RISK ASSESSMENT MODEL FOR PIPE REHABILITATION AND
REPLACEMENT IN A WATER DISTRIBUTION
SYSTEM

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ABSTRACT

Risk Assessment Model for Pipe Rehabilitation and Replacement

In a Water Distribution System

Jan Devera

The efficient delivery of potable water for a community through its distribution system has historically been the backbone of nearly all metropolitan developments. Much of these systems are comprised of pipe networks made of various materials including concrete, iron, PVC, and even steel. As these communities expand and urbanize, water demand and population density simultaneously increase. This develops higher strains and stresses in the community's water distribution network causing pipes to corrode, crack, or rupture prematurely while in service. As a result, the deterioration of water distribution systems in growing cities is increasingly becoming a major concern for our nation.

There have been several publications on the subject of evaluating pipe conditions within a water distribution network that use statistical models, estimation, and other mathematical analyses. However, many of these publications are cumbersome and are difficult to understand from a non-engineering perspective. In order to simplify the evaluation process for all varying professions in a city's public works division, the primary objective of this study was to develop a user-friendly risk assessment model that was practical, cost effective, and easy to follow.

This risk assessment model focuses primarily on the physical condition of pipes in a water distribution system. It assesses the installation year, age, material, and break history of these water mains. It does not consider pipe fittings, pumps, or other network components. A pipe's probability of failure is determined from its physical condition.

The model then considers various economic degrees of impact that may affect the rehabilitation or replacement of these water mains. These degrees of impact include raw material costs, customer criticality, land use, demand, pipe material, and traffic impact. By focusing on pipes having the highest probability of failure and considering their economic impacts, this model identifies and prioritizes the most vulnerable water mains that require immediate attention.

In order to validate this developed risk assessment model, the method was applied to a real water distribution system. Data from the City of Arroyo Grande, California was used in conjunction with WaterCAD and geographic information systems (ArcGIS) software during analysis.

Application of the risk assessment model identified six cast iron pipes in Arroyo Grande's water distribution system as having a high risk of failure. Of the city's 3,057 individual pipe segments, recognizing only five of these pipes as high risk indicated that the assessment model was functional.

Developing and testing this risk assessment model with real city data effectively demonstrated its practicality and easy application to a real water distribution system. If utilized, city officials can quickly identify and prioritize pipes needing rehabilitation or replacement by using reliable, up-to-date water distribution data from their city with this risk assessment model. Furthermore, use of this model may also simplify allocation of capital funds for future pipe improvement projects as the city continues its urbanization.

Keywords: Water Distribution System, Condition Assessment, Risk of Failure

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CHAPTER 1

INTRODUCTION

1.1 Background

Virtually all U.S. metropolitan areas are experiencing population growth and urbanization that consist of a multitude of economic improvements including new housing development, demolishing and reconstructing existing city infrastructure, or retrofitting other city subsystems. Regardless of the economic growth trend, numerous infrastructural subsystems are experiencing progressive deterioration in our nation's cities. These subsystems can include potable water distribution systems, transportation networks, sewer systems, and electrical grids. As these critical infrastructures deteriorate while cities experience economic growth, there arises a scientific need to assess their operating conditions to maintain optimum performance and safeguard public health standards.

The primary goal of this study is to focus on evaluating the physical operating conditions of a potable water distribution system. Although there is already an abundance of regional standards that have been established for maintaining various utility infrastructures, there is, however, a lack of a national standard for the maintenance of our nation's water distribution systems. In past years, engineers and scientists have compiled a number of publications on various methods pertaining to the conditional assessment of water mains in a water distribution system. However, these methods heavily rely on the use of statistical models, mathematical estimations, and other complex regression analyses that prove to be time-and cost-intensive to apply to real water distribution

systems (WDS). These methods are also not very user-friendly for city and county officials, engineers, and utility workers.

1.2 Scope of Work

In order to effectively evaluate the operating conditions of a water distribution system, this study aimed to develop a simple, easy to follow risk assessment model that was practical for use by a city's public works division. This developed model was applied to the water distribution system of the City of Arroyo Grande to assess its overall validity.

Considering that our nation's economy operates and thrives under the ideals of supply and demand, developing a complex risk assessment model would have proved to be expensive, cumbersome, and inefficient for practical use. So considering time, cost, and the diversified pool of varying professionals within a city's governing body, it became the primary goal for this study to develop a practical risk assessment model that was both easy to understand and user-friendly. The model involved analyzing the physical characteristics of a real water distribution network including its pipe material, age, and main break history. Several economic degrees of impact were also incorporated into the assessment model before final identification was possible for those pipes that posed the highest risk of failure. These degrees of impact included water demand, land use, customer criticality, pipe material phasing, traffic impact, and estimated cost of repair.

The analysis of the water distribution network and implementation of the risk assessment model was conducted in geographic information systems software known as

ArcGIS. Use of this software was necessary in order to present the results in a clear, easy to understand, and visually appealing manner.

1.3 Research Objective

As previously mentioned, the importance of assessing this type of infrastructure is crucial to the overall functioning of a community. Proper maintenance of a water distribution system ensures that adequate water is supplied for a city's daily operations, whether it is for human consumption, industry, public safety, commerce, or even agriculture. Furthermore, a well maintained water distribution system can promote a strong basis for a city's future economic growth by providing a robust foundation for new development. It can also minimize interruptions in utility services by closely monitoring the deterioration of its water mains. Lastly, a properly maintained distribution system can potentially decrease negative impacts on our environment by avoiding substantial water loss through preventative maintenance against leaks, cracks, and pipe breaks during normal operations.

Governing powers within a municipality can directly benefit from the proper evaluation of their water distribution network by empowering their public works division with an efficient, economical means of anticipating pipe failure. With the ability to forecast the deterioration of pipe components with a practical and easy to follow risk assessment model, cities can proactively maintain optimal operating conditions in their WDS by rehabilitating and or replacing pipe segments that have surpassed their serviceable life. As a result, local governments can effectively prioritize pipe replacement and allocate the necessary capital funds for future pipe improvement projects long before

the occurrence of a catastrophic failure in their distribution system. Likewise, community members, businesses, and emergency services will also benefit from the proper maintenance of their city's water distribution infrastructure by avoiding subsequent interruptions in water services from a water main failure.

CHAPTER 2

LITERATURE REVIEW

2.1 General Theory

Gradual deterioration of pipes within a water distribution system is an inevitable issue that is recognized among engineers and city officials. Physical processes such as corrosion, soil mechanics, and manufacturing defects can all contribute to the deterioration of these water mains. Unfortunately, the only way to properly assess the physical condition of pipes in today's state of affairs requires the old-school method of observing these pipes up close and on site. This fact alone adds limitations to the effort of maintaining proper flow conditions and preventing pipe failures that may result in costly losses for a city's daily operations and impact its general population. Figure 2.1 below is an example of a severely deteriorated pipe segment compared to a new sample.

Figure 2.1 Example of severe pipe deterioration (Bryant, 2011).

It is estimated that roughly \$325 billion dollars are needed to adequately rehabilitate and replace much of our nation's water distribution systems (Stratus

Consulting, 1998). Likewise, the maintenance and operation of these distribution systems alone, accounts for approximately eighty percent of all capital funds invested into a city's water supply infrastructure (Kleiner and Rajani, 2001). The harsh reality is that economy revolves around a limited supply of natural resources and construction materials. If cities had a readily available supply of provisions necessary for pipe replacement, then regular rehabilitation and renewal of water mains would not be a problem.

As a result, municipalities have begun focusing greater attention on developing cheap and efficient strategies for rehabilitating their water distribution infrastructures. This includes the use of condition-based risk assessment models that yield cost effective results in assessing the conditions of their water distribution system. Consequently, these municipalities are able to make better decision on determining the parts of their water infrastructure that require immediate attention and capital funding. But before a city can evaluate the deteriorating conditions of its potable infrastructure, it is necessary to first understand the physical factors that elicit a pipe to reach failure.

2.2 Causes of Pipe Failure

There are several physical factors that can contribute to pipe failure. Many of which can be determined simply by close inspection of the pipe material and its surroundings while others require a more in-depth analysis. Table 2.1 presents a summary of typical causes of water main failure along with some examples of each.

Table 2.1 Typical causes of water main breaks and failures

Failure Criteria	Examples
Type of Material	Cast iron vs. PVC
Pipe Dimensions	Length, diameter, and shape
Manufacturing	Defects and irregularities
Pipe Age	Service life and year of installation
External Forces	Loading from buildings, soil cover, snow, and traffic
Internal Forces	Pressure and flow within the pipe system
Weather Variations	Expansion and contraction due to temperature changes
Soil Environment	alkalinity, acidity, and moisture content
Location	Relative to other utility structures or seismically active faults

In addition to the failure constituents mentioned in the table above, studies have shown that there exist other external mechanisms that can contribute to pipe failure. In a report titled *Predicting the Failure Performance of Individual Water Mains* by Mavin (1996), the following are also common causes of pipe failure:

- I. *Poor storage and handling*- Resulting in deformation, cracking, or other physical damage to pipe coatings prior to installation.
- II. *Improper installation*- As a result of incorrect laying, fitment, tapping, and soil cover.
- III. *Soil Erosion*- Causing loss of bed support or soil cover as a result of flooding from groundwater or rainfall.
- IV. *Impact damage*- Resulting from installation equipment such as hammers or picks; variable traffic loading or excavation machinery.
- V. *Pipe Corrosion*- Creating poor flow conditions and diminishing structural strength as a result of aggressive water flows or chemical processes.

2.3 Impact on Municipal Operations

Regardless of the physical causes that may contribute to pipe failure, the end result remains the same for all scenarios. In the event of an unexpected failure within a water distribution system, the municipality that is dependent upon that distribution system would experience economic losses from the disruption of their water utilities. These losses could be in the form of decreased agricultural production, disruption of the manufacturing of commercial goods, indefinite interruption of regular business operations, or even the disruption of food production services. Furthermore, public health and safety would immediately be at risk as critical emergency services, such as fire, police, and hospital aid, would also experience a disruption in their normal operations. The looming threat of flooding and possible soil liquefaction near a localized pipe failure could also undermine the safety of nearby citizens and businesses.

2.4 Classification of Pipe Failures

Most water mains in a distribution system typically experience two common forms of pipe failure under normal operation. Although the magnitude of a pipe failure can vary on a case by case basis, they typically occur in the form of a break or a leak along the physical structure of the pipe. According to a research publication from Texas A&M University, city engineers use the terms ‘break’ and ‘leak’ to distinguish the level of urgency between different pipe failures (Yamijala, 2007). To further explain this, table 2.2 summarizes the conditional variations between pipe breaks and pipe leaks.

Table 2.2 Differences between pipe leaks and pipe breaks (Mays, 2000).

	Breaks	Leaks
Detection	Easily identified by ground level conditions and water pressure	Difficult to detect, specialized equipment is necessary
Service Impact	High likelihood of service interruption	Low likelihood of service interruption
Occurrence	Typical along the length of the pipe	Usually found at pipe fittings and laterals
Repair Urgency	Require immediate attention	Repairs can be scheduled and are not urgent

Figure 2.2 below is an illustration of several failure conditions that may cause a pipe to break or leak. Since there are myriad combinations of physical externalities that can cause a pipe to experience any of these failure modes, the following figure is intended to illustrate the most typical causes and types of failure a water main may experience.

Figure 2.2 Various water main failure conditions (Kleiner and Rajani, 2001).

As evident in the illustration above, pipes can break or leak under varying stress conditions such as tension and compression. Depending on the magnitude and direction of these physical forces, a pipe will break or crack accordingly.

Although identifying a pipe break is much easier than identifying a leaking pipe, addressing both of these issues is an essential part of maintaining the longevity of a water distribution system. However, identification of a pipe failure once it occurs inherently deviates from the primary focus of this study. The goal is to develop and implement an assessment model that can successfully forecast the occurrence of such pipe failures before they happen, so as to avoid catastrophic failure and subsequent interruption of water utilities.

2.5 Statistical Methods for Modeling Pipe Failure

This section of chapter 2 introduces several statistical methods developed earlier for predictively assessing pipe failure. These statistical methods are mathematical estimation models that utilize varying characteristics of water mains and compare their relationship to external factors that may contribute to their likelihood of failure.

Depending on the analytical basis, each method each can be classified as either regression or aggregate type. Regression-type models predict the number of pipe failures or the time expectancy of the next pipe failure as a function of varying pipe characteristics and environmental conditions. On the contrary, aggregate-type models anticipate failure by referencing specific, conditional parameters as a function of time only.

2.5.1 Introduction to Aggregate-type Models

According to Shridhar Yamijala (2007), one of the very first aggregate type models was based on linear and exponential equations that predicted the yearly number of pipe breaks as a function of economic growth. Shamir and Howard (1979) introduced this early aggregate type model based on the following two equations:

$$N(t) = N(t_0)e^{A(t-t_0)} \quad (1)$$

$$N(t) = N(t_0) + A(t - t_0) \quad (2)$$

Where: N = Anticipated number of pipe breaks per year, per unit length

t = Time (years)

t₀ = Base reference year

A = Growth rate coefficient (0.01 – 0.15)

The Shamir and Howard model anticipated pipe failure by assuming that all pipe components had similar physical characteristics internally and externally, including pipe diameter, pipe material, etc. Furthermore, the growth rate coefficient, established by Shamir and Howard, conditionally applies to varying economic conditions from city to city.

Although their model was very simplified and easy to use, its application proved to be impractical in making maintenance decisions due to its limited criteria. The model lacked consideration for environmental factors, historical break history of individual pipe segments, and operating pressures. Also, the Shamir and Howard model did not incorporate a statistical component, such as the Akaike Information Criterion (AIC), to

determine its goodness of fit and to verify its computational accuracy. Without these statistical components, the reliability of this model was difficult to justify.

2.5.2 Introduction to Regression-Type Models

Regression models tend to be more comprehensive than aggregate-type models in that they can account for a greater degree of variables to assess pipe failure. They can vary in complexity and form, typically ranging from simple linear regression equations to complex multiple regression equations. The following is an example of linear regression model that was developed by McMullen (1982). His linear model related pipe age to various soil properties surrounding each pipe segment based on the following equation:

$$Age = 0.028(SR) - 6.33(pH) - 0.049 (r_d) \quad (3)$$

Where: Age = Pipe age at the first failure incident (years)

SR = Saturated soil resistivity (Ω cm)

pH = Acidic or basic value of the surround soil

r_d = Redox potential (millivolts)

McMullen tested his linear regression model by applying it to a water distribution system in Des Moines, Iowa. He found that the primary cause of pipe break incidents was soil corrosion. His studies revealed that soils that had a saturated resistivity less than 2000 Ω cm had a 94 percent probability of causing pipe failure.

However, despite its application to a real water distribution system, this linear model inadequately projects pipe failure due to its limited consideration towards other variables. According to Kleiner and Rajani (2001), the McMullen model falls short of

forecasting pipe failure primarily because it only predicts the time until a pipe's first break incident. Also, it does not take into account other factors such as pipe' material, demand patterns, or placement.

Another, simpler example of a linear regression model is one developed by Kettler and Goulter (1985). Their model primarily focuses on the following equation:

$$N = k_0 A \quad (4)$$

Where: N = Number of break incidents per pipe (per year)

k_0 = Regression parameter (scenario specific)

A = Pipe age at the first break incident

Kettler and Goulter tested the validity of their model on a set of pipe data from Winnipeg, Manitoba. Characteristics of their sample set included pipes that shared similar properties and had varying ages of less than 10 years. Their study determined that pipes that were made of cast iron and asbestos cement exhibited a similar failure rate of 0.103 and 0.563 between pipe age and annual breakage rate, respectively.

Although the Kettler and Goulter model appears to be more simplified and easier to use than the McMullen model, it does present some limitations towards its practical application for forecasting pipe failure. For one, the regression parameter (k_0) is scenario specific and its determination requires a large amount of reliable data, conditional assumptions, and analysis prior to the application of this model. Therefore it is safe to say that its universal use on a multitude of water distribution systems could quite possibly be uneconomical and daunting. However, its primary strength is that it considers multiple break incidents per year, rather than just the time to the first break incident.

Linear regression models may seem mathematically simple to understand, but they involve a great deal of conditional assumptions, specified data, and statistical analysis. The more complex a regression model becomes, the greater its accuracy in forecasting pipe failure. A model proposed by Clark et al. (1982) which incorporates multiple linear and exponential regression equations was previously developed for analyzing pipe failure.

First Failure Incident Equation:

$$NY = 4.13 + 0.338(D) - 0.022(P) - 0.265(I) - 0.0983(RES) - 0.003(LH) + 13.28(T) \quad (5)$$

Where: NY = Anticipated number of serviceable years from a pipe's installation date to its very first failure incident

D = Diameter of the pipe in question (inches)

P = Absolute internal pipe pressure (lbs/in²)

I = Percentage of pipe covered by industrial development

RES = Percentage of pipe covered by residential development

LH = Length of pipe exposed to corrosive soil conditions

T = Pipe material (0 = *reinforced concrete*, 1 = *metallic*)

The Clark et al. model uses this linear regression equation (5) to forecast the first incident of a pipe's failure by calculating the number of serviceable years (NY) that the pipe remains fully operational. It incorporates a number of physical pipe characteristics and conditions into its criteria, most of which can be obtained from performance records or other municipal documentations. More specifically, the exact percentage of pipe that is

overlain by development such as residential, commercial, or industrial structures can be obtained from a municipal census tract.

After this preliminary analysis phase, the Clark et al. model then predicts the number of anticipated repairs a pipe may experience after its first break incident by using the following exponential regression equation:

Subsequent Failure Equation:

$$REP = (0.1721)(e^{0.7197})^T(e^{0.0044})^{PRD}(e^{0.0865})^A(e^{0.0121})^{DEV}(SL)^{0.014}(SH)^{0.069} \quad (6)$$

Where: REP = Number of anticipated repairs after the first failure incident

T = Pipe material (0 = *reinforced concrete*, 1 = *metallic*)

PRD = Pressure differential before and after first failure (lbs/in²)

A = Age of pipe from its first repair incident (years)

DEV = Percentage of developed land beneath the pipe

SL = Surface area of pipe exposed to moderately corrosive soils

SH = Surface area of pipe exposed to highly corrosive soils

Although the Clark et al. model involved multiple regression equations in its analysis, the large assortment of variables involved in each equation provided a stronger basis for investigating pipe failure compared to the aggregate-type model proposed by Shamir and Howard (1979). This provided a significant improvement in the collective effort of predicting pipe failure overall.

However, according to Yamijala (2007), a study was conducted to validate the reliability of the Clark et al. model which resulted in increased concerns regarding its overall accuracy. Based on his literature, Yamijala stated that Clark et al. conducted the

study and obtained coefficient of determination (R^2) values for each regression equation involved. The linear regression equation had an R^2 value of 0.23 while the exponential regression equation had an R^2 value of 0.47. Ideally, an R^2 value roughly equal to 1 would confirm the accuracy and reliability of a mathematical equation to a given set of data. But the low R^2 values indicated that the Clark et al. regression model did not perform as satisfactorily as anticipated. Furthermore, the study also revealed that the availability and accuracy of appropriate data pertaining to each of the regression equations' criteria may contribute to the model's unsatisfactory performance.

2.5.3 Real World Application of Regression Models

The following case studies utilized various statistical methods in assessing water main conditions of several water distribution systems as early as the 1980's. The results from these studies were determined from regression type or aggregate type models that considered various pipe criteria including, but not limited to, weather characteristics and the relative location of water mains to residential and/or commercial development.

Kettler and Goulter (1985) applied their linear regression model to pipe breakage data from two cities in the United States, specifically New York and Philadelphia. They also applied the same model to two other cities in Canada, Winnipeg and St. Catharines. Their study indicated that the diameter of a pipe had a huge impact on its failure rate. As the diameter of a pipe increased, there was an associative decrease in the pipe's failure rate. Furthermore, their study also revealed that cast iron pipes had an increase in failure rate as they aged and that the type of failure was typically caused by corrosion, producing

circular cracks along the pipe. The end result of their research yielded a satisfactory R^2 value of 0.963. Table 2.3 below summarizes the results of their study.

Table 2.3 Kettler and Goulter pipe failure study in various cities (Mays, 2000).

Pipe Failures per kilometer per year					
City	Manhattan, New York	Philadelphia	St. Catharines	Winnipeg (District)	
Examined Pipe Material	Cast Iron	Cast Iron	63% Cast Iron	Cast Iron	Pipe Diameter (mm)
	-	0.26	0.49	1.05	100
	0.34	0.32	0.3	1.06	150
	-	0.07	0.16	0.76	200
	-	0.13	-	0.39	250
	0.11	0.05	-	0.07	300
	-	0.07	-	-	400
	5 years	17 years	6 years	6 years	Time Frame
	1959, 1964, 1969, 1974, 1975	1964-1980	1977-1982	1975-1980	

Another real world study was conducted by Jacobs and Karney (1994) in which they applied their own linear regression model to city data from Winnipeg, Canada. Their linear regression equation is defined below:

$$P = a_0 + a_1(\text{length}) + a_2(\text{age}) \quad (7)$$

Where: P = Reciprocal of the probability of a day without pipe failure

$a_{(i)}$ = Regression coefficients

Length = Length of pipe in question (kilometers)

Age = Age of pipe since first installation (years)

Jacob and Karney focused their study particularly on 390 kilometers of pipe in Winnipeg's water distribution system. This segment of their system was comprised of 6

inch cast iron water mains that had about 3,550 historical break events on record. In order to homogeneously analyze all 390 km of piping, Jacob and Karney divided the water mains into three age groups: 0-18 years, 19-30 years, and greater than 30 years.

The results of their study yielded R^2 values ranging between 0.704 and 0.937 for each age group, which indicated that the predictions by their linear regression model were fairly accurate. It also showed that the consideration for pipe age significantly improved the effectiveness of their regression model.

2.5.4 Other Statistical Methods for Predicting Pipe Failure

Aside from the aggregate and regression type models mentioned, there also exist more complex models that are non-linear and mathematically intensive. Some examples of these types of models include, but are not limited to, the time-exponential model and the proportional hazards model. Although there is a generic form for each of these modeling types, this study will specifically look at only a few time-exponential models and a proportional hazard model.

Time-exponential modeling involves the transformation of non-linear data into linear parameters that can then be applied to a linear regression model. Shamir and Howard (1979) developed the following non-linear regression model to relate the exponential aging of a pipe to the likelihood of its fracture.

Their model is as follows:

$$N(t) = N(t_0) e^{A(t+g)} \quad (8)$$

Where: $N(t)$ = Number of breaks (Per pipe, per unit length, per year)

$N(t_0)$ = Number of breaks at the year of installation

A = Breakage rate coefficient (years⁻¹)

t = Time period between the occurrence of a given break and
the present time when analysis is being conducted (years)

g = Age of the pipe at time (t) in years

According to Yamijala (2007), Shamir and Howard had conducted a case study to test the validity of their model but they did not provide any details on the location of their study. Instead, they provided recommendations on the application of their model with pipes that shared homogenous properties. Aside from testing their non-linear regression model, Shamir and Howard conducted the case study to analyze the costs of pipe rehabilitation and replacement as a function of their repair services, present worth, and available capital funds.

In an effort to improve the Shamir and Howard time-exponential model, Walski and Pellicia (1982) developed a modified equation that extended the original model parameters to include two additional variables into the analysis. The reason behind the addition of these variables was to incorporate the break frequency of cast iron pipes and associate them with their specific size and construction method, such as pit or sand-spun cast iron piping.

The Walski and Pellicia modified time-exponential model is defined below:

$$N(t) = C_1 C_2 N(t_0) e^{A(t+g)} \quad (9)$$

Where: $N(t)$ = Number of breaks (Per pipe, per unit length, per year)

C_1 = Ratio between the frequency of a pipe's breaks with
the overall break frequency of that pipe's material type

C_2 = Ratio between the frequency of a pipe's breaks as a
function of its size relative to the break frequency of that
pipe's material type.

$N(t_0)$ = Number of breaks at the year of installation

A = Breakage rate coefficient (years⁻¹)

t = Time period between the occurrence of a given break and
the present time when analysis is being conducted years

g = Age of the pipe at time (t) in years

Walski and Pellicia recognized the importance of adding the C_1 and C_2 variables base on observations made by the U.S. Army Corps of Engineers in Binghamton, NY. They observed that pipes were more likely to break again after already experiencing a break and large diameter pit cast iron pipes exhibited variability in break rates.

Clark et al.(1982), founders of the multiple regression-type model mentioned previously in section 2.5.2, also modified their linear model to mimic the Shamir and Howard time exponential-model.

Their two-phase non-linear regression model is explained in greater detail below:

First Failure Incident Equation:

$$NY = X_1 + X_2(D) + X_3(P) + X_4(I) + X_5(RES) + X_6(LH) + X_7(T) \quad (10)$$

Where: NY = Anticipated number of serviceable years from a pipe's
installation date to its very first failure incident

X_i = Conditional parameters for regression-type analysis

D = Diameter of the pipe in question (inches)

P = Absolute internal pipe pressure (lbs/in²)

I = Percentage of pipe covered by industrial development

RES = Percentage of pipe covered by residential development

LH = Length of pipe exposed to corrosive soil conditions (ft)

T = Pipe material (*0 = reinforced concrete, 1 = metallic*)

Subsequent Failure Equation:

$$REP = Y_1 (e^{Y_2 t}) (e^{Y_3 T}) (e^{Y_4 (PRD)}) (e^{Y_5 (DEV)}) (SL^{Y_6}) (SH^{Y_7}) \quad (11)$$

Where: REP = Number of anticipated repairs after the first failure incident

Y_i = Conditional parameters for regression-type analysis

t = Age of pipe from its first repair incident (years)

T = Pipe material (*0 = reinforced concrete, 1 = metallic*)

PRD = Pressure differential before and after first failure (lbs/in²)

DEV = Percentage of developed land beneath the pipe

SL = Pipe surface area exposed to moderately corrosive soils (ft)

SH = Pipe surface are exposed to highly corrosive soils (ft)

By modifying their two-phase linear regression model, Clark et al. (1982) observed that there was a much more defined time period between the first break incidents of a pipe from the year of its installation. As a result, the group recommended that their newly refined model be used for forecasting a pipe's serviceable life up until its first break and also the number of subsequent breaks that pipe may experience if it were to remain in service.

The use of non-linear statistical models may be necessary on a case by case basis, considering that nearly all natural processes such as deterioration or aging occur in a non-linear and sometimes exponential fashion. For example, previous research has shown that the initial strength of concrete rapidly increases before eventually leveling off over a period of time and thus it is good to consider non-linear modeling when necessary and possible.

The last model that will be covered in this section is a proportional hazards model originally proposed by Cox (1972). His method statistically analyzes the duration of specific events in the form of a general regression model. The general form of the Cox proportional hazards model is shown below:

$$h(t, Z) = h_0(t) e^{bZ} \quad (12)$$

Where: $h(t, Z)$ = The probability of an event occurring at time $t + t_0$

$h_0(t)$ = An arbitrary baseline hazard function

t = Time of occurrence of a specific incident of interest (years)

Z = A vector of covariates for the hazard function $h(t, Z)$

b = A vector of coefficients estimated by regression analysis

While the parameters of this hazard model appear to be cumbersome on their own, use of this model may prove to be useful for predicting pipe failure. According to research conducted by Yamijala (2007), this model can be modified and used to predict pipe breaks by modifying the basic parameters of the equation. For example, the covariates (Z) can represent operational as well as environmental factors that may promote the failure of a pipe. Furthermore, the baseline hazard function [$h_0(t)$] can represent a time-dependent aging component for each pipe segment in question, (t) can signify the time of occurrence of pipe breaks, and $h(t, Z)$ can represent the probability of a pipe's failure.

Although the Cox proportional hazard model is commonly used in other professional fields, such as clinical AIDS trials (e.g. Kim and Gruttola, 1999) or the medical evaluation of cancer treatment effectiveness (e.g. Schoenfeld, 1982), it has previously been applied to a real municipal system by Andreou (1986). He applied the model to a water distribution network in Cincinnati, Ohio and concluded that the Cox proportional hazard model can successfully predict the occurrence of the first and successive failure incidents of a pipe during the early stages of its service life.

The main limitation of the Cox proportional hazard model is that it relies heavily on data that may be available or unavailable during its application in predicting pipe failure. Furthermore, without a data set large enough to represent a long time period for analysis, the model has great difficulty in obtaining decent failure risk estimates, according to Yamijala (2007).

2.6 Systematical Models for Assessing Pipe Failure

Aside from all of the mathematical models previously mentioned, there have also been several conditional models that are simpler to follow, easier to understand, and do not involve the use of statistical, regression, or aggregate type of mathematical analysis. However, the majority of these tend to be evaluative models rather than predictive models. To provide a greater breadth of comparison between the varying availability of pipe assessment methods, this study takes a brief look into three particular assessment models.

2.6.1 Break-Even Analysis

The goal of conducting a break-even analysis is to estimate the ideal economic time for rehabilitating or replacing a pipe failure based on its present worth and the economic cost associated with its repair. It is typically conducted once a pipe break or failure has been found. This method simultaneously considers the expected repair and replacement costs for a pipe failure by taking into account the depreciative worth of replacing a pipe segment entirely versus the increasing repair costs for maintaining that same length of pipe during the same, observed time period. In other words, break-even analysis weighs the economic benefit of either replacing or maintaining a pipe depending on the overall cost associated with either situation. It determines where or not it is economically cheaper to replace a pipe entirely instead of investing capital funds towards its maintenance and long term rehabilitation. Although there is not a specific model to follow, break even analysis can be considered as a strategy in weighing economic costs and benefits in analyzing pipe failures, once they have occurred.

2.6.2 Mechanistic Modeling

Mechanistic models are both evaluative as well as predictive models used in assessing pipe deterioration based on a range of physical criteria. They are usually geared towards determining the ideal time for pipe rehabilitation or replacement. Mechanistic models rely heavily on the use of data that includes, but is not limited to, detailed environmental factors, placement, economics, and physical pipe properties. Past studies have incorporated additional factors into the assessment process such as water quality and transportation capacity (e.g. Stacha (1978)), nodal demands and pressure requirements (e.g. Su et al. (1987) and Wagner et al. (1988)), physical corrosion effects (e.g. Rossum (1969), and temperature effects due to changes in weather or water flow (e.g. Walski and Pellicia (1982)).

A study conducted by Lee (2011) at Texas A&M University incorporated the effects of corrosion on cast iron and ductile iron pipes along with other physical factors, such as loading and stress, into a physical failure risk model he developed. His risk model analyzed corrosion growth rates, such as pitting, and their direct effect on the interior lining of a pipe. The goal of his study was to determine the residual life of the pipes in questions as well as their priority for replacement or rehabilitation. Figure 2.3 presents a schematic of his risk model.

These are just a few examples of the various mechanistic assessment models that have been previously established. Further investigation of the credibility and application of these models will be circumvented in this study as these examples are provided here for comparison purposes only.

Figure 2.3 Physical Failure Risk Model (Lee, 2011).

2.7 Historical Research Studies

Assessing the failure risk and the priority of pipes for repair through the development of a statistical or systematical model has been an ongoing endeavor for the interested community. Table 2.4 is a collection of past studies from a dissertation by Vanrenterghem (2003). The table summarizes their water distribution issue, objective of their model, and the type of model used in assessing their problem.

Table 2.4 Historical research studies in assessing pipe failure (Vanrenterghem 2003).

Author	Year of Study	Issue	Objective	Model Type
Shamir	1979	Pipe Breaks & other structural degradation	Modeling pipe breaks over a period of time	Regression-type
Howard				
Clark	1982	Pipe Breaks & other structural degradation	Risk analysis based on number of breaks	Regression-type
Andreau	1986	Pipe Breaks & other structural degradation	Identification of risk factors	Survival analysis (PHM)
Marks	1988			

Continued to next page...

Table 2.4 Continued

Author	Year	Issue	Objective	Model Type
O'day	1989	Pipe Breaks & structural degradation	Pipe risk assessment and predicting service life up to first break incident	Regression-type
Woodbum	1986	Hydraulic Insufficiency	Minimize operational costs from increase pumping	Mixed integer non-linear programming
Lansay	1992			
Kim	1994			
Li	1992	Pipe Breaks & structural degradation	Minimize rehabilitation costs of each pipe	Semi-Markov model; Probability calculations with non-linear programming & hazard/survival functions.
Cabrera	1994	Pipe Leaks	Determination of optimal time for leak detection	Pragmatic methodology. Expert System
Halla	1997	Pipe breaks and hydraulic insufficiency	Minimize costs while maximize benefits under a specific budget	Structured Messy Genetic Algorithm
Elbanousy	1997	Pipe Breaks & structural degradation	Minimizing operational costs and optimizing pipe conditions	Survival analysis (WPHM-probability of failure, life cycle, and assessment costs)
Kleiner	1998	Hydraulic Insufficiency	Minimize operational costs	Dynamic programming
Deb	1998	Pipe Breaks & structural degradation	Determining length of pipes requiring yearly rehabilitation	Survival functions utilizing scarce data (most realistic)
Utilnets	1999	Effects of external loads and corrosion	Determination of pipe residual life	Deterministic model for cast iron pipes
Rajani	2000	Effects of external/internal loads and corrosion	Pipe risk assessment and determination of residual life	Deterministic model for cast iron pipes; external corrosion and residual strength model
Malandain	2000	Pipe Breaks & structural degradation	Pipe prioritization for rehabilitation	Poisson regression model, WPHM, and Time-Exponential
Rostum	2000	Pipe Breaks & structural degradation	Pipe prioritization for rehabilitation	Survival analysis (NHPP-WPHM)
Eisenbers	1994 & 1999	Pipe Breaks & structural degradation	Obtain probability of pipe failures and prioritize pipes for rehabilitation	Survival analysis (WPHM-Monte Carlo Simulation used in forecasting future breaks)
Le Gatt	2000			
Loganathan	2002	Pipe Corrosion	Predicting pipe failure rates in a water distribution system	NHPP-Determination of a threshold failure rate based on economic factors
Deb	2002	Effects of external/internal loads and corrosion	Pipe risk assessment and determination of residual life	External corrosion model with residual strength modeling; deterministic model specifically for cast iron pipes

2.8 General Limitations of Statistical and Systematical Models

As with nearly all specialized research studies, statistical and systematical modeling methods are both limited to the availability and reliability of the data they are analyzing. The accuracy and satisfactory outcome of these modeling methods rely heavily on the overall completeness of pipe data, the extent of time in which the data covers, and also the general applicability of the data set. The lack of reliable data presents the need for establishing conditional assumptions during the course of the modeling, indefinitely yielding less than accurate results.

In addition, the greatest obstacle that these methods share is due to their complexity and specialization. The relative application of these methods into a municipal working environment may present issues for city employees and government officials. The depth of understanding as well as the availability of investible time necessary for the utilization of these methods in assessing pipe failures may be cumbersome and financially unsatisfactory for a city's public works division. As a result, there is a growing need for a simpler modeling scheme that is easy to follow, easy to understand, and financially affordable in its application in various water distribution systems.

CHAPTER 3

RISK ASSESSMENT METHODOLOGY

3.1 Overview

The risk assessment model that was developed in this study was intended to provide various cities with a method that was not only simple to follow, but also economically affordable to use. It was designed with the objective of being universally applicable to different water distribution systems while also being customizable in its macroscopic assessment approach. The core basis of this model was originally developed by Water Systems Consulting Inc. (WSC) in San Luis Obispo, California. However, due to some financial limitations, their prototype risk assessment model remained incomplete and untested. This study undertakes to complete the WSC risk assessment model and validate its performance against a real water distribution system.

Although the primary goal of this study was to develop a model specifically for assessing pipe conditions and predicting pipe failure within a water distribution network, a large amount of consideration was invested into ensuring that a wide range of professionals in a governing division of a municipality could thoroughly understand all aspects of this model and apply it to their water distribution system. The secondary goal of this study was essentially to provide these municipalities with an organized method for prioritizing water mains that had a high risk of failure. The purpose of establishing this heuristic order or ranking of pipes was to grant cities with greater economic control over the allocation of capital funds for current or future pipe improvement projects.

This condition-based risk assessment model is comprised of two systematical components that analyze individual pipe characteristics in a water distribution system.

The overall assessment process can be considered a three-stage procedure in which a pipes residual life and its relative importance in a water distribution system are assessed. The first stage of analysis is focused on computing the Remaining Useful Life (RUL) of each pipe by taking into consideration their individual installation year, their pipe material, and any historical record of previous failure events such as breaks or leaks. Once the remaining useful life of each pipe is determined, they are individually assigned a numerical score representing their Probability of Failure.

The second stage of analysis involves assessment of the geospatial location of each pipe within the water distribution network along with their individual material properties and water flow values during normal operation. Economic components are also taken into consideration during the second stage of this model. These components include estimated costs for rehabilitation or replacement of each pipe segment as well as the level of impact that such repairs may have on nearby traffic flow and transit services. Once all of these components are collectively taken into consideration, each pipe is assigned a numerical score that represents its overall Degree of Impact, or relative importance, in the water distribution system.

The final stage of analysis combines the results from stage one and stage two and applies both of these values to a predefined risk assessment table. By combining each pipe's Probability of Failure score with its Degree of Impact score, this table assigns a numerical Risk of Failure score and visual color to each individual pipe segment. This Risk of Failure score represents the likelihood of a pipe's failure and it also signifies the precedence of the pipe over other water mains that require rehabilitation or replacement. With this information, cities can begin to formulate and plan for water main improvement

projects by categorizing the risk of failure for each individual pipe segment in their water distribution system. Figure 3.1 below is a visual schematic of the risk assessment model in this study. Each individual assessment component is explained in greater detail in the subsequent sections of this chapter.

Figure 3.1 Condition-Based Risk Assessment Model

3.2 Stage One: Computing Remaining Useful Life

The primary goal of this stage in the assessment model is to compute the Remaining Useful Life (RUL) of a water main. This is accomplished by assessing the current age of a pipe and comparing it to the anticipated service life of its material type. The necessary components for this analysis include the pipe’s installation year, its material type, and the anticipated service life of its material type. Historical records of break events are also taken into account before the Remaining Useful Life of the pipe is determined. Once a pipe’s RUL is determined, it is assigned a Probability of Failure (PF) score by applying the value of its Remaining Useful Life to a predefined PF table, specifically table 3.3.

3.2.1 Pipe Age

The age of a pipe can be derived from calculating the number of years since its original installation year up to the present day. This length of time represents the period in which that pipe remained in service by providing flow or a component of flow in a water distribution system. This period of time does not account for intermittent interruptions in service due to pipe repair or replacement. It assumes that the pipe remained continually in service for the entire duration of time in question. Therefore, the numerical value of a pipe's age disregards all other factors and only represents the total number of years between its installation date and present day.

3.2.2 Pipe Material and Anticipated Service Life

With the increasing selection of pipe materials available in today's market, each material type has an associative length of time in which its structural strength and operational efficiency is expected to remain intact. Many producers of water distribution pipes and fittings advertise a manufacturer recommended service life, usually represented by a range of years, under the product specifications of their merchandise. Although other factors may contribute to the increase or decrease in a pipe's service life as determined by the manufacturer, this risk assessment model takes only into account the pipe's material type and the suggested service life of that material. In other words, the manufacturer's service life of a pipe does not consider other factors such as pipe diameter, protective coating, or corrosion inhibitors. It assumes that the pipe segments in this analysis are purely made of a single, untreated and unprotected raw material such as cast iron, cement, polyvinyl chloride (PVC), or steel.

Table 3.1 below is a summary of the material types that were observed in this study. It also denotes their abbreviation, their manufacturer's service life, and the Anticipated Service Life (ASL). Most of the values listed under the *manufacturer's service life* column were originally defined in the prototype WSC risk assessment model. This information was obtained through the firm's own research and information resources. The only materials that did not have specific values from WSC were composite (techite), galvanized iron, and steel. Values for these pipe materials were retrieved from the following online sources: Accurate Inspections Inc., InspectAPedia, and Paint Square.

Table 3.1 Pipe materials and Anticipated Service Life

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

The individual values specified under the ASL column were calculated by computing the mean value of the manufacturer's service life for each pipe material. These values were then used in this study to represent a conservative ASL for each pipe material (in years). As for the *unknown* material class, the accompanying specifications are to be used in rare instances when the pipe's material is unknown. This may be the

result of missing pipe data, an inability to examine the pipe physically, or a severely damaged pipe that is unidentifiable beyond conventional means.

3.2.3 Break History Adjustment

In order to properly assess the Remaining Useful Life (RUL) of a water main, an adjustment was necessary to account for any historical breaks or failures that the pipe may have experienced. Ideally, a percent adjustment was favored over a specific numerical deduction with the intent of preserving the universal application of this model to other water distribution systems. Table 3.2 summarizes the parameters involved in this break history adjustment. It is important to note that the values listed under the *Original RUL* column are provided as examples only. They are simply showing the percent reduction of a pipe's RUL in accordance to the number of break incidents it has on record.

Table 3.2 Break history adjustment table

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

This risk assessment model is designed to consider only the historical breaks and failures of a pipe within the last 20 years of its service, from the time of this study. Furthermore, all reports of pipe failures, regardless of their severity, were taken into account and treated as a single break incident. In other words, pipes that had multiple failures on record had break incidents greater than one, resulting in an increased percent reduction of that pipe's Remaining Useful Life. In addition, the reports that were considered in this analysis included official municipal documentation of pipe breaks as well as water quality complaints filed by individual homeowners from a residential subdivision. Each complaint that was filed was treated as a single incident, and so forth. Lastly, the percent adjustment values for each break incident were established purely on logical assumptions.

Once all break incidents have been accounted for, the Remaining Useful Life of each pipe is recalculated by multiplying its original RUL with the corresponding percent reduction specified in the table above. The newly adjusted RUL values are then used in the following stages of this assessment model.

3.3 Determining Probability of Failure

The next phase of analysis involves combining the entire collection of pipe properties previously mentioned thus far and calculating the probability of failure for each water main. The first step in doing so is to calculate the Remaining Useful Life (RUL).

The following equation illustrates the necessary variables required in calculating the RUL for each water main:

$$RUL = ((ASL) - Age) \times P_{adj}. \quad (13)$$

Where: RUL = Remaining useful life of pipe (years)

ASL = Anticipated service life of pipe (years)

Age = Pipe age from present year to year of installation (years)

P_{adj} = Break history percent adjustment

This risk assessment model requires that the RUL equation above be applied to each individual water main from the distribution network in question. As long as there is enough data from municipal records to account for each pipe's original installation year as well as its material type, the final outcome of this assessment phase is a tabulated collection of remaining useful lives for all pipe segments in the network.

With the tabularized summary of pipe RUL's in hand, the next step is to assign a probability of failure score to each water main. Table 3.3 defines the criteria for assigning this failure score to each pipe, based on its Remaining Useful Life (RUL).

Table 3.3 Probability of failure

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

From this table, the Probability of Failure score for each water main can be determined by examining the corresponding range of RUL values. For example, if a pipe has a RUL of 17 years, this pipe has a Probability of Failure score equal to 3, based on the criteria above. The significance of this score is that this pipe has a relatively low risk of experiencing failure. On the contrary, a pipe with an RUL of 1.5 years has a Probability of Failure score equal to 10, signifying that it has a very high chance of failure.

The specific criteria outlined in table 3.3 above were originally from the prototype risk assessment model from WSC. However, the initial concept was much more conservative in that it was comprised of a shorter range of RUL values at increments of 5 years and a range of failure scores at increments of 2. Nevertheless, each assignment criteria shared the same absolute limits. In other words, both models observed the same range of RUL's, specifically 1 to 20 years, and the same Probability of Failure scale of 1 to 10. By expanding the criteria of the Probability of Failure table, this risk assessment model has a greater degree of narrowing down the list of pipes that have the highest risk of failure.

3.4 Stage Two: Assessing the Degree of Impact

The second stage of this risk assessment model is the investigation of various conditional criteria that may affect the rehabilitation or replacement of a particular water main. This portion of the analysis focuses on identifying economic factors that may experience a negative impact from the pipe renovation. The significant impact criteria considered in this study included customer criticality, pipe material phasing, land use,

service demand, traffic impact, and estimated cost for pipe replacement. Each impact criteria is explained in greater detail in the following subsections.

The simultaneous evaluation of all six impact criteria yields a cumulative Degree of Impact (DI) score for each pipe segment in the water distribution system. This is obtained from a predefined DI table that numerically assigns a score to each impact criteria mentioned above. Subsequently, the final Degree of Impact for each pipe segment is evaluated by taking the sum of the scores from all six impact criteria.

The significance of this score is that it establishes the relative importance of each individual water main within a water distribution network. It not only takes into account the economic costs that are associated with pipe improvement projects, but it also assesses the impact that such a project may have on daily municipal operations and customer demand patterns. By incorporating the relative effects of pipe rehabilitation on various impact criteria into this risk assessment model, the priority of pipes in a WDS is greatly enhanced, in addition to the individual evaluation of their probability of failure.

3.4.1 Land Use

The relative use of a specific plot of land in a town or a large city is an important factor to be considered since most of the water distribution systems, especially water mains, are located underground. Land use includes single or multi-family residential housing, agricultural development, commercial space, conservation open space, and community facilities. Without proper consideration towards various land uses during a pipe improvement project, municipalities could suffer hefty financial losses, project delays, and interruptions in daily operations.

This risk assessment model takes into consideration a collection of land uses found typically in most cities across the country. These land uses vary in occupational density, agricultural activity, as well as commercial use. Table 3.4 is a summary of all the observed land uses in this model and their relative importance.

Table 3.4 Land use criteria

Land Use	Example	Level of Importance
No Use	--	<div>Low</div> <div>↑</div> <div>↓</div>
Conservation Open Space	Parks for recreation	
Agriculture	crop land	
Low Density Single Family Residential	single story to three story housing divisions (neighborhoods)	
Medium Density Single Family Residential		
High Density Single Family Residential		
Low Density Multi-Family Residential	Multi story apartment complex	<div>Moderate</div> <div>↑</div> <div>↓</div>
Medium Density Multi-Family Residential		
High Density Multi-Family Residential		
Mixed Use	Business and residential areas	
Commercial Office Space	Store fronts and local businesses	
Community Facilities	Hospitals and fire department	High

It is essential to note that the relative importance of each land use is in regards to its overall location to a nearby water main that may require repair services. Plots of land that have a high degree of importance will have a more significant impact on the relative priority of a nearby pipe's rehabilitation compared to a land use that has a low degree of

importance. For the purposes of this study, the relative importance of each pipe was assessed based on its location and vicinity to a nearby land use. The level of importance outlined in the table above applies to pipes located within a 30 foot radius from a specific land use. This numerical value was established for reasonable estimations in this analysis and can be adjusted according to the specific conditions of a water distribution system.

It is important to keep in mind that this risk assessment model does not limit consideration of various land use criteria strictly to the ones mentioned in table 3.4. Other land uses may be successfully applied to this model so long as careful consideration is implemented into assigning their relative importance.

3.4.2 Service Demand

Due to the steady economic growth of most U.S. cities along with the relative increase in their population, there exists a varying array of water demand and flow values within different components of their water distribution system. It is therefore necessary to consider the relative importance of a pipe segment in light of the public's dependence on its distributive capabilities during its assessment for repair.

To briefly understand how water is distributed within a municipality, it is essential to become familiar with what the basic components of a water distribution system. First and foremost, water is typically supplied to a municipality from some natural source or artificial storage unit such as a lake, stream, manmade reservoir, or water tank. Water enters the city's underground distribution system typically through junction sources also known as nodes. Similarly, water is removed from the system through these same nodes. In essence, a node is the point in which water can enter or exit

a distribution system. Secondly, water is conveyed throughout the system via the intricate network of smaller pipes and water mains. Depending on the length and diameter of these pipes, they can either be considered as arterial water mains or branches. The difference between the two is that water mains convey the majority of the water in the distribution system and they are much larger in diameter, sometimes as large as 16 to 20 inches. Pipes that branch off from these water mains are connected to them via nodes or junctions. These pipes exhibit smaller diameters than water mains and they are typically connected to the final conveyance point for water when it reaches its customer.

There are also other components of a water distribution system that are critical in the distribution of water throughout a city network. These include mechanical pumps that help to maintain hydraulic pressure within the pipe network, pipe fittings at junction points, pressure release valves, check valves, and flow meters. However, the primary focus of this assessment model is the various water mains and pipes within a water distribution system. All other network components are omitted during the remainder of this analysis.

After a general understanding of water conveyance through a city's distribution system, we need to focus back at the significance of a pipe's serviceable demand. Practically all pipe components of a water distribution system have some sort of demand or volumetric flow that travels through it. These values may fluctuate between different hours of the day, where high flow values are typically observed in the mornings while low flow values are sometimes observed at noon. It is important to note that every city has its own unique demand pattern. Therefore, in order to consider the serviceable

demand value of a pipe segment, it is necessary to consider its average daily demand or average daily flow.

Most municipalities have some sort of physical record or computer aided model that calculates and records the average daily demand of the individual pipe segments in its network. By using such data in this risk assessment model, the relative importance of a pipe segment can easily be determined simply by looking at its serviceable demand volume and comparing it with demand volumes from other pipes within the same network. By ranking the average daily flow values for each pipe segment, we can easily identify pipes of higher importance, relative to their high flow values, and compared to pipes of lower importance and lesser flow values.

3.4.3 Customer Criticality

The third impact criterion included into this risk assessment model was the consideration for nearby critical customers located within the proximity of a damaged water main. In order to address the safety and well-being of the general public within a municipality, this model was designed to identify pipes and water mains that were both critical in providing water to these customers and also highly at risk of failing. Given the unpredictable nature of external factors associated with the repair or replacement of a water main, the duration of time associated with the disruption of water utility services to a particular customer(s) may last temporarily or indefinitely.

Identifying the critical customers in a water distribution system is a simple and practical process. Since the main point to consider is to maintain public health and safety, critical customers that are essential to a city's emergency response and its municipal

operations should be easily identifiable. For the purpose of this study, the specific customers that were considered critical in this risk assessment model included hospitals, nursing homes, public schools, private schools, business centers, police stations, and fire stations. It is important to note that in the consideration process for customer criticality, this model is not limited to those customers mentioned above. In the event that a municipality identifies a critical customer in their water distribution network that falls beyond of the parameters outlined in this study, then this risk assessment model can easily be adapted to include these additional critical customers.

Once all critical customers have been identified in a water distribution network, any pipe segments that fall within a specific radius of each critical customer are categorized and prioritized. The original WSC risk assessment model suggested a radius of influence equal to 0.25 miles (1320 feet) for each critical customer. Furthermore, the WSC model only considered pipes with diameters greater than or equal to 8 inches. In turn, this risk assessment model adopted the same selection criteria to identify the water mains located in each critical customer zone.

The next phase of analysis was to determine the relative significance level of each pipe. Table 3.5 summarizes the priority criteria for these pipes. Essentially, any pipe that did not fall within a zone of influence did not have a critical customer and was considered to have a low priority level. On the contrary, pipes that fell within a zone of influence were considered to have a higher priority level due to the presence of one or more critical customers. Overall, the priority level of these pipes increase if their present location falls within multiple critical customer zones.

Table 3.5 Pipe priority level with increasing number of critical customers

Number of Critical Customers	Pipe Priority Level
No critical customers	Low ↑ ↓ High
At least 1 critical customer	
2 critical customers	
3 critical customers	
4 or more critical customers	

Without careful considerations toward critical customers and operations, major consequences could arise for a city if this risk assessment model were to be implemented in the evaluation of their water distribution system. By considering the need of preserving water supply to emergency response services and key municipal operations, such as fire stations and hospitals, this model safely ensures public safety by prioritizing pipes that have the least amount of impact on these critical services.

3.4.4 Pipe Material Phasing

As technological advancements are steadily achieved over the years and stronger pipe materials begin to surface on the market, there develops a practical need to upgrade any outdated components of a water distribution system. In order to maintain the health and public safety of its population, cities need to consider the replacement of these aging and outdated pipe segments with newer and stronger pipe materials to avoid catastrophic failures and possible water contamination.

This risk assessment model takes into account the importance of pipe phasing as its fourth impact criterion. Once an outdated pipe is identified and undergoes a rehabilitation or replacement process, it would be impractical to replace that pipe with the

same outdated material. For example, actual city data, presented later in this study, has shown that galvanized iron pipes have been installed and used in various sections of a water distribution system as early as the 1970's. According to an article by Stonemark Construction Management titled, "Pipes are *Not* a Lifetime Component," galvanized iron has an estimated life expectancy of 30-50 years, with 30 years considered as the maximum life expectancy by many municipalities. They are known to experience high failure rates over time, specifically due to corrosion. Depending on the original installation year, many of these pipes may have already surpassed their 30 year maximum service life. This clearly identifies the need for a complete pipe replacement and upgrade to a much more dependable and cheaper pipe material such as PVC. Although galvanized iron is not necessarily an outdated material for use with water mains, it does, however, have a shorter service life and higher cost than most other pipe materials available today.

The overall importance, or priority, for upgrading of a pipe can be determined simply by comparing its present age with its anticipated service life. However, it is important to note that this anticipated service life typically refers to the manufacturer's anticipated service life. But, in the case of this risk assessment model, the Anticipated Service Life (ASL) of a pipe can be obtained by taking the mean value of the manufacturer's anticipated service life for each specific material class. Currently, the most common material types used in producing pipes for water distribution systems are polyvinyl chloride (PVC) and cement due to their high ASL values. The more uncommon pipes that are being phased out of service from a water distribution system include galvanized iron and unlined cast iron pipes. Table 3.6 below ranks these pipe materials

based on their ASL, the overall quality of their material type, as well as the urgency for their upgrade.

Table 3.6 Ranking of pipe materials that require urgent upgrades

Pipe Material	Pipe Quality	ASL	Quality	Upgrade Urgency
Polyvinyl Chloride	PVC	100	<div>High</div> <div>↑</div> <div>↓</div> <div>Low</div>	<div>Low</div> <div>↑</div> <div>↓</div> <div>High</div>
Asbestos Cement Pipe	ACP	100		
Ductile Iron Pipe	DIP	100		
Composite (Techite)	COMP	50		
Steel	STL	40		
Galvanized Iron	GALV	25		
Unlined Cast Iron Pipe	CIP	75		
unknown	unknown	-		

Although the classification of these pipe materials do not coincide with the numerical order of their ASL, the ranking criteria specified in table 3.6 was established under the specific guidance and suggestions of Water Systems Consulting Inc. (WSC). The basis of their ranking criteria was the result of various field investigations where the performance and integrity of these pipe materials were closely observed.

By taking pipe material into consideration and ranking their relative importance for an upgrade, this risk assessment model establishes a reliable, evaluative basis from which cities could entrust the prolong operation and efficiency of their water distribution system. Without considering the need to replace outdated pipe materials, various municipalities could suffer from more pipe failures as well as an intermittent drop in water efficiency in their network.

3.4.5 Traffic Impact

This study also considered the effects of pipe improvement projects on a city's daily traffic patterns. Before conducting any sort of pipe rehabilitation or replacement project, it is important to consider the possible impacts such a project may have on the daily commercial, transit, and public transportation operations of a municipality. Depending on the severity of the pipe failure and the magnitude of repairs that need to be implemented, a pipe rehabilitation operation may have detrimental effects on various transit systems in a city, which would cause indefinite delays for commuters and businesses.

In order to consider transportation operations and reduce overall impact on existing traffic patterns within a municipality, this model takes into account various transit routes by classifying their level of importance in daily municipal operations. The importance of each transit route is determined by its roadway classification, the number of commuters that frequent it and its relative location near a water main that may require repair. Although there are a number of transit routes that are typical to a municipality, this model will specifically examine each route based on the following classification:

- Local Streets
- Collector Streets
- Secondary Priority Transit Routes
- Primary Priority Transit Routes
- Major Arterial Streets

In addition, the following table is a summary of these roadway classifications along with their individual priority level from least importance to highest importance.

Table 3.7 Roadway classification and priority level

Roadway Class	Priority Level
Local Streets	Low ↑ ↓ High
Collector Streets	
Second Priority Transit Route	
First Priority Transit Route	
Major Arterial Street	

By categorizing the relative importance of these roadway classes, this risk assessment model establishes a suitable basis from which cities could entrust the preservation and efficient operation of their daily transit routes and activities. Furthermore, by considering the possibility of creating delays and detours for daily traffic patterns in a city, this assessment model helps to ensure that future pipe improvement projects will have as small of an impact as possible towards businesses operations and individual travels.

3.4.6 Estimating Costs for Pipe Repair

Accounting for all of the necessary components of a pipe improvement project and estimating the total cost involved is probably the most difficult task associated with planning and financially preparing for any municipal improvement project. The process of tallying all financial factors involved in such a project can take several months or even years for a city's planning commission. Although there can be a multitude of factors for consideration in a pipe improvement project, a few can be easily identified as being

typical and most often necessary. These included, but are not limited to, costs associated with pipe materials, excavation and earthwork, traffic control, construction labor, and installation components such as pipe fittings. Essentially, each factor in consideration is dependent on the relative location of a pipe that requires repair as well as its ease of access. Other factors may also depend on specific conditions that vary between municipalities, making each improvement project different from one city to the next.

Cities can estimate the total cost of a pipe improvement project using several pricing strategies. The public works division of a city can conduct the price estimation through in depth research and investigation or with the use of a construction cost estimation manual such as RS Means. A city can also employ specialized consulting firms to conduct the cost estimation for them. In this study, two particular pricing strategies, top down and bottom up pricing, were recognized.

Top down pricing is the most commonly used estimating strategy implemented by city planning commissions and consultants. According to a top down versus bottom up business article by Ben Yoskovitz (2009), the top down business approach is described as being the older, more recognized approach for business models. It involves pricing and estimating the costs associated with an improvement project by tallying and comparing each fee with other competitors who offer the same services for construction, installation, excavation, etc. Furthermore, the final cost for each component is variable and subjective, depending on who is conducting the pricing strategy. It is typically found that construction estimation manuals such as RS Means are widely used in top down pricing strategies (according to Water Systems Consulting Inc).

According to business writer Joyce Weinberg (2007), the right price for any improvement project is stated to exist in between the cost of the materials, labor, overhead, and what the current market will bear. In other words, the current economic needs and relative urgency for conducting a pipe improvement project will determine what type of top down pricing strategy a city may conduct, whether it is on their own or with the aid of a private consulting firm. The following figure is an example of a top down pricing quote created by Water Systems Consulting Inc. for a pipe improvement project.

Figure 3.2 Example of top down cost estimation

Based on the information from figure 3.2, it is evident that estimating the final cost of a pipe improvement project can contain subjective and variable pricing parameters. Although the estimated project costs contain some specific unit-prices for several components in the pipe improvement plan, there is still a large margin of flexibility in the final project price quote.

The other type of cost estimation strategy that was considered during this study is bottom up pricing. This method involves the direct price evaluation of an improvement project based on specific unit costs of raw materials. This can include total expenses for pipe materials in terms of their price per foot, price per diameter, and so on. It can also include the total costs for dirt infill, roadway pavement materials, and pipe fittings. Compared to top down pricing, this form of cost estimation is much more intensive because it involves tallying up the total price for the comprehensive list of raw materials necessary for a pipe improvement project. It does not contain prices associated with labor or any other services that have a variable or unspecified price.

If a city were to conduct their own bottom up pricing strategy through their public works division, the main benefit or advantage would come from the money saved by conducting the price investigation on their own. On the contrary, hiring a specialized consulting firm may prompt a higher degree of benefits due to their specialization. With a comprehensive list of raw materials necessary for a particular pipe improvement project, a consulting firm may also reduce overall project costs for a city by incorporating competitive price comparisons and cost estimations for variable services, such as hourly construction labor or equipment rental fees, during the course of the improvement project.

For the methods outlined in this risk assessment model, a bottom up pricing strategy was selected as one of the impact criteria due to its overall simplicity. The only cumbersome part of conducting this type of cost estimation would be the process of obtaining a comprehensive listing of raw materials necessary for a particular pipe improvement project. But the process of obtaining a final price estimate for the project is relatively simple in nature.

The following two tables are a comprehensive listing of common pipe materials found in a water distribution network. Table 3.8 shows a list summary of each pipe material along with their relative reference source. It is important to note that the final determination of each price per linear foot was subjective, all of which were later verified and supported by Water Systems Consulting, Inc.

Table 3.8 Common pipe materials and their observed pricing source

Material Type	Pricing Source	Type
Composite (Techite)	City of Rockville, MD.	City
	Town of Mount Pleasant, NY	City
	Information Resources of Maine	State
Steel	Columbia Pipe & Supply Co.	Distributor
Cast Iron Pipe	Charlotte Pipe & Foundry Company	Distributor
PVC (schedule 40)	Charlotte Pipe Distributor	Distributor
	US Plastic Corp. Distributor	Distributor
Asbestos Cement Pipe	County of San Diego, CA	County
Ductile Iron Pipe	City of Lake Charles, Louisiana	City
Galvanized Iron Pipe	Discount Steel.com	Distributor

Each pipe material is listed in table 3.9 along with their diameter and price per linear foot. The specific prices for each pipe material and each diameter were obtained from the online resources in table 3.8.

Table 3.9 Estimating pipe material costs

Material	Abbreviation	Diameter (in)	Price per Linear Foot
Cast Iron	CIP	2	\$10
		4	\$18
		6	\$32
		8	\$50
		12	\$123
Ductile Iron	DIP	8	\$22
		10	\$24
		14	\$40
		16	\$50
Galvanized Iron	GALV	2	\$11
		4	\$26
		6	\$40
		8	\$55
Steel	STL	8	\$138
PVC(Schedule 40)	PVC	2	\$2
		4	\$5
		6	\$8
		8	\$12
		10	\$19
		12	\$28
		14	\$33
		16	\$43
Composite (Techite)	COMP	2	\$30
Asbestos Cement	ACP	2	\$30
		4	\$42
		6	\$55
		8	\$64
		10	\$69
		12	\$77
		14	\$87
		16	\$98
unknown	-	n/a	n/a

Accounting for the relative costs associated with raw materials for any municipal improvement project allows cities to proactively plan for and allocate capital funds that are necessary for a future project. By incorporating pipe material expenses into this risk assessment model as the last impact criterion, the final result is a comprehensive analysis of the potential economic impacts a city may experience during a pipe improvement project.

3.5 Determining Risk of Failure

The last phase of this risk assessment model is determining the overall risk of failure for each pipe and water main in a distribution system. All of the impact criteria mentioned in the previous subsections of section 3.4 are combined to assess the overall degree of impact for each pipe segment. A cumulative Impact Score (IS) is assigned to each pipe, which represents the various degrees of impact it has on municipal demand, criticality, land use, traffic, material phasing, and estimated repair costs. Figure 3.3 below is a visual schematic of this final phase.

Figure 3.3 Final phase of analysis

The conclusive result of this risk assessment model is a Risk of Failure Score (RFS) assigned to each pipe segment. This final score represents the overall urgency for rehabilitation or replacement of each water main. With this numerical score, cities can easily prioritize their attention towards pipes that require the most attention and begin planning for future improvement projects by creating a hierarchal listing of these RFS scores.

In order to calculate the Risk of Failure Score for each pipe segment, its cumulative Impact Score (IS) must first be determined. Table 3.10 is the scoring table used to find these values. This table combines all of the impact criteria previously mentioned and assigns a corresponding Impact Score to each of their specific characteristics and priority levels.

Table 3.10 Impact Criteria Scoring table

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

It is important to note that several of the numerical parameters in table 3.10 are highly subjective. The upper and lower limits in the Service Demand and Estimated Total Cost for Repair criteria are dependent on specific conditions within a municipality, therefore the numerical parameters specified in table 3.10 should not be treated as absolute values for all municipalities.

Also, not all of these impact criteria may apply to a water distribution system. Depending on specific conditions within a municipality, some criteria may be omitted or included in the application of this risk assessment model to their water distribution system. Regardless of what criteria are being considered, it is recommended that at least three of the above impact criteria are implemented into this risk assessment model. This will ensure that there is a minimum amount of applicable impact criteria for use with the final steps outlined later in this study.

Furthermore, this scoring table was originally developed in the prototype WSC risk assessment model but it only employed a maximum impact score of 3 for each impact criterion. In an effort to improve the degree of analysis in this risk assessment model, the table was expanded to include a maximum possible impact score of 5, with each criterion's characteristics being adjusted accordingly. By increasing the maximum possible score to 5, a degree of flexibility was added into this model.

Once an Impact Score has been assigned to each impact criterion, the cumulative Impact Score for each pipe segment can then be calculated simply by combining all of the individual Impact Scores into one numerical value.

The following equation illustrates this process:

$$Total\ IS = IS_{criticality} + IS_{demand} + IS_{Land\ Use} + IS_{traffic} + IS_{phasing} + IS_{cost} \quad (14)$$

Where: Total IS = Cumulative Impact Score for each pipe segment

$IS_{criticality}$ = Customer criticality impact score

IS_{demand} = Service demand impact score

$IS_{land\ use}$ = Land use impact score

$IS_{traffic}$ = Traffic impact score

$IS_{phasing}$ = Pipe material phasing impact score

IS_{cost} = Estimated total cost for repair impact score

The final step towards determining the Risk of Failure for an individual pipe segment in a water distribution system is to multiply its cumulative Impact Score with its respective Probability of Failure (PF) score, which was previously determined in section 3.3. The following equation illustrates this final step in this risk assessment model:

$$(RFS) = (Total\ IS) \times (PF) \quad (15)$$

Where: RFS = Pipe Risk of Failure Score

Total IS = Cumulative Impact Score for each pipe segment

PF = Pipe Probability of Failure obtained from table 3.3

This Risk of Failure Score is a numerical representation of the overall probability of a pipe experiencing a failure during its serviceable life. The RFS of a pipe is the final product and the most significant result of this risk assessment study. It is essentially what determines the priority of a pipe amongst all other pipe segments in a water distribution system. The following matrix, specifically table 3.11, summarizes the results of this risk

assessment model into a visually organized manner. It categorizes the priority of each pipe based on its Risk of Failure Score. It includes the complete range of possible PF scores for a pipe segment along the left vertical column as well as the minimum and maximum possible cumulative Impact Scores (IS) along the top of the table. The values in between are the product range, or the Risk of Failure Scores, a pipe may have. The range of possible RFS scores is from 3 to 300. This range was subdivided into four major categories, each with its own specific color coding as illustrated in table 3.12. Pipes that have a Risk of Failure score less than or equal to 20 are considered very low risk. Those that have RFS values in between 21 to 70 are considered low risk. Similarly, those pipes that have scores between 71 to 150 are considered medium risk. Pipes that have the highest risk of failure are those that have scores greater than 150 and less than 300.

As with many other components in this risk assessment model, Table 3.11 was originally from the prototype WSC risk assessment model. However, the original table was much smaller in that it only had a maximum Impact Score of 18, resulting in a range of RFS values in from 3 to 180. Because the original table had a much smaller range of values, the associated ranges of risk level subdivisions were much smaller. On the contrary, the risk assessment model developed in this study utilizes a larger, more expanded version of Table 3.11 due to the greater number of impact criteria that were considered.

Consequently, in the event that a municipality decides to omit or include a number of impact criteria into this risk assessment model, aside from the ones already considered, Table 3.11 must be expanded or contracted to reflect the maximum possible Impact Scores (IS) and table 3.12 must also be adjusted subjectively.

Table 3.11 RFS table summary

		Total Impact Score																														
		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30			
Probability of Failure Score	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Risk of Failure Score (RFS)		
	2	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60			
	3	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72	75	78	81	84	87	90			
	4	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100	104	108	112	116	120			
	5	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150			
	6	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150	156	162	168	174	180			
	7	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126	133	140	147	154	161	168	175	182	189	196	203	210			
	8	24	32	40	48	56	64	72	80	88	96	104	112	120	128	136	144	152	160	168	176	184	192	200	208	216	224	232	240			
	9	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243	252	261	270			
	10	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300			

Table 3.12 Legend for RFS table summary

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

The Risk of Failure score of a pipe segment allows for easy identification and classification of pipes that have a greater degree of urgency for rehabilitation or replacement compared to other pipe segments in the same water distribution system. By applying this risk assessment model to determine RFS values for water mains in an existing pipe system, various municipalities can use the RFS of individual water mains from their distribution system to begin planning and allocating capital funds towards future plans to conduct improvement projects for these water mains. This information alone can prove to be a powerful tool for any municipality.

By knowing the risk of failure of individual water mains within their water distribution system, cities can save money and time by planning ahead for future pipe improvement projects. Simultaneously, assessing the risk of failure and determining the service priority of each pipe segment will help insure that water dependent activities for businesses as well as residents within a municipality will be safeguarded from unexpected water shortages as well as intermittent water utility services. The overall health and safety of the general public will also be preserved by insuring that emergency services such as fire stations, hospitals, and police will have the sufficient means to respond to a danger, given the proper maintenance of a city's water distribution system.

CHAPTER 4

CASE STUDY: CITY OF ARROYO GRANDE

Figure 4.1 City of Arroyo Grande water distribution system (WSC Inc., 2012)

4.1 Data Acquisition

In an effort to test the validity and reliability of this risk assessment model, this study involved the application of this model with real water distribution data which was obtained from the City of Arroyo Grande, California. Through cooperative efforts between Water Systems Consulting, Inc. and the City of Arroyo Grande (AG), data on the city's potable water distribution network was provided. This data was comprised of a digital water distribution model for use with specific software such as WaterCAD V8i and ArcGIS. The data included overall information pertaining to the city and its hydraulic network.

The following is a comprehensive list of data files that were provided for this study:

- Land use within in city limits
- Roadway information-*classification type and name*
- Property lines and parcels
- Hydraulic information- *specifically peak average daily demand values*
- Physical pipe properties-*length, diameter, installation year, and location*
- History of pipe breaks and water complaints

The information listed above is just an overview of the various materials that were implemented into this model. Much of the remaining hydraulic network information was extracted from specific software files for ArcGIS and Bentley WaterCAD V8i.

4.2 Computer Aided Modeling and Analysis

In order to conduct this study in an efficient manner, the use of computer aided modeling was implemented to obtain various results that were necessary for the risk assessment of the Arroyo Grande hydraulic network. Theoretically, this risk assessment model can be conducted without the use of computer modeling software. However, given the large size of the Arroyo Grande hydraulic network, with a total of 3,572 individual pipe segments, the use of computer modeling software was highly necessary in order to complete this study in a timely manner.

4.2.1 Bentley WaterCAD V8i

WaterCAD V8i is a water distribution modeling program that is part of the Bentley software suite. It is a Windows based program that specializes in modeling

hydraulic operations and skeletonizing an existing water distribution system. It has a wide variety of tools applicable to hydraulic analysis such as fire flow, criticality, water quality, and variable demand patterns. It can simulate the functions of individual hydraulic network components such as pipe segments, nodes, reservoirs, tanks, check valves, and even booster pumps. WaterCAD is also cross compatible with AutoCAD, allowing individuals to import AutoCAD drawings and drafting files. It also interfaces with ArcGIS through its WaterGEMS platform, which gives users the ability to export their hydraulic network to a geographic information system such as ArcGIS.

WaterCAD V8i was implemented into this risk assessment model in order to obtain necessary pipe flow data for the Arroyo Grande water distribution system. The hydraulic model that was used in this program had already been calibrated by Water Systems Consulting, Inc. prior to its acquisition. Specifically, this model was calibrated to reflect actual pipe flow and demand patterns measured in the water distribution system. A steady state analysis was performed on the hydraulic model in order to obtain the peak average daily flow values, in gallons per minute, for each pipe segment. These flow values were then extracted from the pipe flex tables and exported as an ESRI shape file for integration into ArcGIS. This data is available in Appendix A: Hydraulic Network Properties for the City of Arroyo Grande.

4.2.2 ESRI ArcGIS

ArcGIS is a geographic information system software developed by Environmental Systems Research Institute (ESRI). It is a Windows based program that utilizes a geographic information system (GIS) to visually present geographic data in the form of

tables, charts, maps, and globes. According to the ESRI website, ArcGIS is a useful software tool in that it utilizes computer hardware and software technology in order to display, analyze, manage, and capture all forms of geographically referenced information. Use of this software allows individuals to reveal patterns, trends, and relationships between geographically referenced data by viewing, interpreting, questioning, visualizing, and understanding such data.

Use of ArcGIS with this risk assessment model was highly recommended by Water Systems Consulting, Inc. Its utilization allowed for better decision making, better record keeping, and data management; improved communication, increased work efficiency, and overall cost savings in analyzing the Arroyo Grande water distribution system. WSC recognized the importance of this software in that it allows users to implement this risk assessment model by digitally mapping key features, quantities, densities, conditional information, and the relative location of individual pipe segments within the network. Figure 4.2 is the plan view of the Arroyo Grande water distribution system in ArcGIS.

Figure 4.2 Plan view: City of A.G. water distribution network

4.3 Critical Components for Analysis

To apply the developed risk assessment model for the conditional assessment of water mains in the Arroyo Grande water distribution network, an assortment of pipe data was used from the ArcGIS network model (originally provided by Water Systems Consulting, Inc.).

The following information was extracted from the model's attributes table and replicated in a stand-alone GIS shape file dedicated for use with this risk assessment model:

- FID-Pipe identification number
- Full Name- Roadway name
- Installation Year
- Demand (gallons per minute)
- Diameter (inches)
- Material
- Length (feet)

All pipe segments in this water distribution network are classified by their relative location beneath a particular segment of roadway in Arroyo Grande. Therefore, the name of the roadway also represents the segment of pipe located beneath it. Furthermore, the numerical ID (FID), of each pipe segment is merely an identification number used in ArcGIS to reference the location of each pipe segment in the digital model. It does not represent an actual identification number assigned to the pipe segment by the city or by the pipe manufacturer. In addition, all demand and pipe length values were rounded up to the nearest whole number in order to simplify analysis. Finally, the pipe demand values contained in the stand-alone GIS shape file were imported from the WaterCAD hydraulic model previously mentioned in section 4.2.1. As previously mentioned, all of this information is available for viewing in Appendix A.

4.4 Data Additions to the GIS Model

Over the course of this study, additional data that was either calculated or obtained from subsequent portions of this risk assessment model were manually entered into the stand-alone GIS shape file for analysis. These data were produced by closely following the specific steps and subsections outlined in Chapter 3. The following paragraphs explain in greater detail the method in which each critical data set was entered into the GIS shape file.

The age of each pipe segment was calculated in the GIS shape file by using the provided installation years and subtracting that value from the present year, 2013. A simple mathematical equation was created the GIS field calculator to automatically calculate and import these values into the attributes table. This equation can be seen in Appendix B: GIS Field Calculation and Python Equations.

The Anticipated Service Life (ASL) of each pipe segment was determined using table 3.1 in conjunction with the provided pipe materials data in the GIS shape file. A degree of programming was required to effectively digitize the parameters outlined in table 3.1 into the GIS attributes table. The automated calculation and import of these ASL values were due to a custom Python equation created specifically for this task. This equation is available for viewing in Appendix B.

The Remaining Useful Life (RUL) of each pipe segment in the Arroyo Grande water distribution system was calculated with a GIS field calculator equation similar to the one featured in section 3.3 of this study. This specific equation can also be viewed in Appendix B.

The break history component of this risk assessment model was manually entered into the GIS attributes table for each respective pipe. It involved subjective analysis of pipe break data as well as water complaints from the City of Arroyo Grande. Table 4.1 is an example of a pipe break history table and Figure 4.3 is a sample of a water quality complaint, both of which were provided by Water Systems Consulting, Inc. in conjunction with the city of AG.

Table 4.1 A.G. recorded pipe break histories

Year	Street	Location	Pipe	Notes
1997	Fair Oaks	Between Walnut and Elm	8" Cast Iron 1929	
	S. Traffic Way Extension		8" ACP	3 breaks last 20 years
	McKinely		193X Cast Iron	
	LePoint Street		193X Cast Iron	
	Dianna Place		ACP	
	Vernon Street			
	Tally Ho Eastment	Tally Ho to Paseo	12" ACP	Under Creek

Each pipe break or water quality complaint on record was treated as a single break history incident for the respective water main in question in this analysis. For example, pipes that had a single water quality complaint on file were designated with a single break incident. On the contrary, pipes that had a combination of complaints and/or break histories were designated with a number of incidents equal to the number of complaints and breaks on file. Once all break history incidents were manually entered into the GIS attributes table of the Arroyo Grande model, the RUL of each water main was adjusted according to table 3.2. A custom python equation was developed to calculate the percent adjustment value for each pipe break incident and a simple GIS field calculation was

implemented to calculate the adjusted RUL for each pipe segment. These equations are listed in Appendix B.

THE CITY OF
Arroyo Grande
CALIFORNIA
P. O. B.

214 EAST BRANCH STREET
PHONE 805 489-1303

Water Taste and Odor Complaint

Date: 4/21/10 Time: 10:30AM

Utility Service Area and Location: _____

Complainant Information: Name: _____ Address: _____ Telephone: _____

Confidential

Description of Taste (T) or Odor (O) (Check appropriate boxes)

T	O	T	O	T	O
☐	☐ Musty	☐	☐ Grassy	☐	☐ Rotten
☐	☐ Earthy	☐	☐ Fishy	☐	☐ Septic
☐	☐ Chlorinous	☐	☐ Other (Describe _____)		

Where Odor Noticed (Sink, Shower, etc.): SINK

Other Comments: Brown water, cloudy water
1.12 fl oz Residual
mg

Yard Water Lopez
flush sinks in House for 20 min's. They will call if get worse.

PW-92

Figure 4.3 Sample - A.G. Water quality complaint

The probability of Failure (PF) Score of each pipe segment in the GIS model was calculated using table 3.3 along with a custom python equation specifically developed for this model (available in Appendix B). The python script was implemented into the GIS attributes table and it was used to assign the specific PF score with the corresponding adjusted RUL value of each pipe segment.

The price per linear foot of each water main in the Arroyo Grande water distribution system was calculated using table 3.9. Pipe data provided by WSC, Inc. and the City of Arroyo Grande were used in conjunction with this table to determine an estimated worth for the various pipe diameters, pipe lengths, and material types. For each material class, a custom python equation had to be developed in order to properly assign prices to each pipe diameter. A total of seven python equations were developed specifically for estimating pipe material costs (appendix B). A simple field calculation was implemented to calculate the estimated repair cost of each water main. This involved multiplying the price per linear foot of each pipe segment from its respective python equation with its overall length.

During the critical customer analysis phase of this risk assessment model, several GIS tools were implemented in order to properly locate and map out the location of these customers along with the pipes within their vicinity. Figure 4.4 below is a plan view of all the critical customers located within the Arroyo Grande Water Distribution network. A GIS buffer tool was used to establish a 0.25 mile radius of influence around each critical customer and a python equation was implemented to identify and consider only those pipes that had a diameter greater than or equal to 8 inches for criticality analysis.

Figure 4.4 Location of all critical customers in Arroyo Grande

ArcGIS was then used to locate those pipes that fell within the radius of influence of any critical customer. Once the locations of these pipes were determined, each was assigned a numerical value of 2 for each zone it intersected in the GIS attributes table. All other pipes that did not fall within a critical customer zone were given a numerical

value of 1. The final step in this criticality analysis involved another field calculation that summarized the total number of critical customer zones a pipe fell within. The python and the field calculation equations mentioned in this portion of the risk assessment analysis are provided in Appendix B. Moreover, the location and names of individual critical customers can be found in Appendix C: Critical Customers within the City of Arroyo Grande.

The next phase in the risk assessment of Arroyo Grande's water distribution system involved the determination of the Impact Scores (IS) of the individual impact criteria outlined in section 3.4 of this report. Table 3.10 was used in conjunction with a collection of custom made python equations, all of which can be found in Appendix B, to determine these IS values. These equations were used in calculating the customer criticality (IS), estimated total cost for repair (IS), service demand (IS), and pipe material phasing (IS). Determining the Impact Score for the land use and traffic impact criteria involved GIS special analysis on the Arroyo Grande hydraulic network.

In order to determine the land use (IS) for each pipe segment in the hydraulic network, a GIS proximity tool was used in conjunction with table 3.10 to identify pipes that were located within 30 feet of a neighboring land use. Identification began with land use components that had a low Impact Score, such as agriculture and open spaces. Once the proximity tool identified all of the pipes within 30 feet of these land uses, each pipe segment was manually assigned a corresponding IS value of 1 in the GIS model attributes table. The next step was to identify land uses that had a higher impact score of 2, 3, and so forth and then locate those pipes that fell within 30 feet of each land use. If a pipe was determined to be in the vicinity of a land use of higher importance, the original IS score

of that pipe was adjusted to reflect the IS value of the higher land use. For example, if a pipe was initially assigned an IS score of 1 because it was located near an agricultural area, its score would increase to 2 if it was once again located near a more important land use such as a medium density residential area. Figure 4.5 is an aerial view of the various land uses in Arroyo Grande considered in this study.

Figure 4.5 Various land uses in Arroyo Grande

The last criterion implemented into the assessment of the Arroyo Grande network was traffic impact. In order to incorporate the possible impact on traffic circulation into this risk assessment model, the circulation map featured in figure 4.6 was used in conjunction with table 3.10 to determine IS values for each roadway classification. Figure 4.6 was obtained from the City of Arroyo Grande website archives. The specific routes and roadway classes depicted in figure 4.6 were replicated in the GIS model and then later assigned their respective Impact Scores according to table 3.10.

The final stage of applying this risk assessment model to the Arroyo Grande water distribution system involved calculating the total Impact Score (IS) for each pipe segment and then using table 3.11 and 3.12 to determine the Risk of Failure Score (RFS). A simple field calculation was performed in the GIS model to manually input the RFS values into the pipe attributes table. This equation (Appendix B) involved the summation of all IS values for each impact criteria, for a single pipe, and then multiplying that total value with the corresponding Probability of Failure score (PF) of that pipe.

The final result is an attributes column dedicated solely towards the RFS value of every single pipe segment in the water distribution system. The RFS values of all 3,572 individual pipe segments in the network were then categorized and symbolized in GIS to visually illustrate the priority and risk level of each pipe in chapter 5.

Figure 4.6 Traffic circulation element map (City of A.G., 2001)

CHAPTER 5

RESULTS

5.1 GIS Simulation Results

The final result of this condition-based risk assessment of Arroyo Grande's water distribution system is a base map representation of the failure risk of pipes in the network. Figure 5.1 is a map of these pipes and their corresponding risk levels.

Figure 5.1 Base map of the fully assessed A.G. water distribution system

ArcGIS was the primary tool used in developing this figure. This program utilized the individual pipe RFS values obtained from this risk assessment model and symbolized them on a base map of the City of Arroyo Grande, according to the parameters outlined in table 3.11 and table 3.12. Figure 5.2 is a close up view of the pipes exhibiting the highest risk of failure. There were a total of 6 individual pipe segments located along Fair Oaks Avenue, four of which were comprised of cast iron and two of which were galvanized iron. These pipes also had an installation date as early as 1929 and as late as 1982.

Figure 5.2 Close up view of highest risk water mains

The collection of pipe segments featured in figures 5.1 and 5.2 were color coded based on their risk levels according to table 3.12. The pipes that are colored red have RFS values greater than or equal to 151. They were determined to have the highest risk of failure in the water distribution network and are therefore considered to have the highest priority for pipe rehabilitation or replacement. Subsequently, all pipes colored in orange have RFS values in between 71 and 150. These pipes are considered to have a medium risk of experiencing failure. Lastly, all pipes that were colored green and blue had Risk of Failure Scores in between 21 to 70 or scores less than or equal to 20, respectively. These pipes were considered to have the least chance of experiencing failure, compared to all the other pipe segments in the hydraulic network. For a complete listing of these high risk water mains, please refer to Appendix A: Hydraulic Network Properties for the City of Arroyo Grande.

5.2 Comparative Evaluation with Varying Impact Criteria

In order to investigate the significance level of each impact criteria outlined in section 3.4, multiple instances of risk assessment were employed in this study. These instances are later designated as model variations (A) and (B). ArcGIS was again, the main tool used in conducting these simulation variations. The impact criteria that were omitted from the first model variation (A) included service demand, estimated total cost for repair, and land use. In other words, only customer criticality, traffic impact, and pipe material phasing were taken into consideration in this model variation along with all other components of this risk assessment model. Figure 5.3 illustrates the modifications made to the degree of impact assessment phase of this particular model variation.

Figure 5.3 Modified degree of impact diagram for variation (A)

There was also a need to adjust tables 3.10, 3.11 and tables 3.12 to reflect the new range of possible RFS values with the use of only three impact criteria. The following tables contain the modified parameters that were necessary for this model variation.

Table 5.1 Modified impact criteria scoring table for variation (A)

Impact Criterion	Impact Score				
	1	2	3	4	5
<i>Customer Criticality</i>	No critical customers or pipe size < 8"	At least 1 Critical Customer	2 Critical Customers	3 Critical Customers	4 or more Critical Customers
<i>Traffic Impact</i>	Local Streets	Collector Street	Priority 2 Transit	Priority 1 Transit	Arterial Street
<i>Material Phasing</i>	PVC and ACP	Ductile Iron	Steel & Techite	Galvanized Iron	Unlined Cast Iron or unknown material

Table 5.2 Modified RFS table summary for variation (A)

		Total Impact Score													
		3	4	5	6	7	8	9	10	11	12	13	14	15	
Probability of Failure Score	1	3	4	5	6	7	8	9	10	11	12	13	14	15	Risk of Failure Score (RFS)
	2	6	8	10	12	14	16	18	20	22	24	26	28	30	
	3	9	12	15	18	21	24	27	30	33	36	39	42	45	
	4	12	16	20	24	28	32	36	40	44	48	52	56	60	
	5	15	20	25	30	35	40	45	50	55	60	65	70	75	
	6	18	24	30	36	42	48	54	60	66	72	78	84	90	
	7	21	28	35	42	49	56	63	70	77	84	91	98	105	
	8	24	32	40	48	56	64	72	80	88	96	104	112	120	
	9	27	36	45	54	63	72	81	90	99	108	117	126	135	
	10	30	40	50	60	70	80	90	100	110	120	130	140	150	

Table 5.3 Modified legend for RFS table summary for variation (A)

RFS Value	Color	Failure Risk Level
≤ 18	<i>Blue</i>	<i>Very Low</i>
19 to 36	<i>Green</i>	<i>Low</i>
37 to 60	<i>Orange</i>	<i>Medium</i>
≥ 61	<i>Red</i>	<i>High</i>

The range of cut-off values illustrated in table 5.2 and 5.3 for each failure risk level were subjectively established. Given that there were only three impact criteria considered in this modeling variation, the maximum possible Impact Score (IS) for each pipe segment was 15 and the corresponding RFS values were within the range of 3 to 150.

The results of applying these changes to this risk assessment variation yielded a larger collection of water mains that were identified as having a high risk of failure in the Arroyo Grande water distribution system. There were a total of 23 individual pipe segments that were identified as high risk in this variation of the GIS model. Five of these pipes were comprised of asbestos cement, 11 were made of cast iron, and seven of which were made of galvanized iron. These pipes exhibited installation years as far back as 1929, 1970, and the 1980's. The much older pipes were made of cast iron whereas the newer pipes were made of asbestos cement. Although this variation of the GIS model contains the original 6 cast iron pipes that were identified in section 5.1, the omission of service demand, land use, and estimated total cost for repair from the modeling impact criteria generated a larger collection of high risk water mains. Essentially, the omission of these impact criteria created an over estimation of pipes that were identified as high risk. Figure 5.4 provides a base map of these newly identified water mains. For the complete list of high risk water mains identified in this model variation, refer to Appendix A.

Figure 5.4 Model variation (A): Base map of high risk water mains

As evident from the figure above, the GIS model detected a greater number of high risk water mains aside from the original 6 that were identified along Fair Oaks Avenue. These additional pipe segments were found along Chilton Street, West Branch Street, North Alpine Street, and West Cherry Avenue. Figure 5.5 presents a closer view of these newly identified high risk water mains.

Figure 5.5 Close up view of high risk water mains for model variation (A)

The second and final variation of this risk assessment model involved the complete omission and total disregard of all impact criteria previously mentioned in section 3.4. The defining factor for identifying high risk water mains for this variation of the risk assessment model was the Probability of Failure (PF) score for each pipe segment. These PF values were determined using the procedures outlined in section 3.3. The corresponding Probability of Failure table from that section, specifically table 3.3,

was also modified to visually reflect the risk level of these water mains in ArcGIS. Table 5.4 below is the modified Probability of Failure table which contains the new parameters necessary for this version of the risk assessment model. The cut-off values for each risk level were determined subjectively.

Table 5.4 Modified Probability of Failure (PF) table for variation (B)

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

With the new parameters outlined in table 5.4, this risk assessment model was reapplied to the water distribution data for Arroyo Grande. ArcGIS was once again used to visually identify and symbolize all of the high risk water mains in the hydraulic network. Similar to the results found in modeling variation (A), the results in variation (B) identified 23 individual pipe segments as having a high risk for failure. All of these pipes shared the same Probability of Failure (PF) score which was equal to 10. All other pipes within the water distribution network had PF scores less than 9 and were not considered as high risk during this analysis.

Coincidentally, this variation of the risk assessment model yielded the same exact results as variation (A). The GIS modeling software identified the same, exact 23 pipe

segments. Recall that 5 of these high risk pipes were made of asbestos cement, 11 were made of cast iron, while the remaining 7 were made of galvanized iron. As previously mentioned, these pipes were installed as far back as 1929 and as recent as 1987. Figure 5.6 is the graphical base map that was developed to illustrate these results.

Figure 5.6 Model variation (B): Map of high risk water mains using only PF values

Similarly, figure 5.7 provides a closer view of these high risk water mains. The relative location of each pipe segment is designated by the street names in the figure.

Through visual comparison of figure 5.7 and figure 5.5, it is clearly evident that the classification and identification of risk levels using only the Probability of Failure scores for each pipe segment resulted in exactly the same results as in variation (A), in which service demand, land use, and estimated repair costs were omitted from the risk assessment impact criteria. Appendix A provides a comprehensive list of these high risk water mains that were identified in model variation (B).

Figure 5.7 Close up view of high risk water mains for model variation (B)

5.3 Optimal Conditions for Risk Assessment

In conducting both of the model variations A and B, it is clearly evident that the consideration and application of various impact criteria into this risk assessment model is highly necessary in order to identify a much more narrow and specific collection of high risk water mains. Although the application of this risk assessment model is possible without the consideration for any of the specific impact criteria mentioned in section 3.4, the results would yield a much broader collection of high risk water mains.

Since the primary goal of this study was to develop a cost effective and practical risk assessment model, the use of a power modeling software such as ArcGIS is highly recommended along with the full consideration and implication of all of the impact criteria previously mentioned in section 3.4. As in the case of Arroyo Grande, the application of service demand, customer criticality, land use, traffic impact, pipe material phasing, and estimated total cost for repair as impact criteria into this risk assessment model resulted in the identification of 6 specific water mains that posed a high risk of failure in the city's water distribution system. This outcome was highly favorable in that the model accurately identified and classified the various pipe risk levels while only focusing attention on 6 out of the total 3,572 individual pipe segments.

In the event that another municipality wishes to implement this risk assessment model into the evaluation of pipe conditions within their potable water distribution system, it is highly recommended that all parameters outlined in this model be treated as a minimum standard, as well as necessary criteria, for proper and effective analysis of their hydraulic network.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Evaluation of Results

At the conclusion of this study, it has become clearly evident that the condition-based risk assessment model featured in this analysis can be effectively applied to a real water distribution system. Furthermore, the individual components involved in this model proved to be highly practical and applicable for most municipalities in the United States. The only real limitation that this risk assessment model may experience is the availability of comprehensive data pertaining to the individual pipe segments in their water distribution system.

Furthermore, the use of computer aided modeling software such as WaterCAD V8i or ArcGIS is highly recommended to ensure a proper application of this risk assessment to any water distribution system. The use of these modeling programs would help to ensure efficient use of time and capital funds in the event that a municipality implements this risk assessment model for their own personal use. ArcGIS, or some form of geographic information systems software, is highly recommended to be used in conjunction with this risk assessment model. Use of ArcGIS with this model guarantees a streamline modeling strategy that is fully compatible with all of the risk assessment parameters, tables, and figures previously mentioned in this study. Most importantly, the use of ArcGIS will allow municipalities to present the results of this risk assessment model in a graphical appealing and visual simplified manner for all stakeholders and professionals.

6.2 Assessment of the Reliability of Data

Given that the hydraulic information pertaining to the Arroyo Grande water distribution system was originally provided by Water Systems Consulting, Inc., in collaboration with the City of Arroyo Grande, it is in the best interest of this study to acknowledge that the sources of this hydraulic information are highly reliable and highly applicable to the goals previously set forth over the course of this study. The basis of this risk assessment model was built upon the original WSC condition-based risk assessment model that was specially designed for the Arroyo Grande water distribution system. However, given that the original model was incomplete and it was never fully applied or verified against real water distribution data. The successful results of this study would not have been possible if it was not for the combined efforts and the aid provided by Water Systems Consulting, Inc. and the City of Arroyo Grande.

6.3 Recommended Areas for Improvement and Future Research

Due to specific time constraints and limited academic resources, necessary assumptions had to be made during the development and application of this risk assessment model. In the event that more time is available for data acquisition, it is recommended that comprehensive data pertaining to traffic information be implemented into this risk assessment model. The original impact criteria in this study only considered roadway classes and routes for a particular city. However, if peak Average Daily Traffic values (ADT) were made available by that city's public works department, it would have promoted a stronger basis for evaluating and analyzing the possible effects that pipe failures and improvement projects may have on the city's daily traffic patterns.

Similarly, the bottom up pricing strategy implemented in estimating the total cost for pipe repair in this risk assessment model was a very simplified and conservative methodology. To promote a greater degree of accuracy and practicality, it would be much more favorable to conduct a top down pricing strategy for every pipe segment in a water distribution system, similar to the example created by WSC, Inc. in figure 3.2. By conducting a this type of pricing strategy rather than the bottom up strategy originally proposed in this risk assessment model, municipalities would be able to forecast a much more realistic cost for a particular pipe improvement project through the inclusion of monetary variables such as labor, hourly wages, and rental fees into this model. Depending on the information available for application in a top down pricing strategy, the rule of thumb is simply that a higher degree of accuracy and realism can be achieved in estimating the total cost of a project as long as there are a greater number of construction variables being accounted for.

Lastly, the overall accuracy of this risk assessment model can be further improved by enhancing the available pipe flow data. The demand values featured in this risk assessment model only represent peak average daily demand values. They were also extracted from a steady state hydraulic analysis of the Arroyo Grande water distribution system in Bentley WaterCAD V8i. If an extended period simulation (EPS) was implemented into this risk assessment model along with any available fire flow, daily demand patterns, or record of varying monthly pipe flows, then the increased complexity of the demand criteria would create much more favorable results. In other words, expanding the parameters involved in the service demand criteria would result in a much

more realistic and accurate representation of actual hydraulic flow patterns in a water distribution system.

The primary reason behind the simplified nature of the service demand criteria in this risk assessment model was due to an unfortunate, limited licensing situation that involved hydraulic modeling and simulation with WaterCAD V8i. It became quickly apparent that developing comprehensive demand criteria for this risk assessment model was not possible with the California Polytechnic State University's current WaterCAD license, which had a limited pipe simulation value of 1,000 or less. As a result, full hydraulic simulation of the Arroyo Grande water distribution system was not possible due to the fact that network was comprised of 3,572 pipe segments. However, despite this unfortunate set back, the enhancement of the original service demand criteria originally proposed in this risk assessment model is still very much possible, given a greater degree of time for research and upgrading necessary licensures for modeling software critical to this analysis.

Regardless of whatever improvement is to be implemented into the future development of this risk assessment model, the primary recommendation of this study would be to conduct the risk assessment of a municipality's potable water distribution system into a geographic information systems software such as ESRI's ArcGIS. The use of this program alone is incredibly invaluable in that it boasts a hefty collection of tools, graphical options, and analytical methods for use with this risk assessment model. Use of ArcGIS would not only provide the efficient use of time along with a stable and reliable basis for analysis, but it would also yield very desirable results that are easy to present and convey to a large audience.

Considering that there is an ever growing public appreciation for our environment along with a greater understanding for conservative efforts, use of ArcGIS with the condition-based risk assessment model would indefinitely yield positive results in the long run. Combined with the goal of developing a practical, easy to follow, and time efficient risk assessment model for analyzing and maintaining optimal pipe conditions within a water distribution system, the combined use of ArcGIS with this risk assessment model would indirectly promote a new way of thinking aimed by revolutionizing the way in which we as engineers, city planners, and business officials understand and manage our cities and our planet as a whole.

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APPENDICES

- A. Hydraulic Network Properties for the City of Arroyo Grande
- B. GIS Field Calculation and Python Equations
- C. Critical Customers within the City of Arroyo Grande

APPENDIX A

Hydraulic Network Properties for the City of Arroyo Grande

Due to the sheer magnitude and quantity of data pertaining to the Arroyo Grande water distribution system, including all of this information physically into Appendix A is quintessentially counterproductive and highly impractical. In order to preserve the integrity of this report along with special consideration towards the preservation of our environment, it is recommended that specific inquiries pertaining to pipe information from the entire Arroyo Grande water distribution system be redirected to the accompanying Excel file included with this digital report. This file is identified as ***Master Attributes Table.xlsx*** and it contains all applicable data values for each of the 3,573 individual pipe segments in the A.G. network.

On the contrary, Appendix A contains shorter, more condensed pipe data tables which pertain to the experimental results and model variations outlined in chapter 5. These tables only contain information on pipes that were identified as having a high risk of failure.

A1. Simulation Results from Chapter 5.1

Table ID	Full Name	Diameter (in)	Material	Installed	ASL	Pipe Age	RUL	Break Incidents	Percent Reduction	Adjusted RUL	PF Score	Final RFS
1	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6	10	170
2	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6	10	170
3	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10	180
4	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10	190
5	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10	180
6	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10	180
Table ID	Demand (gpm)	Demand (IS)	Critical Size? (≥8 inch)	Hospital	Nursing Home	Public Schools	Private Schools	Fire Station	Police Station	Shopping Center	Sum	Criticality (IS)
1	1.00	1	critical	1	2	2	1	1	1	1	9	3
2	1.00	1	critical	1	2	2	1	1	1	1	9	3
3	18.00	1	critical	1	2	1	2	1	1	1	9	3
4	16.00	1	critical	1	2	1	2	1	1	1	9	3
5	18.00	1	critical	1	2	1	2	1	1	1	9	3
6	18.00	1	critical	1	2	1	2	1	1	1	9	3
Table ID	Length (ft) rounded up	Price per Ft.	Estimated Repair Cost	Repair Cost (IS)	Material Phasing (IS)	Land Use (IS)	Traffic Impact (IS)	Demand (IS)	Criticality (IS)	Total IS	PF Score	Final RFS
1	18	55	\$990	1	4	3	5	1	3	17	10	170
2	43	55	\$2,365	1	4	3	5	1	3	17	10	170
3	8	50	\$400	1	5	3	5	1	3	18	10	180
4	411	50	\$20,550	1	5	4	5	1	3	19	10	190
5	32	50	\$1,600	1	5	3	5	1	3	18	10	180
6	114	50	\$5,700	1	5	3	5	1	3	18	10	180

A2. Simulation Results from Chapter 5.2 (Variation A)

Table ID	Full Name	Diameter (in)	Material	Installed	ASL	Pipe Age	RUL	Break Incidents	Percent Reduction	Adjusted RUL		Material Phasing (IS)	Traffic Impact (IS)	Criticality (IS)	Total IS	PF Score	Final RFS
1	VERNON ST	4.00	CIP	1929	75	84	-9	0	100%	-9		5	1	1	7	10	70
2	VERNON ST	4.00	CIP	1929	75	84	-9	0	100%	-9		5	1	1	7	10	70
3	W BRANCH ST	4.00	CIP	1929	75	84	-9	0	100%	-9		5	1	1	7	10	70
4	N ALPINE ST	4.00	CIP	1929	75	84	-9	0	100%	-9		5	1	1	7	10	70
5	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9		5	1	2	8	10	80
6	N ALPINE ST	4.00	CIP	1929	75	84	-9	0	100%	-9		5	1	1	7	10	70
7	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9		5	1	2	8	10	80
8	S TRAFFIC WY	8.00	GALV	1987	25	26	-1	0	100%	-1		4	1	2	7	10	70
9	TRAFFIC WY OFF-RAMP	8.00	GALV	1987	25	26	-1	0	100%	-1		4	1	2	7	10	70
10	W CHERRY AV	4.00	GALV	1982	25	31	-6	0	100%	-6		4	1	1	6	10	80
11	W CHERRY AV	4.00	GALV	1982	25	31	-6	0	100%	-6		4	1	1	6	10	80
12	FAIR OAKS AV	2.00	GALV	1982	25	31	-6	0	100%	-6		4	1	1	6	10	80
13	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6		4	5	3	12	10	120
14	FAIR OAKS AV	2.00	GALV	1982	25	31	-6	0	100%	-6		4	1	1	6	10	80
15	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6		4	5	3	12	10	120
16	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9		5	5	3	13	10	130
17	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9		5	5	3	13	10	130
18	CHILTON ST	6.00	GALV	1970	25	43	-18	0	100%	-18		4	1	1	6	10	70
19	CHILTON ST	2.00	GALV	1970	25	43	-18	0	100%	-18		4	1	1	6	10	70
20	CHILTON ST	2.00	GALV	1970	25	43	-18	0	100%	-18		4	1	1	6	10	70
21	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9		5	5	3	13	10	130
22	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9		5	5	3	13	10	130
23	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9		5	1	2	8	10	80

Continued to next page...

A4. Simulation Results from Chapter 5.2 (Variation B)

Table ID	Full Name	Diameter (in)	Material	Installed	ASL	Pipe Age	RUL	Break Incidents	Percent Reduction	Adjusted RUL	PF Score
1	VERNON ST	4.00	CIP	1929	75	84	-9	0	100%	-9	10
2	VERNON ST	4.00	CIP	1929	75	84	-9	0	100%	-9	10
3	W BRANCH ST	4.00	CIP	1929	75	84	-9	0	100%	-9	10
4	N ALPINE ST	4.00	CIP	1929	75	84	-9	0	100%	-9	10
5	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9	10
6	N ALPINE ST	4.00	CIP	1929	75	84	-9	0	100%	-9	10
7	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9	10
8	S TRAFFIC WY	8.00	GALV	1987	25	26	-1	0	100%	-1	10
9	TRAFFIC WY OFF-RAMP	8.00	GALV	1987	25	26	-1	0	100%	-1	10
10	W CHERRY AV	4.00	GALV	1982	25	31	-6	0	100%	-6	10
11	W CHERRY AV	4.00	GALV	1982	25	31	-6	0	100%	-6	10
12	FAIR OAKS AV	2.00	GALV	1982	25	31	-6	0	100%	-6	10
13	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6	10
14	FAIR OAKS AV	2.00	GALV	1982	25	31	-6	0	100%	-6	10
15	FAIR OAKS AV	8.00	GALV	1982	25	31	-6	0	100%	-6	10
16	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10
17	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10
18	CHILTON ST	6.00	GALV	1970	25	43	-18	0	100%	-18	10
19	CHILTON ST	2.00	GALV	1970	25	43	-18	0	100%	-18	10
20	CHILTON ST	2.00	GALV	1970	25	43	-18	0	100%	-18	10
21	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10
22	FAIR OAKS AV	8.00	CIP	1929	75	84	-9	0	100%	-9	10
23	N ALPINE ST	8.00	CIP	1929	75	84	-9	0	100%	-9	10

APPENDIX B

GIS Field Calculation and Python Equations

B.1 Pipe Age

$$\text{Pipe age} = 2013 - [\text{Installed}]$$

B.2 Calculating Anticipated Service Life (ASL)

```
def function (MATERIAL):  
    if (MATERIAL == 'ACP'):  
        return 100  
    elif (MATERIAL == 'PVC'):  
        return 100  
    elif (MATERIAL == 'STL'):  
        return 40  
    elif (MATERIAL == 'DIP'):  
        return 100  
    elif (MATERIAL == 'CIP'):  
        return 75  
    elif (MATERIAL == 'GALV'):  
        return 25  
    elif (MATERIAL == 'COMP'):  
        return 50  
    else:  
        return 50
```

B.3 Calculating Remaining Useful Life (RUL)

$$[\text{ASL}] - [\text{Pipe_Age}]$$

B.4 Break History Percent Adjustment

```
def function (Break_Issu):  
    if (Break_Issu == 1):  
        return 0.3  
    elif (Break_Issu == 2):  
        return 0.2  
    elif (Break_Issu == 3):  
        return 0.1  
    else:  
        return 1
```

B.5 Calculating the Adjusted RUL

$$[\text{Precent_Ad}] * [\text{RUL}]$$

B.6 Calculating Probability of Failure (PF) score

```
def function (ARUL):  
    if (ARUL >= 20):  
        return 1  
    elif (ARUL >= 17):  
        return 2  
    elif (ARUL >= 14):  
        return 3  
    elif (ARUL >= 12):  
        return 4  
    elif (ARUL >= 10):  
        return 5  
    elif (ARUL >= 8):  
        return 6  
    elif (ARUL >= 6):  
        return 7  
    elif (ARUL >= 4):  
        return 8  
    elif (ARUL >= 2):  
        return 9  
    elif (ARUL < 2):  
        return 10
```

B.7 Calculating Price per Linear Foot-ACP

```
def function(DIAM):  
    if (DIAM == 2):  
        return 30  
    elif (DIAM == 4):  
        return 42  
    elif (DIAM == 5):  
        return 48  
    elif (DIAM == 6):  
        return 55  
    elif (DIAM == 8):  
        return 64  
    elif (DIAM == 10):  
        return 69  
    elif (DIAM == 12):  
        return 77  
    elif (DIAM == 14):  
        return 87  
    elif (DIAM == 16):  
        return 98  
    else:  
        return 0
```

B.8 Calculating Price per Linear Foot-CIP

```
def function(DIAM):  
    if (DIAM == 2):  
        return 10  
    elif (DIAM == 4):  
        return 18  
    elif (DIAM == 6):  
        return 32  
    elif (DIAM == 8):  
        return 50  
    elif (DIAM == 12):  
        return 123  
    else:  
        return 'error'
```

B.9 Calculating Price per Linear Foot-COMP

```
def function(DIAM):  
    if (DIAM == 2):  
        return 30  
    else:  
        return 0
```

B.10 Calculating Price per Linear Foot-DIP

```
def function(DIAM):  
    if (DIAM == 8):  
        return 22  
    if (DIAM == 10):  
        return 24  
    elif (DIAM == 14):  
        return 40  
    elif (DIAM == 16):  
        return 50  
    else:  
        return 'error'
```

B.11 Calculating Price per Linear Foot-GALV

```
def function(DIAM):  
    if (DIAM == 2):  
        return 11  
    elif (DIAM == 4):  
        return 26  
    elif (DIAM == 6):  
        return 40  
    elif (DIAM == 8):  
        return 55  
    else:  
        return 'error'
```

B.12 Calculating Price per Linear Foot-PVC

```
def function(DIAM):  
    if (DIAM == 2):  
        return 2  
    if (DIAM == 3):  
        return 4  
    elif (DIAM == 4):  
        return 5  
    elif (DIAM == 6):  
        return 8  
    elif (DIAM == 8):  
        return 12  
    elif (DIAM == 10):  
        return 19  
    elif (DIAM == 12):  
        return 28  
    elif (DIAM == 14):  
        return 33  
    elif (DIAM == 16):  
        return 43  
    else:  
        return 0
```

B.13 Calculating Price per Linear Foot-STEEL

```
def function(DIAM):  
    if (DIAM == 8):  
        return 138  
    else:  
        return 0
```

B.14 Critical Pipe Sizes for Consideration

```
def function (DIAM):  
    if (DIAM >= 8):  
        return 'critical'  
    elif (DIAM < 8):  
        return 'NC'
```

B.15 Summation of Critical Customers

$[Hospital] + [Nursing_H] + [School_Pub] + [School_Pri] + [Shopping_C] + [Fire_Stn] + [Police_Stn]$

B.16 Calculating Criticality Impact Score (IS)

```

def function(sum):
    if (sum == 7):
        return 1
    if (sum == 8):
        return 2
    if (sum == 9):
        return 3
    if (sum == 10):
        return 4
    else:
        return 5

```

B.17 Calculating Estimated Total Cost for Repair Impact Score (IS)

```

def function (RepairCost):
    if (RepairCost < 26440):
        return 1
    elif (RepairCost >= 26440 and RepairCost < 52882):
        return 2
    elif (RepairCost >= 52882 and RepairCost < 79322):
        return 3
    elif (RepairCost >= 79322 and RepairCost < 105762):
        return 4
    elif (RepairCost >= 105762):
        return 5

```

B.18 Calculating Service Demand Impact Score (IS)

```

def function(Demand):
    if ( Demand < 160.00):
        return 1
    elif ( Demand >= 160 and Demand < 320):
        return 2
    elif ( Demand >= 320 and Demand < 480):
        return 3
    elif ( Demand >= 480 and Demand < 640):
        return 4
    elif ( Demand >= 640):
        return 5

```

B.19 Calculating Pipe Material Phasing Impact Score (IS)

```
def function(MATERIAL):  
    if (MATERIAL == 'PVC'):  
        return 1  
    elif (MATERIAL == 'ACP'):  
        return 1  
    elif (MATERIAL == 'DIP'):  
        return 2  
    elif (MATERIAL == 'CIP'):  
        return 3  
    elif (MATERIAL == 'STL'):  
        return 4  
    elif (MATERIAL == 'COMP'):  
        return 4  
    elif (MATERIAL == 'GALV'):  
        return 5  
    else:  
        return 0
```

B.20 Calculating the final Risk of Failure Score (RFS)

$$([LandUseIS] + [Phase_IS] + [Repair_IS] + [Demand_IS] + [Traffic_IS] + [Crticality]) * [Prob_Fail]$$

APPENDIX C

Critical Customers within the City of Arroyo Grande

C.1 Fire Stations

C.2 Hospitals

C.3 Nursing Homes

C.4 Police Stations

C.5 Private Schools

C.6 Public Schools

C.7 Shopping Centers