DISSERTATION

# FAILURE ASSESSMENT MODEL TO PRIORITIZE PIPE REPLACEMENT IN WATER UTILITY ASSET MANAGEMENT

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY PETER D. ROGERS ENTITLED FAILURE ASSESSMENT MODEL TO PRIORITIZE PIPE REPLACEMENT IN WATER UTILITY ASSET MANAGEMENT BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

**Committee on Graduate Work**

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# ABSTRACT OF DISSERTATION

## FAILURE ASSESSMENT MODEL TO PRIORITIZE PIPE REPLACEMENT IN WATER UTILITY ASSET MANAGEMENT

The condition of a water distribution system has strong correlations with community health and economic development. However, studies indicate an urgent need to upgrade the nation's aging and deteriorating distribution systems if they are to continue to provide customers with reliable and safe water supplies. In response, water utilities are using various performance measurement initiatives including pipeline asset management. These require assessment of each pipeline's condition to identify failure-prone pipes and prioritize their renewal. However, the below ground location of the pipes and lack of standard guidelines or tools to assist in assessment make pipeline assessment and renewal decisions difficult.

In this research, a pipe failure assessment model was developed and tested to assist water utilities with their pipe renewal decisions. A conceptual model was created from a review of case studies, theories and asset management tools. The model consists of several modules (components) written in Visual Basic for Application (VBA) within a Microsoft Excel platform. Rather than requiring extensive field data to determine the cause of breaks, the model's failure prediction module and Multicriteria Decision Analysis (MCDA) modules use pipe inventory and break data compiled from the utility's existing operation

and maintenance records. Recognizing that pipe renewal decisions are based on risk avoidance as well as on failure probabilities, a unique feature of the model is a consequence module that allows the decision maker to compare "what-if" infrastructure investment scenarios.

The conceptual model was refined through collaboration of a focus group of water utility professionals. By drawing on the knowledge and experience of these experts, the review process added unique features that facilitate the model's use and responsiveness to the industry's needs. The model was tested using pipe inventory and break history information contributed by Laramie (Wyoming) Water and Colorado Springs Utilities. Although each water supplier differs in population served, operating conditions, pipe inventories, and pipe break histories, both utilities were able to provide their pipe inventory and break history in electronic form which facilitated the model processing.

Evaluations from the participating utilities indicated that the pipe failure assessment model would enhance the industry's ability to prioritize pipe renewal decisions and improve their return on investment. Utility personnel indicated that the model's use of routine pipeline operation and maintenance records, combined with its consequence modeling features, addresses both the data limitations and risk avoidance characteristics of the industry in a way that is intuitive and understandable to utility staff. Utility personnel also commented that the model adds knowledge and transparency to the decision process, which is critical in an environment in which decisions will have to withstand scrutiny from various interest groups. Lastly, the investigation illustrates the need for better inventory and break data since this data plays such an important role in the industry's buried infrastructure planning programs.

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## DEDICATION

Esta obra está dedicada a “El Coronel” quien falleció durante las etapas finales de su realización. Siempre he valorado sus enseñanzas sobre la posibilidad de cambiar nuestra vida y la importancia de dedicarse a algo con todo el corazón.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Scope of the Problem

Water utilities are facing unprecedented challenges resulting from aging infrastructure, tighter water quality and environmental regulations, and declining maintenance budgets. In responding to these challenges, utilities must learn to "work smarter" by embracing performance measurement initiatives. One such approach involves leveraging the use of information technology combined with the use of asset management systems to improve the efficiency and effectiveness of the asset management work process (Halfawy, 2005). The primary goal of asset management is to maintain the condition of the assets at agreed customer and environmental service levels at the lowest life-cycle costs. For infrastructure, life-cycle costs include all the costs incurred throughout the different stages of its life from the "cradle to the grave" including capital, maintenance, operating and replacement costs (Grigg, 2003).

Because most of a water utility's infrastructure is contained within the distribution and transmission systems, the subject of buried infrastructure asset management has developed into one of the priority issues facing the water supply industry. This topic has also gained momentum from numerous highly-publicized studies conducted by prominent organizations such as the American

Society of Civil Engineers (ASCE) and the American Water Works Association (AWWA), documenting the urgent need to upgrade the nation's aging pipe infrastructure with cost estimates ranging anywhere from $100 to $325 billion over the next 20 years (Grablutz, 2001). Without the assistance of a unified funding mechanism, the water supply industry must confront these staggering estimates by developing and financing their own pipeline renewal plans. In terms of buried pipeline infrastructure renewal, the term "renewal" encompasses both pipe rehabilitation (repair) and replacement.

The water supply industry has traditionally been managed by very conservative, slow-changing, and risk-adverse organizations. Accordingly, the management and operation of water distribution systems has been conducted in a reactive mode with pipeline renewal activities occurring in response to emergency water main leaks or breaks. Although this reactive approach has functioned over the years, as underground pipelines continue to age and approach the end of their useful life, many utilities are discovering the inadequacy of this approach in dealing with the increasing breakage rates typical of decaying systems. Aside from the costs associated with pipeline renewal, water pipe breaks present a myriad of other problems including decreasing hydraulic capacity, degradation of water quality, increasing customer complaints, and increased liability resulting from the direct and indirect economic consequences of service disruption.

Water utilities attempting to take a more proactive stance in their pipeline renewal programs discover an overall lack of standardized methodologies and tools to assist them. Without any guidelines to follow, and acknowledging that the real-time pipe inspection of entire distribution system is economically and logistically infeasible, decision makers base their renewal decisions on broad-based factors including pipe age, material, maintenance histories, and customer complaints (AWWA, 2002). While this approach provides utilities with a prioritization mechanism, there are numerous limitations which stifle its overall effectiveness. Broad-based approaches oversimplify a highly-complex deterioration process which often leads to replacement activities in which pipes with adequate remaining useful life might be prematurely removed from service, or conversely, pipes which should be replaced are kept in service. Aside from basing prioritization decisions on insufficient information, this approach also lacks the necessary forecasting ability required to proactively develop pipe renewal plans.

## 1.2 Water Distribution Infrastructure in the United States

Water infrastructure is one of the six key infrastructure groups that provide essential services to the citizens of our nation. Embedded within the water infrastructure group are water distribution systems, which consist of an interconnected network of pipelines and accessories (valves, fittings, meters, etc.) that supply water from the treatment plant and/or storage facilities to the end user. Figure 1.1 shows an example of a water distribution network. According to a recent utility survey conducted by AWWA, there are nearly 1 million miles of distribution pipe inventory in the United States (Grigg, 2005).

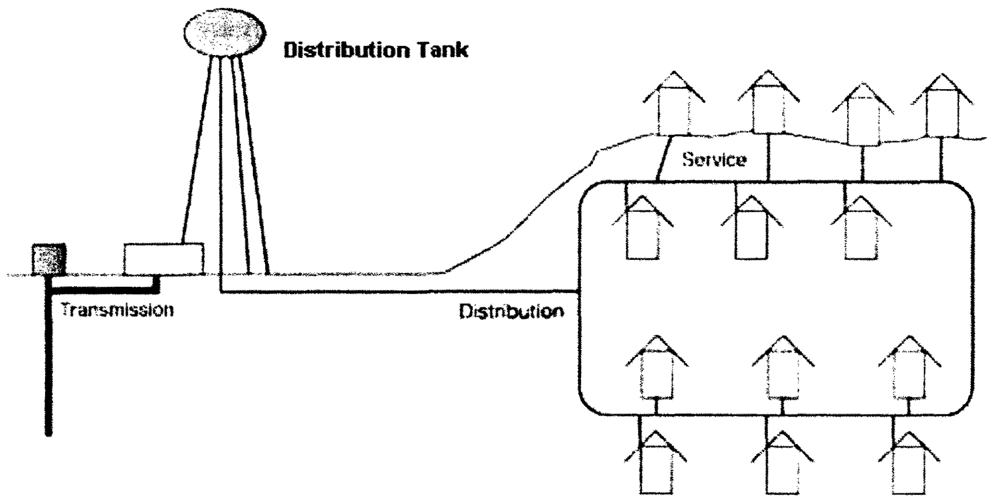


Figure 1.1 Schematic of a Water Distribution System

### 1.2.1 Distribution Pipe Inventory

The water distribution piping in the United States is comprised of a mixture of old and new materials. Most of the water pipes installed from the late 1800's through the 1960's were manufactured from cast iron. The earliest cast iron pipe, commonly referred to as "pit" cast iron, was manufactured by pouring molten iron into a sand mold. Due to potential inconsistencies with the wall thickness, the pipe was designed with a wall thickness that exceeded the required thickness for the subjected internal and external pressures. In 1920, the process of pouring molten iron into the mold was replaced with a process of centrifugally casting pipe. The resultant pipe, known as "spun" or "centrifugally" cast iron pipe, had a superior material strength which allowed for a thinner wall thickness than pit cast iron pipe. During the next 40 years, there were numerous improvements to cast iron pipe including the use of cement-mortar lining to prevent corrosion, advances in manufacturing processes, and the advancement of pipe joint technologies (AWWA, 2002).

The next major improvement in pipe materials occurred in the late 1960's with the introduction of ductile iron pipe. The principal difference between ductile iron and cast iron relates to the each material's graphite form. Whereas cast iron has a flake-like form, ductile iron has a spherical graphite form. This graphite form provides both a superior strength and higher resistance to graphitic corrosion (AWWA, 2002). In addition to this advancement in iron pipe technology, there were numerous innovations from the 1970's through the 1990's with the development of other pipe materials including polyvinyl chloride (PVC) and high-density polyethylene (HDPE). Although these materials are not as strong as ductile iron, their superior corrosion resistance has had a significant effect on the industry's pipe failure rate. Table 1.1 shows the progression of pipe technology in the United States during the 20$^{th}$ century (AWWA, 2002).

### 1.2.2 Water Supply System Characteristics and Operation

Public water systems in the United States are classified as either community or noncommunity systems. The distinction between the two types is specified by the Safe Drinking Water Act (SDWA). SDWA criteria specify that community systems must have a minimum of 15 connections or an average of 25 persons for a period of at least 60 days/year (SWDA, 1996). Noncommunity systems serve the public in a more sporadic basis and normally include hotels, businesses, parks, etc. Of the approximate 170,000 public water systems within

## Table 1.1 Timeline of Pipe Technology in the United States in the 20th Century

| Material | Joint Type | Corrosion Protection | | 1900's | 1910's | 1920's | 1930's | 1940's | 1950's | 1960's | 1970's | 1980's | 1990's |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Interior | Exterior | | | | | | | | | | |
| Steel | Welded | None | None | ■ | ■ | ■ | ■ | ▨ | ▨– | | | | |
| Steel | Welded | Cement | None | | | | | ■ | ■▨ | ▨ | ▨ | ▨ | ▨ |
| Cast Iron (pit) | Lead | None | None | ▨ | ▨ | | | | | | | | |
| Cast Iron | Lead | None | None | | | ▨ | ▨■ | ■ | ■– | | | | |
| Cast Iron | Leadite | Cement | None | | | –■ | ■▨ | ■▨ | ▨■ | ■ | ■ | ■ | |
| Cast Iron | Leadite | None | None | | | –■ | ■ | ■ | ■– | | | | |
| Cast Iron | Rubber | Cement | None | | | –■ | ■ | ■▨ | ■ | ■ | ■– | | |
| Cast Iron | Rubber | Cement | None | | | | | | –▨ | ▨ | ▨■ | ■ | |
| Ductile Iron | Rubber | Cement | None | | | | | | | –▨ | ▨ | ▨ | ▨ |
| Ductile Iron | Rubber | Cement | PE Encasement | | | | | | | –■ | ■▨ | ▨ | ▨ |
| Asbestos Cement | Rubber | Material | Material | | | | –■ | ■ | ■▨ | ▨■ | ■ | ■ | ■ |
| Rein. Concrete | Rubber | Material | Material | –■ | ■ | ■ | ■ | ■▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| Prestressed Concrete | Rubber | Material | Material | | | | | ■▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| PVC | Rubber | Material | Material | | | | | | ■ | ■ | ■▨ | ▨ | ▨ |
| HDPE | Fused | Material | Material | | | | | –■ | ■ | ■ | ■ | ■ | ▨ |
| Molecularly Oriented PVC | Rubber | Material | Material | | | | | | | | ■ | ■ | ■▨ |

Commercially Available ■
Predominately In Use ▨

U.S., an estimated 115,000 (68%) are designated as noncommunity systems and the remaining 55,000 as community systems. Although community systems comprise a mere 32% of the total public water system inventory, they serve an estimated 96% of the population or 264 million persons (CDC, 2002).

The ownership of water supply systems is mixed between the private and public sectors. Generally, water systems serving larger communities tend to owned and operated by municipal governments, whereas systems that serve smaller communities tend to managed by private enterprises. This trend is the result of a historical progression of water system development in the U.S. in which private companies struggled to meet the social needs of growing cities and municipal governments became financially empowered to manage their water systems (Rogers, unpublished manuscript, 2005). Accordingly, the majority of citizens receive their water services from municipally owned and operated systems.

Although the water supply industry has traditionally been managed by very conservative, slow-changing, and risk-adverted organizations, numerous issues are emerging that require the industry's transformation into a more competitive, customer-focused, continuous improvement culture (Davies, 2001). One such issue relates to the water consumers: water utilities, whether public or private, are no longer unnoticed monopolies. Not only do consumers have high expectations with regard to water quality, reliable services and low rates, they now have greater access to information and demand greater involvement in the decision making process (Davies, 2001). Aside from high public expectations and accountability, utilities must also contend with a myriad of pressures including tighter drinking water and environmental regulations resulting from improved science, water resource stressing, aging infrastructure, shifting workforce demographics, and a political environment with a low recognition of the value of water. As a result of these formidable obstacles, water utilities are under great pressure to "do more with less" (Grigg, 2005).

### 1.3 Distinction between Pipe Breaks and Leaks

The distinction between pipe breaks and leaks is of fundamental importance to the water supply industry for two primary reasons. First, it provides a snapshot of the problems and causes within a system, and secondly, it provides a measure for performance comparisons between systems. Although water utilities recognize the importance of this distinction, the industry still lacks a consistent definition for each event. This inconsistency often leads to large variances in reported break rates amongst utilities. For example, O'Day (1982) reported that some systems such as New York City report only main breaks whereas as others such as Houston report both breaks and leaks.

The primary distinction between breaks and leaks is that breaks represent a structural failure in the pipe, whereas leaks occur when either joints or service connections are not tight (O'Day,1982). Pipe breaks occur when the culmination of loading events (internal pressure, earth loads, etc.) exceeds the pipe's material strength. Breaks are usually detectable because they lead to substantial losses of pressure and flow at the point of the break and possibly elsewhere in the system. In the context of this research, the term "break" and "failure" are used interchangeably. Water pipe leaks normally produce smaller, less easily detected and less disruptive changes in pressure and flow that may go undetected and/or uncorrected for some time. Unfortunately, the distinction between a large leak and a main break is often unclear.

### 1.4 Causes of Pipe Breaks

The mechanisms that lead to pipe deterioration are very complex and not completely understood. In addition to numerous interconnected factors that influence pipe performance and longevity, their "out of sight, out of mind" nature and a shortage of reliable breakage data also contribute to this incomplete knowledge (Kleiner and Rajani, 2001). The primary reason for the lack of reliable breakage data relates to a historical lack of awareness by water utilities regarding the importance of collecting this information as a basis for future renewal activities.

Buried water mains are designed to withstand a combination of internal and design loads. External loads include live loads, earth loads, and frost loads whereas the internal loads consist of internal water pressure and water hammer. Aside from these loading conditions, pipes are often exposed to a beam loading scenario resulting from the disruption of the pipe bed material caused by pipe leaks and/or poor construction practices.

The structural integrity of a water main is jeopardized by deterioration process that occurs on both the inside and the outside surfaces of the pipe. The rate of external corrosion is dependent on the pipe material type and characteristics of the surrounding soil. Highly corrosive soils accelerate the formation of pits on the pipe's exterior, effectively reducing the thickness of the pipe wall. Internal deterioration is related to the hydraulic and chemical properties of the water flowing through the pipe. If the water flowing through a pipe is corrosive, eventually the thickness of the pipe wall will be reduced internally through a process known as graphitization (Agbenowosi, 2000). The water quality also influences the growth of tuberculation within the pipe, reducing the effective pipe diameter.

Numerous descriptive statistical studies indicate that small diameter pipes (6~8 in.) are susceptible to circumferential breaks whereas larger diameter pipes (exceeding 10 in.) are prone to longitudinal breaks. Longitudinal breaks (splitting) are usually caused by ring failure or crushing whereas circular breaks are considered to result from beam failure (O'Day, 1982).

### 1.5 Costs and Consequences of Pipe Failure

Table 1.2 summarizes the cost estimates provided by the American Society of Civil Engineers (ASCE), the United States Environmental Protection Agency (USEPA), the American Water Works Association (AWWA), and the Water Infrastructure Network (WIN) to upgrade the nation's drinking water infrastructure (AWWA, 2002).

In addition to pipe replacement costs, water utilities must incur the day-to-day pipe repair costs. According to a distribution survey conducted by the AWWA in 2002, the average yearly break rate for water mains in North America is 22 breaks per 100 miles with an average repair cost of $3,000 per break and average pipe replacement rate of once every 200 years (AWWA, 2002). Aside from pipeline renewal costs, water pipe breaks reduce hydraulic capacity, degrade water quality, cause customer dissatisfaction, and increase the potential for service disruption. In the case of service disruptions, as a result of the numerous direct and indirect economic consequences, the final outcome can be very expensive. For example, a disruption of water services to a commercial site depending largely on water for serving their customers would lead to significant business losses

Table 1.2 Cost Estimates for Drinking Water Infrastructure

| **Organization** | **Cost Estimate** | **Period** | **Comments** |
|---|---|---|---|
| ASCE | $11 billion | per year | |
| USEPA | $151 billion | next 20 years | $83 billion allocated towards underground |
| AWWA | $250billion | next 30 years | |
| WIN | $460 billion | next 20 years | Includes both water and wastewater |

## 1.6 Study Objectives

The primary objective of this research was to develop a failure assessment model capable of addressing two crucial issues of pipeline infrastructure management: identifying failure-prone pipes and prioritizing individual pipes to be replaced. Rather than attempting to measure the structural deterioration of each pipeline within the water system, the model uses a performance-based approach to estimate the present and future state of each pipeline from routine operation and maintenance data. A key component of the model is the separation of pipelines into two principal groups: pipelines with a minimum of three break records and pipelines with less than three break records. Whereas pipelines with a minimum of three break records are analyzed in the model's probabilistic module, pipelines with either one or two break records are profiled within the model's Multicriteria Decision Analysis (MCDA) module.

The failure prediction module uses the Power Law form of a Non-Homogeneous Poisson Process (NHPP) to calculate the probability of failure, expected number of failures, and time to next failure. A NHPP approach was selected based on its widespread application to reliability modeling for repairable systems and its flexibility through the use of the ROCOF (rate of occurrence of failure) function. The model's MCDA module is based on a Weighted Average Method (WAM) in which points are assigned to variables identified as having an influence on the overall life expectancy of each pipe. The resultant point total provides a relative ranking that corresponds to a replacement priority for each pipe. Whereas the water mains analyzed through the failure prediction module pose the greatest threat to the overall system performance, and thus receive first replacement priority, information from the MCDA module is useful in utility multiyear planning activities.

Recognizing that renewal decisions in the water supply industry are driven by risk avoidance, a unique feature of the pipe failure assessment model is that it supplements the failure predictive modeling with a risk-based consequence module. This dual approach enables decision makers to prioritize pipe renewal decisions as part of a comprehensive risk management process. As such, utility personnel can forecast the risks associated with a variety of "what if" infrastructure investment scenarios including a prediction of the consequences relating to the "do nothing" alternative. The model also provides transparency in the decision making process, which is critical in an environment in which decisions will have to withstand scrutiny from various interest groups.

## 1.7 Dissertation and Research Outline

The structure and outline of the dissertation parallels closely the research methodology used to undertake the research project. Following the introduction provided in Chapter 1, Chapter 2 presents a summary of the extensive literature review that was performed to develop the foundation for the research. Drawing from several case studies, the review provides key insights regarding the data requirements, limitations and accuracy in predicting future breaks of various approaches, and important concepts relating to the role of risk management in pipeline replacement prioritization process. Chapter 3 presents several important reliability modeling concepts and discusses how reliability modeling can be applied to water main failure analysis. In Chapter 4, the author discusses the contribution of industry experts to the development of the model and presents the final version of the failure assessment model. The author also presents the features of each module in such a manner that the chapter can be used as a program manual. Chapter 5 describes the application of the model for two case studies, including the necessary alterations to the pipe inventory and break data as well as the results of the correlation analysis to identify each utility's unique break frequency variables. Chapter 6 provides a comprehensive discussion and interpretation of the modeling results for each case study. Finally, Chapter 7 discusses the attributes and limitations of the methodology developed in the research and provide suggestions for future research.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Review of Existing Pipeline Asset Management Models

A review of existing pipeline asset management models identified common features relevant to the development of the failure assessment model. First, regardless of each model's sophistication and unique capabilities, all existing asset management models utilize a centralized database to manage the utility's pipeline inventory. This feature is important since the database serves as a critical media for the exchange and sharing of information in an industry whose internal operations tend to function as a series of "islands of information" (Halfawy, 2005). In addition, database query features enable users to access a wealth of inventory, asset condition, inspection and maintenance history information.

The review also revealed the frequent use of broad-based planning approaches such as KANEW and Nessie curves (AWWARF, 2001). These methods forecast pipe replacement rates and financial expenditures based on pipe material useful life estimates provided by expert opinions and/or by utility personnel. While this information is valuable in planning applications, because the process involves grouping pipes within age and material categories, it can not identify or prioritize individual pipes to replace. Also, because the life expectancies are merely estimates, the results are highly subjective (AWWA, 2002). Aside from broad-based approaches, the review also revealed the frequent use of deterioration point assignment (DPA) models to prioritize pipe replacement. The basis of the DPA technique is to provide the decision maker with a "failure score" for each pipe by summing individual scores for each factor believed to influence pipe failure rates. If the total failure score exceeds an established threshold value, then the pipe is considered a candidate for replacement or rehabilitation. While this approach is useful in providing a snapshot of a pipeline's current condition, it does not provide a forecasting mechanism needed for developing a pipeline replacement program.

## 2.2 Descriptive Statistical Studies for Deteriorating Water Mains

The earliest investigations relating to pipe breakage were based on descriptive statistical studies aimed at providing insights regarding failure patterns and identifying potential break-causing factors. One of the first statistical investigations of pipe breakage was published in 1960, in which a series of reports (Arnold 1960; Clark 1960; Niemeyer 1960, Remus 1960) examined the water main breaks in four large cities: Detroit, Indianapolis, New York, and Philadelphia. The purpose of their investigation was to identify the causes of pipe failures, provide a statistical analysis of the break information, and propose preventative measures to enhance water main performance. One of the primary conclusions from this investigation was that utilities should evaluate the relationship between renewal costs and failure rates. A more recent descriptive statistical study was conducted by O'Day (1982) on the pipe breakage data for the city of Philadelphia. The author concluded that small diameter pipes (6 ~ 8 in.) are susceptible to circumferential breaks whereas larger diameter pipes (exceeding 10 in.) are prone to longitudinal breaks. O'Day's investigation also concluded that pipeline management decisions should be based on analytical techniques rather than the application "rule of thumb" approaches such as useful life and pipe age.

Although descriptive statistical studies of deteriorating water distribution systems provide researchers with valuable insights regarding failure patterns and possible break-causing factors, this form of analysis is limited in its application to pipe renewal and prioritization. Because these studies focus on identifying trends in the overall system, as opposed to failure analysis at the individual pipe level, they tend to obscure the high variability of failure patterns that exist among different pipes within a given system (Andreou, 1986). Hence, this information is difficult to apply in assessing the failure behavior of individual pipes. This point is further illustrated by the overwhelming amount of statistical information generated by this form of analyses, which can not be easily translated for individual pipes.

### 2.3 Pipe Renewal and Prioritization Methodologies

As a result of the aforementioned limitations of descriptive statistical approaches, several quantitative tools have been developed to assist the water supply industry with their pipeline renewal and prioritization operations. A review of the scientific literature identified that the prioritization approaches can be classified into the following categories:

- Deterioration point assignment methods
- Break-even analyses
- Mechanistic models
- Regression methods
- Failure Probability methods

### 2.3.1 Deterioration Point Assignment Methods

In the deterioration point assignment (DPA) method, the modeler defines a set of factors which are known to contribute to the pipe failure rate. While these factors are system-specific, they typically include pipe age, pipe material, location, soil type, and break history. Having established these factors, quantitative items such as pipe age are divided into class intervals (vintages) and then assigned numeric scores (weights). For linguistic factors such as soil type or pipe material, the scores are based on utility-specific preferences. For example, clay material might be assigned a score of 1 whereas sandy soil receives a score of 0. Once the scores for each factor are established, a total failure score is calculated for each pipe by summing the individual factor scores. If the total failure score exceeds a utility-established threshold value, then the pipe is considered a candidate for replacement or rehabilitation (Loganathan et al., 2002). While this approach provides decision makers with a transparent and documented prioritization process, its reliance on user-defined class intervals and scores makes it very subjective to user preferences. Moreover, it provides only a snapshot assessment of the current condition and lacks the necessary predictive power for planning future renewal activities.

An example of a DPA model is the Pipe Evaluation Model (PEM) used by the Louisville Water Company (LWC) which includes a detailed scoring system that assigns points based upon 23 parameters (Bates and Gregory, 1994).

### 2.3.2 Break-Even Analysis

A break-even analysis is an economics-oriented approach which determines the present worth costs associated with the future life of a pipe based on its future repair costs and eventual replacement costs. In order to forecast the number of breaks in future years, the method must be augmented with either a regression or probability-based predictive model described later in the chapter. Figure 2.1 provides a graphical illustration of the approach in which only the direct costs are considered. The curve representing the present worth repair costs increases over time since these costs are cumulative in nature. In the case of the replacement costs, assuming that the replacement costs is fixed over time, their present worth decreases over time. The total cost curve is the sum of the repair and replacement cost curves with an optimal replacement time, $t^*$, occurring at the point where the total cost curve is at a minimum. Assuming that at the $n^{th}$ break, a decision has to be made whether to repair or replace the pipe and that for the previous (n-1) breaks only repairs have been performed, the present worth of the total cost at the $n^{th}$ break can be expressed as (Loganathan et al., 2002):

$$T_n = \sum_{i=1}^{n} \frac{C_i}{(1+R)^{t_i}} + \frac{F_n}{(1+R)^{t_n}} \qquad (2.1)$$

where:

| | |
|---|---|
| $t_i$: | time of the $i^{th}$ break measured from the installation year |
| $C_i$: | repair costs at the $i^{th}$ break |
| $F_n$: | replacement cost at time $t_n$ |
| R: | discount rate |

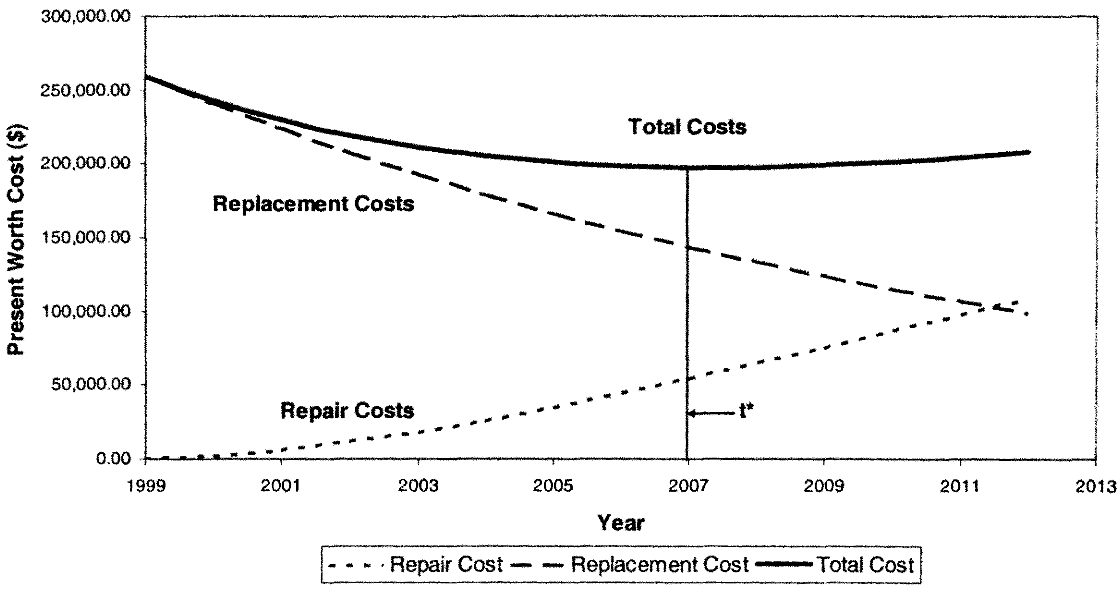


Figure 2.1 Example of a Break-Even Analysis Excluding Indirect Costs (Grablutz et al, 2000)

### 2.3.3 Mechanistic Models

Mechanistic models are physical models which attempt to address the specific factors that lead to pipe failure while also providing some form of condition assessment. As shown in Table 2.1, the mechanisms that lead to pipe failure are often grouped into three principal categories.

Table 2.1 Principal Pipe Failure Categories (Makar and Kleiner, 2000)

| Failure Category | Description |
|---|---|
| 1. Physical | Structural properties of pipe, material type, pipe-soil interaction, and the quality of installation. |
| 2. Loading | Internal loads: operational pressure<br>External loads: traffic, frost, soil, third party |
| 3. Deterioration | External and internal deterioration resulting the biochemical and electro-chemical environment. |

Recent investigations have provided scientists with an improved understanding of the issues that influence the structural behavior of buried pipes. Accordingly, several failure models now address failure processes such as temperature-induced stresses, pressure loads, and frost load. Likewise, there is now a better understanding of interior and exterior corrosion as a function of soil properties, pipe coatings, water quality parameters, and installation depth (Agbenowosi, 2000). Despite these advances, the complex interaction between the various pipe failure mechanisms is still not completely understood and difficult to model. Mechanical modeling efforts have also been stifled by an industry-wide lack of available data, since so much of the data pertains to the condition of the pipe underground.

Agbenowosi (2000) developed a mechanistic model that attempted to incorporate several of the interconnected mechanisms that contribute to failure in underground pipe. The researcher's model is comprised of three separate sub-models: a pipe load model (PLM), pipe deterioration model (PDM), and a pipe break model (PBM). The premise of Agbenowosi's approach was to compare the predicted residual pipe strength to the subjected loads. The PLM calculates the total loading condition by assessing several of the physical forces such as the earth, traffic, internal pressure, expansive soil, thermal, and frost loads. The pipe's residual strength was determined through the PDM, which simulated both the deterioration of the pipe due to corrosion and its effect on the thinning of the pipe walls. Based on the pipe wall thickness, the pipe's fracture toughness, and the initial design strength of the pipe, the PDM calculated the overall residual strength of the pipe. Having completed the first two portions of the model, the PBM was then applied to assess the vulnerability of the pipe at any time. This vulnerability was determined relative to a critical safety factor, as specified by the user, which is defined as the ratio of residual strength to the applied stress.

While mechanistic models appeal to many researchers because of their robust theoretical basis, they have several characteristics that limit their usefulness to the water supply industry. One such barrier relates to the high level of technical expertise required to use the models. For instance, at the conclusion of his investigation, Agbenowosi (2000) indicated that mechanistic models normally require case by case calibration and field verification. This is particularly true in cases where certain below-ground parameters have to be assumed due to data limitations. It appears that the lack of below-ground data and the need for high levels of technical expertise present formidable barriers in the application of these forms of models.

### 2.3.4 Regression Methods

Regression methods are closely related to DPA methods in that they utilize the same deterioration factors. However, an important distinction is that regression methods provide an added predictive capability by identifying breakage patterns. These patterns are established by curve-fitting plots of cumulative breaks versus time generated from historical break records. Having established these breakage patterns, it is assumed that the patterns will continue into the future which allows for the forecasting of break rates (breaks per distance at some year).

Shamir and Howard (1979) applied linear (equation 2.2) and exponential (equation 2.3) regression techniques to obtain a relationship for the breakage rate of a pipe as a function of time:

$$N(t) = N(t_o) + A(t - t_o) \tag{2.2}$$

$$N(t) = N(t_o)\, e^{A(t - t_o)} \tag{2.3}$$

where:

- N(t): number of breaks per length of pipe in year t
- t: time in years
- $t_o$: base year for the analysis
- A: growth rate coefficient determined by regression (1/year) ranging from 0.05 ~ 0.15

After considerable evaluation, the authors determined that the exponential function provided a better fit of the observed trends. Based on the costs associated with pipe repairs and forecasted breakage rates, the authors applied a break-even analysis to determine the optimal year of pipe replacement.

Following this study, Walski and Pelliccia (1982) proposed a regression model that closely resembled the model by Shamir and Howard (1979) but incorporated two correction factors based pipe size and pipe material. The authors also attempted to include a third factor within their model to address the effect of cold temperatures (frost penetration). However, due to the difficulty in predicting the severity of wintertime temperatures, they concluded that the use of this factor could prove erroneous. Walski (1987) improved on the previous research by introducing a cost model that accounted for the lost water due to leakage and broken valves.

The model proposed by Clark et al. (1982) was unique in that it was the first to employ a multiple regression approach in evaluating two distinctly different deterioration stages over the life of a water main. Their model contained a linear regression equation to predict the time elapsed between the original installation date and the first break and an exponential expression to predict the number of subsequent breaks. The purpose of the exponential expression in forecasting the subsequent breaks was based on the desire to account for the impacts of various external factors. Although the authors reported low coefficients of determination ($R^2$) of 0.23 and 0.47 for the linear and exponential components respectively, several of their observations proved invaluable for future modelers. For example, the authors observed that the time between subsequent repairs shortens as pipes age and their study validated earlier descriptive studies which reported a general tendency for larger pipes to have fewer breaks.

McMullen (1982) applied a linear regression model to the water distribution system of Des Moines, Iowa. Based on the observation that 94% of the observed pipe failures occurred in soils with low resistivities (below 2,000 Ω cm), the report concluded that external pipe corrosion was a major factor in pipe failures and estimated an expected age reduction of 28 years for every decrease of 1,000 Ω cm (Kleiner and Rajani, 2001).

Kettler and Goulter (1985) provided linear regression expressions for the number of breaks as a function of diameter and time for cast iron and asbestos-cement water mains in Winnipeg, Canada. Their study identified a strong inverse correlation between pipe diameter and breakage rates, confirming the earlier observation by Clark et al. (1982). The authors also observed that asbestos cement pipes predominately break as a result of circular cracking whereas cast iron pipe breaks were predominately related to reduction in pipe wall thickness as a result of corrosion pitting.

Although several researchers including Jacobs and Karney (1994) and Kleiner and Rajani (1999) continued to develop and test various regression based models to forecast break rates, the focus of the pipe failure modeling shifted to probability-based models.

## 2.4 Failure Probability Models

Probability-based methods apply probability distributions (Exponential, Poisson, Weibull, etc.) to estimate the probability that a break will occur at some future time during the life cycle of a pipe. Models vary in the way they predict the probabilities of failure, the number of variables (land use, pipe diameter, etc.) that are included, and the phases of a pipe's life cycle that they attempt to model.

The phases of a buried pipe's life cycle is often depicted by the well-known "bathtub curve" as shown in Figure 2.2. The first phase, commonly referred to as the "burn-in" phase, represents the period following the installation in which the probability of breakage drops significantly until it eventually reaches a lower threshold. Any breaks occurring in this phase are not operational in nature, but related to either faulty pipe material or installation. Having stabilized, the pipe enters the second phase in which it operates with minimal failures unless acted upon by some form of random phenomena such as an extreme loading condition or possibly some form of third party interference. The second phase is the phase in which the pipe passes the majority of its useful life. The third phase, referred to as the "wear-out" phase, is characterized by increasing break frequencies as the pipe experiences a combination of aging and deterioration processes. One of the fundamental differences amongst the probability-based approaches relates to the manner in which the models evaluate the life cycle phases of the pipe. Whereas some models attempt to consider all three phases of a buried pipeline life cycle, most consider only one or two phases. The y-axis title in Figure 2.2 illustrates that the life cycle curve can be described based on two unique probabilistic predictive approaches.

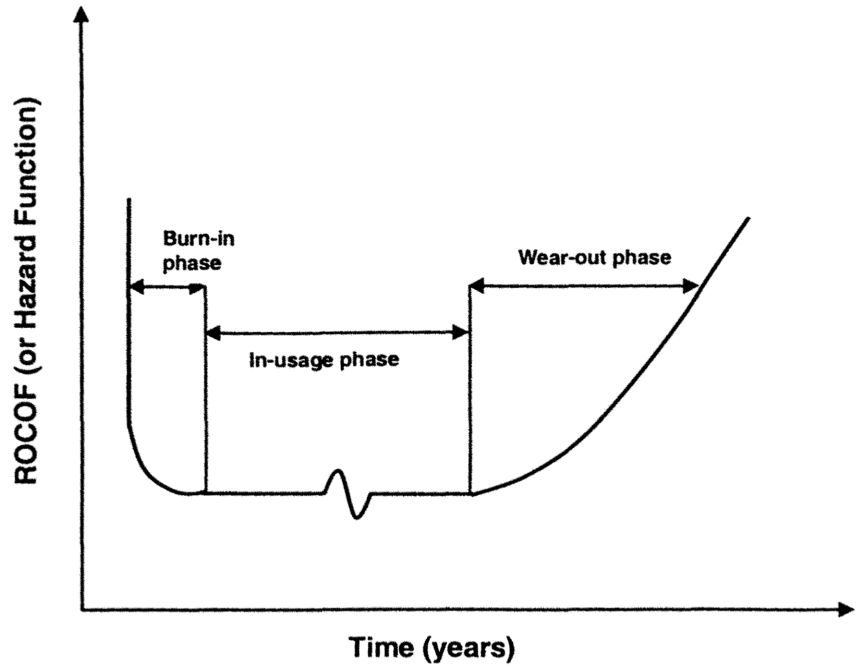


Figure 2.2 Life Cycle Phases of a Buried Pipe (Kleiner and Rajani, 2001)

### 2.4.1 Hazard Function Approach

A hazard function, commonly referred to as the risk function or failure rate, provides a measure the conditional probability that a component will fail at a time T given that has survived until this time. In equation form, it is expressed as the ratio of the probability density function to the survival function (Meeker and Escobar, 1998):

$$h(T) = \frac{f(T)}{s(T)} = \frac{f(T)}{1 - F(T)} \tag{2.4}$$

The probability density function, f(T), in equation (2.4) represents the probability that the random variable T takes on a value in the interval [a, b]. This probability is often expressed in terms of an integral between the points a and b, which represents the area under the density function between the points (Meeker and Escobar, 1998):

$$\Pr\left[a \le T \le b\right] = \int_{a}^{b} f\left(T\right)dx \tag{2.5}$$

The survival function term, also referred to as the reliability function, is the complement of the cumulative distribution function (CDF). If the CDF represents the probability that a pipe will fail sometime between time 0 and time T, then the survival function yields the probability that the pipe survives without a failure beyond time T (Meeker and Escobar, 1998):

$$s\left(T\right) = \Pr\left[T > t\right] = 1 - \int_{0}^{t} f\left(s\right)ds \ = 1 - F\left(T\right) \tag{2.6}$$

Under the hazard function approach, each pipe within the water system is modeled with a respective distribution function representing a single lifetime. Because hazard functions represent a single lifetime, they inherently do not allow for more than one failure. Accordingly, hazard functions are applicable to non-repairable items, because it is assumed that after each component failure the item is replaced with a new component and the entire system is again "as good as new" (Crow, 2004). Although this assumption is not valid for pipes, which are repairable, the models that apply hazard functions do so with the intent of examining the time between consecutive breaks. In order to apply this method, after each break the data needs to be transformed so that each observation corresponds to a particular failure time. For example, a pipe with two break records corresponds to three observations: the time to failure from installation to the first break, the time to failure from the first to second break, and a third observation which is "censored" from the second break to the termination of the study (Andreou, 1986).

The first application of the hazard function appeared in the proportional hazard model (PHM) proposed by Cox (1972). Cox's failure prediction model was originally developed for analyzing survival data in medical statistics and for evaluating the effectiveness of various treatment alternatives. Although the author's research was conducted within a medical framework, the method has numerous applications outside medicine including pipe deterioration modeling. The most-encountered form of the PHM is given as:

$$h(t,z) = h_o(t)e^{zb} \tag{2.7}$$

where:

- $h(t,z)$: hazard function
- $h_0(t)$: baseline hazard function
- $z$: vector of variables acting multiplicatively on the hazard function
- $b$: coefficient of the z vector estimated with regression analysis

Equation (2.7) can be interpreted as follows: the baseline hazard function, $h_0(t)$, represents the aging process (internal and external corrosion) of the pipe occurring as a function of time and independent of the stressing variables.

Assuming that the conditional probability of failure is the product of the time-dependent aging process and the stress-dependent term, $e^{zb}$, this form is intuitively correct since it implies that, while the aging process continues, the pipe is exposed to additional threats. Inherent in this model is the assumption that the exponential stress term, $e^{zb}$, acts multiplicatively on the hazard rate. This concept is further demonstrated in Figure 2.3, which illustrates the influence of the stress dependent term on the probability of failure. In this example, the baseline hazard term represents a scenario in which 20% of a pipeline's length lies under a low development area with an operating pressure of 30m. Based on these conditions, the break hazard at an age of 70 years is about 1.6%. However, in the scenario in which 80% of the pipeline is under a low development area, then the break hazard decreases to 1.2%. Conversely, if the pipeline operates with 60m of pressure, the break hazard increases to 2.0%.

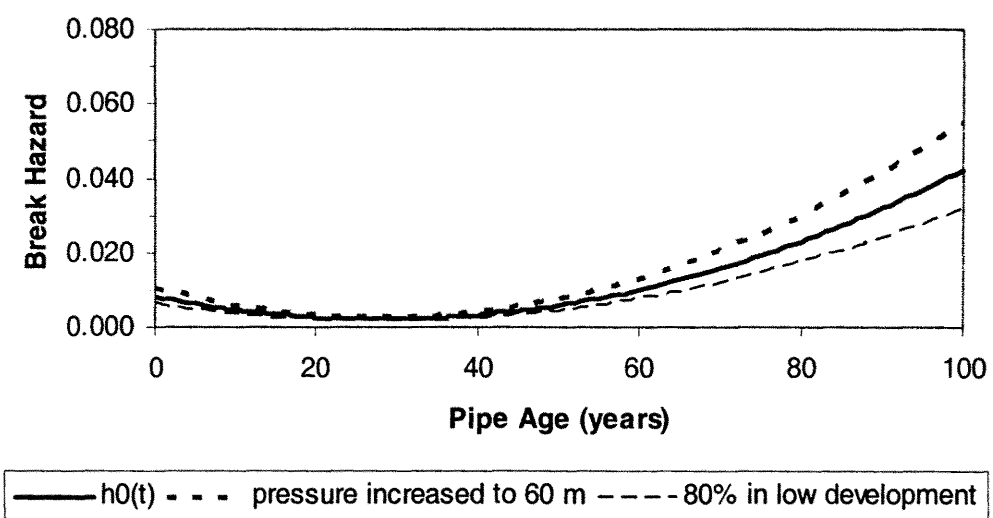


Figure 2.3 Example Illustrating the Results of the Proportional Hazard Model (Andreou, 1986)

Marks (1985) were the first to use the PHM in computing the probability of failure for the water distribution system of New Haven, Connecticut. In order to determine the factors (covariates) that influence the system's pipe breakage rates, several multiple regression techniques were applied. The study concluded that the most pertinent covariates were pressure, land development, pipe length, installation date, and the number of previous breaks. The baseline hazard term was approximated using the following second degree polynomial:

$$h_o(t) = 2x10^{-4} - 10^{-5}\, t + 2x10^{-7}\, t^2 \qquad (2.8)$$

Andreou (1986) extended the use of the proportional hazard model in analyzing data from water utilities at New Haven and Cincinnati. However, unlike the model developed by Marks (1985) which applied the hazard function throughout a pipe's entire life cycle, Andreou incorporated a two-stage failure analysis. The PHM was used to model the early stage of the pipe failure process characterized by fewer breaks. Referring to Figure 2.2, this portion of the model corresponds to the "in-usage" stage in which there normally is a large time gap between the installation date and the first break. To represent the "wear-out" region of the pipe life cycle curve, which is characterized by multiple and frequent break patterns, the author applied a Poisson distribution. The use of this distribution to represent the second stage of the pipe deterioration process was based on the observation that the breakage rates appeared to be constant over time and thus the inter-breakage times were exponentially distributed. The author indicated that these constant breakage rates appeared after the third break, so the third break was selected as the cut-off point between the two failure stages. When using the third break at the cut-off, Andreou (1986) reported a low coefficient of determination of 0.34 in the prediction of the late stage. When the cut-off was taken at six breaks, the prediction accuracy improved to $R^2 = 0.46$.

Although the accuracy of the model in predicting individual pipe failures was limited, it did provide insight regarding the influence of factors such as internal pressure, land development, and installation date. The PHM's ability to incorporate various factors makes it quite powerful. However, the model's need of large amounts of data and technical expertise to evaluate/identify the covariates with the best predicting ability, severely hinder its application in utilities. Moreover, the use of a constant hazard function for the second stage of the author's model implies that, after the third stage, pipes no longer age. Although this observation has been corroborated by other researchers (e.g. Herz, 1996), it contradicts the physical realm of aging pipes, especially in regions where corrosion is significant. Kleiner and Rajani (2001) suggests perhaps such a limiting state does exist, however, that it occurs much later than three or even six breaks.

Mavin (1996) provided a review of several existing failure models. One of his principal recommendations relates to the importance of filtering breakage data prior to constructing a failure model. He suggested that break data occurring within three years from installation (within the burn-in phase of a pipe's life cycle) or breaks that occur within six months from a previous break should not be included in the analysis. The basis of his argument was that these types of failures are likely to be associated with construction faults and not with the deterioration of the pipe itself. Based on this filtering criterion, the author derived a set of regression equations to forecast the number of failures over a time period and time interval between breaks.

An application of the proportional hazards model was reported by Brémond (1997) in which the model was applied to water distribution networks in France. Rather than approximate the baseline hazard as a second degree polynomial, a Weibull probability baseline hazard function was used. Although the author did not specify if a two stage failure approach was applied as in Andreou (1986), he reported good break predictions over an 11-year period based on failure data from the proceeding 33 years in the town of Bordeaux (Kleiner and Rajani, 2001).

A Weibull version of the proportional hazards model was recently used by Vanrenterghem (2003) to model the structural degradation of the New York City water system. As part of the model, the author used a statistical software package called EGRET to evaluate the covariates with the best predicting capability. The study concluded that, although location factors such as proximity to highways, subways, and aquifers play a minor role in pipe degradation, the pipe material and break history covariates played an overwhelming role. Likewise, the model reiterated the conclusions from several other pipe degradation studies emphasizing that pipe age is not a significant factor and should be taken into account when prioritizing pipe replacement activities.

Herz (1996) developed a lifetime density function, referred to as the Herz function, based on the principles of a cohort survival model. The term "cohort" was originally used by the ancient Romans to signify special units of security police and fire brigades in Rome (Herz, 1996). Since then, it has been commonly used by demographers to signify a group of individuals that were born during a certain time period. Herz argued that the subject of pipeline aging and deterioration could be approached in a similar manner to that used by population forecasters (Mehle et al., 2001). Under his scenario, water mains are born the day that they are constructed, and from that point onward, commence the process of aging and decay. Eventually the pipe fails, which corresponds to death in the human cohort model. Whereas in a human cohort model death is replenished by reproduction, infrastructure is replaced through new construction, rehabilitation, or reconstruction. The Herz distribution for pipeline applications was developed by equating pipelines to populations and grouping them according to construction dates. Based on this distribution, if the term c represents the time up to which no major rehabilitation is taken place, then the probability density f(t), cumulative distribution F(t), survival S(t), and hazard h(t) functions over a life-span of time t are expressed as:

Probability Density Function:

$$f(t \le c) = 0$$

$$f(t > c) = \frac{(a+1)b\,e^{b(t-c)}}{\left[a + e^{b(t-c)}\right]^2} \qquad (2.9)$$

Cumulative Distribution Function (CDF):

$$F(t \leq c) = 0$$

$$F(t > c) = 1 - \frac{a+1}{a+e^{b(t-c)}} \tag{2.10}$$

Survival function (defined as 1 – CDF):

$$S(t \leq c) = 1$$

$$S(t > c) = \frac{a+1}{a+e^{b(t-c)}} \tag{2.11}$$

Hazard Function:

$$h(t \leq c) = 0$$

$$h(t > c) = \frac{b e^{b(t-c)}}{a+e^{b(t-c)}} \tag{2.12}$$

where:

a: aging factor (no aging takes place when a=0)
b: failure factor

Note that the c term corresponds to the time allocated to the "burn-in" phase of the bathtub curve shown in Figure 2.2. Although several statistical distributions can be applied as aging functions, the Weibull and the Herz distributions were developed specifically for the aging of pipelines (Herz, 1996). The Herz distribution has several unique features that distinguish it from the Weibull distribution. One such feature is that the hazard function increases with age more and more, then increases more gradually, and finally approaches the failure factor (b) asymptotically. This agrees with the observations of Andreou

(1986) in which the author observed a point in time in which the hazard is constant, implying that the pipe is not aging.

In order to apply the model, the data must be separated into cohorts of pipes that are homogeneous with respect to their material type, periods of installation, and environmental/operational stress class. The survival functions are then defined based on either failure data or expert opinion regarding the life expectancy of each pipe type. In most applications, three points relating to the life expectancy of each pipe type are estimated: the 50%(median) age, the 100% of the resistance time up to only spot repair is done (variable c), and the age of the most resistant 10%. Having defined these points, the variables a, b, and c are then calculated and applied to the cohort survival model to forecast the total length of pipes reaching the end of their useful life in any year. This is achieved by applying the survival functions of each cohort on a year-by-year basis to the entire stock. An example of the final output is provided in Figure 2.4 below. Although the cohort survival model can be a useful tool for forecasting the future pipe replacement and financial needs of a water distribution system, this broad-based approach applies to groups of pipes and does not provide information regarding the prioritization of individual pipes. Moreover, the approach is very sensitive to the expected life estimates.

Deb et al. (1998) applied their version of the cohort survival model, called KANEW, to one British and four North American water utilities. Whereas all five utilities were able to provide the researchers with the needed pipe inventory data (pipe age, material type, diameter, etc.), because the utilities did not possess ample quantities of pipe failure data to numerically determine the life expectancies of each material type, the researchers used a Delphi process. In order to account for any uncertainties with regard to the estimations of the pipe life expectancies, both pessimistic and optimistic scenarios where also included. Having established the life expectancy information, the three parameters (a, b, and c) of the Herz probability density function were then extracted which eventually lead to the estimation of the final survival probabilities.

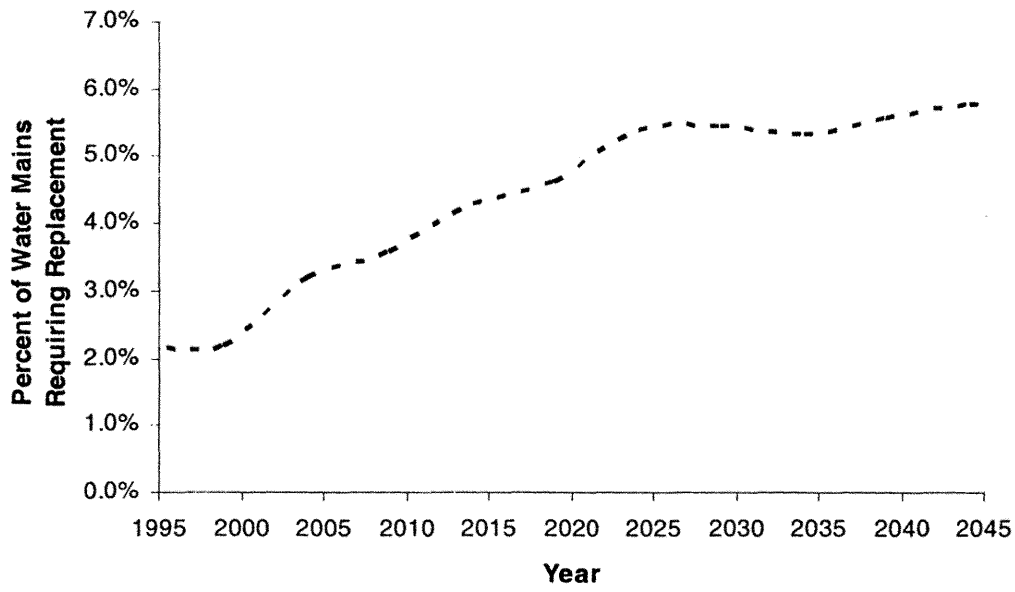


Figure 2.4 Example of a Rehabilitation Rate Forecast Generated by the Cohort Survival Model

The primary objective of the KANEW model was to provide water utilities with a tool to develop their long-range pipe renewal strategies by predicting the miles of different categories of pipes to be rehabilitated and replaced on an annual basis. Because the model is developed on an aggregate (system wide) basis, it does not provide location specific rehabilitation and replacement information. Aside from not providing a method for prioritizing individual pipe rehabilitation, the primary limitations of KANEW are its sensitivity to life expectancy estimations and the need of accurate inventory data.

As part of a study sponsored by the American Water Works Association Research Foundation (AWWARF) in 2001, an analysis of the future pipe replacement needs for 20 water utilities throughout the United States was conducted. The methodology selected to predict the pipe replacement needs entailed the use of "Nessie curves" which had been used throughout Australia. A Nessie curve is a graph illustrating the predicted annual replacement expenditures by type of pipe over a period of time. In a similar manner to the projections generated through the cohort survival mode, a Nessie curve is also generated using pipe installation and life expectancy information. Whereas the graphs in the KANEW model provide the results in terms of miles of pipe to be replaced, Nessie curves provide a forecast in terms of annual costs. Figure 2.5 illustrates the aggregate Nessie curve for all 20 utilities that participated in the AWWARF study. Note that the rising wave shape suggests why the curve is named after the Loch Ness Monster (AWWARF, 2001).

### 2.4.2 Rate of Occurrence of Failure Approach

For systems comprised of interacting parts, such as water distribution systems, the hazard function can only accurately predict the first break because the subsequent breaks do not follow the same distribution. Based on this observation, the second approach to probabilistic modeling, which monitors the Rate of Occurrence of Failure (ROCOF), is not as restrictive as the hazard function in that it merely records the frequency of pipe breaks throughout the life cycle of a pipe. As was shown in life cycle curve in Figure 2.2, over the lifetime of a buried pipe the ROCOF may be increasing, decreasing, or relatively constant. Because the ROCOF does not require that the pipe be replaced after each break, it is more applicable to repairable systems.

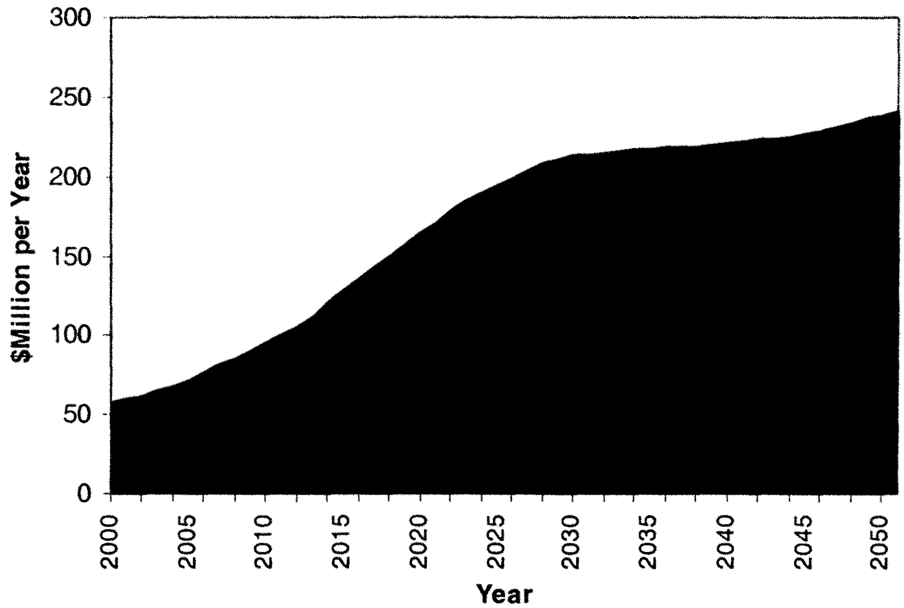


Figure 2.5 Nessie Curve Showing the Projected Replacement Expenditure for 20 U.S. Utilities (AWWARF, 2001)

Another important distinction between the hazard function and ROCOF approaches is that the ROCOF method acknowledges that, due to the varying age and condition of the other pipes within the network, the replacement of one f_ulty pipe does not restore the system to an "as good as new" but rather an "as bad as old" condition". In other words, the ROCOF approach assumes that the condition of the system can be no better than it was prior to the failure. This observation was well documented in a study of by Goulter and Kazemi (1987) in which they observed that approximately 68% of the pipe failures within the water distribution system of Winnipeg occurred within a distance of 20 meters from previous failures. Moreover, it is quite common that the repair of one break results in a nearby break within a span of days.

In the study conducted by Loganathan et al. (2002), the authors reviewed several of existing failure assessment models to assess the strengths and limitations of each approach. One of their principal findings was that the ROCOF is particularly relevant to pipe failure modeling since the ROCOF method can be accurately applied to truncated (incomplete) datasets.

## 2.5 Risk Management Modeling

Unlike the private sector which is driven primarily by financial returns, renewal decisions in water supply industry are driven more by risk-avoidance and holding costs down. Accordingly, utility managers are not judged so much by their profit, but by the service they provide and the efficiency they promote (Grigg, unpublished manuscript, 2003). In recognition of this unique management environment, the industry needs of a pipe replacement prioritization tool that not only provides decision makers with a list of pipes prone to failure but also addresses the need for a risk-based approach.

Although the literature review did not encounter a risk management approach for water supply systems which contains failure prediction and consequence components, the review did identify the presence of this dual approach in other industries. For example, due to the explosive nature and high risk associated with the transportation of natural gas, the natural gas industry has performed numerous risk management studies aimed at optimizing pipeline maintenance. In one such study, Kiefner and Morris (1997) developed a Risk Management Tool (RMT) that calculates a total risk number as the product of the total probability of failure and the total consequence. More recently, Seattle Public Utilities (SPU) developed a Sewer Pipe Risk Model (SPRM) that identifies high risk sewer and drainage pipes (Martin, 2005). In the SPRM, the risk cost of failure is also calculated as the product of the probability times the consequence of failure.

### 2.5.1 Consequences of Pipe Failure

Consequences can be defined as the outcome of an exposure(s). For water pipe breaks, consequences represent the cost and impact of each break. Amongst the various approaches used for classifying consequences, the three categories shown in Table 2.2 are frequently used in the industry.

### 2.5.2 Consequences of Pipe Degradation

In addition to consequences associated with pipe failures, there are also consequences related to water pipe deterioration. In a 2002 publication entitled

"Deteriorating Buried Infrastructure Management Challenges and Strategies", the AWWA identified three primary categories of deterioration-related consequences:

- Loss of carrying capacity resulting in poor pressure.
- Deterioration of water quality.
- Structural deterioration leading to additional leaks and breaks.

Table 2.2 Categories of Consequences for Water Main Breaks (Makar and Kleiner, 2000)

| Category | Examples |
|---|---|
| I. Direct Costs | Break repair cost. |
| | Cost associated with lost water. |
| | Liabilities resulting from death or injury. |
| | Costs related to direct damage of property. |
| | |
| II. Indirect Costs | Production loss related to water outage. |
| | Accelerated deterioration of trenches, roads, sewers, etc. |
| | Loss of adequate fire protection. |
| | |
| III. Social Costs | Water qualify deterioration from the intrusion of contaminants during |
| | pipeline repair operations. |
| | Costs relating to service disruption (quality of life, public perception). |
| | Costs due to the disruption of special services such as schools, hospitals. |
| | Costs associated with the disruption of traffic and business. |

<u>Loss of carrying capacity resulting in poor pressure</u>

Losses in carrying capacity occur through a process called tuberculation, which reduces the internal diameter of unprotected metal pipes (iron, steel, cast iron, lead). There are two general forms of tuberculation. The first form occurs via a chemical process which extracts iron from the pipe, resulting in the formation of tubercles and pits on the wall surface. The second form of tuberculation is caused by the deposit of excess calcium carbonate, sediments, or slime growths on the inside wall of the pipe.

Deterioration of water quality

The deposition of water and pipe constituents in regions of a water main is governed by a complex mixture of physical and chemical processes. Depending on the water PH, temperature, pipe material and flow characteristics, any foreign material may or may not be deposited. In the scenario in which the material is pulled out of the pipe, it can remain suspended or dissolved until consumed by the customer (Vanrenterghem,2003). Aside from internal sources of water contamination, there is also concern regarding water contamination from external sources. Due to aging pipe infrastructure, there are several potential pathways for external contaminants to enter a distribution system including contamination during repair activities and potential groundwater intrusion through existing leaks/breaks during periods of lower pressure.

Structural deterioration leading to additional leaks and breaks

In a descriptive statistical study of the pipe breakage data from the city of Philadelphia, O'Day (1982) indicated that water mains are subject to several categories of deteriorating forces as shown in Table 2.3.

### 2.5.3 Consequence Modeling

The most common form of consequence modeling for water pipe applications involves the use of multipliers (weights) to distinguish between critical factors relating to special services, location, etc. In the case of the SPRM developed by Seattle Public Utilities, the multipliers were calculated as the ratio of the consequence-related repair cost divided by the baseline repair cost. Table 2.4 illustrates the concept behind the use of the weights. The costs shown in the baseline column refer to the fixed costs associated with repairing a pipe. While these costs are utility specific, most utilities have adequate historical records to determine these costs as a function of pipe material type, diameter, and installation depth. For example, in the study performed by Shamir and Howard (1979) for the city of Binghamton, the authors assumed a baseline pipe repair cost of $1,000/break.

Table 2.3 Categories of Deteriorating Forces as Identified by O'Day (1982)

| Category | Examples |
|---|---|
| I. Internal Loads | Working pressure |
| | Surge pressure |
| | Thermal contraction of pipe restricted from expansion/contraction |
| | |
| II. External Loads | Changes in surface loads (earth, traffic, frost, etc.) |
| | Contact during excavation |
| | Poor construction practices |
| | Beam loading if bedding is not sufficient |
| | |
| III. Corrosion | Internal corrosion (function of water quality, pipe coatings, etc.) |
| | External corrosion (function of soil properties, pipe material, etc.) |
| | |

The factors listed in the middle column of the table relate to added repair costs associated with location-specific scenarios. The added difficulty and expense associated with pipe repairs in these locations is expressed my using cost multipliers that exceed one. For instance, if the baseline repair cost is

$1,000/break and the utility determines that repairing a pipe located under a building costs an additional $800/break, then the multiplier would be 1.8 ($1,800/$1,000). In the case of Seattle Public Utility's model, the model includes a total of 18 separate multipliers relating to location-specific scenarios (Martin, 2005). The third column relates to non-construction related multipliers and includes a mixture of indirect and social costs. At the time of the report by Martin (2005), the weights for these factors had yet to be included in the SPRM model.

Table 2.4 Examples of the Financial, Environmental and Social Factors used in the Sewer Pipe Risk Model (Martins, 2005)

| **Baseline Financial Costs To Repair a Sewer Failure** | **Location-Specific Costs Which Increase the Financial Costs of a Sewer Failure** | **Location-Specific Costs Which Increase the Environmental and Environ. Costs of a Sewer Failure** |
|---|---|---|
| • Labor | • Located under a body of water | • Potential damage to public health |
| • Equipment | • Located under railroad tracks | • Regulatory noncompliance potential |
| • Materials | • Located under a building | • Environmental damage potential |
| • Shoring | • Located within a slide area | • Social disruption potential |
| • Dewatering | • Located within a wetland area | • Property damage potential |
| • Bypass Pumping | • Located on a steep slope | • Potential for unfavorable publicity |
| • Administration | • High capacity sewer line | |
| | • Located in a dense urban area | |

### 2.5.4 Threat and Vulnerability

Aside from assessing the consequences of failure, a risk–based approach must also incorporate threats and vulnerability. Although most investigations usually lump vulnerability and threats into a single category, in the application of risk analysis they are separate variables (Grigg, unpublished manuscript, 2003). For water main degradation, threats come from factors relating to the environment (corrosion environment) and loading conditions (external loads, water pressure) whereas vulnerability relates to construction and/or pipe material conditions. The relationship between vulnerability, threats, and consequences is often illustrated in the form of a risk triangle as shown in Figure 2.6.

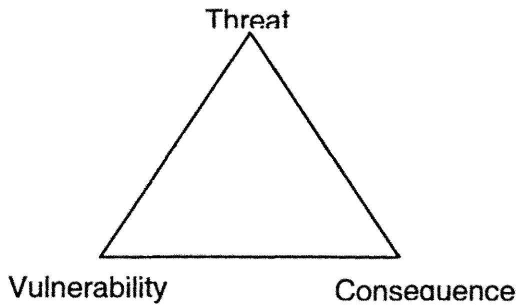


Figure 2.6 Risk Triangle (Grigg, 2005)

### 2.5.5 Remark Concerning Age as a Risk Factor

Acknowledging that the age of a pipe merits consideration as a risk factor, age alone should not serve as the basis for pipe replacement prioritization decisions. In real world applications, deterioration rates of buried pipes vary as a function of not only age, but also of the material properties, time-specific installation factors (manufacturing, design, and construction processes), as well as site-specific conditions including the soil properties and climatic conditions. For example, pipe of the same material can last anywhere from 15 to over 200 years depending on the soil characteristics alone (USEPA, 2002).

# CHAPTER 3

# RELIABILITY MODELING AND ITS APPLICATION TO WATER PIPE FAILURE MODELING

## 3.1 Introduction

An important application of probability theory in engineering and manufacturing applications centers on modeling the performance of an object during its life cycle. This form of modeling uses reliability theory, where the term reliability refers to an object's ability to perform a required function without failure under specified conditions for a stated period of time (Meeker and Escobar, 1998). Whereas reliability measurement at the component-level is based on a statistical analysis of the component's operational performance in the field, system-level reliability analysis requires the use of numerical modeling techniques to evaluate the reliability of combinations of components. Due to the complexity of the numerical modeling techniques, reliability modeling at the system level requires the use of commercial software products such as BlockSim (ReliaSoft Inc.) and PRISM (System Reliability Center).

Reliability modeling of water distribution systems is challenging for several reasons. First, distribution systems are comprised of various interacting components, which through their interaction, exhibit properties that are not properties of the individual components themselves (Auyang, 2003). For example, water pipes corrode differently under different soil and water conditions and their corrosion might depend on system water characteristics. From a reliability modeling perspective, water pipe networks are complex systems in that the pipes are arranged in a labyrinth of series and parallel formations that provide multiple water paths leading to the same points in the system. Another complication is that pipes within a water system experience multiple stages of degradation. One reason for this variance in condition is the diverse mixture of the inventory material types and age. For instance, it is common for water utilities to have significant quantities of 100-year cast iron pipes downstream of recently installed PVC pipe. Another reason for variable levels of pipe degradation relates to the utility's pipeline maintenance operations in which some pipes might have been recently rehabilitated while many others require some form of remediation. In other words, repairing a single pipe does not necessarily improve the reliability of the system.

Aside from the physical characteristics of water distribution systems which limit the effectiveness of a system-wide reliability assessment, the complexity of the pipe network provides multiple levels of defense against a complete system failure. Accordingly, water utilities are not as concerned about the probability of a system-wide failure in the distribution system as they are about identifying failure-prone pipes and prioritizing their renewal on a pipe-by-pipe basis. In consideration of these arguments, the more viable form of reliability modeling for this application is to model reliability of individual pipes. This component-level approach involves using the utility's existing pipe inventory and break data to assess the site-specific performance of each water pipe. The performance information is then analyzed using statistical modeling techniques to provide decision makers with information regarding the probability of pipe failure, forecasts of the number of expected failures over a period of time, and the time to next failure.

Having established the suitability of component-level reliability modeling to water main failure analysis, the focus of this chapter is how traditional component-level reliability techniques can accommodate the unique characteristics of the water service industry.

### 3.2 Reliability Modeling Concepts

This section provides an overview of reliability modeling to illustrate how it applies to water main failure analysis.

#### 3.2.1 Simple and Complex Systems

The premise of a system reliability model is to use the data taken from the system's individual components to forecast the system reliability and probability of failure. The distinction between simple and complex systems is of vital importance to system reliability modeling procedure because it influences the modeling approach. Whereas system reliability for a simple system can be evaluated using spreadsheet programs, reliability analysis for complex systems requires numerical modeling techniques such as path-tracing and decomposition found in commercial reliability software.

Both simple and complex systems are often depicted using reliability block diagrams (RBD), which provide a graphical depiction of the system's components and connectors. For water distribution systems, the components represent pipe intersections (nodes) or water extraction points (household connections, fire hydrants, etc.) and the connectors represent pipes.

Simple Systems

As shown in Figure 3.1, simple systems have their components arranged in either a series or parallel formation.

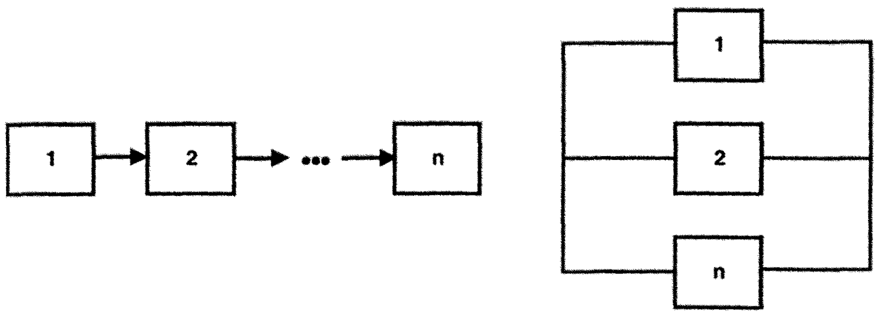


Figure 3.1 Simple Series and Parallel Systems

In a series component formation, an individual component failure results in a system failure. In other words, all of the units in a series system must succeed for the system to succeed. The system reliability of the series system is calculated as the probability of all components executing successfully, or the product of the individual reliabilities (Abd-Allah, 1997):

$$\begin{aligned} R_s &= P(X_1 \cap X_2 \cap \ldots \cap X_n) \\ &= \prod_{i=1}^{n} R_i \end{aligned} \tag{3.1}$$

Where:

$R_S$ = reliability of the system

$X_i$ = event of component $i$ being operational

$P(X_i)$ = probability that unit $i$ is operational

For parallel systems, system failure occurs only when all n components fail. So if component 1 succeeds or component 2 succeeds or any of the n components succeeds, then the system will not fail. Because of this behavior, parallel components are referred to as redundant components. Unlike the series formation in which system reliability is calculated as the product of the component reliabilities, system reliability for parallel formations is calculated as the product of the component failure probabilities (Abd-Allah, 1997):

$$\begin{aligned} R_s &= \prod_{i=1}^{n} (P_i) \\ &= 1 - \prod_{i=1}^{n} (1 - R_i) \end{aligned} \tag{3.2}$$

For systems with series and parallel component formations which are easily distinguishable, the system reliability can be calculated by evaluating the reliabilities for the individual series and parallel sections and then combining them. For the example provided in Figure 3.2, units 1 and 2 would first be evaluated using the series equations, with the resultant evaluated as a parallel component to unit 3.

Complex Systems

Complex systems are systems in which it is difficult to recognize which components are in series and which are in parallel. In the case of the complex system shown in Figure 3.3, the system can not be grouped into series and parallel systems since component *C* has two paths leading away from it and components *B* and *D* have only one path. Under these conditions, system reliability can not be calculated using the series and parallel reliability equations (.3.1) and (3.2) and must be evaluated using numerical modeling methods

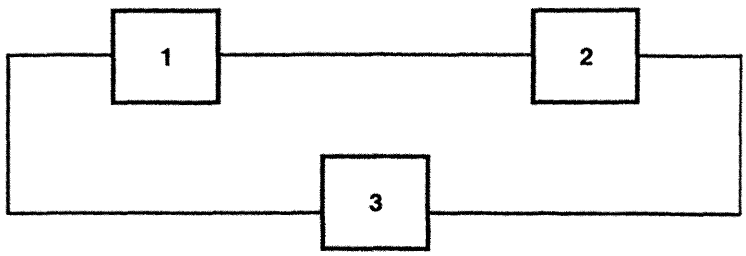


Figure 3.2 Simple Combined Series and Parallel System

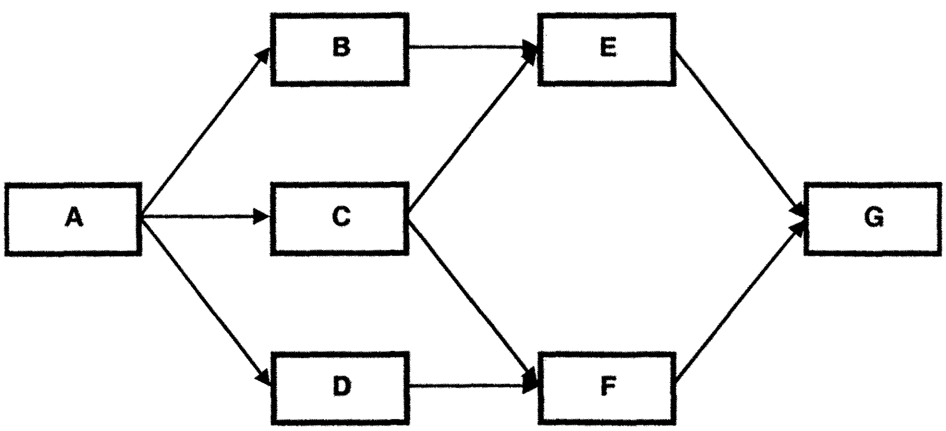


Figure 3.3 Example of a Complex System (Abd-Allah, 1997)

### 3.2.2 Repairable and Nonrepairable Systems

The distinction between repairable and nonrepairable systems is of fundamental importance in reliability modeling. A repairable system is a system that, after it has failed to perform properly, can be restored to an acceptable level of operating condition by some repair process other than replacement of the entire system (Crowder et al., 1991). Water pipes are considered to be repairable in that, if a pipe fails, it can be repaired and restored to an operating state. Conversely, a nonrepairable system is defined as a system which is discarded and/or replaced after its first failure (Watson et al., 2001). A light bulb is an example of a non-repairable system.

In order to better understand the key differences between repairable and nonrepairable systems, consider the three component series system shown in Figure 3.4. If this system is considered to be nonrepairable, then the failure of one component causes the entire system to fail. Under this scenario, the failed component is replaced with a new one and the system is assumed to be restored to an "as good as new" condition. Under this assumption, the one failed component does not affect the performance of a similar component because each has its own failure distribution (lognormal, Weibull, etc.) and follows its own process. So for a particular component of a nonrepairable system, the failures are independent and identically distributed.

If the same three component system is viewed as repairable, the failure of an individual component can no longer be considered as independent from its previous failure(s) since it is repaired instead of replaced. Likewise, system failures are dependent on the failures of the components (which all have different distributions) and the ages of the components. Under this scenario, because the time between successive failures is not independent or identically distributed, successive failures can not be modeled by conventional analysis of a statistical lifetime.

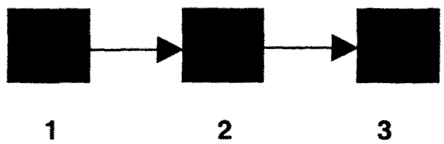


Figure 3.4 Three Components Connected in Series (Crow, 2004)

These differences regarding component dependency and system performance influence the selection of analysis techniques. For nonrepairable systems, where survival times of components are of primary interest, hazard functions are used to analyze systems. Repairable systems are analyzed using Rate of Occurrence of Failures (ROCOF) based techniques because the focus is on individual component failure rates. Having demonstrated that water systems are repairable systems and the merits of applying a ROCOF approach for modeling failure incidences in repairable systems, it was determined that a ROCOF-based technique would be well-suited for analyzing the individual pipe failure records.

### 3.2.3 Homogeneous and Non-Homogeneous Poisson Processes

Where break rates are monotonic, the network is said to be nondeteriorating and a Homogeneous Poisson Process (HPP) can be applied (Mays, 2004). In the "bathtub" curve in Figure 2.2 with three phases of a pipe's life cycle, the region with a constant break rate (ROCOF) is the "in-usage" stage. Under this scenario, the times between failures are independent and distributed according to the exponential distribution shown in the following expressions. Note that the exponential distribution is used for the HPP since it is the only distribution to have a constant failure rate (Mays, 2004).

Cumulative Distribution Function:

$$F(t) = 1 - e^{-\lambda t} \tag{3.3}$$

Probability Density Function:

$$f(t) = \frac{dF(t)}{d(t)} = \lambda e^{-\lambda t} \tag{3.4}$$

Reliability (survival) Function:

$$R(t) = 1 - F(t) = e^{-\lambda t} \tag{3.5}$$

Failure Rate (ROCOF):

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \tag{3.6}$$

where: $\lambda$ represents a constant ROCOF

The assumption of a constant break rate simplifies the forecasting process, but is can model only the flat "in-usage" portion of pipe life cycle curve.

Although a pipe passes through the "in-usage" phase, replacement decisions usually occur in the deterioration or "wear-out" portion of its life cycle (see Figure 2.2). Because of this limitation, it was decided that a Non-Homogeneous Poisson Process (NHPP) would be best suited for the failure prediction portion of the model. The NHPP provides the needed flexibility to address both the "in-usage" and "wear-out" phases of buried pipe's life cycle. The two most commonly applied forms of the NHPP are the exponential and power (Power Law) models.

Exponential Model

In the exponential model, the cumulative number of expected failures between time zero and t is expressed as (Mays, 2004):

$$M(t) = \frac{e^{c}}{b}\left(e^{bt} - 1\right) \tag{3.7}$$

The parameters b and c are empirically determined. Taking the derivative of equation (3.7) with respect to time yields an expression for the rate of failure known as the intensity function (Mays, 2004):

$$u(t) = \frac{dM(t)}{d(t)} = e^{c+bt} \tag{3.8}$$

Power Law Model

In the Power Law model, both the cumulative failure and the intensity functions have polynomial forms (Mays, 2004):

$$M(t) = \lambda t^{\beta} \tag{3.9}$$

$$u(t) = \frac{dM(t)}{d(t)} = \lambda \beta t^{\beta-1} \qquad \text{for } \lambda > 0,\ \beta > 0 \tag{3.10}$$

The $\beta$ and $\lambda$ terms in equations (3.9) and (3.10) represent the shape and scale factors and are determined empirically. Due to its polynomial form, the intensity function of the Power Law model is flexible and can model both increasing ($\beta > 1$) and decreasing ($0 < \beta < 1$) failure rates. These are "sad systems" and "happy systems" (Ascher and Feingold, 1984). For a shape factor of 1 ($\beta = 1$), the Power Law model reduces to the HPP constant repair rate form shown in equation (3.6)

The Power Law form of the NHPP can deal with the practical concept of minimal repair, where the repair of a failed component is just enough to get the system operational again (Crow, 2004). In water distribution systems, a pipe break is repaired to restore the condition prior to the failure without additional maintenance (Vanrenterghem, 2003). In a system with many failure modes, under minimal repair, system reliability after the repair can be no better than prior to the failure. Often this condition is called an "as bad as old" condition. This is in contrast to the hazard function approach (non-repairable system) discussed earlier, where replacement restores the system to a "good as new" condition. In water utilities, minimal repair applies to repair scenarios, whereas non-repairable theory applies to rehabilitation and replacement.

### 3.2.4 Power Model Applications

Under the Power Law model of the NHPP, the first break is modeled using the Weibull distribution with the following cumulative distribution function, reliability function, and failure rate expressions:

Cumulative Distribution Function:

$$F(t) = 1 - e^{-\lambda t^{\beta}} \tag{3.11}$$

Reliability (survival) Function:

$$R(t) = 1 - F(t) = e^{-\lambda t^{\beta}} \tag{3.12}$$

Failure Rate (ROCOF):

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda \beta t^{\beta-1} e^{-\lambda t^{\beta}}}{e^{-\lambda t^{\beta}}} = \lambda \beta t^{\beta-1} \tag{3.13}$$

After the first break, the failure rate for each succeeding break is modeled using the Power Law failure intensity function u(t) (Crow, 2004):

$$u(t) = \lambda \beta t^{\beta-1} \tag{3.15}$$

Although the equation for the first system failure has the same functional form as the failure intensity for the NHPP, there is a considerable difference between the two expressions. Whereas the failure rate produces the instantaneous probability of failure at some time T=t given that the pipe has not failed by time t, the failure intensity expression is not conditioned on having no failures up to time t. The fact that the two expressions have the same functional form makes the Power Law model easier to apply. Figure 3.5 shows a plot the intensity function from an example provided by Loganathan et al (2002) based on a shape factor ($\beta$) and scale factor ($\lambda$) of 2.99 and 0.002 respectively. The increasing intensity indicates that the pipe is deteriorating.

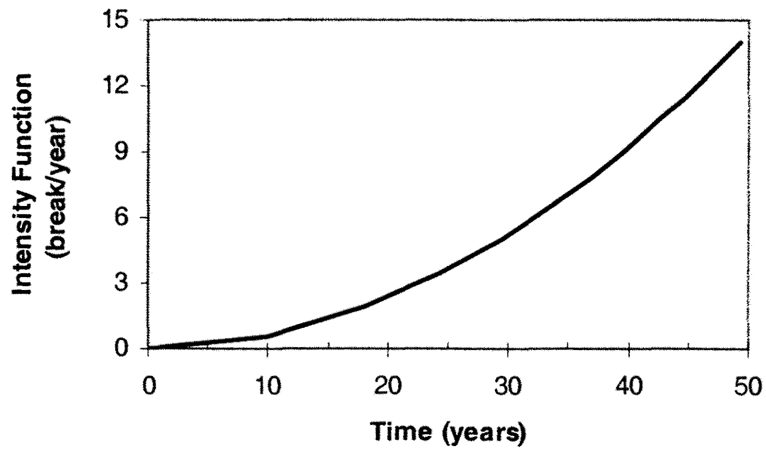


Figure 3.5 Sample Intensity Function (Loganathan et al, 2002)

Since the intensity function is a measure of the rate of failure, integration of equation (3.15) over time ($t_1$, $t_2$) yields the expected number of failures over this period:

$$E(t_1,t_2)= \int_{t_1}^{t_2} u(t)dt = \int_{t_1}^{t_2} \lambda \beta t^{\beta-1}\, dt$$

$$E(t_1,t_2)= \lambda t_2^{\beta} - \lambda t_1^{\beta} \tag{3.16}$$

Another relationship of particular interest to pipe replacement prioritization is the time to next failure. For a Power Law process, the waiting time to the next failure has a Weibull CDF. Given a failure at time T, the following expression is solved to determine the time t in which the CDF yields a probability of 1.

$$F_T(t) = 1 - e^{-\left[\lambda(T+t)^{\beta} - \lambda T^{\beta}\right]} \tag{3.17}$$

Equation (3.17) can also be applied to determine the probability of failure as the system ages from some arbitrary time t to t+dt. Normally, the time t term is taken as the time T shown in equation (3.17) since this is a known failure time.

$$P(t,t+dt) = 1 - e^{-\left[\lambda(t+dt)^{\beta} - \lambda t^{\beta}\right]} \tag{3.18}$$

Knowing that the probability of a failure from time t to t+dt is the complement of the reliability from the same time interval, equation (3.18) can be applied to determine the reliability that a system will age from time t to t+dt without a failure:

$$R(t,t+dt) = e^{-\left[\lambda(t+dt)^{\beta} - \lambda t^{\beta}\right]} \tag{3.19}$$

Solving equations (3.15) ~ (3.19) for the expected number of failures, time to next failure, probability, and reliability estimates, requires that the λ and β terms be estimated from the pipe break data. In order to estimate these values, the general likelihood estimates are applied (Crow, 2004):

$$\lambda = \frac{\sum_{q=1}^{K} N_q}{\sum_{q=1}^{K} \left(T_q^{\beta} - S_q^{\beta}\right)} \tag{3.20}$$

$$\beta = \frac{\sum_{q=1}^{K} N_q}{\hat{\lambda} \sum_{q=1}^{K} \left[T_q^{\hat{\beta}} Ln(T_q) - S_q^{\hat{\beta}} Ln(S_q)\right] - \sum_{q=1}^{K} \sum_{i=1}^{N_q} Ln(X_{iq})} \tag{3.21}$$

where:

| | |
|---|---|
| K: | number of systems |
| $S_q$: | start time |
| $T_q$: | ending time |
| $X_{iq}$: | $i^{th}$ successive failure time for the $q^{th}$ system |
| Nq: | number of failures for the $q^{th}$ system |

For a single pipe (K=1) with a starting time zero and an ending time $t_o$, equations (3.20) and (3.21) reduce to:

$$\lambda = \frac{n}{t_o^{\beta}} \tag{3.22}$$

$$\beta = \frac{n}{n \ln(t_o) - \sum_{i=1}^{n} \ln(t_i)} \tag{3.23}$$

where:

n: number of breaks after the reference break
$t_i$: time between the reference break and the $i^{th}$ failure

## 3.3 Unique Characteristics of Water Utility Break Data

As part of water utility's daily maintenance operations, maintenance crews devote a large portion of their time and budget in rehabilitating and replacing broken water pipes. While a portion of these pipe renewal activities are carried out as part of the utility's renewal operations, the majority of the renewal activities are in response to reported breaks. As part of the pipe renewal process, maintenance crews normally collect information regarding the general characteristics of the pipe (pipe material, pipe diameter), repair-related information (repair date, type of repair) and break information (break type, suspected break cause). Very few water utilities collect additional information regarding the soil properties (type, temperature, and resistivity) or climatic data.

The primary obstacle in modeling the reliability of individual pipe is the lack of pipe inventory and pipe breakage data. Unfortunately, unless a utility is participating as a case study in an external investigation, the necessary data are rarely available for analysis (Christodoulou et al., 2006). While most water utilities have only been rigorously recording breakage histories for a decade, their pipes have been in the ground for much longer. The reasons for this deficiency include: traditional practices in which pipe renewal decisions were made reactively, the large amounts of pipes that make up a normal water distribution network, and the complexities associated with managing below-ground infrastructure.

The impact of limited water main pipe records is twofold. First, in the case of water mains with less than three break records, the NHPP can not be applied because the denominator in the likelihood estimate expressed in equation (3.23) of the shape factor would reduce to zero. Secondly, in the case of water mains containing the minimum three break records, the use of only partial record sets can bias the calculation of the shape and scale terms. As an illustration of the effect of limited break records, the following example compares a cumulative break projection acquired from a reliability modeling example taken from Loganathan et al (2002) to one taken from a water main located within the Laramie, Wyoming water distribution system.

**Example:**

For the example taken from Loganathan et al (2002), Table 3.1 provides a list of the nineteen break times and Figure 3.6 shows a plot of cumulative breaks over time. The values of the shape factor ($\beta$) and the scale factor ($\lambda$) calculated using equations (3.22) and (3.23) for breaks 1~19 are 3.38 and $7.32 \times 10^{-5}$ respectively.

Table 3.1 Cumulative Break Data Taken from a Reliability Modeling Example (Loganathan et al, 2002)

| Cum Break No. | Break Time (years) | Cum Break No. | Break Time (years) |
|---|---|---|---|
| 1 | 10.0000 | 11 | 45.7050 |
| 2 | 18.0000 | 12 | 46.5640 |
| 3 | 24.4000 | 13 | 47.2512 |
| 4 | 29.5200 | 14 | 47.8010 |
| 5 | 33.6160 | 15 | 48.2408 |
| 6 | 36.8928 | 16 | 48.5926 |
| 7 | 39.5142 | 17 | 48.8741 |
| 8 | 41.6114 | 18 | 49.0993 |
| 9 | 43.2891 | 19 | 49.2794 |
| 10 | 44.6313 | --- | --- |

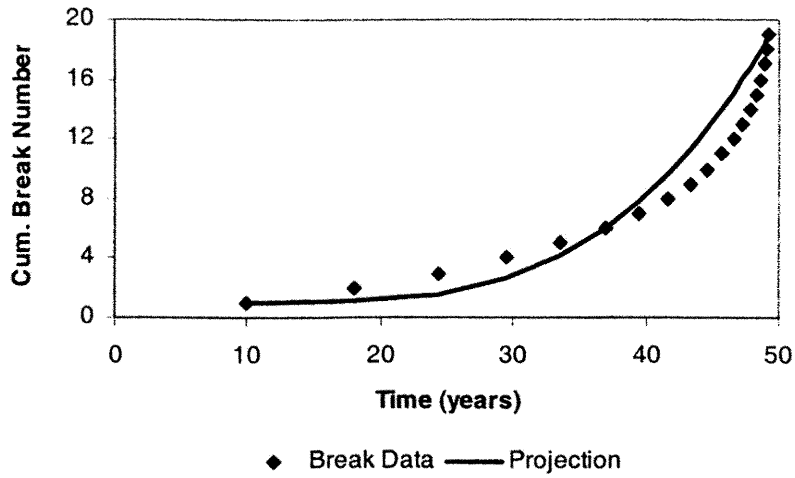


Figure 3.6 Cumulative Breaks over Time (Loganathan et al, 2002)

In Loganathan's example, observe that the break frequency increases sharply after the 6$^{th}$ break. This is indicative of a deteriorating system. In comparison, the break data taken for water pipe 157304SW17 of the Laramie water system consist of 8 break records (Table 3.2). Analyzing all eight breaks yields a shape factor of $\beta$ = 2.377 and a scale factor of $\lambda$ = 0.068 with the projection shown in Figure 3.7.

Table 3.2 Cumulative Break Data for Pipe 157304SW17, Laramie Water System

| Cum Break. No | Break Time (years) |
|---|---|
| 1 | 31.58 |
| 2 | 34.17 |
| 3 | 34.67 |
| 4 | 36.33 |
| 5 | 36.42 |
| 6 | 36.50 |
| 7 | 38.50 |
| 8 | 38.58 |

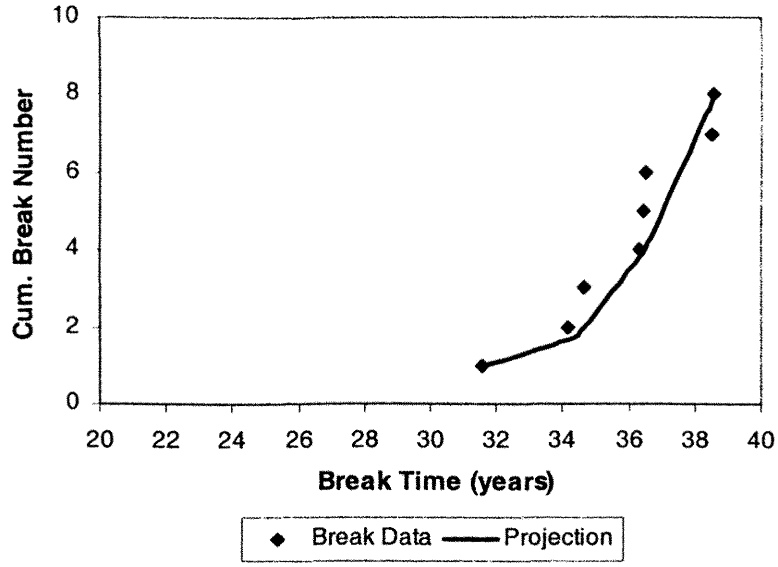


Figure 3.7 Cumulative Breaks over Time for Pipe 157304SW17
Laramie Water System

Aside from having a lower coefficient of determination ($R^2$ = 0.84 as opposed to 0.91 for the theoretical case), the cumulative break plot for pipe 157304SW17 illustrates an important characteristic common to all buried pipeline infrastructure. Although break frequencies usually increase over time, the decreasing break frequency after the sixth break illustrates that pipe deterioration is very unpredictable. This uncertainty results from the presence of numerous interdependent factors with highly-complex relationships. For example, after the repairs 4~6 which occurred within a shot time interval, the sixth repair might have included substantial compaction of the pipe bed soil, which increased the pipe stability and prolonged the time between the subsequent break.

The Laramie example also illustrates another important distinction between break data taken from traditional reliability applications and water pipe break data. The eight break records for pipe 157304SW17 is uncommon, because most water pipes have considerably less break records. In the case of the Laramie break record database, for the 367 water pipes with break histories, the average number of breaks per pipe is 1.8. Because the NHPP requires a minimum of three break records, the limited number of break records implies that only 74 of the 364 water pipes can be evaluated using a reliability modeling approach.

### 3.4 Conclusions Regarding the Application of Reliability Modeling

The purpose of this chapter was to illustrate that, although the use of reliability modeling is new to water pipe applications, it has many attributes that make it suitable to water pipe failure analysis. The NHPP is well-suited to address both the "in-usage" and "wear-out" phases of buried pipe's life cycle and the use of the Power Law form addresses the important issue of minimal repair common to reparable systems. The principal obstacle in applying reliability modeling at the individual pipe level relates to the amount of available break data. Whereas in traditional industrial-oriented applications the reliability analysis might be based on hundreds of failure records, it's rare to encounter water pipes with more than 5 break records over 70+ years of service. Despite this difference in break data availability, for water pipes with a viable documented break history, reliability modeling provides invaluable information to the pipe renewal prioritization process. For water pipes with insufficient break records, the pipe failure assessment model provides another prioritization mechanism. The details of this mechanism will be discussed in the following chapter.

Having presented the fundamental concepts of reliability modeling, the following list summarizes the most important conclusions with regard to how this approach will be applied to the model's pipe failure prediction module:

- Reliability modeling at the individual pipe level is more applicable to pipe replacement prioritization decisions than traditional system-level reliability modeling processes. This approach is based on the use of existing pipe inventory and break data to assess the site-specific performance of each water pipe.
- Water pipes are repairable systems in that, if a pipe fails, it can be repaired and restored to an operating state.
- For repairable systems the time between successive failures is not independent or identically distributed. As such, successive failure repairs cannot be modeled by conventional curve fitting of a statistical lifetime and must be analyzed using ROCOF techniques.
- A NHPP approach is best suited for the failure prediction portion of the model since it addresses both the "in-usage" and "wear-out" phases of a buried pipe's life cycle.
- The Power Law form of the NHPP is an extension of a Weibull distribution and is very flexible in modeling increasing, decreasing, and constant failure rates.
- In order to perform a pipe failure analysis with a NHPP approach, the pipe must have a minimum of three break records. Because most water utilities have only been rigorously recording breakage histories for a decade, this implies that a large portion of their water pipes can not be analyzed using a reliability modeling approach.

# CHAPTER 4

# MODEL DEVELOPMENT AND FEATURES

## 4.1 Introduction

To enhance the responsiveness the pipe failure assessment model to the industry's needs and facilitate its use, the model was developed in consideration of the unique operation and maintenance practices, the distinct properties of buried infrastructure, and the data limitations characteristic of the industry. The model uses a performance-based approach in which each pipe's performance is evaluated using the existing pipe inventory and break records. Having assessed the pipe performance, the model's failure prediction module uses a NHPP to provide the decision maker with various probability-based pipe replacement prioritization criteria. Recognizing that pipe renewal decisions are also based on risk avoidance, a unique feature of the model is that it supplements the failure prediction module with an additional consequence module. This dual approach provides decision makers with the ability to prioritize pipe renewal activities as part of a risk management program in which renewal decisions are based on both the probability and consequence of pipe failures.

The first part of this chapter explains model development for pipes with a minimum of three breaks, pipes with one or two break records, and the model's consequence modeling. The second part of the chapter discusses model features and use, including the model initialization, data input, individual pipe and system-wide assessment, and reporting features.

## 4.2 Contribution of Industry Experts to the Pipe Failure Assessment Model

At various stages during the model's development, its features were demonstrated to officials from Colorado Springs Utilities and Laramie Water who provided pipeline inventory and break history information for analysis studies. Most of the interaction with these utilities occurred through phone conversations and email correspondence. At the completion of the research, the model was demonstrated to representatives from each utility during a meeting held at Colorado State University on July 17, 2006. Aside from the participating case study utilities, a forty minute instructional video showing the model's features was distributed to five other water supply organizations. After viewing the video, each organization responded to a questionnaire addressing the model's features and responsiveness to the industry's needs. Questionnaire responses from each organization are provided in the appendix.

Through the interaction with these utility professionals, the researcher gained insights into the attributes and deficiencies of the model and its applicability to industry needs. In addition to model details, the discussions provided information about methods for pipe replacement prioritization and insight into site-specific factors. Table 4.1 summarizes the principal observations of the industry participants from Colorado Springs Utilities and Laramie Water. The table is divided into two groups of comments. The first group of comments pertains to the mechanisms currently used by the utility management in selecting pipes for replacement. The second group relates to the strengths and weaknesses of the initial model. Both sets of comments were incorporated into the final design of the pipe failure assessment model. The model was then tested with the case studies as presented in Chapter 5.

Many of the comments relating to current pipe replacement mechanisms and practices had already been included in the initial version of model since they had been identified through the researcher's literature and case study review. In particular, the model's use of a performance-based approach addressed several of the industry practices and limitations outlined in Table 4.1. By making use of the data already gathered through the daily pipeline inspection and maintenance activities, the approach not only eliminates the need for utilities to gather data outside their normal realm of operation, but inherently incorporates site-specific conditions. Performance-based modeling also allows for the forecasting of the expected time to next break, which is an essential component of a proactive pipe replacement program. Many of the comments regarding the attributes and shortcomings of the initial model motivated the researcher to make several notable modifications to the initial model. The largest change involved the use of a Decision Support System (DSS) to address the pipe replacement prioritization of pipes with less than 3 breaks since these pipes can not be analyzed through a probabilistic approach. Details regarding the design and use of the DSS will be discussed in the following section. Aside from the DSS, the NHPP portion of the program was restructured so as to eliminate the rigorous process of selecting a minimum break time.

Table 4.1 Observations from Water Utility Professionals Regarding the Existing Industry Practices for Prioritizing Pipe Replacement and the Attributes/Deficiencies of the Conceptual Model.

Comments Regarding the Current Pipe Replacement Practices

1 Decisions regarding water main replacement are normally made by utility management based on recommendations from the maintenance department.
2 Most utilities do not have sufficiently detailed break records to support complex statistical analysis. This is a major impediment to many of the existing pipe failure models.
3 In terms of pipe inventories, most water utilities have their records in some form of electronic form. This form varies from sophisticated databases to simple Excel spreadsheets.
4 There are currently no universally accepted criteria for identifying which water mains should replaced at any given time. Each utility bases its decisions using its own criteria.
5 Experience shows that replacement decisions should not be based solely on pipe age, utilities understand that the pipe deterioration process is related to various factors.
6 Pipe replacement decisions are based on the utility's belief in the potential condition of individual pipes with no regard for assessing the probability of future breaks.
7 The emergence of information technology (databases, GIS) has helped the decision makers identify their most "troubled" pipes. However, what they really need is a tool that will provide decision makers with a quantitative and transparent mechanism to help them prioritize specific pipe replacement activities.

Comments Regarding the Initial Model

1 The program's platform in Excel makes it less imposing to potential users.
2 The inclusion of a consequence module is very useful and appropriate since it addresses the industry's risk avoidance nature.
3 Within the program's system-wide evaluation module, the need for the user to specify a minimum break time is overly cumbersome. The program should make this decision for the user based on either a "best practice" approach or by through optimization.
4 The NHPP approach is only applicable to pipes with a minimum of 3 break records. While this approach is certainly applicable to water mains, it does not provide the decision maker any guidance regarding the 1 or 2 break pipes which make up the majority of the records.
5 The model should employ some form of Decision Support System (DSS) for the 1 and 2 pipes so that the utility can include this information as part of their multi-year plans.
6 The model needs to have several internal checks in order to ensure that the user does not enter values that will cause the program to crash.

### 4.3 Need for Two Prioritization Mechanisms

Due to an industry-wide shortage of water main breakage data, many water pipes have less than three break records. Under this scenario, a NHPP can not be applied because the denominator in expression (3.23) for the likelihood estimate of the shape factor would reduce to zero. However, given the large quantity of pipes with limited break records and the propensity of break frequencies to increase following an initial break, it became apparent that the pipe failure assessment model needed to provide the decision maker with some means of including these pipes within the utility's pipe prioritization program.

Having established the need for two distinct prioritization approaches, the program architecture was modified to include an algorithm that separates the break records into two principal groups:

- Water pipes with 3 or more break records
- Water pipes with either 1 or 2 break records

For water pipes with a minimum of three break records, the Power Law form of the NHPP is applied to calculate the probability of failure, expected number of failures, and time to next failure. However, for pipes with either 1 or 2 total break records, a Multicriteria Decision Analysis (MCDA) module was developed to as a prioritization tool for these pipes. The premise of the MCDA is to assign points to variables identified as having an influence on the overall life expectancy of each pipe. The resultant point total for each pipe provides a relative ranking that corresponds to a replacement priority for each pipe. Whereas the water pipes with three or more break records pose the greatest threat to the overall system performance, and thus would probably receive first replacement priority, the relative ranking information from the MCDA module is more applicable to utility multiyear planning activities.

### 4.3.1 Application of the NHPP for Water Mains

For water mains with a minimum of three break records, the likelihood estimates of the scale ($\lambda$) and shape ($\beta$) factors calculated from equations (3.22) and (3.23) can be applied to calculate the probability of failure, expected number of failures, and time to next failure. Because the shape and scale factor calculations require a minimum of three records, for water mains with exactly three breaks, there is only one value for $\beta$ and $\lambda$. However, for water mains with four or more break records, the $\beta$ and $\lambda$ parameters can be calculated for a multitude of break record combinations. For example, for a pipe with five break records, there are a total of six break record combinations (1~3, 1~4, 1~5, 2~4, 2~5, 3~5) that provide a unique combinations of $\beta$ and $\lambda$. For each $\beta$ and $\lambda$ combination, equation (3.7) produces a projection of the expected number of cumulative breaks over time. The variance between the predicted breaks from this projection and the known breaks is referred to as the coefficient of determination ($R^2$).

The coefficient of determination provides a measure of the variance between a given known value and its predicted value. In the case of the pipe deterioration failure assessment model, it provides an indication of the statistical validity of the NHPP Power Law model in forecasting future pipe break events.

The $R^2$ value is calculated from the sum of square terms as (Miller and Freund, 1985):

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \tag{4.1}$$

The SSR term in equation (4.1) is the regression sum of squares. For pipe i, it represents the total variance between a predicted break ($\hat{y}_i$) and the mean of all the observed breaks ($\bar{y}$). The SSE term, known as the error sum of squares, is a measure of the variance between the predicted break of pipe i ($\hat{y}_i$) and the observed value ($y_i$). Lastly, the SST term represents the total sum of squares, which is defined as the variance between the observed sample and the mean of all the samples. The SSR, SSE and SST terms are expressed as (Miller and Freund, 1985):

$$SSR = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 \tag{4.2}$$

$$SSE = \sum_{i=1}^{n} (\hat{y}_i - y_i)^2 \tag{4.3}$$

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{4.4}$$

The values of the sum of square terms provide an indication of how well the predicted values fit the actual break data. If the prediction is "perfect", then the SSE is zero, which yields a $R^2$ value of 1. Likewise, $R^2$ is also equal to 1 if the explained variance (SSR) is equal to the total variance (SST). Conversely, the prediction is deemed a total failure if the SSE and SST are equal. Under this scenario, $R^2$ is equal to zero.

Within the model's individual pipe assessment module, the user can perform a statistical analysis based on his/her break record preference (1~3, 1~4, 2~4, etc.) or have the program select the optimum break record combination by evaluating the $R^2$ values for each ($\beta$, $\lambda$) combination. In the case of a system-wide statistical analysis, the program will automatically select the parameters $\beta$ and $\lambda$ which yield a maximum value of $R^2$.

As an example of the NHPP process for pipes with multiple break records, Table 4.2 below summarizes the $R^2$ values corresponding to the $\beta$ and $\lambda$ combinations for pipe 157304SW38 from the Laramie Water System. The water pipe has five break records, so there are a total of six break record combinations producing unique shape and scale factor values. Of the six $\beta$ and $\lambda$ combinations, three produce $R^2$ values of zero implying a large variance between the predicted pipe breaks and the observed values. For the other three break record combinations (1~4, 1~5, and 2~5), the $R^2$ values vary from 0.266 to 0.875. So for this particular pipe, the shape and scale factors calculated using break records 1~5 yield the best correlation ($R^2 \approx 0.88$) between the actual break data and the projected values. Figure 4.1 illustrates the accuracy with regard to the forecasted cumulative break projections for all six ($\beta$, $\lambda$) combinations.

### 4.3.2 Application of the MCDA for Water Mains

Based on conversations with water utility professionals as well as a literature review, it was decided that for the model should provide the decision maker with a point-based mechanism to rank pipes based on their potential for future breaking. The approach selected for application is similar to that developed by the City of Boulder, Colorado (Butler and Earley, 2002) for their water distribution pipe replacement prioritization program. Specifically, the program uses a MCDA tool that assigns points to each criterion (variable) identified as influencing the life expectancy of the utility's water pipes. The resultant point total for each pipe provides a relative ranking that corresponds to a replacement priority for each pipe. The higher the point total, the higher the priority for pipe replacement. The point system used by the City of Boulder is referred to as the Weighted Average Method (WAM), which is a popular due to its simplicity and ability to provide a complete ranking.

Table 4.2 Shape Factor ($\beta$), Scale Factor ($\lambda$), and $R^2$ Values for Various Combinations of Break Records for Pipe 157304SW38, Laramie Water System

| Break Records | $\lambda$ | $\beta$ | $R^2$ |
|---|---|---|---|
| 1 ~ 3 | 0.103 | 2.767 | 0.000 |
| 1 ~ 4 | 0.111 | 2.540 | 0.398 |
| 1 ~ 5 | 0.182 | 1.940 | 0.875 |
| 2 ~ 4 | 0.037 | 4.925 | 0.000 |
| 2 ~ 5 | 0.163 | 2.325 | 0.266 |
| 3 ~ 5 | 0.487 | 2.038 | 0.000 |

The first step in the WAM is to identify the variables that are known to influence the life expectancy of buried water pipes. The following variables were identified through the literature review and are available as defaults within the model's MCDA module:

- Break Causes (corrosion, settlement, pressure split, etc.)
- Break History (number of previous breaks)
- Diameter
- Material
- Pipe Age
- Pressure
- Soil Resistivity (a measure of the corrosive environment)
- Soil type

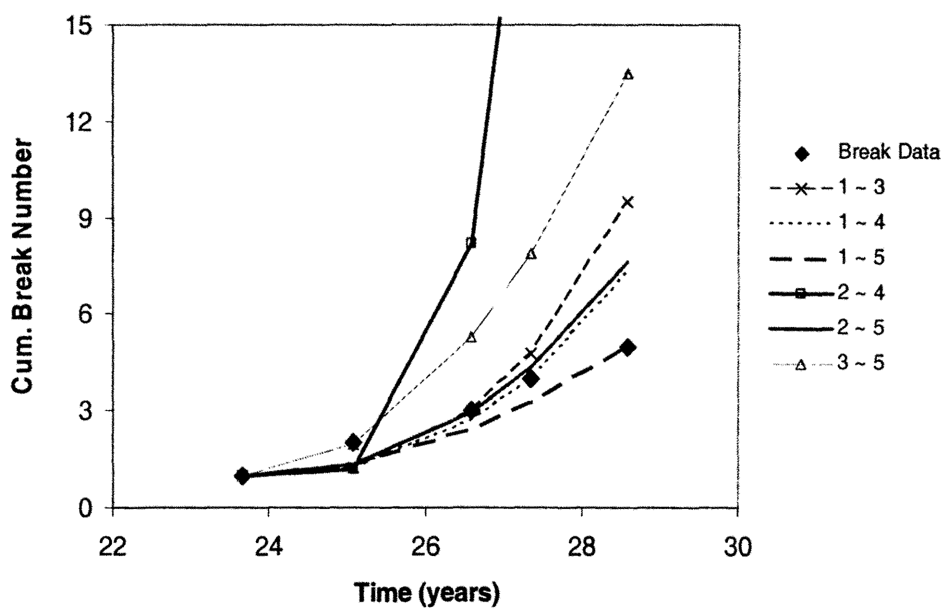


Figure 4.1 Break Projections Based on Various Break Record Combinations, Pipe 157304SW38, Laramie Water System

If the user determines that the life expectancy of their system's pipes is influenced by other criterion not included in defaults, she/he can include this criterion through the model initiation process discussed later in this chapter.

There are two general categories of criterion: static and time-dependent. Examples of static criterion include pipe diameter and material type whereas pipe age and soil temperature are examples of time-dependent criterion. For the eight criterion provided as defaults in the MCDA module, age is the only time-dependent criterion. The argument can be made that soil resistivity (which can change with soil moisture fluctuations or from the application of de-icers) and pressure (which varies relative to the hourly demand and water temperature) should be treated as time-dependent factors. However, modeling these criteria as time-dependent variables requires extensive amounts of data that are historically unavailable and costly to acquire. In the case of temperature-dependent criterion such as soil and water temperature, experts question their use in prediction models since temperature can not be reliably predicted (Kleiner and Rajani, 2000).

The variables affecting pipeline life expectancy are interrelated and site-specific. As such, although utility personnel "have a feel" for which variables impact the failure of their pipe infrastructure, some form of statistical correlation analysis must be performed in order to quantify these hunches. Although there are various correlation techniques ranging from histogram scatters to bivariate and Spearman correlations (Marks, 1985), the principal deterrent in applying these techniques is the large amounts of detailed field data and/or a high level of technical expertise. Often the sophistication of these correlation techniques requires the use of statistical software programs such as EGRET which was used by Vanrenterghem (2003) in her analysis of the New York City water system.

For the case studies included within this dissertation, the researcher opted to apply the same statistical correlation approach used by Butler and Earley (2002) due to its intuitive nature, ease of calculation, and flexibility. These traits are especially relevant to the water utility industry in that, if a technique is overly complex and not intuitive, it simply will not be applied. The approach is based on comparing a variable's break percentage to its overall quantity percentage in the system. For example, if 70% percent of a system's pipe breaks occurred with a certain material type, but this material type was present in only 35% of the system, then it should be assigned a higher point value in the WAM. For the two case studies included as part of this investigation, a detailed description of the correlation analysis for each utility is provided in Chapter 5.

Once all the criteria have been identified, each criterion must be divided into classes (intervals) with points assigned to each class. Continuing with the example from the City of Boulder, Table 4.3 illustrates the classes and points used for the pipe size and soil type variables. It should be emphasized that, although these variables had the strongest correlation to the number of pipe breaks, point values were also assigned to other variables in the Boulder case study.

Table 4.3 Example of the Classes and Points used by the City of Boulder (Butler and Earley, 2002)

| Criterion | Class | Points |
|---|---|---|
| Pipe Size | 4-inch | 20 |
| | 6-inch | 10 |
| | 8-inch | 5 |
| | > 8-inch | 0 |
| Soil Type | LoB-Longmont Clay | 20 |
| | Te-Terrace Escarpments | 10 |
| | NuC-Nunn Clay Loam (3-5% slope) | 10 |
| | NuC-Nunn Clay Loam (1-3% slope) | 5 |
| | All others | 0 |

In MCDA modeling applications, the points assigned to each class within a variable are referred to as the relative importance terms. Having established the classes and relative importance terms for each variable, the decision maker assigns the variable weights in order to prioritize certain variables. The total score for the WAM method is calculated based on the following expression:

$$S_i = \sum_{j=1}^{n} W_j * R_{i,j} \qquad (4.5)$$

where:

$S_i$: total score for pipe i
$W_j$: weight assigned to criterion j
$R_{i,j}$: relative importance of criterion j on pipe i

The weight term, $W_j$, provides the decision maker with a mechanism to prioritize certain criterion. For example, if a weight of two is assigned to criterion A and a weight of one is assigned to criterion B, then it is inferred that criterion A is twice as important to the final decision as criterion B. Although the weight term allows the decision maker to accentuate certain variables, care must be taken to ensure that the weights themselves do not overly influence the final rankings. In the pipe failure assessment model, the user to specify the criterion weights based on utility-specific criteria and experience.

### 4.4 Risk Assessment Modeling

In order to provide will provide utility managers with the ability to prioritize pipe renewal activities as part of a comprehensive risk management approach, the model supplements the pipe failure modeling with an additional consequence module. For an individual segment of pipe i, the relationship between the consequence of a failure and the probability of a failure is expressed as the risk of failure:

$$R_i = P_i * C_i \tag{4.6}$$

where:

$P_i$: probability of failure for pipe i
$C_i$: consequence of failure for pipe i

The consequence term in equation (4.6) is evaluated using multipliers to distinguish between critical factors relating to special services, locations, etc. The approach used with the pipe failure assessment model resembles that developed by the Seattle Public Utilities (SPU) for their Sewer Pipe Risk Model (SPRM). The SPRM classifies consequences into three classes of factors: location-related, indirect, and social factors. For each combination of pipe size and material, weights are assigned based on the ratio of the factor-specific repair costs divided by the baseline repair cost. For example, a weight of 1.5 assigned to pipe located under railroad tracks implies that the repair costs associated with this pipe is 50% higher than a repair for the same pipe located in an area without a location-specific consequence. Whereas location-specific factors and several indirect factors can be quantified in economic terms, the social factors are more difficult to quantify. As such, weights for the social factors are designated based on utility personnel's experience and priorities. Acknowledging that the selection of weights can easily bias pipe renewal decisions, it is strongly recommended that the decision maker employ a sensitivity analysis of the selected weights. Under this approach, the decision maker systematically runs the model for various social factor weight scenarios while looking for any corresponding trends.

### 4.5 Modeling Architecture and Approach

The pipe failure assessment model was written in Visual Basic for Applications (VBA) within a Microsoft Excel platform. Whereas the Excel platform was selected due to its commercial availability, the use of VBA user-forms simplifies the data entry and analysis features of the program. The model consists of several modules (components) which work interactively through the use of various databases. Whereas several modules including the Pipeline Data Module (PDM) and the Consequence Module (CM) are used for data entry, the program's Pipe Failure Prediction (PFP) and Multicriteria Decision Analysis (MCDA) modules perform the pipe replacement prioritization calculations. For an individual pipe, the decision between using the PFP and the MCDA module for the prioritization analysis is based on pipe's break history. For pipes with one or two break repairs, the MCDA module provides a total score that serves as a relative pipe replacement ranking. For pipes with a minimum of three break records, the PFP module produces several probabilistic-related decision criteria to assist in the replacement prioritization process. For the pipes evaluated with the PFP module, the model also uses the pipe-specific consequence data to provide the user with a ranking based on risk. Aside from the model's data input and computational components, the model also contains a variety of standardized reports and graphs. The diagram in Figure 4.2 illustrates the interactions between the various modules.

### 4.6 Model Initialization and Data Input

The following sections discuss the recommended approaches for initializing the model parameters used throughout the program and entering the water distribution pipe inventory and break records.

#### 4.6.1 Model Initialization

Users entering the pipe assessment failure model are presented with a Main Menu page as shown in Figure 4.3 that allows them to access the various modules of the model. For users initializing the model for the first time, selection of the "Model Registration" button allows the user to include general utility, project, and contact information. An illustration of the Model Registration form is shown in Figure 4.4. There is also an "Access Program Instructions" button which provides detailed instructions for every component of the model.

Having completed the model registration process, the user must then initialize the pipeline data and MCDA parameters to reflect project-specific characteristics. Initializing these values simplifies data entry process since the various user forms continually look up values stored within the project initialization module. To initialize these values, exit the program by clicking on the "Exit Program" program. Once within Excel, select the "data" worksheet tab to initialize the pipeline data or the "MCDA" worksheet tab to initialize the MCDA parameters. For the pipeline data, Table 4.4 illustrates the parameters and their relative location (column letter) that must be specified by the user. Once the user has entered the pertinent information, normal Excel protocol should be applied (select the "Save" command located within the File Menu) to save the pipeline data settings.

Table 4.4 Pipeline Data Parameters and their Column Location within the "data" Worksheet

| Parameter | Column |
|---|---|
| Years | C |
| Diameter | D |
| Soil Types | E |
| Pipe Types | F |
| Break Types | G |
| Action Performed | H |
| Model Years | I |

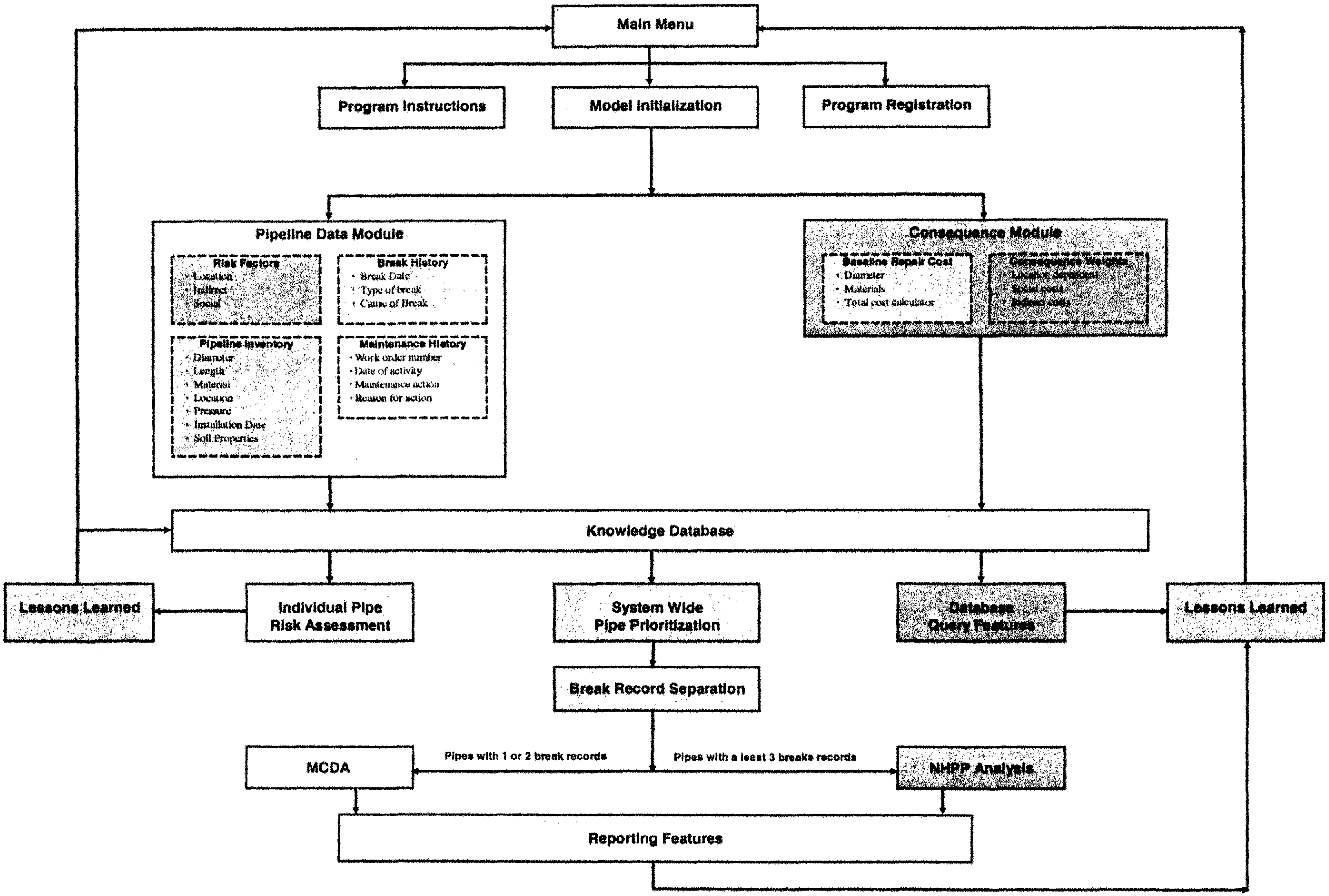


Figure 4.2 Schematic of the Pipe Failure Assessment Model

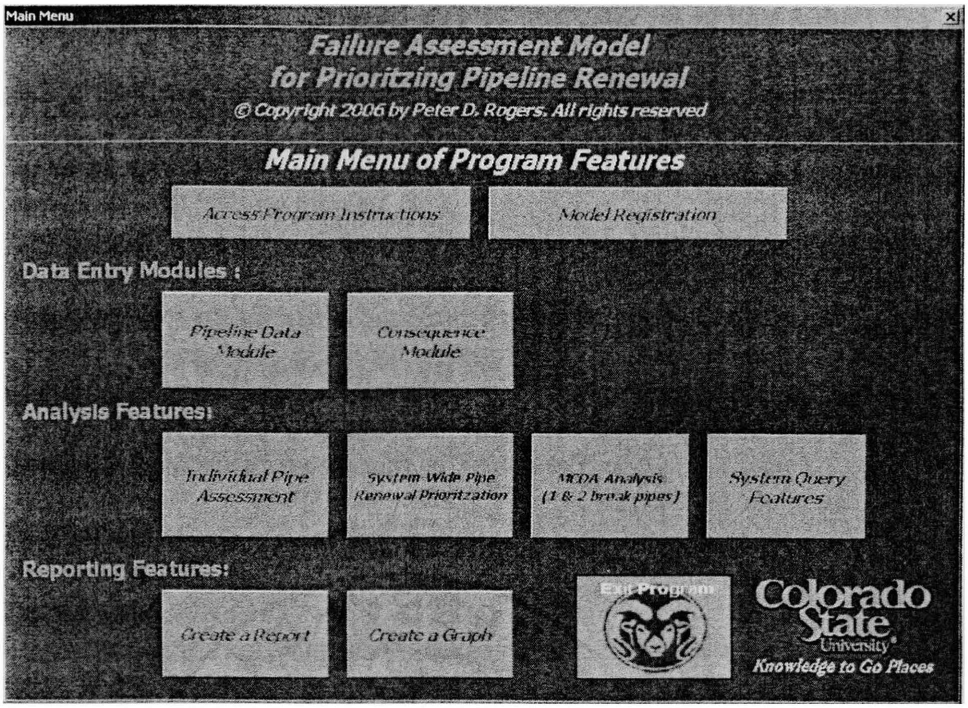


Figure 4.3 Pipe Failure Assessment Model, Main Menu Form

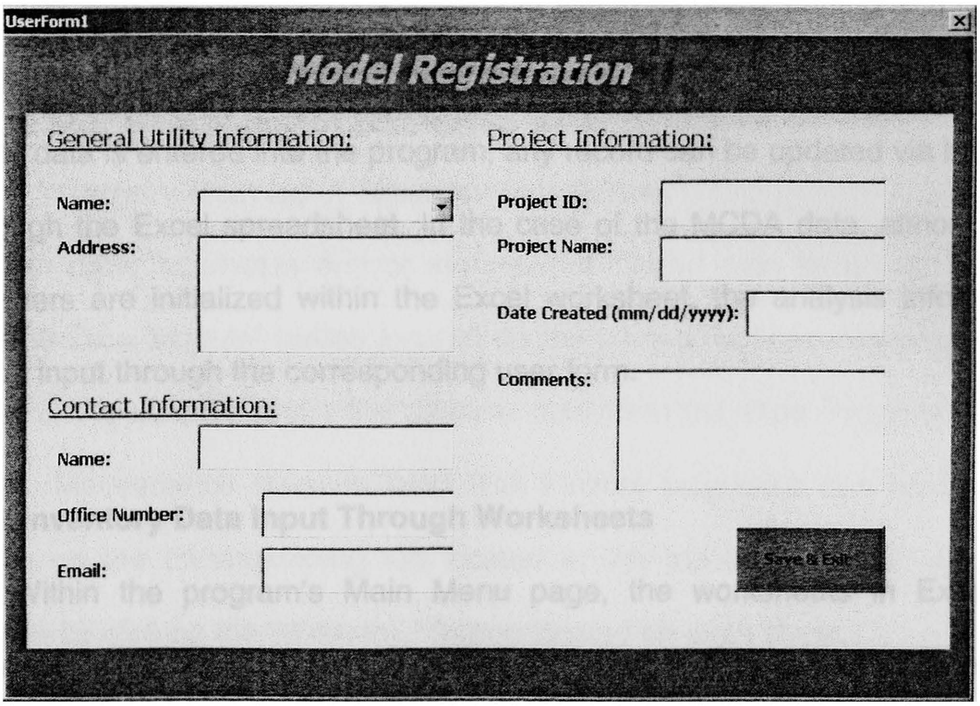


Figure 4.4 Pipe Failure Assessment Model, Model Registration Page

In order to initialize the MCDA parameters, the user must first select the "MCDA" worksheet tab. Within the worksheet there are three principal steps:

- Review the 8 default variables and decide which should be included within the MCDA analysis.
- Specify the range of relative weights that will be used for the variable(s).
- For each variable to be applied in the MCDA analysis, specify both the interval (class) and point allocations. Note that each interval must have a corresponding point assigned. In order to view an example of these interval and point allocations, refer to the values used by the City of Boulder, Colorado as shown in Table 4.3.

### 4.6.2 Data Input

General pipeline inventory data (pipe sizes, installation date, break records, maintenance history, etc.) are entered into the program on a pipe-by-pipe basis through the user-friendly data form or through the Excel worksheets. For utilities with the pipeline data already in electronic form, cutting and pasting this data directly into the appropriate worksheet is the quickest method. Once the pipeline data is entered into the program, any record can be updated via the form or through the Excel spreadsheet. In the case of the MCDA data, although the parameters are initialized within the Excel worksheet, the analysis information must be input through the corresponding user form.

#### 4.6.2.1 Inventory Data Input Through Worksheets

Within the program's Main Menu page, the worksheets in Excel are accessible by clicking on the "Exit Program" button. Once within Excel, the inventory data can either by directly typed into the worksheet or cut and paste from an external source. Table 4.5 provides a list of the worksheets that must be completed within the Pipe Failure Assessment Model and a brief description of the required information. Note that, within the breakhistory worksheet, it is extremely important that the pipe identification number (pipe id) match exactly the pipe id shown within the pipedata worksheet.

Table 4.5 Information Regarding the Worksheets and Data Needed to Run the Pipe Failure Assessment Model

| Worksheet | Description |
|---|---|
| pipedata | Contains general pipe and GPS (optional) information for each pipe. Note that each month should be referenced using 3 letter month abbreviations as shown in the data worksheet. |
| installation | This information can be copied from the pipedata worksheet. The location description is optional. |
| breakhistory | The most important information is the pipe id, break number and repair date (using the same 3 letter month abbreviation). Note that the pipe id must exactly match the id referenced in the pipe data page. |
| maintenance | Data entry for this worksheet is optional and does not impact the pipe failure modeling. |
| piperisks | For each pipe, specify TRUE if the pipe exhibits the associated risk or FALSE if it does not. Columns R and S can be used to identify any risk not mentioned in columns B ~ Q. |

#### 4.6.2.2 Inventory Data Input Through User Forms

In order to access any of the pipeline-related data forms, click on the "Pipeline Data Module" button located on the program's Main Menu page. As shown in Figure 4.5, within the pipeline data form the Pipe Properties, Break History, Maintenance Records, and Risk Factors properties can be accessed clicking on the corresponding tab located at the top of the form. Save any changes by clicking the "Write to..." button located on each sheet.

#### 4.6.2.3 Consequence Input Data

Although the consequence factors can be manually entered through the "risk" worksheet in Excel, the simplest manner to enter this information is through the Consequence Module user form located in the program's Main Menu page. Once within this module, the steps outlined in Table 4.6 should be applied for each pipe size and material combination found within the distribution system.

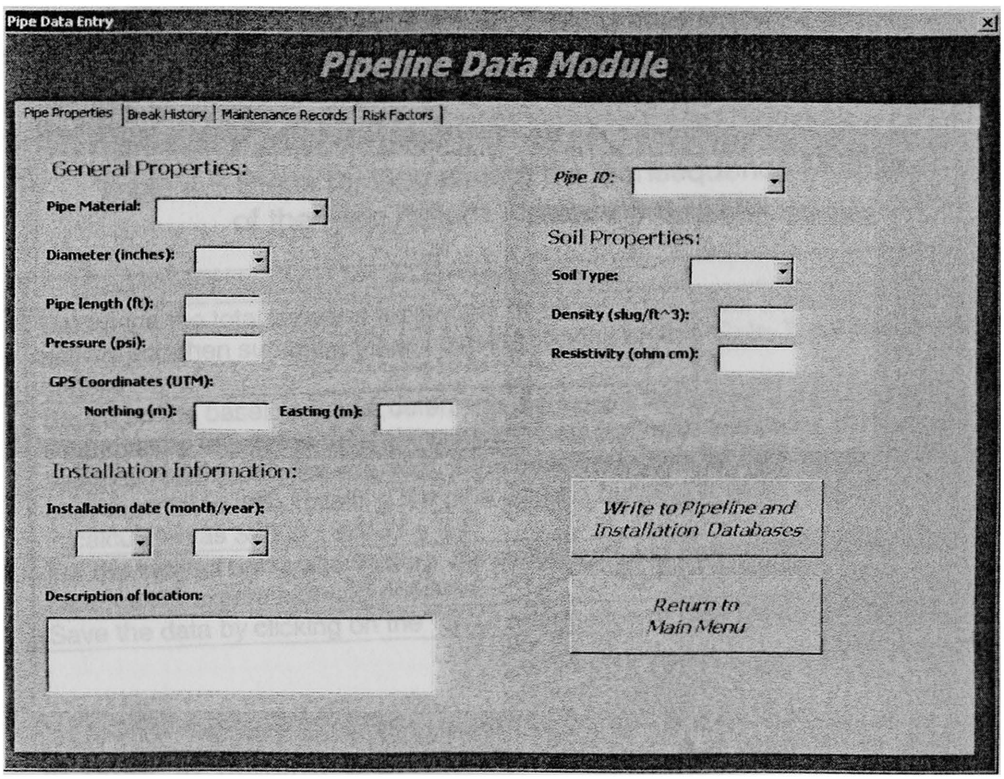


Figure 4.5 Pipe Failure Assessment Model, Pipeline Data Form

### 4.7 Individual Pipe Assessment

Within the program's Individual Pipe Assessment module, the user can view the various combinations of graphical projections and $R^2$ values in a similar format to that shown in Table 4.2 and Figure 4.1. Having viewed this information, the program allows the user to either select the break record combination that he/she prefers or have the program select the appropriate break record combination. If the users opts to have the program choose the break record combination, by default the program will select the combination which yields the largest value of $R^2$. For either selection, the Individual Pipeline Risk Assessment form provides the user with a table summarizing the selected break range and the corresponding $R^2$, $\lambda$ and $\beta$ values.

Table 4.6 Steps for Completing the Consequence Module of the Pipe Failure Assessment Model

| Step | Instructions |
|---|---|
| 1. | Determine the total baseline repair cost by entering the costs associated with each activity and then summing these costs by clicking on the "Calc. Total Repair Cost" button. |
| 2. | Based on the baseline costs, determine the weight factors for the pipe location scenarios by taking the ratio of the repair costs for these scenarios divided by the baseline repair cost. For example, if the baseline cost is $2,000 and the additional cost associated with installing the pipe under a building is $800, then the weight factor is calculated as $2800 / $2000 = 1.4. |
| 3. | For the indirect and social factors, the weights should be established based on utility personnel's experience and priorities. |
| 4. | Save the data by clicking on the "Write Information to Risk Database" button. |

In order to perform a probability analysis, the user must first click the “Analyze Data” button located on the form. This operation then transfers the user to an Excel spreadsheet entitled “Analysis of Break Data”. Once within this worksheet, the reliability, probability of failure, and expected number of failure curves are generated by first specifying the starting and ending years, then clicking the “Generate Curve” button. For example, the probability of failure curve for pipe P18735683 from Colorado Springs Utilities for the years 2006 to 2010 is shown in Figure 4.6. Having generated the curve, the user must then select a specific year to be used for the risk assessment and click the "Send Value to Program" button. Having returned to the form, in addition to the aforementioned summary table, the form now also contains information regarding the probability of failure for the specified year as well as the estimated time to next break. In order to view the cumulative location and indirect/social weights, as well as the final risk score, the user clicks the "Access Records" button. Having completed the entire analysis, the Individual Pipeline Risk Assessment form will look like that shown in Figure 4.7.

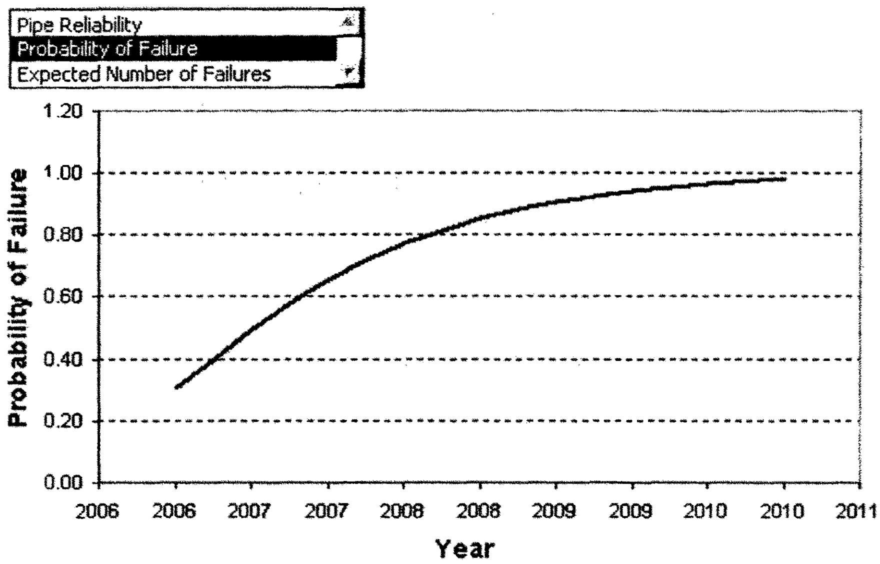


Figure 4.6 Probability of Failure Curve for the Years 2006 ~ 2010
Pipe P18735683, Colorado Springs Utility

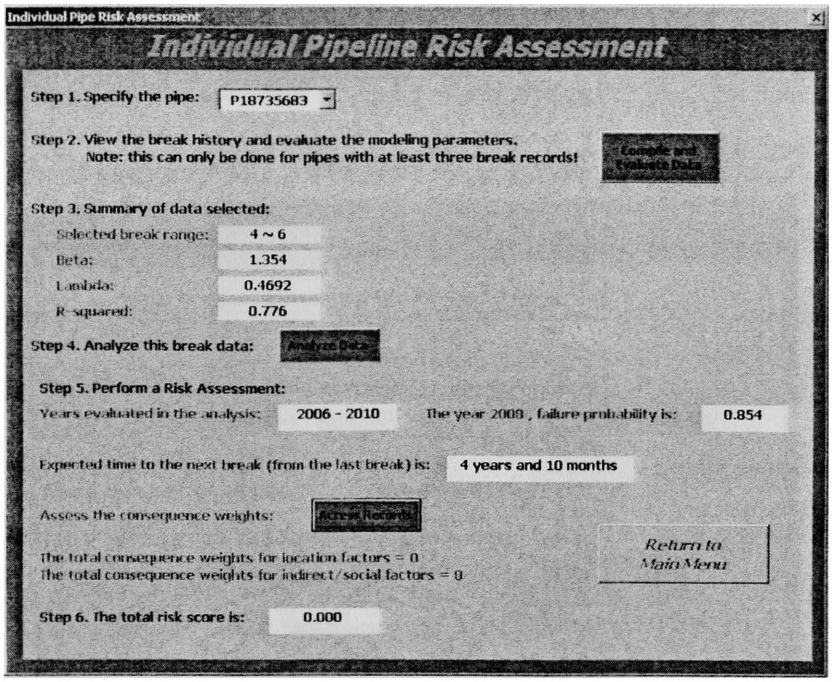


Figure 4.7 Individual Pipeline Risk Assessment Form for Data from Pipe P18735683, Colorado Springs Utility

## 4.8 System-Wide Pipe Renewal Prioritization

Prior to performing either a NHPP for pipes with a minimum of 3 breaks or MCDA for pipes with less than three break records, a system-wide assessment must be performed. The easiest way to access the System-Wide Pipe Renewal Prioritization module is through the Main Menu as shown in Figure 4.3. As shown in Figure 4.8, once inside the module there are three options with regard to specifying which pipes within the network are to be evaluated:

- Selection based on pipe material and size – pull-down menus for both the pipe material and size allow the user to select the desired combination.

- Selection based on a range of pipes – user specifies both the starting an ending pipes from pull-down menus. Because the program uses an ascending ordering of pipe names, the starting and ending pipes must follow an ascending order.

- Analysis of the entire distribution system - this option only requires that the user check the corresponding box.

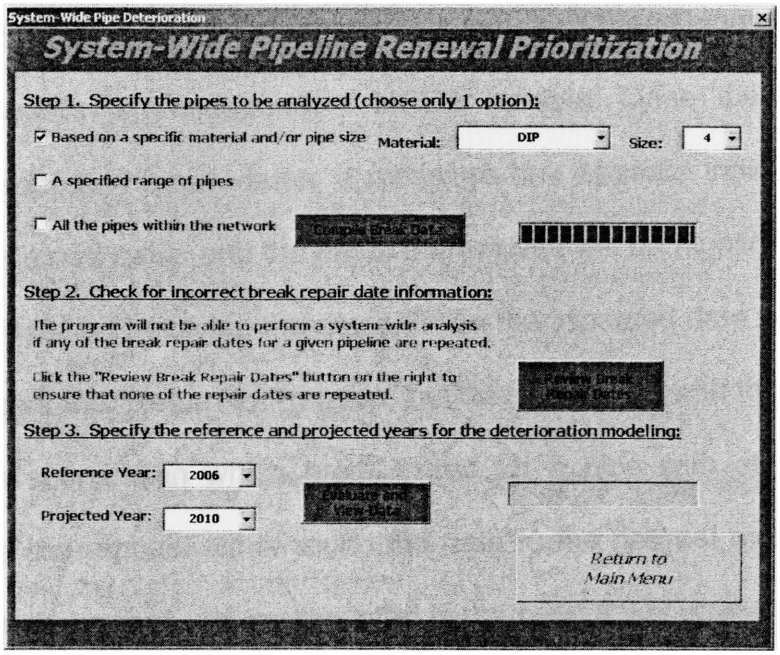


Figure 4.8 System-Wide Pipeline Renewal Prioritization Form

Having specified the pipes to be included in the system analysis, click the "Compile Break Data" button on the form. Once the system-wide analysis has started, a progress bar illustrates program's progress in completing the analysis. Once the system-wide analysis is complete, click the "Review Break Repair Data". This button transfers the user to a spreadsheet with a summary of all the break data for the system analysis. Within this spreadsheet, have the program verify that none of the repair dates are repeated by clicking the “Check for repeated break repair dates” button. This is step is important for pipes with a minimum of three break records since a repeated repair date in the probability (NHPP) modeling will cause the problem to crash. Recalling that the program uses a month time step in its calculations, two concurrent break repair dates within the same month will appear as the same date under the mm/yyyy format. In the case of the one or two break pipes, the presence of consecutive break dates within the same month is less problematic since these pipes are evaluated using the model's time-independent MCDA module. Once the program has checked for repeated break dates, a message box appears indicating the total number of repeated dates and the dates themselves will be highlighted in orange to assist the user in identifying the dates. Once the repeated date issue has been addressed, click the "Return to Program" button to continue with the analysis.

In the scenario in which break dates for a pipe with at least 3 break records, the user should either round the date to the nearest month or remove the date from the record. As is presented in the case study analyses, the "rule of thumb" used by the researcher was to apply a minimum break time of 15 days. This time interval was selected based on the recommendation of the utility personnel participating in the research. For cases in which the time between consecutive breaks exceeded 15 days, the researcher opted to either round up or round down the repair dates to the nearest month. Under this approach, the repair dates 08/09/1978 and 08/21/1978 were modified to 08/1978 and 09/1978 respectively. Likewise, the repair dates 08/09/1978 and 08/13/1978 were reduced to 08/1978. In the case of the water pipes with either one or two breaks, the same 15-day rule applied in terms of date removal, however, the months were not rounded to the nearest month. For example, the dates 08/03/1978 and

08/21/1978 remained the same, but 08/13/1978 and 08/23/1978 was reduced to 08/13/1978.

Having returned to the System-wide evaluation form, prior to calculating the probability of failure for each pipe, the user must specify both the reference and projected years for the analysis. In the case of the example provided in the figure, the reference year is 2006 and the desired forecast year is 2010. Once the reference years are specified, the last step in the system-wide evaluation involves clicking the "Evaluate and View Data" button located on the form. At the completion of the analysis, a message box appears indicating the number of 1 and 2 break records that are not included in the NHPP analysis. These records are available for viewing and/or analysis through the program's Report and MCDA modules. For the pipes included in the NHPP analysis, the user is then taken to a worksheet in which the probability of failure, statistical validity ($R^2$), total risk score, and estimated time to next break for each pipe is reported. Note that, unlike the individual pipe assessment module which provides the user the option of selecting the size ($\lambda$) and shape ($\beta$) parameters, in the system analysis the program chooses the parameters which provide the best correlation ($R^2$) for each individual pipe.

### 4.8.1 Separation of Pipe Break Records

An important process within the system-wide evaluation is the separation of pipelines into two classes: pipes with less than 3 break records to be analyzed through the model's MCDA module, and pipes with 3 or more break records that are evaluated using the NHPP. Aside distributing the two classes of water main break data to their appropriate analysis modules, the separation process also has the added benefit of improving the computational time required for the calculation-intense NHPP to evaluate the $\beta$, $\lambda$, and $R^2$ terms for the various break combinations. As an illustration of the computational time savings, in the case of the break history data from Colorado Springs Utility in which 1,412 of the total 1,797 break records are either one or two break events, the separation of pipeline classes allows the model to apply the NHPP to only a fraction of the total break record inventory.

#### 4.8.2 Non-Homogeneous Poisson Process Analysis

Once the system-wide analysis has separated the break records into the aforementioned classes and completed the NHPP calculations, the user is then taken to a worksheet as shown in Figure 4.9 in which the probability of failure, statistical validity ($R^2$), total risk score, and estimated time to next break for each pipe is reported. Although the worksheet provides the user with a summary of all the pertinent information derived from the NHPP evaluation, the Report and Graph modules located within the Main Menu provide the user with a variety of standardized reports and graphs useful to the pipe replacement prioritization process.

#### 4.8.3 Multicriteria Decision Analysis

Having performed a system-wide analysis, the user can perform a MCDA for the water mains with either one or two break records. Recall that in order to perform a MCDA, the break-related parameters, intervals, interval points, and relative weights must have been specified during the model initialization process described in section 4.6. To begin the MCDA process, click the "MCDA Analysis" button located in the Main Menu page. Once within the “Multicriteria Decision Analysis” form, information regarding the name of the utility, project name, and project ID should already be included since it was provided during the Model Registration portion of the model initialization process. The user must enter the preparer's name and the evaluation date information. The evaluation date information is particularly important since pipe age is calculated relative to this value. As shown in Figure 4.10, the parameters needed for the evaluation are accessed through the pull down menus located on the left hand side of the form.

| 2006 System-Wide Break Analysis Projected for Year 2008 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe ID | Material | Diameter (in) | Last Break | Power Model Terms | | | Prob. Of Failure | Statistical Validity ($R^2$) | Total Consequence Factors | | Total Risk Score | Next Break (from last) | | |
| | | | | Records | Beta | Lambda | | | Location | Indirect/Social | | Years | Months | Date |
| P18426552 | CIP | 8 | Nov-01 | 1 ~ 3 | 2.360 | 1.600E-01 | 1.000 | 0.734 | 0.00 | 0.00 | 0.000 | 4 | 1 | Dec-05 |
| P185810359 | CIP | 4 | Apr-04 | 1 ~ 6 | 0.489 | 1.943E+00 | 0.974 | 0.812 | 0.00 | 0.00 | 0.000 | 4 | 3 | Jul-08 |
| P185811385 | CIP | 6 | May-05 | 1 ~ 3 | 2.769 | 1.033E-01 | 0.761 | 0.734 | 0.00 | 0.00 | 0.000 | 3 | 9 | Feb-09 |
| P185811690 | CIP | 4 | Feb-05 | 1 ~ 3 | 9.629 | 2.000E-07 | 0.005 | 0.734 | 0.00 | 0.00 | 0.000 | 5 | 9 | Nov-10 |
| P185812481 | CIP | 4 | Dec-00 | 1 ~ 3 | 1.420 | 1.075E-01 | 0.818 | 0.734 | 0.00 | 0.00 | 0.000 | 12 | 7 | Jul-13 |
| P18581651 | CIP | 8 | Aug-01 | 1 ~ 6 | 3.040 | 9.572E-03 | 0.927 | 0.772 | 0.00 | 0.00 | 0.000 | 7 | 3 | Nov-08 |
| P185816633 | CIP | 6 | Jan-03 | 1 ~ 3 | 0.982 | 2.709E-01 | 0.726 | 0.734 | 0.00 | 0.00 | 0.000 | 15 | 3 | Apr-18 |
| P185817299 | CIP | 6 | Nov-01 | 1 ~ 3 | 1.696 | 5.131E-02 | 0.666 | 0.734 | 0.00 | 0.00 | 0.000 | 12 | 11 | Oct-14 |
| P186326316 | CIP | 6 | Nov-99 | 1 ~ 3 | 2.223 | 5.803E-02 | 0.998 | 0.734 | 0.00 | 0.00 | 0.000 | 6 | 8 | Jul-06 |
| P186329182 | DIP | 4 | Jul-03 | 1 ~ 5 | 1.009 | 1.441E+00 | 0.998 | 0.877 | 0.00 | 0.00 | 0.000 | 2 | 9 | Apr-06 |
| P186331479 | CIP | 6 | Feb-04 | 1 ~ 6 | 0.796 | 8.700E-01 | 0.921 | 0.857 | 0.00 | 0.00 | 0.000 | 6 | 8 | Oct-10 |
| P1863321022 | CIP | 6 | Aug-04 | 1 ~ 3 | 2.237 | 1.094E-01 | 0.801 | 0.734 | 0.00 | 0.00 | 0.000 | 5 | 0 | Aug-09 |
| P1863321039 | CIP | 6 | Sep-00 | 3 ~ 5 | 0.567 | 1.108E+00 | 0.967 | 0.839 | 0.00 | 0.00 | 0.000 | 9 | 4 | Jan-10 |
| P186332572 | DIP | 12 | Jul-04 | 1 ~ 3 | 5.798 | 6.464E-04 | 0.552 | 0.734 | 0.00 | 0.00 | 0.000 | 4 | 6 | Jan-09 |
| P186847364 | DIP | 8 | Sep-04 | 1 ~ 3 | 3.316 | 1.459E-03 | 0.070 | 0.734 | 0.00 | 0.00 | 0.000 | 10 | 10 | Jul-15 |
| P18684850 | CIP | 8 | May-05 | 1 ~ 3 | 17.474 | 2.619E-17 | 0.000 | 0.734 | 0.00 | 0.00 | 0.000 | 9 | 8 | Jan-15 |
| P187354144 | CIP | 6 | Sep-97 | 1 ~ 4 | 1.994 | 3.356E-01 | 1.000 | 0.824 | 0.00 | 0.00 | 0.000 | 8 | 3 | Dec-05 |
| P187355721 | CIP | 16 | May-01 | 1 ~ 4 | 7.072 | 3.758E-06 | 0.900 | 0.811 | 0.00 | 0.00 | 0.000 | 7 | 2 | Jul-08 |
| P18735683 | CIP | 4 | Feb-05 | 4 ~ 6 | 1.355 | 4.691E-01 | 0.854 | 0.776 | 0.00 | 0.00 | 0.000 | 4 | 10 | Dec-09 |
| P187869186 | CIP | 12 | Sep-00 | 1 ~ 4 | 7.538 | 4.116E-05 | 1.000 | 0.860 | 0.00 | 0.00 | 0.000 | 5 | 3 | Dec-05 |
| P187871103 | CIP | 8 | Nov-94 | 1 ~ 3 | 1.363 | 1.793E+00 | 1.000 | 0.734 | 0.00 | 0.00 | 0.000 | 11 | 1 | Dec-05 |
| P187871572 | CIP | 6 | May-03 | 1 ~ 4 | 0.908 | 3.856E-01 | 0.785 | 0.675 | 0.00 | 0.00 | 0.000 | 12 | 11 | Apr-16 |
| P187871748 | DIP | 4 | Nov-05 | 1 ~ 3 | 3.057 | 2.121E-01 | 0.865 | 0.734 | 0.00 | 0.00 | 0.000 | 2 | 8 | Jul-08 |
| P187871806 | DIP | 4 | Jan-04 | 1 ~ 5 | 2.318 | 6.286E-02 | 0.774 | 0.869 | 0.00 | 0.00 | 0.000 | 6 | 0 | Jan-10 |
| P187878400 | STEEL | 26 | Jun-03 | 1 ~ 3 | 1.101 | 4.904E-01 | 0.923 | 0.972 | 0.00 | 0.00 | 0.000 | 6 | 8 | Feb-10 |

Figure 4.9 Sample Output from the NHPP Analysis

As the parameters are selected, both their intervals and point values will appear. If for whatever reason the user wants to modify these values, he/she must exit the MCDA form and reinitialize these values through the "MCDA" worksheet in Excel. For each of the selected parameters, a relative weight value must be assigned. This value is selected from the pull down menu located to the right of the parameter interval and point information. Having specified the parameters, intervals, interval points, and relative weights, click the "Perform Analysis" button. Once the calculations are finished a message box will appear. In order to view the MCDA results, click the "Return to Main Menu" button and then the "Create a Report" button located within the Main Menu form. An example MCDA report is shown in Figure 4.11.

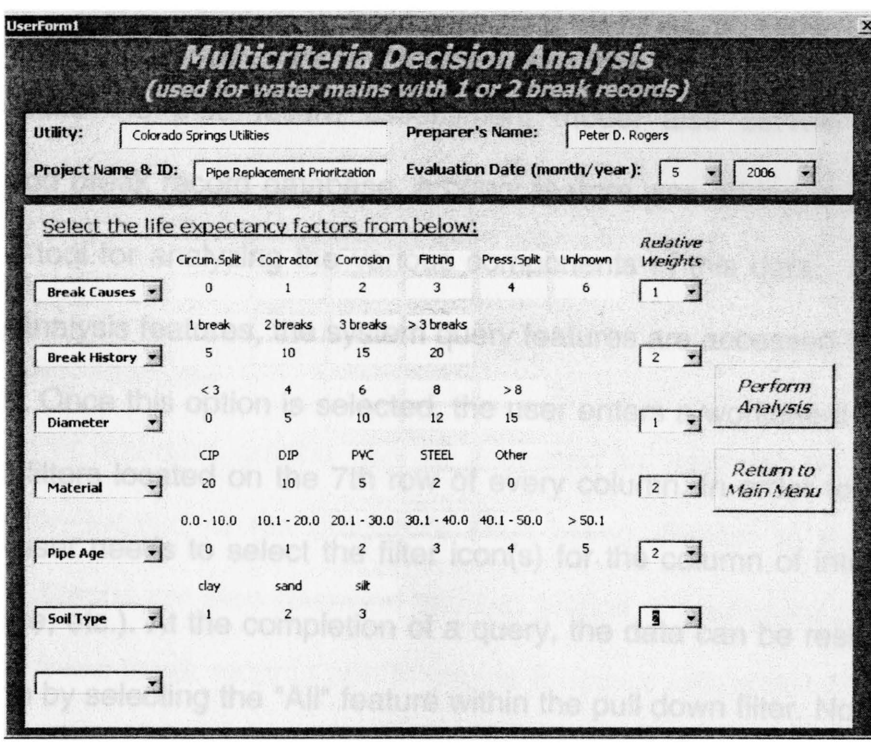


Figure 4.10 Multicriteria Decision Analysis (MCDA) Form

***Pipe Failure Assessment Model***
***MCDA Report - For Pipes with 1 & 2 Breaks***

**Relative Weights:**

| | |
|---|---|
| Break Causes | 1 |
| Break History | 2 |
| Diameter | 1 |
| Material | 2 |
| Pipe Age | 2 |
| Soil Type | 2 |
| Pressure | 2 |

Return to Report Module

Sort By Total Score

**General Information:**

**Utility:** Colorado Springs Utilities
**Project Name & ID:** Pipe Replacement Prioritz
**Preparer's Name:** Peter D. Rogers
**Evaluation Date** May-06

| General Properties | | | | Variable-Specific Pipe Scores (Points * Relative Weights) | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe ID. | Material | Dia. (in) | Install Date | Material | Dia. | Break Hist. | Age | Causes | Press. | Soil Resist | Soil Type | Score |
| P183237332 | PVC | 6 | Aug-91 | 10 | 10 | 10 | 2 | 1 | | | | 33 |
| P183752185 | DIP | 20 | Aug-85 | 20 | 15 | 10 | 4 | 3 | | | | 52 |
| P18375295 | DIP | 20 | Aug-85 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P183753253 | DIP | 6 | Jan-86 | 20 | 10 | 10 | 4 | 2 | | | | 46 |
| P183753306 | DIP | 8 | Jan-86 | 20 | 12 | 10 | 4 | 2 | | | | 48 |
| P183753321 | DIP | 12 | Dec-84 | 20 | 15 | 10 | 4 | 4 | | | | 53 |
| P183753431 | PVC | 8 | Feb-96 | 10 | 12 | 10 | 2 | 0 | | | | 34 |
| P183753525 | DIP | 12 | Oct-96 | 20 | 15 | 10 | 0 | 3 | | | | 48 |
| P1842653 | CIP | 8 | Jan-62 | 40 | 12 | 10 | 8 | 0 | | | | 70 |
| P1842659 | CIP | 8 | Jan-62 | 40 | 12 | 10 | 8 | 2 | | | | 72 |
| P184266120 | CIP | 6 | Jan-62 | 40 | 10 | 10 | 8 | 6 | | | | 74 |
| P18426615 | CIP | 8 | Jan-63 | 40 | 12 | 10 | 8 | 1 | | | | 71 |
| P184266361 | DIP | 12 | Mar-82 | 20 | 15 | 10 | 4 | 3 | | | | 52 |
| P184266378 | DIP | 12 | Mar-82 | 20 | 15 | 10 | 4 | 4 | | | | 53 |
| P184266385 | PVC | 6 | Mar-82 | 10 | 10 | 10 | 4 | 3 | | | | 37 |
| P184267113 | DIP | 16 | Apr-78 | 20 | 15 | 10 | 4 | 6 | | | | 55 |
| P18426712 | DIP | 24 | Jun-79 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P184267149 | DIP | 6 | Oct-78 | 20 | 10 | 10 | 4 | 6 | | | | 50 |
| P184267333 | DIP | 20 | Aug-85 | 20 | 15 | 10 | 4 | 3 | | | | 52 |
| P18426740 | DIP | 24 | Jun-79 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P184267427 | DIP | 24 | Jun-79 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P18426745 | DIP | 24 | Jun-79 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P184268436 | DIP | 24 | Jun-79 | 20 | 15 | 10 | 4 | 3 | | | | 52 |
| P184268552 | DIP | 12 | May-79 | 20 | 15 | 10 | 4 | 2 | | | | 51 |
| P184268712 | DIP | 12 | May-82 | 20 | 15 | 10 | 4 | 0 | | | | 49 |
| P184268735 | PVC | 8 | Dec-81 | 10 | 12 | 10 | 4 | 4 | | | | 40 |

Figure 4.11 Sample MCDA Report for Data from Colorado Springs Utility

## 4.9 Query Features

Because the pipe failure assessment model also serves as a pipe inventory and break record database, a query feature was added to provide the user with a tool for analyzing the various components of this data. As with the other data analysis features, the system query features are accessed through the Main Menu. Once this option is selected, the user enters a worksheet containing a series of filters located on the 7th row of every column. In order to perform a query, the user needs to select the filter icon(s) for the column of interest (pipe material, size, etc.). At the completion of a query, the data can be restored to its original form by selecting the "All" feature within the pull down filter. Note that the information in the query module is automatically updated whenever an inventory change is made.

### 4.10 Reporting Features

A list of standard reports can be accessed by selecting the "Create a Report" button located in the program's Main Menu. As shown in Figure 4.12, once within the Reporting Module, the user can select from various standardized reports. The reports are divided into two types:

- Available reports for pipelines with a minimum of three break records
- Available reports for pipelines with less than three break records

In order to assist the user with his/her report selection, once the checkbox located next to the name of the report is selected, a brief description of the report will appear. Once a selection is made, the user clicks the "View Report" button located on the "Reporting Module" and the program will pull up the corresponding report. Having viewed a specific report, the user can view another report or return to the program's Main Menu by clicking the "Return to Report Module" button.

### 4.11 Graphing Features

A list of standard graphs can be accessed by selecting the "Create a Graph" button located in the program's Main Menu. Similar to the reporting module, the graphs are also classified into two groups: i) graphs for pipes with a minimum of three break records and ii) graphs for pipes with either or two break histories. The checkboxes located next to the name of each graph provide a brief description of the graph. Figure 4.13 shows the format of the program's Graphing Module.

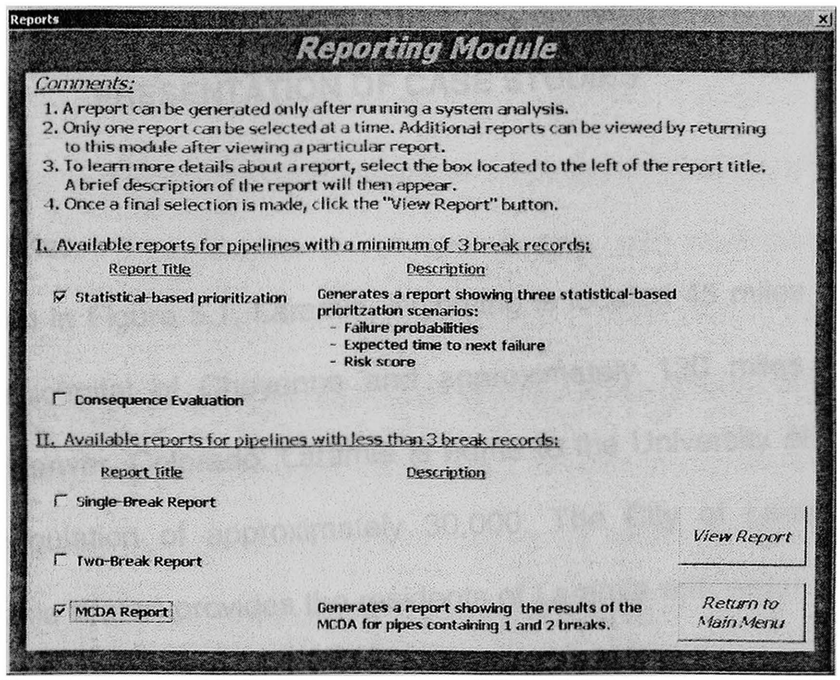


Figure 4.12 Reporting Module Form

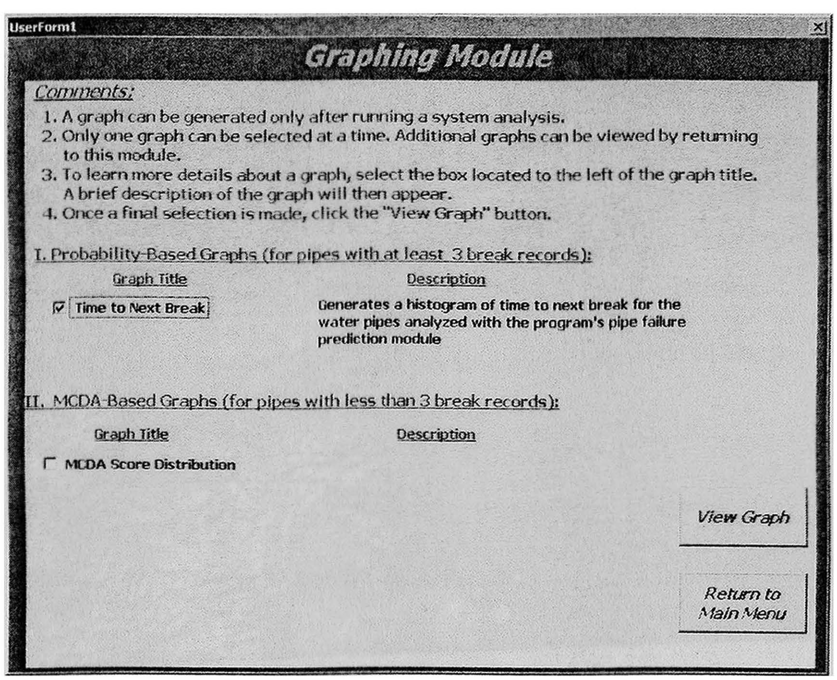


Figure 4.13 Graphing Module Form

# CHAPTER 5

# PRESENTATION OF CASE STUDIES

## 5.1 Laramie Water

As shown in Figure 5.1, Laramie, Wyoming is located 45 miles northeast from the state capital of Cheyenne and approximately 130 miles from the metropolis of Denver, Colorado. Laramie is home to the University of Wyoming and has a population of approximately 30,000. The City of Laramie Utility Division (Laramie Water) provides the residents of Laramie with water and sewer services.

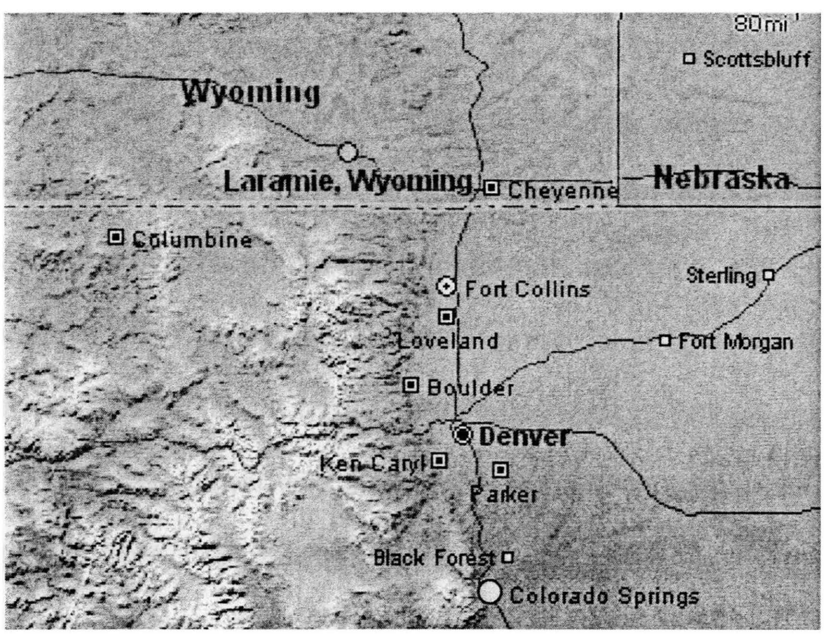


Figure 5.1 Map Showing the Location of Laramie, Wyoming and Colorado Springs, Colorado (Travel Post, 2006)

### 5.1.1 General Water System Characteristics

Laramie's drinking water comes from two principal water sources; surface water from the Laramie River and various well fields which tap into the Casper aquifer. Whereas the surface water from the Laramie River is treated at the water treatment plant, the subterraneous water sources are treated at each individual well head. Laramie Water estimates the total capacity of their existing water sources to be 14.5 million gallons per day (mgd), with estimated system demands varying from 4.5 mgd in the wintertime to 11 mgd during the summer (City of Laramie Water, 2006). Treated drinking water is transported through 206 miles of transmission and distribution water pipes for delivery to customers. The City of Laramie has approximately 8,200 meters of which some are master meters for trailer parks, the University of Wyoming, and subdivisions.

### 5.1.2 Characteristics of the Water Distribution System

The operation, maintenance and replacement of the water system's water mains comprise a large portion of the City of Laramie Utility's annual budget. Aside from allocating $300,000 annually to the water main replacement program, an additional one seventh of the utility's annual operation and maintenance budget is spent repairing the system's water mains (City of Laramie, 2006).

As part of the pipe failure assessment investigation, officials from Laramie Water provided the researcher with a summary of their water pipe breaks during an 18-year period from 1987 through 2005. In addition to reporting the annual water main failure totals, Table 5.1 shows failure allocations between the distribution system and transmission line pipes. For the Laramie water system, 96% of the total 1,136 water pipe failures occurred in the distribution system.

Table 5.1 Yearly Water Pipe Failures for the Distribution System and Transmission Lines, Laramie Water System (City of Laramie, 2006)

| Fiscal Year | Number of Water Main Failures | | |
|---|---|---|---|
| | Distribution System | Transmission Line | Total |
| 1987~1988 | 40 | 0 | 40 |
| 1988~1989 | 38 | 1 | 39 |
| 1989~1990 | 45 | 1 | 46 |
| 1990~1991 | 44 | 4 | 48 |
| 1991~1992 | 53 | 2 | 55 |
| 1992~1993 | 57 | 1 | 58 |
| 1993~1994 | 44 | 2 | 46 |
| 1994~1995 | 38 | 2 | 40 |
| 1995~1996 | 61 | 2 | 63 |
| 1996~1997 | 70 | 1 | 71 |
| 1997~1998 | 57 | 4 | 61 |
| 1998~1999 | 61 | 7 | 68 |
| 1999~2000 | 93 | 3 | 96 |
| 2000~2001 | 77 | 2 | 79 |
| 2001~2002 | 77 | 6 | 83 |
| 2002~2003 | 68 | 2 | 70 |
| 2003~2004 | 99 | 0 | 99 |
| 2004~2005 | 74 | 0 | 74 |

The propensity of pipe failures within the distribution system failures is common throughout the industry since these pipes comprise the majority of a water system's pipe infrastructure. In the Laramie water system, approximately 80% of the total pipe inventory is contained within the distribution system. The dominance of failures within the distribution system is also related to the industry's risk adverse nature. Because transmission lines transport larger volumes of water under high pressure, the potential for major financial and legal consequences associated with a transmission line failure motivates utilities to be more proactive with their pipeline condition program. Whereas the low consequences associated with distribution system failures imply an emphasis on failure management, the high consequences associated with transmission line failures lead to failure prevention polices. Transmission lines are also easier to inspect since they are larger in diameter and contain minimal cross-connections.

In order to better understand the magnitude of the water main failure data provided by the City of Laramie, the break rates were compared to the guidelines established by the American Water Works Association Research Foundation (AWWARF). In a 1995 AWWARF publication entitled "Distribution System Performance Evaluation", the association reported that the industry-wide accepted yearly break rates for water systems vary from 25 to 30 breaks per 100 miles with an average annual rate of 22 breaks per 100 miles (AWWA, 2002). The same publication mentions that utilities are striving for lower annual break rates in the range of 15 ~ 20 breaks per 100 miles. In the case of Laramie Water, the system's average yearly break rate of 36 breaks per 100 miles from 1987~2005 is 1.6 times larger than the industry average. This rate increased significantly from 1999 to 2004 to a yearly average of 42 breaks per 100 miles with highs of 52 and 50 breaks per 100 miles in 1999 and 2003 respectively.

As with most water utilities, Laramie's underground pipe infrastructure is a mixture of old and new. The oldest pipelines within the Laramie water system are the "pit" cast iron pipes (CIP) installed from the 1880's through the 1920's. The system also has large quantities of "spun" cast iron pipe, which was commonplace from the 1920's through the 1960's. As shown in Table 5.2, the combination of these two types of CIP comprise nearly a third of the utility's entire pipeline inventory. This value is slightly larger than the national CIP average percentage of 29% (Grigg, 2004). Aside from CIP, the Laramie system also has large quantities of ductile iron pipe (DIP) and polyvinyl chloride (PVC) pipe. The use of DIP occurred from the 1960's through the 1980's, while the use of PVC pipe started in the mid 1980's and continues to be popular for present-day applications. Laramie Water's steel pipes are used primarily for the transmission lines. Of the 31 miles of steel transmission lines, roughly 90% of these lines were installed prior to the mid 1960's. The remaining 10% was installed in the late 1990's or in 2005.

Table 5.2 Allocation of Pipe Materials within the Distribution System and Transmission Lines, Laramie Water System (City of Laramie, 2006)

| Pipe Material | Inventory | | Range of Installation Dates |
|---|---|---|---|
| | Miles | Percentage | |
| CIP | 65.4 | 31.7% | 1880 ~ 1967 |
| DIP | 60.2 | 29.2% | 1968 ~ 1983 |
| PVC | 48.9 | 23.7% | 1984 ~ 2005 |
| Steel | 31.1 | 15.1% | 1945 ~ 2005 |
| Other | 0.5 | 0.2% | 1927 ~ 2002 |

### 5.1.3 Alterations to the Original Data Set

Laramie Water's pipe inventory and break record data was generated using the utility's Geographic Information System (GIS), which allowed for queried data to be imported into Microsoft Excel as a database file. Having the pipe inventory and break history records in electronic form simplified the model initialization and data entry processes.

In spite of the compatibility between Laramie Water's data files and the model's Excel platform, several alterations to the data set were required prior to importing the information into the model. There were two categories of revisions:

- Revisions relating to incomplete datasets
- Model-induced revisions

Changes relating to incomplete datasets were the less cumbersome to correct than the model-induced changes.

#### 5.1.3.1 Incomplete Dataset Revisions

These revisions relate to inconsistencies with the utility's inventory records and include missing and/or inconsistent material type, diameter, length, and pipe id information. These corrections are normally made by reviewing original installation records and/or examining the records of nearby pipes with similar characteristics. In the Laramie dataset, there were 30 pipes missing installation dates, 32 pipes without pipe lengths, and a handful of pipes with diameter and pipe identification (id) errors.

#### 5.1.3.2 Model-Related Revisions

Whereas incomplete datasets affect the accuracy and completeness of the model's output, model-related revisions are more serious because they affect the model operation. The two most cumbersome model-related deficiencies are missing installation dates and missing pipe identification (id) numbers. Missing installation dates affect the program's ability to evaluate pipe age and missing pipe id numbers make it impossible for the inventory database to interact with the break record database since the pipe id serves as the common link.

Utility personnel at Laramie Water allocated many man-hours to resolving both types of deficiencies. With regard to the pipe inventory records, approximately 8% of pipes had installation dates listed as "Pre-1920" or "Pre-1927", which had to be modified in order for the program to calculate pipe age. Resolving the pipe id issue was even more cumbersome: none of the utility's 738 break records from July, 1996 to February, 2006 had been referenced with the same pipe id number system used in the inventory database. While the majority of these deficiencies were resolved using GIS tools, several cases required the review of original installation and maintenance records.

Resolving the issues relating to the utility's break records also proved to be arduous. Amongst the break records provided by Laramie Water from 1997 to 2006, there were 60 cases in which the water pipe had been repaired more than once during the same month. Many of these cases involved pipes which had repaired within a week of a previous break. Having initially concluded that this occurrence was the result of data entry errors, the researcher had asked utility personnel to investigate these cases. Utility officials confirmed that the break records were correct, explaining that water pipes often experience multiple breaks within a distance of 5 ~ 20 feet. One likely scenario is that once a break has been repaired, because it no longer relieves pressure throughout the pipeline, another weak spot is exposed. It's also plausible that the multiple break events are related to damages resulting from the previous pipe repair(s).

Having confirmed the validity of multiple break dates within the same month, the researcher had to address the model-related consequences of these occurrences and the bigger issue of how break events are defined. From a modeling perspective, because the failure prediction component uses a monthly time step, pipes experiencing multiple breaks within the same month are viewed as lacking sequential break times. A monthly time step was selected for two reasons. First, it acknowledges that month/year is standard precision for maintenance practices within an industry. Secondly, the use of a monthly time step (0.0833 years) provides a more realistic degree of precision than a daily time step (0.0027 years) for the probability modeling. The issue of multiple break dates within the same month also affects the MCDA portion of the model since points are assigned as a function of the number of break events.

Recognizing that the issue of multiple breaks within the same month would have to be evaluated on a case-by-case basis, the researcher consulted with the participating utility personnel to establish some guidelines. Based on these discussions, the researcher applied the following rules:

- Break dates occurring near the end of a month could be rounded up to the following month.
- A 14-day period was established at the minimum time interval between breaks. Any consecutive breaks occurring within this minimum time interval were removed from the break database. For consecutive breaks exceeding the minimum 14 days, the break dates were rounded up and down. For example, the repair dates 08/09/1978 and 08/21/1978 were modified to 08/1978 and 09/1978 respectively.
- In cases in which utility personnel had firsthand knowledge that the successive breaks were not related (i.e. breaks occurring on the extreme ends of a pipeline, etc.), the break date was also rounded up or down to reflect a monthly time step.

Applying these guidelines, 42 of the 60 repeated break records were removed from the database.

### 5.1.4 Correlation Analysis of Break Frequency Variables

For water mains with one or two break records, the model uses a Weighted Average Method (WAM) in which points are assigned to each criterion (variable) identified as having an influence on the break frequency of each pipe. Although Laramie Water personnel certainly "have a feel" for which factors influence the failure of their pipe infrastructure, these hunches had to be quantified through a statistical correlation analysis of the inventory and break record data. As was presented in Chapter 4, the statistical correlation approach used in this research is based on comparing a variable's break percentage to its overall percentage in the system. The following summarizes the results of the correlation analysis for the eight default criteria and an additional utility-specific criterion.

**Pipe Age:**

Researchers ranging from O'Day (1982) to Vanrenterghem (2003) have concluded that, although age is a factor in the frequency of pipe breaks, the assumption that the oldest pipes are in the worst condition is not borne out by experience (Butler and Earley, 2002). Acknowledging that age alone is certainly not the only contributing factor to pipe break frequency, its obvious contribution to the overall deterioration of buried pipeline certainly can not be ignored.

In order to determine a possible correlation between pipe ages and break failures for the Laramie water system, the break age data was normalized in proportion to the percentage of the system pipes within each age bracket. As shown in Table 5.3, pipe breaks rarely occur during the first 20 years of service. From a period of 20 to 40 years the break frequency increases to a level proportional to the inventory percentage. However, after 40 years the break frequency grows dramatically until it starts flattening out at the age of 60 years. The data suggests a definite trend between pipe age and break frequency. The apparent flattening out after the age of 60 years is misleading and most-likely related to a void in the utility's record keeping.

Table 5.3 Pipe Break Distribution by Pipe Age,
Laramie Water System (City of Laramie, 2006)

| Pipe Age (years) | Percent of Breaks | Percent of Inventory |
|---|---|---|
| 0.0 - 10.0 | 2.9% | 21.8% |
| 10.1 - 20.0 | 4.8% | 8.0% |
| 20.1 - 30.0 | 21.4% | 20.1% |
| 30.1 - 40.0 | 21.8% | 20.6% |
| 40.1 - 50.0 | 19.4% | 8.3% |
| 50.1 - 60.0 | 10.7% | 6.5% |
| 60.1 - 70.0 | 0.4% | 2.3% |
| 70.1 - 80.0 | 3.3% | 1.6% |
| 80.1 - 90.0 | 4.9% | 3.1% |
| 90.1 - 100.0 | 2.1% | 1.1% |
| ≥ 100 | 8.4% | 6.6% |

Based on this correlation analysis, the interval and point distributions for the age criterion were assigned as:

| | |
|---|---|
| < 20 years: | 0 points |
| 20 - 40 years: | 5 points |
| 40 - 60 years: | 10 points |
| > 60 years | 15 points |

**Break Causes:**

Information regarding the pipe failure cause was included in only a fraction of the utility's break records and with a high degree of uncertainty. No points for assigned for this criterion.

**Break History:**

Although a single break can be attributed to an isolated cause such as an installation-related error or a material defect that is remedied once the break is repaired, it is usually a strong indicator of potential problems. Accordingly, 10 points were assigned for each reported break event.

**Diameter:**

In order to test for a correlation between pipe diameter and break frequency, break diameter data was normalized in proportion to its inventory percentage. Table 5.4 shows an overwhelming correlation for 6 inch pipe, which accounts for nearly 60% of the total break records. While this correlation has a break frequency to inventory ratio of nearly 2:1, the correlation for both 4 inch and 8 inch pipe is approximately 1:1 while the other pipe diameters have weak correlations. An evaluation of the break records revealed that the dominate break frequency of 6 inch pipe is also related to the presence of CIP, which is the oldest pipe material in the system. Of the total 448 break records involving 6 inch pipe, 96.9% occur with cast iron pipe.

Table 5.4 Pipe Break Distribution by Pipe Diameter, Laramie Water System (City of Laramie, 2006)

| Pipe Diamater (in) | Percent of Breaks | Percent of Inventory |
|---|---|---|
| <4 | 0.0% | 0.1% |
| 4 | 6.1% | 5.1% |
| 6 | 59.4% | 30.1% |
| 8 | 16.4% | 13.8% |
| 10 | 7.8% | 11.0% |
| 12-16 | 7.0% | 16.1% |
| 18-24 | 3.2% | 23.0% |
| ≥ 30 | 0.0% | 0.8% |

Based on these observations, the following point allocations were made for the following pipe diameter intervals:

| | |
|---|---|
| < 4 inch: | 0 points |
| 4 inch: | 5 points |
| 6 inch: | 10 points |
| 8 inch: | 5 points |
| > 8 inch: | 0 points |

**Material:**

Applying a similar approach to that taken for pipe diameter, a correlation analysis was conducted for each pipe material. Not surprisingly, Table 5.5 shows CIP has a disproportionate number of breaks relative to its inventory percentage. Of the other materials, PVC has the second strongest correlation with a break frequency to inventory percentage ratio of approximately 0.25.

Table 5.5 Pipe Break Distribution by Material Type, Laramie Water System (City of Laramie, 2006)

| Pipe | Percent of Breaks | Percent of Inventory |
|---|---|---|
| CIP | 88.1% | 31.7% |
| DIP | 3.8% | 29.2% |
| PVC | 5.7% | 23.7% |
| Steel | 2.3% | 15.1% |
| Other | 0.1% | 0.2% |

Because of the dominance of CIP, this material type was assigned the largest point value, whereas PVC was assigned the second largest point value. Due to the weak correlations for the DIP, Steel and other material types, they were assigned 0 points.

| | |
|---|---|
| CIP: | 10 points |
| PVC: | 5 points |
| Other: | 0 points |

**Pressure:**

Laramie Water does not maintain pressure data for individual water mains within their inventory or break record databases so no points were assigned to this criterion.

**Soil Resistivity:**

As is the case with pressure, no points were assigned to this criterion due to a lack of soil resistivity data for individual pipes.

**Soil Type:**

The City of Laramie's Utility website indicates that the excessive break frequency of the water system pipelines are the result of both pipe aging and corrosive soils. However, because Laramie Water does not maintain soil data for individual water mains within their inventory or break record databases, a correlation analysis could not be performed for this variable.

**Leak Type:**

Aside from the eight standard criteria included as defaults within the model, because the 86% of the break records contained leak type information, this criterion was included in the correlation analysis. Unlike the previous correlation analyses in which each variable's break percentage was compared to its overall percentage in the system, because the dataset is limited to only the break-related events, a different approach was applied.

The approach consisted of evaluating the annual distribution of each leak type in order to look for any time-related trends. Utility break records indicated that the primary leak types were beam breaks (35.8%), blowout (34.8%), and pressure splits (7.3%). The remaining 22.1% was caused by a combination of joint and unknown causes. While the percentages of beam break and blowouts indicate that these leak types are the most prevalent, Figure 5.2 shows that these yearly distribution of these leak types from 1996 to 2006 remained fairly consistent. Note that the percentages for 2006 reflect break records through the month of April. The only leak type that showed some deviation during this period was the blowout, which increased from 2003 to 2005 but appears to have decreased this year. Due to the absence of a significant trend, no points were assigned to this criterion.

### 5.1.5 Consequence Module Configuration

For water pipes with a minimum of three break records, in addition to providing probability-based decision variables, the model calculates a total risk score for as the product of the probability and the consequences. As was presented in Chapter 4, the model groups the consequence factors (weights) into three classes: location-specific, indirect, and social factors. For the 74 water mains with a minimum of three break records, the factors pertaining to each water main were selected through the user-friendly consequence form. Table 5.6 shows the various located-specific, indirect and social weights used for the pipes receiving a risk score. The three most frequently selected consequence factors were the location of the pipe along a high-traffic street (65%), the potential for unfavorable publicity (43%), and the location of the pipe in an alley (%).

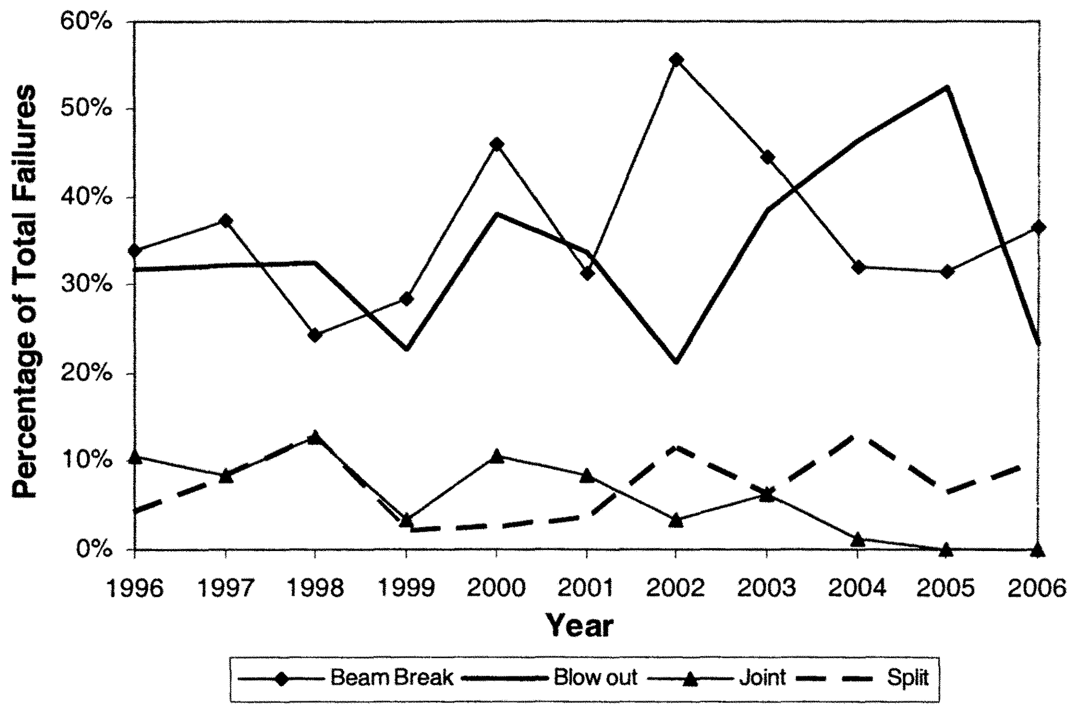


Figure 5.2 Yearly Distributions of Leak Types, Laramie Water System (Laramie Water, 2006)

# Table 5.6 Consequence Factors and Weights, Laramie Water System

| Pipe | Pipe Location Weights | | | | | | | | | Social and Indirect Weights | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | railroad | building | water | population | wetland | traffic | alley | slide | slope | health | social | services | fire | liability | environ | publicity | trench |
| 157303NE10 | | | | | | | 0.80 | | | | | | | | | 1.30 | |
| 157303NW03 | | | | | 1.20 | 1.60 | | | | | | | | | | | 1.20 |
| 157303NW08 | | | | | 1.20 | | | | 1.10 | | | | | | 1.50 | | |
| 157303NW101 | | | | | | | 0.80 | | | | | | | 1.30 | | 1.30 | |
| 157303NW102 | | | | | | 1.60 | | | | | | | | | | | |
| 157303NW105 | | | | 1.60 | | 1.60 | | | | | | | | | | | |
| 157303NW11 | | 1.40 | | | | | 0.80 | | | | | | | | 1.50 | | |
| 157303NW15 | | | | | | | 0.80 | | | | | | | | 1.50 | | |
| 157303NW28 | | | | | 1.20 | | 0.80 | | | | | | | | 1.50 | | |
| 157303NW46 | | | | | | 1.60 | | | | | | | | 1.30 | | 1.30 | |
| 157303NW82 | | | | | | 1.60 | | | | | 1.40 | | | | | 1.30 | |
| 157303SW01 | | | | | | 1.60 | | | | | | | | | | 1.30 | |
| 157304NE07 | | | | 1.60 | | 1.60 | | | | | | | | | | 1.30 | |
| 157304NE103 | | | | | | 1.60 | | | | | | | | | | 1.30 | |
| 157304NE26 | | | | | | 1.60 | | | | | | | | 1.30 | | | |
| 157304NE36 | | | 1.50 | | 1.20 | 1.60 | | | | | | | | | 1.50 | | |
| 157304NE49 | | | | | | 1.60 | | | | | | | | | | | |
| 157304NE54 | | | | 1.60 | | 1.60 | | | | | | | | | 1.50 | 1.30 | |
| 157304NE70 | | | | | | 1.60 | | | | | 1.40 | | | 1.30 | | 1.30 | |
| 157304NE75 | | | | | | | 0.80 | | | | | | | 1.30 | | 1.30 | |
| 157304NE77 | | | | | | 1.60 | | | | | | | | | | | |
| 157304NE82 | | | | | | | 0.80 | | | | | | | | | 1.30 | |
| 157304NW102 | | | | | 1.20 | 1.60 | | | | | | | | | 1.50 | 1.30 | |
| 157304NW14 | | | | | | | 0.80 | | | | | | | | | | |
| 157304NW23 | | | | | | | 0.80 | | | | | | | | | | |
| 157304NW34 | | | | | | 1.60 | | | | | | | | 1.30 | | 1.30 | |
| 157304SW12 | 1.20 | | | | 1.20 | | | | 1.10 | | | | | | 1.50 | | |
| 157304SW15 | | | | | | 1.60 | | | | | | 1.70 | | 1.30 | 1.50 | | |
| 157304SW17 | | | | | 1.20 | 1.60 | | | | | | | | | | | |
| 157304SW38 | | | | | | 1.60 | | | | | | 1.70 | | | | | |
| 157306SE20 | | | | | | 1.60 | | | | | 1.40 | 1.70 | | | 1.50 | 1.30 | |
| 157306SE25 | | | | | | 1.60 | | | | | | 1.70 | | | | 1.30 | |
| 157309NW01 | | 1.40 | | | | | | | | | | 1.70 | | | | | |
| 167304NW24 | | | | | | 1.60 | | | | | | | | | | 1.30 | |
| 167327NW24 | | | | | | 1.60 | | | | | | | | | | 1.30 | |
| 167327SW08 | | | | 1.60 | | 1.60 | | | | | 1.40 | | 1.30 | 1.30 | | 1.30 | |
| 167327SW142 | | | | | 1.20 | 1.60 | | | | | | | | | 1.50 | 1.30 | |
| 167327SW33 | | | | | 1.20 | 1.60 | | | | | | | | | | 1.30 | |
| 167327SW68 | | | | | | 1.60 | | | | | | | | | | | |
| 167328NE24 | | | | | | | 0.80 | | | | | | | | | 1.30 | |
| 167328NE50 | | | | | | 1.60 | | | | | | | | | | | |
| 167328SE18 | | | | | | | 0.80 | | | | | | | | | | |
| 167328SE19 | | | | | | | 0.80 | | | | | | | | | | |
| 167328SW109 | | | | | | | 0.80 | | | | | | | | | | |
| 167328SW114 | | | | | | 1.60 | 0.80 | | | | | | | | 1.50 | | |
| 167328SW116 | | | | | | | 0.80 | | | | | | | | | | |
| 167328SW33 | | | | | | 1.60 | | | | | 1.40 | | | 1.30 | | 1.30 | |
| 167328SW49 | | | | | | 1.60 | | | | | | | | | | 1.30 | |
| 167328SW62 | | | | | | | 0.80 | | | | 1.40 | | | 1.30 | | 1.30 | |
| 167328SW64 | | | | | | | | | | | 1.40 | | | | 1.50 | 1.30 | |
| 167328SW89 | | | | | | | 0.80 | | | | | | | | | | |
| 167329NW02 | | | | | | 1.60 | | | | | | | | 1.30 | | 1.30 | |
| 167329SE35 | | | | | | 1.60 | | | | 1.20 | | | | | 1.50 | | |
| 167329SE47 | | | | | | 1.60 | | | | 1.20 | | | | | 1.50 | | |
| 167331NE18 | | | | | | 1.60 | | | | | | | | | | | |
| 167331NE20 | | | | | | 1.60 | | | | | | | | | | | |
| 167331NE32 | | | | | | 1.60 | | | | | | | | | | | |
| 167331NW01 | | | | | | 1.60 | | | | | | | | | | | |
| 167333NE03 | | | | | | 1.60 | | | | | | | | | | | |
| 167333NE10 | | | | 1 60 | | 1.60 | | | | | | | | 1.30 | | 1.30 | |
| 167333NE120 | | | | | | 1.60 | | | | | | | | | | | |
| 167333NE40 | | | | | | | 0.80 | | | | | | | | | 1.30 | |
| 167333NE90 | | | | | 1.20 | 1.60 | | | | | | | | 1.30 | 1.50 | 1.30 | |
| 167333NW58 | | | | | | | 0.80 | | | | | | | | | 1.30 | |
| 167333NW65 | | | | | | 1.60 | | | | | | | | | | | |
| 167333SE114 | | | | | | | 0.80 | | | | | | | | | | |
| 167333SE115 | | | | | | | 0.80 | | | | | | | | | | |
| 167333SE26 | | | | | | 1.60 | | | | | | | | | | | |
| 167333SW153 | | | | | | 1.60 | | | | | | 1.70 | | | | 1.30 | |
| 167334NW27 | | | | | | | | | | | 1.40 | | | 1.30 | 1.50 | 1.30 | |
| 167334SE60 | | | | | | 1.60 | | | | | | | | | | | |
| 167334SW21 | | | | | | | 0.80 | | | | | | | | | | |
| 167334SW30 | | | | | | 1.60 | | | | | | | | | | | |
| 167334SW35 | | | | | | 1.60 | | | | | | | | | | | |

## 5.2 Colorado Springs Utilities

The city of Colorado Springs, Colorado is located at the foot of Pikes Peak, approximately 70 miles south of state's capital of Denver (see Figure 5.1). Colorado Springs is Colorado's largest city in terms of land area and second only to Denver in population with an estimated 400,000 residents.

Colorado Springs Utilities (CSU) is a community-owned utility that provides natural gas, electricity, water and wastewater services to customers in the Pikes Peak region. Included within its service region are the communities of Colorado Springs, Green Mountain Falls, and Chipita Park as well as contract sales for Fort Carson, Peterson Air Force Base, and the United States Air Force Academy.

### 5.2.1 General Water System Characteristics

The Colorado Springs water system is supplied by a variety of surface water, ground water, and purchased water sources. As shown in Table 5.7, most of the utility's water supply originates from various mountain streams located in the vicinity of Aspen, Leadville and Breckenridge approximately 200 miles away (ECRPD, 2005). Water taken from these surface water sources is collected and stored in a series of reservoirs along the Continental Divide and includes the Homestake Project, Fryingpan-Arkansas, Twin Lakes and Blue River systems. This collected water is then transported through a vast network of transmission lines to the Rampart and Catamount Reservoirs on Pikes Peak where it is stored for future treatment.

Table 5.7 Water Source Allocations for the Colorado Springs Water System (Colorado Springs Utility, 2005)

| Water Sources | Available Capacity (acre-ft/year) |
|---|---|
| **Mountain Sources:** | |
| Blue River Project | 10,200 |
| Fryingpan-Arkansas | 14,200 |
| Homestake Project | 13,800 |
| Twin Lakes | 35,000 |
| **Local Sources:** | |
| Cheyenne Canyon | 3,200 |
| Colorado Canal | 13,700 |
| Monument Creek | 3,100 |
| Northfield | 700 |
| Pikes Peak | 15,800 |
| Pinello Ranch | 1,600 |
| Rosemont | 1,100 |
| **Other Sources:** | |
| Arkansas River and local exchange | 27,700 |
| | |
| **Total Capacity:** | **140,100** |

The utility's local water supplies consist of various surface and ground water sources. The local surface water sources are located along the north and south slopes of Pikes Peak, North and South Cheyenne Creeks, Fountain Creek, Monument Creek/Pikeview Reservoir and the Northfield Watershed. The utility's ground water sources include four wells pumped from the Arapahoe aquifer, one well pumped from the Denver aquifer, one well pumped from the Laramie-Fox Hills aquifer, and four wells pumped from the Widefield aquifer (ECRPD, 2005). In addition to the utility-owned water sources, Colorado Springs Utilities also purchases treated surface water from the Fountain Valley Authority.

Water from the numerous mountain and local sources is treated by the utility's six water treatment plants, which have a combined maximum capacity of

232 million gallons of water per day (mgd). The utility's website reports that the average daily demand is approximately 60 mgd with an all-time peak demand of 182.4 mgd in 2001 (Colorado Springs Utilities, 2005). The utility delivers water to its customers via an intricate series of 28 distribution tanks and 1,800 miles of distribution pipe.

### 5.2.2 Characteristics of the Water Distribution System

Officials from Colorado Springs Utilities provided the researcher with pipe break records from January, 1993 through May, 2005. As shown in Figure 5.3, aside from a minor drop from 1997~1999, the quantity of failures during this period has steadily increased. Note that the figure does not include data for the year 2005 since the break records for this year included data only through the month of May. Although the number of failures has increased over time, because the system's pipeline lineage has also increased, the annual break rates per 100 miles have remained constant varying from 8 to 11 breaks per 100 miles with an average rate of 10 breaks per 100 miles. These rates are significantly lower than standard annual rate of 25 ~ 30 breaks per 100 miles and the target annual rate of 15 ~ 20 breaks per 100 miles referenced by AWWARF.

The oldest water mains in the Colorado Springs water distribution system are the "pit" and "spun" cast iron pipes (CIP) installed from the early 1900's through the mid 1970's. Although CIP makes up a sizeable portion of the utility's pipeline inventory, ductile iron pipe (DIP) and PVC pipe make up the largest quantities of pipe material found in the system with a combined total of 62%. The abundance of the material types is a product of massive system expansions resulting from the absorption of several smaller utility districts and a population boom in the area from the 1960's through the mid 1980's. During the 25 year period from 1960 to 1985, the mileage of water distribution pipelines increased at a yearly average rate of 4.8% from 360 to 1,165 miles. Utility personnel indicated that the large quantity of unknown material type shown in Table 5.8 is mostly related to the pipe inventory inherited through the incorporation of various water districts throughout the utility's history.

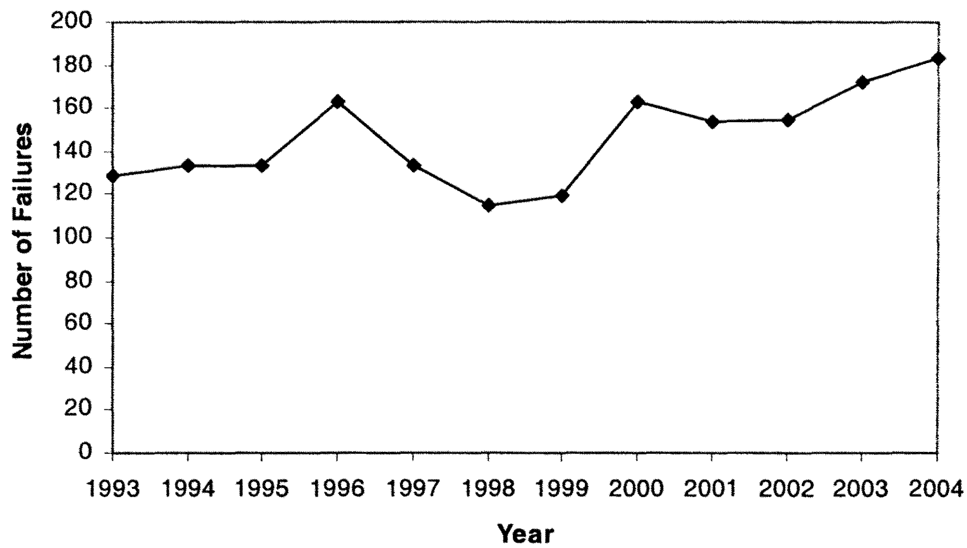


Figure 5.3 Water Main Failures over Time,
Colorado Springs Water System (Colorado Springs Utility, 2006)

Another distinguishing characteristic of the Colorado Springs water system is its large range of pressure zones within the distribution network. As a result of the community's hilly terrain, there are a total of 26 different pressure zones within the distribution system with pressures ranging from less than 60 psi to over 170 psi (ESRI, 2004). As will be discussed in the section devoted to correlation analysis, these extreme pressures within the system impact on the failure frequency of the water mains.

Table 5.8 Distribution of Pipe Material and Installation Date Ranges for the Colorado Springs Water System (Colorado Springs Utilities, 2006)

| Pipe Material | Inventory | | Range of Installation Dates |
|---|---|---|---|
| | Miles | Percentage | |
| Asbestos | 15 | 0.8% | 1959 ~ 1972 |
| Cast Iron | 445 | 23.6% | 1909 ~ 1975 |
| Concrete | 10 | 0.6% | 1985 ~ 2006 |
| Ductile Iron | 568 | 30.2% | 1968 ~ 2006 |
| HDPE | 5 | 0.3% | 2004 ~ 2006 |
| Other | 2 | 0.1% | 1952 ~ 2001 |
| PVC | 592 | 31.5% | 1964 ~ 2006 |
| Steel | 80 | 4.2% | 1941 ~ 2005 |
| Unknown | 163 | 8.7% | 1928 ~ 2006 |

### 5.2.3 Alterations to the Original Data Set

Colorado Springs Utilities maintains all their natural gas, electricity, water and wastewater records electronically in a GIS-based program called Arc-Facility Management (ArcFM). As such, the utility was able to provide the researcher with the necessary water main inventory and break records in a format that allowed the information to be imported directly into the model with minimal data preparation. Unlike the Laramie Water case study, the inventory data provided by the utility for the case study represents only a fraction of the water system's total inventory. The decision to reduce the number of inventory records was based on the limitations inherent to the model's Microsoft Excel platform. The 1,800 miles of water mains of distribution pipelines translates to over 140,000 individual pipes. Because each pipe inventory entry is assigned its own row in Excel, the required 140,000 rows needed for the entire system's pipe inventory exceeds

Excel's row maximum of 65,500 by over 200%. Accordingly, the number of inventory records imported into the model was reduced to coincide with the number of pipes contained within the break records. In other words, rather than storing and processing various water main entries that have no break histories, all 1,471 water mains stored within the inventory module have at least 1 break record.

The original pipe inventory and break history data provided by the utility was ranked based on the utility's confidence in the repair date, material and diameter information. The utility's confidence in these parameters was based on comparisons between GIS-based values and the values reported from field-based operations. For pipes in which the computer and field-based data coincided perfectly, an uncertainty score of zero was assigned to that parameter. Conversely, if there is a major discrepancy between the GIS and field-based parameter, then the pipe received an uncertainty score of 1. For example, if the ArcFM program reported a water main material as PVC whereas the maintenance records reported that the water pipe as steel, then the material uncertainty score for this particular water main was 1. Since there were a total of three confidence parameters (repair date, material and diameter), the total uncertainty scores ranged from 0 and 3 respectively. Based on conversations between the researcher and representatives from Colorado Springs Utilities, it was determined that the case study should use only the pipe inventory/break records with a total uncertainty of 0 or 1. In terms of actual records, this meant that 111 (5.4%) of the total 2,058 records were excluded from the case study.

Of the remaining 1,947 records, 1,359 had uncertainty scores of 0 whereas 588 had uncertainty scores of 1. Although the utility's data-confidence approach was extremely useful in weeding out unreliable data, within the 1,947 records there were still several inconsistencies within the data set that needed to be addressed prior to importing the information into the model. The most notable inconsistency related to the repair dates. Specifically, there were 149 cases in which the time to first break was less than 5 days. For these cases, the utility recommended that these entries not be included within the analysis since these breaks were related to construction practices or material defects in the pipe. Eliminating these 149 records from the database reduced the total dataset to 1,798, which was the number used throughout the case study.

#### 5.2.3.1 Incomplete Dataset Revisions

An important distinction between the dataset provided by Colorado Springs and that provided by Laramie Water related to the nature of the required data alterations. Whereas most of the data revisions for the Laramie system were model-induced, the majority of revisions to the Colorado Springs Utilities data involved "filling in the gaps" of incomplete data sets. For example, there were a total of 75 diameter and 647 material discrepancies between values reported in GIS and values reported from maintenance activities. For the pipe diameters, most of the discrepancies were minor (3 inch versus 4 inch) and the GIS value was assumed to be valid. Also, there were also several data entry errors such as typing 80 inches instead of 8 inches. Most of the material discrepancies were also minor (steel versus ductile iron) and the GIS value was assumed to be valid. For pipes in which the material information was very inconsistent (PVC versus cast iron), the researcher used several guidelines provided by utility personnel to determine which material was valid. For instance, the utility representative indicated that CIP water mains were generally used prior to 1968 and DIP most prevalent after 1974.

Another significant data-induced deficiency related to the installation date. Of the 1,798 total records, 248 (13.8%) were missing installation dates. Although missing installation dates lead to pipe age calculation errors, because the model failure prediction module relies primarily on the age between consecutive breaks, missing installation dates are not considered as model-induced revisions. Regardless of the classification, in an effort to provide the utility with the most meaningful information possible, the utility allocated several man-hours to completing this information. In the end, the utility was able to locate installation dates for only a fraction of 248 records so several pipes were never assigned an installation date. Utility personnel indicated that a large portion of the pipes without installation dates came from portions of the system that were incorporated into the utility from other water districts.

#### 5.2.3.1 Model-Related Revisions

The only significant model-related change involved the 50 break records in which certain water mains had been repaired more than once during a month period. As was discussed with the Laramie Water case study, this phenomenon is common throughout the industry and often the result of repair-induced stress defect or an exposure of a weak spot via a downstream improvement. Using the same guidelines established for the Laramie Water break records, the researcher evaluated each of the break events on a case by case basis and removed a total of 26 from the database.

### 5.2.4 Correlation Analysis of Break Frequency Variables

The first step in performing a Multicriteria Decision Analysis (MCDA) for the 1,420 water mains within the Colorado Springs water system with less than 3 breaks was to determine which combinations of criteria affect the overall pipe break frequency. As was performed for the Laramie Water case study, a statistical correlation analysis of the eight default criteria was performed based on the pipe inventory and break record data provided by the utility.

**Pipe Age:**

Table 5.9 shows the correlation between pipe ages and break failures for the Colorado Springs water system. The data indicates that pipe failure is uncommon for the first 20 years of use, becomes more pronounced during the 21-30 year range, and then increases dramatically from 31 to 50 years. Although the data reveals a drop off in failures after 50 years, this observation most-likely reflects a void in accurate installation records. Table 5.9 supports the utility's existing practice of paying close attention to pipes between the age of 30 and 50 years. Based on this observation, the interval and point distribution for the age criterion were determined to be:

< 20 years: 0 points
21 -30 years: 5 points
31 -50 years: 10 points
> 50 years: 15 points

Table 5.9 Pipe Break Distribution by Pipe Age, Colorado Springs Water System (Colorado Springs Utility, 2006)

| Pipe Age (years) | Percent of Breaks | Percent of Inventory |
|---|---|---|
| 0-10 | 1.7% | 28.1% |
| 11-20 | 5.7% | 14.6% |
| 21-30 | 17.8% | 22.9% |
| 31-40 | 46.4% | 19.5% |
| 41-50 | 21.8% | 9.6% |
| 51-60 | 4.7% | 3.8% |
| > 60 | 2.0% | 1.5% |

## Break Causes:

An analysis of all the break records from 1993 though 2004 indicated that the primary break causes are circumferential splits (39.1%), corrosion (35.4%), and pressure splits (6.8%). The remaining 18.7% is caused by a combination of contractor, fitting, and unknown causes. The total number of breaks for years 1993 through 2004 is shown in Table 5.10.

Table 5.10 Number of Breaks for Several Break Causes, Colorado Springs Water System (Colorado Springs Utility, 2006)

| | Number of Water Main Failures | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | Circum. Split | Corrosion | Contractor | Fitting | Press. Split | Unknown | Total |
| 1993 | 72 | 34 | 1 | 10 | 8 | 4 | 129 |
| 1994 | 56 | 4 | 26 | 9 | 11 | 27 | 133 |
| 1995 | 72 | 6 | 32 | 7 | 14 | 2 | 133 |
| 1996 | 89 | 2 | 42 | 8 | 22 | 0 | 163 |
| 1997 | 52 | 2 | 54 | 9 | 10 | 6 | 133 |
| 1998 | 23 | 0 | 62 | 7 | 4 | 19 | 115 |
| 1999 | 15 | 0 | 40 | 9 | 4 | 51 | 119 |
| 2000 | 47 | 3 | 48 | 7 | 5 | 53 | 163 |
| 2001 | 47 | 3 | 73 | 5 | 7 | 19 | 154 |
| 2002 | 64 | 0 | 68 | 7 | 5 | 11 | 155 |
| 2003 | 76 | 2 | 63 | 8 | 13 | 10 | 172 |
| 2004 | 73 | 1 | 78 | 11 | 12 | 8 | 183 |

Although the large percentage of circumferential splits and corrosion failures suggests that these causes dominate, an evaluation of each break cause's yearly contribution to the total number of failures (Figure 5.4) illustrates that the percentage of each break cause has remained fairly consistent. The only break cause that showed some deviation was the circumferential split case, which dropped from 1998~1999. Due to the absence of a significant trend, no points were assigned to this criterion.

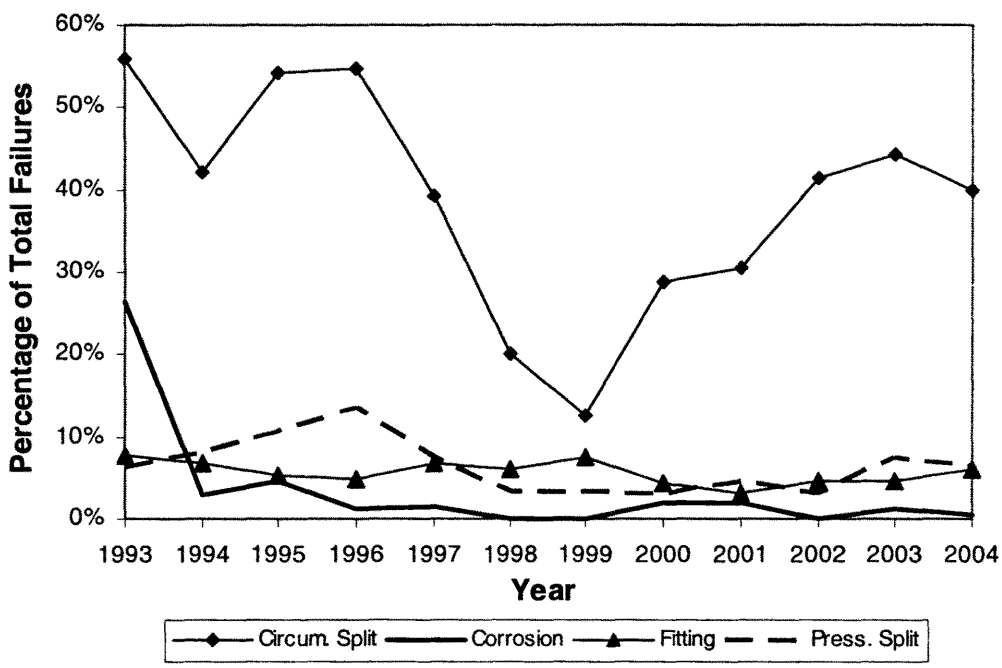


Figure 5.4 Yearly Percentages of Break Causes,
Colorado Springs Water System (Colorado Springs Utility, 2006)

## Break History:

As was done for the Laramie Water case study, 10 points were assigned for each reported break event.

**Diameter:**

Table 5.11 shows a strong correlation between the pipe diameter and break frequency for the 4 inch and 6 inch pipes. An examination of the break record database indicated that this correlation is also related to the presence of CIP, which is the oldest material type in the system. Of the total 964 break records involving either 4 inch or 6 inch pipe, 82.2% occur with cast iron pipe. Amongst the two pipe sizes, there were nearly 3.5 times more break events in the 6 inch pipe than in the 4 inch pipe. This also agrees supports the utility's prioritization policy which closely scrutinizes 6 inch diameter pipes.

Table 5.11 Pipe Break Distribution by Pipe Diameter, Colorado Springs Water System (Colorado Springs Utility, 2006)

| Pipe Diameter (in) | Percent of Breaks | Percent of Inventory |
|---|---|---|
| < 4 | 0.9% | 0.6% |
| 4 | 13.2% | 4.0% |
| 6 | 54.1% | 27.7% |
| 8 | 20.9% | 36.2% |
| 10-12 | 6.2% | 14.8% |
| 14-16 | 1.3% | 5.7% |
| 18-24 | 2.3% | 6.4% |
| >24 | 1.1% | 4.5% |

Based on these observations, the following point allocations were made for the following pipe diameter intervals:

< 4 inch: 0 points
4 inch: 5 points
6 inch: 10 points
> 6 inch: 0 points

**Material:**

Applying a similar approach to that taken for pipe diameter, a correlation analysis was conducted for system pipes for each type of pipe material. Not surprisingly, Table 5.12 shows that the cast iron pipe has a disproportionate number of breaks relative to its percentage within the system. Although ductile iron has a relatively large percentage of breaks, its break frequency is lower than its inventory frequency. This tendency is true for all the other material types, with PVC pipe exhibiting the lowest ratio break frequency to inventory frequency. Points were assigned for pipe material according to the following scale:

| | |
|---|---|
| Cast iron: | 10 points |
| Ductile iron: | 5 points |
| PVC: | 0 points |
| Other: | 0 points |

Table 5.12 Pipe Break Distribution by Material Type, Colorado Springs Water System (Colorado Springs Utility, 2006)

| Pipe Material | Percent of Breaks | Percent of Inventory |
|---|---|---|
| Asbestos | 0.7% | 0.9% |
| Cast Iron | 70.5% | 25.9% |
| Concrete | 0.1% | 0.6% |
| Ductile Iron | 20.2% | 33.1% |
| HDPE | 0.1% | 0.3% |
| Other | 0.0% | 0.1% |
| PVC | 5.5% | 34.5% |
| Steel | 2.9% | 4.6% |

**Pressure:**

Although the utility maintains information regarding the range of pressures within each of the system's pressure zones, presently this information is not correlated with their pipe inventory and break record databases. In consideration of the time required for the utility to develop this form of correlation, and in lieu of the absence of a definitive trend with pressure splits, no points were assigned to this criterion.

**Soil Resistivity:**

While Colorado Springs Utility maintains soil resistivity information for their gas pipelines, this information has not been correlated to their potable water pipe inventory. At this point in time, both the cost and time associated with developing such a correlation make it beyond the scope of this investigation. Consequently, no points were assigned to this criterion.

**Soil Type:**

Like most utilities, Colorado Springs Utilities does not maintain soil records for individual pipes. In order to determine soil type information for all the pipes with break histories, utility personnel used the Soil Survey Geographic (SSURGO) Database from Natural Resources Conservation Service (NRCS). During the evaluation, utility personnel observed that approximately 20% of the pipes contained multiple soil types over the pipe's length. Because the exact location of each pipe repair along each pipe length is not recorded, in these cases the soil type classification was based on averaging and/or applying worse case scenarios. As shown in Table 5.13, for the 1,771 pipes within the break record database, the dominate soil types where silt (60.2%) and sand (35.6%). Despite the prevalence of these soils, the table shows a lack of correlation between the percent breaks and the inventory percentage for these soils. In terms of a yearly distribution of pipe breaks associated with these soils, Figure 5.5 shows that their contribution is fairly consistent from 1996 to 2004. Based on these analyses, no points were assigned to this criterion.

Table 5.13 Pipe Break Distribution by Soil Type,
Colorado Springs Water System (Colorado Springs Utility, 2006)

| Soil Type | Percent of Breaks | Percent of Inventory |
|---|---|---|
| Clay | 1.1% | 0.6% |
| Sand | 35.6% | 40.2% |
| Silt | 60.2% | 56.9% |
| Unknown | 3.2% | 2.4% |

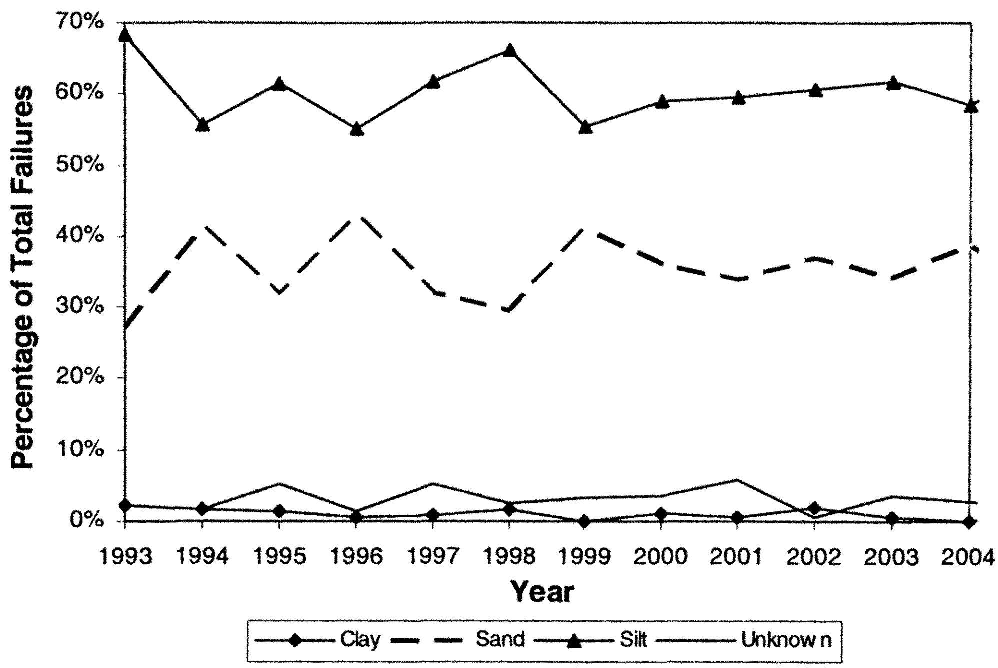


Figure 5.5 Yearly Percentages of Soil Types,
Colorado Springs Water System (Colorado Springs Utility, 2006)

**Corrosion Potential:**

The SSURGO database was also used to assign a corrosion potential classification to each pipe with a break history. Although SSURGO provides corrosion potential information for both concrete and steel, because the water system has very limited quantities of concrete pipe, only the steel corrosion potential was included for the correlation analysis. The analysis concluded that the majority of the steel corrosion potential ratings were either moderate (54.2%) or high (29.3%). Despite the dominance of these ratings, Figure 5.6 shows that their annual distribution changes very little over time. Accordingly, no points were assigned to this criterion.

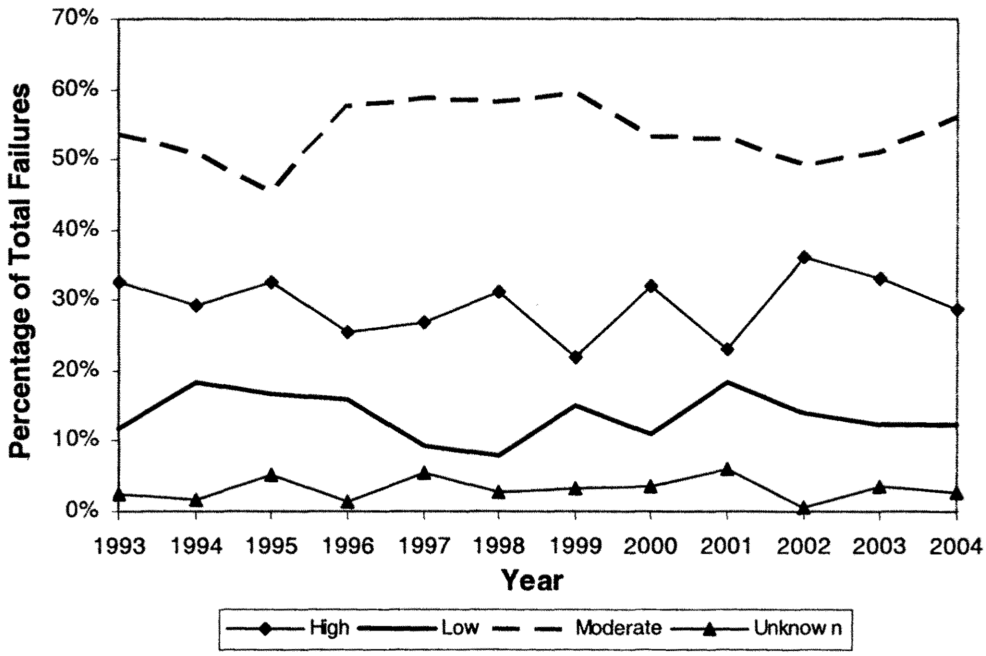


Figure 5.6 Yearly Percentages of Steel Corrosion Potential, Colorado Springs Water System, (Colorado Springs Utility, 2006)

### 5.2.5 Consequence Module Configuration

Table 5.14 shows the located-specific, indirect and social consequence weights provided by utility personnel for the 51 water pipes containing multiple (>3) break records.

Table 5.14 Consequence Factors and Weights, Colorado Springs Water System

| Pipe | Pipe Location Weights | | | | | | | | | Social and Indirect Weights | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | railroad | building | water | population | wetland | traffic | alley | slide | slope | health | social | services | fire | liability | environ | publicity | trench |
| P18426552 | | 1.60 | | | | | | | 1.20 | | | | | | | | |
| P185810359 | | | | | | 1.80 | | | 1.20 | | | | | | | | |
| P185811385 | | | | | | | | | | | | | | | | | |
| P185812481 | | | | | | | | | | | | | | | | | |
| P18581651 | | | | | | | | | | | | | | | | | |
| P185816633 | | | | | | | | | 1.20 | | | | | | | | |
| P185817299 | | | | | | | | | | | | | | | | | |
| P186326316 | | | | | | | | | 1.20 | | | | | | | | |
| P186329182 | | | | | | | | | | | | 1.40 | | | | | |
| P186331479 | | | | | | | | | | | | | | | | | |
| P1863321022 | | | | | | | | | | | | | | | | | |
| P1863321039 | | | | | | | | | | | | | | | | | |
| P186332572 | | | | | | 1.98 | | | | | | | | | | | |
| P186847364 | | | | | | | | | | | | | | | | | |
| P187355721 | | | | | | 2.16 | | | | | | | | | | | |
| P18735683 | | | | | | | | | | | | | | | | | |
| P187869186 | | | | | | | | | | | | | | | | | |
| P187871572 | | | | | | | | | | | | | | | | | |
| P187871806 | | 1.60 | | | | | | | | | | | | | | | |
| P187878400 | | | | | | | | | | | | | | | | | |
| P18788051 | | | | | | | | | | | | | | | | | |
| P18838529 | | | | | | | | | | | | | | | | | |
| P188391444 | | | | | | | | | | | | | | | | | |
| P188897121 | | | | | | | | | 1.20 | | | | | | | | |
| P188899505 | | | | | | | | | | | | | | | | | |
| P188908165 | | | | | | | | | 1.20 | | | | | | | | |
| P188909435 | | | | | | 1.80 | | | 1.20 | | | | | | | | |
| P189412290 | | | | | | | | | 1.20 | | | | | | | | |
| P189422673 | | | | | | | | | | | | | | | | | |
| P189423755 | | | | | | | | | | | | | | | | | |
| P189425242 | | | | | | | | | | | | | | | | 1.00 | |
| P189425264 | | | | | | | | | | | | | | | | 1.00 | |
| P189931876 | | | | | | 1.80 | | | | | | | | | | | |
| P189934751 | | | | | | | | | | | | | | | | | |
| P189934782 | | | | | | | | | | | | | | | | | |
| P189936357 | | | | | | | | | | | | | | | | | |
| P189937367 | | | | | | | | | | | | | | | | | |
| P189939316 | | | | | | | | | | | | 1.40 | | | | | |
| P190959486 | | | | | | | | | 1.20 | | | | | | | | |
| P190966223 | | | | | | | | | | | | | | | | | |
| P190966725 | | | | | | | | | | | | | | | | | |
| P191476497 | | | | | | | | | | | | | | | | | |
| P191477450 | | | | | | | | | | | | | | | | | |
| P191477486 | | | | | | | | | | | | | | | | | |
| P191478190 | | | | | | | | | 1.20 | | | | | | | | |
| P191479273 | | | | | | | | | | | | | | | | | |
| P191480799 | | | | | | | | | | | | | | | | | |
| P191481203 | | | | | | | | | | | | | | | | | |
| P191482993 | | | | | | | | | | | | | | | | | |
| P191997849 | | | | | | | | | | | | | | | | | |
| P192510497 | | | | | | | | | | | | | | | | | |

# CHAPTER 6

# RESULTS OF CASE STUDIES

## 6.1 Introduction

Having presented the pipe failure assessment model for the Laramie Water and Colorado Springs Utilities case studies in Chapter 5, the purpose of this chapter is to provide a comprehensive discussion and interpretation of the results for each utility. In the first part of the chapter, results from the model's failure prediction module are presented with respect to its accuracy in predicting actual breaks and the results of the probability-based prioritization terms. Results from the model's MCDA module are presented in the second part of the chapter.

## 6.2 Failure Prediction Modeling Results

For water pipes with a minimum of three break records, the model's Pipe Failure Prediction (PFP) module uses the Power Law form of a Non-Homogeneous Poisson Process (NHPP) to calculate the probability of failure, expected number of failures, and time to next failure. A critical process in the evaluation these probability-based terms involves the determination of the shape ($\beta$) and scale ($\lambda$) factors which are calculated based on each pipe's break history. Because the calculation of these parameters requires only three break records, for water mains with four or more break records, the model calculates the $\beta$ and $\lambda$ parameters for a multitude of break record combinations and determines the best combination based on an assessment of the coefficient of determination ($R^2$) between the predicted and actual breaks.

### 6.2.1 Comparison between Actual and Predicted Breaks

Figure 6.1 illustrates the variance between the actual and predicted breaks for three pipes within the Laramie water system. Of the 74 pipes analyzed within the PFP module for this system, these three pipes are representative of the varying failure trends and common levels of break histories. For pipe 167327SW142, the decreasing time between successive breaks indicates that the failure rate is increasing. This trend is indicative of a pipe experiencing a normal deteriorating process. The decreasing failure rate for pipe 157304NE70 implies that the pipe's reliability is improving. With the first three breaks occurring within the same year, it appears that the repair efforts at the third break stabilized the pipe's performance. Possible explanations for this phenomenon include the compaction of the pipe bed soil to improve stability, or improvements to upstream/downstream pipes. The cumulative break graph for pipe 157303NW105 illustrates the unpredictable nature of buried pipeline. Whereas the increasing time between the second and third breaks implies an improvement in reliability, the increasing failure rate after the third break is indicative of a decaying pipeline. The cumulative break graphs in Figure 6.1 illustrate the merit in applying the NHPP approach since the NHPP provides the needed flexibility to model a pipe's performance throughout all phases of its life cycle. For the 74 water pipes from the Laramie water system analyzed within the model's PFP module, the $R^2$ values between the predicted and actual breaks range from 0.66 to 0.93 with a mean of 0.77.

For the Colorado Springs water system, Figure 6.2 shows similar graphs of cumulative breaks over time for three pipes representative of the failure trends found throughout the system. For the 51 pipes evaluated within this water system, the $R^2$ values range from 0.68 to 0.93 with a mean of 0.76. The long break times (x-axis) for pipes P185810359 and P187871806 indicate that each pipe is missing its installation date. This does not affect the projection calculations since the model uses the age between consecutive breaks in its algorithm.

### 6.2.2 Probability-Based Prioritization Results

Having calculated shape and scale factors ($\beta$ and $\lambda$) which yield the optimal coefficient of determination ($R^2$) between the predicted and actual breaks, these parameters were used to calculate the probability of failure, time to next failure, and risk score for each water pipe. Recall that the risk score is the product of the probability and the total risk score shown in Tables 5.6 and 5.13. A summary of these results is available through the model's reporting module, which also allows the user to sort the results based on pipe id, probability value, time to next failure and risk score. Tables 6.1 and 6.2 provide a partial summary of the probability-based results for each case study for the year 2010

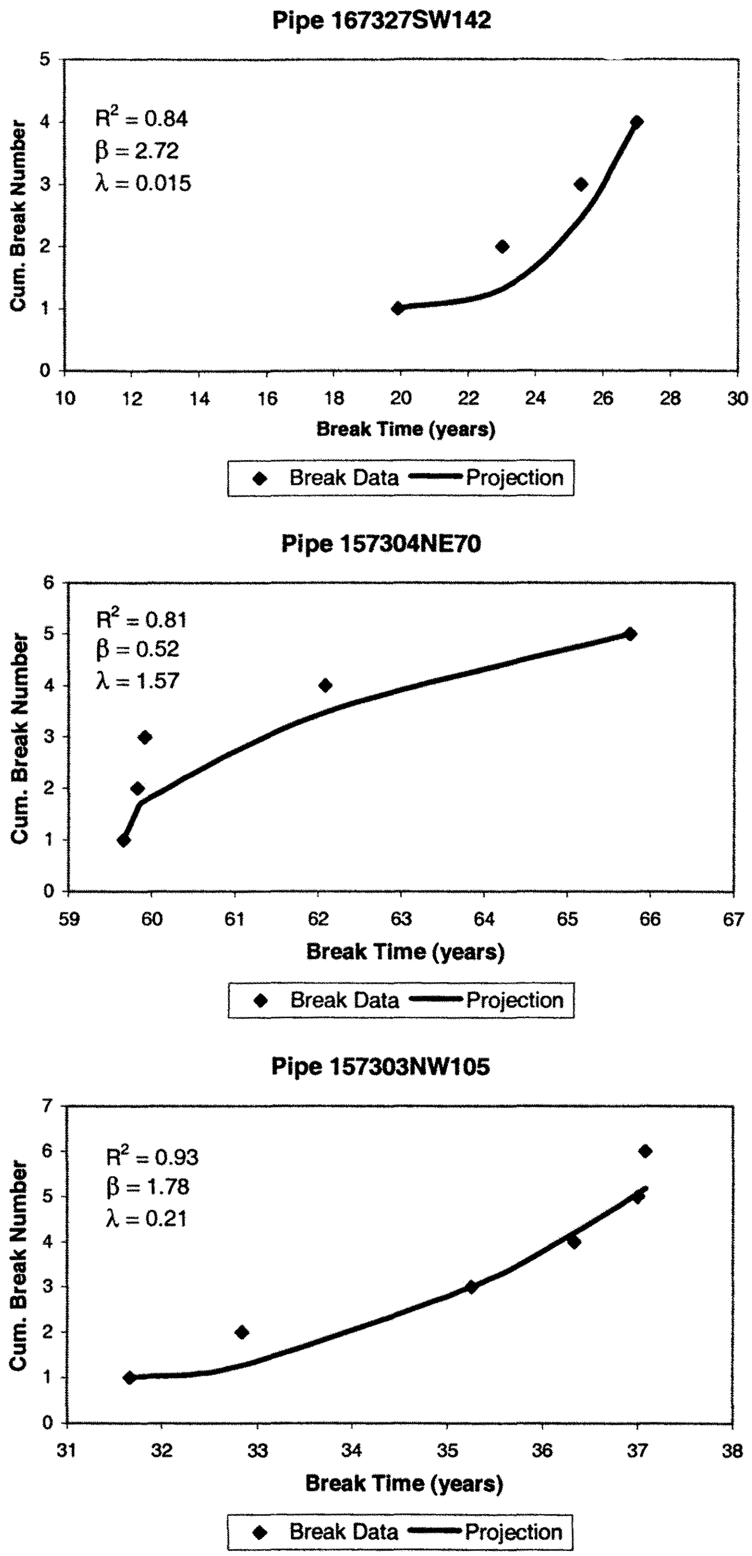


Figure 6.1 Variance between the Actual and Predicted Breaks for Three Water Pipes in the Laramie Water System

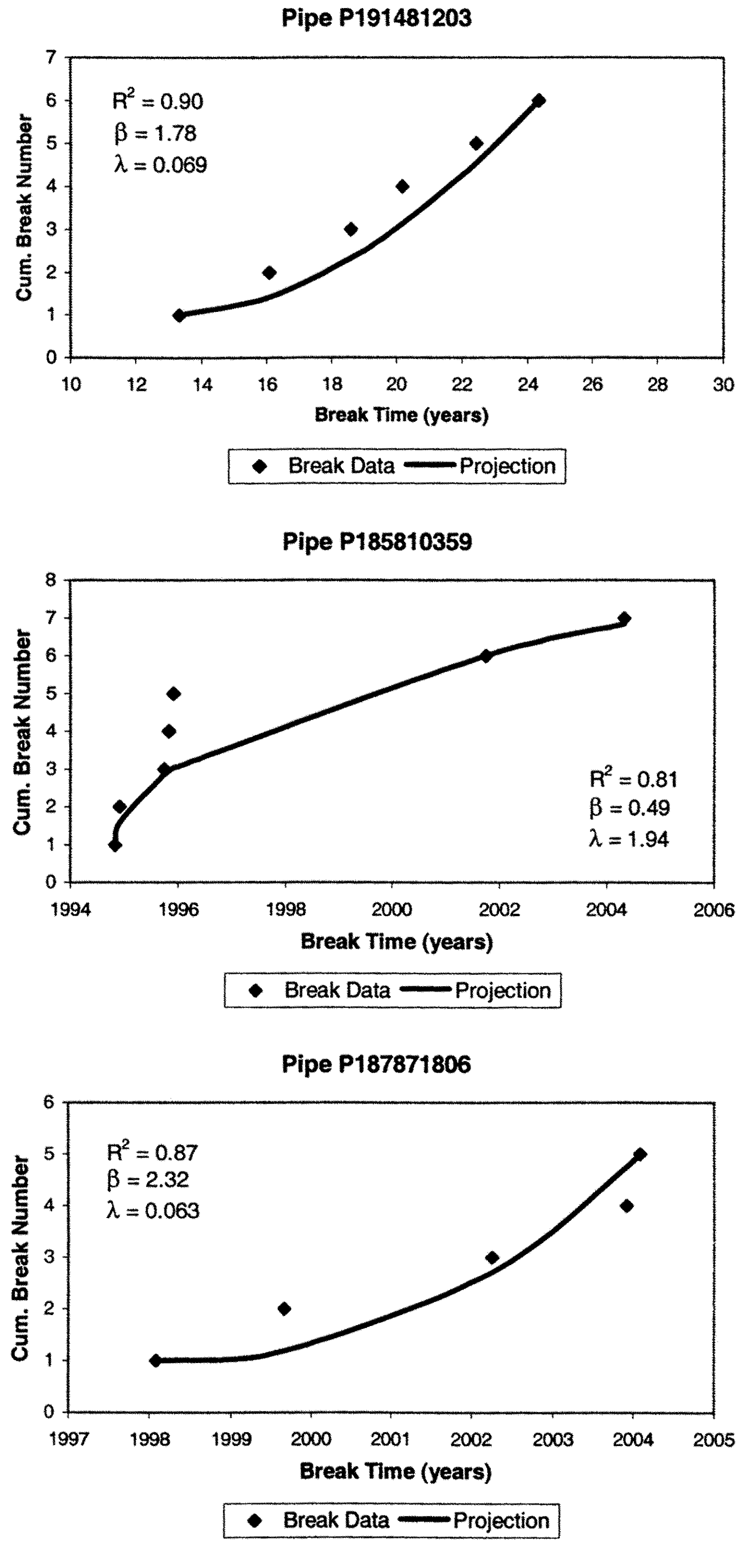


Figure 6.2 Variance between the Actual and Predicted Breaks for Three Water Pipes in the Colorado Springs Water System

Table 6.1 Partial Summary of the Probability-Based Results for the Year 2010, Laramie Water System

| Pipe ID | Material | Diameter (in) | Prob. Of Failure | $R^2$ | Next Break Date | Total Risk Score |
|---|---|---|---|---|---|---|
| 157303NE10 | CIP | 6 | 0.000 | 0.734 | Aug-15 | 0.000 |
| 157303NW03 | CIP | 16 | 0.999 | 0.734 | Jun-08 | 3.997 |
| 157303NW08 | CIP | 6 | 0.418 | 0.814 | Jun-14 | 1.588 |
| 157303NW101 | CIP | 8 | 0.809 | 0.728 | Sep-13 | 2.752 |
| 157303NW102 | DIP | 6 | 0.889 | 0.893 | Jun-13 | 1.423 |
| 157303NW105 | CIP | 6 | 0.998 | 0.928 | Apr-08 | 3.195 |
| 157303NW11 | CIP | 6 | 0.961 | 0.738 | Nov-10 | 3.556 |
| 157303NW15 | CIP | 6 | 0.963 | 0.729 | Jan-11 | 2.215 |
| 157303NW28 | CIP | 6 | 1.000 | 0.734 | Mar-09 | 3.500 |
| 157303NW46 | CIP | 4 | 1.000 | 0.734 | Dec-06 | 4.200 |
| 157303NW82 | CIP | 6 | 0.822 | 0.890 | Sep-13 | 3.534 |
| 157303SW01 | DIP | 6 | 1.000 | 0.734 | Dec-06 | 2.900 |
| 157304NE07 | CIP | 8 | 0.978 | 0.834 | Jan-10 | 4.400 |
| 157304NE103 | CIP | 6 | 0.975 | 0.816 | Feb-10 | 2.827 |
| 157304NE26 | CIP | 6 | 0.019 | 0.734 | Nov-10 | 0.055 |
| 167333NE120 | CIP | 6 | 0.913 | 0.860 | Jul-12 | 1.460 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 167333NE40 | CIP | 4 | 1.000 | 0.734 | Dec-06 | 2.100 |
| 167333NE90 | CIP | 8 | 0.139 | 0.734 | Aug-14 | 0.961 |
| 167333NW58 | CIP | 6 | 0.769 | 0.667 | Aug-18 | 1.615 |
| 167333NW65 | CIP | 6 | 0.991 | 0.774 | Jan-09 | 1.585 |
| 167333SE114 | CIP | 4 | 1.000 | 0.834 | Dec-06 | 0.800 |
| 167333SE115 | CIP | 4 | 0.789 | 0.875 | Nov-14 | 0.631 |
| 167333SE26 | CIP | 6 | 0.784 | 0.734 | Sep-15 | 1.254 |
| 167333SW153 | CIP | 16 | 1.000 | 0.734 | Dec-06 | 4.598 |
| 167334NW27 | DIP | 16 | 0.999 | 0.925 | Dec-06 | 5.494 |
| 167334SE60 | CIP | 6 | 0.910 | 0.887 | May-15 | 1.455 |
| 167334SW21 | CIP | 4 | 0.988 | 0.734 | Sep-08 | 0.791 |
| 167334SW30 | CIP | 6 | 0.027 | 0.734 | Jun-12 | 0.044 |
| 167334SW35 | CIP | 6 | 0.993 | 0.734 | Mar-09 | 1.589 |

In addition to summarizing the probability-based decision variables in tabular form, the model's graphing module converts the time to next failure data into a histogram showing the expected number of failures per year. This information is particularly useful for the utility's short-term and long-term planning activities. Figure 6.3 and 6.4 show the histograms of the expected number of failures for the Laramie and Colorado Springs systems respectively. In the case of the Laramie water system, 44 of the expected 74 failures (59%) are forecasted to occur by 2011 and 69 failures (93%) by the year 2016. The Colorado Springs system has a similar trend with 29 of the expected 51 failures (57%) by year 2011 and 44 failures (86%) by year 2016.

Table 6.2 Partial Summary of the Probability-Based Results for the Year 2010, Colorado Springs Water System

| Pipe ID | Material | Diameter (in) | Prob. Of Failure | $R^2$ | Next Break Date | Total Risk Score |
|---|---|---|---|---|---|---|
| P18426552 | CIP | 8 | 1.000 | 0.734 | Dec-05 | 2.800 |
| P185810359 | CIP | 4 | 0.989 | 0.812 | Jul-08 | 2.968 |
| P185811385 | CIP | 6 | 0.999 | 0.734 | Feb-09 | 0.000 |
| P185812481 | CIP | 4 | 0.912 | 0.734 | Jul-13 | 0.000 |
| P18581651 | CIP | 8 | 0.998 | 0.772 | Nov-08 | 0.000 |
| P185816633 | CIP | 6 | 0.852 | 0.734 | Jan-38 | 1.022 |
| P185817299 | CIP | 6 | 0.831 | 0.734 | Oct-14 | 0.000 |
| P186326316 | CIP | 6 | 1.000 | 0.734 | Jul-06 | 1.200 |
| P186329182 | DIP | 4 | 0.999 | 0.874 | Feb-07 | 1.399 |
| P186331479 | CIP | 6 | 0.971 | 0.857 | Oct-10 | 0.000 |
| P1863321022 | CIP | 6 | 0.990 | 0.734 | Aug-09 | 0.000 |
| P1863321039 | CIP | 6 | 0.980 | 0.739 | Jan-10 | 0.000 |
| P186332572 | DIP | 12 | 1.000 | 0.734 | Jan-09 | 1.980 |
| P188391444 | CIP | 6 | 0.212 | 0.734 | Nov-19 | 0.000 |
| P188897121 | DIP | 6 | 1.000 | 0.734 | Dec-05 | 1.200 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| P190959486 | DIP | 8 | 1.000 | 0.734 | Oct-08 | 1.200 |
| P190966223 | CIP | 8 | 0.144 | 0.734 | May-15 | 0.000 |
| P190966725 | CIP | 6 | 0.541 | 0.734 | Jul-14 | 0.000 |
| P191476497 | DIP | 6 | 1.000 | 0.734 | Nov-06 | 0.000 |
| P191477450 | DIP | 12 | 0.988 | 0.734 | Oct-09 | 0.000 |
| P191477486 | DIP | 6 | 0.574 | 0.734 | Oct-12 | 0.000 |
| P191478190 | CIP | 8 | 0.993 | 0.734 | Jan-09 | 1.192 |
| P191479273 | CIP | 6 | 0.908 | 0.734 | Sep-11 | 0.000 |
| P191480799 | CIP | 6 | 0.837 | 0.734 | Aug-36 | 0.000 |
| P191481203 | DIP | 6 | 0.736 | 0.901 | May-14 | 0.000 |
| P191482993 | DIP | 6 | 1.000 | 0.734 | Dec-05 | 0.000 |
| P191997849 | DIP | 8 | 1.000 | 0.734 | Dec-05 | 0.000 |
| P192510497 | DIP | 6 | 1.000 | 0.734 | May-09 | 0.000 |

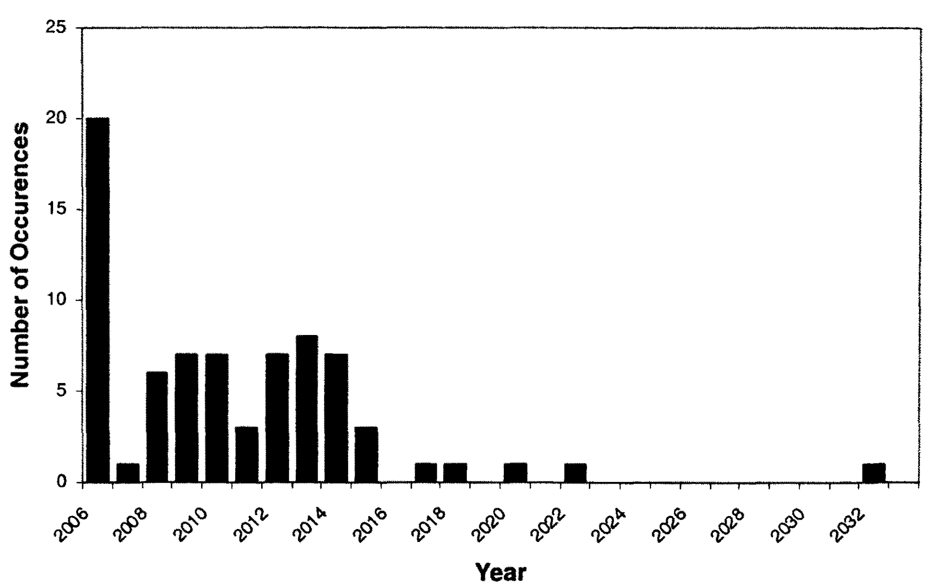


Figure 6.3 Forecasted Number of Failures over Time, Laramie Water System

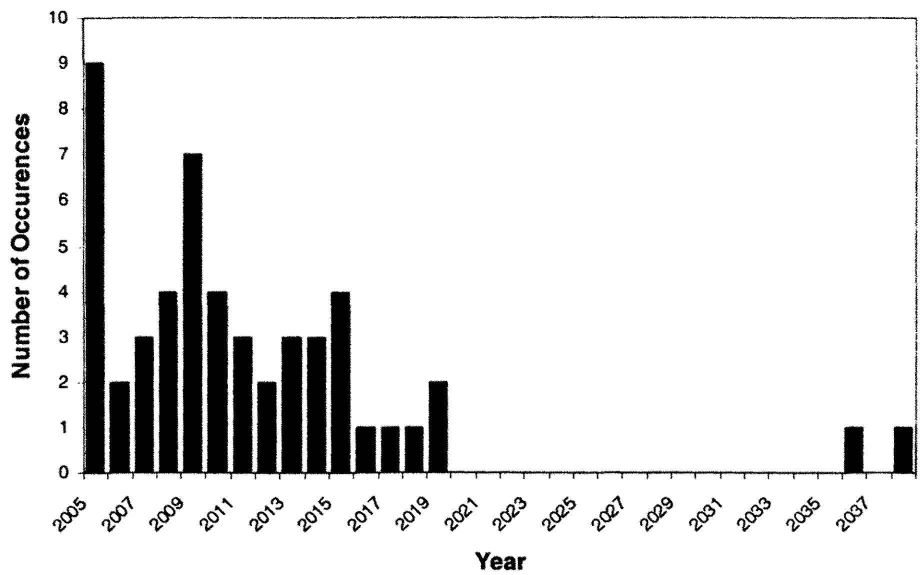


Figure 6.4 Forecasted Number of Failures over Time,
Colorado Springs Water System

### 6.3 MultiCriteria Decision Analysis Results

For pipes with one or two break repairs, the model's Multicriteria Decision Analysis (MCDA) module assigns points to each variable identified as having an influence on the overall life expectancy to each pipe. The resultant point total for each pipe provides a relative ranking that corresponds to a replacement priority for each pipe. The higher the point total, the higher the priority for pipe replacement. Whereas the water mains with three or more break records pose the greatest threat to the overall system performance, and thus receive first replacement priority, the information from the MCDA module can be used to profile pipes as part of a utility's multiyear planning activities.

Similar to the probability-based results, a summary of MCDA scores for each pipe is provided in both the model's reporting and graphing modules. As shown in Tables 6.3 and 6.4 for the Laramie and Colorado Springs water systems, the report summarizes the points for each variable and a point total. Within this report, the model provides the user with the ability to sort the results based on either pipe id or the point total. Note that both Tables 6.3 and 6.4 provide only a partial list of the total number of pipes included in the MCDA. For the Laramie Water case study, the are a total of 293 pipes with either one or two breaks whereas the Colorado Springs case study includes 1,420 pipes with either one or two break records. In both tables, the relative importance factors (weights) for each variable (age, break history, diameter, and material) is one. Lastly, observe that the installation dates for the Laramie system are given in years whereas these dates for the Colorado Springs are provided as month/year.

Table 6.3 Partial Summary of the MCDA Results for the Laramie Water System

| General Properties | | | | Variable-Specific Pipe Scores (Points * Relative Weights) | | | | | | | | Total Score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe ID. | Material | Dia. (in) | Install Date | Material | Dia. | Break Hist. | Age | Causes | Press. | Soil Resist | Soil Type | |
| 147502SW06 | STEEL | 20 | 1945 | 0 | 0 | 10 | 15 | | | | | 25 |
| 157303NE08 | CIP | 4 | 1954 | 10 | 5 | 10 | 10 | | | | | 35 |
| 157303NE33 | CIP | 6 | 1962 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE41 | CIP | 6 | 1955 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE44 | CIP | 6 | 1960 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE50 | CIP | 6 | 1954 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE56 | CIP | 6 | 1965 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE74 | PVC | 8 | 1988 | 5 | 5 | 10 | 0 | | | | | 20 |
| 157303NE79 | CIP | 6 | 1962 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NE83 | CIP | 6 | 1960 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NW07 | CIP | 6 | 1949 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NW10 | PVC | 8 | 1992 | 5 | 5 | 10 | 0 | | | | | 20 |
| 157303NW110 | CIP | 6 | 1949 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NW117 | CIP | 6 | 1950 | 10 | 10 | 10 | 10 | | | | | 40 |
| 157303NW118 | PVC | 6 | 1988 | 5 | 10 | 10 | 0 | | | | | 25 |
| • • • | • • • | • • • | • • • | • • • | • • • | • • • | • • • | | | | | • • • |
| 167331SW65 | DIP | 8 | 1972 | 0 | 5 | 20 | 5 | | | | | 30 |
| 167331SW81 | DIP | 10 | 1972 | 0 | 0 | 20 | 5 | | | | | 25 |
| 167332NE15 | CIP | 10 | 1962 | 10 | 0 | 20 | 10 | | | | | 40 |
| 167332NE40 | CIP | 6 | 1958 | 10 | 10 | 20 | 10 | | | | | 50 |
| 167332NE47 | CIP | 6 | 1958 | 10 | 10 | 20 | 10 | | | | | 50 |
| 167332SE15 | CIP | 4 | 1949 | 10 | 5 | 20 | 10 | | | | | 45 |
| 167332SE32 | CIP | 6 | 1949 | 10 | 10 | 20 | 10 | | | | | 50 |
| 167333SE18 | CIP | 10 | 1908 | 10 | 0 | 20 | 15 | | | | | 45 |
| 167333SE85 | CIP | 16 | 1927 | 10 | 0 | 20 | 15 | | | | | 45 |
| 167334SE102 | CIP | 4 | 1951 | 10 | 5 | 20 | 10 | | | | | 45 |
| 167334SE54 | CIP | 6 | 1956 | 10 | 10 | 20 | 10 | | | | | 50 |
| 167334SE59 | CIP | 6 | 1951 | 10 | 10 | 20 | 10 | | | | | 50 |
| 167334SW44 | CIP | 6 | 1920 | 10 | 10 | 20 | 15 | | | | | 55 |
| 167335SW196 | DIP | 10 | 1981 | 0 | 0 | 20 | 5 | | | | | 25 |
| 167426SW01 | PVC | 12 | 2000 | 5 | 0 | 20 | 0 | | | | | 25 |

Table 6.4 Partial Summary of the MCDA Results for the Colorado Springs Water System

| General Properties | | | | Variable-Specific Pipe Scores (Points * Relative Weights) | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pipe ID. | Material | Dia. (in) | Install Date | Material | Dia. | Break Hist. | Age | Causes | Press. | Soil Resist | Soil Type | Score |
| P183237332 | PVC | 6 | Aug-91 | 0 | 10 | 10 | 0 | | | | | 20 |
| P183752185 | DIP | 20 | Aug-85 | 5 | 0 | 10 | 5 | | | | | 20 |
| P18375295 | DIP | 20 | Aug-85 | 5 | 0 | 10 | 5 | | | | | 20 |
| P183753253 | DIP | 6 | Jan-86 | 5 | 10 | 10 | 5 | | | | | 30 |
| P183753306 | DIP | 8 | Jan-86 | 5 | 0 | 10 | 5 | | | | | 20 |
| P183753321 | DIP | 12 | Dec-84 | 5 | 0 | 10 | 5 | | | | | 20 |
| P183753431 | PVC | 8 | Feb-96 | 0 | 0 | 10 | 0 | | | | | 10 |
| P183753525 | DIP | 12 | Oct-96 | 5 | 0 | 10 | 0 | | | | | 15 |
| P1842653 | CIP | 8 | Jan-62 | 10 | 0 | 10 | 10 | | | | | 30 |
| P1842659 | CIP | 8 | Jan-62 | 10 | 0 | 10 | 10 | | | | | 30 |
| P184266120 | CIP | 6 | Jan-62 | 10 | 10 | 10 | 10 | | | | | 40 |
| P18426615 | CIP | 8 | Jan-63 | 10 | 0 | 10 | 10 | | | | | 30 |
| P184266361 | DIP | 12 | Mar-82 | 5 | 0 | 10 | 5 | | | | | 20 |
| P184266378 | DIP | 12 | Mar-82 | 5 | 0 | 10 | 5 | | | | | 20 |
| P184266385 | PVC | 6 | Mar-82 | 0 | 10 | 10 | 5 | | | | | 25 |
| •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | •<br>•<br>• | | | | | •<br>•<br>• |
| P191476459 | DIP | 6 | Jan-81 | 5 | 10 | 20 | 5 | | | | | 40 |
| P191477493 | DIP | 6 | Nov-79 | 5 | 10 | 20 | 5 | | | | | 40 |
| P191477499 | DIP | 12 | Mar-73 | 5 | 0 | 20 | 10 | | | | | 35 |
| P191477546 | DIP | 8 | Nov-79 | 5 | 0 | 20 | 5 | | | | | 30 |
| P191477582 | DIP | 6 | Nov-79 | 5 | 10 | 20 | 5 | | | | | 40 |
| P191477631 | DIP | 6 | Apr-82 | 5 | 10 | 20 | 5 | | | | | 40 |
| P191478168 | CIP | 8 | Jan-72 | 10 | 0 | 20 | 10 | | | | | 40 |
| P191479321 | CIP | 8 | Aug-72 | 10 | 0 | 20 | 10 | | | | | 40 |
| P191479431 | CIP | 6 | Jul-68 | 10 | 10 | 20 | 10 | | | | | 50 |
| P191479435 | CIP | 8 | Sep-72 | 10 | 0 | 20 | 10 | | | | | 40 |
| P191479470 | CIP | 8 | Aug-72 | 10 | 0 | 20 | 10 | | | | | 40 |
| P191479492 | CIP | 8 | Aug-72 | 10 | 0 | 20 | 10 | | | | | 40 |
| P191479621 | CIP | 6 | May-73 | 10 | 10 | 20 | 10 | | | | | 50 |
| P1919913 | DIP | 12 | Nov-86 | 5 | 0 | 20 | 0 | | | | | 25 |
| P192510627 | CIP | 6 | --- | 10 | 10 | 20 | --- | | | | | 40 |

Figure 6.5 and 6.6 show the histograms of the MCDA point totals for each case study. One notable difference between the two histograms is that the Laramie system has a more diverse spread of point values than the Colorado Springs system. Observe that in the Laramie system approximately 48% of the pipes have point totals that exceed 85 points, whereas in the Colorado Springs system only 8% of the pipes have point totals exceed 85. One explanation for this difference in point totals relates to percentage of one break pipes within each system's break database. In the Laramie water system, 72% of the pipes evaluated using the MCDA module have only one break record. In the case of the Colorado Springs system, this percentage is substantially larger at 88%. Another notable difference between the two histograms relates to the number of pipes evaluated. Whereas the MCDA analysis for the Laramie system includes 293 pipes, the MCDA analysis for the Colorado Springs system consists of a total of 1,420 pipes.

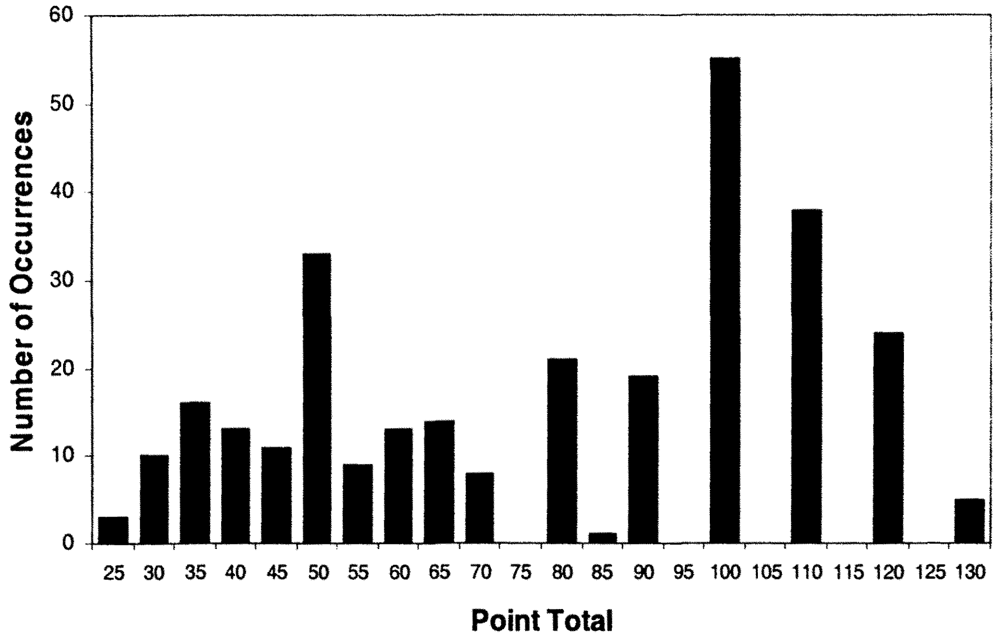


Figure 6.5 Distribution of the MCDA Point Totals
for the Laramie Water System

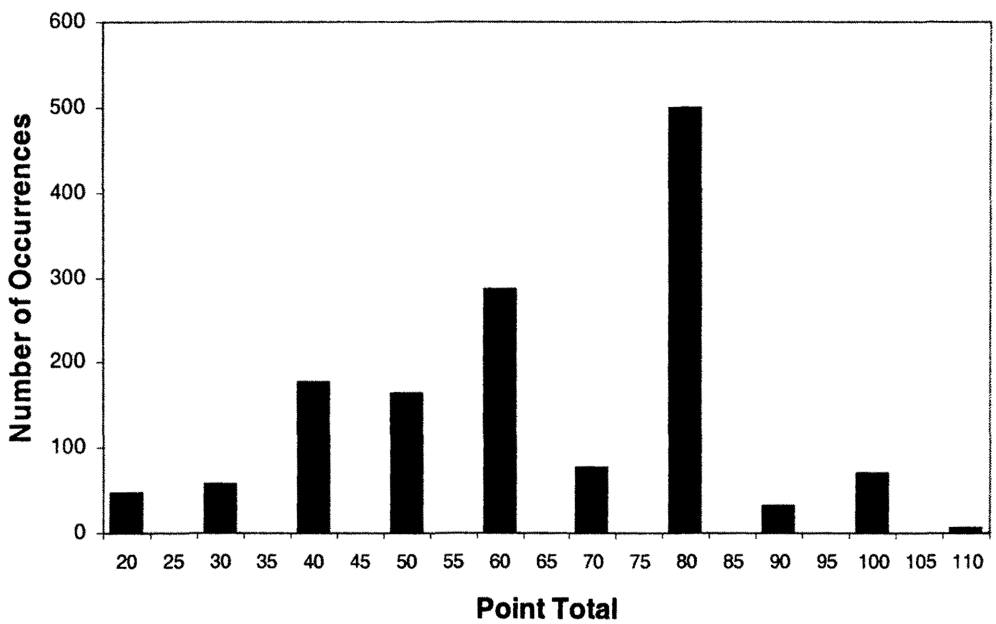


Figure 6.6 Distribution of the MCDA Point Totals
for the Colorado Springs Water System

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

## 7.1 Background

Like other civil infrastructure systems, the nation's aging water distribution systems are deteriorating due to neglect and excessive demand. As a result, water utilities are faced with the formidable task of renewing their buried water pipes in order to provide customers with reliable and safe water supplies. However, the repair and/or replacement of water pipes, especially in urban environments, impose major expenditures on organizations that are already financially strained. In response to this dilemma, the water supply industry is embracing a variety of scientific approaches aimed at quantifying their pipeline renewal decisions. One such approach involves the use of information technology combined with the application of pipeline asset management. A key component in the asset management process is the assessment of each pipe's condition to identify failure-prone pipes and prioritize their renewal. However, the below ground location of pipes and large quantities make the direct inspection of these pipes prohibitively expensive. Aside from not knowing the condition of the pipe inventory, the lack of standard guidelines or tools to assist utility managers with their daily renewal decisions further complicates these decisions.

The purpose of this research was to develop a pipe failure assessment model to assist water utilities with their pipe renewal decisions. Rather than creating a data-intensive physical model aimed at determining the cause of pipe breaks, the model's performance-based approach makes use of pipe inventory and break record data gathered from the utility's daily operation and maintenance activities. Aside from eliminating the need for utilities to allocate financial resources to gather additional data, these approaches inherently incorporate site-specific data. Lastly, performance-based models have the added benefit of not requiring high levels of technical expertise to calibrate and verify below-ground parameters common to physical models.

The conceptual model was developed from an extensive literature review of existing pipe deterioration models, reliability modeling applications, and risk management concepts. The assessment of the existing deterioration models provided the researcher with insights regarding the data requirements, modeling limitations, and forecasting accuracy of each approach. The focus of the reliability modeling review was to determine how traditional reliability techniques can be applied to water main failure analysis. The risk management research helped clarify the role of risk management in the pipeline replacement prioritization, highlighting the need to include a consequence component within the model. The conceptual model was refined through collaboration of a focus group of water utility professionals. By drawing on the knowledge and experience of these experts, the review process added unique features that facilitate the model's use and its responsiveness to the industry's needs.

The model consists of several modules (components) written in Visual Basic for Application (VBA) within a Microsoft Excel platform. Excel was selected due to its commercial availability and the use of VBA user-forms simplifies the data entry and analysis features of the program. Each module works interactively through the use of various databases. Whereas the Pipeline Data Module (PDM) and the Consequence Module (CM) are used for data entry, the program's Pipe Failure Prediction (PFP) and Multicriteria Decision Analysis (MCDA) modules perform the pipe renewal replacement calculations. The model's output is managed through the Reporting and Graph modules, which produce several standardized reports and graphs. The characteristics that distinguish the model from its predecessors are:

- For water pipes with a minimum of three break records, the model's pipe failure prediction module applies a performance-based approach through a Non-Homogeneous Poisson Process (NHPP) to calculate the probability of failure, expected number of failures, and time to next failure.
- Recognizing that pipe renewal decisions are also based on risk avoidance, the failure predictive modeling is supplemented with a risk-based consequence module. This dual approach enables decision makers to prioritize pipe renewal decisions as part of a comprehensive risk management process.
- In order to provide utilities with a tool for pipe profiling as part of multiyear planning activities, for pipes with either one or two break records, the program uses a MCDA approach to provide the decision maker with a relative ranking.

The model was tested using pipe inventory and break history information contributed by Laramie (Wyoming) Water and Colorado Springs Utilities. The data for each utility was provided as Excel files and imported directly into the model's platform. For each utility, the model's failure prediction module was tested by comparing the actual break records to the forecasted breaks and observing the associated coefficients of determination ($R^2$). The program's MCDA module was tested by first performing a correlation analysis of each utility's data set to determine which factors contribute to the pipes' failure rates. Having identified these factors, weights were assigned to each factor and the module was tested. The MCDA results were verified by utility personnel based on their familiarity of the system and pipe data. The model's consequence module was tested using the consequence factors provided by utility personnel.

The results from the two case studies proved to be very insightful since each utility is vastly different with regard to population served, operating conditions, pipe inventories, failure rates, and break causes. The Laramie water distribution system is relatively small with 206 miles of pipes of predominately cast iron and ductile iron pipe. Due to the age of the system and abundance of corrosive soils in the region, Laramie's water pipes fail at a rate twice the industry average. Conversely, the Colorado Springs distribution network is comprised of over 1,800 miles of newer and more diverse pipe materials. Although the system's pipes also fail due to corrosion, the utility's pipe failure rate is approximately half the national average with many failures occurring due to pressure splits.

## 7.2 Conclusions

The overall conclusion resulting from this research is that, while the pipe failure assessment model is a step in the right direction, much more work needs to be done. Whereas the pipe failure prediction and consequence modules provide decision makers with a transparent and quantifiable process for prioritizing their short-term pipe renewal decisions, the model's MCDA module is useful in determining the failure potential of water pipes as part of a multiyear planning process. The participating utility professionals also indicated that the model's use of data already gathered as part of the day-to-day operation and maintenance activities, intuitive nature, and Excel platform makes it more responsive to the industry's needs. During a panel discussion held at Colorado State University, utility personnel pointed out that the model's Excel format was particularly appealing since Excel's popularity makes the program less intimidating to first time users.

Ultimately, the quality of any model's predictions is only as good as the data used to support it. While most utilities now acknowledge the importance of maintaining accurate inventory and break history records of their pipe supplies, this practice has only been emphasized for the past decade. This gap between the age of each utility's pipeline infrastructure and the degree of reliable pipe inventory and break history information affected the results generated from the model's failure prediction and MCDA modules. In the case of the failure prediction modeling, because the NHPP approach requires a minimum of three break records, many water pipes with known break histories could not be included in the analysis. For example, a total of 87 pipes in the Laramie system and 172 pipes in the Colorado Springs system were not analyzed using the program's predictive module because they only had two break records. Had these pipes' break histories included one additional break, the number of pipes evaluated by the model's prediction component would have doubled. For the MCDA modeling, the lack of break cause, pressure, and soil type data limited the ability of the MCDA module to differentiate between the various water pipes competing for renewal prioritization. Because the MCDA scores had been based on factors common to numerous pipes throughout each system (size, diameter, material, break history), there were several pipes with identical/close resultant scores. For example, in the MCDA scores for the Laramie Water system, nearly 19% of the 293 pipes had between 100-105 points. The inclusion of variables would have proven invaluable in differentiating the total scores and thus providing a more complete pipe prioritization.

Aside from identifying deficiencies that influence the performance and accuracy of the model, this investigation also clearly identified deficiencies that affect the model's responsiveness to the industry's needs. For example, information regarding the exact break location should be included in future data sets since this could resolve much of the ambiguity about how various risk factors such as soil type and corrosion potential are distributed along the length of the pipe. Likewise, a more concerted effort by utility maintenance personnel to provide detailed information regarding the break type and suspected cause would be invaluable to the MCDA correlation analysis as well as enhancing utility personnel's understanding of their system's behavior.

## 7.3 Future Research Needs

Improvements in Data Management

Statistically-based models provide an effective and economically viable alternative to measuring the deterioration of water pipes. However, in order for the water supply industry to take full advantage of these models such as the one developed in this dissertation, water utilities must improve their data collection and management procedures.

Future research efforts should concentrate on developing standard protocols for water pipe data collection and management. Such protocols need to be comprehensive, addressing the full spectrum of data-related issues such as collection procedures, quality control, data storage, and updating procedures. Such protocols would also facilitate the sharing of information among utilities and researchers. Ongoing research should also address the need to coordinate the data collection efforts between utility's maintenance and management personnel. Whereas maintenance personnel have access to a wealth of pipeline condition and break information on a regular basis, far too often this information does not reach the individuals responsible for making pipe renewal decisions. Similarly, maintenance personnel usually are not aware of the data needs of the utility decision makers.

Potential Modeling Improvements

From a modeling perspective, there are several modeling approaches for enhancing both the failure prediction and MCDA capabilities of the pipe failure assessment model that should be considered in future research. For water systems in which break data is too scarce to apply a NHPP approach, one promising technique involves the use of Bayesian statistical modeling. Bayesian modeling combines data taken from a limited data set with information derived from a "lessons learned" database for a similar pipe (Watson et al., 2001). For example, data taken from a pipe failure on one side of a network can be combined with the knowledge acquired from a similar pipe taken from the other side of the network. Because of the sophistication associated with this form of modeling, care must taken to assure that model's complexity does not require a level of expertise too high to be comfortably used by utility decision makers.

The MCDA technique chosen by the researcher, known as the Weighted Average Method, is appealing due to its simplicity and ability to provide a complete ranking. Despite these merits, the method must be used with care since the relative importance weights can easily bias the overall rankings. Within the MCDA literature there are a multitude of other methods including PROMETHEE (Preference Ranking Organization Method for Enrichment) and Goal Programming that are less sensitive to weights and also provide complete rankings. Aside from the actual MCDA technique, several utilities indicated the need to simply the assignment of consequence weights. In particular, they felt that the interval and relative weight terms were confusing and also recommended that the program provide the users with industry-wide weight values to serve as guidelines.

In terms of correlation techniques for quantifying the factors that influence break frequency, while the approach used in the model based on comparing a variable's breakage percentage to its overall inventory percentage is intuitively appealing, there are numerous more sophisticated approaches such as Artificial Neural Networks (ANN), fuzzy programming, and survival analysis that are better-equipped to assess the interrelationships between the various factors that influence a pipe failure rate. As is the case with the Bayesian modeling, it is vital that the approach does not reach a level of complexity which deters utility personnel from applying the model.

**THE END**

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# Appendix

# QUESTIONNAIRES FROM INDUSTRY EXPERTS

**COLORADO STATE UNIVERSITY**
**DEPARTMENT OF CIVIL ENGINEERING**
**FORT COLLINS, CO 80523**

**WATER UTILITY QUESTIONNAIRE**
**PIPE FAILURE ASSESSMENT MODEL**

**INSTRUCTIONS:** Please answer all questions. For multiple choice questions, please CIRCLE the number that corresponds to your response. For the remaining questions, please FILL IN the blanks as indicated.

## I. GENERAL INFORMATION: **DATE:** 07/17/2006

**Utility Information:**

| | |
|---|---|
| Utility Name: | Colorado Springs Utilities |
| Utility Address: | 1521 Hancock Expressway<br>P.O. Box 1103, Mail Code 1825<br>Colorado Springs, CO 80947-1825 |

**Reviewer Information:**

| | |
|---|---|
| Name: | David Totman |
| Title: | Engineering Systems Planner |
| Office Number: | (719) 668 – 8493 |
| Email: | dtotman@csu.org |

**II. QUESTIONS REGARDING THE MODEL'S RESPONSIVENESS TO INDUSTRY'S NEEDS :**

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's statistical (probability) approach is more appropriate than physical model. | 1 | 2 | ③ | 4 |
| The model's consequence feature adequately addresses the industry's risk avoidance needs. | 1 | 2 | ③ | 4 |
| This kind of model is likely to be accepted by decision makers investing in pipe renewal. | 1 | 2 | ③ | 4 |
| Overall, the model addresses the industry's needs | 1 | 2 | ③ | 4 |

**III. QUESTIONS REGARDING THE MODEL'S DESIGN :**

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's format makes it easy to use. Conceptually the model is easy to understand. | 1 | 2 | 3 | ④ |
| The probability model provides valid information even with limited data. | 1 | 2 | ③ | 4 |
| The use of a Decision Support System (DSS) for pipes with limited break histories is appropriate. | 1 | 2 | 3 | ④ |
| The model's combined probability and DSS method is superior to models which prioritize replacement solely on assigning points to risk factors. | 1 | 2 | ③ | 4 |
| The program's Excel format is desirable. | 1 | ② | 3 | 4 |
| The model is simple to use yet powerful enough to be an effective prioritization tool. | 1 | 2 | ③ | 4 |

## IV. RECOMMENDATIONS:

What do you feel are the strengths and weaknesses of the model?

- Strengths
  - Brings powerful mathematics to the user in an easy to use front end.
  - Ability to work individual pipe data, yet compute system wide metrics.
  - Based on availability of data, provides both probability and correlation analysis where appropriate.

- Weaknesses
  - Population constrained by Excel's original 16-bit limit (65,536 rows). Ok for break modeling, not suitable for complete inventory holdings of large Utilities.
  - To meet the model's full potential, it seems to require a significant amount of pre-analysis (consequence module).

What are your recommendations for future additions to the model?

- Process
  - Reduce/simplify factors in consequence module.

- Programming
  - In inventory module, link all 4 tabs to single Pipe ID when first populated in any of the tabs.
  - Increase date granularity from MM/YYYY to MM/DD/YYYY h24:mm:ss. Minutes and seconds not realistic, however provides sufficient detail to accommodate multiple breaks in same day if necessary.
  - Attach hard-coded worksheets in workbook to ODBC-linked database tables to support larger utilities with enterprise systems.
  - Expose actual polynomial used in generating probability failure curves when $\beta$ and $\lambda$ are decided upon. May already be identified in documentation? Intended use is to generate useful life for entire population of pipes based on behavior of leaky pipes.

**COLORADO STATE UNIVERSITY**
**DEPARTMENT OF CIVIL ENGINEERING**
**FORT COLLINS, CO 80523**

## WATER UTILITY QUESTIONNAIRE
## PIPE FAILURE ASSESSMENT MODEL

**INSTRUCTIONS:** Please answer all questions. For multiple choice questions, please CIRCLE the number that corresponds to your response. For the remaining questions, please FILL IN the blanks as indicated.

## I. GENERAL INFORMATION:

**DATE:** 07/18/2006

**Utility Information:**

| | |
|---|---|
| Utility Name: | City of Laramie Water and Utilities |
| Utility Address: | P.O. Box C<br>Laramie WY 82073 |

**Reviewer Information:**

| | |
|---|---|
| Name: | Cal Van Zee |
| Title: | Utility Maintenance Supervisor |
| Office Number: | (307) 721 - 5206 |
| Email: | cvanzee@ci.laramie.wy.us |

## II. QUESTIONS REGARDING THE MODEL'S RESPONSIVENESS TO INDUSTRY'S NEEDS :

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's statistical (probability) approach is more appropriate than physical models. | 1 | 2 | 3 | ④ |
| The model's consequence feature adequately addresses the industry's risk avoidance needs. | 1 | 2 | ③ | 4 |
| This kind of model is likely to be accepted by decision makers investing in pipe renewal. | 1 | 2 | ③ | 4 |
| Overall, the model addresses the industry's needs. | 1 | 2 | 3 | ④ |

## III. QUESTIONS REGARDING THE MODEL'S DESIGN :

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's format makes it easy to use. Conceptually the model is easy to understand. | 1 | 2 | 3 | ④ |
| The probability model provides valid information even with limited data. | 1 | 2 | 3 | ④ |
| The use of a Decision Support System (DSS) for pipes with limited break histories is appropriate. | 1 | 2 | 3 | ④ |
| The model's combined probability and DSS method is superior to models which prioritize replacement solely on assigning points to risk factors. | 1 | 2 | 3 | ④ |
| The program's Excel format is desirable. | 1 | 2 | 3 | ④ |
| The model is simple to use yet powerful enough to be an effective prioritization tool. | 1 | 2 | 3 | ④ |

**IV. RECOMMENDATIONS:**

What do you feel are the strengths and weaknesses of the model?

The strengths of the model are the ease of operation and the ability of the model to fit each system regardless of size or complexity. The one downside may be the size of the computer necessary to run the model, particularly for small systems.

What are your recommendations for future additions to the model?

The one thing that would make this system easier to run and operate is a conversion table for address to pipe node number. Smaller systems usually do not have the funding to provide pipe node identification.

**COLORADO STATE UNIVERSITY**
**DEPARTMENT OF CIVIL ENGINEERING**
**FORT COLLINS, CO 80523**

**WATER UTILITY QUESTIONNAIRE**
**PIPE FAILURE ASSESSMENT MODEL**

**INSTRUCTIONS:** Please answer all questions. For multiple choice questions, please CIRCLE the number that corresponds to your response. For the remaining questions, please FILL IN the blanks as indicated.

**I. GENERAL INFORMATION:** **DATE:** 7-18-06

**Utility Information:**

| | |
|---|---|
| Utility Name: | City of Loveland, Department of Water and Power |
| Utility Address: | 200 N. Wilson Ave<br>Loveland, CO 80537 |

**Reviewer Information:**

| | |
|---|---|
| Name: | Thomas Greene |
| Title: | Utility Information Manager |
| Office Number: | (970) 962-3706 |
| Email: | greent@ci.loveland.co.us |

## II. QUESTIONS REGARDING THE MODEL'S RESPONSIVENESS TO INDUSTRY'S NEEDS :

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's statistical (probability) approach is more appropriate than physical model. | 1 | 2 | ③ | 4 |
| The model's consequence feature adequately addresses the industry's risk avoidance needs. | 1 | 2 | ③ | 4 |
| This kind of model is likely to be accepted by decision makers investing in pipe renewal. | 1 | 2 | ③ | 4 |
| Overall, the model addresses the industry's needs | 1 | 2 | ③ | 4 |

## III. QUESTIONS REGARDING THE MODEL'S DESIGN :

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's format makes it easy to use. Conceptually the model is easy to understand. | 1 | 2 | 3 | ④ |
| The probability model provides valid information even with limited data. | 1 | 2 | ③ | 4 |
| The use of a Decision Support System (DSS) for pipes with limited break histories is appropriate. | 1 | 2 | ③ | 4 |
| The model's combined probability and DSS method is superior to models which prioritize replacement solely on assigning points to risk factors. | 1 | 2 | ③ | 4 |
| The program's Excel format is desirable. | 1 | 2 | ③ | 4 |
| The model is simple to use yet powerful enough to be an effective prioritization tool. | 1 | 2 | 3 | ④ |

## IV. RECOMMENDATIONS:

**What do you feel are the strengths and weaknesses of the model?**

It appears to be easy to use and requires minimal effort to import data. Users are given the opportunity to "weight" pipe elements by assigning points which provides a better assessment for future pipe failures. Typically the utility company has the best knowledge why a pipe failed.

Some additional enhancements in the program could allow the input of data and the analysis process to "flow" easier. I really think that this model is a "diamond-in-the-rough".

**What are your recommendations for future additions to the model?**

Provide comments for users when filling in point values. The comments could contain typical or industry values and or reasons why you would assign that variable a higher or lower value.

If the assessment model gains acceptance, it would be nice to obtain the general weighted values by other users.

I don't recall seeing any variables that evaluates temperature, differential temperature between ground and water... Not sure if that has much influence on breaks or not. One of our "old timers" that has retired always said that the frost from a long cold winter would be "driven" down deep into the ground as spring started to return. We did experience more breaks during those winter/springs. Fortunately we have not had many cold winters for the past decade.

I also did not see any variable that would evaluate the pipe segment velocity. Utilities like Loveland are now using hydraulic water models that evaluate every pipe so it would very easy to provide velocities.

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**FORT COLLINS, CO 80523**

# WATER UTILITY QUESTIONNAIRE
# PIPE FAILURE ASSESSMENT MODEL

**INSTRUCTIONS:** Please answer all questions. For multiple choice questions, please CIRCLE the number that corresponds to your response. For the remaining questions, please FILL IN the blanks as indicated.

## I. GENERAL INFORMATION:

**DATE:** 08/01/2006

**Utility Information:**

| | |
|---|---|
| Utility Name: | Albuquerque Bernalillo County Water Utility Authority |
| Utility Address: | One Civic Plaza, Room 5027<br>Albuquerque, NM 87102 |

**Reviewer Information:**

| | |
|---|---|
| Name: | Stephen W. Bockemeier, P.E. |
| Title: | Manager, Utility Engineering & Planning Division |
| Office Number: | (505) 768-3646 |
| Email: | Bockemeier@cabq.gov |

**II. QUESTIONS REGARDING THE MODEL'S RESPONSIVENESS TO INDUSTRY'S NEEDS :**

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's statistical (probability) approach is more appropriate than physical models. | 1 | 2 | 3√ | 4 |
| The model's consequence feature adequately addresses the industry's risk avoidance needs. | 1 | 2 | 3√ | 4 |
| This kind of model is likely to be accepted by decision makers investing in pipe renewal. | 1 | 2 | 3√ | 4 |
| Overall, the model addresses the industry's needs. | 1 | 2 | 3√ | 4 |

**III. QUESTIONS REGARDING THE MODEL'S DESIGN :**

| | Strongly Disagree | Disagree | Agree | Strongly Agree |
|---|---|---|---|---|
| The model's format makes it easy to use. Conceptually the model is easy to understand. | 1 | 2 | 3 | 4√ |
| The probability model provides valid information even with limited data. | 1 | 2 | 3√ | 4 |
| The use of a Decision Support System (DSS) for pipes with limited break histories is appropriate. | 1 | 2 | 3√ | 4 |
| The model's combined probability and DSS method is superior to models which prioritize replacement solely on assigning points to risk factors. | 1 | 2 | 3 | 4√ |
| The program's Excel format is desirable. | 1 | 2 | 3 | 4√ |
| The model is simple to use yet powerful enough to be an effective prioritization tool. | 1 | 2 | 3 | 4√ |

## IV. RECOMMENDATIONS:

What do you feel are the strengths and weaknesses of the model?

1. User interface seems easy to use, i.e. Excel plus VBA enhancements.
2. Variety of available inputs (which the user can define) is useful for interfacing with modern CMMS and work order tracking system data on types of line failure mechanisms, and with GIS attribute data typical for pipelines.
3. Good use of site factors to simulate varying conditions contributing to break frequency.
4. Good use of consequence factors to weight the costs of pipeline failures.
5. Bias may be introduced by modeling line segments with 1 or 2 breaks differently than lines with 3 or more breaks.
6. Guidelines needed on varying model inputs to adjust for better fit of break history data.
7. Reference values need benchmarking with other utility's data.

What are your recommendations for future additions to the model?

1. Have ability to select pipes meeting a specified Probability of failure versus time.
2. Add life cycle costing calculation to evaluate when deferral of line replacement and increased line repair is preferred over line replacement at the predicted end point. Higher costs of repairs can result in shifting analysis to more frequent line replacements. These cost factors might be characterized geographically (like ENR index values).
3. Constrain the pipe system analysis to "geographical block area groups" as opposed to individual pipeline segments which may be scattered geographically. Projects are usually built to limit neighborhood areas being disturbed.