life (yr)	75	75	75	50	75	75	50
Vintage (yr)	1974	2001	1970	1926	1975	1963	1922
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	95	100	90	50	90	85	50
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	Unpaved	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	DI	Copper	DI	Galvanized	DI	CI	Galvanized
Dissimilar Metals	Yes	Yes	No	No	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Low	Moderate	Low	Moderate	Low
Coating	Yes	No	Yes	No	Yes	No	No
L Expectancy Output	2.42	1.42	2.32	4.44	2.42	2.46	4.40
S Condition Output	1.52	1.36	1.98	4.56	1.98	2.30	4.56
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.52	1.38	1.82	4.56	1.78	2.38	4.56
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	3.00	1.00	1.00	3.00
E Corrosion Output	1.00	3.00	1.00	2.00	1.00	2.00	1.00
Performance Output	**1.52**	**3.00**	**1.84**	**4.56**	**1.78**	**2.36**	**4.56**
Performance Rating	Excellent	Fair	Good	Very Poor	Good	Good	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 29**	**Pipe 30**	**Pipe 31**	**Pipe 32**	**Pipe 33**	**Pipe 34**	**Pipe 35**
Diameter (in)	6	6	1	6	6	6	1
Age (yr)	79	16	14	60	50	53	110
Design Life (yr)	100	75	75	75	75	75	120
Vintage (yr)	1931	1994	1996	1950	1960	1957	1900
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	100	95	80	85	80	60
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	DI	DI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	High
Coating	No	Yes	Yes	No	No	No	No
L Expectancy Output	3.66	1.32	1.36	2.98	2.46	2.56	1.22
S Condition Output	3.32	1.40	1.40	3.00	2.30	3.00	4.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.32	1.40	1.40	3.00	2.38	3.00	4.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Corrosion Output	2.00	1.00	1.00	2.00	2.00	2.00	3.00
Performance Output	**3.32**	**1.40**	**1.40**	**3.00**	**2.36**	**3.00**	**4.00**
Performance Rating	Fair	Excellent	Excellent	Fair	Good	Fair	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 36**	**Pipe 37**	**Pipe 38**	**Pipe 39**	**Pipe 40**	**Pipe 41**	**Pipe 42**
Diameter (in)	6	1	6	2	1	8	24
Age (yr)	90	85	98	55	63	63	15
Design Life (yr)	100	50	100	50	75	75	75
Vintage (yr)	1920	1925	1912	1955	1947	1947	1995
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	50	75	50	70	80	115
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	NHS	Unpaved
Material Type	CI	Galvanized	CI	Galvanized	CI	CI	DI
Dissimilar Metals	No	No	No	No	No	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Moderate	Low	Low	Low
Coating	No	No	No	No	No	No	Yes
L Expectancy Output	3.62	4.44	3.46	4.56	3.30	3.30	1.32
S Condition Output	3.32	4.56	3.32	4.56	3.28	3.00	1.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.36	4.56	3.40	4.56	3.28	3.00	1.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	3.00	2.00	3.00	1.00	2.00	1.00
E Corrosion Output	2.00	2.00	1.00	2.00	1.00	1.00	1.00
Performance Output	**3.36**	**4.56**	**3.40**	**4.56**	**3.28**	**3.00**	**1.32**
Performance Rating	Fair	Very Poor	Fair	Very Poor	Fair	Fair	Excellent

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 43**	**Pipe 44**	**Pipe 45**	**Pipe 46**	**Pipe 47**	**Pipe 48**	**Pipe 49**
Diameter (in)	12	0.75	1	4	6	1	1
Age (yr)	93	50	80	111	110	102	109
Design Life (yr)	100	50	100	120	120	120	50
Vintage (yr)	1917	1960	1930	1899	1900	1908	1901
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	50	60	65	75	100	50
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	Galvanized	CI	CI	CI	Copper	Galvanized
Dissimilar Metals	No	No	Yes	Yes	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Moderate	Low	Moderate	High
Coating	No	No	No	No	No	No	No
L Expectancy Output	3.56	4.68	3.62	1.22	1.22	1.34	4.52
S Condition Output	3.32	4.56	4.00	3.98	3.32	1.36	4.56
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.40	4.56	4.00	3.88	3.32	1.36	4.52
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	3.00	2.00	2.00	1.00	3.00	3.00
E Corrosion Output	2.00	2.00	3.00	3.00	1.00	3.00	3.00
Performance Output	**3.40**	**4.56**	**4.00**	**3.88**	**3.32**	**3.00**	**4.52**
Performance Rating	Fair	Very Poor	Poor	Poor	Fair	Fair	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 50**	**Pipe 51**	**Pipe 52**	**Pipe 53**	**Pipe 54**	**Pipe 55**	**Pipe 56**
Diameter (in)	8	1	6	6	6	6	10
Age (yr)	20	90	117	108	119	86	119
Design Life (yr)	75	100	120	120	120	100	120
Vintage (yr)	1990	1920	1893	1902	1891	1924	1891
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	105	60	75	75	75	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	DI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	Yes	No	Yes	Yes	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Low	Moderate	High	Low
Coating	Yes	No	No	No	No	No	No
L Expectancy Output	2.98	3.62	1.22	1.22	1.22	3.54	1.22
S Condition Output	1.34	4.00	3.32	3.32	3.32	3.32	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.82	4.00	3.32	3.32	3.32	3.40	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	1.00	1.00	1.00
E Corrosion Output	1.00	2.00	3.00	3.00	2.00	4.00	1.00
Performance Output	**1.84**	**4.00**	**3.32**	**3.32**	**3.32**	**3.98**	**3.32**
Performance Rating	Good	Poor	Fair	Fair	Fair	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 57**	**Pipe 58**	**Pipe 59**	**Pipe 60**	**Pipe 61**	**Pipe 62**	**Pipe 63**
Diameter (in)	1	12	8	6	12	6	1
Age (yr)	2	57	57	118	2	3	85
Design Life (yr)	75	75	75	120	75	75	100
Vintage (yr)	2008	1953	1953	1892	2008	2007	1925
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	100	85	80	75	125	120	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	Yes	No	No	No	No	No	No
Break <5 Years Ago	Yes	No	No	No	No	No	No
Defect Type	Extreme	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	Segment	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	Non-NHS	Non-NHS	NHS	Unpaved	NHS
Material Type	Copper	CI	CI	CI	DI	DI	Copper
Dissimilar Metals	Yes	No	No	No	No	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	High	Low	High
Coating	No	No	No	No	Yes	Yes	No
L Expectancy Output	1.52	3.00	3.00	1.22	1.52	1.50	3.56
S Condition Output	1.36	3.00	3.00	3.32	1.18	1.20	1.36
Break Rate Output	5.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.78	3.00	3.00	3.32	1.34	1.34	2.40
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	2.00	1.00	1.00	1.00	1.00	3.00
E Corrosion Output	3.00	2.00	2.00	1.00	1.00	1.00	4.00
Performance Output	**4.76**	**3.00**	**3.00**	**3.32**	**1.36**	**1.36**	**4.00**
Performance Rating	Very Poor	Fair	Fair	Fair	Excellent	Excellent	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 64**	**Pipe 65**	**Pipe 66**	**Pipe 67**	**Pipe 68**	**Pipe 69**	**Pipe 70**
Diameter (in)	6	8	1	1	1	1	1
Age (yr)	98	2	96	98	89	97	90
Design Life (yr)	100	75	100	100	100	100	100
Vintage (yr)	1912	2008	1914	1912	1921	1913	1920
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	120	65	100	60	100	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	Yes	No
Break <5 Years Ago	No	No	No	No	No	Yes	No
Defect Type	N/A	N/A	N/A	N/A	N/A	Extreme	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	Segment	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Unpaved	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	DI	DI	Copper	CI	Copper	Copper
Dissimilar Metals	No	No	No	Yes	No	Yes	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	High	Moderate	Moderate	Moderate
Coating	No	Yes	Yes	No	No	No	No
L Expectancy Output	3.46	1.52	3.50	3.46	3.60	3.50	3.62
S Condition Output	3.32	1.20	3.98	1.36	4.00	1.36	1.36
Break Rate Output	1.00	1.00	1.00	1.00	1.00	5.00	1.00
C Integrity Output	3.40	1.34	3.74	2.40	3.98	4.76	2.36
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	2.00	3.00
E Corrosion Output	2.00	1.00	1.00	4.00	2.00	3.00	3.00
Performance Output	**3.40**	**1.36**	**3.74**	**4.00**	**3.98**	**4.76**	**3.00**
Performance Rating	Fair	Excellent	Poor	Poor	Poor	Very Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 71**	**Pipe 72**	**Pipe 73**	**Pipe 74**	**Pipe 75**	**Pipe 76**	**Pipe 77**
Diameter (in)	6	6	6	6	6	6	6
Age (yr)	110	48	80	121	57	85	118
Design Life (yr)	120	75	100	120	75	100	120
Vintage (yr)	1900	1962	1930	1889	1953	1925	1892
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	85	75	75	80	75	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Low
Coating	No	No	No	No	No	No	No
L Expectancy Output	1.22	2.46	3.62	1.22	3.00	3.56	1.22
S Condition Output	3.32	2.30	3.32	3.32	3.00	3.32	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.32	2.38	3.36	3.32	3.00	3.40	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	1.00	2.00
E Corrosion Output	2.00	2.00	2.00	1.00	2.00	2.00	1.00
Performance Output	**3.32**	**2.36**	**3.36**	**3.32**	**3.00**	**3.40**	**3.32**
Performance Rating	Fair	Good	Fair	Fair	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 78**	**Pipe 79**	**Pipe 80**	**Pipe 81**	**Pipe 82**	**Pipe 83**	**Pipe 84**
Diameter (in)	6	6	6	6	8	6	6
Age (yr)	120	87	81	97	57	40	71
Design Life (yr)	120	100	100	100	75	75	100
Vintage (yr)	1890	1923	1929	1913	1953	1970	1939
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	75	75	75	80	85	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	High	Low	Moderate	Moderate	Low	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	1.22	3.56	3.62	3.50	3.00	2.32	2.50
S Condition Output	3.32	3.32	3.32	3.32	3.00	2.30	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.32	3.40	3.36	3.42	3.00	2.32	3.42
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	2.00	2.00	2.00	1.00	1.00
E Corrosion Output	2.00	3.00	1.00	2.00	2.00	1.00	2.00
Performance Output	**3.32**	**3.40**	**3.36**	**3.42**	**3.00**	**2.32**	**3.42**
Performance Rating	Fair	Fair	Fair	Fair	Fair	Good	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 85**	**Pipe 86**	**Pipe 87**	**Pipe 88**	**Pipe 89**	**Pipe 90**	**Pipe 91**
Diameter (in)	6	4	6	6	4	4	6
Age (yr)	52	118	52	59	111	120	70
Design Life (yr)	75	120	75	75	120	120	100
Vintage (yr)	1958	1892	1958	1951	1899	1890	1940
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	65	80	80	65	65	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	Non-NHS	Non-NHS	NHS	NHS	Non-NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	Moderate	Low	Moderate	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.54	1.22	2.54	2.98	1.22	1.22	2.52
S Condition Output	3.00	3.98	3.00	3.00	3.98	3.98	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	3.88	3.00	3.00	3.88	3.88	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	1.00	2.00	2.00	1.00
E Corrosion Output	2.00	1.00	2.00	2.00	1.00	2.00	2.00
Performance Output	**3.00**	**3.88**	**3.00**	**3.00**	**3.88**	**3.88**	**3.00**
Performance Rating	Fair	Poor	Fair	Fair	Poor	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 92**	**Pipe 93**	**Pipe 94**	**Pipe 95**	**Pipe 96**	**Pipe 97**	**Pipe 98**
Diameter (in)	6	6	2	12	1	12	12
Age (yr)	14	59	93	16	45	37	2
Design Life (yr)	75	75	50	75	75	75	75
Vintage (yr)	1996	1951	1917	1994	1965	1973	2008
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	100	80	50	110	80	95	125
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	Yes	No	No	No	No
Break <5 Years Ago	No	No	Yes	No	No	No	No
Defect Type	N/A	N/A	Extreme	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	Segment	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	NHS	Non-NHS	Non-NHS	Unpaved
Material Type	DI	CI	Galvanized	DI	CI	DI	DI
Dissimilar Metals	No	No	No	No	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	Moderate	Low	Low
Coating	Yes	No	No	Yes	No	Yes	Yes
L Expectancy Output	1.36	2.98	4.44	1.32	2.42	2.40	1.52
S Condition Output	1.40	3.00	4.56	1.38	2.30	2.00	1.18
Break Rate Output	1.00	1.00	5.00	1.00	1.00	1.00	1.00
C Integrity Output	1.40	3.00	4.78	1.38	2.36	2.00	1.34
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	4.00	1.00	1.00	1.00	1.00
E Corrosion Output	1.00	2.00	2.00	1.00	2.00	1.00	1.00
Performance Output	**1.40**	**3.00**	**4.76**	**1.38**	**2.36**	**2.00**	**1.36**
Performance Rating	Excellent	Fair	Very Poor	Excellent	Good	Good	Excellent

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 99**	**Pipe 100**	**Pipe 101**	**Pipe 102**	**Pipe 103**	**Pipe 104**	**Pipe 105**
Diameter (in)	6	2	4	1	12	6	2
Age (yr)	95	53	120	85	2	94	45
Design Life (yr)	100	50	120	50	75	100	75
Vintage (yr)	1915	1957	1890	1925	2008	1916	1965
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	50	65	50	125	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	No	Yes
Break <5 Years Ago	No	No	No	No	No	No	Yes
Defect Type	N/A	N/A	N/A	Extreme	N/A	N/A	Extreme
Rehab Type	N/A	N/A	N/A	Segment	N/A	N/A	Segment
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	Galvanized	CI	Galvanized	DI	CI	CI
Dissimilar Metals	No	Yes	Yes	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	High	Moderate	Moderate	Moderate	Low	Low	Low
Coating	No	No	No	No	Yes	No	No
L Expectancy Output	3.52	4.62	1.22	4.44	1.52	3.54	2.42
S Condition Output	3.32	4.56	3.98	4.56	1.18	3.32	2.30
Break Rate Output	1.00	1.00	1.00	4.00	1.00	1.00	5.00
C Integrity Output	3.42	4.56	3.88	4.78	1.34	3.40	4.80
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	3.00	1.00	3.00	1.00	1.00	1.00
E Corrosion Output	3.00	3.00	3.00	3.00	1.00	1.00	1.00
Performance Output	**3.42**	**4.56**	**3.88**	**4.76**	**1.36**	**3.40**	**4.80**
Performance Rating	Fair	Very Poor	Poor	Very Poor	Excellent	Fair	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 106**	**Pipe 107**	**Pipe 108**	**Pipe 109**	**Pipe 110**	**Pipe 111**	**Pipe 112**
Diameter (in)	6	6	6	12	4	2	8
Age (yr)	95	85	58	15	121	72	20
Design Life (yr)	100	100	75	75	120	100	75
Vintage (yr)	1915	1925	1952	1995	1889	1938	1990
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	75	80	110	65	60	105
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	Yes	No	No	No	No	No	No
Break <5 Years Ago	Yes	No	No	No	No	No	No
Defect Type	Extreme	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	Segment	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	NHS	NHS	Non-NHS	NHS
Material Type	CI	CI	CI	DI	CI	CI	DI
Dissimilar Metals	No	No	Yes	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Low	Low	Moderate	Moderate	Low
Coating	No	No	No	Yes	No	No	Yes
L Expectancy Output	3.52	3.56	3.00	1.32	1.22	2.48	2.98
S Condition Output	3.32	3.32	3.00	1.38	3.98	4.00	1.34
Break Rate Output	5.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.78	3.40	3.00	1.38	3.88	3.98	1.82
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	2.00	1.00	1.00
E Corrosion Output	1.00	2.00	3.00	1.00	2.00	2.00	1.00
Performance Output	**4.76**	**3.40**	**3.00**	**1.38**	**3.88**	**3.98**	**1.84**
Performance Rating	Very Poor	Fair	Fair	Excellent	Poor	Poor	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 113**	**Pipe 114**	**Pipe 115**	**Pipe 116**	**Pipe 117**	**Pipe 118**	**Pipe 119**
Diameter (in)	2	1	10	1	6	6	2
Age (yr)	19	4	111	85	16	46	69
Design Life (yr)	75	75	120	100	75	75	100
Vintage (yr)	1991	2006	1899	1925	1994	1964	1941
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	90	100	80	60	100	85	70
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	Yes	No	No	No	Yes
Break <5 Years Ago	No	No	Yes	No	No	No	Yes
Defect Type	N/A	N/A	Extreme	N/A	N/A	N/A	Extreme
Rehab Type	N/A	N/A	Segment	N/A	N/A	N/A	Segment
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	NHS
Material Type	CI	Copper	CI	CI	DI	CI	CI
Dissimilar Metals	No	Yes	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Moderate
Coating	No	No	No	No	Yes	No	No
L Expectancy Output	2.98	1.48	1.22	3.56	1.32	2.44	2.54
S Condition Output	1.54	1.36	3.32	4.00	1.40	2.30	3.28
Break Rate Output	1.00	1.00	5.00	1.00	1.00	1.00	5.00
C Integrity Output	1.76	1.42	4.84	4.00	1.40	2.38	4.78
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	1.00	1.00	2.00	2.00
E Corrosion Output	2.00	3.00	2.00	2.00	1.00	1.00	2.00
Performance Output	**2.00**	**3.00**	**4.84**	**4.00**	**1.40**	**2.36**	**4.76**
Performance Rating	Good	Fair	Very Poor	Poor	Excellent	Good	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 120**	**Pipe 121**	**Pipe 122**	**Pipe 123**	**Pipe 124**	**Pipe 125**	**Pipe 126**
Diameter (in)	6	6	8	1	6	1	1
Age (yr)	87	71	70	97	36	55	71
Design Life (yr)	100	100	100	100	75	75	100
Vintage (yr)	1923	1939	1940	1913	1974	1955	1939
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	75	80	100	90	100	60
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	No	No
Break <5 Years Ago	No	No	No	Yes	No	No	No
Defect Type	N/A	N/A	N/A	Extreme	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	Segment	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	CI	CI	Copper	DI	Copper	CI
Dissimilar Metals	No	No	No	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	High	Moderate	Low	Moderate	High
Coating	No	No	No	No	Yes	No	No
L Expectancy Output	3.56	2.50	2.52	3.50	2.42	3.00	2.50
S Condition Output	3.32	3.32	3.00	1.36	1.98	1.36	4.00
Break Rate Output	1.00	1.00	1.00	5.00	1.00	1.00	1.00
C Integrity Output	3.40	3.42	3.00	4.76	1.78	1.98	4.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	3.00	1.00
E Corrosion Output	2.00	2.00	3.00	3.00	1.00	2.00	3.00
Performance Output	**3.40**	**3.42**	**3.00**	**4.76**	**1.78**	**3.00**	**4.00**
Performance Rating	Fair	Fair	Fair	Very Poor	Good	Fair	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 127**	**Pipe 128**	**Pipe 129**	**Pipe 130**	**Pipe 131**	**Pipe 132**	**Pipe 133**
Diameter (in)	6	6	12	6	1	6	8
Age (yr)	29	38	15	84	80	85	26
Design Life (yr)	75	75	75	100	100	100	75
Vintage (yr)	1981	1972	1995	1926	1930	1925	1984
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	95	90	110	75	100	75	105
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	DI	DI	CI	Copper	CI	DI
Dissimilar Metals	No	No	No	No	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	Low	Moderate	Moderate	Low
Coating	No	Yes	Yes	No	No	No	Yes
L Expectancy Output	2.58	2.38	1.32	3.56	3.62	3.56	2.74
S Condition Output	1.52	1.98	1.38	3.32	1.36	3.32	1.34
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.54	1.80	1.38	3.40	2.36	3.40	1.70
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	1.00	2.00	2.00	2.00	1.00
E Corrosion Output	2.00	1.00	1.00	1.00	3.00	2.00	1.00
Performance Output	**2.00**	**1.80**	**1.38**	**3.40**	**3.00**	**3.40**	**1.72**
Performance Rating	Good	Good	Excellent	Fair	Fair	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 134**	**Pipe 135**	**Pipe 136**	**Pipe 137**	**Pipe 138**	**Pipe 139**	**Pipe 140**
Diameter (in)	1	6	12	6	6	12	6
Age (yr)	105	12	12	40	28	54	28
Design Life (yr)	120	75	75	75	75	75	75
Vintage (yr)	1905	1998	1998	1970	1982	1956	1982
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	60	95	105	90	95	85	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	NHS	NHS	Non-NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	DI	CI	CI	DI
Dissimilar Metals	No	Yes	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Coating	No	No	No	Yes	No	No	Yes
L Expectancy Output	1.22	1.38	1.38	2.32	2.64	2.60	2.64
S Condition Output	4.00	1.52	1.50	1.98	1.52	3.00	1.40
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.00	1.52	1.50	1.82	1.56	3.00	1.60
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	2.00	2.00	1.00	2.00	1.00	1.00
E Corrosion Output	2.00	3.00	2.00	1.00	2.00	2.00	1.00
Performance Output	**4.00**	**3.00**	**2.00**	**1.84**	**2.00**	**3.00**	**1.60**
Performance Rating	Poor	Fair	Good	Good	Good	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 141**	**Pipe 142**	**Pipe 143**	**Pipe 144**	**Pipe 145**	**Pipe 146**	**Pipe 147**
Diameter (in)	6	12	16	8	1	8	2
Age (yr)	63	16	119	8	82	55	93
Design Life (yr)	75	75	120	75	100	75	50
Vintage (yr)	1947	1994	1891	2002	1928	1955	1917
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	110	85	120	100	80	50
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	NHS	NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	DI	CI	DI	Copper	CI	Galvanized
Dissimilar Metals	No	Yes	No	No	Yes	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	Low	Moderate	Low	High
Coating	No	Yes	No	Yes	No	No	No
L Expectancy Output	3.30	1.32	1.22	1.46	3.60	3.00	4.44
S Condition Output	3.00	1.38	3.30	1.20	1.36	3.00	4.56
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	1.38	3.32	1.32	2.36	3.00	4.56
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	3.00	1.00	3.00
E Corrosion Output	2.00	1.00	2.00	1.00	3.00	1.00	4.00
Performance Output	**3.00**	**1.38**	**3.32**	**1.32**	**3.00**	**3.00**	**4.56**
Performance Rating	Fair	Excellent	Fair	Excellent	Fair	Fair	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 148**	**Pipe 149**	**Pipe 150**	**Pipe 151**	**Pipe 152**	**Pipe 153**	**Pipe 154**
Diameter (in)	1	6	6	8	1	6	1
Age (yr)	90	82	79	119	110	85	37
Design Life (yr)	100	100	50	120	120	100	75
Vintage (yr)	1920	1928	1931	1891	1900	1925	1973
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	60	75	50	75	60	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	No	No
Break <5 Years Ago	No	No	No	Yes	No	No	No
Defect Type	N/A	N/A	N/A	Extreme	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	Segment	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	NHS	NHS	Non-NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	CI	Galvanized	CI	CI	CI	CI
Dissimilar Metals	No	Yes	Yes	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	High	Low	Moderate	Moderate	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	3.62	3.60	4.34	1.22	1.22	3.56	2.40
S Condition Output	4.00	3.32	4.66	3.32	4.00	3.32	2.30
Break Rate Output	1.00	1.00	1.00	5.00	1.00	1.00	1.00
C Integrity Output	4.00	3.38	4.64	4.84	4.00	3.40	2.36
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	2.00	4.00	1.00	2.00	1.00	1.00
E Corrosion Output	2.00	3.00	4.00	1.00	2.00	2.00	2.00
Performance Output	**4.00**	**3.38**	**4.64**	**4.84**	**4.00**	**3.40**	**2.36**
Performance Rating	Poor	Fair	Very Poor	Very Poor	Poor	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 155**	**Pipe 156**	**Pipe 157**	**Pipe 158**	**Pipe 159**	**Pipe 160**	**Pipe 161**
Diameter (in)	1	6	2	2	6	1	6
Age (yr)	85	31	58	70	40	63	58
Design Life (yr)	100	75	75	100	75	75	75
Vintage (yr)	1925	1979	1952	1940	1970	1947	1952
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	60	90	70	70	85	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	No	No
Break <5 Years Ago	No	No	No	Yes	No	No	No
Defect Type	N/A	N/A	N/A	Extreme	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	Segment	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	DI	CI	CI	CI	DI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Low	Moderate	Low	Low
Coating	No	Yes	No	No	No	Yes	No
L Expectancy Output	3.56	2.50	3.00	2.52	2.32	3.30	3.00
S Condition Output	4.00	1.98	3.28	3.28	2.30	3.00	3.00
Break Rate Output	1.00	1.00	1.00	5.00	1.00	1.00	1.00
C Integrity Output	4.00	1.74	3.28	4.78	2.32	3.00	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	1.00	1.00	2.00	1.00	1.00
E Corrosion Output	2.00	1.00	1.00	1.00	2.00	1.00	1.00
Performance Output	**4.00**	**1.76**	**3.28**	**4.76**	**2.32**	**3.00**	**3.00**
Performance Rating	Poor	Good	Fair	Very Poor	Good	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 162**	**Pipe 163**	**Pipe 164**	**Pipe 165**	**Pipe 166**	**Pipe 167**	**Pipe 168**
Diameter (in)	16	6	4	2	6	6	8
Age (yr)	93	96	121	121	83	110	121
Design Life (yr)	100	100	120	120	100	120	120
Vintage (yr)	1917	1914	1889	1889	1927	1900	1889
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	85	75	65	60	75	75	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Low	High	Low	Moderate	Low
Coating	No	No	No	No	No	No	No
L Expectancy Output	3.56	3.50	1.22	1.22	3.58	1.22	1.22
S Condition Output	3.30	3.32	3.98	4.00	3.32	3.32	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.38	3.42	3.88	4.00	3.38	3.32	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	1.00	1.00	2.00
E Corrosion Output	1.00	2.00	1.00	4.00	1.00	2.00	1.00
Performance Output	**3.38**	**3.42**	**3.88**	**4.00**	**3.38**	**3.32**	**3.32**
Performance Rating	Fair	Fair	Poor	Poor	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 169**	**Pipe 170**	**Pipe 171**	**Pipe 172**	**Pipe 173**	**Pipe 174**	**Pipe 175**
Diameter (in)	8	8	6	6	6	8	6
Age (yr)	54	59	54	24	71	56	53
Design Life (yr)	75	75	75	75	100	75	75
Vintage (yr)	1956	1951	1956	1986	1939	1954	1957
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	80	80	95	75	80	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Interstate	Non-NHS	Non-NHS	Unpaved	Non-NHS	NHS	Non-NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Moderate	Low	Moderate	Moderate	Low
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.60	2.98	2.60	3.00	2.50	3.00	2.56
S Condition Output	3.00	3.00	3.00	1.52	3.32	3.00	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	3.00	3.00	2.00	3.42	3.00	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	3.00	1.00	1.00	1.00	1.00	2.00	1.00
E Corrosion Output	1.00	2.00	2.00	1.00	2.00	2.00	1.00
Performance Output	**3.00**	**3.00**	**3.00**	**2.00**	**3.42**	**3.00**	**3.00**
Performance Rating	Fair	Fair	Fair	Good	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 176**	**Pipe 177**	**Pipe 178**	**Pipe 179**	**Pipe 180**	**Pipe 181**	**Pipe 182**
Diameter (in)	12	4	12	8	1	6	1
Age (yr)	26	119	58	121	43	88	42
Design Life (yr)	75	120	75	120	75	100	75
Vintage (yr)	1984	1891	1952	1889	1967	1922	1968
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	110	65	85	75	80	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	NHS	Non-NHS	Unpaved	Non-NHS	Non-NHS
Material Type	DI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	Yes	No	Yes	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	High	Low	Low	Moderate	High	Moderate
Coating	Yes	No	No	No	No	No	No
L Expectancy Output	2.74	1.22	3.00	1.22	2.40	3.58	2.38
S Condition Output	1.38	3.98	3.00	3.32	2.30	3.32	2.30
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.68	3.88	3.00	3.32	2.36	3.38	2.34
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	2.00	1.00	1.00	1.00	1.00
E Corrosion Output	1.00	3.00	3.00	1.00	2.00	3.00	2.00
Performance Output	**1.68**	**3.88**	**3.00**	**3.32**	**2.36**	**3.38**	**2.32**
Performance Rating	Good	Poor	Fair	Fair	Good	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 183**	**Pipe 184**	**Pipe 185**	**Pipe 186**	**Pipe 187**	**Pipe 188**	**Pipe 189**
Diameter (in)	6	6	6	2	4	6	8
Age (yr)	59	106	101	2	121	6	71
Design Life (yr)	75	120	120	75	120	75	100
Vintage (yr)	1951	1904	1909	2008	1889	2004	1939
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	75	75	115	65	120	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	Yes	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	Extreme	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	Segment	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	Non-NHS	NHS	NHS	Non-NHS
Material Type	CI	CI	CI	DI	CI	DI	CI
Dissimilar Metals	No	No	No	Yes	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	High	Low	Moderate	Low
Coating	No	No	No	Yes	No	Yes	No
L Expectancy Output	2.98	1.22	1.36	1.52	1.22	1.48	2.50
S Condition Output	3.00	3.32	3.32	1.22	3.98	1.20	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	4.00	1.00
C Integrity Output	3.00	3.32	3.36	1.36	3.88	3.98	3.42
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	2.00	1.00	1.00
E Corrosion Output	2.00	2.00	2.00	1.00	3.00	1.00	1.00
Performance Output	**3.00**	**3.32**	**3.36**	**1.36**	**3.88**	**3.98**	**3.42**
Performance Rating	Fair	Fair	Fair	Excellent	Poor	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 190**	**Pipe 191**	**Pipe 192**	**Pipe 193**	**Pipe 194**	**Pipe 195**	**Pipe 196**
Diameter (in)	1	2	1	8	6	2	6
Age (yr)	102	50	110	57	84	53	52
Design Life (yr)	120	75	120	75	100	75	75
Vintage (yr)	1908	1960	1900	1953	1926	1957	1958
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	60	80	60	80	75	70	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	1.34	2.46	1.22	3.00	3.56	2.56	2.54
S Condition Output	4.00	2.30	4.00	3.00	3.32	3.28	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.00	2.38	4.00	3.00	3.40	3.36	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	2.00	1.00	1.00	1.00	1.00
E Corrosion Output	2.00	2.00	2.00	2.00	2.00	3.00	2.00
Performance Output	**4.00**	**2.36**	**4.00**	**3.00**	**3.40**	**3.36**	**3.00**
Performance Rating	Poor	Good	Poor	Fair	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 197**	**Pipe 198**	**Pipe 199**	**Pipe 200**	**Pipe 201**	**Pipe 202**	**Pipe 203**
Diameter (in)	8	8	6	0.75	2	1.25	6
Age (yr)	99	40	59	27	72	57	85
Design Life (yr)	100	75	75	75	100	75	100
Vintage (yr)	1911	1970	1951	1983	1938	1953	1925
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	95	80	100	60	70	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	Yes	No
Break <5 Years Ago	No	No	No	Yes	No	Yes	No
Defect Type	N/A	N/A	N/A	Extreme	N/A	Extreme	N/A
Rehab Type	N/A	N/A	N/A	Segment	N/A	Segment	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Unpaved	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	DI	CI	Copper	CI	CI	CI
Dissimilar Metals	No	Yes	Yes	Yes	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	High	Moderate	Moderate	Moderate
Coating	No	Yes	No	No	No	No	No
L Expectancy Output	3.44	2.32	2.98	2.68	2.48	3.00	3.56
S Condition Output	3.32	1.52	3.00	1.36	4.00	3.28	3.32
Break Rate Output	1.00	1.00	1.00	5.00	1.00	5.00	1.00
C Integrity Output	3.40	1.52	3.00	4.82	3.98	4.86	3.40
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	2.00	1.00	1.00	1.00
E Corrosion Output	2.00	1.00	3.00	4.00	3.00	2.00	2.00
Performance Output	**3.40**	**1.52**	**3.00**	**4.82**	**3.98**	**4.84**	**3.40**
Performance Rating	Fair	Excellent	Fair	Very Poor	Poor	Very Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 204**	**Pipe 205**	**Pipe 206**	**Pipe 207**	**Pipe 208**	**Pipe 209**	**Pipe 210**
Diameter (in)	8	1	2	6	6	1	1
Age (yr)	59	80	63	14	1	40	85
Design Life (yr)	75	100	75	75	75	75	100
Vintage (yr)	1951	1930	1947	1996	2009	1970	1925
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	100	70	100	120	85	60
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	Copper	CI	DI	DI	DI	CI
Dissimilar Metals	No	Yes	No	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Low	High	Moderate
Coating	No	No	No	Yes	Yes	Yes	No
L Expectancy Output	2.98	3.62	3.30	1.36	1.44	2.32	3.56
S Condition Output	3.00	1.36	3.28	1.40	1.20	1.98	4.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	2.36	3.28	1.40	1.32	1.82	4.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	1.00	1.00	1.00	1.00
E Corrosion Output	2.00	3.00	2.00	1.00	1.00	1.00	2.00
Performance Output	**3.00**	**3.00**	**3.28**	**1.40**	**1.32**	**1.84**	**4.00**
Performance Rating	Fair	Fair	Fair	Excellent	Excellent	Good	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 211**	**Pipe 212**	**Pipe 213**	**Pipe 214**	**Pipe 215**	**Pipe 216**	**Pipe 217**
Diameter (in)	6	6	1	8	4	12	6
Age (yr)	59	85	110	4	120	100	57
Design Life (yr)	75	100	120	75	120	100	75
Vintage (yr)	1951	1925	1900	2006	1890	1910	1953
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	75	60	120	65	80	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	Non-NHS	NHS	NHS	NHS
Material Type	CI	CI	CI	DI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	High	Low	Low
Coating	No	No	No	Yes	No	No	No
L Expectancy Output	2.98	3.56	1.22	1.48	1.22	2.54	3.00
S Condition Output	3.00	3.32	4.00	1.20	3.98	3.32	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	3.40	4.00	1.34	3.88	3.40	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	2.00	2.00	2.00
E Corrosion Output	2.00	2.00	2.00	1.00	3.00	3.00	1.00
Performance Output	**3.00**	**3.40**	**4.00**	**1.36**	**3.88**	**3.40**	**3.00**
Performance Rating	Fair	Fair	Poor	Excellent	Poor	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 218**	**Pipe 219**	**Pipe 220**	**Pipe 221**	**Pipe 222**	**Pipe 223**	**Pipe 224**
Diameter (in)	6	12	8	30	2	6	6
Age (yr)	53	58	119	64	59	6	64
Design Life (yr)	75	75	120	75	50	75	75
Vintage (yr)	1957	1952	1891	1946	1951	2004	1946
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	85	75	90	50	115	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	Yes	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	Extreme	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	Segment	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	NHS	NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	CI	Galvanized	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Low	Moderate	Low	Moderate	Low	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.56	3.00	1.22	3.28	3.48	1.48	3.28
S Condition Output	3.00	3.00	3.32	3.00	4.56	1.24	3.00
Break Rate Output	1.00	4.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	4.00	3.32	3.00	4.52	1.36	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	2.00	2.00	3.00	1.00	1.00
E Corrosion Output	1.00	1.00	2.00	1.00	2.00	1.00	2.00
Performance Output	**3.00**	**4.00**	**3.32**	**3.00**	**4.52**	**1.36**	**3.00**
Performance Rating	Fair	Poor	Fair	Fair	Very Poor	Excellent	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 225**	**Pipe 226**	**Pipe 227**	**Pipe 228**	**Pipe 229**	**Pipe 230**	**Pipe 231**
Diameter (in)	2	6	1	6	6	1	6
Age (yr)	38	119	88	104	118	78	15
Design Life (yr)	75	120	100	120	120	100	75
Vintage (yr)	1972	1891	1922	1906	1892	1932	1995
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	75	100	75	75	60	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	Copper	CI	CI	CI	DI
Dissimilar Metals	No	No	Yes	No	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Low	Moderate	Moderate	Low	High	Low
Coating	No	No	No	No	No	No	Yes
L Expectancy Output	2.38	1.22	3.58	1.26	1.22	3.66	1.32
S Condition Output	2.30	3.32	1.36	3.32	3.32	4.00	1.40
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	2.34	3.32	2.38	3.32	3.32	4.00	1.40
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	3.00	1.00	1.00	1.00	1.00
E Corrosion Output	1.00	1.00	3.00	2.00	3.00	3.00	1.00
Performance Output	**2.32**	**3.32**	**3.00**	**3.32**	**3.32**	**4.00**	**1.40**
Performance Rating	Good	Fair	Fair	Fair	Fair	Poor	Excellent

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 232**	**Pipe 233**	**Pipe 234**	**Pipe 235**	**Pipe 236**	**Pipe 237**	**Pipe 238**
Diameter (in)	8	8	1	0.75	6	2	6
Age (yr)	36	43	110	58	105	72	51
Design Life (yr)	75	75	120	75	120	100	75
Vintage (yr)	1974	1967	1900	1952	1905	1938	1959
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	95	95	100	70	75	60	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	DI	DI	Copper	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Low	Moderate	Low	Moderate	Moderate	Low
Coating	Yes	Yes	No	No	No	No	No
L Expectancy Output	2.42	2.40	1.22	3.00	1.22	2.48	2.50
S Condition Output	1.52	1.52	1.36	3.28	3.32	4.00	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.52	1.52	1.36	3.28	3.32	3.98	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	3.00	1.00	1.00	2.00	1.00
E Corrosion Output	1.00	1.00	2.00	1.00	2.00	3.00	1.00
Performance Output	**1.52**	**1.52**	**3.00**	**3.28**	**3.32**	**3.98**	**3.00**
Performance Rating	Excellent	Excellent	Fair	Fair	Fair	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 239**	**Pipe 240**	**Pipe 241**	**Pipe 242**	**Pipe 243**	**Pipe 244**	**Pipe 245**
Diameter (in)	6	24	6	1	2	6	6
Age (yr)	62	15	24	95	57	81	55
Design Life (yr)	75	75	75	100	75	100	75
Vintage (yr)	1948	1995	1986	1915	1953	1929	1955
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	85	115	100	100	70	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	No	No	No
Break <5 Years Ago	No	No	No	Yes	No	No	No
Defect Type	N/A	N/A	N/A	Extreme	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	Segment	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	DI	DI	DI	Copper	CI	CI	CI
Dissimilar Metals	No	Yes	Yes	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Low	Moderate	Moderate	Moderate	Moderate	High
Coating	Yes	Yes	Yes	No	No	No	No
L Expectancy Output	3.30	1.32	3.00	3.52	3.00	3.62	3.00
S Condition Output	2.30	1.32	1.40	1.36	3.28	3.32	3.00
Break Rate Output	1.00	1.00	1.00	5.00	1.00	1.00	1.00
C Integrity Output	2.32	1.32	1.98	4.78	3.28	3.36	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	1.00	1.00
E Corrosion Output	1.00	1.00	1.00	3.00	2.00	2.00	3.00
Performance Output	**2.32**	**1.32**	**1.98**	**4.76**	**3.28**	**3.36**	**3.00**
Performance Rating	Good	Excellent	Good	Very Poor	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 246**	**Pipe 247**	**Pipe 248**	**Pipe 249**	**Pipe 250**	**Pipe 251**	**Pipe 252**
Diameter (in)	8	6	6	0.75	2	6	12
Age (yr)	59	62	89	56	32	80	57
Design Life (yr)	75	75	100	75	75	100	75
Vintage (yr)	1951	1948	1921	1954	1978	1930	1953
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	80	75	70	85	75	85
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Unpaved	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	CI	DI	CI	CI
Dissimilar Metals	Yes	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Moderate	Low	Moderate	Moderate	Moderate
Coating	No	No	No	No	Yes	No	No
L Expectancy Output	2.98	3.30	3.60	3.00	2.48	3.62	3.00
S Condition Output	3.00	3.00	3.32	3.28	1.98	3.32	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	3.00	3.38	3.28	1.74	3.36	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	1.00	1.00	1.00	2.00
E Corrosion Output	3.00	2.00	2.00	1.00	1.00	2.00	2.00
Performance Output	**3.00**	**3.00**	**3.38**	**3.28**	**1.76**	**3.36**	**3.00**
Performance Rating	Fair	Fair	Fair	Fair	Good	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 253**	**Pipe 254**	**Pipe 255**	**Pipe 256**	**Pipe 257**	**Pipe 258**	**Pipe 259**
Diameter (in)	6	8	6	2	1	8	1
Age (yr)	51	56	33	69	110	119	95
Design Life (yr)	75	75	75	100	50	120	100
Vintage (yr)	1959	1954	1977	1941	1900	1891	1915
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	80	90	70	50	75	60
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	CI	DI	CI	Galvanized	CI	CI
Dissimilar Metals	No	No	No	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	High	Moderate	High
Coating	No	No	Yes	No	No	No	No
L Expectancy Output	2.50	3.00	2.46	2.54	4.54	1.22	3.52
S Condition Output	3.00	3.00	1.98	3.28	4.56	3.32	4.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.00	3.00	1.76	3.36	4.56	3.32	3.98
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00	3.00	2.00	1.00
E Corrosion Output	2.00	2.00	1.00	3.00	3.00	2.00	3.00
Performance Output	**3.00**	**3.00**	**1.76**	**3.36**	**4.56**	**3.32**	**3.98**
Performance Rating	Fair	Fair	Good	Fair	Very Poor	Fair	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 260**	**Pipe 261**	**Pipe 262**	**Pipe 263**	**Pipe 264**	**Pipe 265**	**Pipe 266**
Diameter (in)	6	36	6	6	6	6	6
Age (yr)	48	64	104	54	102	40	93
Design Life (yr)	75	75	120	75	120	75	100
Vintage (yr)	1962	1946	1906	1956	1908	1970	1917
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	85	90	75	80	75	90	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	NHS	NHS	Non-NHS	Non-NHS	Unpaved	NHS
Material Type	CI	CI	CI	CI	CI	DI	CI
Dissimilar Metals	No	Yes	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	High	Low	Low	High	Moderate	Low	Low
Coating	No	No	No	No	No	Yes	No
L Expectancy Output	2.46	3.28	1.26	2.60	1.34	2.32	3.56
S Condition Output	2.30	3.00	3.32	3.00	3.32	1.98	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	2.38	3.00	3.32	3.00	3.32	1.82	3.40
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	2.00	2.00	1.00	1.00	1.00	2.00
E Corrosion Output	3.00	3.00	1.00	3.00	2.00	1.00	1.00
Performance Output	**3.00**	**3.00**	**3.32**	**3.00**	**3.32**	**1.84**	**3.40**
Performance Rating	Fair	Fair	Fair	Fair	Fair	Good	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 267**	**Pipe 268**	**Pipe 269**	**Pipe 270**	**Pipe 271**	**Pipe 272**	**Pipe 273**
Diameter (in)	6	1	1	1	8	1	6
Age (yr)	90	65	105	3	61	121	100
Design Life (yr)	100	100	120	75	75	50	100
Vintage (yr)	1920	1945	1905	2007	1949	1889	1910
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	100	100	100	80	50	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	Yes	Yes	No	No	Yes	No
Break <5 Years Ago	No	Yes	Yes	No	No	Yes	No
Defect Type	N/A	Extreme	Extreme	N/A	N/A	Extreme	N/A
Rehab Type	N/A	Segment	Segment	N/A	N/A	Segment	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	Copper	Copper	Copper	CI	Galvanized	CI
Dissimilar Metals	No	Yes	Yes	Yes	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Moderate
Coating	No	No	No	No	No	No	No
L Expectancy Output	3.62	2.62	1.22	1.50	3.30	4.58	2.54
S Condition Output	3.32	1.36	1.36	1.36	3.00	4.56	3.32
Break Rate Output	1.00	5.00	5.00	1.00	1.00	5.00	1.00
C Integrity Output	3.36	4.82	4.82	1.42	3.00	4.78	3.40
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	2.00	2.00	1.00	4.00	1.00
E Corrosion Output	2.00	3.00	3.00	3.00	2.00	3.00	2.00
Performance Output	**3.36**	**4.82**	**4.82**	**3.00**	**3.00**	**4.76**	**3.40**
Performance Rating	Fair	Very Poor	Very Poor	Fair	Fair	Very Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 274**	**Pipe 275**	**Pipe 276**	**Pipe 277**	**Pipe 278**	**Pipe 279**	**Pipe 280**
Diameter (in)	1	1	2	6	4	6	1
Age (yr)	94	5	71	85	59	64	29
Design Life (yr)	100	75	100	100	75	75	75
Vintage (yr)	1916	2005	1939	1925	1951	1946	1981
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	100	110	60	80	75	80	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	Yes	No	Yes	No	No	No	No
Break <5 Years Ago	No	No	Yes	No	No	No	No
Defect Type	Extreme	N/A	Extreme	N/A	N/A	N/A	N/A
Rehab Type	Segment	N/A	Segment	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	NHS	Non-NHS	NHS	Non-NHS
Material Type	Copper	CI	CI	DI	CI	CI	Copper
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	High	Moderate	Low	Low	Moderate	Low	Moderate
Coating	No	No	No	Yes	No	No	No
L Expectancy Output	3.54	1.48	2.50	3.56	2.98	3.28	2.58
S Condition Output	1.36	1.26	4.00	3.00	3.00	3.00	1.36
Break Rate Output	4.00	1.00	5.00	1.00	1.00	1.00	1.00
C Integrity Output	4.00	1.38	4.76	3.00	3.00	3.00	1.58
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	2.00	1.00	1.00	2.00	2.00
E Corrosion Output	3.00	2.00	1.00	1.00	2.00	1.00	2.00
Performance Output	**4.00**	**2.00**	**4.76**	**3.00**	**3.00**	**3.00**	**2.00**
Performance Rating	Poor	Good	Very Poor	Fair	Fair	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 281**	**Pipe 282**	**Pipe 283**	**Pipe 284**	**Pipe 285**	**Pipe 286**	**Pipe 287**
Diameter (in)	6	8	6	12	8	0.75	1
Age (yr)	85	118	71	12	119	53	73
Design Life (yr)	100	120	100	75	120	75	100
Vintage (yr)	1925	1892	1939	1998	1891	1957	1937
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	75	75	110	75	70	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	NHS	Unpaved	Non-NHS
Material Type	CI	CI	CI	DI	CI	CI	Copper
Dissimilar Metals	No	No	No	No	No	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	High	Moderate	Low	Low	Low	High
Coating	No	No	No	Yes	No	No	No
L Expectancy Output	3.56	1.22	2.50	1.38	1.22	2.56	2.46
S Condition Output	3.32	3.32	3.32	1.38	3.32	3.28	1.36
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.40	3.32	3.42	1.40	3.32	3.36	1.46
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00	2.00	1.00	2.00
E Corrosion Output	2.00	3.00	2.00	1.00	1.00	1.00	4.00
Performance Output	**3.40**	**3.32**	**3.42**	**1.40**	**3.32**	**3.36**	**4.00**
Performance Rating	Fair	Fair	Fair	Excellent	Fair	Fair	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 288**	**Pipe 289**	**Pipe 290**	**Pipe 291**	**Pipe 292**	**Pipe 293**	**Pipe 294**
Diameter (in)	8	6	8	6	6	6	8
Age (yr)	111	16	61	58	121	95	66
Design Life (yr)	120	75	75	75	120	100	100
Vintage (yr)	1899	1994	1949	1952	1889	1915	1944
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	100	80	80	75	75	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	Yes	No	Yes	No	No	No	No
Break <5 Years Ago	No	No	Yes	No	No	No	No
Defect Type	Extreme	N/A	Severe	N/A	N/A	N/A	N/A
Rehab Type	Segment	N/A	Segment	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	NHS	Non-NHS	NHS	Non-NHS	Non-NHS
Material Type	CI	DI	CI	CI	CI	CI	CI
Dissimilar Metals	No	Yes	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Low	Moderate	Low	High	Low
Coating	No	Yes	No	No	No	No	No
L Expectancy Output	1.22	1.32	3.30	3.00	1.22	3.52	2.60
S Condition Output	3.32	1.40	3.00	3.00	3.32	3.32	3.00
Break Rate Output	4.00	1.00	4.00	1.00	1.00	1.00	1.00
C Integrity Output	4.00	1.40	4.30	3.00	3.32	3.42	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	2.00	1.00	2.00	1.00	1.00
E Corrosion Output	1.00	1.00	1.00	2.00	1.00	3.00	1.00
Performance Output	**4.00**	**1.40**	**4.32**	**3.00**	**3.32**	**3.42**	**3.00**
Performance Rating	Poor	Excellent	Poor	Fair	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 295**	**Pipe 296**	**Pipe 297**	**Pipe 298**	**Pipe 299**	**Pipe 300**	**Pipe 301**
Diameter (in)	6	6	1	8	6	4	6
Age (yr)	81	117	90	34	82	26	121
Design Life (yr)	100	120	100	75	100	75	120
Vintage (yr)	1929	1893	1920	1976	1928	1984	1889
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	75	75	60	95	75	100	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	Yes	No	No	No	No	No	No
Break <5 Years Ago	Yes	No	No	No	No	No	No
Defect Type	Extreme	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	Segment	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	DI	CI	DI	CI
Dissimilar Metals	Yes	Yes	No	No	No	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	High	Low	Moderate	Low	Moderate	Moderate	Moderate
Coating	No	No	No	Yes	No	Yes	No
L Expectancy Output	3.62	1.22	3.62	2.44	3.60	2.74	1.22
S Condition Output	3.32	3.32	4.00	1.52	3.32	1.36	3.32
Break Rate Output	5.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.82	3.32	4.00	1.52	3.38	1.68	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	1.00	1.00	1.00	1.00	2.00
E Corrosion Output	4.00	3.00	2.00	1.00	2.00	1.00	2.00
Performance Output	**4.82**	**3.32**	**4.00**	**1.52**	**3.38**	**1.68**	**3.32**
Performance Rating	Very Poor	Fair	Poor	Excellent	Fair	Good	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 302**	**Pipe 303**	**Pipe 304**	**Pipe 305**	**Pipe 306**	**Pipe 307**	**Pipe 308**
Diameter (in)	6	6	8	12	6	6	6
Age (yr)	53	40	60	61	43	95	85
Design Life (yr)	75	75	75	75	75	100	100
Vintage (yr)	1957	1970	1950	1949	1967	1915	1925
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	85	80	85	90	80	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	Yes	Yes	No	No
Break <5 Years Ago	No	No	No	Yes	Yes	No	No
Defect Type	N/A	N/A	N/A	Mild	Extreme	N/A	N/A
Rehab Type	N/A	N/A	N/A	Segment	Segment	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Unpaved	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	CI	DI	DI	DI
Dissimilar Metals	No	No	Yes	No	Yes	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Low	Moderate	Moderate	Moderate	Moderate	High
Coating	No	No	No	No	Yes	Yes	Yes
L Expectancy Output	2.56	2.32	2.98	3.30	2.40	3.52	3.56
S Condition Output	3.00	2.30	3.00	3.00	1.98	3.00	3.00
Break Rate Output	1.00	1.00	1.00	3.00	5.00	1.00	1.00
C Integrity Output	3.00	2.32	3.00	3.32	4.80	3.00	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	1.00	1.00
E Corrosion Output	1.00	1.00	3.00	2.00	1.00	1.00	1.00
Performance Output	**3.00**	**2.32**	**3.00**	**3.32**	**4.80**	**3.00**	**3.00**
Performance Rating	Fair	Good	Fair	Fair	Very Poor	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 309**	**Pipe 310**	**Pipe 311**	**Pipe 312**	**Pipe 313**	**Pipe 314**	**Pipe 315**
Diameter (in)	12	1	6	6	1	6	8
Age (yr)	12	68	86	118	98	121	81
Design Life (yr)	75	100	100	120	100	120	100
Vintage (yr)	1998	1942	1924	1892	1912	1889	1929
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	110	70	75	75	100	75	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	Yes	No	No
Break <5 Years Ago	No	No	No	No	Yes	No	No
Defect Type	N/A	N/A	N/A	N/A	Extreme	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	Segment	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	DI	CI	CI	CI	Copper	CI	CI
Dissimilar Metals	No	No	No	No	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Low	High	High	Low	Moderate
Coating	Yes	No	No	No	No	No	No
L Expectancy Output	1.38	2.56	3.54	1.22	3.46	1.22	3.62
S Condition Output	1.38	3.28	3.32	3.32	1.36	3.32	3.32
Break Rate Output	1.00	1.00	1.00	1.00	5.00	1.00	1.00
C Integrity Output	1.40	3.36	3.40	3.32	4.78	3.32	3.36
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00	2.00	2.00	1.00
E Corrosion Output	1.00	2.00	1.00	3.00	4.00	1.00	2.00
Performance Output	**1.40**	**3.36**	**3.40**	**3.32**	**4.76**	**3.32**	**3.36**
Performance Rating	Excellent	Fair	Fair	Fair	Very Poor	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 316**	**Pipe 317**	**Pipe 318**	**Pipe 319**	**Pipe 320**	**Pipe 321**	**Pipe 322**
Diameter (in)	4	6	1	2	1	1	6
Age (yr)	121	61	56	103	20	54	63
Design Life (yr)	120	75	75	50	75	75	75
Vintage (yr)	1889	1949	1954	1907	1990	1956	1947
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	65	80	75	50	90	70	80
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS
Material Type	CI	CI	DI	Galvanized	CI	CI	CI
Dissimilar Metals	No	No	No	Yes	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	High	Moderate	High	Low	Moderate
Coating	No	No	Yes	No	No	No	No
L Expectancy Output	1.22	3.30	3.00	4.44	2.98	2.60	3.30
S Condition Output	3.98	3.00	3.00	4.56	1.54	3.28	3.00
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	3.88	3.00	3.00	4.56	1.76	3.34	3.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	2.00	1.00	1.00	3.00	1.00	2.00	1.00
E Corrosion Output	1.00	2.00	1.00	3.00	3.00	1.00	2.00
Performance Output	**3.88**	**3.00**	**3.00**	**4.56**	**3.00**	**3.34**	**3.00**
Performance Rating	Poor	Fair	Fair	Very Poor	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 323**	**Pipe 324**	**Pipe 325**	**Pipe 326**	**Pipe 327**	**Pipe 328**	**Pipe 329**
Diameter (in)	2	1	0.75	6	1	6	1
Age (yr)	34	84	90	44	104	84	98
Design Life (yr)	75	100	100	75	120	100	100
Vintage (yr)	1976	1926	1920	1966	1906	1926	1912
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	85	100	100	85	60	75	60
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	Yes	No	No	No	No
Break <5 Years Ago	No	No	Yes	No	No	No	No
Defect Type	N/A	N/A	Extreme	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	Segment	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	DI	Copper	Copper	CI	CI	CI	CI
Dissimilar Metals	Yes	Yes	Yes	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Low	Moderate	Moderate	Low	Moderate	High
Coating	Yes	No	No	No	No	No	No
L Expectancy Output	2.44	3.56	3.62	2.42	1.26	3.56	3.46
S Condition Output	1.98	1.36	1.36	2.30	4.00	3.32	4.00
Break Rate Output	1.00	1.00	5.00	1.00	1.00	1.00	1.00
C Integrity Output	1.76	2.40	4.82	2.36	4.00	3.40	4.00
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	2.00	2.00	2.00	1.00	1.00	1.00
E Corrosion Output	1.00	3.00	3.00	2.00	1.00	2.00	3.00
Performance Output	**1.76**	**3.00**	**4.82**	**2.36**	**4.00**	**3.40**	**4.00**
Performance Rating	Good	Fair	Very Poor	Good	Poor	Fair	Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 330**	**Pipe 331**	**Pipe 332**	**Pipe 333**	**Pipe 334**	**Pipe 335**	**Pipe 336**
Diameter (in)	6	6	6	6	6	6	6
Age (yr)	41	57	86	55	87	84	120
Design Life (yr)	75	75	100	75	100	100	120
Vintage (yr)	1969	1953	1924	1955	1923	1926	1890
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	85	80	75	80	75	75	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	Yes	Yes	No	No	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Low
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.36	3.00	3.54	3.00	3.56	3.56	1.22
S Condition Output	2.30	3.00	3.32	3.00	3.32	3.32	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	2.32	3.00	3.40	3.00	3.40	3.40	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	1.00	1.00	2.00
E Corrosion Output	2.00	3.00	3.00	1.00	2.00	2.00	3.00
Performance Output	**2.32**	**3.00**	**3.40**	**3.00**	**3.40**	**3.40**	**3.32**
Performance Rating	Good	Fair	Fair	Fair	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 337**	**Pipe 338**	**Pipe 339**	**Pipe 340**	**Pipe 341**	**Pipe 342**	**Pipe 343**
Diameter (in)	1	1	8	6	8	6	1
Age (yr)	102	6	60	32	61	26	20
Design Life (yr)	120	75	75	75	75	75	75
Vintage (yr)	1908	2004	1950	1978	1949	1984	1990
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	100	100	80	85	80	100	90
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	NHS	Non-NHS	Non-NHS	Non-NHS	NHS	Non-NHS	NHS
Material Type	Copper	Copper	CI	CI	CI	DI	CI
Dissimilar Metals	Yes	Yes	No	No	Yes	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Low	Low	Moderate	Low
Coating	No	No	No	No	No	Yes	No
L Expectancy Output	1.34	1.48	2.98	2.48	3.30	2.74	2.98
S Condition Output	1.36	1.36	3.00	2.30	3.00	1.40	1.54
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	1.36	1.42	3.00	2.40	3.00	1.66	1.76
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	3.00	2.00	1.00	1.00	2.00	1.00	2.00
E Corrosion Output	3.00	3.00	1.00	1.00	3.00	1.00	1.00
Performance Output	**3.00**	**3.00**	**3.00**	**2.40**	**3.00**	**1.66**	**2.00**
Performance Rating	Fair	Fair	Fair	Good	Fair	Good	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 344**	**Pipe 345**	**Pipe 346**	**Pipe 347**	**Pipe 348**	**Pipe 349**	**Pipe 350**
Diameter (in)	1	6	20	10	6	1	2
Age (yr)	38	85	33	111	70	39	85
Design Life (yr)	75	100	75	120	100	75	50
Vintage (yr)	1972	1925	1977	1899	1940	1971	1925
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	75	105	80	80	85	50
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	NHS	Unpaved	NHS
Material Type	CI	CI	DI	CI	CI	DI	Galvanized
Dissimilar Metals	No	No	No	Yes	No	No	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Low	Moderate	Moderate	Moderate	Low	Moderate	Moderate
Coating	No	No	Yes	No	No	Yes	No
L Expectancy Output	2.38	3.56	2.46	1.22	2.52	2.36	4.44
S Condition Output	2.30	3.32	1.52	3.32	3.00	1.98	4.56
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	2.34	3.40	1.52	3.32	3.00	1.80	4.56
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	2.00	1.00	4.00
E Corrosion Output	1.00	2.00	1.00	3.00	1.00	1.00	3.00
Performance Output	**2.32**	**3.40**	**1.52**	**3.32**	**3.00**	**1.80**	**4.56**
Performance Rating	Good	Fair	Excellent	Fair	Fair	Good	Very Poor

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 351**	**Pipe 352**	**Pipe 353**	**Pipe 354**	**Pipe 355**	**Pipe 356**	**Pipe 357**
Diameter (in)	1	6	12	8	6	6	1
Age (yr)	50	63	84	36	45	40	10
Design Life (yr)	75	75	100	75	75	75	75
Vintage (yr)	1960	1947	1926	1974	1965	1970	2000
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	80	80	80	95	85	90	100
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	NHS	NHS	Non-NHS	Non-NHS	Non-NHS
Material Type	CI	CI	CI	DI	CI	DI	Copper
Dissimilar Metals	No	Yes	No	No	No	Yes	Yes
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Low	Low	Moderate	Moderate
Coating	No	No	No	Yes	No	Yes	No
L Expectancy Output	2.46	3.30	3.56	2.42	2.42	2.32	1.42
S Condition Output	2.30	3.00	3.32	1.52	2.30	1.98	1.36
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	2.38	3.00	3.40	1.52	2.36	1.82	1.38
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	2.00	1.00	1.00	1.00	2.00
E Corrosion Output	2.00	3.00	2.00	1.00	1.00	1.00	3.00
Performance Output	**2.36**	**3.00**	**3.40**	**1.52**	**2.36**	**1.84**	**3.00**
Performance Rating	Good	Fair	Fair	Excellent	Good	Good	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 358**	**Pipe 359**	**Pipe 360**	**Pipe 361**	**Pipe 362**	**Pipe 363**	**Pipe 364**
Diameter (in)	6	6	1	12	2	4	2
Age (yr)	40	55	49	63	88	120	58
Design Life (yr)	75	75	75	75	50	120	75
Vintage (yr)	1970	1955	1961	1947	1922	1890	1952
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	90	80	80	85	50	65	70
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	Yes	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	Extreme	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	Segment	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS	NHS	NHS	Non-NHS
Material Type	DI	CI	CI	CI	Galvanized	CI	CI
Dissimilar Metals	No	No	No	Yes	Yes	Yes	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate
Coating	Yes	No	No	No	No	No	No
L Expectancy Output	2.32	3.00	2.46	3.30	4.40	1.22	3.00
S Condition Output	1.98	3.00	2.30	3.00	4.56	3.98	3.28
Break Rate Output	1.00	1.00	1.00	1.00	4.00	1.00	1.00
C Integrity Output	1.82	3.00	2.38	3.00	4.78	3.88	3.28
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	2.00	4.00	2.00	1.00
E Corrosion Output	1.00	2.00	1.00	3.00	3.00	3.00	2.00
Performance Output	**1.84**	**3.00**	**2.36**	**3.00**	**4.76**	**3.88**	**3.28**
Performance Rating	Good	Fair	Good	Fair	Very Poor	Poor	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 365**	**Pipe 366**	**Pipe 367**	**Pipe 368**	**Pipe 369**	**Pipe 370**	**Pipe 371**
Diameter (in)	1	8	1	6	2	1	8
Age (yr)	100	111	85	78	52	55	111
Design Life (yr)	100	120	100	100	75	75	120
Vintage (yr)	1910	1899	1925	1932	1958	1955	1899
Rehab-Lining	No	No	No	No	No	No	No
HWCF (c value)	60	75	60	75	70	70	75
R Thickness (%)	100	100	100	100	100	100	100
Tuberculation	None	None	None	None	None	None	None
Leak	No	No	No	No	No	No	No
Pipe Break	No	No	No	No	No	No	No
Break <5 Years Ago	No	No	No	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No	No	No	No
Pressure Surges	No	No	No	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No	No	No	No
Discolored Water	No	No	No	No	No	No	No
Disturbances	No	No	No	No	No	No	No
Flooding	Never	Never	Never	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	Non-NHS	Non-NHS	NHS	NHS
Material Type	CI	CI	CI	CI	CI	CI	CI
Dissimilar Metals	No	No	No	No	No	No	No
Cathodic Protection	No	No	No	No	No	No	No
Stray Currents	No	No	No	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	High	Moderate	Moderate	Low
Coating	No	No	No	No	No	No	No
L Expectancy Output	2.54	1.22	3.56	3.66	2.54	3.00	1.22
S Condition Output	4.00	3.32	4.00	3.32	3.28	3.28	3.32
Break Rate Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C Integrity Output	4.00	3.32	4.00	3.32	3.36	3.28	3.32
I Condition Output	1.00	1.00	1.00	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00	1.00	2.00	2.00
E Corrosion Output	2.00	2.00	2.00	3.00	2.00	2.00	1.00
Performance Output	**4.00**	**3.32**	**4.00**	**3.32**	**3.36**	**3.28**	**3.32**
Performance Rating	Poor	Fair	Poor	Fair	Fair	Fair	Fair

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)

Table D.1 Field Data Samples Cont.

Sample	**Pipe 372**	**Pipe 373**	**Pipe 374**	**Pipe 375**
Diameter (in)	2	6	12	8
Age (yr)	63	103	59	26
Design Life (yr)	75	120	75	75
Vintage (yr)	1947	1907	1951	1984
Rehab-Lining	No	No	No	No
HWCF (c value)	70	75	85	105
R Thickness (%)	100	100	100	100
Tuberculation	None	None	None	None
Leak	No	No	No	No
Pipe Break	No	No	No	No
Break <5 Years Ago	No	No	No	No
Defect Type	N/A	N/A	N/A	N/A
Rehab Type	N/A	N/A	N/A	N/A
Pressure Exceeded	No	No	No	No
Pressure Surges	No	No	No	No
Adequate Fire Flow	Yes	Yes	Yes	Yes
Pressure Complaints	No	No	No	No
Discolored Water	No	No	No	No
Disturbances	No	No	No	No
Flooding	Never	Never	Never	Never
Live Load	Non-NHS	Non-NHS	Non-NHS	NHS
Material Type	CI	CI	CI	DI
Dissimilar Metals	Yes	No	No	Yes
Cathodic Protection	No	No	No	No
Stray Currents	No	No	No	No
Soil Corrosivity	Moderate	Moderate	Moderate	Moderate
Coating	No	No	No	Yes
L Expectancy Output	3.30	1.30	2.98	2.74
S Condition Output	3.28	3.32	3.00	1.34
Break Rate Output	1.00	1.00	1.00	1.00
C Integrity Output	3.28	3.32	3.00	1.70
I Condition Output	1.00	1.00	1.00	1.00
E Stress Output	1.00	1.00	1.00	1.00
E Corrosion Output	3.00	2.00	2.00	1.00
Performance Output	**3.28**	**3.32**	**3.00**	**1.72**
Performance Rating	Fair	Fair	Fair	Good

Hazen Williams C Factor (HWCF), Remaining Thickness (R Thickness), Life Expectancy (L Expectancy), Structural Condition (S Condition), Current Integrity (C Integrity), Internal Condition (I Condition), External Stress (E Stress), External Corrosion (E Corrosion)