Minimizing the Risk Exposure Resulting from Asset Failures for Water/Wastewater Facility Owners

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Abstract

MINIMIZING THE RISK EXPOSURE RESULTING FROM ASSET FAILURES FOR WATER/WASTEWATER FACILITY OWNERS

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Infrastructure is the foundation upon which a viable civilization is built. It is necessary to advance the economy and to sustain society's basic needs. The infrastructure around the world is aging, but is not being maintained at a level that is keeping pace with deterioration. Some organizations have adopted Asset Management Programs in an effort to keep track of their assets and make predictions as to when assets will fail. Asset management programs are useful and have improved the position of facility owners, but do not specifically address the problem of business risk exposure caused by assets failing while in service. Prior research in this area has addressed the likelihood of failure, but has not looked at true risk to the system. The consequence of failure has always been an afterthought. Past work has also depended heavily on past system failures to address future failures and prediction. The goal of this research was to develop a framework that can be used to prioritize infrastructure maintenance and/or replacement by reducing the

total system risk using information from the Asset Management Plan. An optimization model was developed that utilizes the likelihood of failure and the consequence of those failures to identify the total risk to the system. The model was run for different scenarios to determine what segments should be replaced to remove the greatest amount of risk from the system given some set amount of spending on the system. The framework developed by this work addresses an important gap in utility system maintenance and replacement prioritization.

1 Introduction

1.1 Background

The infrastructure of America is crumbling and in need of vast repair and modernization. The American Society of Civil Engineers (ASCE) gives the American infrastructure a grade of “D” and states that the country is falling far behind with regard to the level of investment that is being made on repair and replacement of the infrastructure (ASCE, 2009). ASCE proposes that $2.2 trillion is needed over the next five years to raise the grade to a more acceptable level (D to B). In an effort to improve the grade of the infrastructure, utility facility owners must get better at asset management and recognize the optimal time to repair and/or replace assets. While utility owners seek to make investments in their facilities, a delicate balance must be achieved when replacing facilities so as not to waste much useful life of the assets. However, it is important to replace assets before they fail in service. An in-service failure may cost more than the useful life lost due to early replacement. Owners must determine if the cost of replacement is more than the benefit gained by that replacement.

The research and validation of this paper will focus on Water Mains. The needed investment in water mains to maintain the current level of service is estimated to be at least $1 trillion over the next 25 years (AWWA, 2011). Figure 1 displays the investments that have been made in water infrastructure from 1870 up to 2000. As can be seen in the graphic, it should not be a surprise that many of the water lines have reached or are reaching the end of their useful lives. Planning for the replacement of these lines will become more and more important in order to avoid costly emergency repairs and other ancillary costs that go along with in service failures.

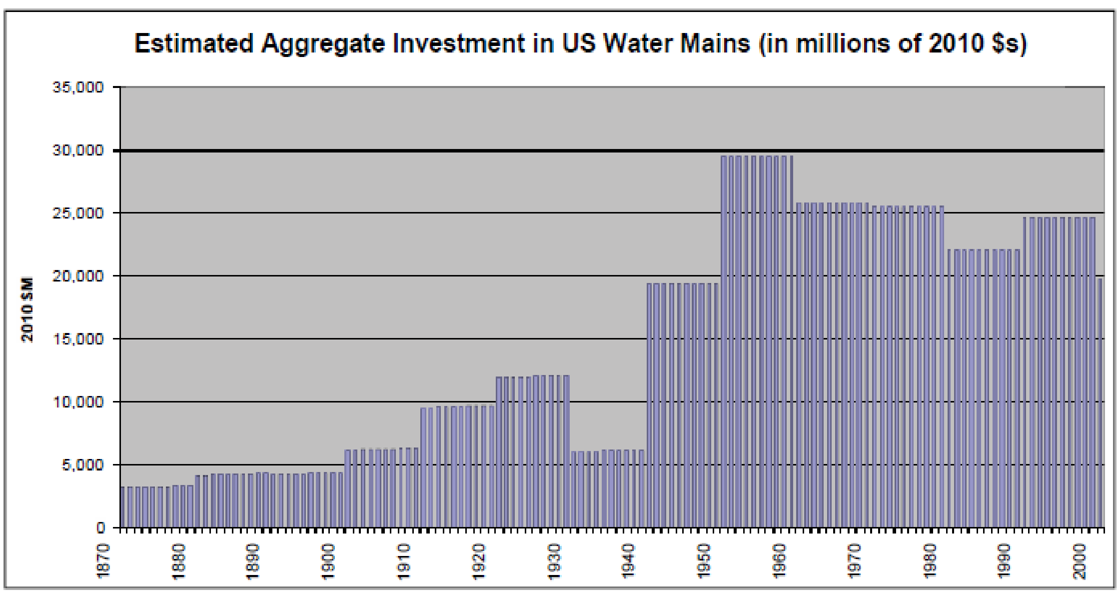


Figure 1 Historical Investment in Waterlines in US (AWWA, 2011)

Table 3 shows the locations of the needed investments which include replacement and expansion needs. This graphic also specifies the different types of pipes that will need to be replaced and expanded in order to maintain the current level of service. Figure 2 is a graphic of the cost of replacement needs by region.

Table 1 Needed Investment in Waterline Replacement and Expansion over the next 25 Years (AWWA, 2011)

Region	CI	CICL	DI	AC	PV	Steel	PCCP	TOTAL
Northeast Large	48,958	8,995	5,050	2,308	1,875	335	0	67,522
Northeast Medium & Small	66,357	61,755	28,777	26,007	16,084	5,533	6,899	211,411
Northeast Very Small	14,491	15,992	10,661	7,281	7,937	329	462	57,152
Midwest Large	37,413	9,151	3,077	2,504	1,098	784	512	54,539
Midwest Medium & Small	74,654	92,106	51,577	37,248	30,506	8,682	11,152	305,925
Midwest Very Small	37,597	28,943	25,464	12,428	19,720	601	828	125,581
Southeast Large	30,425	28,980	29,569	21,229	14,936	9,337	7,227	141,703
South Medium & Small	54,772	98,608	140,079	103,659	102,804	21,394	17,160	538,475
South Very Small	43,183	24,998	49,791	34,529	47,823	1,461	1,244	203,028
West Large	15,448	16,055	28,949	14,774	14,723	7,443	6,215	103,607
West Medium & Small	15,775	50,145	70,355	50,541	48,885	12,276	9,806	257,782
West Very Small	16,344	11,199	17,910	13,166	17,245	545	453	76,862
Total	455,416	446,927	461,258	325,674	323,637	68,719	61,957	2,143,589

CI: cast iron; CICL: cast iron cement lined; DI: ductile iron; AC: asbestos cement; PV: polyvinyl chloride; PCCP: prestressed concrete cylinder pipe

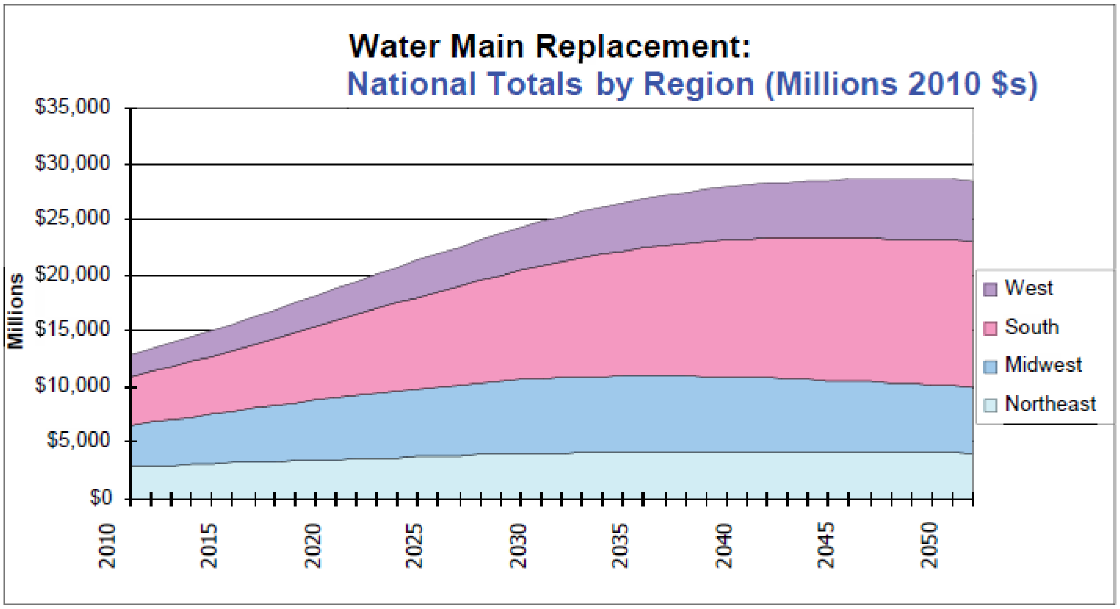


Figure 2 Water Main Replacement Cost Totals by Region (AWWA, 2011)

Asset management programs have evolved over the last 10-20 years and this evolution has helped improve the planning and operating of infrastructure facilities. Asset management programs are used by utilities to store and manage information about the infrastructure facilities. Investment strategies for particular facilities are determined. Decisions for replacement, repair or some other alternative are recommended.

Australia, New Zealand, the United Kingdom, and the Water Resource Consortium have utilized asset management practices for many years. These countries and organizations have reported benefits from the collection and management of data related to their infrastructure facilities. Australia and New Zealand have been pioneers of asset management and most utility asset management programs around the world are based on these programs. Asset management programs aid the utilities in setting broad goals concerning the level of service commitment and specific goals that guide how levels of service should be achieved. The ability to establish these goals is dependent upon the collection, sorting, processing and utilization of system information for planning, managing, and operating the organization's facilities. The tools that comprise the asset management program record and store physical attribute information of the assets that deliver the organization's services. The tools are also used to manage the maintenance efforts, condition assessments, risk management and capital planning. One other important use of the information stored in the databases within the asset management program is the identification of owned facilities and their valuation, which in turn is used to derive a total value of the organization (USEPA, n.d.).

A good asset management program can help utility owners better service the needs of the customer and increase or maintain profitability of the organization by improving the reliability of the system, planning better for capital improvements and facility expansions, and improving the ability to deal with supply and demand balance. An asset management program that provides spatial information about the facilities of the organization can help predict locations that are highly problematic (Wood et al., 2006; 2007).

Many asset management programs are utilized to identify where the highest level of facility threats exist. This information is then used to develop work plans or capital improvement programs to minimize the maximum threat. Other factors are taken into consideration to help shape the ultimate planning such as other affected improvement programs, internal initiatives, capacity needs, future expansions, and internal business decisions to name a few. The asset management program also helps the facility owner become better at managing the business lifecycle process, shown in Figure 3, which is essential to controlling the ownership cost of facilities. Internal initiatives may or may not be related to the vulnerability of the system. Some of these might include growing the customer base through acquisitions; making visible facilities more aesthetically pleasing to the community; or upgrading accounting systems for better tracking of resources.

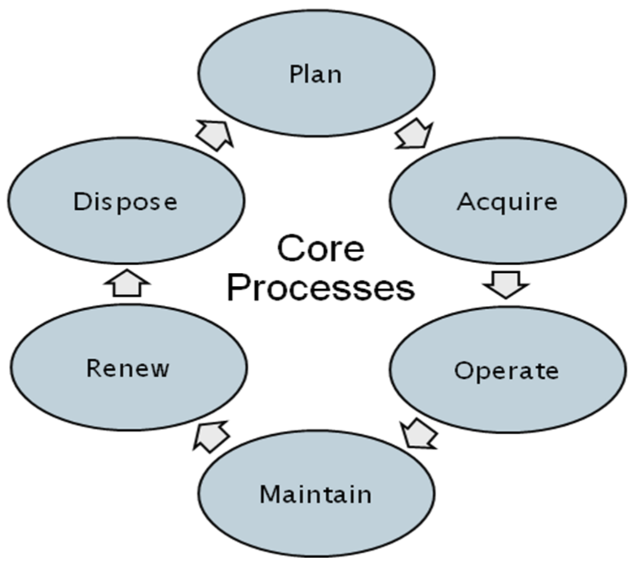


Figure 3 Infrastructure Life Cycle Business Process (Lewis, 2009)

1.2 Statement of the Problem and Research Questions

This research will address how to minimize the Business Risk Exposure (BRE) of a utility owner that it faces as a result of failing facilities. When facilities fail in service, the major cost of the failure is not necessarily getting the facilities back on line, but rather the damage to other property, loss of productivity, overall system contamination, and deterioration of customer confidence in the reliability of the system. Loss of life represents the most significant consequence. Owners need to know how the risk level of their system can be reduced without changing the adopted level of spending planned for repairs, upgrades and improvements. They need to understand how to optimally prioritize these plans to address the most risk to the system. This research is in response to this need. The research does not address natural and man-made threats which are addressed in the ANSI/AWWA J100 – Risk and Resilience Management of Water and Wastewater Systems (J100) standard. It focuses on deterioration threats which could enable the J100 to more fully address the risks associated with a water system operation.

The literature review will show significant progress has been made in the area of component failure. Methods for better predicting failure of utilities are well researched. One noteworthy effort is the work of Thomas Walski and Bentley Systems (2010), who have developed a hydraulic model that is used extensively in the water sector to optimize maintenance expenditures. The WaterGEMS tool looks at system criticality and helps direct system repairs based on system performance and how failures affect the hydraulic model. This tool does not, however, consider the impact that a failure has on the customer base. This gap is one that this research will fill.

Previous research has focused on the collection and analysis of failure data related to physical facilities and the environment in which they perform. Little has been done to investigate the performance of a water system as a whole. The objective of this research is to combine the knowledge gained from previous research on component failures with the consequences of these failures in an optimization model. In-service failures carry consequences at different levels for the facility owner whether it is reduced confidence in the services being provided, lost revenues through service interruptions, or payments for damages caused by the failure. This research effort will investigate how to minimize this risk by changing the manner in which maintenance projects are prioritized for implementation. The model that is being proposed is intended to show how the risk can be minimized without an increase in capital expenditures.

1.3 Research Hypothesis

The development of an optimization model will enable the evaluation of a variety of repair and maintenance scenarios and the risk factors associated with failures in the system. The model will identify the combination of repairs and replacements that minimize the total risk of failure for the utility system, subject to the limits of a predefined spending plan and costs associated with repair/replace options for each project. The model is adaptable to other infrastructure maintenance allocations for which component risk of failure is well understood. The process differs from that of most asset management programs in that the focus is on the Business Risk Exposure (BRE) of the organization. Factors that influence community confidence, convenience, health and human safety are addressed.

The service area priorities and the consequences of failure are incorporated into the model using a criticality index for water utilities similar to ones used for other civil infrastructure. For example transportation has developed an asset management based index that has been used to prioritize maintenance expenditures (WSDOT, 2011). Once the criticality index has been assigned, the predetermined spending plan will be utilized as a constraint in the optimization model with an objective to minimize the BRE. The asset management program will be utilized to identify the most critical and most vulnerable components of the system and ensure that these receive the appropriate attention. The model must decide between low risk – low cost options, low risk – high cost options, high risk – low cost options and high risk – high cost options. The benefits of maintaining a high risk asset are greater than the benefits of maintaining a lower risk asset. However, the costs associated with either repairing or replacing the asset must be included in the optimization. Low hanging fruit (high risk – low cost) options are selected first. A non-linear optimization model is developed to make decisions regarding the trade-offs for the other options.

The hypothesis is that utility owners can reduce the BRE of the organization by utilizing a model similar to the one that will result from this work to guide capital investments and maintenance expenditures in infrastructure facilities. Figure 4 outlines the steps that need to be taken to implement a successful asset management program. This research will focus on the assigning of a BRE rating or assessing the criticality of an asset by considering the consequences of an asset failing in service. The objective is to show that when the BRE is reduced, the organization will also see a reduction in the number and expenses associated with in-service failures of critical assets.

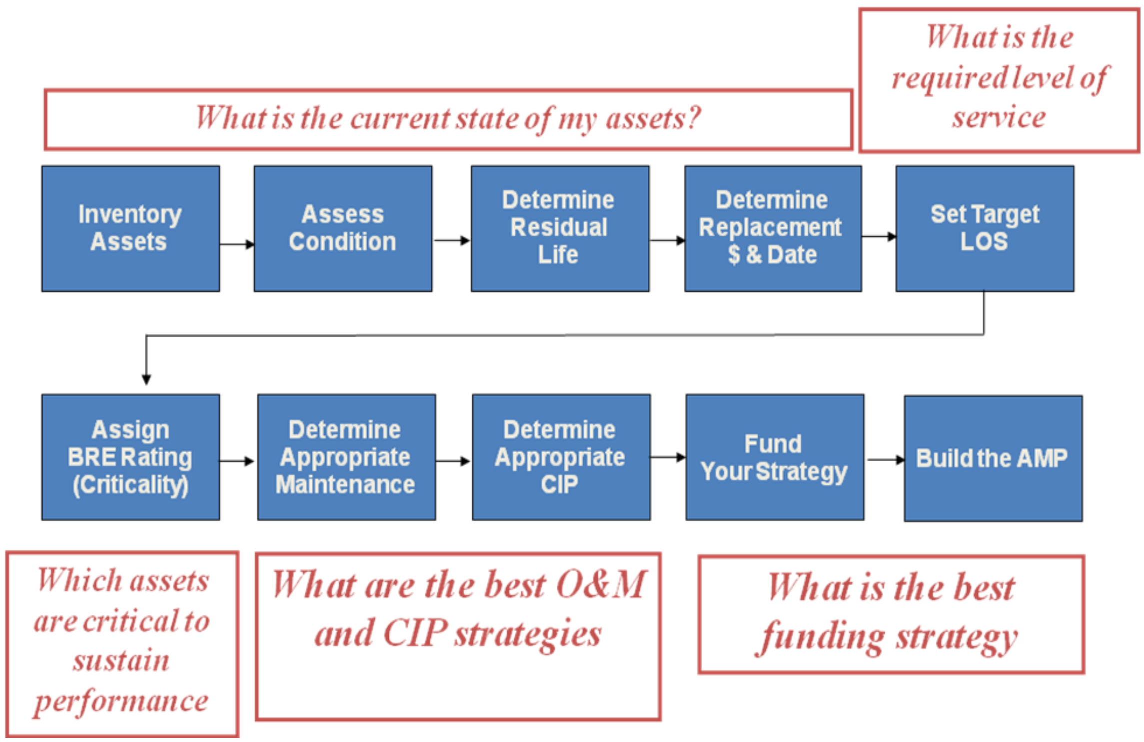


Figure 4 Asset Management Framework (Lewis, 2009)

1.4 Research Contribution

The contribution of this research will be to develop a model framework that can be used by facility owners to reduce BRE as it relates to the consequences of water facility failures. Other contributions include the development of consequence of failure and a likelihood of failure indices for the water sector. Once the consequences of failures are identified, understood and quantified, alternatives can be compared and better decisions can be made concerning the allocation of financial resources. As resources are allocated to minimize the severity of consequences, the overall BRE of the utility organization will be reduced.

The primary objective of this research is to create a model framework that can be utilized to minimize the overall risk to the organization by strategically identifying a maintenance and capital investment plan subject to budgetary limitations. This will lead to more financially sound organizations that can use the increased net revenues to expand, reduce rates, or upgrade technology. Implementation of a model that follows this framework will also lead to decreased downtime and fewer in-service failures, which cause disruptions in schedules associated with traffic flow, facility closings, and even product usage restrictions.

The approach used in the development of the model framework is applicable to transportation facilities, power grids, computer systems for controls, and other facilities that require maintenance or replacement prior to failure. This work aims to fill one of the missing gaps with current asset management research efforts. Specifically, the research demonstrates a framework for improving overall system health through the minimization of system BRE by carefully analyzing the consequences of failure. Current theories focus on optimizing performance as defined by hydraulic similarity to original design. The consequence of failure is not integrated into these models as related to customer needs.

The objective of the research is to reduce the overall BRE of the organization by identifying the consequences of failure for all parts of the system and minimizing the risk associated with the failure. The model is based on the premise that organizations can assign a criticality value to assets that when combined with an index that represents likelihood of failure, the overall risk can be quantitatively represented. An optimization model is developed with an objective of minimizing the overall BRE of the organization constrained by utilizing the planned level of investment into the system. This research supports the ideas promoted by USEPA (2008) that understanding the full life-cycle cost of a system can help a utility justify large capital expenditures for renewal programs and reduce costs by improving bond ratings (Qureshi and Shah, 2014).

2 Literature Review

2.1 Asset Management

Asset management has undergone continual improvements since it came into widespread use. As utility owners implement asset management programs, they typically go through the same continual improvement stages until a robust, informative asset management program is in place (Wood and Lence, 2006). In the primary years of a program, asset management mainly consists of trying to keep track of what assets a utility owns; in some cases, what the physical characteristics of these assets are; and how the assets have historically performed. As the organization becomes more comfortable with the processes of asset management, and wants to improve the value of the asset management program, additional information such as age of facilities, repair history, cost of installation, and cost of maintenance and repairs will be gathered and added to the database of the asset management program. This additional information is used to try to predict what might happen with the facility in the event of failure and what the cost of returning the facility to an operational state might be (Wood et al, 2007). While the costs of returning the system to operational status can be tremendous in terms of hard cost, the soft or social costs of system failure can also be costly. Some researchers place this cost at two times the actual repair cost (Piratla and Ariaratnam, 2013).

Australian, New Zealand, British, and Water Resource Consortium utility owners are far ahead of most U.S. organizations when it comes to understanding the importance of asset management and implementing the same. The Canadians are also far outpacing the U.S. on the utilization of effective asset management programs (Rose and Albee, 2009). The value of an asset management program has been recognized by many agencies within the U.S. federal government as well as several numerous state agencies. The U.S. Department of Transportation formed an office of Asset Management as part of its Infrastructure Core Business Unit within the Federal Highway Administration. They have developed an asset management primer aimed at charting a path for the organization to implement and utilize asset management to improve the overall condition of its assets over time (USDOT, 1999). The primer recognizes the importance of understanding the assets of the organization's system and recording the conditions of these assets. A good asset management program is useful for knowing what the condition of facilities is and helps decision makers know what should be expected to fail based on condition ratings (Wood and Lence, 2006). While there is still much more work and information needed to utilize the collected information for reducing risk to the system, an effort can be made to improve the condition ratings when assessments are made and recorded. Improving the system in this way can be looked upon more as reactive rather than proactive as most improvements are made based on past failures (Duncan and Allbee, 2009). The implementation of an asset management program will include some analysis as well, including cost/benefit analysis, efficiency analysis, and some risk analysis. Over time, the asset management tool being utilized should begin to drive decisions on maintenance, replacement, and preventive maintenance of facilities (Wood et al, 2007).

Efforts to make predictions have been limited in scope and have traditionally only focused on asset failure and primarily considered historical performance of the facility and not the operating environment. It is a fact that any asset put into service will eventually fail (Singh and Adachi, 2013). Failure can happen in many ways and does not always mean that the facility is no longer functional and can no longer deliver the product that it was designed and constructed to deliver. Failure can be an inability to meet capacity demands, an inability to meet current regulatory requirements, a lack of confidence in the system causing customers to seek to fill the need in some other manner, or it could indeed mean a physical breakdown of the facility and its inability to perform the functions for which it was installed (Rose and Allbee, 2009). The actual failure of a facility being one day, two days, one month, or ten years from some point in time cannot be known for certain, but the probability of the failure happening can be derived utilizing information that is collected as part of a good asset management program and by understanding the service conditions of the facility (Lewis, 2009).

Extensive research has been performed and equations developed to develop failure prediction methods. One widely utilized approach is to utilize a Power Law form of a Non-Homogenous Poisson Process (NHPP). In this Power Law approach, the cumulative number of expected failures, $M(t)$, between time 0 and t and the intensity function are expressed as (Mays, 2004):

$$M(t) = \lambda * t^{\beta} \quad \mathbf{1}$$

$$u(t) = \frac{dM(t)}{d(t)} = \lambda * \beta * t^{\beta - 1} \quad \mathbf{2}$$

Where:

M	=	Cumulative number of expected failures
u	=	Intensity Function
t	=	Time
λ	=	Scale Factor
β	=	Shape Factor

The scale term provides the measure of the magnitude and the shape factor provides an indication of the system condition. Scale factors exceeding 1 (β >1) indicates an increasing failure rate which likely means the system is approaching wear out. A factor between 0 and 1 (0< β <1) suggests that the failure rate is decreasing. This is often the case if the system is being adjusted or perhaps going through burn in. A shape factor of 1 (β = 1) is a sign of constant failure rate. This is also known as Homogenous Poisson Process (HPP). Now, knowing that the intensity functions measures failure rate, integrating Equation 2 over time (t_1, t_2) would give the expected number of failures over this period:

$$E(t_1, t_2) = \int_{t_1}^{t_2} u(t)dt = \lambda * t_2^{\beta} - \lambda * t_1^{\beta} \quad \mathbf{3}$$

Another relationship that is always interesting when addressing pipe replacement prioritization is the time to next failure. When dealing with a Power Law process, the waiting time to the next failure takes on a Weibull CDF. If there is failure time T, then Equation 4, below, is solved to determine the time t at which the CDF yields a probability of 1, which indicates a failure:

$$F(t) = 1 - e^{-[\lambda (T+t)^{\beta} - \lambda * T^{\beta}]} \quad \textbf{4}$$

Equation 4 can also be used to determine the probability of failure of the system as it ages from some arbitrary time t to t+dt. The time T shown in Equation 4 is normally shown as time t in the arbitrary case because this is known failure time:

$$P(t, t+dt) = 1 - e^{-[\lambda (t+dt)^{\beta} - \lambda * t^{\beta}]} \quad \textbf{5}$$

Further knowing that Equation 5 represents the probability that a pipe will experience a failure between time t and t+dt, the compliment of this equation can be applied to determine the reliability of the pipe that it can age from time t to time t+dt without a failure:

$$R(t, t+dt) = 1 - e^{-[\lambda (t+dt)^{\beta} - \lambda * t^{\beta}]} \quad \textbf{6}$$

Finally in order to solve Equations (3) – (6) for the expected number of failures, time to next failure, probability, and reliability estimates, the values of λ and β must be estimated using the pipe break data. For example, a single pipe with starting time 0 and ending time t_0, the λ and β terms are approximated using the maximum likelihood estimates (Crow, 2004):

$$\lambda = \frac{n}{t_0^{\beta}} \qquad \textbf{7}$$

$$\beta = \frac{n}{n\ln(t_0) - \sum_{i=1}^{n}\ln(t_0)} \qquad \textbf{8}$$

Where:

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

Researchers have also worked to develop curves to explain asset failure and to help guide the need for rehabilitation or replacement. These curves are general in nature and attempt to exhibit the changes that should be noticed in assets, particularly those that are visible and can easily be observed in service (Rose and Albee, 2009). Two of these curves are shown in Figure 5 and Figure 6. Figure 7 shows a survival curve for a steel pipe used by Nagel and Elenbaas in their 2006 work. This is a typical curve showing the stages of life that a pipe goes through from the installation to failure. Owners should take note of these changes and perform maintenance as needed to prevent in service failures. Singh and Adachi (2013) looked at bathtub curves and failure rates of various material types and sizes of pipes in an effort to provide insight as to the expected life of different classes of facilities. A typical bathtub curve is shown in Figure 8 depicting the three distinct phases of these assets: early life, useful life, and wear out. The first phase has high failures that show up in early usage, the second phase has low failure rates and are relatively random and unexpected, and the final phase has high failures as facilities have aged and deterioration has set in.

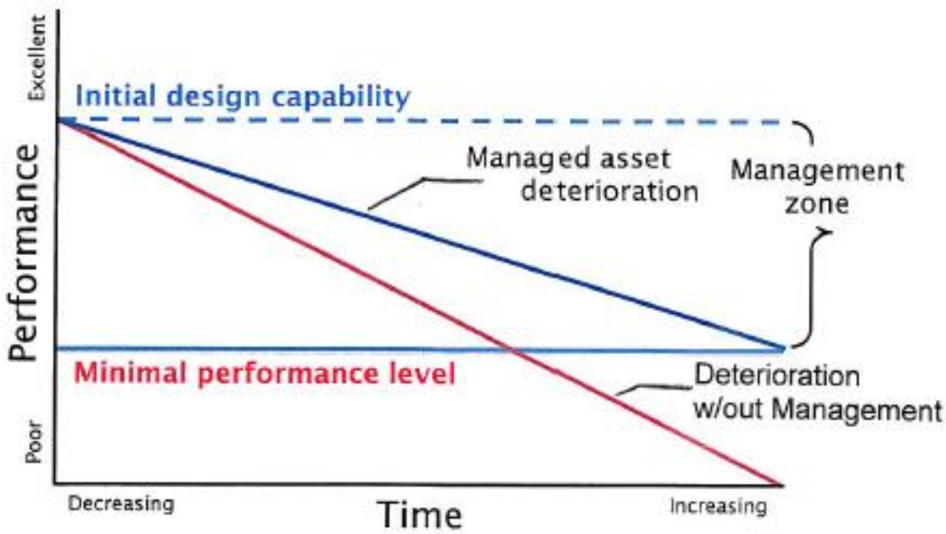


Figure 5 Example Asset Deterioration Curve and LOS Monitoring (Rose and Albee, 2009)

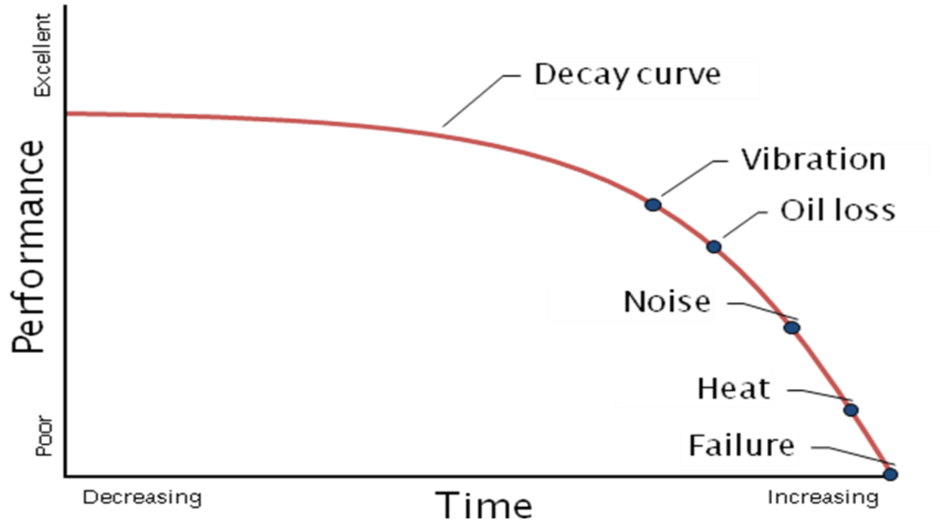


Figure 6 Example Asset Deterioration Decay Curve (Rose and Albee, 2009)

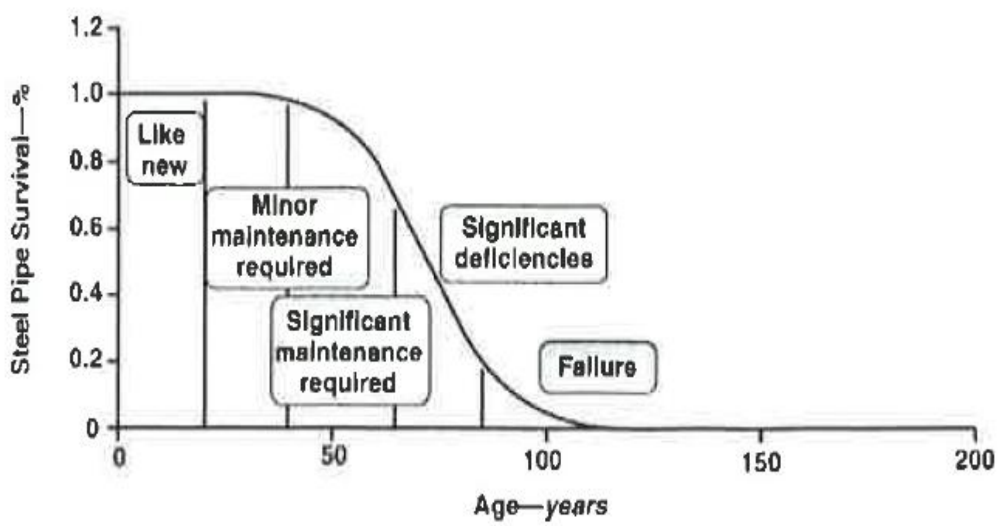


Figure 7 Sample Survival Curve

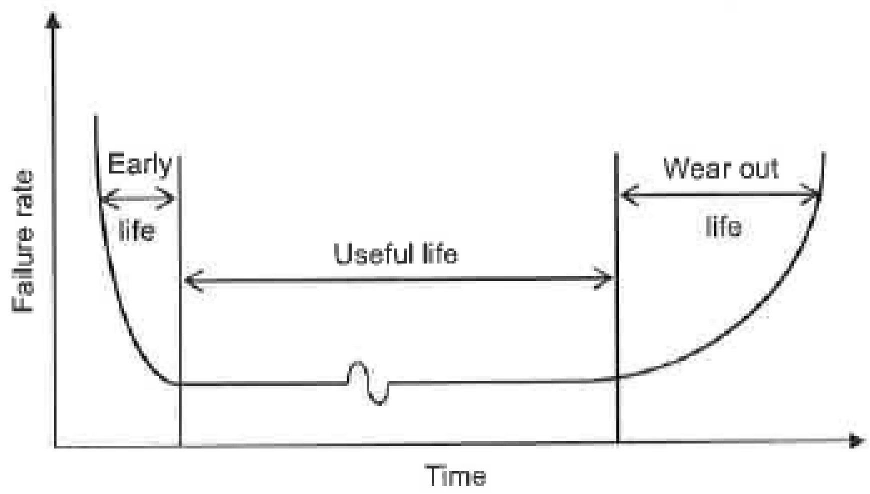


Figure 8 Bathtub Curve for the Life Cycle of a Buried Pipe

A predictive model for the probability of asset failure due to deterioration is:

$$P = 1 - \frac{UL - EUL}{UL} \qquad \mathbf{9}$$

Where:

P	Probability of failure due to deterioration
UL	Estimated Useful Life – asset based primarily on past performance and operating conditions
EUL	Expended Useful Life – the amount of used useful life based primarily on time in service, and operating conditions

And the risk of failure (R) can be defined as:

$$R = T * V * C \qquad \mathbf{10}$$

Where:

T	**Threat:** Probability that a given event will occur. A threat is defined as any known mechanism or hazard that could result in the failure of the asset. Threats can be of natural or man-made origin and include floods, hurricanes, tornadoes, terrorist actions, accidents, deterioration, etc.

V	**Vulnerability**: Probability that the asset will fail as a result of the given threat.
C	**Consequence** of Failure – magnitude of the failure. The consequence can be measured in monetary units, loss of life, or other scale that represents the level of adversity caused by the asset failure.

The standard developed for the water and wastewater industry is the ANSI/AWWA J100 – Risk and Resilience Management of Water and Wastewater Systems (J100). The J100 outlines several methods to estimate the probability of a threat depending on the origin or nature of the threat. Threats addressed by the J100 are either a malevolent threat or a natural hazard threat. Malevolent threats are those that are manufactured or man-made and are typically intentional. However, accidental breakages are also taken into consideration. Accidental damage that cripples a system is no less problematic than damage that is intentionally inflicted. Natural Hazard threats result from events such as hurricanes, tornadoes, floods or earthquakes. For malevolent threats probability is estimated by a proxy measure, best estimate, or conditional assignment. A proxy measure is based on the attractiveness of the region. For example highly urbanized regions are considered to be more likely targets than less populated areas. Landmarks, financial institutions and other symbolic facilities are similarly considered to be likely targets. A best estimate is based on the facility owner's knowledge of past activities and the details surrounding past attacks. A treatment plant that has a history of vandalism or rogue operator attacks will have a higher likelihood of similar events occurring in the future. A conditional assignment sets the likelihood to 1.0 (as directed by J100) and is useful for evaluating the results of a worst-case scenario. The probability of natural hazard threats are based on established models that predict the probability of future incidents (AWWA 2010).

The focus of the J100 is on man-made and natural threats. It does not address the threat to deteriorating assets due to natural aging. In Equation 9 above, P represents the probability of failure due to deterioration. This threat begins as soon as assets are placed in service and continues to increase in likelihood as assets age. Assets become increasingly vulnerable to this threat as they meet and exceed the useful life. This threat is part of the risk (R) calculation in Equation 10.

The aging of infrastructure and the lack of programs and commitment of replacement/repair funds is a critical threat to system performance (ASCE, 2011). Many systems around the country are dealing with assets that are seventy, eighty, and even over one hundred years old. Chelan, Washington reports the use of a six inch wood pipe for potable water delivery (Cooper, 2009). The bulk of water and sewer lines beneath American Streets were installed in three phases: At the end of the 19th century, in the late 1920s, and just after World War II, all following periods of population growth in cities and expansion into suburbs (Yardley, 2007). This is critical information to consider as water mains fail mostly due to deterioration (Piaratla and Ariaratnam, 2013) and the age of many global assets suggest advanced deterioration. ASCE currently predicts an $84 billion annual deficit in water infrastructure needs (CH2MHill, 2013). The estimated 240,000 water main beaks per year are expected to rise as assets continue to be in use well beyond the estimated useful life (Cooper, 2009). A recent ASCE report (2011) suggests that an investment in water/wastewater infrastructure is needed to avoid personal income losses of $541 billion.

Approximately 65% of the water industry has adopted an asset management program that supports four or more functions (CH2MHILL, 2013). The need to address the poor condition of the water infrastructure is the primary driver behind this adoption. Increased fiscal pressure on the water utilities further supports the need for an asset management system. Wood and Lence (2006) provide an approach for the collection and categorization of water asset data for evaluating and managing water main breaks. Their methods were based on information gathered from surveys sent to approximately 337 small, medium, and large US and Canadian utilities. Their findings showed that very little data was available for asset failure (Wood and Lence, 2006).

The National Research Council (NRC, 2005) identifies water main breaks as a water supply health risk. Wood et al (2007) identify the need for a quantifiable approach that will help to identify urgent water system repair needs to help minimize the risks to the system. Regardless of the renewal method used, all decisions about infrastructure renewal are based on risks (Grigg, 2005).

2.2 Deterioration Modeling

There are several different methods for identifying the vulnerability of a pipe network to deterioration failure:

- Deterioration Point Assignment (DPA) methods
- Break-even analysis
- Mechanistic analysis
- Regression and Failure Probability methods

In a DPA model a set of factors that are known to contribute to facility failure are identified and given a point value. These factors can include pipe size, pipe age, pipe material, location of installation, break history, and quality of installation to name a few. Once the scores of each factor are determined, the score for each pipe is added up. If the score exceeds some pre-determined threshold, then that pipe is considered in the candidates for replacement or rehabilitation (Rogers and Grigg, 2006).

The breakeven analysis uses an economic model to determine the present worth costs of a pipe as it relates to the future life of the pipe and its repair and eventual replacement costs. This method must be supplemented by a regression or probability based model in order to predict future breaks of the pipe (Rogers and Grigg, 2006).

Mechanistic models attempt to relate the structural processes of the pipe such as temperature-induced stressed, pressure loads, and frost loads as well as interior and exterior corrosion caused by soil properties, pipe coatings, and water quality parameters to pipe failure. There have been many advances in modeling, but the complexity of pipe failure and the different factors that influence it is still not completely understood. These methods do not always yield dependable results (Rogers and Grigg, 2006).

Regression models attempt to identify break patterns and develop curves that can be used to predict future breaks based on historical breaks. Once the break patterns are determined, future breaks can be predicted based on the patterns and curves. Shamir and Howard (1979) applied linear and exponential regression techniques to obtain a breakage rate relationship based on time. They also used the costs associated with repairs and breakage rates to develop a break-even analysis to determine the optimal year for replacement. Walski and Pelliccia (1982) proposed a model similar to Shamir and Howard (1979), but used a correction factor based on pipe size and material. Then Walksi (1987) further improved on previous research by developing a cost model for replacement which accounted for lost water due to leakage and broken valves (Rogers and Grigg, 2006).

In addition to models, mechanical means such as electronic stress gauges and sonar listening setups are used to predict pipe failures. Electronic stress gauges are usually installed on the surface of pipes or embedded into the pipe walls. When certain levels of stress are recorded from the gauges, the run of pipe is evaluated and an appropriate action is decided. Sonar listening set-ups require that the pipes be wrapped with a wire mesh and a sound pattern established. A change in pattern predicts a failure. Periodic checking of the facilities is required with the use of this technology. Both method have had limited success, but has not always allowed adequate time to react to failure warnings. In some tests, the failure of the first wire causing the change in tones was followed immediately by failure of additional wires leading to a catastrophic failure of the facility in lab tests. The time between the first failure and the catastrophic failure was not long enough to allow preparation or planning for the failure of the facility (Sinha, 2009).

Additional work concerning the management of assets and improving the ability to make systems more reliable has been published by Halfway, Vanier and Hubble (2004) in which they promote the need to integrate information systems into asset management. This process is becoming more popular as more municipalities move towards GIS systems. Bentley reports approximately 90% of water/wastewater utilities use GIS (Baird, 2010). GIS allows for a display of the pipe breaks for easy identification of clusters. The geographical display of pipe breaks can be used to support the need for repair or replacement and also help to identify other public facilities of concern (schools, nursing homes, hospitals, etc.) that are in close proximity to the breaks (Halfway, Vanier, and Hubble, 2004).

St. Clair and Sinha (2012) studied the water pipe deterioration phenomena and existing models. Results of their research suggest a gap between the models published in literature and those used in modern asset management systems. Independent variables that affect the deterioration are identified and the use of these variables in over 50 models is presented. The consensus of pipe modeling experts shows the following variables contribute significantly to pipe failure: physical (size, material type, and age); geographical (soil, corrosion, field samples, paving and redevelopment); hydraulic (Hazen Williams C-factor, fire flow and operational pressure); maintenance (breaks and leak rates); and quality of service/reliability (discolored water and outage rates) (St. Clair and Sinah, 2012). The different approaches to modeling and predicting deterioration fall into six categories: deterministic, statistical, probabilistic, advanced mathematical models including artificial neural networks (ANN), fuzzy logic, and heuristic. The conclusion and need identified by St. Clair and Sinha (2012) are for a standardized and agreed upon definition of failure and for a model(s) to be developed that can be utilized by utilities to make predictions and guide the renewal, repair, and replacement process.

In a landmark study, AWWA (2011) investigated the factors affecting useful life in pipes including material type, installation method, operating environment, and age. Figure 9 shows the fabrication and installation of water lines based on materials and availability. It is useful to know that all materials have not been readily available during certain periods of system installations and expansions thereby leading to different types of material being utilized for systems. The material selected has a direct effect on the life of the system and the likelihood of in-service failures. AWWA (2011) further summarized the effects of pipe material, soil type, vibration, manufacturing method and quality, installation method, and service environment on estimated useful life for different regions of the country as shown in Table 2 Clark et al, (2010) also show results indicating that pipe diameter effects pipe failure rates. Larger pipes generally have lower failure rates.

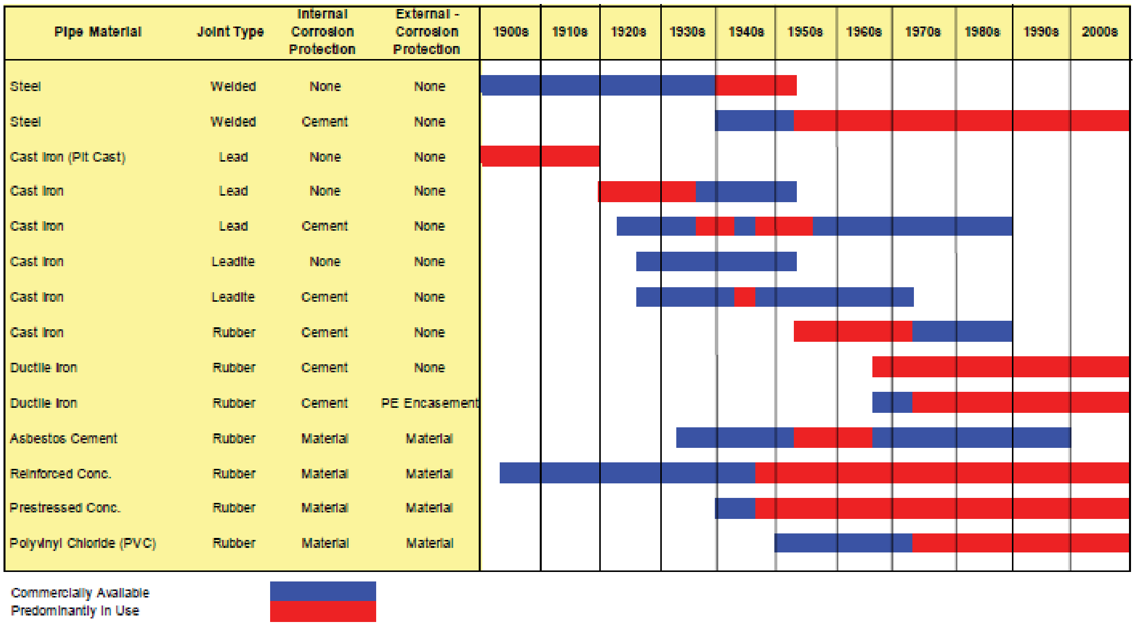


Figure 9 Historic Production and Use of Water Pipe by Material (AWWA, 2011)

Table 2 Average Estimated Service Lives of Pipe Materials (average years of service) (AWWA, 2011)

Derived Current Service Lives (Years)	CI	CICL (LSL)	CICL (SSL)	DI (LSL)	DI (SSL)	AC (LSL)	AC (SSL)	PVC	Steel	Conc & PCCP
Northeast Large	130	120	100	110	50	80	80	100	100	100
Midwest Large	125	120	85	110	50	100	85	55	80	105
South Large	110	100	100	105	55	100	80	55	70	105
West Large	115	100	75	110	60	105	75	70	95	75
Northeast Medium & Small	115	120	100	110	55	100	85	100	100	100
Midwest Medium & Small	125	120	85	110	50	70	70	55	80	105
South Medium & Small	105	100	100	105	55	100	80	55	70	105
West Medium & Small	105	100	75	110	60	105	75	70	95	75
Northeast Very Small	115	120	100	120	60	100	85	100	100	100
Midwest Very Small	135	120	85	110	60	80	75	55	80	105
South Very Small	130	110	100	105	55	100	80	55	70	105
West Very Small	130	100	75	110	60	105	65	70	95	75

LSL indicates a relatively long service life for the material resulting from some combination of benign ground conditions and evolved laying practices etc.
SSL indicates a relatively short service life for the material resulting from some combination of harsh ground conditions and early laying practices, etc.

Johnson (2005) presents a model developed by Brown and Caldwell for predicting asset failures for the Seattle Public Utilities. In this study, a Weibull curve was fitted to the historical data (Johnson, 2005). The consequences of failure are not incorporated into the funding decision; this is a significant weakness in the Brown and Caldwell study's model. Similarly asset failure predictions are based on historical data thus exposing the utility to the consequences associated with elevated future risks.

Work done by Liner, Binning and Gardner (2009) identifies the need and presents a conceptual approach for the incorporation of a dynamic risk assessment approach into the funding of water line improvements. The authors look at optimization techniques for budget planning based on the vulnerability of the system. The authors suggest planning maintenance budgets based on reducing vulnerability to the system will yield preferred results. Nagel and Elenbaas (2006) developed a method for prioritizing projects to improve system reliability by assessing the overall vulnerability of the proposed projects and prioritizing decisions based on the assessments.

A final approach to improving system reliability and decreasing the total cost of ownership is through design. Cunha and Sousa (2007) argue that optimal performance can be gained by optimizing the system design for materials and environment. The limitation to this approach is that it can only be applied to new designs or system replacements.

3 Methodology

3.1 Research Objectives

The objective of this research is to develop an optimization model that will enable the evaluation of a variety of repair and maintenance scenarios combined with the consequences of infrastructure failure. A risk index is developed to reflect both the likelihood of failure and consequence of these failures. A repair and replacement strategy for the system is developed by minimizing the sum of the total risk indices subject to a predetermined spending plan. This nonlinear model framework is adaptable to other infrastructure maintenance applications for which component risk of failure is well understood.

This chapter will discuss the methodology used in the development of the model and associated parameters. The methodology and case study used to demonstrate and validate the model are also presented.

3.2 Failure and Consequence Indices

As discussed in the literature review, risk is defined as the possibility of loss or injury (Webster, 2011). Risk is defined by the EPA (2008) under the Check Up Program for Small Systems (CUPSS) as the product of two indices that represent probability of failure and consequence of failure. The EPA uses the information to generate a Risk Matrix similar to the example shown in Figure 10. A detailed description of the CUPSS methodology is provided in Appendix A. The methodology uses indices on a 10 point scale that represent both probability of failure and consequence of failure.

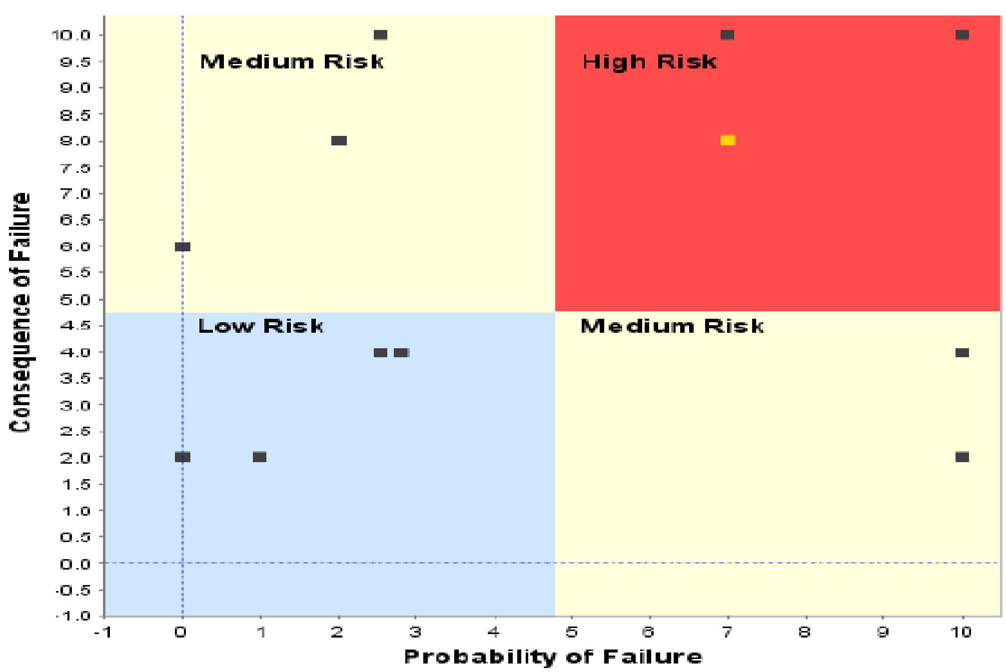


Figure 10 Risk Matrix (EPA, 2008)

Vulnerability is defined as capable of being physically or emotionally wounded and as being open to attack or damage (Webster, 2011). It is important to distinguish the difference between risk and vulnerability. The National Oceanic and Atmospheric Administration (NOAA) Coastal Service Center says that "Risk areas identify geographically those areas most likely to be affected by a given hazard. People and resources located within the risk areas are considered to be at risk from hazards and may or may not be vulnerable to hazard impacts. The vulnerability of the people and resources within the risk areas is a function of their individual susceptibility to the hazard impacts" (OSC-NOAA, n.d.). In order to perform a vulnerability assessment, the hazards that need to be evaluated, must be determined. This research is based on the concept of risk minimization. As such, both the likelihood of a service disruption and the consequences associated with the disruption must be combined to reflect the interests of the public utility.

The model for this work will be based on a DPA model. As described in the literature review, in a DPA model a set of factors that are known to contribute to facility failure are identified and given a point value. These factors can include but are not limited to pipe size, pipe age, pipe material, location of installation, break history, and quality of installation. Scores for each factor are assigned and the sum of these is the score for each pipe segment. If the score exceeds some pre-determined threshold, then that pipe is considered in the candidates for replacement or rehabilitation (Bates and Gregory, 1994).

Figure 11 is a flow diagram of traditional optimization or replacement prioritization models. Contemporary models are driven by economics and seek to minimize either total cost or lost revenues.

As mentioned in the literature review, several problems exist with the current methodologies. Most notably the probability of failure analyses are inaccurate and in some cases do not produce actual probabilities. In addition the existing models do not incorporate the consequences of failures with the likelihood of failure. Consequently the true risk related to failure of the system is not reflected in the current models.

Figure 12 illustrates a framework that forms the basis of this research. Notably, the differences are the inclusion of an index based approach to quantifying risk and the explicit inclusion of the consequences in the development in the risk index. While consideration is given to the financial impacts, importance is also placed on the societal costs associated with failures such as reduced system confidence, public health and safety, political agenda, and damage to other infrastructure.

According to Thomas Walksi of Bentley Systems (2014), the framework as described in Figure 12 provides a complement to the work that Bentley's WaterGems model performs. WaterGems predicts system failures based on parameters such as past failures, pipe size, pipe length, and pipe materials which are entered into the model. The model optimizes the repair and replacement strategy based on the option that provides the minimum difference from the original hydraulic design and performance. WaterGems does not address system reliability from a consequences standpoint. The framework staged by this research is the first step in bridging the gap between the WaterGems model (and other similar models) and societal needs.

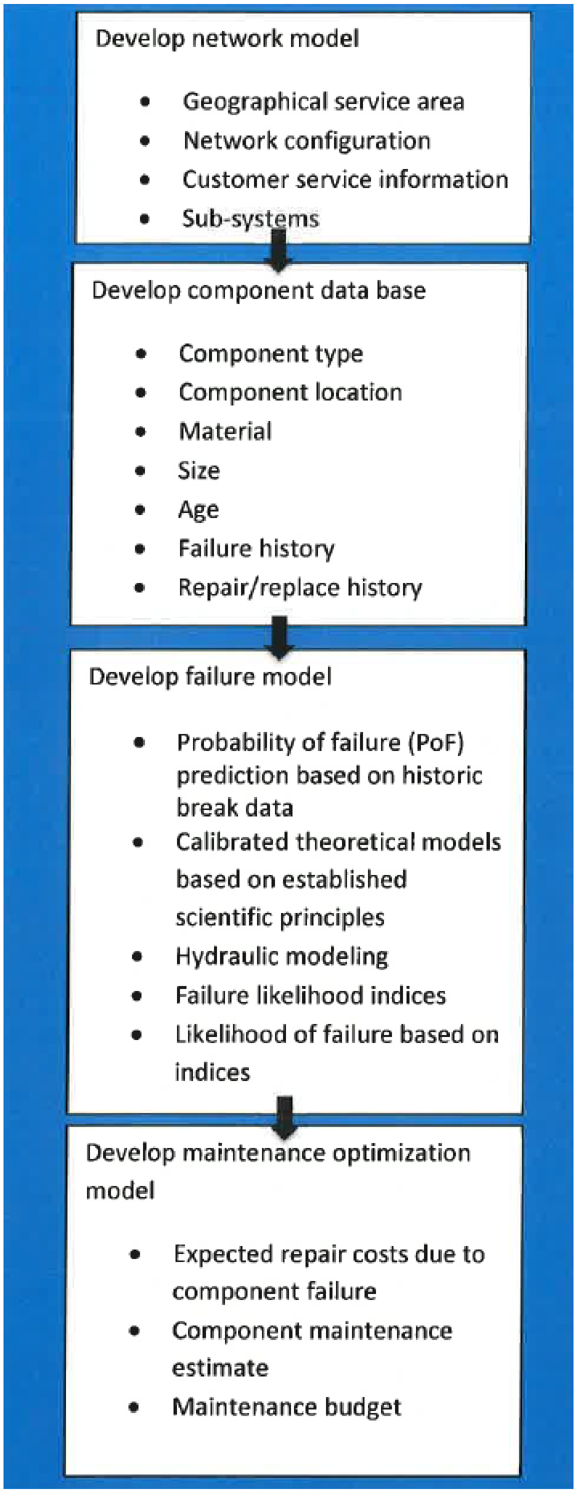


Figure 11 Current Optimization Frameworks (Optimize based on economics)

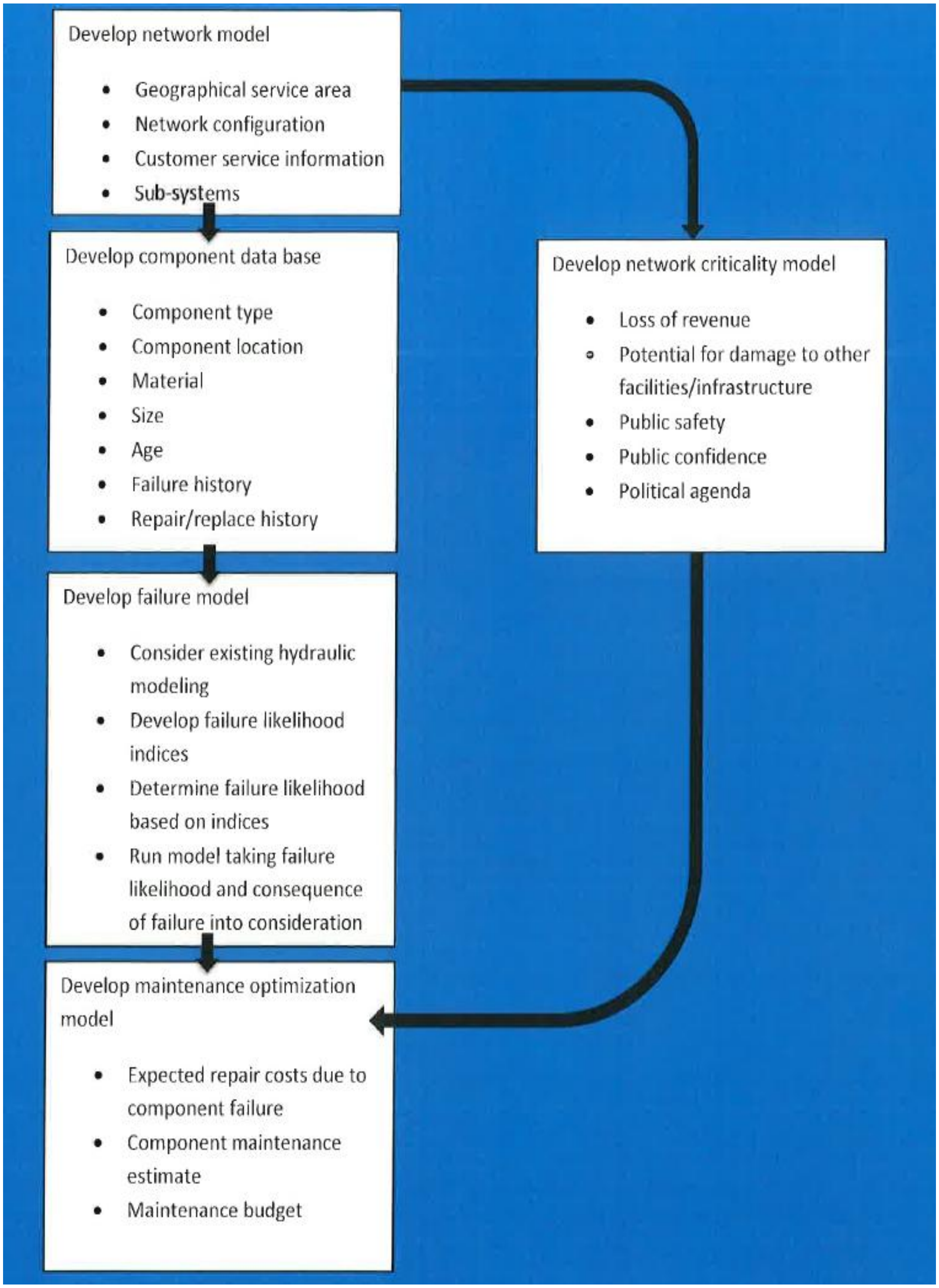


Figure 12 Proposed Optimization Framework (Optimize based on criticality index)

Because of the aforementioned problems associated with probability of failure models, this research incorporates the development of the following three indices:

- Failure Likelihood Index
- Consequence of Failure Index
- Business Risk Exposure (BRE) Index

The failure likelihood and consequence of failure indices are on 1 to 5 point scale. The BRE index is on a 25 point scale. The indices were developed using a survey approach.

Similar to the work performed by Rogers and Grigg (2008), consideration was given to using a predictive model based on a Power Law form of a Non-Homogenous Poisson Process (NHPP). Utilization of this approach, discussed in chapter 2, requires that pipes have at least three (3) break records in order to perform a meaningful analysis and solve Equation 8. Pipes with zero (0) breaks cause the model to become unsolvable and thus yield no results. In the Rogers and Grigg model, the consequences of failure were only considered after the failure probabilities are ranked. Thus only pipes with a high likelihood of failure are considered for repair and replacement. Pipes with a moderate probability of failure and significant consequences are never prioritized for replacement. These pipes present a relatively high risk to the utility as compared with pipes that display the characteristics of a high probability of failure and a low to moderate consequence of failure. In this research, the BRE index acts as a surrogate for risk. It is calculated as the product of the likelihood of failure and the consequence of failure indices. To develop a measure of the business risk exposure for the entire system, the component failure index and the failure consequence index are combined in the manor shown in the following equation:

$$SRE = \sum_{i=1}^{n} BRE_i = \sum_{i=1}^{n} L_i C_i \qquad \textbf{11}$$

Where:

SRE	= Utility System Risk Exposure
BRE_i	= Business Risk Exposure Index for subsystem i
L_i	= Likelihood of Failure Index for subsystem i
C_i	= Consequence of Failure Index for subsystem i
i	= Index of subsystems
n	= Number of subsystems in the utility system

Use of the indices resolves the limitations posed by the lack of realized breaks in many of the pipes in the system. The likelihood of failure index was developed by assigning a point value to each variable that has an effect on the life expectancy of a pipe as shown in Table 3. The variables selected were based on the results of the literature review. The City of Manassas was used as a case study to test the capabilities of the model. The consequence of failure index was developed in a similar manner.

For this study, the likelihood of failure and the consequence of failure indices were chosen to be linear. A scale could be developed that is non-linear allow more weight to be place on certain parameters and consequences. Development of a non-linear index table would change the weighting of a risk table. For example a 4 likelihood with a

2 consequence would be located differently on an index table than a 2 likelihood with a 4 consequences. The focus of this work was to develop a framework for utilizing an index and linear indices were chosen. The indices could have been made non-linear as well.

The specific model characteristics such as the pipe sizes, pipe materials, age, subsystem definition and other system assets were based on the City of Manassas water system. The consequences selected for the study were also based on information for the City of Manassas water system and include the following: impact on local businesses, traffic patterns, sensitive populations (hospitals, nursing homes, etc.) and public confidence. Values were assigned to the likelihood and consequences (on a 5 point scale) based on information gained from the survey as discussed above. The actual values for the indices assigned to system components and sub-systems are shown in Table 4.

Table 3 Likelihood of Failure Index Values

Likelihood							
Rating	Break history over last 12 months	Breaks per 1000 ft	% Expected useful life expended	No. of valves/fittings per 100 ft of line	Material	% of connections covered by redundancy	Largest affected size of pipe
5	>10	>5	>125	> 20	1950 – 1960 DI	0	≤3”
4	>7 to 10	≤4	>110 to 125	>15 to 20	1880 – 1950 Iron	>0 to 20	> 3” to 8”
3	>3 to 7	≤3	>95 to 110	>10 to 15	1960 – 1980 Iron 1920 – 1950 Plastic	>20 to 40	>8” to 12”
2	>1 to 3	≤3	>80 to 95	>5 to 10	1950 – 1990 Plastic	>40 to 80	>12” to 24”
1	>1	≤1	≤80	≤5	Post 1990 Plastic or Iron	>80	>24”
Note: DI = Ductile Iron; Iron = Ductile Iron, Cast Iron, or Steel; Plastic = PVC or CPVC							

Table 4 Consequence of Failure Index Values

Consequences						
Rating	Loss or Destruction	Deaths or Injuries	Media Coverage or Regulatory Investigation	Service Interruptions	Traffic Pattern Disruption	Loss of Sales or Water
5	>$5M	≥2 Deaths	National Media and/or federal investigation	Total cessation of service > 7 days and >2 months of critical service disruptions	Normal traffic disruptions for > 7 days	Loss of sales or product equal to >75%of affected area
4	>$100K to $5M	1 death or ≥2 serious injuries	State Media and/or state investigation	Total cessation of service for >1 to 7 days and >1 to 2 months of critical service disruptions	Traffic disruptions for >1 to 7 days	Loss of sales or product equal to >50% to 75% of the affected area
3	>$10K - $100K	1 serious injury	Regional Media and/or regional investigation	Total cessation of service for up to 1 day and >1 to 2 months of any service disruptions	Disruption of traffic for >8 – 24 hours	Loss of sales or product equal to >25% to 50% of affected area
2	>$2K - $10K	Any non-serious injury	Local Media and/or local investigation	Minor disruptions for up to 1 month of any customers	Disruption of traffic for up to 8 hours	Loss of sales or product ≤ 25% of affected area
1	≤$2K	0 injuries	No media and no investigation	No disruption of service	No traffic disruptions	No loss of sales or product
Note: All consequences are expected results that would result from failure						

3.3 Industry Survey

To assign the point values for the likelihood of failure and consequence indices, a survey of industry professionals was conducted. A Likert scale was used to solicit the feedback from the survey participants. The survey and procedures for data collection were reviewed and approved by the George Mason University Institutional Subject Review Board (IRB). It is recorded and assigned Exempt Protocol #8507 with the IRB. Survey questions are listed in Appendix B.

The questions focus on the relative importance of different factors that are known to influence system failure. The factors were derived from the literature review and include such things as pipe size, pipe material, failure history, installation procedure, and age. The questions also asked the survey participants to rate the significance of failure consequence factors including ease of repair, death and injuries, and media coverage.

For each of the failure consequences identified, five levels were predetermined based on a review of literature and information obtained from the City of Manassas. These were assigned values between 1 and 5 with 1 being the least significant and 5 being the most significant. It should be noted that other values could be added to reflect the values of the consequences, but a 1 to 5 allocation was used for model illustration purposes.

Table 3 and Table 4 above define what each index score will mean for this study and shows the information sought from the survey. There were 33 water professionals invited to take the survey including elected officials, appointed utility board members, water system managers, water system operators, and design professionals. Of those invited 16 responded which included three elected officials, two appointed utility board members, six system managers, three system operators and two design professionals. This group provided a representative cross section of professionals involved in the operation and decision making of a water distribution system. As can be seen from the invited and responding participants, the survey was sent to all levels of the organization. As such, the responses reflect a variety of responsibilities. Individuals with" hands on" experiences to individuals that make final financial decisions were included.

The values of the median Likert scores are weighted based on the responses to the relative importance for each pipe characteristic to determine the likelihood of failure index. The consequence index was based solely on the median score of the relative importance.

3.3 Model Development

Asset management has focused on gathering and cataloguing information about facilities. The information has been used to make predictions as to what facilities carry the highest likelihood of failure; how reliable the system is, based on system attributes and past performance; and what the cost would be to return the system to an operational level in the event of a failure. An effective asset management program must consider the consequences of failures to truly reflect the desires of elected officials, the public, and system operators. To test the effectiveness of the system risk exposure index (SRE), a model was developed using the City of Manassas, Virginia, as a case study.

To determine the optimal repair and replacement strategy, models for three scenarios were developed. The LINGO© optimization software produced by LINDO™ Systems Inc. was used to generate the results for each of the three optimization models. The mathematical models and the scenarios that they represent are presented below.

Scenario 1: Minimize System Risk Exposure (SRE)

$$
\begin{aligned}
&Min : SRE \\
&s.t. \\
&\sum_{i=1}^{n} j_i R_i \leq Budget \\
&SRE = \sum_{i=1}^{n} j_i L_i C_i \\
&j_i \in \{0,1\} \forall_i
\end{aligned}
$$

Where:

SRE	=	Utility System Risk Exposure
L_i	=	Likelihood of Failure index in subsystem i
C_i	=	Consequence of Failure Index for subsystem i
i	=	Index of subsystems
n	=	Number of subsystems in the utility system
R_i	=	Repair or replacement cost for subsystem i ($)

j_i = Indicator variable for repair or replacement of subsystem i

$j_i = 0$ when no repair or replacement is planned

$j_i = 1$ when repair or replacement is planned

Budget = Utility repair and replacement budget for the upcoming year

Scenario 2: Minimize the total Likelihood of Failure (L)

$$
\begin{aligned}
&Min : L \\
&s.t. \\
&\sum_{i=1}^{n} j_i R_i \leq Budget \\
&L = \sum_{i=1}^{n} j_i L_i \\
&j_i \in \{0,1\} \forall_i
\end{aligned}
$$

Scenario 3: Minimize the total Consequences of Failure (C)

$$
\begin{aligned}
&Min : C \\
&s.t. \\
&\sum_{i=1}^{n} j_i R_i \leq Budget \\
&C = \sum_{i=1}^{n} j_i C_i \\
&j_i \in \{0,1\} \forall_i
\end{aligned}
$$

Where:

SRE = Utility System Risk Exposure

L_i = Likelihood of Failure index in subsystem i

C_i = Consequence of Failure Index for subsystem i

i = Index of subsystems

n = Number of subsystems in the utility system

R_i = Repair or replacement cost for subsystem i ($)

j_i = Indicator variable for repair or replacement of subsystem i

$j_i = 0$ when no repair or replacement is planned

$j_i = 1$ when repair or replacement is planned

Budget = Utility repair and replacement budget for the upcoming year

These scenarios represent the added framework shown in Figure 12 above. The model will optimize the sum of the SRE indices for the subsystems in the case study. Figure 13 shows a map for a portion of the water system for the City of Manassas, the area selected for the case study. Appendix C contains a listing of the likelihood of failure and the consequence indices for each segment of pipe as raw data.

To test the strength of the model, several scenarios were optimized. The first scenario minimizes the SRE subject to various funding limitations (as shown in Figure 12). The second scenario minimizes the sum of the likelihood of failure indices. This scenario represents the current methodology (Figure 11) in which the consequence of failure is not considered. The last scenario minimizes the sum of the consequence of failure indices. The idea of this scenario was to represent the preferences of elected officials.

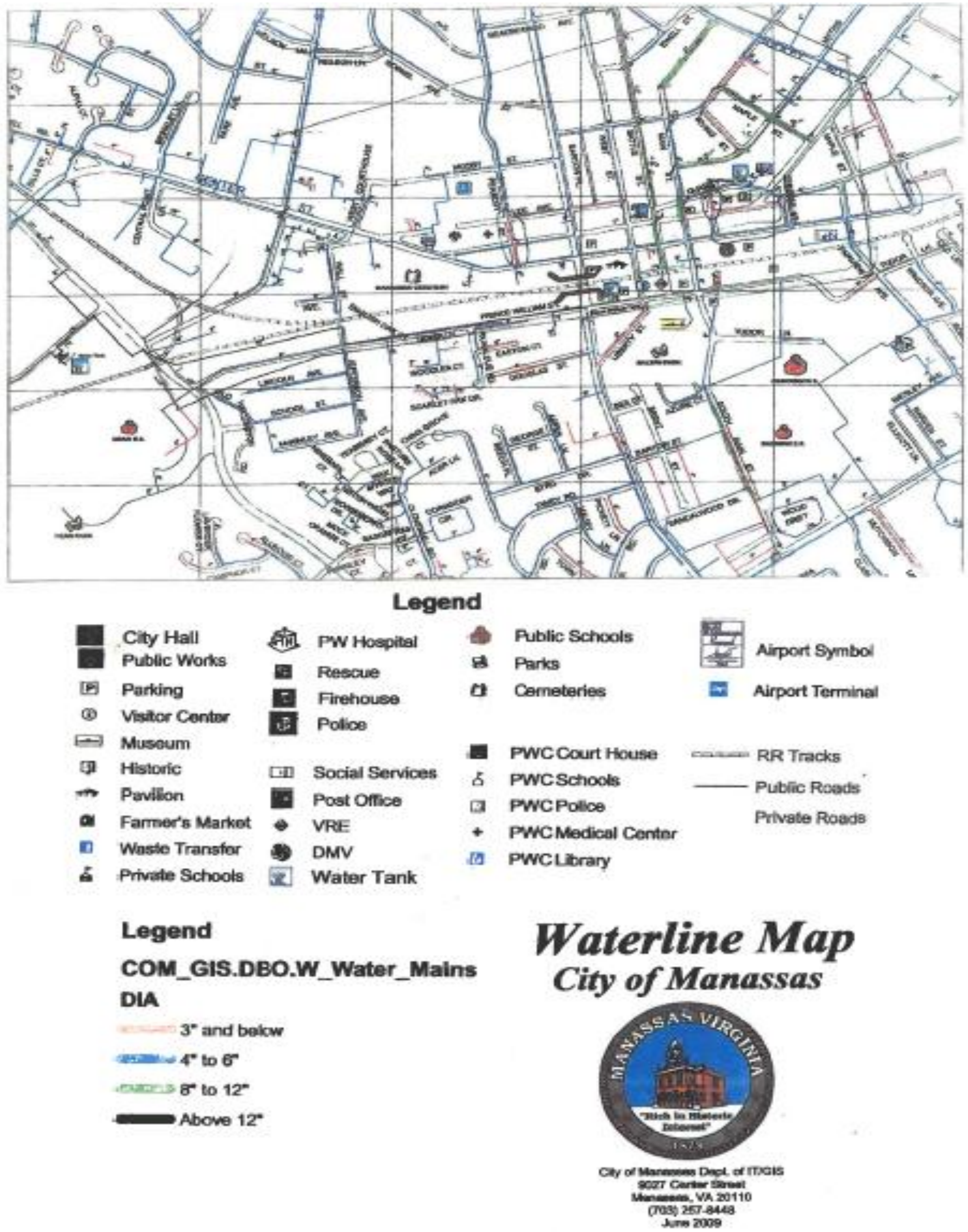


Figure 13 Partial Map of City of Manassas Water System

The model was run for data from the period of 1985 through 2012. For each scenario, the model was run sequentially. The results were assumed to be implemented and the breaks that occurred outside of the repair or replacement scenario were recorded and tabulated. To validate the model, the breaks averted were compared to the actual breaks that were experienced by the City. It was assumed that if the repair or replacement was called for in the model, the break would have been averted. Additionally, the cost averted was determined by comparing what the City spent with what the model suggested.

Pipe failures have a dramatic effect on system maintenance in two major ways: they take away from crews doing routine scheduled maintenance and they take away from funds for planned replacements. According to data from Fairfax Water, the average unplanned emergency replacement costs 2.7 times that of the average non-emergency repair between 2010 and the present (Kingsbury, 2014) . In the model, a value of 1.5 was selected as the multiplier for unplanned emergency replacement work. It was felt that this number would be conservative and not overestimate the value of the model cost savings.

To further validate the model, data were gathered from the Washington Suburban Sanitary Commission (WSSC) for the Laurel, Maryland, water system. Appendix C contains a map of the study area and a listing of the pipe segments. The likelihood of failure index and consequence index for each pipe segment are listed as raw data in this appendix also. The values for the consequences are surrogates for what would be expected to happen in the event of failure. It should be noted that it is impossible to determine if there will be national media coverage or a specific number of fatalities based purely upon the failure. The values shown in Appendix C reflect engineering judgment on the part of the author. This system was selected for comparison with the City of Manassas because of the similarities in age, geographical location, and size, type and number of assets. These data were compiled in the same manner as the City of Manassas and the model was run for the same scenarios. The rationale for using an additional study area was to test the model capability on a system for which it was not originally intended. The results of the survey and model runs for both Manassas and Laurel are provided in Chapter 4.

4 Results

4.1 Survey of Utility System Stakeholders

As discussed in Chapter 3, a survey was developed to understand how different stakeholders of a system view the various scenarios of failure, repairs, and capital investments that a system routinely experiences. The scenarios were based on historic failures for the City of Manassas. The survey results are summarized in Appendix B.

There were 33 water utility professionals invited to take the survey of which 16 responses were received. Those responding included three elected officials, two appointed utility board members, six system managers, three system operators, and two design professionals. This gives a representative cross section of the individuals involved in the operation of a system.

In Table 5 the survey responses for characteristics that contribute to pipe failure are summarized. The three factors that the survey respondents felt contributed the least to the failure were size of pipe, material, and depth of the pipe. To further elicit information regarding the factors that contribute to failure, scenarios were developed as shown in Table 6. The respondents were asked to evaluate the likelihood of failure for each of the scenarios. The results of the survey for the scenarios are also shown in Table 6 with the respective scenario description. The average rating was calculated.

The weightings in Table 5 were determined by minimizing the difference between the product of the weights and the likelihood index value of each parameter for the scenarios shown in Table 3. For example in scenario 1, the failure index value for the 8 inch pipe is 4. Calculation of the weights is show in Table 28 in Appendix E. As a validation of the survey, the weights derived from the water professionals' assessments of the scenarios were fairly consistent with the actual survey results. The bottom three factors - size of the pipe, material, and depth of installation had weighted values of zero to produce the best results. The other factors were all in the 3 to 4 index range. This means that they have some bearing on the likelihood of failure.

Table 5 Characteristics Contributing to Pipe Failure

Characteristic	Survey Response						
	1- Has Nothing to do with Failure (%)	2- May Effect Failure (%)	3-Somewhat Contributes to Failure (%)	4- Contributes to Failure (%)	5- Contributes Heavily to Failure (%)	Mean Score	Weighting
Size of Pipe	23	31	15	15	15	2.69	0
Pipe Age	0	8	8	38	46	4.23	0.12
Material	0	38	31	23	8	2.99	0
Expended Useful Life	0	0	31	46	23	3.92	0.15
No. of Breaks per 1000 ft	0	23	8	31	38	3.85	0.29
No. of Breaks in previous calendar year	0	23	15	38	23	3.62	0.19
# of fittings	8	31	31	23	8	2.92	0.26
Depth of Pipe	8	62	15	15	0	2.38	0
Note: Highlighted cells signify the median.							

A summary of the responses regarding the effect of the physical characteristics on the likelihood of failure is shown in Table 6. Table 7 summarizes how the conditions of the pipe's service will affect the severity of the consequences. Table 8 outlines consequence scenarios and show how the design professionals assigned consequence values based on certain conditions in the failure area.

Table 6 Likelihood Scenarios

Survey Scenarios	1-Not Expected to Fail (%)	2-Slightly Expected to Fail (%)	3-Somewhat Expected to Fail (%)	4-Likely to Fail (%)	5-Expected to Fail (%)	Rating Average
8 in.1945 DI with 15 fittings per 100 ft.; 90% of useful life expended; 7 breaks in last 12 months; with 2 breaks per1000 ft.	0	0	15	38	46	4.31
12 in.1980 DI with 20 fittings per100 ft.; 60% of useful life expended; 6 breaks in last 12 months; with 4 breaks per 1000 ft.	8	0	31	38	23	3.69
6 in.1960 CI with 10 fittings per 100 ft.; 80% of useful life expended; 2 breaks in last 12 months; with 2 breaks per 1000 ft.	0	15	54	31	0	3.15
12 in.1975 DI with 10 per 100 ft.; 70% of useful life expended;10 breaks in last 12 months; with 4 breaks per 1000 ft.	0	15	23	46	15	3.62
3 in. 1980 PVC with 10 fittings per 100 feet; 35% of useful life expended; 8 breaks in the past 12 months; with 10 breaks per 1000 ft.	15	8	23	15	38	3.54

Table 4 above defines the consequence index rating. These consequences can also be referred to as surrogate consequences since the failures have not actually happened yet and these are what are expected to happen. Surrogate consequences are used to identify potential problems that could occur from a failure. These consequences may or may not actually happen, but they represent levels of failure that could be expected. In the event of a failure all of the consequences identified at a given level are not expected to occur. These are generic consequences and can be adapted to most any system to help with preparing for a failure response. Scenarios were evaluated based on an average value of the combined outcomes. For example, one scenario might be expected to produce several consequences at level 3 and several at level 5. Although, none of the consequences are rated at level 4, the overall index would be assigned a value of 4.

Table 7 Contributions to Consequence Rating

Conditions	1-No effect (%)	2-Minor effect (%)	3-Somewhat contributes (%)	4-Contributes (%)	5-Contributes heavily (%)	Average score
Redundancy in pipe run	0	0	25	25	50	4.25
Community type/Customer type	0	0	8	75	17	4.08
Density of customers	0	0	33	50	17	3.83
Perceived difficulty of repair	0	25	33	33	8	3.25
Effect on overall system	0	17	0	33	50	4.17
Level/No. of anticipated complaints	0	33	42	17	8	3.00
Note: Highlighted cells signify the median.						

The survey was used to see how the professionals ranked consequences. As seen in Table 7, all six factors were considered to influence the consequences. The factor that contributed the most was the redundancy of service and the factor contributing the least was the anticipated number of complaints. The results of the survey were taken into consideration in the assignment of consequence index values to the pipe segments as shown in Appendix C.

Table 8 Consequence Scenarios

Survey Scenario	1-Not Severe (%)	2-Severe (%)	3-Somewhat Severe (%)	4-Severe (%)	5-Very Severe (%)	Rating Average
Several neighborhoods and assisted living home. Line failure in the inside traffic lane of busy commuter route. Depth: 5.5 ft.; service disruption for 12-24 hours; possible contamination; Traffic will need to be diverted in order to make the repair.	0	8	8	58	25	4.00
Townhouse community; break along busy connector street; service will be disrupted until the repair is finished; no system redundancy	8	25	33	17	17	3.08
Single family development; no service outages; redundant source; line in high density residential arterial street; depth is 6 ft.	67	25	8	0	0	1.42
Hospital; no service outages – redundant lines; pressure delivered by second line will not be as high as normal and hospital officials have historically complained about this; line is located in a major street leading to various businesses; depth: 6 ft.	8	25	25	25	17	3.17
Single family development; no outages only pressure drops redundancy; Line is in local street; depth: 3.5 ft.	75	17	8	0	0	1.33
Main downtown business area (3 square blocks); can isolate and feed some, but at least half will be without water; depth: 4 ft in one of the main local streets.	0	33	50	17	0	2.83
Line runs for a ½ mile down a major thru route; 1200 VPH peak; serves shopping center and 75 home subdivision; depth: 6 ft. traffic will be disrupted likely including rush hour.	0	8	42	50	0	3.42

Table 9 shows the results of the survey question that asked what types of projects the professionals felt were most important to fund. The responses to these questions also helped to better understand what types of customers carried a higher level of consequence rating if service is lost to them. Table 9 also shows the resulting factors that influence the decisions regarding projects to be funded. The factor that is most likely to influence funding decisions is engineering judgment. It is important to note that engineering judgment was used in the assignment of the consequence indices.

Table 9 Project Types Most Likely to be Funded

Survey Project Type	1-Very Unlikely to Fund (%)	2-Unlikely to Fund (%)	3-Somewhat Likely to Fund (%)	4-Likely to Fund (%)	5-Very Likely to Fund (%)	Rating Average
150 unit townhome community	8	42	42	0	8	2.58
1000 bed hospital	0	0	8	25	67	4.58
Elementary school campus	8	8	17	33	33	3.75
250 bed retirement home	0	17	25	25	33	3.75
Fire/rescue facility	8	17	25	33	17	3.33
75 home VIP community	8	33	50	8	0	2.58
4 blocks of 26 varying businesses	8	8	42	17	25	3.42
Note: Highlighted cells indicate the mode						

Table 10 summarizes the results of the survey question that asked the professionals what characteristics would make them more likely to think a project was a worthwhile project. The answers to this question offer insight into what is important to decision makers and what might drive the inclusion of a project in a capital program.

Table 10 Characteristics that Increase the Likelihood of Funding

Decision Driver	1- Very Unlikely to Influence Decision (%)	2-Unlikely to Influence Decision (%)	3-Somewhat Likely to Influence Decision (%)	4-Likely to Influence Decision (%)	5-Very Likely to Influences Decision (%)	Rating Average
Engineering judgment or staff recommendation	0	0	8	33	58	4.50
Most bang for buck	0	0	17	83	0	3.83
% of budget used	0	17	58	25	0	3.08
Location of project	0	33	33	17	17	3.17
Recent projects done in area	17	42	25	17	0	2.42
No recent projects done in area	25	33	8	33	0	2.50
Visibility of project	17	42	33	8	0	2.33
Community pressure or desire	0	25	42	25	8	3.17
Economic ramifications	0	8	17	58	17	3.83
Past performance of infrastructure segment	0	0	42	25	33	3.92
Note: Highlighted cells indicate the mode						

Graphic results of the survey are shown in Appendix B. From the results of the survey, three important tables were derived: the Risk Consequence table (Table 11), the Risk Likelihood table (Table 12), and the Risk Calculation table (Table 13). In accordance with the ISO 31000 risk management standard, a combination of likelihood and consequence generates an initial risk. The general forms of these tables were adapted from similar tables from the Department of Occupational Safety and Health at Murdoch University (Murdoch, 2005) and follows closely to those developed by the EPA (2008) under the Check Up Program for Small Systems (CUPSS).

Table 11 and Table 12 present the consequence and likelihood of failure indices developed for the purpose of this research. Table 11 provides a detailed description of each of the 5 levels for the consequence index. The table is set up using a 5 point scale with 1 representing insignificant consequences and 5 representing severe consequences. Table 12 provides a detailed description of each of the 5 levels for the likelihood index. In the case of likelihood, 1 represents a rare event and 5 represents near certainty. The tables include factors such as cost of damages, regulatory involvement, criticality of facilities disrupted and disruptions to traffic to name a few. The tables also consider the likelihood of a failure happening based on characteristics of the pipe and past performance information gathered.

When Table 11 and Table 12 are combined, Table 13 is developed to drive the decision making process. Each utility will set a threshold of risk tolerability and will make repair/replacement decisions based on where individual pipe segments fall in the table. While engineering judgment will be used to ultimately make the decision, the information from the table will be the starting point to help reduce the risk to the system posed by the identified threats. The colors provide a visual guideline: green signifies a very low level of risk and red a very high level of risk. It should be noted that risk increases with both likelihood and consequence.

Table 11 Consequence Index Table

Index Value	Consequence Level	Description
5	Severe	• Loss/destruction of assets greater than $5M • Multiple Deaths • Serious difficulties with adding customers • National media coverage and/or a federal regulatory investigation • Total cessation of service for greater than one week and disruptions over following months of major/critical facilities • Negative effect on utility for greater than two years • Loss of confidence in management and utility • Disruption of normal traffic patterns for greater than 1 week
4	Major	• Loss/destruction of assets of $100K - $5M • Single Death and/or multiple injuries • State media coverage and/or state regulatory investigation • Total cessation of services for up to 7 days and subsequent disruptions of 2-3 months in major/critical facilities • Low confidence in management and utility • Negative perception of utility for 1 – 2 years • Some loss of customers • Disruption of normal traffic patterns for up to 7 days
3	Moderate	• Loss/destruction of assets of $10K - $100K • Individual serious injury • Regional media coverage and/or regional regulatory and/or internal investigation • Total cessation of services for up to 1 day and subsequent disruptions for 1-2 months of any customers • A negative effect on utility for up to 1 year • No loss of customers or base • Disruption of normal traffic patterns for greater than 12 hours
2	Minor	• Loss/destruction of assets of $2K - $10K • Injury only requiring first aid • Minor disruptions for up to 1 month for any customers • No loss of customers or base • Disruptions in normal traffic patterns for less than eight hours
1	Insignificant	• Loss/destruction of assets up to $2K • No Injuries • No disruption of services • No loss of customers or base • No major disruptions in normal traffic patterns

Table 12 Likelihood Index Table

Index Value	Likelihood Level	Description
5	Almost Certain	• Can expect more than one break annually • Occurs frequently in this area
4	Likely	• Can expect break to occur annually
3	Moderate	• Can expect break to occur once every three years
2	Unlikely	• Can expect break to occur once every 10 years • There has been an break to occur before
1	Rare	• Can expect break to happen only in exceptional circumstances • No break is known to have ever happened in this area

Table 13 Risk Index Table

		Consequence Index				
		Insignificant *1*	Minor *2*	Moderate *3*	Major *4*	Severe *5*
Likelihood Index	Almost Certain *5*	Moderate **5**	High **10**	Extreme **15**	Extreme **20**	Extreme **25**
	Likely *4*	Low **4**	Moderate **8**	High **12**	Extreme **16**	Extreme **20**
	Moderate *3*	Low **3**	Moderate **6**	Moderate **9**	High **12**	Extreme **15**
	Unlikely *2*	Low **2**	Low **4**	Moderate **6**	Moderate **8**	High **10**
	Rare *1*	Very Low **1**	Low **2**	Low **3**	Low **4**	Moderate **5**

4.2 Model Runs

Ten iterations were run to ensure that the model was producing the same solution for each budget allocation. As discussed in Chapter 3, different scenarios for the optimization model were run to reflect the viewpoints of the parties that influence repair and replacement budget allocations. These scenarios are referenced by the following names: status quo, planned replacement, repair, engineer, and council. The "status quo" represents the actions taken by the utility for the historic data period used in the model (1985 – 2012). The "planned replacement" minimizes the sum of the risks for the system as described in the scenario 1 mathematical model shown in Chapter 3. The "repair" scenario was the same as scenario 1 with the additional assumption that in lieu of replacement, repairs were made to the system at a cost of 75% of the cost of replacement. The repair was assumed to increase the useful life of the pipe segment by 50%. The "engineer" optimization depicts scenario 2 in which the likelihood of failure was minimized without consideration to consequence. Lastly, the "council" scenario represents scenario 3, in which the consequences are minimized without consideration of the likelihood of failure. The LINGO code developed for the scenario 1 optimizations is included in Appendix D.

Figure 14 shows the amount of risk reduction as a function of the amount expended for each of the scenarios. It is important to note that the project expenditures are not equal to the budget.

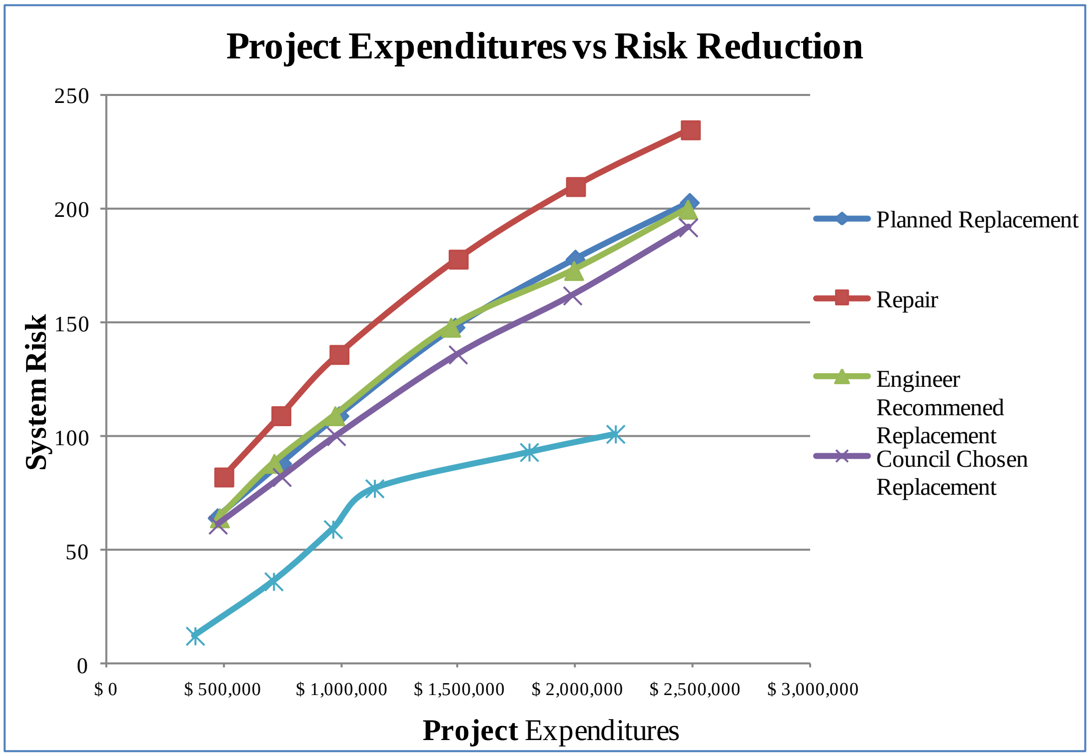


Figure 14 Project Expenditures vs Risk Reduction

Table 14 through Table 18 compare the optimized expenditures as constrained by the budget for the different implementation strategies. The level of risk reduction that would be achieved by implementing each strategy is also shown.

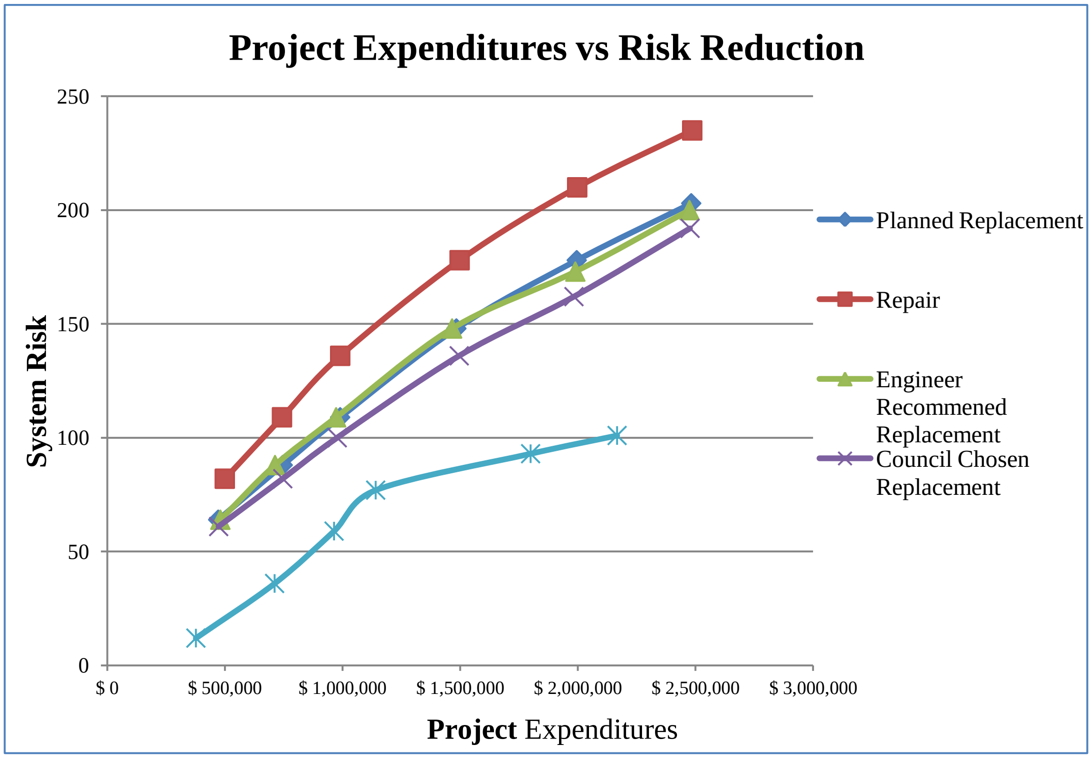


Figure 14 Project Expenditures vs Risk Reduction

Table 14Annual Project Budget, Status Quo and Optimized Expenditures and Risk Reduction (Manassas)

Annual Budget	Status Quo		Planned Replacement		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 377,000	12	$ 471,750	64	433
$ 750,000	$ 711,450	36	$ 746,000	88	144
$ 1,000,000	$ 964,050	59	$ 990,700	109	85
$ 1,500,000	$ 1,141,050	77	$ 1,483,850	148	92
$ 2,000,000	$ 1,799,250	93	$ 1,995,200	178	91
$ 2,500,000	$ 2,166,750	101	$ 2,481,800	203	100

Table 15 Annual Project Budget, Optimized Expenditures and Risk Reduction – Engineer (Manassas)

Annual Budget	Planned Replacement		Engineer Recommended		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 471,750	64	$ 480,975	64	0
$ 750,000	$ 746,000	88	$ 713,175	88	0
$ 1,000,000	$ 990,700	109	$ 972,825	109	0
$ 1,500,000	$ 1,483,850	148	$ 1,465,725	148	0
$ 2,000,000	$ 1,995,200	178	$ 1,989,375	173	-3
$ 2,500,000	$ 2,481,800	203	$ 2,474,325	200	-2

Table 16 Annual Project Budget, Optimized Expenditures and Risk Reduction – Council (Manassas)

Annual Budget	Planned Replacement		Council Chosen		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Council Chosen	Risk Reduced	
$ 500,000	$ 471,750	64	$ 473,850	61	-5
$ 750,000	$ 746,000	88	$ 746,250	82	-7
$ 1,000,000	$ 990,700	109	$ 977,700	100	-6
$ 1,500,000	$ 1,483,850	148	$ 1,496,100	136	-8
$ 2,000,000	$ 1,995,200	178	$ 1,983,600	162	-9
$ 2,500,000	$ 2,481,800	203	$ 2,477,025	192	-5

Table 17 Annual Budget, Optimized Expenditures and Risk Reduction with Repair and Replacement (Manassas)

Annual Budget	Planned Replacement		Repair instead of Replace		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 471,750	64	$ 499,725	82	28
$ 750,000	$ 746,000	88	$ 742,837	109	24
$ 1,000,000	$ 990,050	109	$ 990,225	136	25
$ 1,500,000	$ 1,483,850	148	$ 1,497,600	178	20
$ 2,000,000	$ 1,995,200	178	$ 1,997,254	210	18
$ 2,500,000	$ 2,481,800	203	$ 2,486,136	235	16

Table 18 Annual Budget, Optimized Expenditures and Risk Reduction with Status Quo and Repair (Manassas)

Annual Budget	Status Quo		Repair instead of Replace		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 377,000	12	$ 499,725	82	583
$ 750,000	$ 711,450	36	$ 742,837	109	203
$ 1,000,000	$ 964,050	59	$ 990,225	136	131
$ 1,500,000	$ 1,141,050	77	$ 1,497,600	178	131
$ 2,000,000	$ 1,799,250	93	$ 1,997,254	210	126
$ 2,500,000	$ 2,166,750	101	$ 2,486,136	235	133

Figure 15 displays the number of breaks averted as a function of project expenditures for the various model scenarios. The results show that the planned replacement, repair and engineer recommended strategies performed better than the council chosen and status quo alternatives. It is interesting to note that the engineer recommended solution out-performed the planned replacement strategy. The repair strategy showed mixed results depending on the expenditure level.

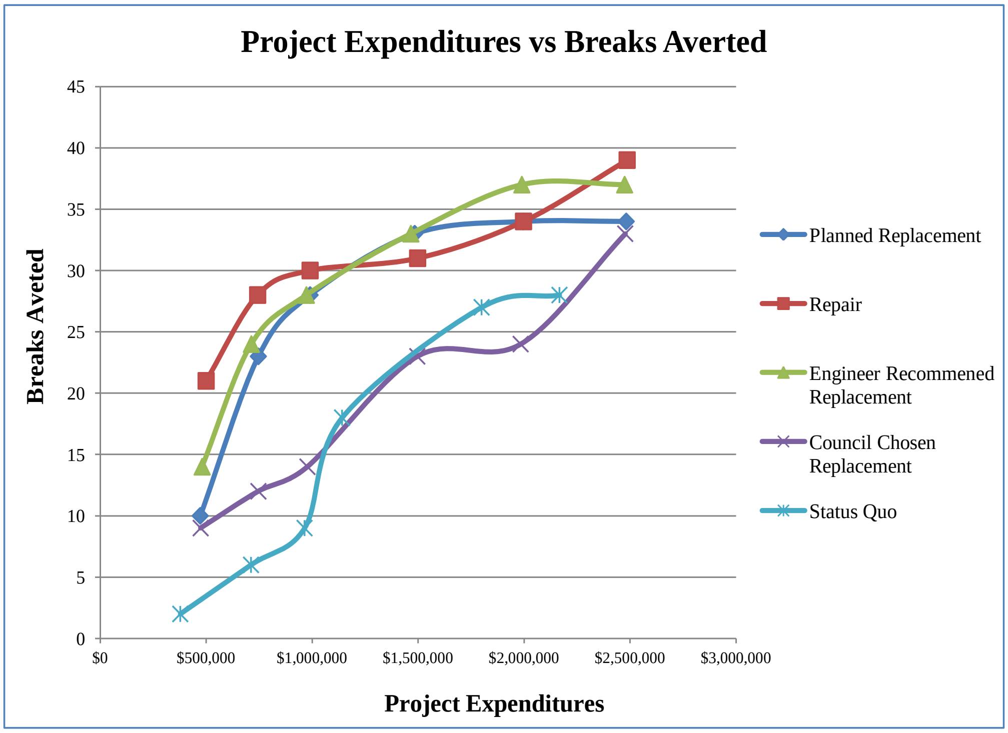


Figure 15 Project Expenditures vs Breaks Averted

The model results do not take into consideration the logic of construction sequences. The results were not logical in the suggested implementation of projects and sacrificed efficiency as they moved around to different locations. However, the results could be considered conservative from the perspective that by combining projects in close proximity to each other, mobilization costs could be further reduced. Mobilization costs are typically between 7.5% and 15% of the costs of construction depending on specific project factors. If the model resulted in the replacement of two segments that are immediately adjacent to each other, it is likely to assume that an engineer would replace both segments at the same time. This would be an additional saving that is not reflected in the model.

One of the survey questions asked respondents if there was a repair that would cost 75% of the replacement cost, but extended the useful life by 50% would they recommend implementing the project. The results showed a strong consensus by the professionals that this practice would not be recommended. It is interesting to note that the model enables the analysis and comparison of the result of this strategy with the replacement strategy. The numerical difference in risk reduction between the planned replacement and the repair strategy is shown in Table 17. Although repairing the assets does not give new assets, it does remove the risk by renewing the asset. The decision to repair or replace would still have to be handled on a case by case basis depending on other factors specific to the particular asset and its function within the system such as fire flow needs, capacity needs, relocation needs, or other factors that might be more economically addressed during a renewal. These considerations typically do not primarily address the level of risk in the system, but rather address functionality of the system. These functionality requirements have to be taken into consideration as part of normal operations of the system and decisions on renewals, replacements or upgrades must take these requirements into consideration. The model enables an improved view at the potential risk reductions through the implementation of this strategy. It is important to note that the long term effects of a repair strategy were not taken into consideration. Further research is needed before this should be a recommended asset management strategy.

There are several new and old technologies utilized in performing repairs including repair sleeves, joint sealing, pipe cleaning technologies, lining technologies, trenchless technologies, and cathotic protection to name a few (Grigg, 2005).   The introduction and more widespread usage of these technologies could greatly influence the renewal of infrastructure. These techniques could also prove to be critical in helping utilities fund renewal needs to keep their system in good repair.

The model was run for the WSSC (Laurel, MD) data in a similar fashion for the years (1991 – 2010). The intent was to demonstrate the usefulness of the model for a utility for which the model was not originally designed. The results of the WSSC model runs are shown in Table 19 through Table 23 and Figure 16 and Figure 17. Similar results were obtained in that the repair strategy yielded the best reduction in risk and the existing strategy yielded the lowest reduction in risk. The planned replacement, engineer's recommendation, and council choices were similar in risk reduction and fell somewhere between the other two results.

Table 19 Annual Project Budget, Status Quo and Optimized Expenditures and Risk Reduction (WSSC)

Annual Budget	Status Quo		Planned Replacement		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 490,050	62	$ 499,650	178	187
$ 750,000	$ 735,900	86	$ 747,300	215	150
$ 1,000,000	$ 974,850	122	$ 991,500	248	103
$ 1,500,000	$ 1,461,850	184	$ 1,500,000	307	110
$ 2,000,000	$ 1,943,650	204	$ 1,999,950	357	75
$ 2,500,000	$ 2,443,450	232	$ 2,499,150	401	73

Table 20 Annual Project Budget, Optimized Expenditures and Risk Reduction – Engineer (WSSC)

Annual Budget	Planned Replacement		Engineer Recommended		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 499,650	178	$ 492,150	164	-8
$ 750,000	$ 747,300	215	$ 747,000	202	-6
$ 1,000,000	$ 991,500	248	$ 999,450	233	-6
$ 1,500,000	$ 1,500,000	307	$ 1,483,350	291	-5
$ 2,000,000	$ 1,999,950	357	$ 1,969,350	335	-6
$ 2,500,000	$ 2,499,150	401	$ 2,467,200	375	-6

Table 21 Annual Project Budget, Optimized Expenditures and Risk Reduction – Council (WSSC)

Annual Budget	Planned Replacement		Council Chosen		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 499,650	178	$ 499,950	174	-2
$ 750,000	$ 747,300	215	$ 737,550	214	-0.5
$ 1,000,000	$ 991,500	248	$ 996,750	248	0
$ 1,500,000	$ 1,500,000	307	$ 1,497,750	306	-0.3
$ 2,000,000	$ 1,999,950	357	$ 1,979,100	356	-0.3
$ 2,500,000	$ 2,499,150	401	$ 2,499,150	401	0

Table 22 Annual Budget, Optimized Expenditures and Risk Reduction with Repair and Replacement (WSSC)

Annual Budget	Expended Budget for Planned Replacement	Risk Reduced when Planned Replacement	Expended Budget for Repairs (75% of Replacement Cost)	Risk Reduced by doing Repairs	% Increase in Risk Reduction for Repairs v/s Replacement
$ 500,000	$ 499,650	178	$ 498,487	203	28
$ 750,000	$ 747,300	215	$ 743,625	248	24
$ 1,000,000	$ 991,500	248	$ 999,562	289	25
$ 1,500,000	$ 1,500,000	307	$ 1,499,962	357	20
$ 2,000,000	$ 1,999,950	357	$ 1,999,462	415	18
$ 2,500,000	$ 2,499,150	401	$ 2,499,975	461	16

Table 23Annual Budget, Optimized Expenditures and Risk Reduction with Status Quo and Repair (WSSC)

Annual Budget	Status Quo		Repair instead of Replace		% Increase in Risk Reduction
	Expended Budget	Risk Reduced	Expended Budget	Risk Reduced	
$ 500,000	$ 490,050	62	$ 498,487	203	227
$ 750,000	$ 735,900	86	$ 743,625	248	188
$ 1,000,000	$ 974,850	122	$ 999,562	289	137
$ 1,500,000	$ 1,461,850	184	$ 1,499,962	357	94
$ 2,000,000	$ 1,943,650	204	$ 1,999,462	415	103
$ 2,500,000	$ 2,443,450	232	$ 2,499,975	461	99

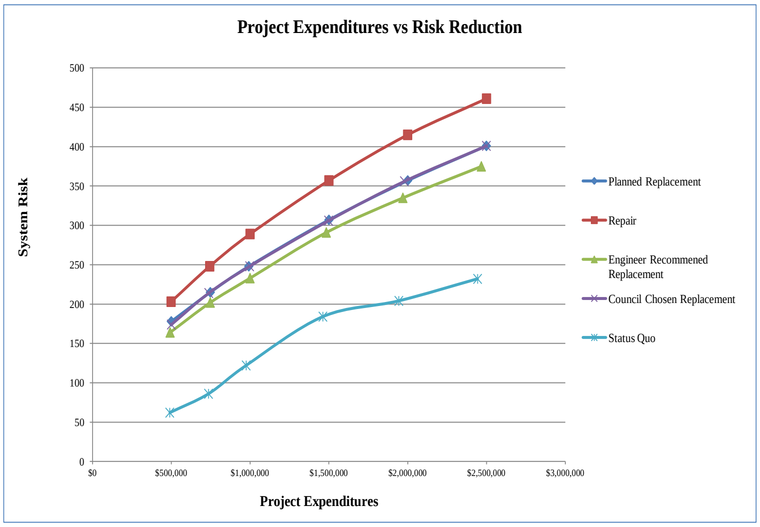


Figure 16 Project Expenditures vs Risk Reduction (WSSC - Laurel)

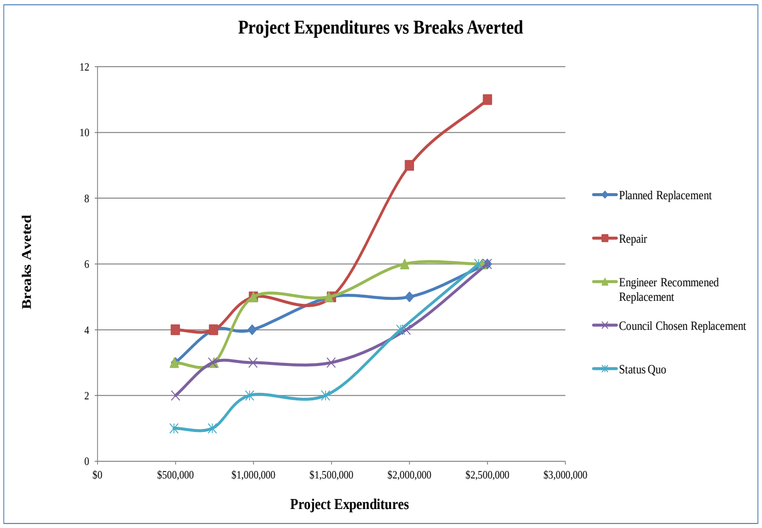


Figure 17 Project Expenditures vs Breaks Averted (WSSC - Laurel)

The model was initially developed using a budget of $1M for capital expenditures on an annual basis. When the results of the $1M runs are considered, the optimized (planned) replacement improves the system risk reduction by 84% when compared to spending $1M in the status quo manner which is to choose projects until the funding is exhausted. When optimizing the replacement based on maximizing the reduction in likelihood of failure (engineer's choice), there is not a noticeable difference in this implementation and the planned replacement. The maximization of the reduction of consequence of failure (council chosen), there is a 6% less risk removed compared to the planned replacement. When the repair method is deployed instead of replacing, the results show 25% increase in risk reduction when compared to the planned replacement and 130% increase in risk reduction when compared to the status quo. The results for the WSSC facilities were similar in scale as can be seen in the tables above. The actual percentages could fluctuate depending on some engineering choices with the status quo, but the improvements from utilizing the optimization tool are realized.

5 Summary and Conclusion

5.1 Noteworthy Contributions

This research investigated the use of an index based risk management approach. An optimization model was developed and applied to two water utilities. Two contributions to research were achieved. First and foremost, a framework was developed to enable the incorporation of likelihood of failure into water asset repair and replacement funding decisions, without the need for pipe failure data. Previous work in this field, most notably by Howard (1979) and Walksi et al. (1982 and 1987), requires extensive investment to develop probability of failure values for pipe segments and other assets. These investments include the acquisition of software and collection of extensive failure data.

If no failures have occurred for pipes of specific characteristics, these pipes will not be considered a risk for failure. Although failure may be unlikely, this approach ignores parts of the system that have historically performed well. Unfortunately, this results in a "ticking time bomb" such as the recent Bladensburg failure experienced by WSSC (Washington Post, 2015). This catastrophe resulted in significant loss of property and threatened the safety of numerous residents. This pipe segment was 90 years old. Although it had performed well, it was ready to fail. Methodologies that encourage failure prior to action result in the loss of confidence of the public and put human life and property at risk. It is important to note that although the objective of the framework minimized risk, a significant number of breaks were averted through the use of the model.

The cost of obtaining and developing data driven models can be cost prohibitive. This is particularly true when the discussion turns to small utilities with correspondingly small budgets. These small utilities are not able to afford this type of analysis and are in need of more economical ways to engage in proactive asset management rather than reactive repair or replacement of their system. The use of indices to measure failure enables the utility to incorporate the age and materials into the decision without the associated problems and barriers associated with other methodologies.

The use of a true probability of failure value (between 0 and 1) was investigated in this research. Pipe segment data were analyzed for Laurel (WSSC) to determine if pipe characteristics could be correlated with the probability of failure. The results of this analysis are included in Appendix E. No characteristic of the pipe segment was found to be a reasonable indicator of pipe failure. Past research does show that pipe size seems to play a role in failures mainly when dealing with small lines. The correlation between probability of failure and age proved to be the highest ($R^2 = 0.44$). The probability of failure did increase as the age of the pipes increased. The problem with the use of this approach for the City of Manassas (a small utility), was that specific ages were not available for many of the pipe segments. Instead a range of ages was listed in the asset management system. No correlation between age and failure probability could be determined.

The second contribution of this work lies in the demonstrated ability of the framework to incorporate the consequences associated with a failure into the decision strategy. Previous methods were not truly risk-based in that consequences were measured in terms of repair or replacement costs or loss of product sales. This financial measurement does not incorporate the full extent of the loss of water, the damage to other structures or the loss of public confidence in the municipality. In-service failures also have other costs that are not accounted for until the full repair has been completed and all resultant claims have been filed and resolved.

5.2 Future Work

The framework is more than a tool for allocating maintenance budgets; it is a mindset and a paradigm that can be used to increase the overall value of an organization. When implemented properly, it should improve the confidence of customers by reducing system failures and minimizing the associated consequences.

The survey results within the research can be used to gauge the perspectives of different individuals working in the operation of a utility system. These results can shed light on the level of importance of buried infrastructure systems and can be used to design capital programs that most closely follow the opinions of a cross section of industry professionals. These results are most applicable to buried wet infrastructure, but can be translated to other types of infrastructure as well. The use of carefully constructed indices can serve as surrogates for failure probability and consequence. The use of this framework in bridges, highways, wastewater collection systems, electrical power networks, telecommunication systems and other infrastructure asset management warrants promise and should be investigated.

This work outlines the importance of a good asset management program and exemplifies what can be done with the data obtained from the program to improve and/or better maintain the system. Clearly, the consequences of a failure are often as important, if not more so, than the failure itself. The framework can be used to further develop models that can bridge the gap between system criticality and the consequences of failure when considering system risk. This work takes a closer look at the consequence of failure as it contributes to the risk to the system. Previous work and models in the field have focused on the criticality of the system using product or revenue loss as a primary driver and giving little regard to the consequences of failures of the system.

The model that has been developed by this project can be used as a support tool for facility owners which will help increase the overall value of the organization by minimizing the business risk exposure that result from in-service failures of the system. The research performed while developing the model also found an important gap in a very valuable resource - the ANSI/AWWA Risk and Resiliency Model or J100. The J100 does not to address component failure as a threat to continued operation. While there are many hazards that are physical in nature and receive appropriate attention, aging assets constitute a significant problem. Infrastructure is falling into a state of neglect and is threatened by age. Many systems are relied upon to operate well beyond the end of their useful life. This model can be utilized by the J100 committee as they seek to update the existing water system risk and resiliency model.

From a socio-economic perspective, this work can be used to explore another important aspect of utility operations – customers' willingness to pay and expected level of service. As systems are being improved, there will inevitably be additional costs that will be passed on to customers in order to upgrade and make necessary system repairs. A model can be extracted from this work to optimize level of service provided based on the existing conditions and planned facility improvements. Future research could investigate the relationship between the level of service expected and a customers' willingness to pay. What level of service is required to keep customers happy for the rates that they are paying? Further work is needed to investigate how unplanned breaks affect society and the unrecoverable consequences such as lost time from work, transportation impacts, public confidence in the water, and loss of service impacts.

The framework is generic, in that it optimizes the system by minimizing the risk associated with failure. Alternative means of evaluating failure, vulnerability and consequence may be researched. The benefits, specifically to smaller water utilities, lie in the simplicity of the model and ease of interpretation. Thomas Walski of Bentley Systems, states that an area of future work that should be undertaken is to combine the criticality risk analysis that most models are currently using with the consequence risk analysis to develop a model and guidance that takes all system aspects into consideration. The consequence analysis looks at the system as a whole while the criticality analysis looks at each component and how the failure will affect the hydrology of the system. Being able to combine these two results will further improve system maintenance and reduce impacts caused by system failure. This work could be accomplished by skeletonizing the model until sub-systems can be viewed as one component. This will help bring more understanding to the consequences associated with the failure of a component from a hydraulic and delivery of service perspective. Specific questions that might be addressed include:

- How does the skeletonization of a system affect the level of accuracy in predictive models for system failure?
- What attribute is the most indicative for predicting asset failures in infrastructure systems and how do predictions degrade as attributes are removed from models?
- What changes to the optimization model may be needed to analyze risk to a system based on hydraulic modeling?
- In the absence of the ability to bridge system criticality and consequence of failure, which leads to higher customer satisfaction?
- How does system reliability correlate with the level of customer complaints when rate increases are requested? In other words, is there a break-even point?

Appendix A – Survey and Survey Results

<STRONG>Infrastructure Risk Survey</STRONG>

1. Framework for Infrastructure Risk Management

RESEARCH PROCEDURES
This research is being conducted to help understand the characteristics that different individuals involved in the maintenance of a utility system view as being important in managing the risk of that system. If you agree to participate, you will be asked to complete a survey about factors contributing to the failure of a segment of a system, the consequences of failures to the system, and the distribution of funds needed for the implementation of projects to reduce the risk of failure in the system. The response to the survey will be used to understand how the decisions of individuals involved with a system compare to the suggestions that result from using the model developed by this research project. The results will also be used to understand the difference system views and funding distribution for Risk Management in the system employed by different levels of individuals charged with managing the system. It is expected that completion of the survey will take approximately thirty minutes.

By proceeding with the survey, you are agreeing to participation and are giving your consent to utilize the responses that you provide.

RISKS
There are no foreseeable risks for participating in this research.

BENEFITS
There are no benefits to you as a participant other than to further research in the area of Infrastructure Risk Management (Risk Management/Risk Reduction).

CONFIDENTIALITY
The data in this study will be confidential. The results of this survey will be integrated into the Infrastructure Risk Management research and will be included in a PhD graduate dissertation, presented at conferences, and may also be published in journal articles. All results will be presented in aggregate and no data will be directly related to a respondent. While it is understood that no computer transmission can be perfectly secure, reasonable efforts will be made to protect the confidentiality of your transmission.

PARTICIPATION
Your participation is voluntary, and you may withdraw from the study at any time and for any reason. If you decide not to participate or if you withdraw from the study, there is no penalty or loss of benefits to which you are otherwise entitled. There are no costs to you or any other party.

CONTACT
This research is being conducted by Nichalos D. Gardner, a doctoral student at the Civil, Environmental, and Infrastructure Engineering at George Mason University. He may be reached at (703) 266-1186 or via email ngardne1@masonlive.gmu.edu for questions or to report a research related problem. Dr. Sharon DeMonsabert , Professor Emeritus George Mason University Department of Civil, Environmental, and Infrastructure Engineering is directing this research project and may be reached at (703) 993-1747 or via email sharon.demonsabert@aemcorp.com. You may contact the George Mason University Office of Research Subject Protection at (703) 993-4121 if you have questions or comments regarding your rights as a participant in the research.

This research has been reviewed according to George Mason University procedures governing your participation in this research.

<STRONG>Infrastructure Risk Survey</STRONG>

1. NOTE 1: If you would like to have a copy of this consent form, please print this page prior to proceeding to the survey.
NOTE 2: If you would like to receive a copy of the public report of this research please check the box below and provide your email address.

I Would like to Receive Survey Results	I would Not like to Receive Survey Results
◯	◯

Email address to send results to

2. What would best characterize the role you would play in the Maintenance or Management of a piping system?

- ◯ Operations Personnel
- ◯ System Manager
- ◯ Design Professional
- ◯ System Owner/Elected Official
- ◯ Appointed Operations Board Member

Other (please specify)

<STRONG>Infrastructure Risk Survey</STRONG>

2. Likelihood of Failure

Based on your knowledge of underground utility systems, review the described conditions of pipe segments. Please rate the likelihood of all or part of the pipe segment failing within the next 12 months using the following scale

1 – Not Expected to Fail
2 – Slightly Expected to Fail
3 – Somewhat Expected to Fail
4 – Likely to Fail
5 – Expected to Fail

3. A run of 8 inch 1945 ductile iron pipe with approximately 15 fittings or valves every 100 feet; this pipe has had 90% of its expected useful life expended and has had 7 breaks in the past 12 months; with 2 breaks per 1000 ft.

Not Expected to Fail	Slightly Expected to Fail	Somewhat Expected to Fail	Likely to Fail	Expected to Fail
○	○	○	○	○

4. A run of 12 inch 1980 ductile iron pipe with approximately 20 fittings or valves every 100 feet; this pipe has had 60% of its expected useful life expended and has had 6 breaks in the past 12 months; with 4 breaks per 1000 ft.

Not Expected to Fail	Slightly Expected to Fail	Somewhat Expected to Fail	Likely to Fail	Expected to Fail
○	○	○	○	○

5. A run of 6 inch 1960 ductile iron pipe with approximately 10 fittings or valves every 100 feet; this pipe has had 80% of its expected useful life expended and has had 2 breaks in the past 12 months; with 2 breaks per 1000 ft.

Not Expected to Fail	Slightly Expected to Fail	Somewhat Expected to Fail	Likely to Fail	Expected to Fail
○	○	○	○	○

6. A run of 12 inch 1975 ductile iron pipe with approximately 10 fittings or valves every 100 feet; this pipe has had 70% of its expected useful life expended and has had 10 breaks in the past 12 months; with 4 breaks per 1000 ft.

Not Expected to Fail	Slightly Expected to Fail	Somewhat Expected to Fail	Likely to Fail	Expected to Fail
○	○	○	○	○

7. A run of 3 inch 1980 PVC pipe with approximately 10 fittings or valves every 100 feet; this pipe has had 35% of its expected useful life expended and has had 8 breaks in the past 12 months; with 10 breaks per 1000 ft.

Not Expected to Fail	Slightly Expected to Fail	Somewhat Expected to Fail	Likely to Fail	Expected to Fail
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

3. Likelihood of Failure

Please rank these characteristics according to how you believe they contribute to pipe failure using the following scale

1 – Has Nothing to do with Failure
2 – May Affect Failure, but does not Contribute to it
3 – Somewhat Contributes to Failure
4 – Contributes Some to Failure
5 – Contributes Heavily to Failure

8. Size of Pipe

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

9. Age of Pipe

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

10. Expended Useful Life/Remaining Useful Life

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

11. Depth of Pipe

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

12. # of Breaks in Past 12 Months

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

13. # of Breaks / 1000 ft

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

14. # of Fittings

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

15. Other – Please list as many as thought of and briefly explain

Has Nothing to do with Failure	May Affect Failure, but does not Contribute to it	Somewhat Contributes to Failure	Contributes Some to Failure	Contributes Heavily to Failure	N/A
○	○	○	○	○	○

Other (please specify)

<STRONG>Infrastructure Risk Survey</STRONG>

4. Likelihood of Failure

16. How many repeat failures (regardless of cause of failure) in a general area within a year would trigger a need for replacement (regardless of expended useful life)?

◯ 1-2 ◯ 3-6 ◯ 7-10 ◯ 11-15 ◯ >16

17. How many non-human error failures / year would trigger a need for replacement (regardless of expended useful life)?

◯ 1-2 ◯ 3-6 ◯ 7-10 ◯ 11-15 ◯ >16

18. How much expended useful life would trigger the planning and/or implementation of a replacement project?

◯ 50% ◯ 75% ◯ 76-90% ◯ 91-105% ◯ 106-120% ◯ >125%

<STRONG>Infrastructure Risk Survey</STRONG>

5. Consequence of Failure

Based on your knowledge of underground utility systems and the effects on customers and their ability to carry out their routine functions when a system fails, review the described environment of a failed segment of pipes. Please rate the severity of this failure using the following scale

1 – Not Significant
2 – Significant
3 – Somewhat Severe
4 – Severe
5 – Very Severe

19. This line serves several neighborhoods as well as an assisted living home occupied primarily by the elderly. The line experiences a failure that takes place in the inside traffic lane of a very busy commuter route. The line is buried at a depth of approximately 5.5'. The repair will require water services to be disrupted for 12-24 hours. There was possible contamination in the lines and a boil water notice has been issued. Traffic will need to be diverted and services will be cut in order to make the repair.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
○	○	○	○	○

20. The line serves a townhouse community and the leak is found along a busy connector street within the City. The water service will be completely disrupted until the repair is finished due to a lack of redundancy in the system.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
○	○	○	○	○

21. The line serves a single family development, but there will be no service outages as the community has redundant sources of water entering the community. The broken line is located in high density residential arterial street and is buried at approximately 6'.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
○	○	○	○	○

22. The line serves the hospital, but there are no expected service outages due to redundant lines, but the water pressure delivered by the second line will not be as good as normal and hospital officials have historically complained when outages have caused water service to be delivered by the alternative service lines. The broken line is located in a major street that is well traveled by residents getting to various businesses and is buried at approximately 6'.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

23. The line serves a single family development, but there will be no service outages only pressure drops as the community has redundant sources of water entering the community. The broken line is located in local neighborhood street and is buried at approximately 3.5'.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
◯	◯	◯	◯	◯

24. The line runs through the main downtown business area and provides water to a variety of businesses in a 3 square block area. There is a way to isolate and feed some of the businesses, but at least half will be without water as a result of the failure. The line is buried 4' deep in one of the main local streets.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
◯	◯	◯	◯	◯

25. A line runs for a ½ mile down a major commuter route. There are at least 1200 Vehicles Per Hour during the peak periods passing along this stretch on average days. The line serves a shopping center, and feeds a 75 home subdivision. The line is buried 6' deep and any work on this line always disrupts traffic. Most work on this line cannot be done without affecting rush hour unless it is carefully planned.

Not Significant	Significant	Somewhat Severe	Severe	Very Severe
◯	◯	◯	◯	◯

<STRONG>Infrastructure Risk Survey</STRONG>

6. Consequence of Failure

Please rank these perceived consequences of breaks in the scenarios as to how they affect the rating of the consequences using the following scale

1 – Has Nothing to do with the Rating of Consequence
2 – Affects the Rating of Consequence, but does not Contribute to it
3 – Somewhat Contributes to Rating of Consequence
4 – Contributes Some to Rating of Consequence
5 – Contributes Heavily to Rating of Consequence

26. Redundancy in the pipe run for customers served.

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

27. Community type/Customer type

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

28. Density of Customers

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

29. Perceived Difficulty of Repair

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

30. Affect on Overall System

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

31. Other known factors about System

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

32. Level/Amount of Anticipated Complaints

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence
○	○	○	○	○

33. Other – Please list as many as thought of and briefly explain

Has Nothing to do with the Rating of Consequence	Affects the Rating of Consequence, but does not Contribute to it	Somewhat Contributes to Rating of Consequence	Contributes Some to Rating of Consequence	Contributes Heavily to Rating of Consequence	N/A
○	○	○	○	○	○

Other (please specify)

<STRONG>Infrastructure Risk Survey</STRONG>

7. Consequence of Failure

Please review the following communities knowing that all projects cannot be done at once, but all projects have very similar likelihood of another failure and very similar costs of replacement/repair. Of these 7 locations, there is funding available to implement 3 projects in the next 5 years. Which projects do you implement, knowing that there is a very high likelihood that the others will have beaks before the next round of projects can be funded? Please rank the projects as to the likelihood to fund using the following scale

1 – Very Unlikely to Fund
2 – Unlikely to Fund
3 – Somewhat Likely to Fund
4 – Likely to Fund
5 – Very Likely to Fund

34. 150 unit Town Home Community

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

35. 1000 bed Hospital

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

36. Elementary School Campus

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

37. 250 bed Retirement Home

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

38. Fire/Rescue Facility

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

39. 75 home Community that is home to local celebrities and public figures

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

40. 4 blocks that contain 26 businesses of varying types

Very Unlikely to Fund	Unlikely to Fund	Somewhat Likely to Fund	Likely to Fund	Very Likely to Fund
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

8. The Capital Budget for Water Line Replacement is $1M. 7 Projects Have Been...

Scenario #1
A run of 8" 1945 ductile iron pipe with approximately 15 fittings or valves every 100'; this pipe has had 90% of its expected useful life expended and has had 7 breaks in the past 12 months; with 2 breaks per 1000' This line serves several neighborhoods as well as an assisted living home occupied primarily by the elderly. The line experiences a failure that takes place in the inside traffic lane of a primary commuter route. The line is buried at a depth of approximately 5.5' The repair will require water services to be disrupted for 12-24 hours. There is a possibility of contamination with a break. Traffic will need to be diverted and services interrupted in order to make a repair. ($775,000.00)

Scenario #2
A run of 12" 1980 ductile iron pipe with approximately 20 fittings or valves every 100'; this pipe has had 60% of its expected useful life expended and has had 6 breaks in the past 12 months; with 4 breaks per 1000'. The line serves a single family development, but there will be no service outages as the community has redundant sources of water entering the community. The broken line is located in busy through street and is buried at approximately 6'. ($550,000.00)

Scenario #3
A run of 6" 1960 ductile iron pipe with approximately 10 fittings or valves every 100'; this pipe has had 80% of its expected useful life expended and has had 2 breaks in the past 12 months; with 2 breaks per 1000'. The line serves a townhouse community and the pipe is buried at 3.5' along a local street. The water service will be completely disrupted until the repair is finished as there is no redundancy for this segment. ($550,000.00)

Scenario #4
A run of 12" 1975 ductile iron pipe with approximately 10 fittings or valves every 100'; this pipe has had 70% of its expected useful life expended and has had 10 breaks in the past 12 months; with 4 breaks per 1000'. The line serves the hospital, but there are no expected service outages due to redundant lines. The water pressure delivered by the second line will not be as good as normal and hospital officials have historically complained when outages have caused water service to be delivered by the alternative service lines. The broken line is located in a major through street and is buried at approximately 6'. ($425,000.00)

Scenario #5
A run of 3" 1980 PVC pipe with approximately 10 fittings or valves every 100'; this pipe has had 35% of its expected useful life expended and has had 8 breaks in the past 12 months; with 10 breaks per 1000'. The line serves a single family development, but there will be no service outages only pressure drops as there are redundant sources of water entering the community. The segment in question is located in a local through street and is buried at approximately 3.5'. ($300,000.00)

Scenario #6
A run of 6" 1960 ductile iron pipe with approximately 10 fittings or valves every 100'; this pipe has had 80% of its expected useful life expended and has had 2 breaks in the past 12 months; with 2 breaks per 1000'. The line runs through the main downtown business area and provides water to a variety of businesses in a 3 square block area. There is a way to isolate and feed some of the businesses, but at least half will be without water as a result of the failure. The line is buried 4' deep in one of the main local streets. ($800,000.00)

Scenario #7
A run of 12" 1975 ductile iron pipe with approximately 10 fittings or valves every 100'; this pipe has had 70% of its expected useful life expended and has had 10 breaks in the past 12 months; with 4 breaks per 1000'. A line runs for a ½

<STRONG>Infrastructure Risk Survey</STRONG>

mile down a major commuter route. The line serves a shopping center, and feeds a 75 home subdivision. The line is buried 6' deep and any work on this line always disrupts traffic. Most work on this line cannot be done without affecting rush hour unless it is carefully planned. ($600,000.00)

41. Please choose the combination of project(s) that you would choose to implement keeping your cost within the $1M cap for this year's capital program.

- [ ] #1
- [ ] #2
- [ ] #3
- [ ] #4
- [ ] #5
- [ ] #6
- [ ] #7
- [ ] #2,4
- [ ] #2,5
- [ ] #3,4
- [ ] #3,5
- [ ] #4,5
- [ ] #5,7

<STRONG>Infrastructure Risk Survey</STRONG>

9. Project Implementation

Please rank the following factors surrounding the decision to implement and the timing of implementation of projects using the following scale

1 – Very Unlikely to Influence Decision
2 – Unlikely to Influence Decision
3 – Somewhat Likely to Influence Decision
4 – Likely to Influence Decision
5 – Highly Likely to Influences Decision

42. Engineering judgment/staff recommendation

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

43. Largest project possible that gives the most "Bang for the Buck"

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

44. % of budget used

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

45. Location of project

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

46. Location of previous projects – Recent projects done in this area

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

47. Location of previous projects – No recent projects done in this area

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

48. Visibility of project

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
○	○	○	○	○

<STRONG>Infrastructure Risk Survey</STRONG>

49. Community pressure/desires to have project implemented

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
◯	◯	◯	◯	◯

50. Economic backlash or affects on businesses

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
◯	◯	◯	◯	◯

51. Past performance of infrastructure segment

Very Unlikely to Influence Decision	Unlikely to Influence Decision	Somewhat Likely to Influence Decision	Likely to Influence Decision	Very Likely to Influences Decision
◯	◯	◯	◯	◯

<STRONG>Infrastructure Risk Survey</STRONG>

10. Project Implementation

52. If a repair is available that will extend the useful life by 50% and cost approximately 75% of the cost of a full replacement; how likely are you to recommend implementing the repair instead of the replacement?

◯ Certainly Not Likely ◯ Not Likely ◯ Somewhat Likely ◯ Likely ◯ Certainly Likely

Number of responses

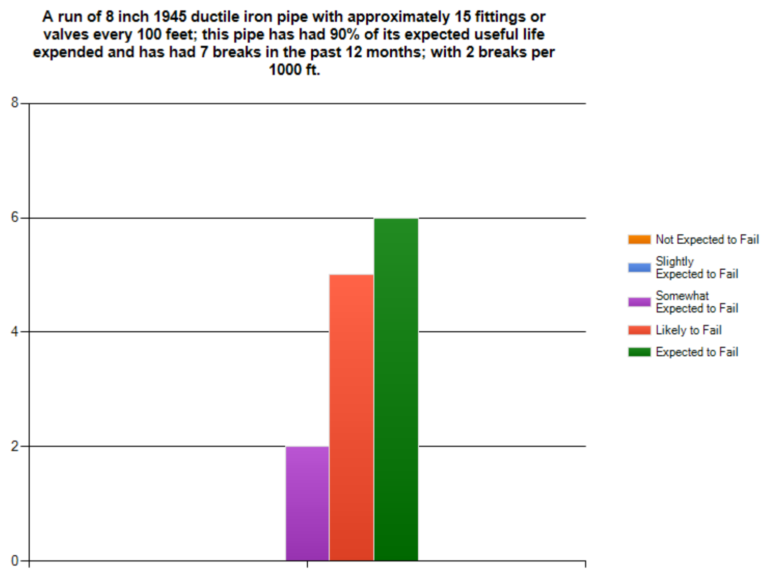
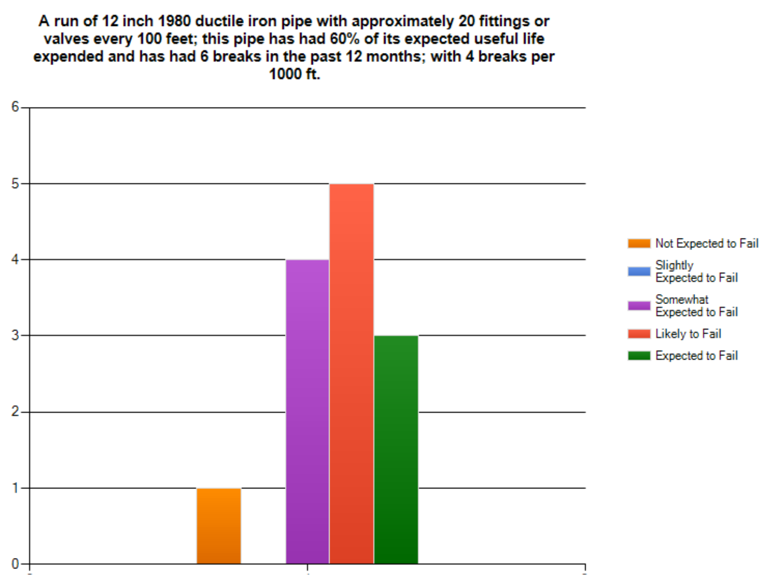


Figure A18 Survey Question 3

Number of responses



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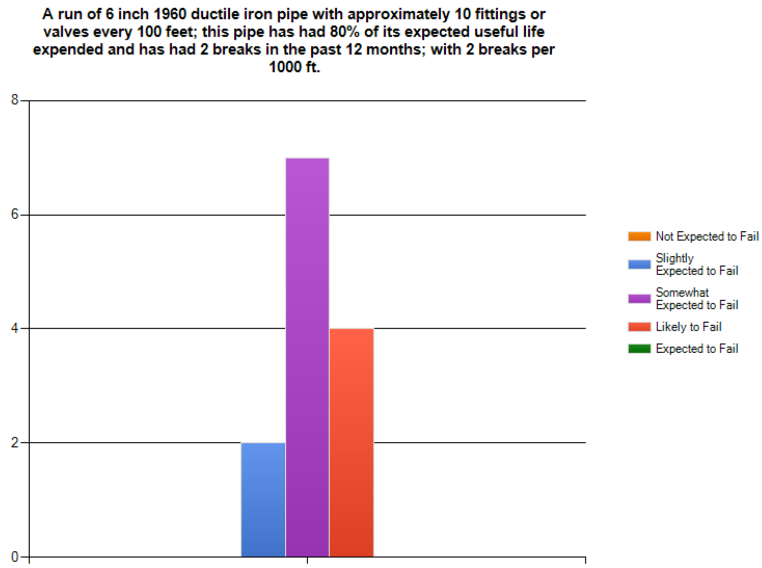
Number of responses



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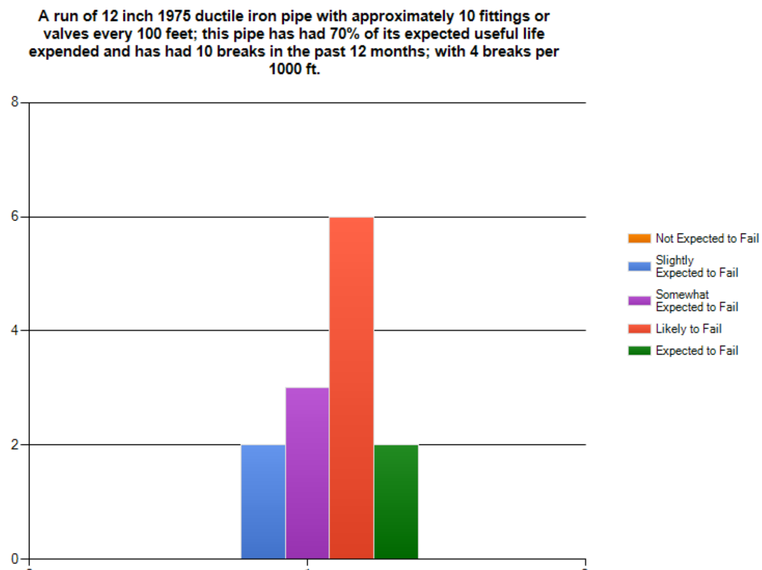
Number of responses



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Number of responses

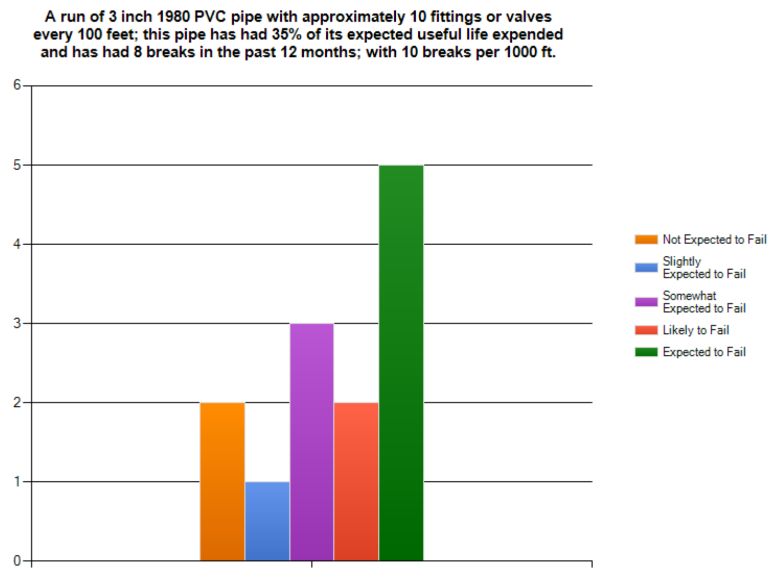
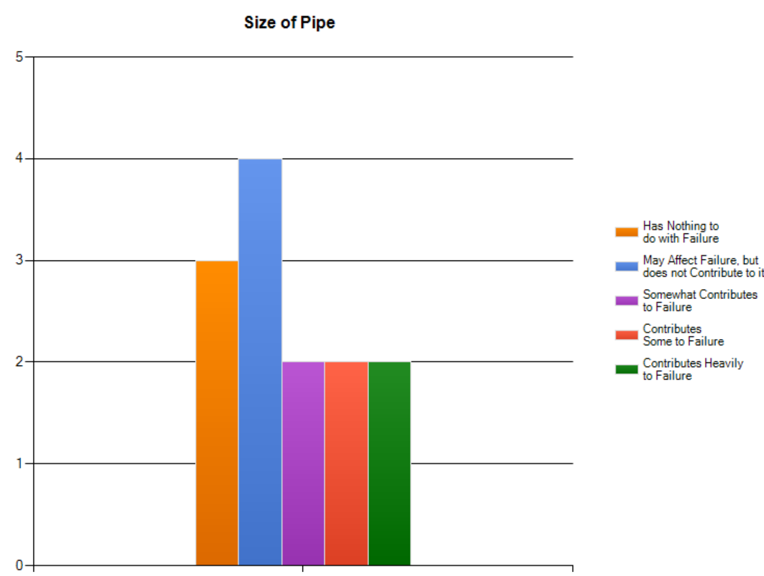


Figure A22 Survey Question 7

Number of responses



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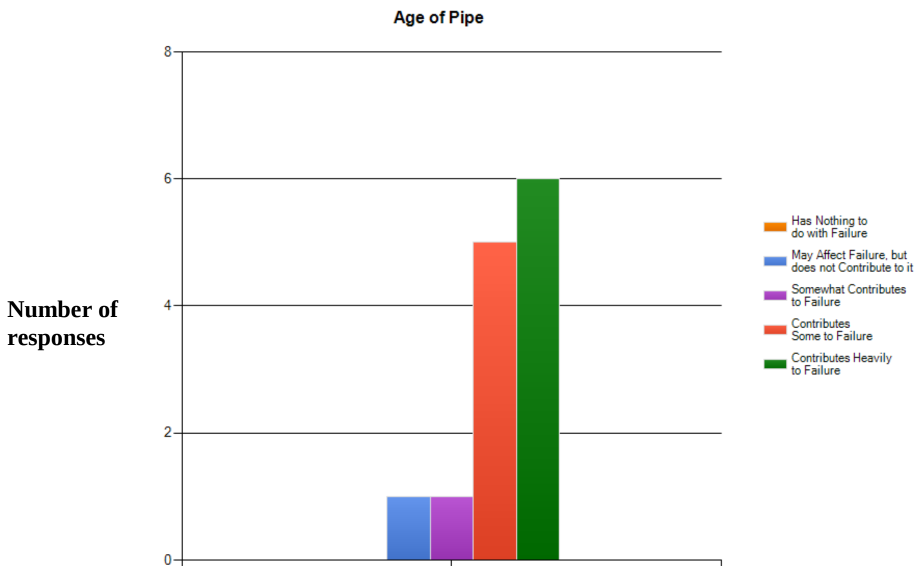

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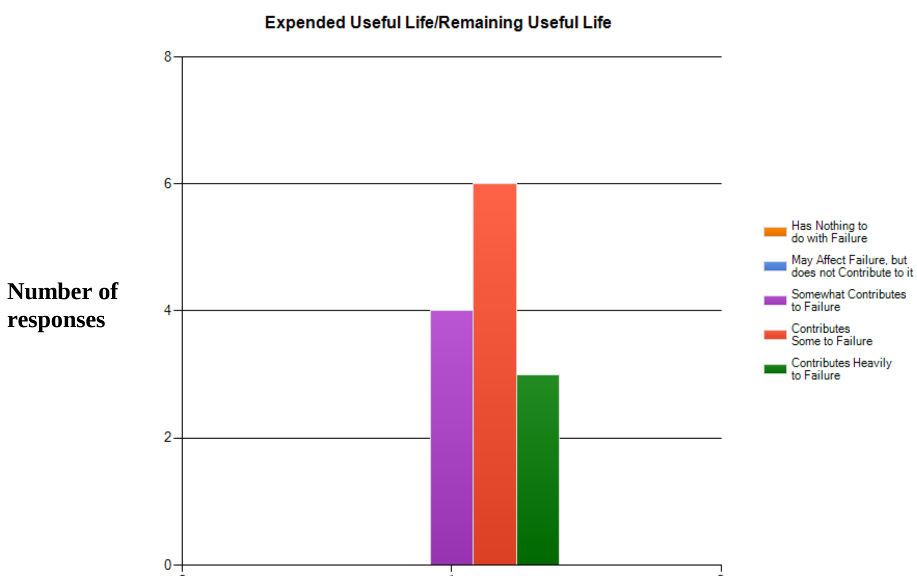

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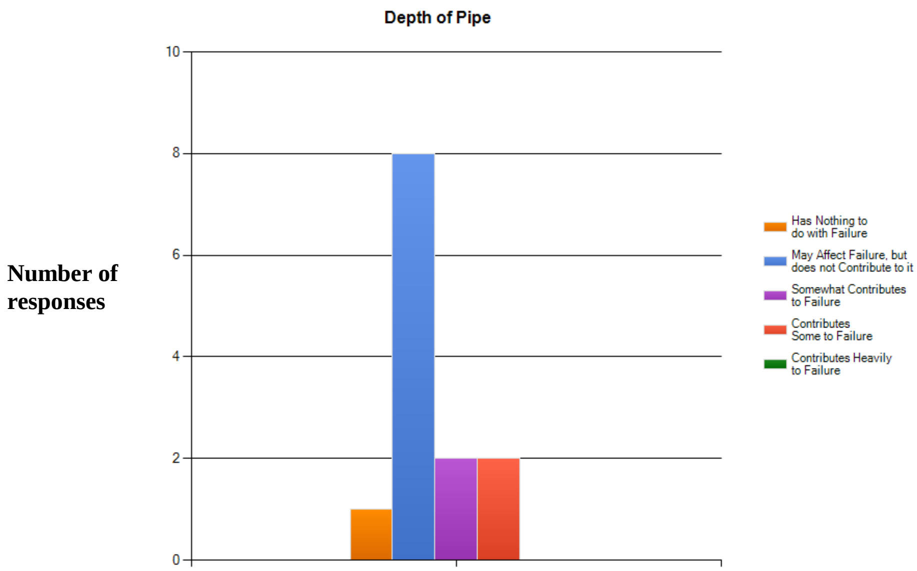

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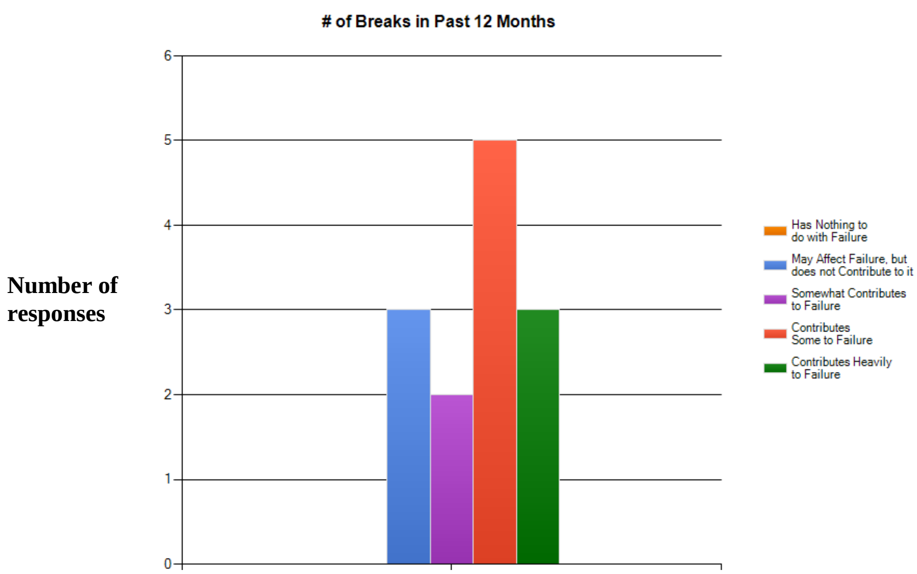

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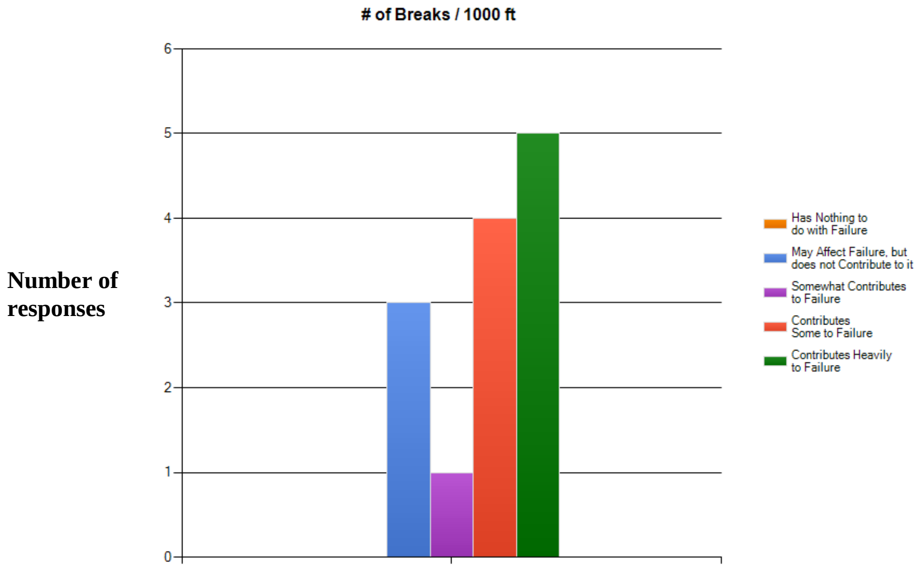

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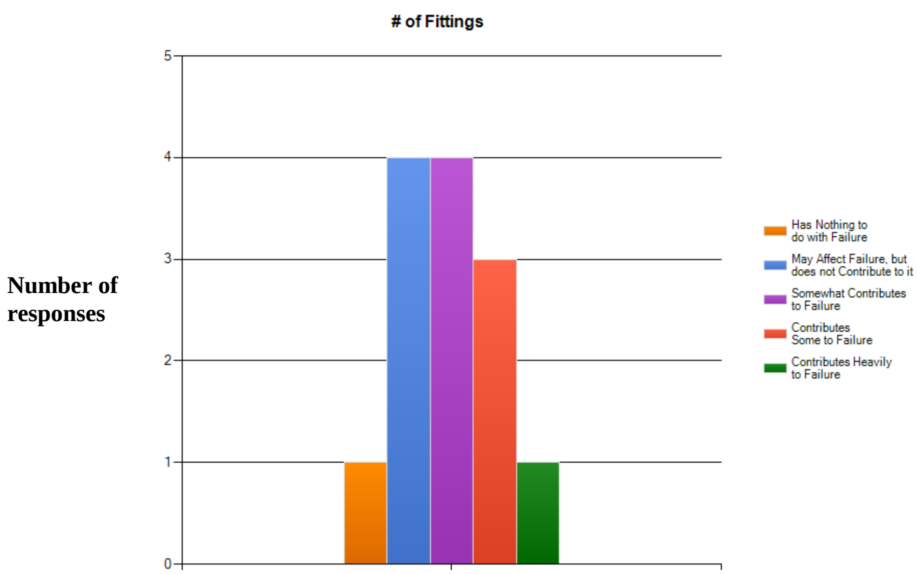

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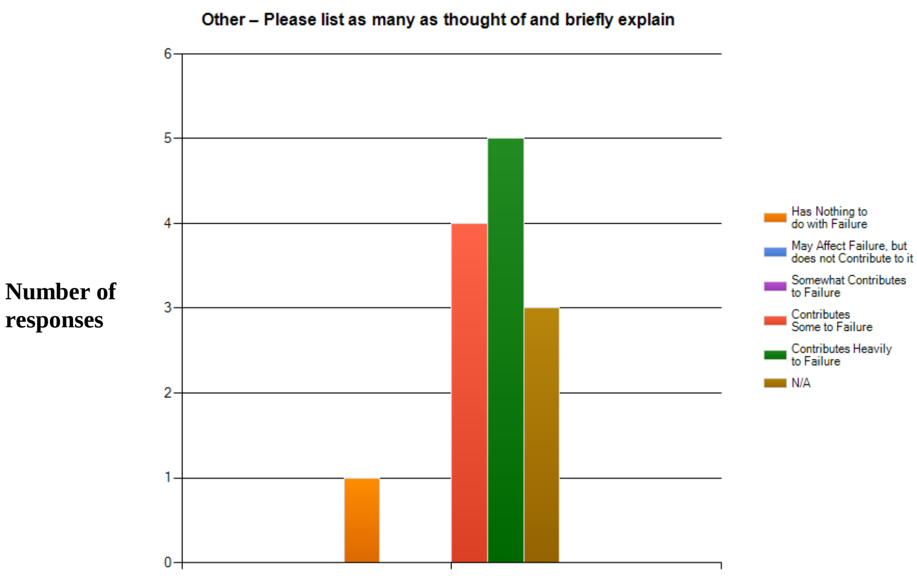

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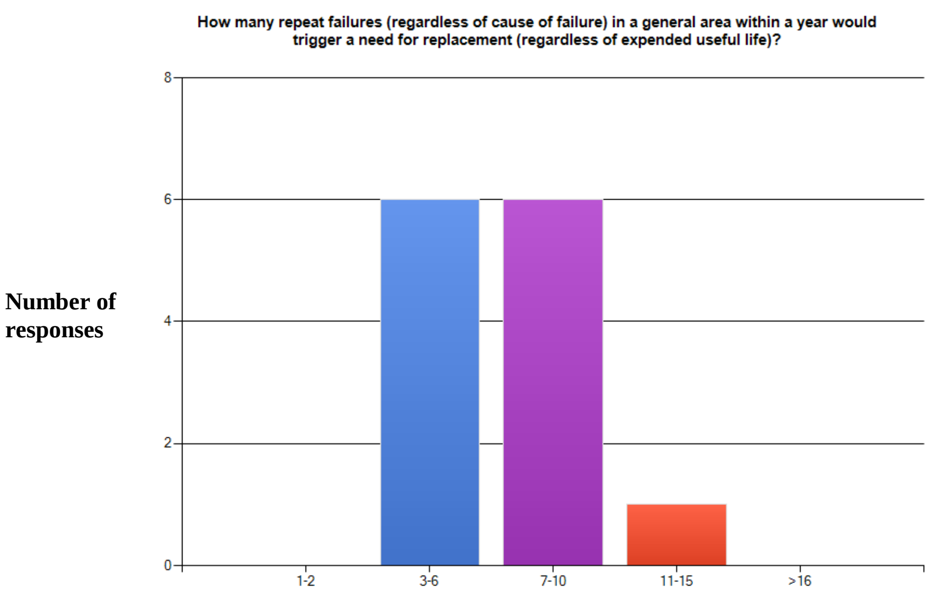

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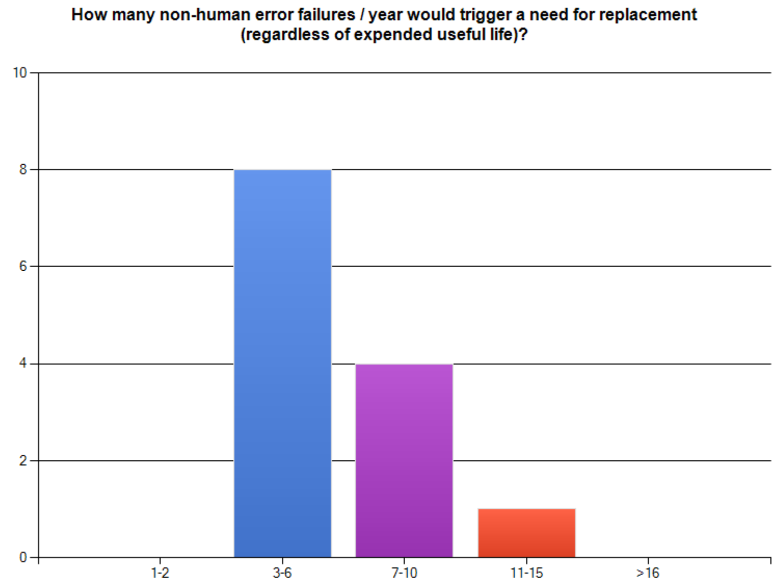
Number of responses



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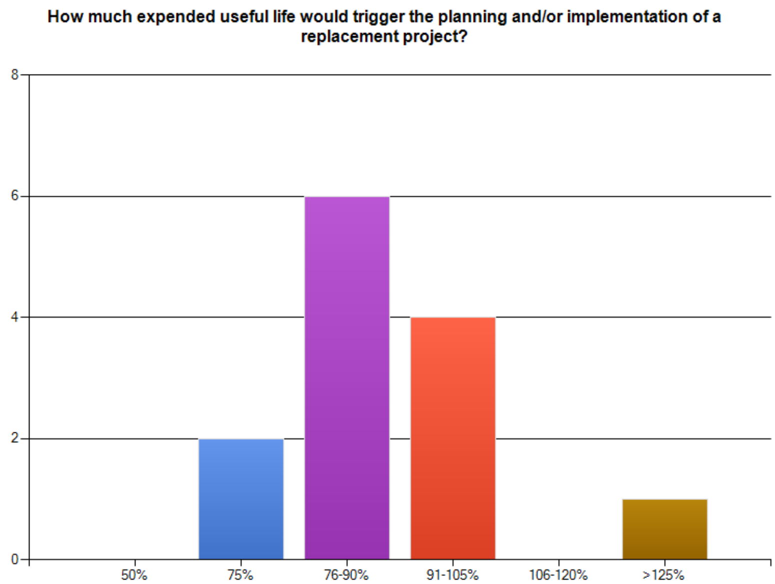
Number of responses



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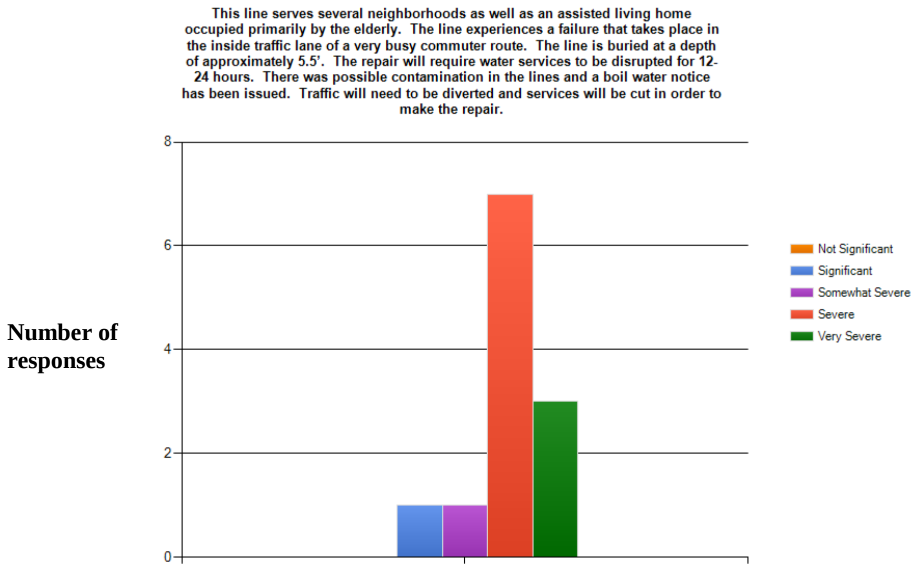

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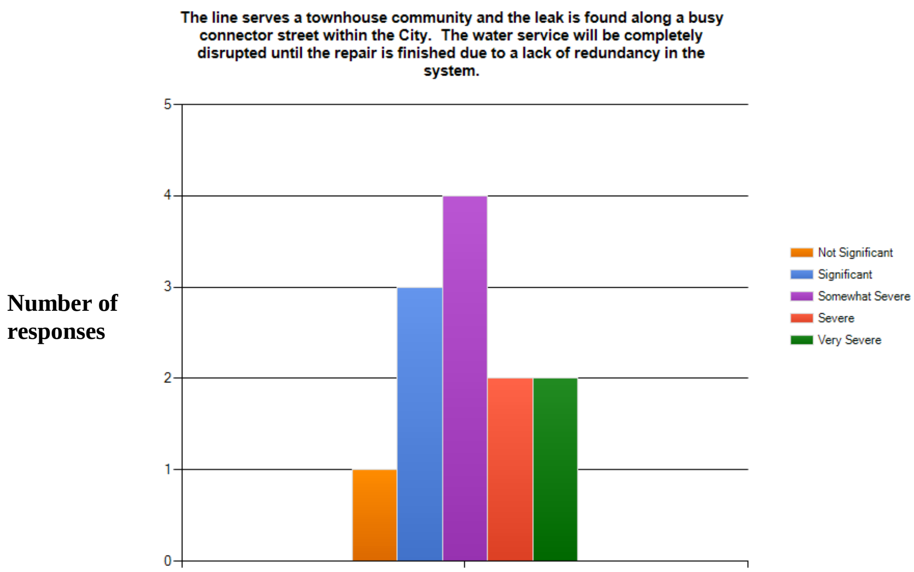

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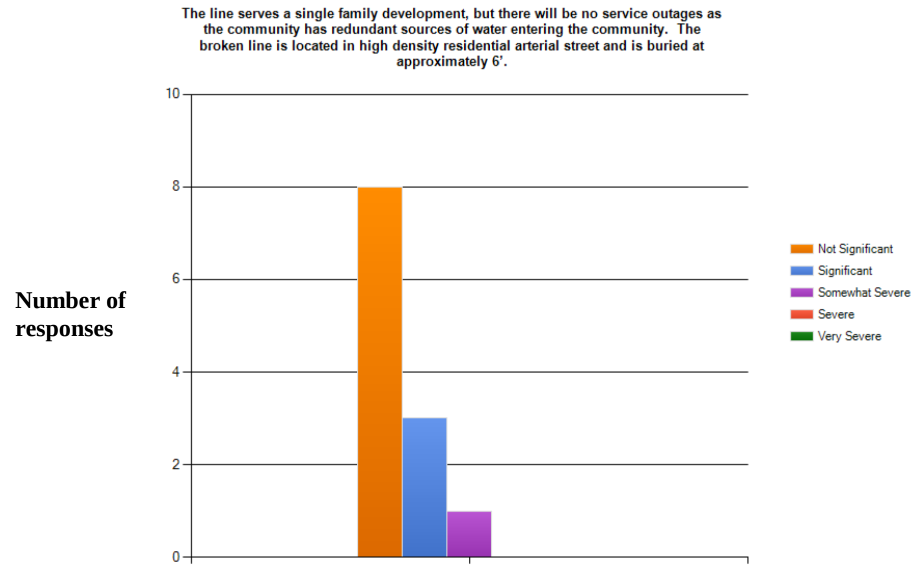

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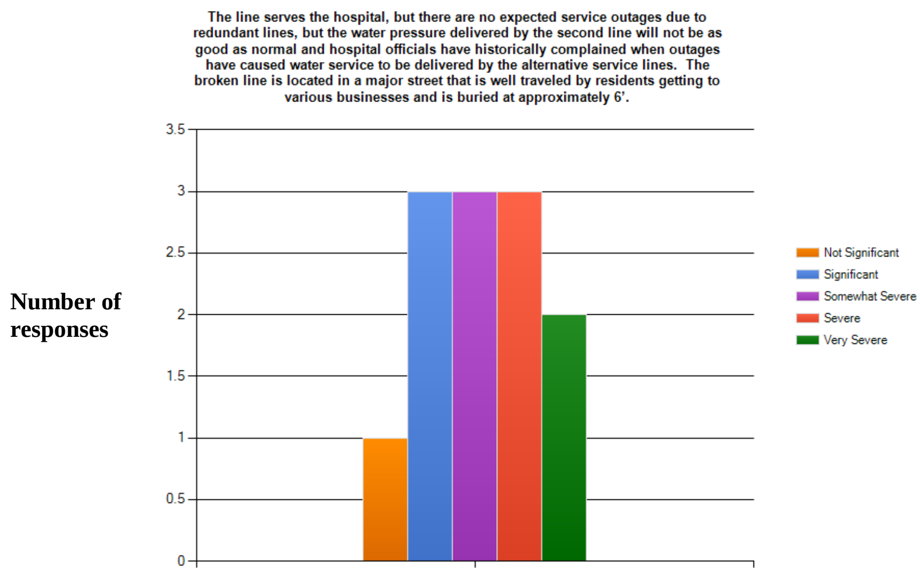


Figure A37 Survey Question 22

Number of responses

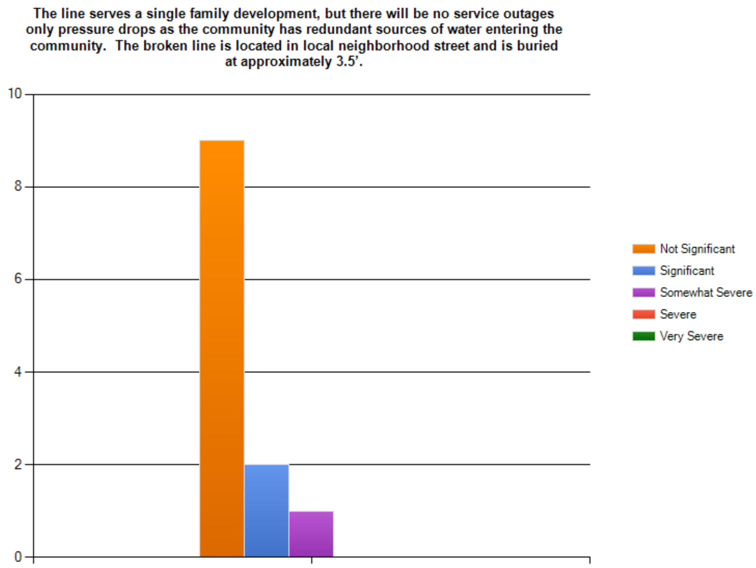
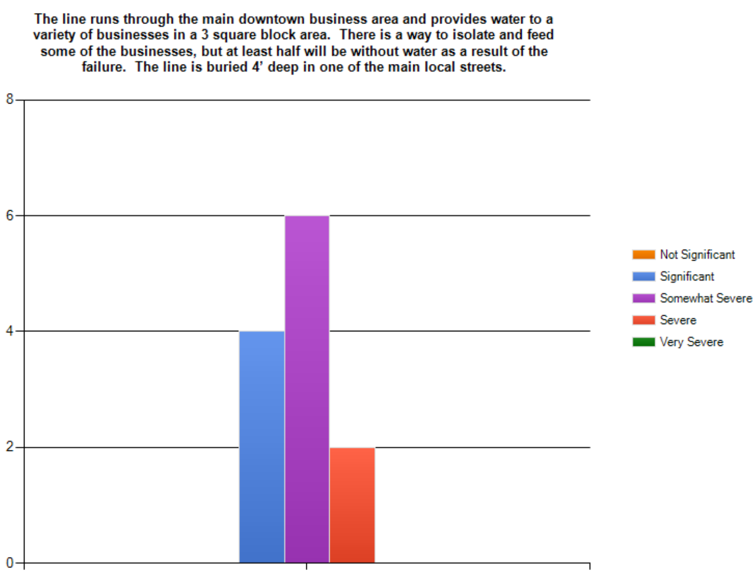


Figure A38 Survey Question 23

Number of responses



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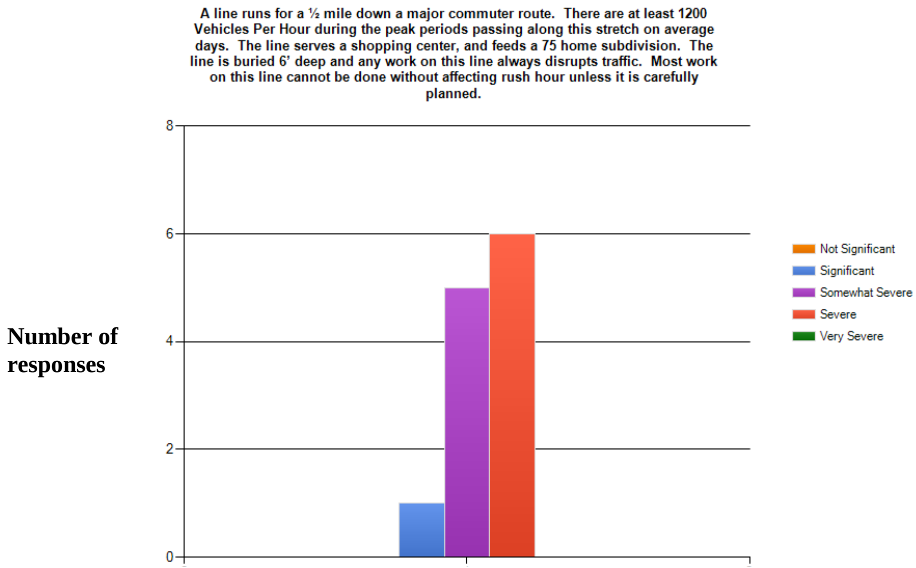

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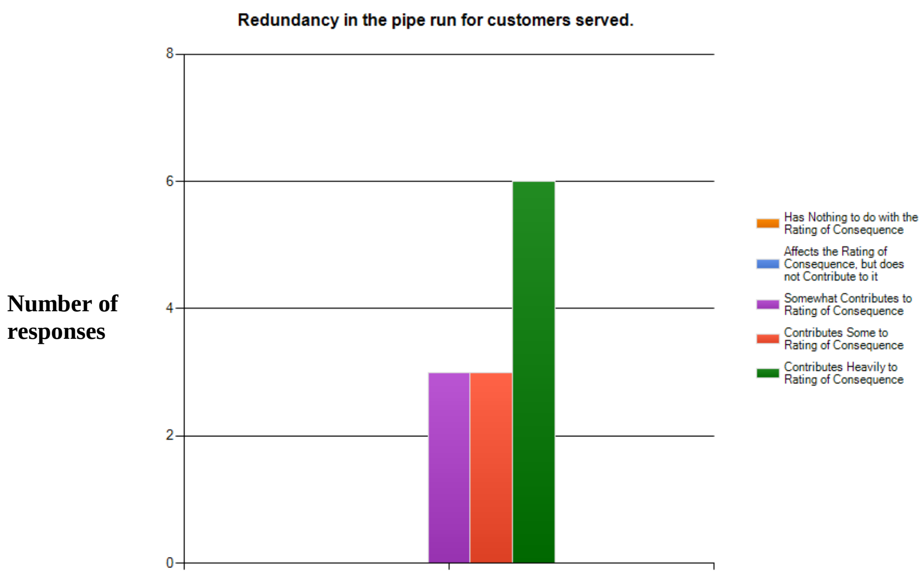
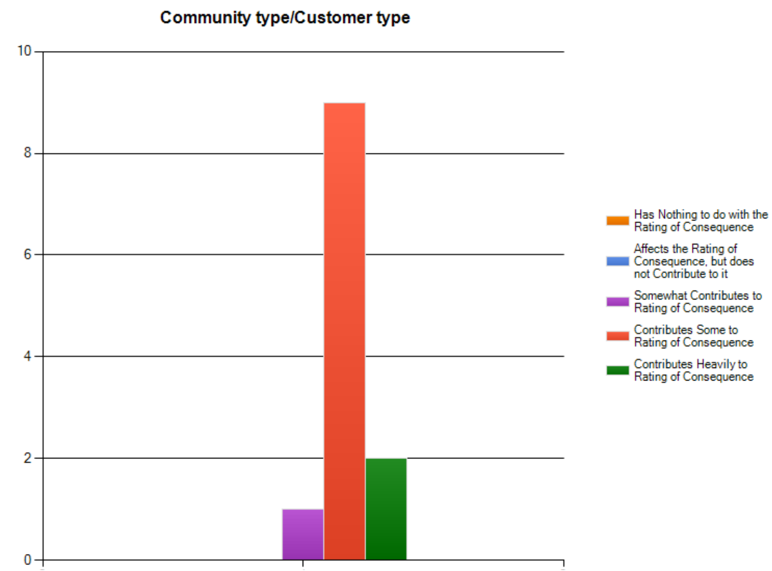


Figure A41 Survey Question 26

Number of responses



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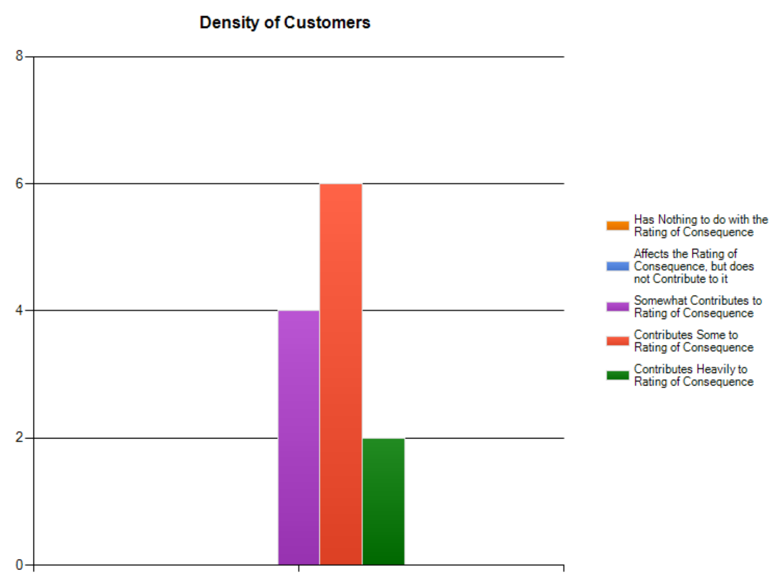
Number of responses



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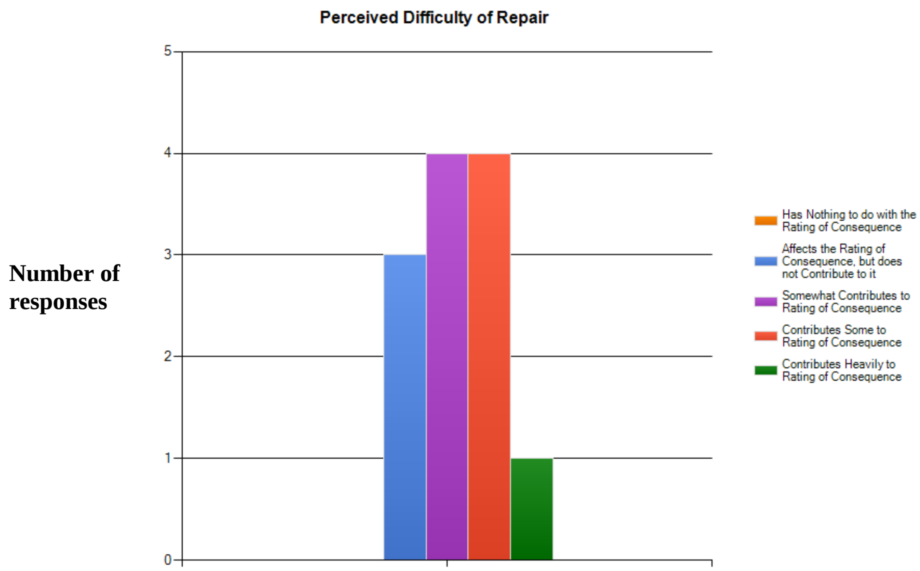

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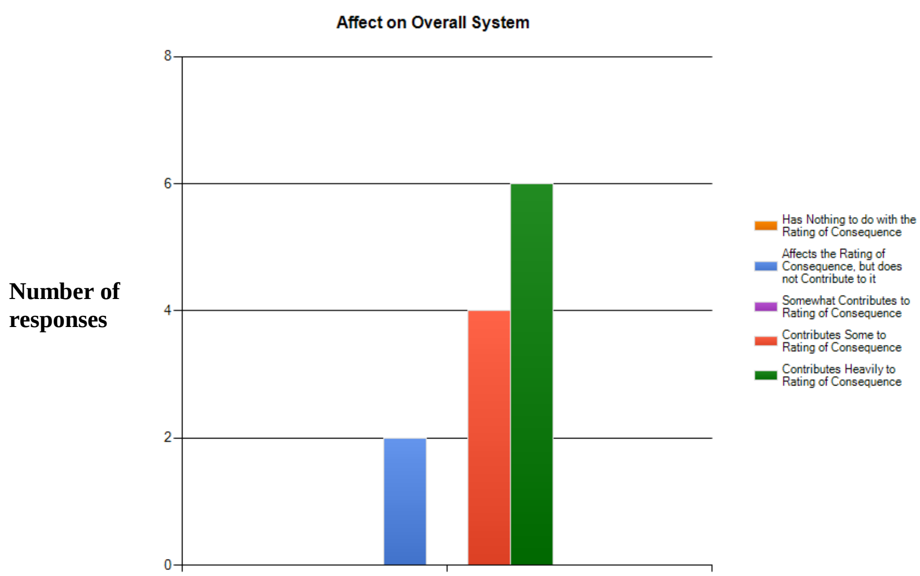

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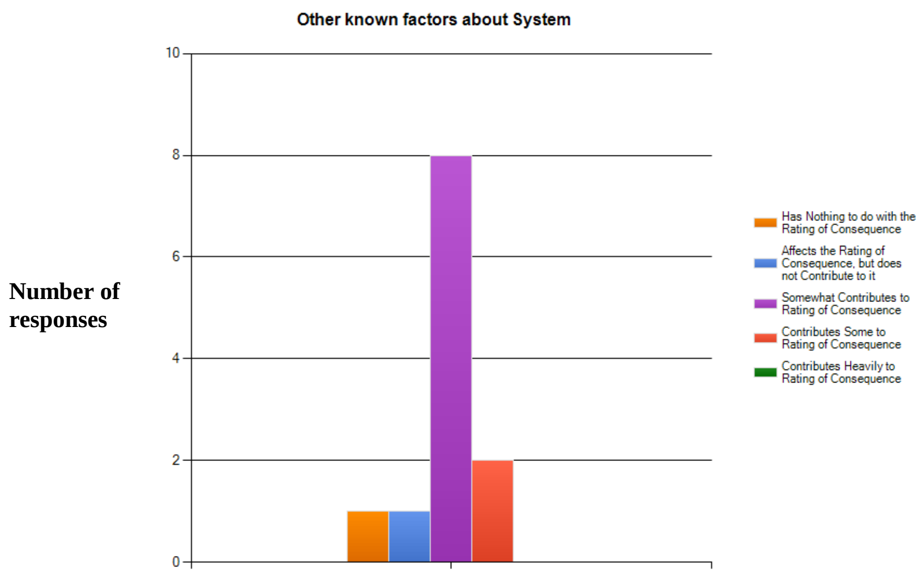

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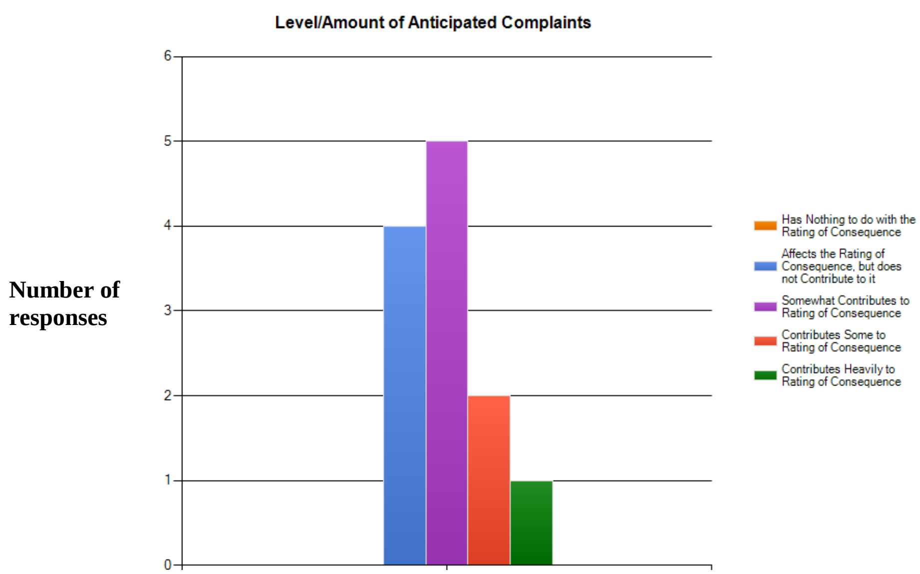

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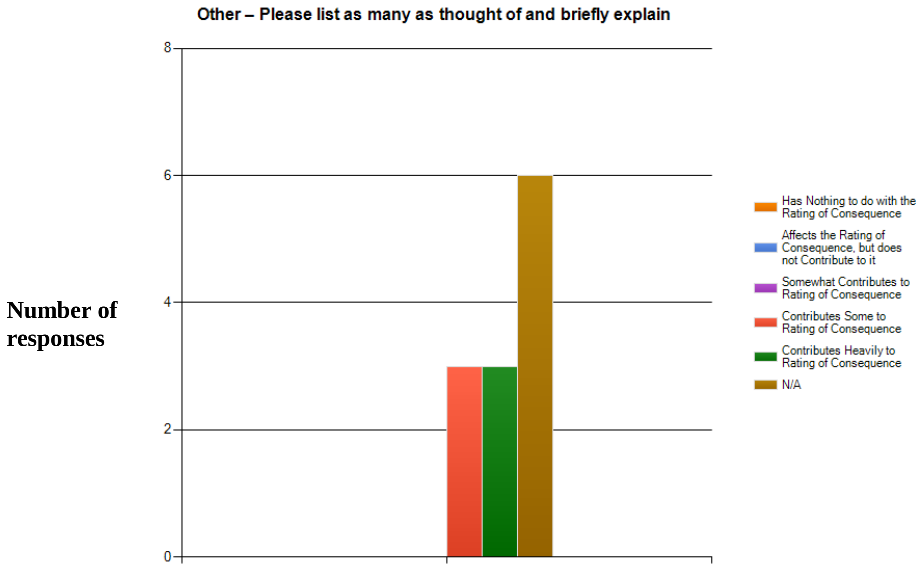


Figure A48 Survey Question 33

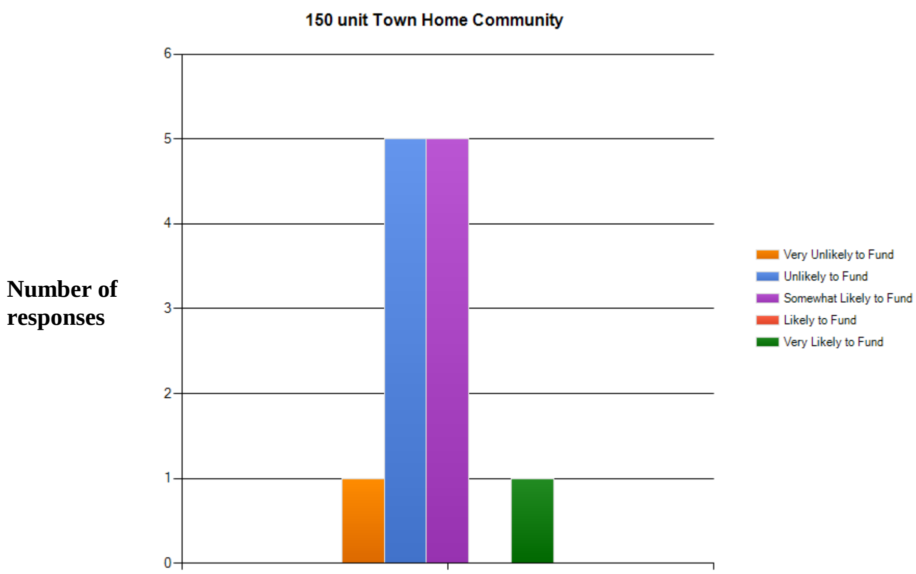


Figure A49 Survey Question 34

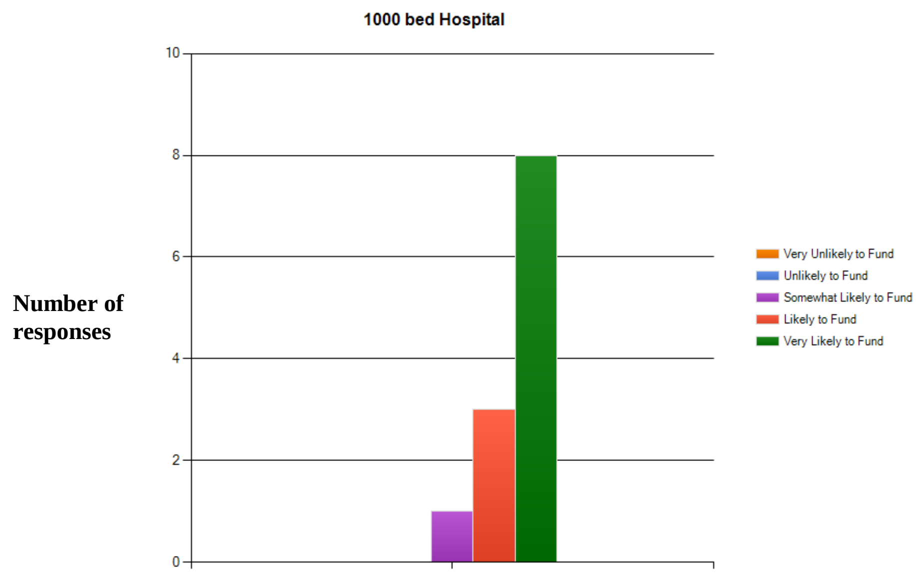


Figure A50 Survey Question 35

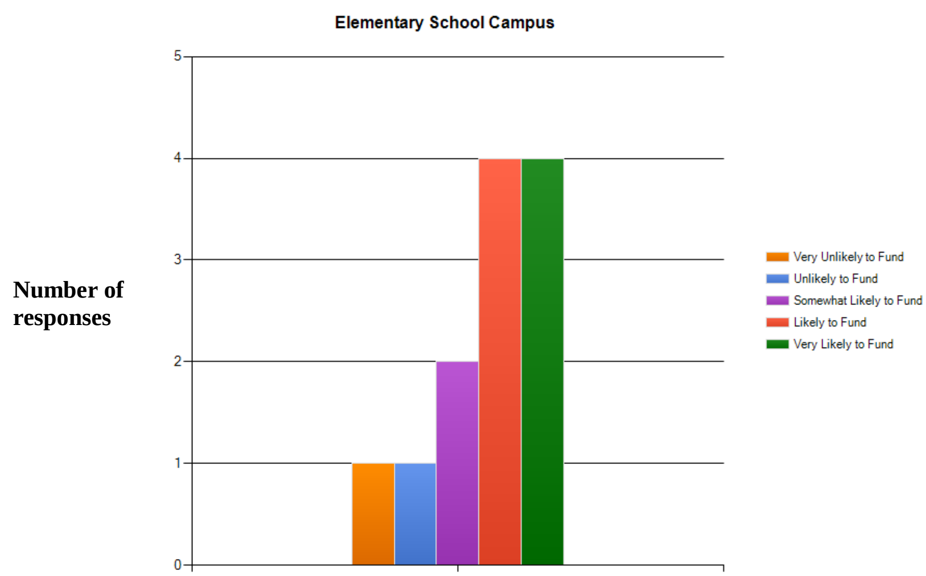


Figure A51 Survey Question 36

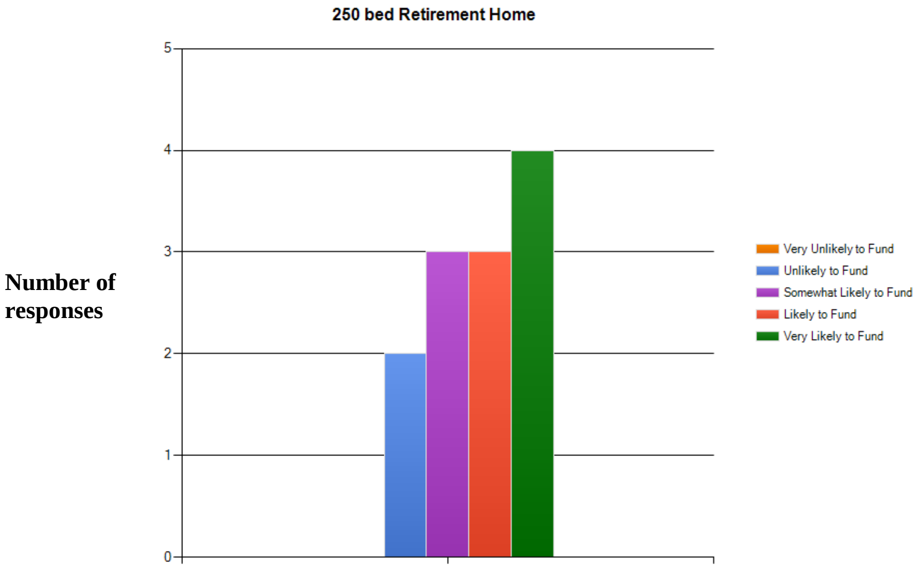
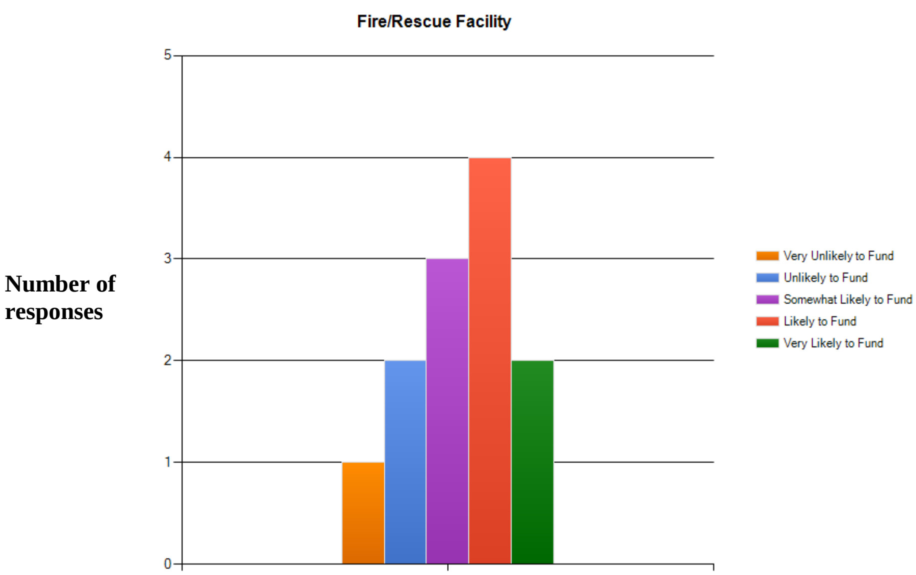


Figure A52 Survey Question 37



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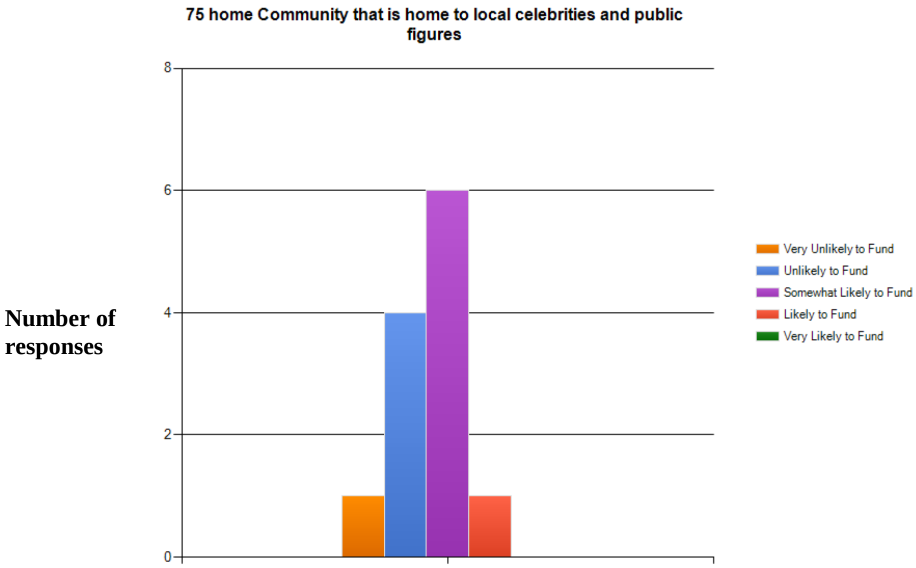
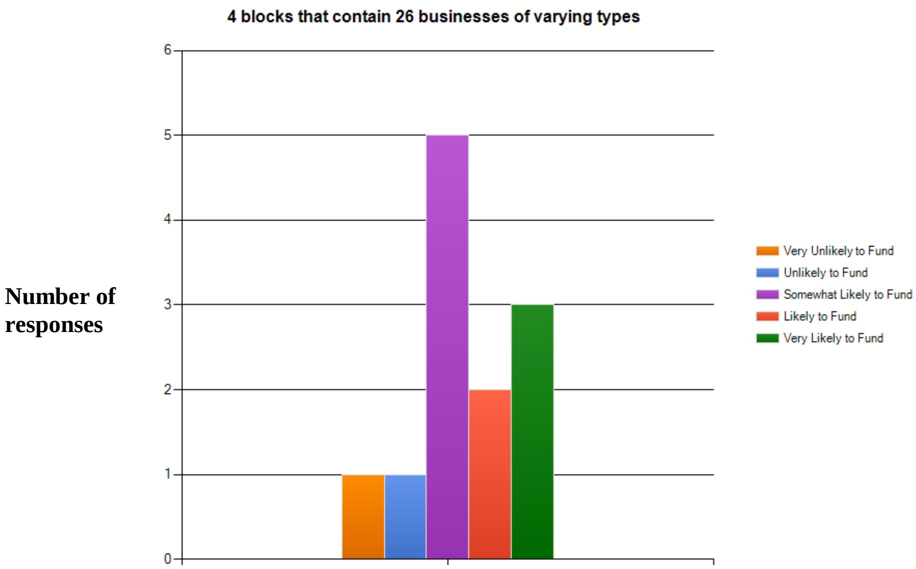


Figure A54 Survey Question 39



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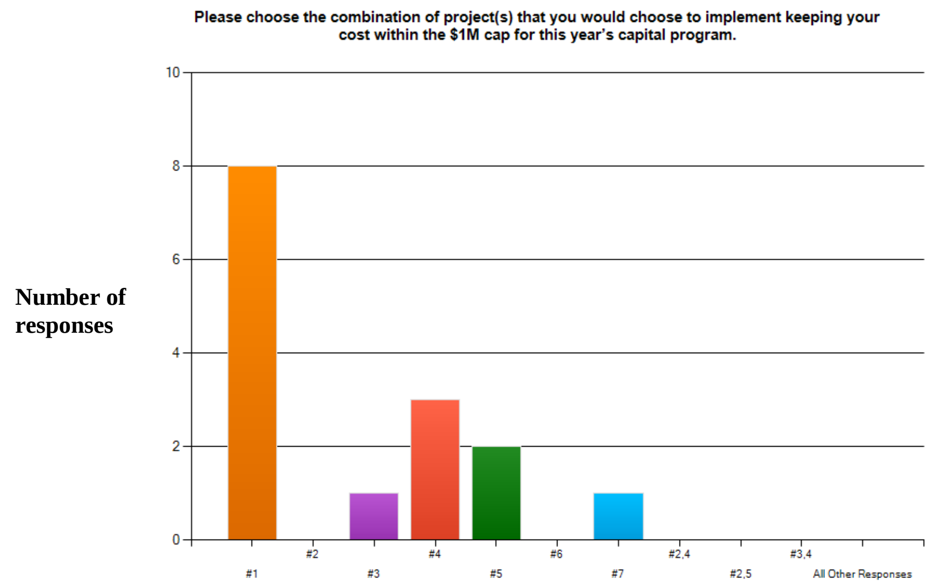


Figure A56 Survey Question 41

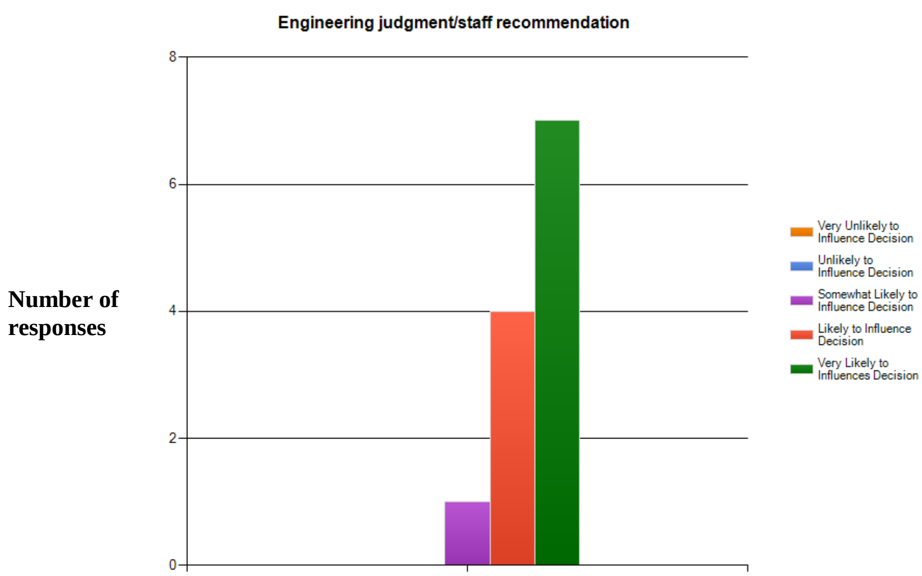


Figure A57 Survey Question 42

Number of responses

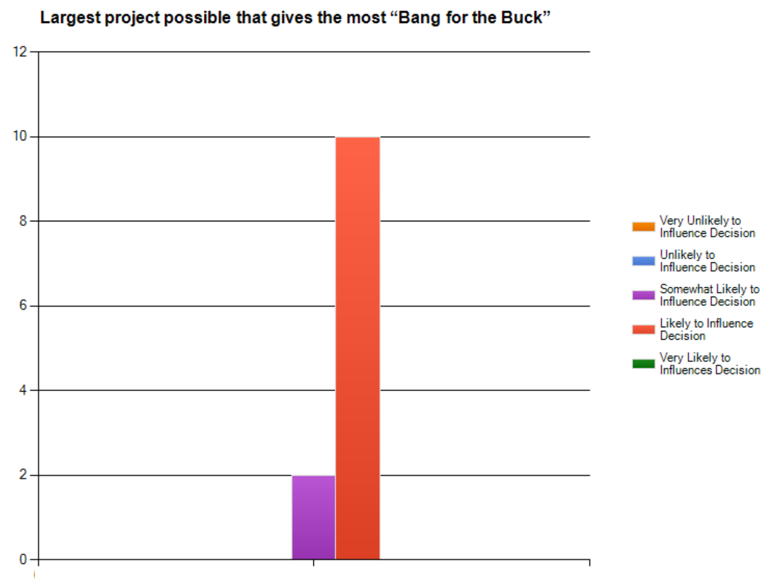


Figure A58 Survey Question 43

Number of responses

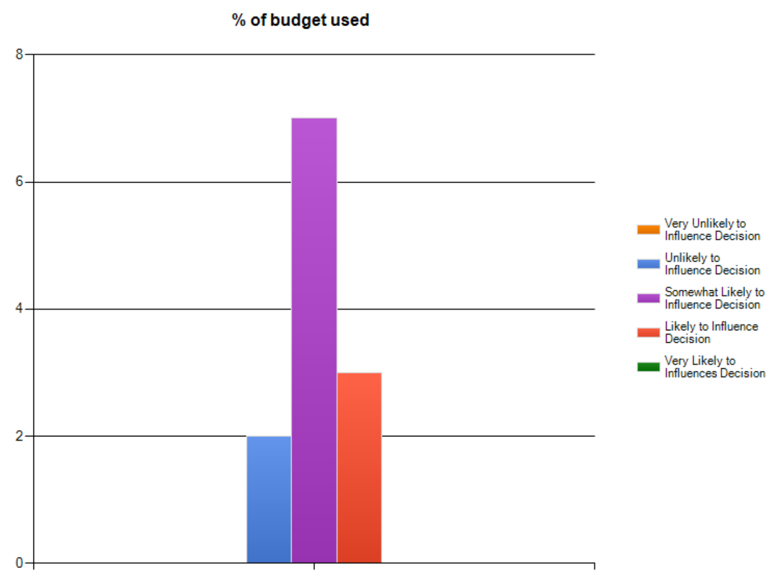


Figure A59 Survey Question 44

Figure A60 Survey Question 45

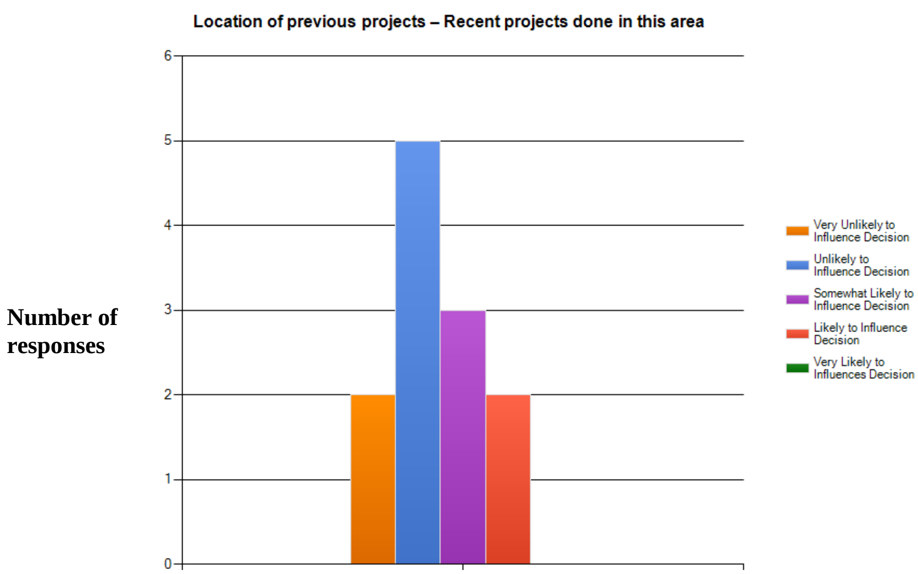


Figure A61 Survey Question 46

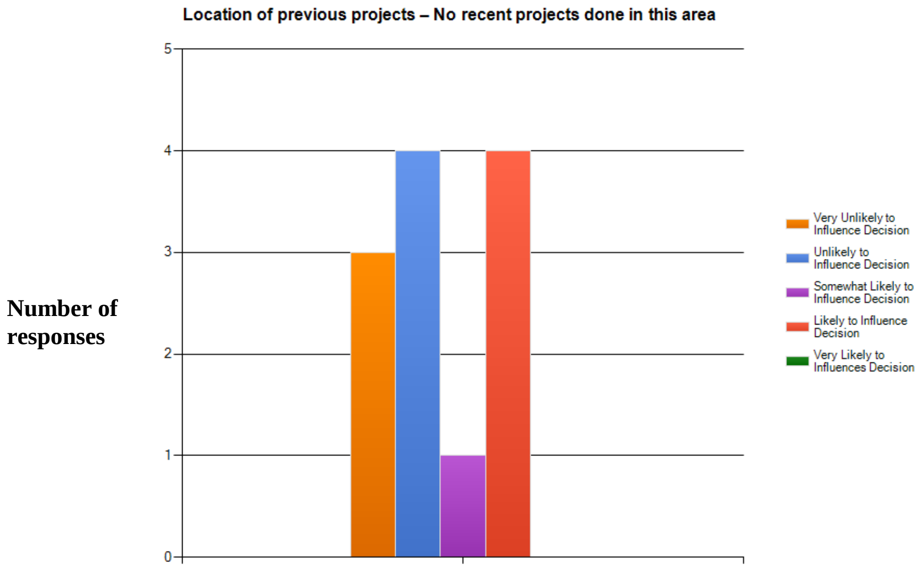
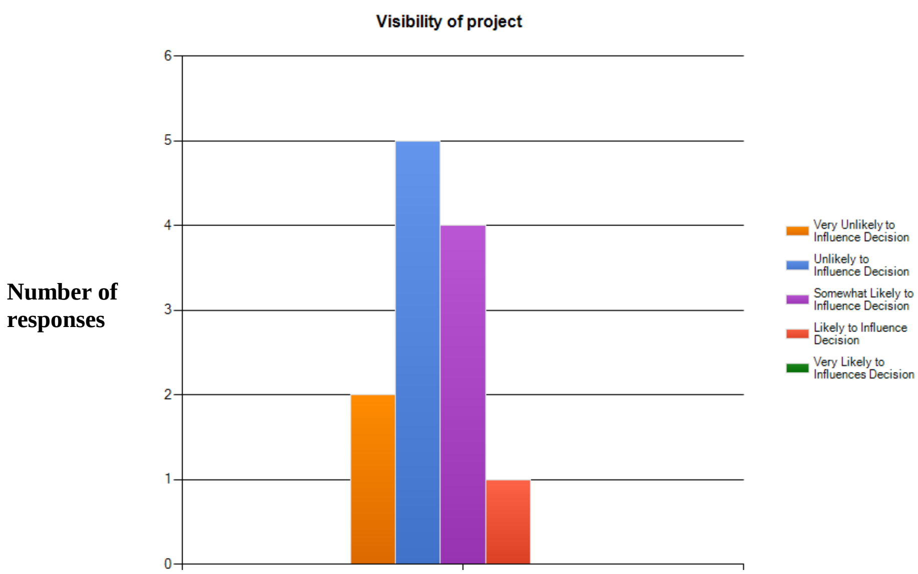


Figure A62 Survey Question 47



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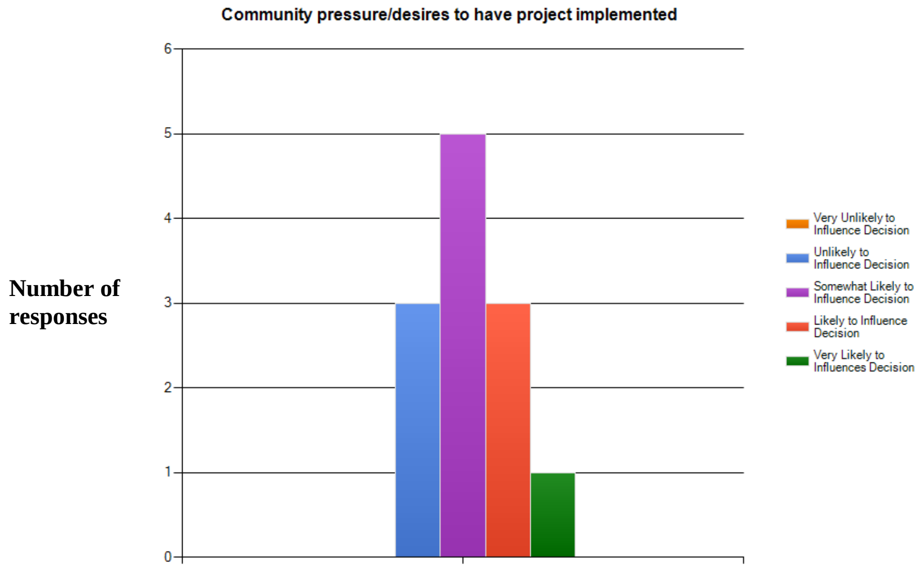

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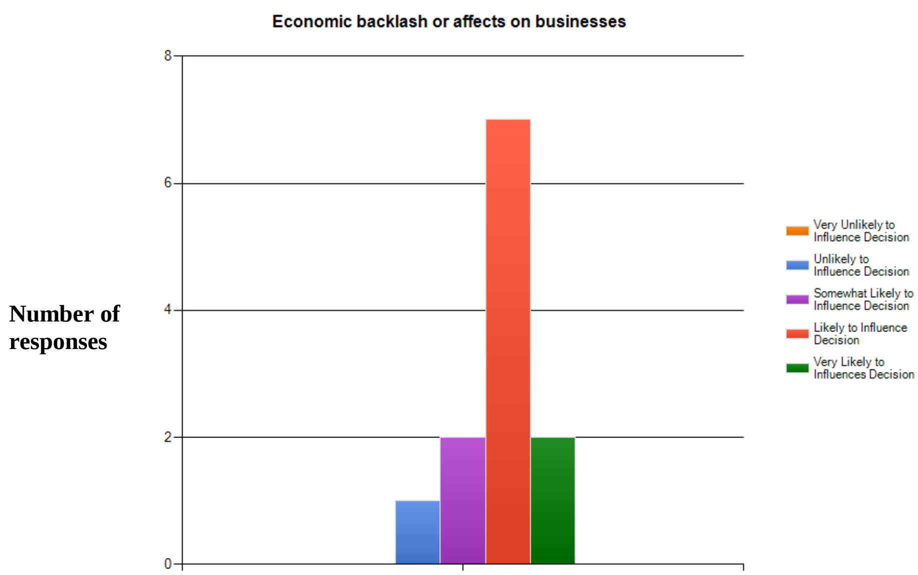

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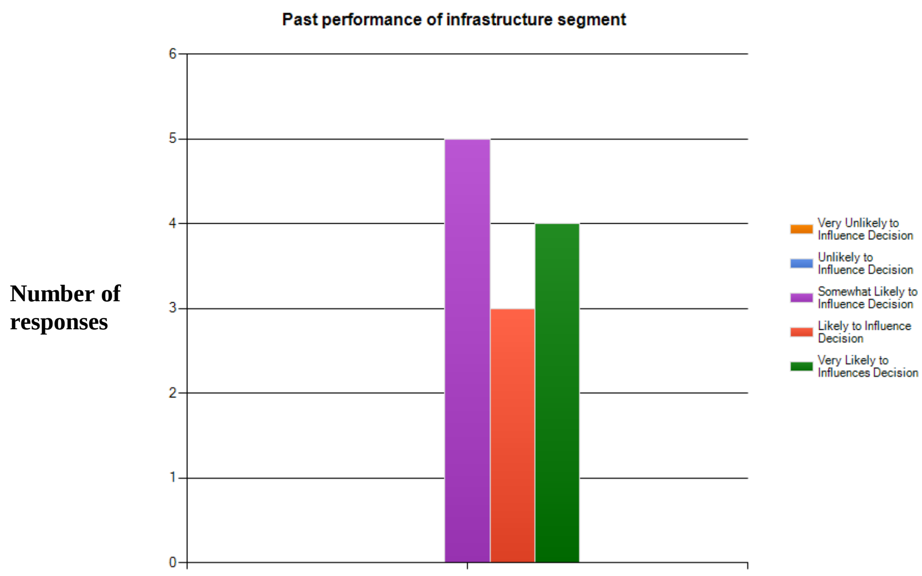

Figure A66 Survey Question 51

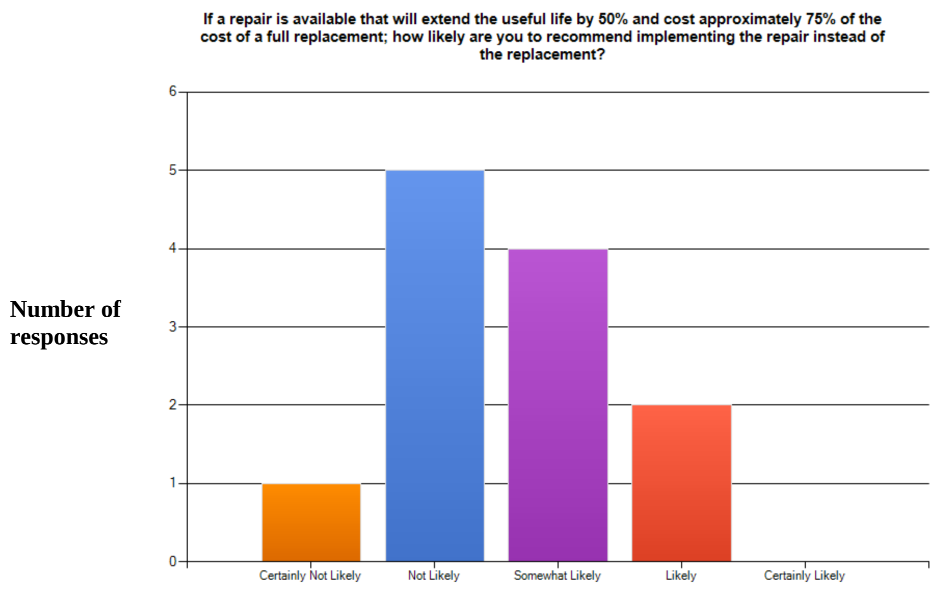

Figure A67 Survey Question 52

Appendix B – EPA CUPSS Asset Management System and Risk Calculations

Field Label	Description
Asset Name	The name of the technology or equipment that is used for the system to properly function. If there are many assets of the same time, consider differentiating them with a letter or a number so that they can easily and quickly be told apart.
Location	Where the asset is within the system. For example Pipe X is on Main Street 1/2 mile south of Franklin Boulevard.
Installation Date	Indicate the date that the asset was installed. If an exact date is unknown, estimate as close as possible, or include a range. This might lend information for analysis (i.e. brittle steel used in the 1940's because of the amount of steel being used for war related activities).
Original Cost	Indicate the amount paid for the asset
Expected Useful Life	The value used in this field should be extracted from tables as appropriate and should indicate the expected life when installed new and properly maintained
Replacement Cost	Indicate the amount it would cost to replace the asset (in away that provides a similar or agreed upon level of functionality)
Routine Maintenance Cost	Indicate the cost expenditures made for normally anticipated maintenance activities.
Frequency of Rountine Maintenance	Indicate the frequency in which maintenance is performed and that the maintenance costs will be incurred.
Maintained according to factory recommendations?	Indicate if the asset has been maintained according to the manuracturer's or factory's recommendations
Condition	Select the most appropriate value to indicate the current condition of the asset (based on age and physical functionality). The options will include Excellent (35 years remaining), Good (20 years remaining), Fair (10 years remaining), Poor (5 years remaining), and Very Poor (1-5 years remaining).
CoF is Consequence of Failure	Select the mose appropriate value indicating the consequences of asset failure ranging from insignificant to catastrophic impacts. Consequence of Failure estimates the degree of impact on utility services should the asset fail. Consider the real or hypothetical resultes when selecting a value, including impacts on regulatory compliance, local government, customers, adn the community. The question must be asked, "How bad would it be if this asset failed unexpectedly?"
Redundancy	Select the value that best represents the functional redundancy of an asset. The value should indicate what percentage of the asset's functionality is duplicated by other assets
Asset Status	What is the current status of the asset
Can the Asset be Repaired	Indicate whether or not the asset can be repaired in casof failure or disrepair
Can the Asset be Rehabilitated?	Indicated whether or not the asset can be rehabilitated (have its capabilities or condition restored) in case of failure.

Figure B68 Asset Management Data Collection Checklist (EPA, 2008)

Inventory List (Drinking Water)

Asset Name	**Location**
Associated Asset	**Associated Location**

Asset Category

❑ Source ❑ Pumping Facility ❑ Treatment ❑ Storage ❑ Distribution ❑ Other

Asset Type

❑ Wells and Springs ❑ Intake Structures ❑ Pumping Equipment ❑ Disinfection Equipment ❑ Hydropneumatic Tanks ❑ Concrete & Metal Storage Tanks ❑ Transmission Mains ❑ Distribution Pipes	❑ Valves ❑ Computer Equipment/ Software ❑ Transformers/ Switchgears/ Wiring ❑ Motor Controls/Drives ❑ Sensors ❑ Buildings ❑ Service Lines	❑ Hydrants ❑ Treatment Equipment ❑ Lab/Monitoring Equipment ❑ Tools and Shop Equipment ❑ Transportation Equipment ❑ Security Equipment ❑ Land	❑ Galleries and Tunnels ❑ Meters ❑ Raw Water Reservoirs ❑ Generators ❑ Liquid Waste Handling & Disposal ❑ Solid Waste Handling & Disposal ❑ Other

Asset Status

❑ Active ❑ Not in Use – Abandoned ❑ Not in Use – Back Up ❑ Future Investment

Can this Asset be Repaired? ❑ Yes ❑ No

Can this Asset be Rehabilitated? ❑ Yes ❑ No

Condition

❑ Excellent ❑ Good ❑ Fair (Average) ❑ Poor ❑ Very Poor

Is the asset maintained according to manufacturer's recommendations? ❑ Yes ❑ No

Consequence of Failure

❑ Insignificant – CoF of 2 ❑ Minor – CoF of 4 ❑ Moderate – CoF of 6
❑ Major – CoF of 8 ❑ Catastrophic – CoF of 10

Redundancy

❑ 0% Backup ❑ 50% Backup ❑ 100% Backup ❑ 200% Secondary Backup

Installation Date	**Original Cost**
	$
Expected Useful Life	**Replacement Cost**
	$
Routine Maintenance Costs	**Timeframe**
$	❑ per/day ❑ per/week ❑ per/month ❑ per/year ❑ lifetime

Optional Information

Frequency of Routine Maintenance	**Start Date**
Model Number	**Manufacturer**
Supplier Name	
Address	**City, State, Zip**
Phone Number	**Fax Number**
Notes	

Figure B69 Sample Asset Management Data Collection Sheet (EPA, 2008)

New Task

Staff Name	Task Name

Task Type

❑ Monitoring ❑ Routine Monitoring ❑ Repair ❑ Rehabilitation ❑ Replacement ❑ Other

Is this task planned? ❑ Yes ❑ No

Task Details

Task Notes

Cost of the Task	$

Asset Tasks

Asset Name	

Condition

❑ Excellent ❑ Good ❑ Fair (Average) ❑ Poor ❑ Very Poor

Is the asset maintained according to manufacturer's recommendations? ❑ Yes ❑ No

Monitoring Tasks

Chemicals	Amount

Schedule

Task Start-End Date	Completed Date

Frequency

❑ Daily ❑ Weekly ❑Monthly ❑ Annually

Recurs every

________ days	______ week on ______ (Day of week)	_____ day of every ____ (Month)

Recurrence End Date	

Optional Parts Information

Manufacturer/Supplier	
Parts Name	
Parts Number	
Parts Cost	$
Labor Maintenance Costs	$

Figure B70 Sample Task Information Entry Form (EPA, 2008)

Inventory Calculations

Estimated Remaining Useful Life

Estimated Remaining Useful Life = Estimated Useful Life – (Install Year-Current Year)

Remaining Useful Life (RUL)

Remaining Useful Life = Estimated Remaining Useful Life * Condition

Condition (Rating according to table of %Remaining useful Life)

Table B24 Condition Rating of Remaining Useful Life (EPA, 2008)

Rating	% Estimated RUL Remaining	
	If asset is maintained according to manufacturer's recommendtions	If asset is NOT maintained according to manufacturer's recommendations
Excellent	120	110
Good	110	105
Fair(Average)	100	100
Poor	95	90
Very Poor	90	80

Replacement Year

Replacement Year = Current Year + Remaining Useful Life

(The risk factor will prioritize asset replacement within a given replacement year)

Redundancy

Table B25 Redundancy Rating for Assets (EPA, 2008)

Redundancy	Value used in Calculations
0%	0
50%	0.5
100%	0.9
200%	98

Probability of Failure (PoF) = ((Estimated Useful Life – Remaining Useful Life)/Estimated Useful Life)*(1-Redundancy)*10

Consequence of Failure (CoF)

Table B26 Consequence of Failure Value (EPA, 2008)

CoF	Value
Insignificant	2
Minor	4
Moderate	6
Major	8
Castastrophic	10

- A value must be assigned to the consequence of a failure. The value is chosen based on impacts to regulatory compliance, local government, customers and the community. The asset manager must ask *"how bad would it be if the asset failed unexpectedly"*. Some of the major categories that should be considered as value assignment is made include:
  - Spill, Flood, Odor – Consider the duration (short, substantial, or sustained), the quantity (small, medium, or large) and the number of complaints (none, few, or many). The larger the spill, or number of anticipated complaints, the higher the CoF.
  - Water or Effluent Quality – Consider the impact on the water or effluent quality from no impact to loss of full control and effect on human health. Larger impacts on water or effluent will indicate higher CoF
  - Regulatory Compliance – How will the failure affect permit violations – from no impact to violation of the daily, weekly, or monthly standards that affect the ability to meet the permit requirements? The greater the impact on standards, the higher the CoF
  - Loss of Service to Customers – Think about if the asset can be down for a day, month, week or hour and how this down time will impact service provided to customers. The shorter the asset can be offline without severe impact, the higher the CoF.
  - Equipment and Safety – If the asset fails, will it affect the system at the asset, system, or plant level? The greater the impact on the overall utility's services, the higher the CoF.
  - Economic Impact – Consider the cost for repairing the asset and the associated system parts. Can emergency funds be used to cover the cost of the asset failure and the associated costs of the failure including the repair, loss of revenue, utility property damage, private property damage, and other claims that might be attributable to the failure? Will additional or

new resources be needed to help manage the economic impact of the failure? The higher the cost, the greater the CoF.

Risk Factor

Risk Factor = PoF x CoF

Risk factors can be placed into a category of High, Medium or Low and actions should be taken accordingly.

Table B27 Risk Factor and Action Guidance (EPA, 2008)

Category	Value	Action
High	If CoF>5 and PoF>5	Immediate Attention
Medium	If CoF<5 and PoF>5 Or If CoF>5 and PoF<5	Aggressive Monitoring
Low	If CoF<5 and PoF<5	Routine Maintenance

Appendix C – Manassas and WSSC Study Area

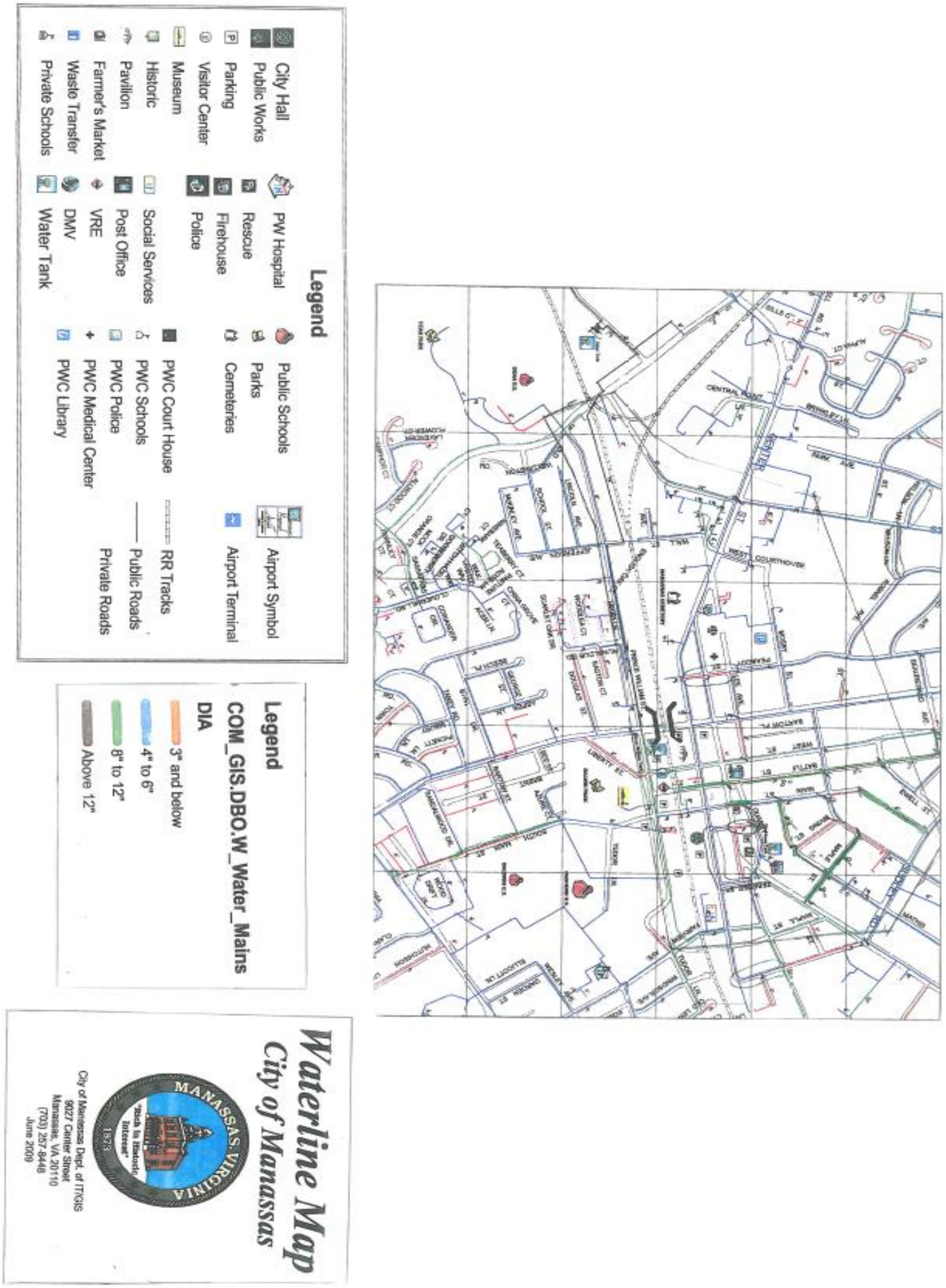

Figure C71 Validation Study Area

Raw Data for Developing Theory

The raw data below was the author's first look at the theory. With this data, several parameters that were believed to affect facility failure were listed. These parameters were given values based on data from the City of Manassas database. The information in the database included repair write-ups in which technicians described the failure and required repairs. This raw data was run through the model to see if, based on recorded break information (or in absence of breaks standard numbers were assigned), the model would suggest different repair or replacement. The consequences were based on known information about the system. This was an initial test to see if the theory seemed to be completely off, and perhaps give some insight into possible adjustments that could be made. The number of significant digits was not reduced since these numbers would not actually end up in actual data publications.

A similar process was done with the WSSC data to see how it fared as well. There was no survey done based on WSSC information, so the actual weighting and index numbers were from the surveys of the industry professionals with the City of Manassas in mind.

Segment	Threat	Shear (from Lateal Pressure)	Freeze (bury depth)	Puncture (from other work)	Age of pipe	Fitting (how many fittings	Installation (how well installed)	Pipe Size (What size is pipe)	Material	Past failures	Joint Failure	Vulnerability	Normalized	Set for Table
1	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
2	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
3	1	0.5	0.3	0.6	0.8	0.1	0.3	0.5	0.7	0.1	0.1	0.4	0.75	4
4	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
5	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
6	1	0.5	0.3	0.6	0.5	0.1	0.3	0.8	0.5	0.1	0.1	0.38	0.7125	3.8
7	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
8	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
9	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
10	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.2	0.1	0.35	0.65625	3.5
11	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
12	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
13	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
14	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.1	0.1	0.32	0.6	3.2
15	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.1	0.1	0.32	0.6	3.2
16	1	0.5	0.3	0.6	0.5	0.1	0.3	0.3	0.4	0.1	0.1	0.32	0.6	3.2
17	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
18	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.1	0.1	0.32	0.6	3.2
19	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
20	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
21	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
22	1	0.5	0.3	0.6	0.8	0.1	0.3	0.4	0.7	0.1	0.1	0.39	0.73125	3.9
23	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
24	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
25	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
26	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
27	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.2	0.1	0.34	0.6375	3.4
28	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.2	0.1	0.35	0.65625	3.5
29	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.1	0.1	0.32	0.6	3.2
30	1	0.5	0.3	0.6	0.8	0.1	0.3	0.4	0.7	0.3	0.1	0.41	0.76875	4.1
31	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
32	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
33	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
34	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.2	0.1	0.1	0.31	0.58125	3.1
35	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.2	0.1	0.33	0.61875	3.3
36	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
37	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.4	0.1	0.1	0.33	0.61875	3.3
38	1	0.5	0.3	0.6	0.5	0.1	0.3	0.8	0.5	0.1	0.1	0.38	0.7125	3.8
39	1	0.5	0.3	0.6	0.5	0.1	0.3	0.8	0.5	0.1	0.1	0.38	0.7125	3.8
40	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
41	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
42	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
43	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
44	1	0.5	0.3	0.6	0.9	0.1	0.3	0.4	0.3	0.1	0.1	0.36	0.675	3.6
45	1	0.5	0.3	0.6	0.9	0.1	0.3	0.4	0.3	0.1	0.1	0.36	0.675	3.6
46	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.7	0.1	0.1	0.36	0.675	3.6
47	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.2	0.1	0.1	0.31	0.58125	3.1
48	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.2	0.1	0.1	0.32	0.6	3.2
49	1	0.5	0.3	0.6	0.5	0.1	0.3	0.4	0.2	0.1	0.1	0.31	0.58125	3.1
50	1	0.5	0.3	0.6	0.5	0.1	0.3	0.5	0.4	0.1	0.1	0.34	0.6375	3.4
51	1	0.5	0.3	0.6	0.5	0.1	0.3	0.8	0.5	0.1	0.1	0.38	0.7125	3.8
52	1	0.5	0.3	0.6	0.5	0.1	0.3	0.8	0.5	0.1	0.1	0.38	0.7125	3.8
													33.4125	

Total Vulnerability to System:	17.82
Average Vulnerability	3.426923077
Median Vulnerability	3.4
Minimum Vulnerability	3.1
Maximum Vulnerability	4.1
Standard Deviation	0.226754929
Coefficent of Variance	0.066168666

Average Consequence	2.898076923
Median Consequence	2.9
Minimum Consequence	2.3
Maximum Consequence	4.2
Standard Deviation	0.439023151
Coefficent of Varation	0.15148775

Consequence	Normalized	Set for Table	Risk	Normalized	Set for Table								
					Risk	Vulnerability	Rounded Vulnerability	Consequence	Rounded Consequence	Rounded Risk	Risk when Rounded	Repair Vulnerability	Repair Risk
0.33	0.61875	3.3	0.1122	0.210375	11.22	3.4	3	3.3	3	11	9	1.5	4.5
0.26	0.4875	2.6	0.0858	0.160875	8.58	3.3	3	2.6	3	9	9	1.5	4.5
0.35	0.65625	3.5	0.14	0.2625	14	4	4	3.5	4	14	16	2	8
0.37	0.69375	3.7	0.1258	0.235875	12.58	3.4	3	3.7	4	13	12	1.5	6
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.37	0.69375	3.7	0.1406	0.263625	14.06	3.8	4	3.7	4	14	16	2	8
0.23	0.43125	2.3	0.0782	0.146625	7.82	3.4	3	2.3	2	8	6	1.5	3
0.23	0.43125	2.3	0.0782	0.146625	7.82	3.4	3	2.3	2	8	6	1.5	3
0.23	0.43125	2.3	0.0782	0.146625	7.82	3.4	3	2.3	2	8	6	1.5	3
0.23	0.43125	2.3	0.0805	0.1509375	8.05	3.5	4	2.3	2	8	8	2	4
0.23	0.43125	2.3	0.0782	0.146625	7.82	3.4	3	2.3	2	8	6	1.5	3
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.27	0.50625	2.7	0.0918	0.172125	9.18	3.4	3	2.7	3	9	9	1.5	4.5
0.27	0.50625	2.7	0.0864	0.162	8.64	3.2	3	2.7	3	9	9	1.5	4.5
0.41	0.76875	4.1	0.1312	0.246	13.12	3.2	3	4.1	4	13	12	1.5	6
0.42	0.7875	4.2	0.1344	0.252	13.44	3.2	3	4.2	4	13	12	1.5	6
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.4	0.75	4	0.128	0.24	12.8	3.2	3	4	4	13	12	1.5	6
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.1131	0.2120625	11.31	3.9	4	2.9	3	11	12	2	6
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0957	0.1794375	9.57	3.3	3	2.9	3	10	9	1.5	4.5
0.31	0.58125	3.1	0.1023	0.1918125	10.23	3.3	3	3.1	3	10	9	1.5	4.5
0.31	0.58125	3.1	0.1054	0.197625	10.54	3.4	3	3.1	3	11	9	1.5	4.5
0.31	0.58125	3.1	0.1085	0.2034375	10.85	3.5	4	3.1	3	11	12	2	6
0.29	0.54375	2.9	0.0928	0.174	9.28	3.2	3	2.9	3	9	9	1.5	4.5
0.29	0.54375	2.9	0.1189	0.2229375	11.89	4.1	4	2.9	3	12	12	2	6
0.33	0.61875	3.3	0.1089	0.2041875	10.89	3.3	3	3.3	3	11	9	1.5	4.5
0.25	0.46875	2.5	0.085	0.159375	8.5	3.4	3	2.5	3	9	9	1.5	4.5
0.25	0.46875	2.5	0.085	0.159375	8.5	3.4	3	2.5	3	9	9	1.5	4.5
0.25	0.46875	2.5	0.0775	0.1453125	7.75	3.1	3	2.5	3	8	9	1.5	4.5
0.25	0.46875	2.5	0.0825	0.1546875	8.25	3.3	3	2.5	3	8	9	1.5	4.5
0.25	0.46875	2.5	0.085	0.159375	8.5	3.4	3	2.5	3	9	9	1.5	4.5
0.25	0.46875	2.5	0.0825	0.1546875	8.25	3.3	3	2.5	3	8	9	1.5	4.5
0.25	0.46875	2.5	0.095	0.178125	9.5	3.8	4	2.5	3	10	12	2	6
0.29	0.54375	2.9	0.1102	0.206625	11.02	3.8	4	2.9	3	11	12	2	6
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.29	0.54375	2.9	0.1044	0.19575	10.44	3.6	4	2.9	3	10	12	2	6
0.29	0.54375	2.9	0.1044	0.19575	10.44	3.6	4	2.9	3	10	12	2	6
0.29	0.54375	2.9	0.1044	0.19575	10.44	3.6	4	2.9	3	10	12	2	6
0.29	0.54375	2.9	0.0899	0.1685625	8.99	3.1	3	2.9	3	9	9	1.5	4.5
0.29	0.54375	2.9	0.0928	0.174	9.28	3.2	3	2.9	3	9	9	1.5	4.5
0.29	0.54375	2.9	0.0899	0.1685625	8.99	3.1	3	2.9	3	9	9	1.5	4.5
0.29	0.54375	2.9	0.0986	0.184875	9.86	3.4	3	2.9	3	10	9	1.5	4.5
0.25	0.46875	2.5	0.095	0.178125	9.5	3.8	4	2.5	3	10	12	2	6
0.25	0.46875	2.5	0.095	0.178125	9.5	3.8	4	2.5	3	10	12	2	6
	28.25625			9.6766875									
	Total Risk to System		**5.1609**		5.1609					522	511		255.5

Aveage Risk	9.924807692
Median Risk	9.57
Minimum Risk	7.75
Maximum Risk	14.06
Standard Deviation	1.589747163
Coefficient of Variation	0.16017914

WSSC System description

During the process of researching the need of such a decision support system, engineers from the Washington Suburban Sanitary Commission (WSSC) were interviewed to discuss their needs, pipe failures, and general relative information concerning pipes and their distribution system. The primary types of pipes that are utilized in the WSSC system are welded steel, pre-stressed concrete, ductile iron, cast iron, and PVC. The WSSC owns and maintains approximately 5500 miles of pipe. Eight inch cast iron is the most popular pipe in the system.

The cast iron pipe has performed well in sizes up to approximately 36". Good success has also been realized with Cast Iron pipes with cement lining to slow corrosion. One practice that has improved the performance and life of some pipes has been to clean and line if it is done early enough in the pipe's life prior to major corrosion forming inside the pipe. Installing a polywrap on pipe and installing cathotic protection has also been helpful in improving the performance of pipe. In many cases WSSC has found that 1914/1915 pipe has performed better than 1970's era pipe. The thought is that the lack of any kind of wrap or cathotic protection has been the cause of much of the poor performance. It is also theorized that the installation location has played a large part in the performance as well.

Pre-stressed concrete pipe has performed well also. The majority of it was installed in the 1940s, 1950s, and 1960s. These pipes were really abused in the 1960s however with drastic pressure changes caused by surges. The electronics that are available now were not available then and pressures could not be monitored and controlled to cut down on the abuse. In the 1970s and 1980s there were high early failures with this pipe. The problem seemed to be linked to the plants' manufacturing processes and the molds leading to bad wire wrapping.

When asked about replacement methods and the best method to do replacements, WSSC engineers reported using several approaches. One study that was heavily relied upon for guidance suggested that it was cheaper to do spot replacements rather than entire run replacements due to forgoing remaining useful life. Also the types of failures sometime determined the level of damage – splits are usually catastrophic causing more damage than circular failures. Old six inch unlined pipes are being removed and replaced with eight inch lines due to fire flow needs. There has been an effort to do work and complete neighborhoods when work starts in them to reduce the number of disruptions. Efforts have been made to test as many pipes as possible in particular the larger pre-cast pipes and replace those that fail during testing. Replacing larger pipes has been harder as large segments have to be taken out of service to perform these replacements. When these replacements are done, the new pipes are equipped with computer monitoring equipment to better predict when non-disaster caused failures are eminent.

Some of the major causes of failures are stress breaks which often happen shortly after pipes are lined. Crew errors cause failures with pipes. The WSSC does not currently have a valve exercise program which will lead to stuck valves and resulting failures. Smaller pipes are often put under stress when large mains are out of service for repairs which causes failures also. Cold river water being sent to the plant also causes failures when the temperatures have sudden changes. Leaky pipes have a tendency to accelerate corrosion and cause more premature failures (Wright, 2013; Burke, 2013).

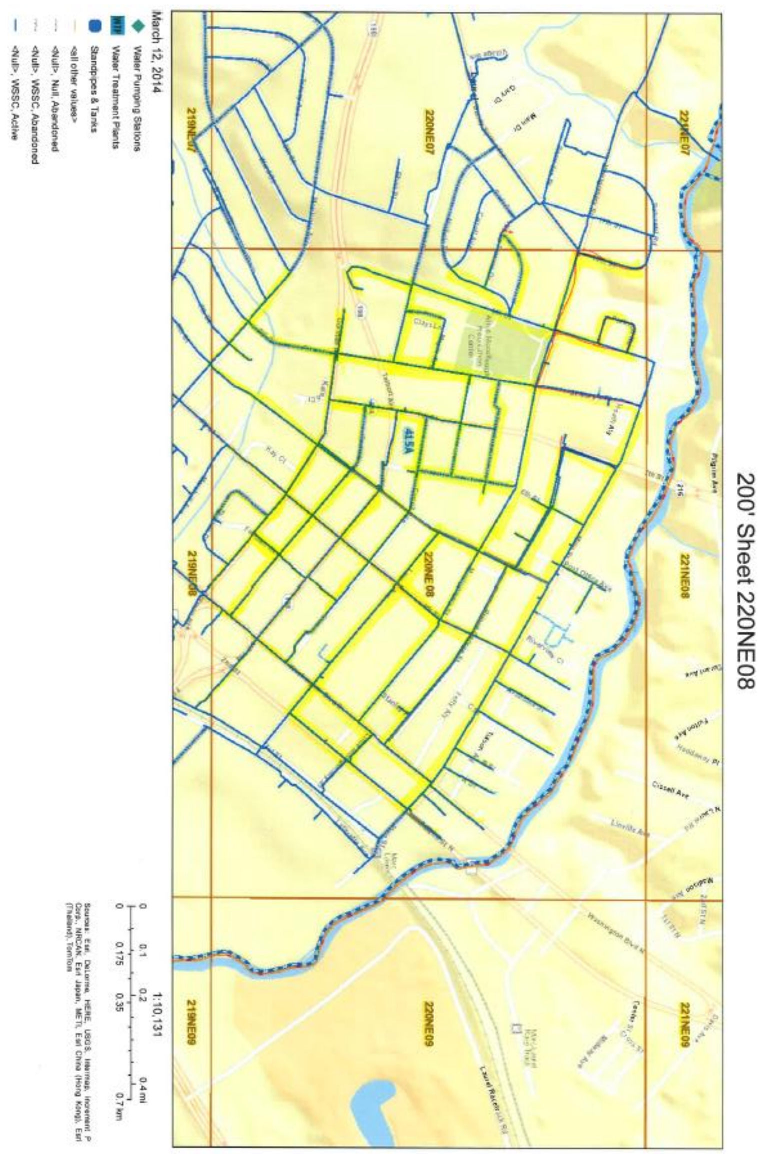

Figure C72 WSSC Validation Area

Segments	Reported Breaks	Pipe ID/Segment	Diameter	Length	Installation Date	Install Year	Material	Useful Life	Age	Repair Date	% Life	Recorded Break(s)?	Breaks/12 months
1		WS00063265	8"	206	12/31/2009	2009	Ductile Iron	90	5		0.056		
2		WS00193306	7"	177	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
3		Null	2"	90	12/31/2009	2009	Ductile Iron	90	5		0.056		
4		WS00193304	8"	607	9/26/1968	1968	Cast Iron or Sand Spun	115	46		0.400		
5		WS00192523	6"	463	11/6/1981	1981	Ductile Iron	90	33		0.367		
6		WS00063220	6"	325	8/31/1989	1989	Ductile Iron	90	25		0.278		
7		WS00164134	6"	385	9/7/1984	1984	Ductile Iron	90	30	11/23/1979	0.333		
8		WS00063180	6"	565	11/6/1981	1981	Ductile Iron	90	33		0.367		
9		WS00063181	8"	90	11/23/1979	1979	Ductile Iron	90	35		0.389		
10		WS00063512	6"	110	11/6/1981	1981	Ductile Iron	90	33		0.367		
11		WS00063513	6"	70	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
12		WS00063173	1"	160	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
13		WS00063174	6"	130	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
14		WS00063176	6"	130	7/3/1985	1985	Ductile Iron	90	29		0.322		
15		WS00063177	6"	320	7/3/1985	1985	Ductile Iron	90	29		0.322		
16		WS00164133	8"	55	11/23/1979	1979	Ductile Iron	90	35		0.389		
17		WS00162424	8"	200	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
18		WS00162425	8"	230	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
19		WS00169717	8"	80	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
20		WS00063329	8"	60	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
21		WS00063328	8"	20	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
22		WS00168747	8"	35	3/6/1998	1998	Ductile Iron	90	16		0.178		
23		WS00169716	8"	190	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
24		WS00165862	6"	35	7/18/2000	2000	Ductile Iron	90	14		0.156		
25		WS00165860	8"	95	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
26		WS00169715	8"	345	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
27		WS00063534	8"	30	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
28		WS00063533	8"	240	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
29		WS00063532	8"	20	11/23/1979	1979	Ductile Iron	90	35	12/31/1974	0.389		
30		WS00063531	8"	30	11/23/1979	1979	Ductile Iron	90	35	12/31/1974	0.389		
31	WS00063530	WS00063530	8"	230	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522	Y	
32		WS00063529	8"	50	11/23/1979	1979	Ductile Iron	90	35	12/31/1974	0.389		
33		WS00063528	8"	400	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
34	WS00063527	WS00063527	8"	170	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522	Y	
35		WS00063526	8"	30	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
36		WS00063232	8"	180	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
37		WS00063229	8"	97	12/31/2009	2009	Ductile Iron	90	5		0.056		
38		WS00063347	8"	182	12/31/2009	2009	Ductile Iron	90	5		0.056		
39		WS00193314	6"	654	8/1/1985	1985	Ductile Iron	90	29		0.322		
40	WS00063179	WS00063179	6"	440	11/6/1981	1981	Ductile Iron	90	33		0.367	Y	
41		WS00063204	2"	90	11/6/1981	1981	Ductile Iron	90	33		0.367		
42		WS00063441	8"	600	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
43		WS00063356	8"	550	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
44		WS00193187	8"	21	12/31/2009	2009	Ductile Iron	90	5		0.056		
45		WS00193188	8"	140	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
46		WS00192186	8"	485	11/6/1981	1981	Ductile Iron	90	33		0.367		
47		WS00063231	8"	550	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
48		WS00193258	6"	350	1/1/1954	1954	Ductile Iron	90	60	12/31/1974	0.667		
49		WS00063170	12"	335	12/22/1971	1971	Cast Iron or Sand Spun	130	43		0.331		
50		WS00063443	8"	320	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
51		WS00063439	4"	480	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
52		WS00063165	8"	530	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
53		WS00141465	8"	300	11/6/1981	1981	Ductile Iron	90	33		0.367		
54		WS00172266	8"	120	11/6/1981	1981	Ductile Iron	90	33		0.367		
55		WS00192144	8"	265	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
56	WS00192149	WS00192149	8"	380	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522	Y	
57		WS00063158	4"	270	1/4/2010	2010	Ductile Iron	90	4		0.044		
58		WS00063156	4"	510	1/4/2010	2010	Ductile Iron	90	4		0.044		
59		WS00192136	6"	445	6/3/1992	1992	Ductile Iron	90	22		0.244		
60		WS00141467	8"	5	11/6/1981	1981	Ductile Iron	90	33		0.367		
61		WS00063160	4"	60	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
62		WS00063161	4"	40	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
63		WS00063164	8"	490	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
64		WS00063446	4"	560	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
65		WS00063445	4"	30	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
66		WS00063163	8"	30	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
67		WS00063167	8"	20	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
68		WS00063168	8"	20	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
69		WS00169164	8"	500	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
70		WS00063319	4"	620	1/1/1954	1954	Cast Iron or Sand Spun	115	60		0.522		
71		WS00168901	8"	350	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
72		WS00169165	8"	10	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
73		WS00193189	12"	75	12/22/1971	1971	Ductile Iron	80	43		0.538		
74		WS00193204	8"	667	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
75	WS00156910	WS00156910	10"	915	12/22/1971	1971	Ductile Iron	90	43		0.478	Y	
76		WS00156911	8"				Cast Iron or Sand Spun	115	2014		17.513		
77		WS00063214	8"				Cast Iron or Sand Spun	115	2014		17.513		
78		WS00063499	8"	150	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
79		WS00063344	8"	78	12/22/1971	1971	Cast Iron or Sand Spun	115	43		0.374		
80		WS00192130	8"	735	1/4/2010	2010	Ductile Iron	90	4	12/31/1974	0.044		
81		WS00141452	8"	305	1/4/2010	2010	Ductile Iron	90	4	12/31/1974	0.044		
82		WS00141455	4"	50	1/4/2004	2004	Ductile Iron	90	10		0.111		
83		WS00141453	8"	215	1/4/2010	2010	Ductile Iron	90	4	12/31/1974	0.044		
84		WS00192132	8"		1/4/2010	2010	Ductile Iron	90	4	12/31/1974	0.044		
85	WS00192134 (3)	WS00192134	8"	650	1/4/2010	2010	Ductile Iron	90	4	12/31/1974	0.044	Y	
86		WS00193221	8"	1186	1/1/1954	1954	Ductile Iron	90	60		0.667		
87		WS00172931	6"	260	8/1/1985	1985	Ductile Iron	90	29		0.322		
88		WS00172930	6"	419	8/1/1985	1985	Ductile Iron	90	29		0.322		
89		WS00193280	8"	495	1/26/1976	1976	Ductile Iron	90	38	12/31/1974	0.422		
90		WS00193273	6"		1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
91		WS00193195	12"	189	12/22/1971	1971	Cast Iron or Sand Spun	130	43		0.331		
92		WS00193196	12"	158	12/22/1971	1971	Cast Iron or Sand Spun	130	43		0.331		
93		WS00063194	6"	120	1/1/1954	1954	Cast Iron or Sand Spun	115	60	11/25/1992	0.522		
94		WS00192182	6"	265	1/1/1954	1954	Cast Iron or Sand Spun	115	60	11/25/1992	0.522		
95		WS00063473	6"	300	1/1/1954	1954	Cast Iron or Sand Spun	115	60	11/25/1992	0.522		
96		WS00063472	6"	310	1/1/1954	1954	Cast Iron or Sand Spun	115	60	11/25/1992	0.522		
97		WS00192151	8"	305	1/4/2010	2010	Ductile Iron	90	4		0.044		
98		WS00192191	8"	320	11/6/1981	1981	Ductile Iron	90	33		0.367		
99		WS00063466	8"	285	11/6/1981	1981	Ductile Iron	90	33		0.367		
100	WS00188956	WS00188956	8"	400	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522	Y	
101		WS00192192	8"	100	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		
102		WS00063185	6"	915	1/1/1954	1954	Cast Iron or Sand Spun	115	60	12/31/1974	0.522		

103		WS00063419	6"	40	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
104		WS00138080	6"	115	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
105	WS00138079	WS00138079	6"	595	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	Y
106		WS00065997	4"	490	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
107		WS00063418	6"	250	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
108		WS00063420	6"	370	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
109		WS00063477	6"	330	1/27/1961	1961 Cast Iron or Sand Spun	115	53	11/25/1992	0.461	
110		WS00063479	6"	370	3/24/1987	1987 Ductile Iron	90	27		0.300	
111		WS00192162	6"	450	11/6/1981	1981 Ductile Iron	90	33	11/25/1992	0.367	
112		WS00138082	6"	465	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
113	WS00063332	WS00063332	6"	140	1/13/1958	1958 Cast Iron or Sand Spun	115	56	11/25/1992	0.487	Y
114		WS00138096	6"	215	9/5/1985	1985 Ductile Iron	90	29		0.322	
115		WS00192173	6"	450	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
116	WS00192174	WS00192174	6"	470	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	Y
117		WS00192160	8"	290	1/4/2010	2010 Ductile Iron	90	4		0.044	
118		WS00192158	8"	205	1/4/2010	2010 Ductile Iron	90	4		0.044	
119		WS00192157	8"	65	1/4/2010	2010 Ductile Iron	90	4		0.044	
120		WS00063475	8"	430	1/27/1961	1961 Cast Iron or Sand Spun	115	53	12/31/1974	0.461	
121		WS00063245	8"	490	1/27/1961	1961 Cast Iron or Sand Spun	115	53	12/31/1974	0.461	
122	WS00063352	WS00063352	8"	290	5/31/1983	1983 Ductile Iron	90	31		0.344	Y
123		WS00141456	8"	445	8/1/1993	1993 Ductile Iron	90	21		0.233	
124		WS00141457	6"	100	8/1/1993	1993 Ductile Iron	90	21		0.233	
125		WS00063240	24"	405	6/1/1970	1970 Cast Iron or Sand Spun	130	44		0.338	
126	WS00141463	WS00141463	8"	285	9/5/1958	1958 Cast Iron or Sand Spun	115	56	11/25/1992	0.487	Y
127	WS00141462 (2)	WS00141462	8"	600	9/5/1958	1958 Cast Iron or Sand Spun	115	56	11/25/1992	0.487	Y
128		WS00063486	8"		1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
129		WS00063484	8"	260	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
130		WS00063485	8"	90	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
131		WS00063483	8"	270	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
132		WS00063280	6"	160	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
133		WS00063279	4"	70	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
134		WS00068817	8"	270	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
135		WS00161751	6"	1165	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
136		WS00063285	8"	80	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
137		WS00063286	8"	190	1/27/1961	1961 Cast Iron or Sand Spun	115	53	12/31/1974	0.461	
138		WS00063287	8"	120	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
139		WS00141103	8"	420	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
140		WS00141102	8"	7	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
141		WS00063241	24"	70	6/1/1970	1970 Cast Iron or Sand Spun	130	44		0.338	
142		WS00063459	6"	330	12/18/1967	1967 Cast Iron or Sand Spun	115	47		0.409	
143		WS00192153	8"	230	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
144		WS00192180	8"	510	8/9/1978	1978 Ductile Iron	90	36		0.400	
145		WS00063305	6"	210	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
146	WS00138086 (3)	WS00138086	6"	535	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	Y
147		WS00193202	12"	295	12/22/1971	1971 Cast Iron or Sand Spun	130	43		0.331	
148		WS00063301	12"	393	12/22/1971	1971 Cast Iron or Sand Spun	130	43		0.331	
149		WS00063302	12"	235	12/22/1971	1971 Cast Iron or Sand Spun	130	43		0.331	
150		WS00184419	12"	360	12/22/1971	1971 Null (Cast Iron)	130	43		0.331	
151		WS00063348	4"	340	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
152		WS00063254	6"	275	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
153		WS00063255	6"	8	1/9/1984	1984 Ductile Iron	90	30	11/25/1992	0.333	
154		WS00063253	1"	90	3/29/1962	1962 Cast Iron or Sand Spun	115	52		0.452	
155		WS00193223	8"	574	12/31/2009	2009 Ductile Iron	90	5		0.056	
156		WS00193231	8"	960	12/31/2009	2009 Ductile Iron	90	5		0.056	
157		WS00193228	8"	134	12/31/2009	2009 Ductile Iron	90	5		0.056	
158		WS00193234	8"	102	12/31/2009	2009 Ductile Iron	90	5		0.056	
159		WS00063417	8"	309	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
160		WS00193285	8"	295	1/1/1954	1954 Ductile Iron	90	60	12/31/1974	0.667	
161		WS00138103	6"	155	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
162		WS00138102	6"	170	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
163		WS00138101	6"	270	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	
164		WS00141448	8"	142	1/9/1984	1984 Ductile Iron	90	30		0.333	
165		WS00141445	8"	420	1/9/1984	1984 Ductile Iron	90	30		0.333	
166		WS00063546	8"	578	1/9/1984	1984 Ductile Iron	90	30		0.333	
167		WS00193256	12"	534	1/1/1954	1954 Cast Iron or Sand Spun	130	60		0.462	
168		WS00063545	8"	320	9/26/1983	1983 Ductile Iron	90	31		0.344	
169		WS00141442	12"	465	1/1/1954	1954 Cast Iron or Sand Spun	130	60		0.462	
170		WS00141444	12"	706	1/1/1954	1954 Cast Iron or Sand Spun	130	60		0.462	
171		WS00135260	12"	806	11/18/1958	1958 Cast Iron or Sand Spun	130	56		0.431	
172		WS00141450	8"	322	6/7/1993	1993 Ductile Iron	90	21		0.233	
173		WS00063407	8"	310	9/26/1983	1983 Ductile Iron	90	31		0.344	
174	WS00063510	WS00063510	4"	160	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	Y
175		WS00063509	2"	110	1/26/1976	1976 Cast Iron or Sand Spun	115	38		0.330	
176		WS00063508	2"	60	1/26/1976	1976 Cast Iron or Sand Spun	115	38		0.330	
177		WS00063428	8"	330	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
178	WS00063495 (3)	WS00063495	8"	725	1/26/1976	1976 Cast Iron or Sand Spun	115	38		0.330	Y
179		WS00063406	8"	440	1/26/1976	1976 Cast Iron or Sand Spun	115	38		0.330	
180		WS00063336	8"	260	1/26/1976	1976 Cast Iron or Sand Spun	115	38		0.330	
181	WS00063501	WS00063501	8"	540	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	Y
182		WS00137092	8"	300	11/13/1992	1992 Ductile Iron	90	22		0.244	
183	WS00063535	WS00063535	8"	690	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	Y
184	WS00063519 (3)	WS00063519	6"	690	1/1/1954	1954 Cast Iron or Sand Spun	115	60	11/25/1992	0.522	Y
185		WS00063294	6"	80	1/1/1954	1954 Cast Iron or Sand Spun	115	60		0.522	
186		WS00063292	8"	220	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
187		WS00137090	8"	200	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
188		WS00137089	8"	385	1/1/1954	1954 Cast Iron or Sand Spun	115	60	12/31/1974	0.522	
189		WS00174146	8"	260	3/1/1967	1967 Cast Iron or Sand Spun	115	47	12/31/1974	0.409	

Breaks/1000'	Size	Age	%Life	Material	Breaks/12 months	Breaks/1000 ft	# of Fittings	Vulnerability	Rounded	Consequences	Raw Risk	Rouonded (Raw)Risk	Rounded Risk	Difference
	0	0.115727	0	0.149989	0.292869	0.184982	0.256434							
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	5	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	5	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	2	1	2	1	1	3	1.778585	2	3	5.335755	5	6	1
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	5	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	3	5.682936	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
4.3478	3	3	2	3	2	3	3	2.707134	3	3	8.121402	8	9	1
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
5.8824	3	3	2	3	1	4	3	2.599247	3	2	5.198494	5	6	1
0	3	3	2	3	1	1	3	2.044301	2	4	8.177204	8	8	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
2.2727	3	3	1	2	1	3	3	2.264276	2	1	2.264276	2	2	0
0	5	3	1	2	1	1	3	1.894312	2	3	5.682936	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	5	10.22151	10	10	0
0	3	3	3	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	2	3	1	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	4	3	2	3	1	1	3	2.044301	2	4	8.177204	8	8	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
2.6316	3	3	2	3	1	3	3	2.414265	2	2	4.82853	5	4	-1
0	5	1	1	2	1	1	3	1.662858	2	3	4.988574	5	6	1
0	5	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	4	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	4	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	4	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	4	3	2	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	4	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	2	3	2	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
1.0929	2	3	1	2	1	2	3	2.079294	2	2	4.158588	4	4	0
0	3			3	1		3	1.512138	2		0	0	0	0
0	3			3	1		3	1.512138	2		0	0	0	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	4	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
4.6154	3	1	1	2	1	4	3	2.217804	2	2	4.435608	4	4	0
0	3	3	3	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	3	5.335755	5	6	1
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
2.5000	3	3	2	3	1	2	3	2.229283	2	1	2.229283	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0

0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
1.6807	3	3	2	3	1	2	3	2.229283	2	2	4.458566	4	4	0
0	4	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
7.1429	3	3	1	3	1	5	3	2.784229	3	3	8.352687	8	9	1
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
2.1277	3	3	2	3	1	3	3	2.414265	2	2	4.82853	5	4	-1
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
3.4483	3	3	1	2	1	3	3	2.264276	2	2	4.528552	5	4	-1
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	1	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
3.5088	3	3	1	3	2	3	3	2.707134	3	2	5.414268	5	6	1
3.3333	3	3	1	3	1	3	3	2.414265	2	2	4.82853	5	4	-1
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3		3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	4	3	2	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	1	3	1	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	3	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
5.6075	3	3	2	3	3	4	3	3.184985	3	2	6.36997	6	6	0
0	2	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	3	6.132903	6	6	0
0	4	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	3	5.682936	6	6	0
0	5	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	3	4.988574	5	6	1
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	1	1.662858	2	2	0
0	3	1	1	2	1	1	3	1.662858	2	2	3.325716	3	4	1
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	3	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	2	1	1	3	1.894312	2	2	3.788624	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	2	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	2	3	1	3	1	1	3	2.044301	2	1	2.044301	2	2	0
0	3	2	1	2	1	1	3	1.778585	2	1	1.778585	2	2	0
0	3	3	1	2	1	1	3	1.894312	2	1	1.894312	2	2	0
6.2500	4	3	2	3	1	4	3	2.599247	3	1	2.599247	3	3	0
0	5	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	5	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
	3	3	2	3	1	1	3	2.044301	2	1	2.044301	2	2	0
4.1379	3	3	1	3	3	4	3	3.184985	3	1	3.184985	3	3	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0
1.8519	3	3	2	3	2	2	3	2.522152	3	2	5.044304	5	6	1
0	3	2	1	2	1	1	3	1.778585	2	2	3.55717	4	4	0
1.4493	3	3	2	3		2	3	1.936414	2	2	3.872828	4	4	0
4.3478	3	3	2	3	3	4	3	3.184985	3	2	6.36997	6	6	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	2	3	1	1	3	2.044301	2	2	4.088602	4	4	0
0	3	3	1	3	1	1	3	2.044301	2	2	4.088602	4	4	0

Appendix D – LINGO Code for Optimization Model

Optimization Model for Scenario 1

```
! A Risk Minimization Model for addressing water line replacements
      52 Segments are taken into consideration for the model;

!     Model Variable Defined:

      PROJCOST = Cost of Projects: CS1 - CS52
      RISK = Risk that segments add to system: RS1 - RS52
      COST = Cost of Implementing Projects
      BUDGET = Total annual project expenditures
      INCLUDE = Switch - Binary was project implemented or not
 RISK = Same value as RS;

MODEL:

SETS:
      PROJCOST/ CS1..CS52/: INCLUDE, COST, RISK;

ENDSETS

DATA:
COST RISK =

145350.00  6.0
170700.00  6.0
462300.00 8.0
377700.00 12.0
196950.00 6.0
28800.00 4.0
98250.00 4.0
52500.00 2.0
77400.00 2.0
70500.00 6.0
110250.00 4.0
73950.00 6.0
83250.00 3.0
210000.00 6.0
195900.00 8.0
195900.00 12.0
393750.00 6.0
367500.00 8.0
88200.00 6.0
72450.00 6.0
260700.00 6.0
137850.00 12.0
```

```
88500.00  9.0
163950.00  12.0
78750.00  6.0
157500.00  3.0
46650.00  6.0
46650.00  6.0
91950.00  3.0
88650.00  9.0
132450.00  6.0
190500.00  6.0
181050.00  6.0
78750.00  6.0
51750.00  6.0
29850.00  6.0
105000.00  6.0
19650.00  3.0
93750.00  6.0
69000.00  6.0
105000.00  6.0
33450.00  3.0
33450.00  3.0
37950.00  6.0
57450.00  6.0
20850.00  6.0
131250.00  6.0
78750.00  6.0
43650.00  6.0
73500.00  3.0
33000.00  3.0
48150.00  3.0;

BUDGET = 2500000;

ENDDATA

MAX = @SUM(PROJCOST: RISK * INCLUDE);
@SUM( PROJCOST: COST * INCLUDE) <=
BUDGET;
@FOR( PROJCOST: @BIN( INCLUDE));
@FOR (PROJCOST: RISK <=25);
```

Optimization Model – Scenario 1 (Repair not Replace)

```
! A Risk Minimization Model for addressing water line replacements
      52 Segments are taken into consideration for the model;

!     Model Variables Defined:

      PROJCOST = Cost of Projects: CS1 - CS52
      RISK = Risk that segments add to system: RS1 - RS52
      COST = Cost of Implementing Projects
      BUDGET = Total annual budget available for project expenditures
      INCLUDE = Switch - Binary was project implemented or not
      RISK = Same value as RS;

MODEL:

SETS:
      PROJCOST/ CS1..CS52/: INCLUDE, COST, RISK;

ENDSETS

DATA:
COST RISK =

145350.00  6.0
170700.00  6.0
462300.00 8.0
377700.00 12.0
196950.00 6.0
28800.00 4.0
98250.00 4.0
52500.00 2.0
77400.00 2.0
70500.00 6.0
110250.00 4.0
73950.00 6.0
83250.00 3.0
210000.00 6.0
195900.00 8.0
195900.00 12.0
393750.00 6.0
367500.00 8.0
88200.00 6.0
72450.00 6.0
260700.00 6.0
137850.00 12.0
```

```
88500.00  9.0
163950.00  12.0
78750.00  6.0
157500.00  3.0
46650.00  6.0
46650.00  6.0
91950.00  3.0
88650.00  9.0
132450.00  6.0
190500.00  6.0
181050.00  6.0
78750.00  6.0
51750.00  6.0
29850.00  6.0
105000.00  6.0
19650.00  3.0
93750.00  6.0
69000.00  6.0
105000.00  6.0
33450.00  3.0
33450.00  3.0
37950.00  6.0
57450.00  6.0
20850.00  6.0
131250.00  6.0
78750.00  6.0
43650.00  6.0
73500.00  3.0
33000.00  3.0
48150.00  3.0;

BUDGET = 2500000;

ENDDATA

MAX = @SUM(PROJCOST: RISK * INCLUDE);
@SUM( PROJCOST: 0.75*COST * INCLUDE) <=
BUDGET;
@FOR( PROJCOST: @BIN( INCLUDE));
@FOR (PROJCOST: RISK <=25);

END
```

Appendix E – Pipe Failure Analyses

Table 28 Calculation of Weights for Model

Survey Weight Assignment						
Scenario #	3	4	5	6	7	**Weights**
Size	4	4	4	4	5	0
Age	4	2	3	2	2	0.12
Material	2	2	2	2	4	0
% Life	5	3	4	4	1	0.15
Breaks/12 Months	4	4	3	5	5	0.29
Breaks/ 1000 ft	3	3	3	3	5	0.18
Fittings	5	5	3	3	3	0.26
Survey Average for Likelihood of Failure	4.31	3.69	3.15	3.62	3.54	1
Verification Total (Weight x Selected Parameter Index Value)	4.22	3.69	3.15	3.62	3.54	**Total Difference**
Difference	0.089	9.83E-06	1.14E-05	8.79E-09	1.41E-06	0.089

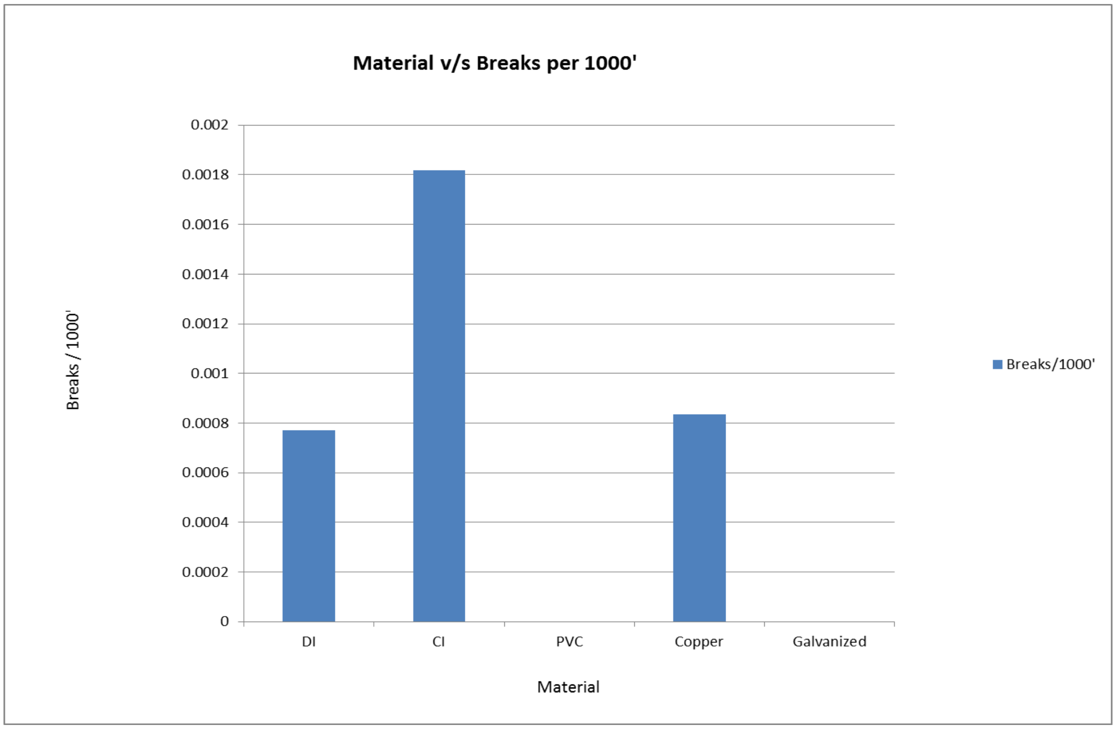

Figure E73 Pipe Material v/s Breaks per 1000' (Manassas)

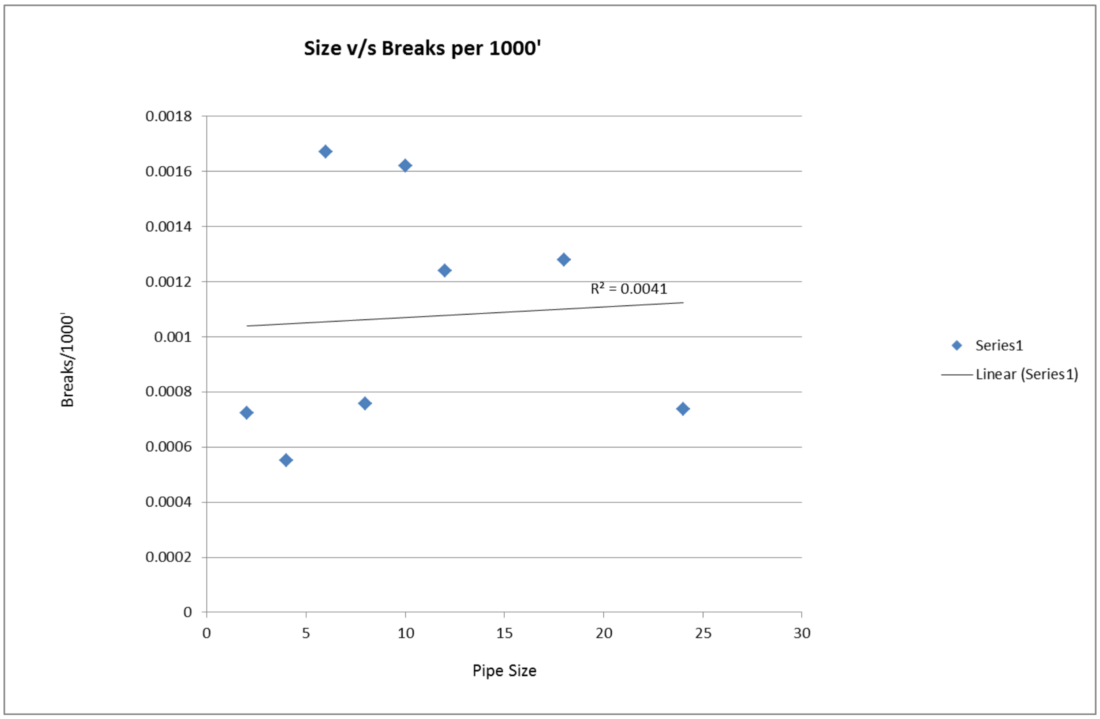

Figure E74 Pipe Size v/s Breaks per 1000' (Manassas)

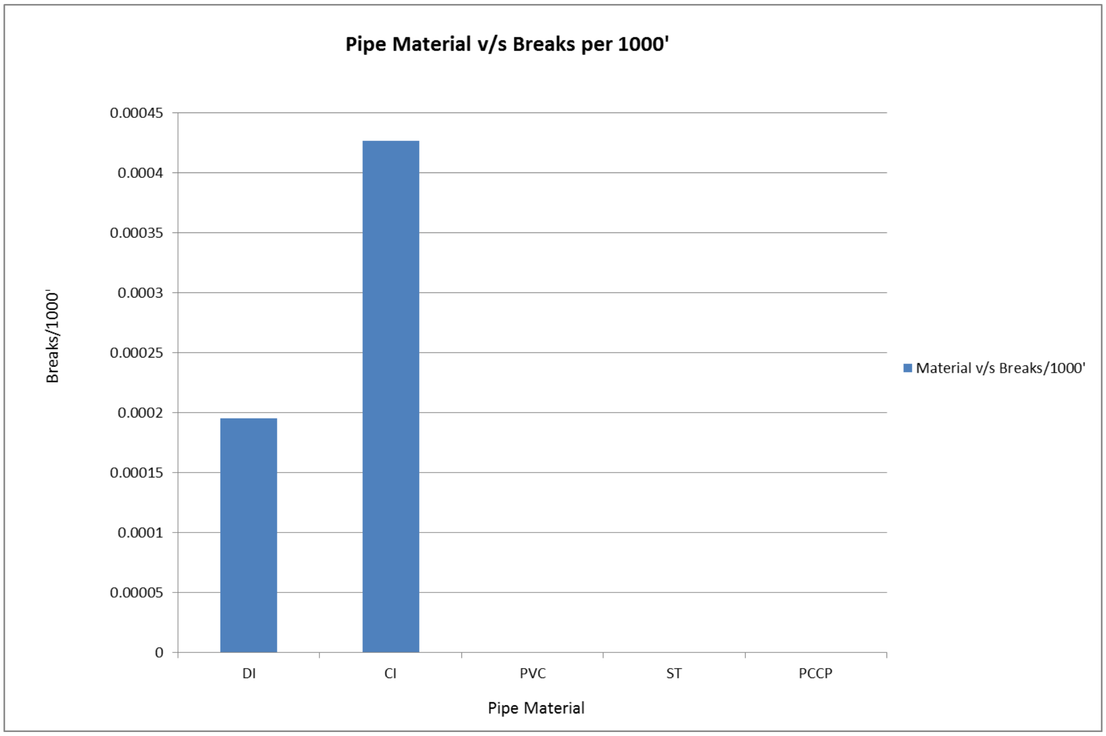

Figure E75 Pipe Material v/s Breaks per 1000' (WSSC - Laurel)

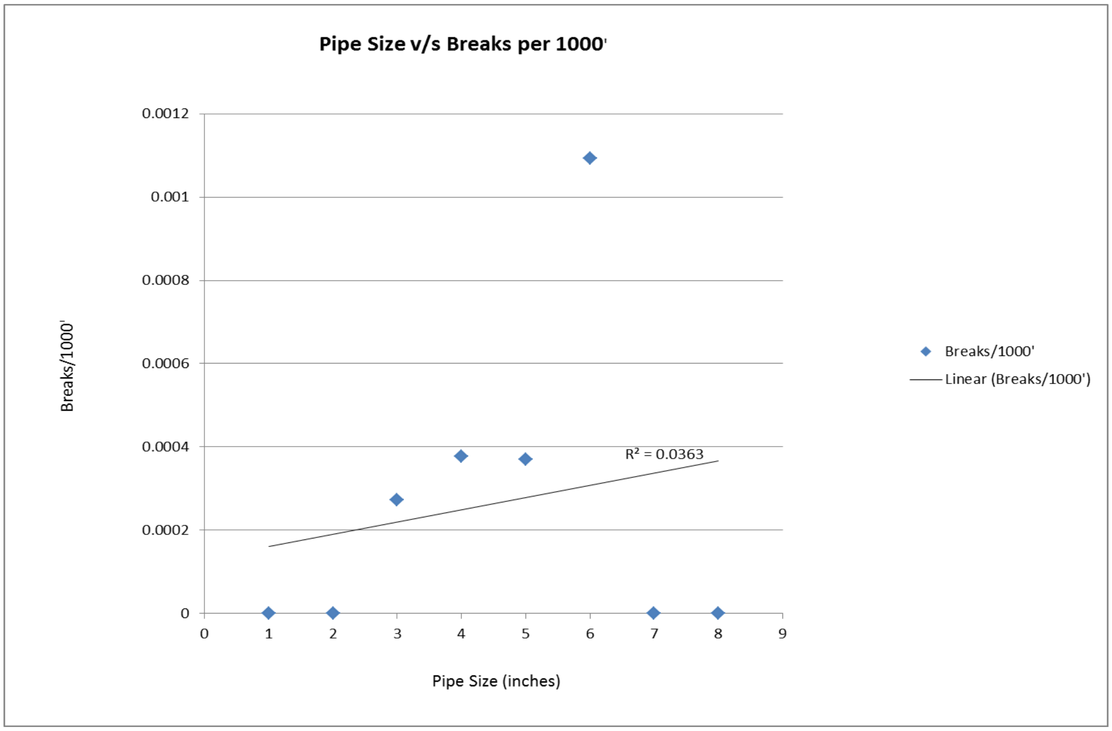

Figure E76 Pipe Size v/s Breaks per 1000' (WSSC – Laurel)

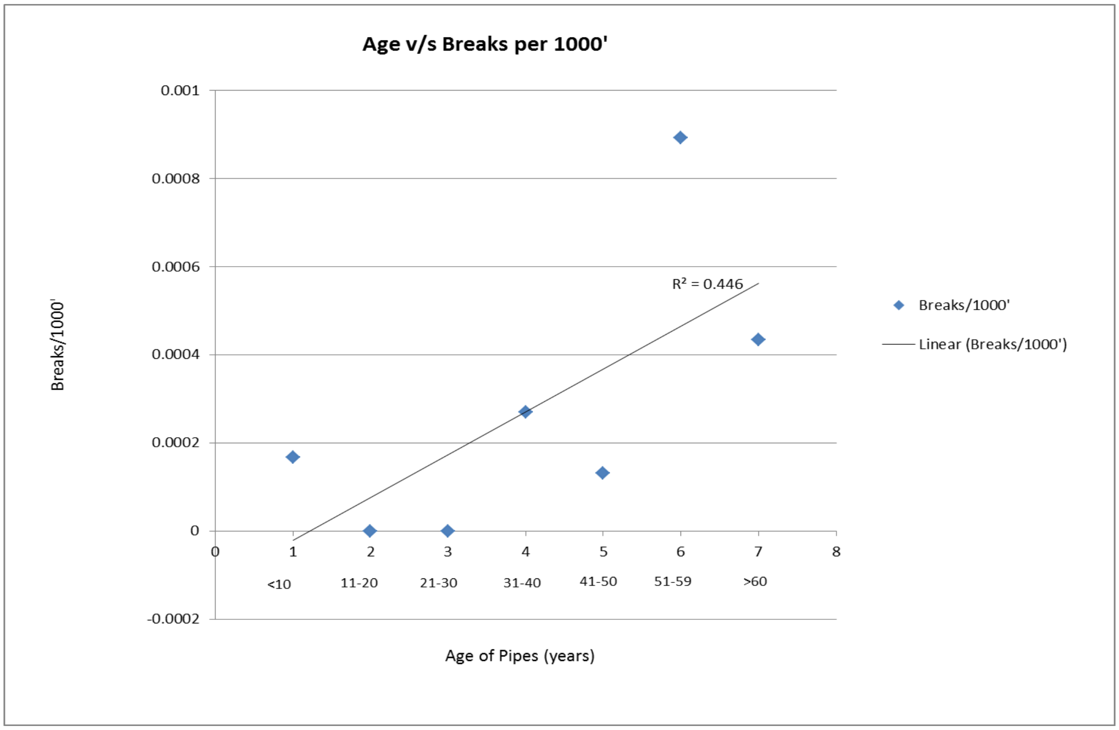

Figure E77 Pipe Age v/s Breaks per 1000' (WSSC- Laurel)

Appendix F – Key Terms

Key Terms

Asset – A component of a facility with an independent physical and functional identity and age

Asset Category – Where asset best fits into the system for organizational purposes

Asset Inventory – A list of assets with details about each one (sometimes referred to as an asset register)

Asset Management – A process for maintaining a desired level of customer service at the best appropriate cost

Asset Name – The name of the equipment that is used for the system to properly function

Asset Status – This is how the utility views an asset. An asset can be active, not in use, or a future investment (which are assets that should be added)

Asset Type – The asset's functional purpose for a specific asset category

Capital Improvement (Expense) – Funds required for the future purchase, repair and/or alteration to or for an asset, structure, or major piece of equipment.

Capital Improvement Program (CIP) – A plan that projects and assesses which projects (including asset improvements, repairs, replacement, etc.) need to be completed in the future and assigns a cost value and time frame to them

Condition – The current condition, in the asset manager's opinion, of an asset based on age and physical functionality (ranging from poor to excellent)

Consequence of Failure (CoF) – The real or hypothetical results associated with the failure of an asset.

Expected Useful Life – The average amount of time, in years, that a system or component is estimated to function when installed new.

Growth – The amount, as a percent, a community's demand for water or wastewater treatment has increased or decreased. This value will be used to adjust future revenues and expense

Inflation – The anticipated rate of increase in the price level of goods and services

Level of Service - The characteristics of system performance such as how much, of what nature, and how frequently with regard to the system's service

Maintained According to Factory Recommendation – The frequency of routine maintenance as recommended by the manufacturer.

Original Cost – The amount paid for the initial purchase of an asset.

Probability of Failure (PoF) – the chance an asset will fail based on the percent of effective life consumed and redundancy.

Redundancy – Square assets that have the ability to do the same job, if a failure of the primary asset were to occur.

Replacement Cost – How much will it cost to replace the asset, if required today?

Risk – The potential for realization of unwanted adverse consequences or events; possibility of loss or injury.

Vulnerability – Capable of being wounded; open to attack or damage.

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Biography

Nichalos D. Gardner graduated from Myrtle High School, Myrtle, Mississippi in 1993. He received his Bachelor of Science in Civil Engineering in 1997. He worked as a consultant for two years. He then went to receive a Master of Science in Civil Engineering (Water Resources) from Mississippi State University in 2000. He worked for in the engineering field for eight years. He earned a Master of Business Administration from Marymount University in 2007.