4-20-2011

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Recommended Citation

Marsee, Megan. "Integrating external costs into water utility asset management : an application of the threshold break rate method." (2011). https://digitalrepository.unm.edu/wr_sp/5

Integrating External Costs into Water Utility Asset Management: An Application of the Threshold Break Rate Method

by

Megan Marsee

B.A., English, University of Texas, 1997

PROFESSIONAL PROJECT

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Water Resources
Policy/Management Concentration

The University of New Mexico

Albuquerque, New Mexico

July, 2010

Acknowledgments

This Professional Project is derived from a larger research project funded by the Water Research Foundation titled "Setting Water Utility Investment Priorities: Assessing Customer Preferences and Willingness to Pay." I would first like to thank the Foundation for the rich research experience they provided to me and the other participants in the project.

Most importantly, I would like to thank Principal Investigator and chair of my Professional Project committee, Dr. Jennifer Thacher, Associate Professor of Economics at UNM. The trust and autonomy she offered her research assistants allowed me to experience research as a creative process, in which you bring to light something that didn't before exist. Her door was always open to discuss a question, problem, or idea, and her input made this a better project many times over.

To Dr. Bruce Thomson, Director of the Water Resources program at UNM, who has been a source of support throughout my entire Master of Water Resources degree. Thank you for having a measure of faith in an English major.

To Dr. Janie Chermak, Professor of Economics at UNM, who is largely responsible for the fact that I finished this project. As a teacher and as a committee member, she helped me to understand and appreciate the contributions that economics makes to water resource management.

To Heather Himmelberger, Director of the New Mexico Environmental Finance Center, whose extensive, on-the-ground knowledge of how utilities approach pipe replacement and asset management added a good measure of realism to this project. I was very happy to have had the opportunity to get to know Ms. Himmelberger in the context of my Water Resources degree, and very much look forward to working with her in life outside of graduate school.

Deepest thanks to fellow research assistants Heidi Pitts (UNM Economics Ph.D. candidate) and Jason Hansen (now Assistant Professor of Economics at the Naval Postgraduate Institute). Particularly to Heidi, for the experience of sharing every minute detail of one another's lives in our tiny office, which I will remember very fondly, despite the impossible stress of graduate school.

To my parents - this is one of many chapters that couldn't have been started or finished without you. And, finally, to Ryan, who has supported me through countless hours of work towards this degree, for being my closest friend.

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Abstract

The goal of an asset management program is to minimize the life-cycle cost of water utility assets, while continuing to provide the service levels expected by utility customers. The life-cycle cost of an asset includes both the utility's internal costs to maintain the asset, and external costs borne by customers, the community, and the environment when the asset fails. This project demonstrates how to integrate external costs into asset management through an application of the threshold break rate model, a pipe-replacement decision-model that minimizes the life-cycle cost of water mains. The model is employed to determine which six-inch-diameter steel water pipes in the Albuquerque Bernalillo County Water Utility Authority (ABCWUA) distribution system should be scheduled for replacement. The external costs of water outages, estimated through a choice-experiment survey of ABCWUA residential customers, are included in the model, and model outputs with and without external costs are compared. Assuming a 5% discount rate, 6% percent more pipes in the distribution system are recommended for replacement when external costs are taken into consideration. The threshold break rate model is appealing because it does not require estimation of future pipe-break rates, and it can be used even when a full history of pipe breaks is not available. However, data from the ABCWUA may not satisfy an underlying assumption of the model that the function representing the present worth of a pipe over time is unimodal.

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Chapter 1

Introduction

> *It's very difficult to run a first class country or city on second rate infrastructure. - Melanie Worley, County Commissioner, Douglas County, Colorado*

1.1 Motivation

Water utilities in the United States face significant challenges in the 21^{st} century. They are working to maintain the levels of service their customers have come to expect, while contending with aging infrastructure and diminishing financial resources. Studies have estimated a growing gap between existing water infrastructure investment and projected water infrastructure investment needs. From 2000 to 2019, the projected shortfall ranges between 485 billion and 2 trillion dollars [Water Infrastructure Network, 2000, EPA, 2002].

One of the most important management paradigms to emerge in the water utility sector in recent years is asset management. Briefly stated, asset management aims to minimize the total, life-cycle cost of a utility's assets, as the utility continues to meet its customers' desired levels of service. Although asset management focuses on the sound management of capital assets, it is, more broadly, a business model for organizations like utilities whose wealth lies principally in assets. The tenets of asset management will be explored in more detail in Section 2.2.

One important component of asset management is the integration of customer input into utility decision-making. Water utilities have typically gathered information from their customers through their customer service representatives, public or town hall meetings, and customer satisfaction surveys. While information from these sources is important, it often not representative of all utility customers, or it is qualitative in nature, making it difficult to incorporate into utility planning.

Within the discipline of economics, methodologies have been developed to estimate the value of goods that do not have a market price. Because water is typically not traded in a formal market in the United States, these methodologies can be used to estimate the value customers assign to the services provided by water utilities. In economics, this value is expressed in terms of *willingness-to-pay*, defined as the maximum amount individuals are willing to pay, sacrifice, or exchange for a good.

Willingness-to-pay is a quantitative input from customers, and it can be used by a water utility in different ways. In the context of asset management, it can be used to set appropriate service levels or to improve investment prioritization and rate setting. I focus in this study on how it can be used in determining the minimum life-cycle costs of assets, one of the five core components of an asset management program.

The life-cycle cost of an asset is the total cost of owning, operating, maintaining, and disposing of the asset over its life. It includes both the utility's internal costs, and the *external costs* incurred by customers, the community, or the environment when the asset performs below expected service levels. Willingness-to-pay can be used to value external costs.

1.2 Objective

This Professional Project demonstrates how external costs can be integrated into water utility planning for pipe replacement. First, external costs are estimated through an economic-valuation survey conducted among Albuquerque Bernalillo County Water Utility Authority (ABCWUA) customers. Second, these external costs are input into a pipe-replacement decision-model for assessing the minimum life-cycle costs of water-pipe assets called the *threshold break rate*. Developed by Loganathan et al. [2002], the threshold break rate estimates the number of breaks per year in a pipe at which the total cost of the pipe is at a minimum. The model provides an analytical framework for making decisions about the optimal time to replace pipes in a distribution network.

I apply the threshold break rate to a small cohort of water pipes, six-inch-diameter steel mains, in the ABCWUA's distribution system. I demonstrate the effect of external costs on pipe-replacement schedules by comparing model results including and excluding external costs. I also test the applicability of the threshold break rate model for water utility use.

This Professional Project contributes to research on how non-market valuation can be applied to benefit water utilities. It details the design and implementation of an example economic-valuation survey, and demonstrates its application in a pipe-replacement decision-model that is consistent with asset management. It also contributes to research aimed at improving water utility pipe-replacement decision-models, by testing a relatively new methodology, the threshold break rate, using primary data from the ABCWUA on repair and replacement costs, external costs associated water outages, and pipe breaks. Both of these are areas of recent, active research in which few studies have been completed.

1.3 Organization of paper

This paper is organized as follows: Chapter 2 provides an introduction to the valuation of non-market goods. This chapter also presents a brief overview of asset management, then focuses on several ways that customer willingness-to-pay can be integrated in the core components of an asset management program. I offer examples of how willingness-to-pay data has been previously used in utility decision-making.

Chapter 3 presents a review of existing methods for prioritizing water mains for replacement. This chapter is intended to provide context and justification for the selection of the threshold break rate model. I also provide a detailed description and discussion of threshold break rate.

In Chapter 4, I demonstrate how external costs of pipe repair and replacement can be quantified through an economic-valuation survey. I use the economic-valuation survey conducted for the ABCWUA as an example. I describe the methodology employed in the survey, the study design, and survey results.

In Chapter 5, I delve into the case study. I apply the threshold break rate method to six-inch-diameter steel water mains operated by the ABCWUA. I provide background on ABCWUA's distribution system from a recent study conducted by the New Mexico Environmental Finance Center to justify the selection of this cohort of pipes for analysis. I outline the methodology used in the case study, and present and discuss the model results.

In Chapter 6, I provide a discussion of the limitations of this analysis, recommendations for future work, and final thoughts on integrating external costs into asset management.

Chapter 2

Background

2.1 Valuing non-market goods

Generally, the price of a good that is traded on the market reflects its value to consumers. However, goods offered by public agencies, including most water utilities in the U.S., are rarely exchanged in a competitive market. Water rates and fees are typically based on utility costs of provision, rather than the value that customers derive from water. Projects that impact utility services may have different values to customers that cannot be discerned from consumer behavior.

Economists have developed techniques for estimating the value of non-market goods. One type of empirical method for deriving the value of non-market goods is the *stated-preference* method.[1] Stated-preference approaches estimate the value

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[1] Non-market goods can also be valued through revealed-preference methods. Revealed-preference studies seek to measure the value of a good indirectly through observed behavior. A well-known example is the travel cost method for determining the value of sites used for recreation. The value individuals attribute to a site is estimated from the time and travel expenses incurred to visit it. As is clear in this example, to value a non-market good using revealed preferences, a proxy good (e.g. travel expenses) must be used to value the good of interest (e.g. recreational sites). Water utilities must rely on stated-preference methods

of a non-market good by asking people to state the value they assign to the good. They infer the value from choices individuals make in hypothetical scenarios, instead of observing the actual choices made by the individuals participating in a competitive market. U.S. government agencies that use stated-preference methods include the Department of Interior, National Forest Service, and National Oceanic and Atmospheric Administration. International organizations that use stated-preference methods include the World Bank.

Stated-preference methods rely on surveys (hereafter called *economic-valuation surveys*) to elicit willingness-to-pay from a population of interest. There are several different stated-preference survey methodologies; I focus in this project on *choice experiments*. In a choice experiment, individuals are presented with competing alternatives and asked to choose their preferred one. Variation among the choice questions answered by individuals allows the researcher to estimate the value of the alternatives (or, alternatively, attributes of the alternatives). I explore the choice-experiment method in greater depth in Chapter 4.

Input from economic-valuation surveys can be used by water utilities in different ways. Many of these practices fit within the paradigm of asset management. In the following sections, I provide several example applications of willingness-to-pay data from economic-valuation surveys, accompanied by actual studies that illustrate the approach. I seek here to clearly illustrate the connections between asset management and non-market valuation, since very little work has been done on this subject. I begin with a brief overview of asset management to contextualize the discussion.

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to value their services, because there is no proxy for water service.

2.2 Asset management

2.2.1 Asset management defined

All water utilities rely heavily on infrastructure - pipes, pumps, reservoirs, treatment facilities - to provide water and wastewater services to customers. They must cost-effectively manage these infrastructure assets over time, in order to maintain the levels of service customers expect. This task is complicated by aging infrastructure, increasingly stringent regulatory requirements, and diminishing funding levels.

Many utilities have implemented asset management programs to minimize the total, life-cycle cost of their capital assets, while continuing to meet customers' desired levels of service. The life of an asset includes acquisition, operation, maintenance, and disposal.

Although asset management focuses on the the sound management of capital assets, it is, more broadly, a business model for organizations like utilities whose wealth lies principally in assets. Seattle Public Utilities (SPU) provides the following summary of their approach to asset management [Brown and Caldwell, 2006, p. 3]:

> *Asset Management at SPU has been developed around a core philosophy that focuses on the delivery of cost-effective services to customers - today and into the future. Asset management requires making deliberate decisions regarding allocation of resources. And we intend for these decisions to be made in a transparent manner, fully informed by knowledge of life cycle triple bottom line costs and benefits. Asset management penetrates nearly every facet of our capital and operational resource allocation decision making, including risk management, customer and environmental service levels, trade-offs between capital and [operations and maintenance] dollars, efficiency in our delivery of services, and the tracking and re-*

> *porting of results. At SPU we now think of asset management as nearly analogous to utility management.*

Asset management is still a relatively new concept in the United States. Water utilities in Australia and New Zealand, where asset management was first developed, have been using asset management for more than 15 years. These utilities claim asset management has improved service reliability, lowered life-cycle costs, reduced risk exposure, and improved overall service levels to their customers [Seattle Public Utilities, 2008].

Core components of asset management

Asset management is a systematic, utility-wide approach to managing capital assets. An asset management program is built around five, core components [Himmelberger, 2010]:[2]

1. Assessing the current state of the system's assets
2. Determining required levels of service
3. Determining critical assets in the system
4. Determining the minimum life-cycle cost of assets
5. Creating a long-term funding strategy

Information on willingness-to-pay can be useful in determining required levels of service, determining the minimum life-cycle cost of assets, and creating a long-term funding strategy. More broadly, the emphasis in asset management on developing an economic case for expenditures provides ready opportunity for application of economic-valuation survey data.

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[2] Adapted from the International Infrastructure Management Manual [Association of Local Government Engineers of New Zealand et al., 2006].

2.3 Applying willingness-to-pay data in asset management

2.3.1 Determining levels of service

A level of service is a quantitative measure that defines the services that will be provided by a water utility. Levels of service are generally defined with reference to targets or benchmarks. They are driven by stakeholder demand, regulatory requirements, resource constraints, and system-design constraints [Allbee and Rose, 2009].

Determining appropriate levels of service is a key component of asset management. Within the context of asset management, levels of service can be said to [Himmelberger, 2010]:

- Define how to operate the system
- Clarify what the customer will get from the utility
- Help to identify critical assets
- Allow the utility to assess its performance
- Help to identify when investment in an asset is needed

A water utility typically sets levels of service based on its professional judgement, given the funding constraints under which it operates. But what is the appropriate level of service from the customer's perspective? Water utilities generally gather information from their customers through their customer service representatives, public or town hall meetings, and customer satisfaction surveys. While information from these sources is important, it is often not representative of all utility customers, or it is qualitative in nature, making it difficult to incorporate into utility planning.

Economic-valuation surveys can provide a quantitative input on customers' desired levels of service. They ask customers to make tradeoffs between a given level of service and its cost. Thus, they allow the utility to determine whether customers are willing to pay for an investment that will increase service levels. If assets are deteriorating, they allow the utility to determine if customers are willing to pay for asset rehabilitation in order to maintain current levels of service, or, alternatively, if customers prefer decreased levels of service and current rates. This information gives the utility a powerful justification for its management decisions. Economic-valuation surveys support the determination of defensible levels of service based upon input from customers.

In the following case study, I examine in more detail how economic-valuation surveys can be applied to determine levels of service.

Example: Seattle Public Water Utilities, 2006

Study overview

In 2006, Seattle Public Water Utilities (SPU) completed three choice-experiment surveys on mainline sewer backups, planned water service outages, and in-home water quality. The survey was conducted among residential water utility customers. Specific utility services valued in the survey are outlined in Table 2.1. The column titled "Survey attribute" gives a description of the performance measure or program. The "Level" columns outline the levels of service or program options presented in the survey. The choice experiments were designed to elicit the dollar value that customers place on a change in these levels.

Survey attribute	**Level 1 (Status quo)**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Mainline sewer backups:					
Frequency	No more than once every 2 years	No more than once every 5 years	No more than once every 10 years	No more than once every 20 years	
Response time	1 hour	45 minutes	2 hours		
Average duration	4 hours	2 hours	6 hours	8 hours	
Planned water outages:					
Average length	4 hours	2 hours	6 hours	8 hours	
Time of day	8:30 am to 4:30 pm	4:00 pm to 12:00 pm	9:00 pm to 5:00 am		
Time of week	Monday through Friday	Saturday	Sunday		
Pre-notification	48 hours	12 hours	24 hours	72 hours	
Method of notification	Door hanger	Telephone	Mail	E-mail	
In-home water quality:					
In-home testing	None	Mail-in sample with letter or email follow-up	Mail-in sample with personal consultation follow-up	Technician collects sample with letter or email follow-up	Technician collects sample with personal follow-up
Plumbing referral	None	Contractor list, printed advice	Contractor list, printed advice with personal consultation		
Information on water quality	Web and brochure	Dedicated email “hotline”	Telephone “hotline”		

Table 2.1: Survey attributes and levels, SPU, 2006 (adapted from Seattle Public Utilities [2006])

Implementation of survey results

Seattle's 2006 choice-experiment surveys covered a wide range of program options in both the water and wastewater divisions of the utility. For simplicity, I focus here on willingness-to-pay for changes in sewer backup service levels.

Marginal willingness-to-pay (MWTP) estimates from the survey are presented in Table 2.2:

Service level change	**MWTP**	**Significantly different from 0 at 90%?**	**Standard deviation**	**Percent with WTP < 0**
Value of reducing backup frequency by one year	\$0.08/mo	Yes	\$0.25/mo	38%
Value of reducing backup duration by one hour	\$0.38/mo	Yes	\$0.57/mo	25%
Value of increasing response time by one minute	\$0.01/mo	Yes	\$0.01/mo	19%

Table 2.2: Marginal willingness-to-pay estimates for sewer service backup attributes, SPU, 2006 (adapted from Seattle Public Utilities [2006])

The first column in the table describes the change in service levels valued in the survey. The second column shows the marginal willingness-to-pay estimates. The third column indicates whether the estimates are statistically significant, based on the value of the t-statistic. The fourth column shows the standard deviation of the distribution of willingness-to-pay values. When the standard deviation is large relative to the mean, there is substantial variation in customer preferences. Because all water utility customers are subject to rate increases implemented by the utility, the standard deviation is an important indicator of the uniformity of customer support for the change in service levels. The fifth column is another expression of the diversity of preferences on sewer service backups; it shows the estimated percentage of the population who are not willing to pay anything for the proposed change in service levels. In this study, marginal willingness-to-pay varied greatly for changes in the frequency and duration of sewer backups. Thirty-eight percent of respondents were not willing to pay anything for a one-year decrease in the frequency of sewer backups. Twenty-five percent of respondents were not willing to pay anything for a one-hour decrease in the duration of sewer backups.

At the time the survey was conducted, all households served by SPU experienced sewer backups no more than once every two years. The marginal willingness-to-pay for proposed changes to the current service level could thus be quantified. For example, Table 2.3 outlines willingness-to-pay estimates for changes to service levels for sewer backup frequency considered in the Wastewater System Plan.

Service level target	**WTP**
No more than once every 5 years for all households	\$0.24/mo
No more than once every 10 years for all households	\$0.64/mo
No more than once every 20 years for all households	\$1.44/mo

Table 2.3: Willingness-to-pay estimates for changes in sewer service backup frequency, SPU, 2006 (adapted from Seattle Public Utilities [2006])

Seattle Public Utilities quantified the per customer costs of implementing these proposed service level changes and compared them to the benefits estimated from the survey data. The cost-benefit analysis indicated that customers were willing to pay for a sewer backup service level of "once every 5 years." Costs exceeded benefits for higher service levels. As a result, the sewer backup target service level was defined in the 2006 Wastewater System Plan as follows: "By 2020, there will be no more than one backup in 5 years, on average, at any location, caused by a problem with the SPU sewer system" (Brown and Caldwell 2006, p. ES-4).

2.3.2 Creating a long-term funding strategy

Another step in the development of an asset management program is to create a long-term funding strategy. The same procedures described in the previous section can be applied to characterize an optimal investment program and associated funding strategy. Economic-valuation surveys can also be used to determine if customers are willing to pay for an asset management program, or aspects of the program, after funding requirements have been determined.

In the following case study, willingness-to-pay data is used to inform a utility business plan and to set rates.

Example: Yorkshire Water, 2005

Background

In the United Kingdom, water and wastewater companies are regional monopolies. These companies are regulated by the Office of Water Services, which sets both service standards and prices. Water companies can provide higher service levels than the minimum standards required by regulation, but additional investment must be justified to the Office of Water Services [Willis et al., 2005]. In 2000, the Office of Water Services required water companies to conduct economic appraisals to justify planned capital and operating expenditures [The Office of Water Services, 2000]. In response, Yorkshire Water,[3] a private U.K. water and wastewater company, developed Leading Edge Asset Decision Assessment (LEADA), a decision tool that ranks proposed investment projects in terms of benefits relative to costs. Benefits were determined from data on customer willingness-to-pay for improved service

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[3] Yorkshire Water serves some 1.9 million residential customers and 130,000 businesses in and around Yorkshire, England.

performance. This data was acquired through a choice-experiment survey.

Study overview

Yorkshire Water mapped potential investments to at least one of fourteen service factors. Table 2.4 lists the service factors of interest to the utility, the attribute used to describe that service factor in the survey, and associated levels that could be expected under different investment scenarios. The survey quantified willingness-to-pay for changes in the service factor levels.

Service factor	Survey attribute	Level 1	Level 2	Level 3	Level 4
Security of supply	Risk of having no water	1 year in 250	1 year in 500	1 year in 750	1 year in 1,000
	Minimum stock of water in reservoirs in a repeat of the worst drought on record (as percent of reservoir capacity)	20%	30%	40%	50%
Drinking water biological quality	Out of 250,000 samples, number of times water failed to meet required chemical and biological standards	750 (99.7% compliance)	275 (99.89% compliance)	125 (99.95% compliance)	25 (99.99% compliance)
Sewage flooding into properties	Number of properties affected by internal flooding with sewage in living accommodation	1200	540	450	400
Pollution incidents	Number of pollution incidents on water courses from unplanned sewage escape with some short-term impact on rivers	640	320	160	80
Inadequate mains pressure	Number of properties affected by inadequate pressure	1,000	200	150	100
Interruptions to supply	Number of properties affected by temporary interruption to supply with duration of interruption per year	8,000 7-12 hrs, 1,300 > 12 hrs	4,000 7-12 hrs, 650 > 12 hrs	2,000 7-12 hrs, 325 > 12 hrs	1,000 7-12 hrs, 162 > 12 hrs
Leakage	Water lost through leakage in pipes	30%	24%	21%	15%
Lead in drinking water	Micrograms per liter lead	10 by 2013	10 by year 2010	10 by year 2007	
Drinking water discoloration	Number of households complaining	20,000	15,000	10,000	5,000
Areas flooding by sewage	Percent of areas protected from sewage escape in gardens, roads, paths, and open areas	20%	35%	50%	100%
Ecological quality of rivers	Percent of river length capable of supporting healthy fisheries and other aquatic life in the long term	60%	75%	85%	90%
Nuisance from odor and flies from sewage treatment works	Number of households and businesses affected by odor and high numbers of flies from Sewage treatment works	2,000	600	300	150
Ability to use inland waters for recreation	Number of areas with wastewater discharges designed to allow recreational activities on rivers	0	4	12	
Bathing beach water quality	Sewage works and disinfection designed to meet government standards for bathing water	Meets current government standards	50% better than government standards	100% better than government standards	

Table 2.4: Service factors and levels, Yorkshire Water, 2005 (adapted from Willis et al. [2005])

Implementation of survey results

Just as in the previous example, the economic-valuation survey allowed Yorkshire Water to quantify customer willingness-to-pay, or the benefit, of a change in service levels. The utility then compared the benefits to the costs of investment to achieve service-level upgrades.

Yorkshire Water determined costs of different investment scenarios by first carrying out a risk appraisal of its assets. The appraisal expressed the risk of not delivering services as a function of the probability of a service failure, the severity of the impact of a failure on the customer and/or environment, and the scale or quantity of the impact. Investment options and resulting improvements in risk were then identified. Finally, the costs of implementing the solutions were assessed. This cost was expressed as an annualized net present cost that included both capital and operating expenses.

The costs and benefits of each investment scheme were compared using an economic-optimization program, which allowed for user-defined objectives, such as maximizing benefits to costs, or minimizing cost subject to one or more of the following constraints: maximum level of risk, maximum level of cost, and minimum or maximum level of service.

Yorkshire Water used this process to identify an optimal program of investment, which it then incorporated into its business plan for 2005-2010. In turn, this plan was used by the Office of Water Services to set water and wastewater prices. Customer willingness-to-pay research enabled Yorkshire Water to identify the areas of service that are most important to customers. As a result, the utility was able to create a business plan and funding strategy that balanced the interests of shareholders, customers, and regulators.

2.3.3 Determining the minimum life-cycle cost of assets

A third component of an asset management program is minimizing the total, life-cycle cost of assets. To do so, utilities must ensure that assets are placed in service for the duration of their economic life. The economic life of an asset begins when the asset is put in service, and ends when the costs of operating the asset exceed the cost of replacing it [Damodaran et al., 2005]. If utilities replace an asset before its useful life has been expended, they diminish the value of the asset. If they wait to replace the asset until it fails to perform properly, there are financial, environmental, and social costs that result [Damodaran et al., 2005].

Determining the economic life of an asset requires the utility to quantify the costs of the asset over time. These costs include both the utility's internal costs to repair or replace the asset, and costs that are external to the utility that result when the asset performs below expected service levels. There are many different external costs that may be relevant to a particular utility project; I focus here on those that are incurred by customers. Although internal costs are easy to determine, external costs to customers are harder to quantify. Economic-valuation surveys, however, can elicit this information from customers.

Example: Albuquerque Bernalillo County Water Utility Authority, 2009

The following chapters of this Professional Project present an example methodology for determining the optimal time to replace water pipes in the ABCWUA's water distribution system. The optimal time to replace a pipe is defined as the point in time when the total, life-cycle cost of the pipe asset is at a minimum. In this case study, I demonstrate how willingness-to-pay data from a 2009 economic-valuation survey conducted among ABCWUA customers can be integrated into water utility planning for water-pipe replacement.

Chapter 3

Prioritizing water mains for replacement

U.S. water utilities are facing the need to replace a significant portion of their water-pipe networks over the next 30 to 50 years, due to the age and life span of their pipes [Water Infrastructure Network, 2000, EPA, 2002]. Water pipes are installed as a city grows. In many cities, pipes have been installed over a 100 to 150 year time frame; they will not fail or need replacement all at once.

Cromwell et al. [2001] examined best practices in the economic optimization of water main replacement programs. In this study, Australian water utilities introduced the concept of a "Nessie curve." A Nessie curve is a graph of estimated annual expenditures for repair and replacement of the utility's pipe assets, where time is plotted on the x-axis and cost on the y-axis. Figure 3.1 presents the aggregated Nessie curves of a sample of 20 U.S. water utilities. It illustrates the pattern of pipe infrastructure reinvestment that many U.S. water utilities are facing.

Utilities need tools to assess the state of their water distribution systems and to prepare for a reinvestment in pipe infrastructure. In this chapter, I review existing methods for prioritizing water pipes for replacement. This review is intended to provide context and justification for the threshold break rate methodology I employ to assess the optimal time to replace water mains in the ABCWUA's distribution network. The threshold break rate provides an analytical framework for minimizing the life-cycle costs of water pipes, into which external costs can be integrated.

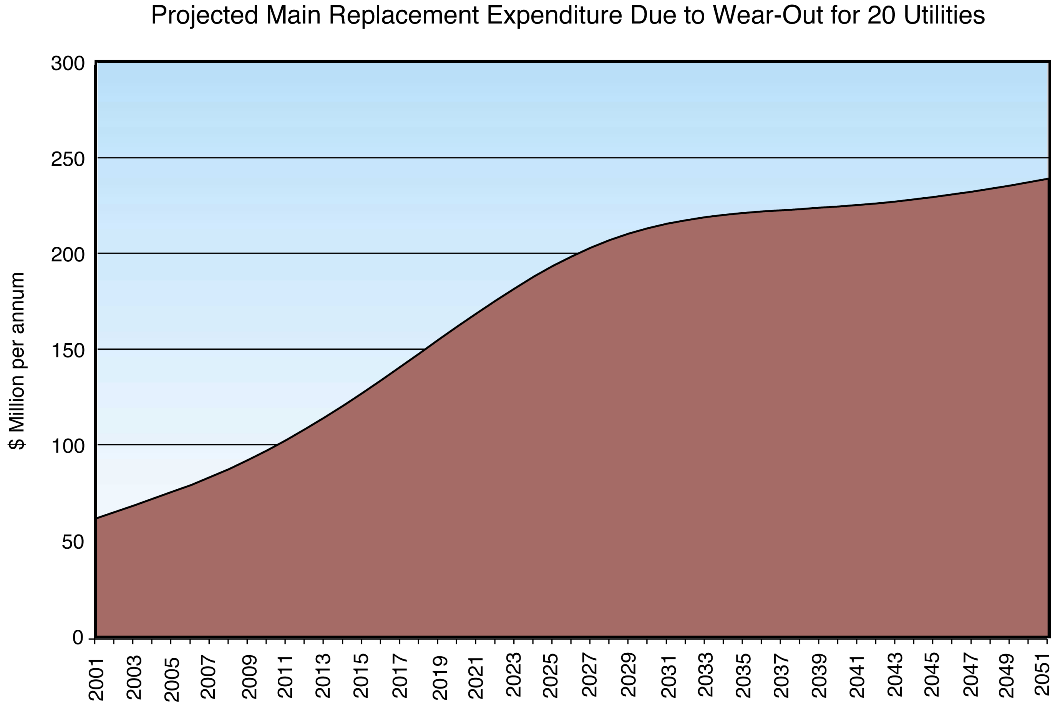

Figure 3.1: Aggregate Nessie curves for 20 U.S. water utilities (from Water Infrastructure Network [2000])

3.1 Decision support systems for pipe replacement

A number of different factors influence the life of a water pipe. These include characteristics inherent to the pipe (e.g. age, material), environmental conditions (e.g.

soil corrosivity, external loads), installation quality (e.g. bedding conditions), and service conditions (e.g. operating pressure). There have been many studies on the physical mechanisms that cause pipe failure; a comprehensive review of pipe-failure modes is provided in O'Day [1982] and Mays [2000].

O'Day [1982] found that pipe age was a poor predictor of pipe-break patterns, whereas localized factors such as corrosion, construction practices, external loads, and soil type are more reliable predictors of future break rates. Jacobs and Karney [1994], however, found that pipe age ranges are relevant, given that pipes of a certain age range are generally uniform with respect to manufacture, installation, and, in many instances, operating conditions. This contrast highlights the fact that the mechanisms that cause pipes to fail are not fully understood. They are difficult to assess given that water pipes are buried. These factors are often specific to a distribution system, and can also vary across a given distribution network.

Over the last 30 years, a large body of research has been developed on quantifying the deterioration of water mains. It remains an area of active, on-going research. Currently, there is no consensus on the parameters that should be included in predictive models on pipe failure [Thomson and Wang, 2009]. By extension, there is no comprehensive method for prioritizing replacement of failing pipes [Loganathan et al., 2002]. Although the focus of this paper is on methods for prioritizing pipes for replacement, it is useful to first understand the predictive models for pipe failure on which many of these methods rely.

3.1.1 Predictive models of pipe failure

Kleiner and Rajani [2001] categorize existing models of the structural deterioration of water pipes as either: (i) physical models or (ii) statistical models. Physical models predict pipe failure by characterizing structural failure modes (e.g. corrosion, temperature-induced stress, frost load), usually based on data from laboratory experiments. The predictive capability of these models is achieved by correlation or probabilistic analysis, where the variables influencing pipe failure are considered to be random. The physical models that have been developed to date have focused on cast-iron and cement pipes.

While physical modeling is scientifically more robust, it requires data that is difficult and costly for a water utility to obtain. Physical models may thus be justified only for major transmission water lines, where the cost of failure is substantial [Kleiner and Rajani, 2001].

Statistical models identify statistical relationships between historical pipe breaks and the factors influencing break rates. Because the actual causes of breaks are difficult to identify, proxies are often used (Table 3.1 outlines the typical inputs used in statistical models, and the pipe-failure mechanisms for which these inputs serve as a proxy). Statistical models can be used with various levels of data input, and thus are easier and more cost-effective to apply. Statistical models can be classified as deterministic and probabilistic models.

In deterministic models, pipe-failure rates are estimated based on a fit of pipe-break data to time-dependent equations. Prior to fitting these functions, water mains must be classified into groups that are reasonably similar with respect to the pipe-failure mechanisms. Because these models implicitly use grouping criteria as variates in the analysis, they employ a simple mathematical framework [Kleiner and Rajani, 2001]. However, partitioning water mains into groups is often difficult, since the groups must be both small enough to be uniform and large enough to provide results that are statistically significant [Kleiner and Rajani, 1999]. Representative works in this category include the time-exponential models proposed by Shamir and Howard [1979], Walski [1987], and Clark et al. [1982], and the time-linear models by Kettler and Goulter [1985], McMullen [1982], and Jacobs and Karney [1994].

Model inputs	**Proxied pipe-failure mechanism**
Age	Method of pipe manufacture, construction standards, deterioration over time
Pipe material	Construction standards, method of manufacture, failure mechanisms
Pipe diameter	Wall thickness and resistance to beam loading, pipe use, method of pipe manufacture, construction standards
Bedding and backfill material	Physical stress caused by construction practices, structural resistance, soil type, fines migration
Soil type	Soil corrosivity, physical loading such as swelling or frost, groundwater effects, bedding and/or backfill material
Roadway or traffic classification	Physical loading from traffic, road salt effects
Surface usage or material	Physical loading from surface use
Normal operating pressure	Internal pressure on pipe structure
Depth of pipe	Physical loading from weigh of soil

Table 3.1: Typical inputs used in statistical models and the pipe-failure mechanisms for which they serve as proxies (adapted from Wood and Lence [2000])

Probabilistic models predict not only the failure potential, but the distribution of failure [Wood and Lence, 2000]. They are more complex than deterministic models and require more data. Probabilistic models can be further sub-categorized into probabilistic multivariate and probabilistic single-variate group-processing models [Kleiner and Rajani, 2001].

Probabilistic multivariate models can explicitly account for many of the variates deemed to influence pipe breaks, which gives them the potential to make more accurate predictions about future pipe-break rates. However, the mathematical framework is more complex and therefore requires expertise to apply. Common forms of probabilistic multivariate models are the proportional hazards model [Marks, 1985, Bremond, 1997], the time-dependent Poisson model [Constantine and Darroch, 1993, Constantine et al., 1996, Mavin, 1996], and the accelerated lifetime model [Lei, 1997, Eisenbeis et al., 1999]. A combination of two probabilistic multivariate models, based on a two-stage failure process, has been used by Marks et al. [1987], Andreou et al. [1987a,b], Li and Haims [1992a,b], and Lei [1997].

Single-variate group-processing models use probabilistic processes on grouped data to derive probabilities of pipe failure over time. Among this class of models, Kleiner and Rajani [2001] identify four subclasses: cohort survival models [Herz, 1996, Deb et al., 2002a], bayesian diagnostic models [Kulkarni et al., 1986], semi-Markovian models [Gustafson and Clancy, 1999], and break clustering models [Goulter and Kazemi, 1988, Goulter et al., 1993]. Kleiner and Rajani [1999] and Mailhot et al. [2000] have specifically addressed modeling pipe failure with brief recorded pipe-break histories.

This overview of existing models is intended to emphasize the complexity of predicting pipe failure, and the variety of approaches that have been developed to date.

3.1.2 Methods for prioritizing water mains for replacement

Broadly speaking, existing methods for prioritizing water mains for replacement can be used in two ways. First, they can be used to identify which individual pipes in a distribution system should be replaced at the current time. Second, they can be used to estimate system-wide replacement needs and associated costs over the long-term. The former class of methods can be called pipe-replacement decision-models; they require data on individual pipe characteristics and pipe-break histories. The latter class of methods can be thought of as long-range planning models. These models have a less substantial data requirement.

I focus in this paper on pipe-replacement decision-models. There are fewer pipe-replacement decision-models in use than long-range planning models. This may be due to the fact that pipe-replacement decision-models require extensive and accurate data on pipes that few utilities maintain.

The ABCWUA currently prioritizes pipes for replacement based on the number of pipe breaks that have occurred in the pipes. Pipes with the most breaks get prioritized for replacement first. A more complex version of this type of approach is the *deterioration point assignment* method [Deb et al., 2002b]. In deterioration point assignment, each pipe in the distribution system is evaluated and scored on a set of factors associated with pipe failure. In addition to the history of previous breaks, these factors might include pipe age, material, size, type of soil, location, water pressure, or susceptibility to frost. If the pipe's total failure score exceeds a threshold value, the pipe is considered a candidate for replacement.

A weakness of the ABCWUA's approach and the deterioration point assignment method is that there is no way to assess how many pipes should be replaced at a given time. The utility has a certain budget for pipe replacement, and it allocates its funds to the pipes with the highest break rates or the highest deterioration points. There is also no obvious way to determine the threshold value at which a pipe should be replaced. Moreover, there is no way to determine whether the costs of replacing the pipe are economically justified.

Deb et al. [2002b] described an alternative approach called *break-even analysis*, where the optimal time to replace a pipe is the point in time where the sum of the present value of replacement and repair is at a minimum. Generally speaking, the pipe should be replaced if the present worth of future breaks is greater than the replacement cost. Many of the decision support systems that have been developed for pipe replacement have included a cost component, such as those developed by Giustolisi and Berardi [2009], Damodaran et al. [2005], Loganathan et al. [2002], Deb et al. [2002a], Grablutz and Hanneken [2000], Walski and Pellicia [1982], Shamir and Howard [1979], and Stancha [1978]. Because break-even analysis seeks to minimize the life-cycle cost of pipes, it is consistent with asset management. These models must be paired with a predictive pipe-failure model in order to project future replacement needs.

Break-even analysis was first introduced by Shamir and Howard [1979]. They applied regression analysis to obtain a break prediction model that relates a pipe's breakage rate to the exponent of its age:

$$N(t) = N(t_0)e^{A(t-t_0)} \tag{3.1}$$

where t is time in years, t_0 is the base year for the analysis (the year the pipe was installed, or the first year for which data are available), $N(t)$ is the number of breaks per 1000-foot-length of pipe in year t, and A is the growth rate coefficient determined through the regression analysis (dimension is 1/year).

This equation was used as the basis for finding the optimal timing of pipe replacement which minimized the total cost of repair and replacement. To find the time when the pipe should be replaced, they sought to identify the year that minimized the present value of the pipe:

$$\min_{t_r} [PV_{t_r}] = \min_{t_r} \left[\sum_{t=t_p}^{t_r} \frac{N(t_0)e^{A(t-t_0)}C}{(1+R)^{t-t_p}} + \frac{F}{(1+R)^{t-t_p}} \right] \tag{3.2}$$

where t_r is the year in which the pipe will be replaced, PV_{t_r} is the present value of the pipe at year t_r, t_p is the present year, C is the cost of a break, F is the cost of replacement, R is the discount rate, and all other terms are as previously defined. Differentiating with respect to t_r, setting equal to zero and solving, they thus defined the optimal timing of replacement as:

$$t_r^* = t_0 + \frac{1}{A} ln \left[\frac{ln(1+R)F}{N(t_0)C} \right]. \tag{3.3}$$

In their analysis, the cost of repair and replacement were assumed to be constant over time. They also assumed that the replacement pipe is virtually break-free (i.e. that breaks develop in the new pipe so far in the future that the present value of those repairs is negligible).

3.1.3 Threshold break rate

It is clear that any change in Shamir and Howard's growth rate coefficient would alter the recommended replacement time. This is the case for any pipe-replacement decision-model that relies on a predictive model of pipe failure.

Loganathan et al. [2002] proposed an alternative method, called the *threshold break rate*, that estimates the rate of breaks per year in a given pipe at which the total cost of the pipe is at a minimum.[1] The threshold break rate is based solely on current cost data; it does not require prediction of future pipe breaks. The model answers the question, "What is the break rate for a given pipe at which it is economically sustainable to maintain the pipe at present day costs?" [Park, 2000]. Following Loganathan et al. [2002], I outline the derivation of the threshold break rate equation below.

At the time of the n^{th} break, the utility must decide whether to replace the pipe at a cost of F_n, or to repair the pipe at a cost of C_n. In this scenario, it is assumed that only repairs have been performed on the prior $n-1$ breaks.

If we assume that the pipe will be replaced at the time of the n^{th} break, t_n, the present value of the total cost of the pipe is:

$$PV_n = \sum_{i=1}^{n} \frac{C_i}{(1+R)^{t_i}} + \frac{F_n}{(1+R)^{t_n}} \tag{3.4}$$

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[1] Walski and Pellicia [1982] were actually the first to define the optimal time to replace a pipe in terms of a threshold break rate.

where R is the discount rate, t_i is the time of the i^{th} break measured from the installation year, t_n is the time of the n^{th} break measured from the installation year, C_i is the repair cost of the i^{th} break, F_n is the replacement cost at time t_n, and PV_n is the present value of the total cost of the pipe. In this analysis, repair and replacement costs include both internal and external costs.

As pipes age, they experience more breaks under the same trench and load conditions. Therefore, over time, the cost of replacement decreases due to discounting, and the total (discounted) cost of maintenance generally increases due an increase in pipe breaks. The total cost curve is therefore typically U-shaped.

An example cost curve is provided in Figure 3.2. In this example, there are no pipe breaks until after year 40. Thus, prior to year 40, the total cost of the pipe is equal to the replacement cost. With time, breaks (and thus repairs) occur more frequently. The total cost of the pipe is minimized around year 50.

Assuming that the total cost curve is a unimodal function, the total cost PV_n is at a minimum at time t_n when:

$$PV_{n-1} > PV_n < PV_{n+1}. \tag{3.5}$$

To determine the threshold break rate, it is necessary to identify the first instance when the condition $PV_{n+1} > PV_n$ holds true. The total cost of the pipe at the time of the $(n+1)^{th}$ break can be expressed as:

$$PV_{n+1} = \sum_{i=1}^{n+1} \frac{C_i}{(1+R)^{t_i}} + \frac{F_{n+1}}{(1+R)^{t_{n+1}}}. \tag{3.6}$$

From Equations 3.4 and 3.6, we obtain:

$$PV_{n+1} - PV_n = \frac{F_{n+1}}{(1+R)^{t_{n+1}}} + \frac{C_{n+1}}{(1+R)^{t_{n+1}}} - \frac{F_n}{(1+R)^{t_n}}. \tag{3.7}$$

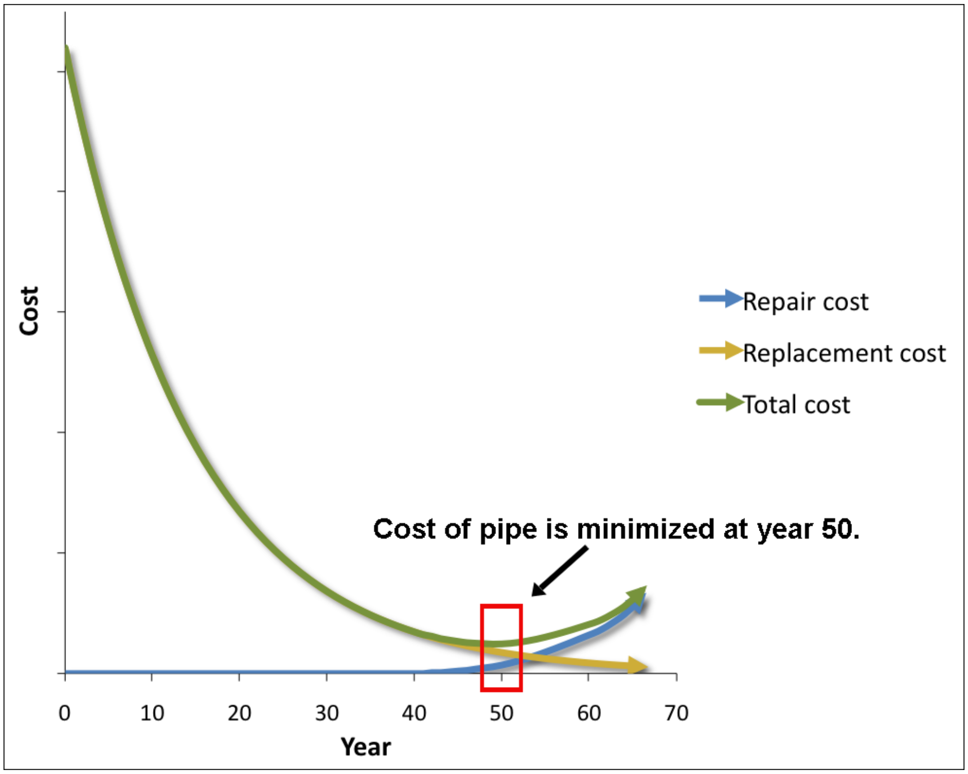

Figure 3.2: Example cost curves for a water pipe (1)

If $PV_{n+1} - PV_n > 0$, then:

$$\frac{F_{n+1}}{(1+R)^{t_{n+1}}} + \frac{C_{n+1}}{(1+R)^{t_{n+1}}} - \frac{F_n}{(1+R)^{t_n}} > 0. \tag{3.8}$$

Solving for $t_{n+1} - t_n$, we obtain:

$$t_{n+1} - t_n < \frac{ln(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n})}{ln(1+R)}. \tag{3.9}$$

$t_{n+1} - t_n$ is the time between the n^{th} and the $(n+1)^{th}$ breaks, or the time interval for the occurrence of one break. Therefore, the threshold break rate, Brk_{th}, is the inverse of $t_{n+1} - t_n$, or:

$$Brk_{th} > \frac{ln(1+R)}{ln(\frac{C_{n+1}}{F_n} + \frac{F_{n+1}}{F_n})}. \tag{3.10}$$

Whenever the current break rate of the pipe, Brk_{cur}, equals or exceeds the threshold break rate, Brk_{th}, the pipe should be replaced. The condition for pipe replacement at the current time is therefore:

$$Brk_{cur} \geq Brk_{th}. \tag{3.11}$$

Loganathan et al. [2002] established equivalence relationships between the threshold break rate and appropriate statistical functions for predicting future pipe breaks (i.e. hazard and rate of occurrence of failure functions).

Discussion of the threshold break rate methodology

The threshold break rate methodology developed by Loganathan et al. [2002] is derived from the early pipe-break model proposed by Shamir and Howard [1979]. Although Shamir and Howard found that an exponential model for describing breaks over time best fit their data sets, they noted that the economic analysis remained valid, regardless of the form of the model. The work of Shamir and Howard demonstrated some of the key relationships between variables in an economic analysis of pipe replacement. However, as illustrated in Section 3.1.1, later work on pipe-break prediction showed that break patterns in pipes were often more complex than was captured in early, deterministic statistical models such has Shamir and Howard's.

The threshold break rate methodology does not require characterization of future pipe-break rates. This is a distinct advantage of the methodology, given the difficulty and uncertainty associated with pipe-break prediction. However, it does rely on the assumption that the function that represents the present worth of a pipe over time is unimodal.[2] Under this assumption, there will be a single global minimum in the

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[2] A function f(x) between two ordered sets is unimodal if for some value m (the mode), it is monotonically decreasing for $x \leq m$ and monotonically increasing for $x \geq m$ (the monotonicity is reversed if the mode is a maximum).

cost function, and no local minima. This Professional Project tests this assumption when applying the threshold break rate to ABCWUA pipe-break data.

Chapter 4

Estimating external costs

The threshold break rate relies on an accurate quantification of pipe repair and replacement costs. When assessing the cost of an asset, both the utility's internal costs and external costs born by customers, the community, and the environment should be taken into account. Thus, both internal and external costs should be included in the calculation of the threshold break rate for a given pipe.

In this chapter, I demonstrate how external costs of pipe repair and replacement can be quantified through an economic-valuation survey. I use the economic-valuation survey conducted among ABCWUA customers in 2009 as an example.[1]

The ABCWUA in Albuquerque, New Mexico, has approximately 172,000 customer accounts, representing some 520,000 water users [ABCWUA, 2010]. The population of interest for the ABCWUA economic-valuation survey was residential customers. The sample size for the survey presented here was 1,900 customers.[2]

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[1] Further detail the ABCWUA customer survey is provided in *Assessing Customer Preferences and Willingness to Pay: A Handbook for Water Utilities* [Thacher et al., Forthcoming].

[2] Two survey methodologies (choice experiments and the contingent valuation method) and five different survey types were employed in this study. The study design allowed for comparison of willingness-to-pay elicitation methods, one of the priorities of the agency

The survey employed the choice-experiment methodology. In order to understand how willingness-to-pay is estimated through a choice-experiment survey, I first provide an explanation of the econometric model that underlies a choice experiment.

4.1 Random utility model

In considering how individuals make choices over goods, Lancaster [1966] noted: (1) It is the characteristics of any good that provide satisfaction to the consumer, not the good itself; (2) Goods usually are made up of multiple characteristics, and one individual characteristic is usually found in many goods; and (3) A combination of goods will give rise to characteristics that do not occur when looking at the goods individually. This approach indicates that to understand consumers' choices, it is necessary to understand how consumers value the specific characteristics that make up goods individually and in combination [Lancaster, 1966].

This idea was formalized in economics by McFadden [1974] with the development of the discrete-choice random utility model. In brief, the random utility model assumes that individuals receive a certain level of utility or satisfaction from consuming a good composed of specific levels; as the levels associated with the attributes change, the level of utility changes. When faced with competing alternatives, individuals will choose the alternative that provides them with the highest overall level of utility or satisfaction. Assume there are J alternatives available to an individual. The utility from alternative j is thus:

$$U_{ij} = V(X;\beta)_{ij} + \epsilon_{ij}. \tag{4.1}$$

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that funded the research. I focus in this paper on a choice-experiment survey that valued all three of the proposed infrastructure investments of interest to the utility. Other survey types addressed only a subset of the investments.

The indirect utility, V_{ij}, is a function of the attributes of alternative j (X_j). These characteristics are observed by both the individual and the researcher. The beta parameters (β) are the weights on each attribute. A large beta on a particular attribute implies that the attribute is a large component of utility and thus will have a large impact on the alternative chosen. ϵ_{ij} is a random term that varies across individuals and alternatives. ϵ_{ij} is known to the individual but not observed by the researcher, so utility is random from the researcher's perspective.

The presence of the error term in the utility function implies that there will be probabilistic model for describing how an individual chooses between alternatives. Consider the case of two alternatives in the utility function. The probability that individual i chooses alternative A over alternative B is the probability that the utility he gets from alternative A is greater than the utility he gets from alternative B:

$$Pr(U_{iA}) = Pr(V_{iA} + \epsilon_{iA} > V_{iB} + \epsilon_{iB}). \tag{4.2}$$

Given that the utility associated with the two alternatives is a function of the attribute levels and their beta weights (as illustrated in Equation 4.1), the choice probability depends upon the varying attribute levels and beta weights.

Assumptions about the distribution of the error term in the utility function determine the form of the probability function. If we assume that ϵ follows an extreme value distribution and that the error terms are independent, the probabilities have a typical logit form:

$$Pr_{ijk} = \frac{e^{V_{ijk}}}{\sum\limits_{m} e^{V_{ijm}}} \tag{4.3}$$

where i is the individual, j is the choice set, and k is the alternative. Given information on the alternatives presented in the choice sets and the choices that survey respondents made, we can construct the likelihood function:

$$L = \prod_{i=1}^{N} \prod_{j=1}^{J} (P_{i,j,A})^{y_{i,j,A}} (P_{i,j,B})^{y_{i,j,B}} \tag{4.4}$$

where $y_{i,j,A}$ is an indicator variable that takes a value of one when individual i chooses alternative A in the choice set j and zero otherwise. J is the total number of choice sets, and N is the sample size. The other indicator variable is defined similarly.

4.2 ABCWUA economic-valuation survey

4.2.1 Survey instrument

The ABCWUA economic-valuation survey presented three different, potential investments to customers: pipe rehabilitation, renewable energy, and water reuse.[3] Consistent with the random utility model, investments were represented in the survey by six *attributes*, or characteristics. Each attribute had various *levels*, or quantitative measures of the attribute. Different goods or *alternatives* can be created by combining the levels in different ways. *Choice sets* are created by putting two or more of these alternatives together. The task for the respondent is to decide which alternative he prefers within a particular choice set. Figure 4.1 provides an example choice question from the survey.[4]

Table 4.1 outlines the investments, attributes, and levels presented in the survey.

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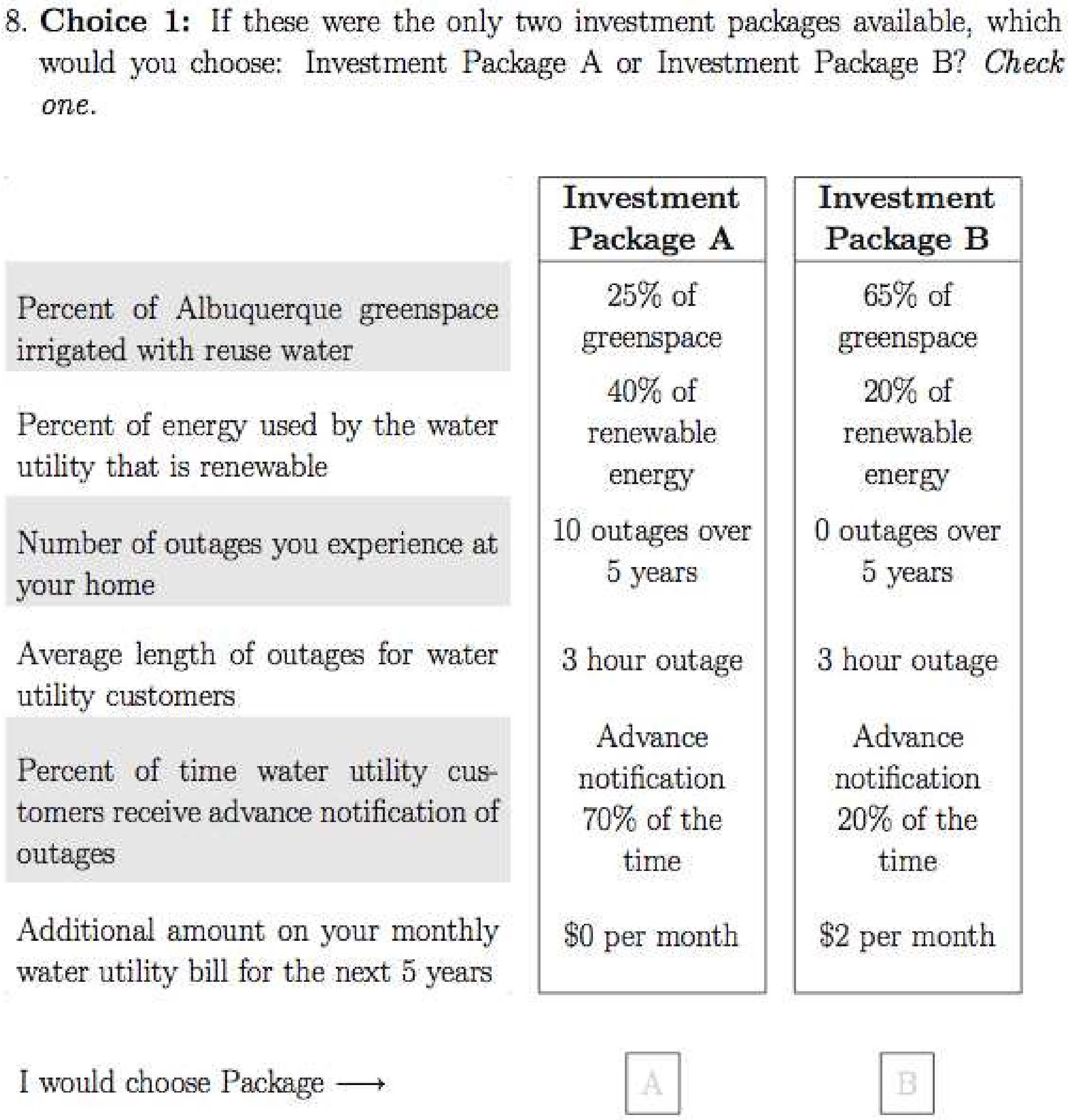
[3] A copy of the survey is provided in Appendix F. It was developed in a multi-stage process that included on-site interviews with five North American utilities, literature reviews, focus groups, debriefings, and a pre-test. For all 5 survey types, a total of 5 community-based focus groups, with 40 residential rate-payers, were held across the city during survey development. The focus groups were used to help identify the most relevant attributes and test prototypes of valuation questions. Eighteen rate-payers participated in debriefing interviews, which led to significant modifications of the survey and cover letter. A pretest



8. **Choice 1:** If these were the only two investment packages available, which would you choose: Investment Package A or Investment Package B? *Check one.*

	Investment Package A	**Investment Package B**
Percent of Albuquerque greenspace irrigated with reuse water	25% of greenspace	65% of greenspace
Percent of energy used by the water utility that is renewable	40% of renewable energy	20% of renewable energy
Number of outages you experience at your home	10 outages over 5 years	0 outages over 5 years
Average length of outages for water utility customers	3 hour outage	3 hour outage
Percent of time water utility customers receive advance notification of outages	Advance notification 70% of the time	Advance notification 20% of the time
Additional amount on your monthly water utility bill for the next 5 years	$0 per month	$2 per month
I would choose Package ⟶	☐ A	☐ B

Figure 4.1: Example valuation question

The attribute levels in the investment packages were varied across eight survey versions. Each respondent answered four valuation questions. This variability allows

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of 200 rate-payers, with a response rate of 45%, was conducted in the summer of 2009.

[4] The survey provided a short description of the attribute, the current status quo level of the attribute, and a description of the way investment could affect that level prior to the choice questions.

the researcher to estimate the value that individuals place on a change in a specific attribute or the value of a change between any two alternatives, including the status quo. The survey design is provided in Appendix E.

Investment	**Attributes**	**Levels**
Renewable energy	Percent of renewable energy used by water utility	20, 40, 60
Reuse water	Percent of greenspace irrigated with reuse water	25, 45, 65
Pipe replacement	Number of outages over 5 years	0, 5, 10
	Average length of outages in hours	3, 8, 15
	Average percent of time customers receive advance notification of outages	20, 70, 90

Table 4.1: Survey attributes and levels

4.2.2 Survey administration and data collection

The survey was conducted through a mailed questionnaire and a web-based survey. Following Don Dillman's Tailored Design Method [Dillman, 2007], customers in the sample received multiple contacts asking them to participate in the survey. Each contact was designed to be unique in its format and its appeal, in order to persuade those customers who had not responded to previous solicitations to complete the survey.

The first contact in September 2009 was a pre-notice letter from the water utility that advised customers they would be receiving a request from the UNM Department of Economics to participate in the study. The pre-notice letter also advised them that early respondents were eligible for a \$5 rebate on their water bills. The second contact was a survey packet. The packet included a cover letter, a questionnaire, a stamped, self-addressed return envelope, a consent form, a \$1 cash incentive, and a postage-paid postcard for requesting a Spanish-language survey. The letter included information for logging into the online survey. Contact 3 was a reminder postcard. Contact 4 was a replacement survey packet. Contact 5 was a second replacement survey packet.

The survey response rate was 45.8%, demonstrating the success of the Tailored Design Method in achieving high response rates.[5] High response rates are important because survey results are not considered valid when a significant number of people do not respond to the survey, and this group has different characteristics from those who do respond [Dillman, 2007].

Table 4.2 compares the demographic characteristics of survey respondents to U.S. Census American Community Survey (ACS) data on Albuquerque adults (i.e. age 18 or older) and Albuquerque homeowners. We assumed when designing the study that the ABCWUA customer list from which we drew our sample included very few renters. In later discussions with renters during focus groups, we found that some unknown share of renters receive their bills directly from the water utility. When we analyzed the survey data, we found that the demographics of our survey respondents better matched demographics of homeowners than adults. I therefore compare our survey respondents to Albuquerque homeowners here, except in cases where no data was available on homeowners in the ACS.

The age of survey respondents closely reflected the age of homeowners in Albuquerque. More females answered our survey (56%) than is reflective of the adult population in Albuquerque (52%). Forty-one percent of homeowners hold a Bachelors or higher degree, compared to 50% of survey respondents. The percentage of Hispanic individuals who answered our survey (35%) was higher than the percentage of Hispanic homeowners in Albuquerque (20%). Ninety-percent of survey respon-

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[5] Response rates were calculated using the equation: $RR = \frac{E_R}{E_R+E_{NR}+UE_{NR}+NE}$, where RR is the response rate, E_R are eligible recipients who returned the survey, E_{NR} are eligible recipients who did not return the survey, UE_{NR} are recipients of unknown eligibility who did not return the survey, and NE are recipients who are not eligible [AAPOR, 2009].

Characteristic		Our survey	2008 ACS 18 & over	2008 ACS Homeowners
Age	18-24	2%	10%	2%
	25-34	11%	15%	13%
	35-44	16%	14%	20%
	45-54	23%	14%	21%
	55-64	24%	11%	20%
	65-74	15%	7%	13%
	75-85	8%	4%	9%
	85 and older	2%	2%	3%
Sex	Male	44%	48%	-
	Female	56%	52%	-
Education	Less than high school	5%	13%	9%
	High school diploma or GED	14%	24%	19%
	Some college or Associates degree	32%	34%	31%
	Bachelors degree or higher	50%	29%	41%
Ethnicity	Hispanic	35%	40%	21%
Race	White alone	90%	74%	81%
	Black or African-American alone	2%	3%	2%
	American Indian or Alaska Native alone	2%	4%	2%
	Asian alone	2%	3%	2%
	Pacific Islander alone	0%	0%	0%
	Some other race alone	0%	14%	11%
	Two or more races	5%	3%	2%
HH income	Less than $19,999	10%	20%	-
	$20,000 $39,999	21%	24%	-
	$40,000 - $59,999	21%	19%	-
	$60,000 - $99,999	27%	21%	-
	$100,000 - $149,999	14%	10%	-
	$150,000 - $199,999	4%	4%	-
	$200,000 or more	3%	3%	-

Table 4.2: Comparison of ABCWUA survey and ACS demographics

dents identified themselves as “white alone,” while 81% of Albuquerque homeowners do so. Zero percent of survey respondents reported they were “some other race alone,” while 11% of homeowners do so. Our survey had a slightly higher percentage of respondents who identified themselves as “two or more races” than Albuquerque homeowners (2%). Other race categories were consistent between our survey and the

ACS. Household incomes of survey respondents were somewhat higher than household income levels for Albuquerque adults. We had low representation from respondents with household incomes of $19,999 or less, and higher representation from middle-income respondents.

Overall, comparison of our survey to the 2008 ACS indicates that our survey was broadly representative of Albuquerque homeowners. ABCWUA survey respondents were likely to be somewhat better educated than the average homeowner and wealthier than the average adult, which is important to consider when applying willingness-to-pay estimates generated from the survey.

4.2.3 Results

Responses to the valuation question can be modeled using a discrete-choice random utility model of the following form:

$$V_j = \beta_1 OutageNumber_j + \beta_2 OutageLength_j + \beta_3 OutageNotify_j + \beta_4 Renewable_j + \beta_5 Reuse_j + \beta_y Cost_j \tag{4.5}$$

In this model, we assume that the utility function is linear in all its attributes and that there are no significant interactions between variables. The model is homogenous, meaning that no personal characteristics are included. Therefore the estimates reflect the preferences of the average respondent.

Results from the survey are presented in Table 4.3. Only willingness-to-pay estimates for the water-pipe-replacement attributes are presented here, because they will be applied in the threshold break model.

Attribute	**Estimate**	**Standard error**	**P-value**	**MWTP [CI]**
Additional monthly cost over 5 years	-0.105	0.00574	<0.001	-
Number of outages over 5 years	-0.0816	0.00627	<0.001	-0.78 [-0.63;-0.93]
Average length of outages	-0.0753	0.00533	<0.001	-0.72 [-0.62;-0.85]
Percent of time customers receive advance notification	0.00675	0.000828	<0.001	0.06 [0.05; 0.08]

Table 4.3: Maximum Likelihood Estimation results (Observations - 3317, lnL = -1783.28)

First, consider the signs on the utility parameters in the column titled "Estimate." The percent of time customers receive advance notification of outages has a positive sign, indicating that an increase in this attribute make customers better off. In contrast, cost, number of outages, and outage length have negative signs, indicating that increases in these attributes make customers worse off.

By combining the parameter estimates and the standard error, we can calculate whether these estimates are statistically significantly different from zero (p-value). A p-value less than 0.05 is considered strongly significant. All of the estimates are strongly significantly different from zero.

Marginal willingness-to-pay, or the willingness-to-pay for a small change in the level an attribute, is calculated as $\frac{\beta_1}{\beta_y}$, where β_1 is the parameter estimate on attribute 1, and β_y is the parameter estimate on cost. Thus, the average household is willing to pay an additional \$0.78 per month for five years to avoid each additional outage at their home. They are willing to pay \$0.72 per month for five years to avoid each additional hour of an outage. The average household is willing to pay an additional \$0.06 on their monthly water bill for five years for each one percent increase in the share of time that customers receive advance notification.

As noted previously, willingness-to-pay is a random variable that we are estimating with error. Using the Krinsky-Robb method with 500 random draws, I report the 95% confidence intervals for each of the marginal willingness-to-pay estimates in the last column of Table 4.3. Note that the confidence intervals are small and do not include zero. This gives us confidence about the accuracy of our estimates.

Willingness-to-pay to avoid a water outage can be interpreted as the external cost of a water outage. To apply the survey results in the calculation of the threshold break rate for a given water main, we can use the marginal willingness-to-pay values generated from the survey to estimate the external cost imposed on the average household for one additional water outage, all else held constant:[6]

$$\$0.78/\text{month} * 12\ \text{months/year} * 5\ \text{years} = \$46.80$$

The 95% confidence interval is $37.80 to $55.80.

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[6] For this application, we would ideally like an estimate of the external cost imposed on an individual household of one outage, without a time frame attached it. However, both the outages and cost were presented in our survey as occurring over 5 years because the value of both is difficult to conceptualize without a finite time frame. $46.80 is actually the amount households are willing to pay to prevent one additional outage over 5 years. How much would customers be willing to pay to avoid 5 outages over 5 years? $234 (5 * $46.80). If these outages were to occur annually, we would make the approximation that they would be willing to pay $46.80 ($234/5). Although not perfect, the best estimate of the external cost associated with a single outage is therefore $46.80.

Chapter 5

Case study: Minimizing the life-cycle cost of six-inch-diameter steel pipe

In this chapter, I present an example application of the threshold break rate methodology to a subset of the pipes in the ABCWUA distribution system - six-inch-diameter steel pipes. I provide background on the distribution system in the following section, in order to justify the focus on this cohort of pipes.

5.1 ABCWUA water distribution system

The ABCWUA[1] maintains on approximately 2,800 miles of water distribution piping. The water system is composed of four main types of pipe (Figure 5.1):[2]

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[1] ABCWUA became an independent Water Authority on June 21, 2003. It was previously operated as part of the City of Albuquerque.

[2] Other types of pipe, such as copper, are present in the system in very minimal quantities.

1. Steel, linear wrapped steel, and galvanized steel (STL, LWS, GSP)
2. Cast iron and ductile iron (CI, DI)
3. Asbestos cement and concrete cylinder (AC, CCYL)
4. Polyvinyl chloride (PVC)

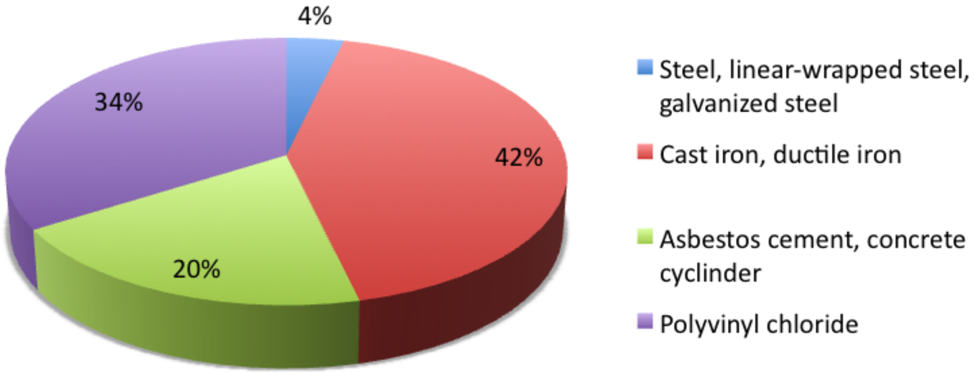

Figure 5.1: ABCWUA water pipes by material (adapted from NMEFC [2010])

5.1.1 NMEFC pipe-break analysis

In 2010, the New Mexico Environmental Finance Center (NMEFC) completed an analysis of ABCWUA water system pipe breakage data from fiscal year 1995-2009 [NMEFC, 2010]. A fiscal year lasts from July 1 of one calendar year to June 30 of the following calendar year. The analysis addressed:

- the number and frequency of repairs to water mains,
- the type and size of the pipe that was repaired, and

- the spatial distribution of water main repairs.

Water can leak in a pipe distribution system through a break in a pipe. It can also leak through a fitting, joint, service connection, or gasket. Although there is a distinction between pipe breaks and leaks, there was insufficient information in the utility data set used for the analysis to differentiate between the two. Therefore, the term “pipe break” is used to refer to both breaks and leaks in the NMEFC analysis, as well as in this paper.

Total pipe breaks by pipe class and size

A summary of pipe-break data from FY95-FY09 by type and size is provided in Table 5.1. The table shows that, among all pipe sizes, most pipe breaks occurred in pipes that are six inches in diameter (58%). The second highest percentage of breaks occurred in four-inch-diameter pipes (14%).

The data set also indicates that, among all pipe types, steel pipe accounts for 33% of the pipe breaks recorded during the study period. Cast-iron pipe accounts for 41% of pipe breaks. The remaining pipe breaks were about evenly distributed among asbestos cement and concrete cylinder cylinder pipe, PVC pipe, and pipes that were not assigned a pipe type in the utility GIS.

Over the fifteen-year study period, there were changes in the break data trends. Notable among them is a decrease in breaks in steel pipe (from 103, or 55% of annual repairs in 1995 to 53, or 20% of annual repairs in 2009), and an increase in the breaks in cast-iron pipe (from 39, or 21% of annual repairs in 1995 to 148, or 55% of annual repairs in 2009). The NMEFC projects that the decrease in steel pipe breaks is due to the fact that:

- Steel pipe in the system is being replaced each year.

Pipe size	**STL LWS GSP**	**CI DI**	**AC CCYL**	**PVC**	**Unknown**	**Total**	**Percent**
42”			4			4	0%
36”	2	6	16			24	1%
30”		8	7		1	16	<1%
24”	2	7	20			29	1%
22”	1					1	0%
20”	7	11	7		1	26	<1%
18”		2	9		2	13	<1%
16”	13	20	40	2		75	4%
14”	2	13	4			19	<1%
12.25”	4					4	<1%
12”	15	85	11	25	4	140	4%
10”	34	42	25	36	12	149	4%
8”	41	33	26	58	16	174	5%
7”			1			1	0%
6”	583	1,068	115	130	153	2,049	58%
5”	50	2	1	1	3	57	2%
4”	326	103	16	5	63	513	14%
2.25”	12	41	1		9	63	2%
2”	21	2			10	33	1%
1.5”	1					1	0%
1.25”	55				6	61	2%
1”	2				3	5	0%
Unknown	8	6			72	86	2%
Total	1,179	1,449	303	257	355	3,543	100%
Percent	33%	41%	9%	7%	10%	100%	

Table 5.1: Pipe breaks, FY 95-09 (from NMEFC [2010])

- The utility has employed asset management techniques to strategically select steel pipes for replacement.
- Some steel pipe may be incorrectly identified in the GIS.
- Replacement of sections of steel pipe would have been excluded from the data set.

The increase in cast-iron breaks is likely due to:

- Cast-iron pipe in the system is increasing in age.
- Pipe-replacement efforts have focused on steel pipe.
- Some cast-iron pipe may be incorrectly identified in the GIS.

Average breaks per year and breaks per mile per year

Table 5.2 illustrates the average pipe breaks and the breaks per mile per year in each pipe type. It indicates that, despite a decrease in steel pipe breaks and an increase in cast-iron pipe breaks, breaks in steel pipe are still occurring at a much higher rate than in other pipes.[3] It also indicates that the high number of cast-iron pipe breaks is due, in part, to the large quantity of these pipes in the system.

Type of pipe	**Total miles of pipe**	**Average breaks per year**	**Breaks per mile per year**
Steel, linear-wrapped steel, galvanized steel	105	79	0.75
Cast iron, ductile iron	1,206	97	0.08
Asbestos cement, concrete cylinder	561	20	0.04
Polyvinyl chloride	960	7	0.02
Unknown	0	24	n/a
Total	2,832	236	0.08

Table 5.2: Average breaks per year and breaks per mile by pipe type, FY 95-09 (from NMEFC [2010])

Table 5.3 shows average pipe breaks and pipe breaks per mile for each pipe size.[4] Four-inch and six-inch pipe have the highest average breaks per year, and

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[3] Pipe quantities are estimates. For example, some utility personnel believe that there are 85 miles of steel pipe in the system. If this were the case, the breaks per mile would be much higher (0.92 instead of 0.75) [NMEFC, 2010].

[4] Table 5.3 only shows pipe sizes that have experienced breaks over the 15-year study period. In some cases, a repair was recorded in a work order on a pipe size that did not exist in the utility's GIS (e.g. 12.25" or 7"). These breaks are included in the break totals presented in the Table 5.1, but not in Table 5.2.

high breakage rates. Breaks rates are deceptively high among certain pipe sizes (e.g. 42", 5", 2.25", 2", 1.25"), because there are so few miles of these pipe sizes in the distribution system.

Pipe size	**Total miles of pipe**	**Average breaks per year**	**Breaks per mile per year**
42"	0.5	0.26	0.52
36"	37	2	0.05
30"	28	1	0.04
24"	62	2	0.03
22"	3	0.07	0.02
20"	44	2	0.05
18"	23	1	0.04
16"	105	5	0.05
14"	54	1	0.04
12"	175	9	0.05
10"	190	10	0.05
8"	263	11	0.04
6"	1,433	137	0.09
5"	4	4	1.0
4"	89	34	0.38
2.25"	14	4	0.28
2"	4.4	2	0.45
1.25"	0.9	4	4.44
Total	2,530	193	0.08

Table 5.3: Average breaks per year and breaks per mile by pipe size, FY 95-09 (from NMEFC [2010])

The overall system break rate over the 15-year study period was 0.08 breaks per mile per year. This is lower than the benchmark rate for municipal water systems of 0.1 - 0.2 breaks per mile per year established by a Water Research Foundation study [Cromwell, 2009]. When steel pipe is removed from the analysis, ABCWUA's system break rate is 0.06 breaks per mile per year.

The NMEFC analysis indicates that steel and cast-iron pipe, and four-inch-diameter and six-inch-diameter pipe are currently experiencing the highest breakage rates in the system. The majority of pipe breaks occur in steel and cast-iron pipe (74%) and four-inch-diameter and six-inch-diameter pipe (72%). Table 5.4 shows the break rates for four-inch-diameter and six-inch-diameter steel and cast-iron pipe. Break rates for four-inch-diameter and six-inch-diameter steel pipe are extremely high, 1.22 and 1.3 breaks per mile per year respectively. This indicates that although steel-pipe breaks are decreasing, steel pipe remains a priority candidate for replacement in the ABCWUA's system.

To test the threshold break rate model, I limit my analysis to the pipes that currently have the highest break rates in the system, six-inch-diameter steel pipes. It is also appropriate to focus on six-inch-diameter steel pipes, because the economic-valuation survey conducted for ABCWUA addressed residential water customers, and six-inch-diameter pipes generally serve residential areas.

Pipe size and type	**Total miles of pipe**	**Average breaks per year**	**Breaks per mile per year**
4” steel, linear-wrapped steel, galvanized steel	18	22	1.22
4” cast iron, ductile iron	48	7	0.14
6” steel, linear-wrapped steel, galvanized steel	30	39	1.3
6” cast iron, ductile iron	773	71	0.09

Table 5.4: Average breaks per year and breaks per mile, selected pipe types and sizes, FY 95-09 (from NMEFC [2010])

5.2 Methodology

To assess whether six-inch-diameter steel pipes should be scheduled for replacement, we must compare the threshold break rate estimate to the current break rate for each pipe. Consistent with the threshold break rate, the current break rate is calculated by dividing one by the interval between breaks; pipes therefore must have experienced at least two breaks to be considered in the analysis. Steps in the analysis completed for this project were as follows:

1. Determine current break rates for all six-inch-diameter steel pipes that have broken more than once during the study period (FY95-FY09)
2. Generate threshold break rate estimates for all pipes in the cohort
    - Excluding external costs
    - Including external costs
3. Compare current and threshold break rates to identify pipes that should be replaced now, and pipes that were replaced at an economically optimal time during the study period
    - Excluding external costs
    - Including external costs

Three types of data were therefore required for this project:

1. Data on pipes and pipe breaks
2. Data on internal costs of pipe repair and replacement
3. Data on external costs of pipe repair and replacement

I discuss each of these types of data in turn.

Data on pipes and pipe breaks came from the ABCWUA pipe GIS and FY95 to FY09 main line break work orders. It is important to note that there are four sources of error in this data set:

1. The locations of pipe breaks recorded in work orders are not exact. The location could be listed as the point where the break surfaced, the address of the house that called to notify the utility of the break, the nearest intersection of streets to the break, etc.

2. Pipe characteristics (e.g. pipe type and size) are not always correct in the pipe GIS.

3. Pipe break work orders do not contain a pipe ID number. Pipe characteristics (e.g. pipe type and size) were recorded in FY95-FY03 work orders, but not in FY04-FY09 work orders. This means that it is possible to use pipe characteristics to verify that pipe breaks are correctly matched to the pipes on which they occurred in the FY95-03 data set, but not in the FY04-FY09 data set.

4. The date of a pipe repair is assumed to be the date of the pipe break in the data set. In fact, a pipe break occurs at some point prior to a pipe repair, but there is no way to identify the exact date of the break.

Given these sources of error, the steps used to process the pipe and pipe break data are outlined in Appendix C.

The NMEFC estimated mean and median costs for repair of six-inch steel lines, based on an analysis of work orders from 1997-1998 [NMEFC, 2002]. The ABCWUA generally repairs a water main line using one of three methods: a clamp, a saddle, or a splice. In the first case, the pipe is surrounded by a clamp which is tightened to repair a break. In the case of a saddle, a saddle and a plug are utilized to repair a break. Again in this case, the saddle is tightened around the pipe. With a splice, a portion of the pipe is removed and typically replaced with PVC pipe and couplings. The length of PVC pipe used in the splice repair is generally around 5 to 6 feet [NMEFC, 2002].

Costs associated with personnel, equipment, excavation, barricades, and materials were included in repair cost estimates. Some repairs in the work order data set took much more time and were more expensive, and thus skewed the average repair cost upward. I therefore report the median internal repair cost in Table 5.5.[5] Further detail is provided in Appendix A on the procedure used by the NMEFC to determine internal repair costs.

In 1992, the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency provided cost data to assist utilities in making replacement and rehabilitation decisions for water distribution systems [Gumerman et al., 1992]. Clark et al. [2002] used regression of the Gumerman et al. [1992] data to develop cost estimates for the base installation costs of several pipe types, as well as optional, add-on costs for trenching; embedment; backfill and compaction; valves, fittings, and hydrants; horizontal boring; sheeting and shoring; pavement removal and replacement; utility interference; traffic control; household service connections; cement mortar lining; sliplining; and corrosion control.

Because no estimates of pipe-replacement costs were available from ABCWUA, I used the Clark et al. [2002] model to develop internal cost estimates for replacement of a six-inch-diameter steel line (Table 5.5).[6] Further detail on the internal replacement cost calculations is provided in Appendix B.

Finally, I used the willingness-to-pay estimates derived from the ABCWUA customer survey described in Chapter 4 to estimate external costs of repair and replace-

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[5] Internal repair cost estimates were converted to 2010 dollars using the Municipal Cost Index.

[6] I assumed: (1) steel lines will be replaced with PVC (150 pressure class) pipes of the same diameter; (2) the pipe depth is 4 feet; (3) the pipe trench is in sandy, gravel soil with 1:1 side slopes; (4) ordinary embedment; (5) backfill material is sandy, native soil; backfill compaction is 90%; (6) valve, fitting, and hydrant frequency is medium (i.e. fire hydrants every 500 feet); (7) pavement is concrete; and (8) traffic conditions are moderate. Internal replacement cost estimates were converted to 2010 dollars using the Municipal Cost Index.

ment of water mains. The estimates are subject to the following assumptions. First, I determined the number of lots served by each pipe in the data set; this was taken to be equivalent to the number of households served by the pipe. I assumed that pipes running underneath feeder roads (as distinct from residential streets) did not directly serve any households. I assumed that valves were located at a cross-joint of two intersecting pipes. Since the majority of water pipes are laid out in a grid, each pipe typically has a valve at either end. The ABCWUA's water distribution system is highly looped, and I assumed that a pipe break on a given pipe would only affect customers directly served by that pipe. The external cost of repair can be considered an upper bound because I assumed all households served by the pipe will experience an outage during a pipe break. The external cost of a pipe repair is thus the willingness-to-pay to avoid an outage multiplied by the number of households served by the pipe on which the break occurs. I assumed that pipe replacement does not result in a water outage, due to the installation of a temporary water line. External cost estimates of pipe repair and replacement are outlined in Table 5.5.

The analysis does not capture the full measure of the external costs associated with pipe repair and replacement, but instead demonstrates how external costs can be integrated into a methodology for determining the optimal time to replace water mains.

Work performed	**Internal cost**	**External cost**
Replacement	\$104/foot	\$0
Repair	\$2,640/repair	\$46.80/affected household

Table 5.5: Estimated replacement and repair costs for six-inch-diameter steel water mains

The form of the threshold break rate equation used in the analysis was as follows:

$$Brk_{th} = \frac{ln(1+R)}{ln\left(1+\frac{C_{int}+(C_{outage}*N_{cust})}{F_{int}}\right)} \tag{5.1}$$

where Brk_{th} is the threshold break rate, R is the discount rate, C_{int} is the internal utility cost of a repair, C_{outage} is the average customer willingness-to-pay to avoid an outage due to a repair, N_{cust} is the number of households affected by the outage, and F_{int} is the internal utility cost of a pipe replacement.

5.3 Results

5.3.1 Pipe characteristics

Among six-inch-diameter steel pipes in the ABCWUA distribution system, there were 114 pipes that broke more than once over the fifteen-year study period.[7] These pipes experienced a total of 409 breaks, which indicates, even at first glance, that many pipes in the cohort broke multiple times.[8] The highest number of breaks in a single pipe was 14.

The average pipe length was 690 feet. The average number of households served by a pipe was 18, with a range of 0 to 95 households. Fifty-three (47%) of pipes in the cohort were replaced during the study period. Of pipes that were not replaced (where information was available on the installation year), install dates ranged from 1935 and 1983. Over half of these pipes were installed in the 1950's.

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[7] All data in the data set is provided in Appendix D.

[8] In the data set there are instances of "clusters" of pipe-break occurrences, where several pipe breaks occur within a short span of time. Following Goulter et al. [1993], Jacobs and Karney [1994], and Mavin [1996], I assumed that these breaks were the result of a faulty repair, rather than deterioration of the pipe. Pipe breaks that occurred within 3 months of another break were excluded from the threshold break rate analysis.

5.3.2 Pipes recommended for replacement

In Table 5.6, we first examine model outputs for a base scenario with a 5% discount rate and external costs valued at $46.80 per household. Among pipes that have not been replaced, the current break rate exceeds the threshold break rate in 27 (44%) pipes. According to the threshold break rate methodology, these pipes have reached the end of their economic lifespan and should be replaced. Thirteen of these pipes (21%) have already experienced breaks subsequent to the first instance when the current break rate exceeded the threshold break rate.

Among pipes that have been replaced, 26 (49%) were replaced after the current break rate exceeded the threshold break rate.[9] Fourteen pipes (26%) experienced breaks subsequent to the first instance when the current break rate exceeded the threshold break rate. Model outputs were thus similar for both pipes that were and were not replaced during the study period.

Pipe description	**Percent of pipes recommended for replacement**
Pipes that have not been replaced	44%
Pipes that were replaced FY95-FY09	49%

5% discount rate, average external costs

Table 5.6: Percent of pipes recommended for replacement, among pipes that have and have not been replaced

The utility prioritizes pipes for replacement based on the number of breaks that have occurred in the pipe, i.e. pipes with the highest number of breaks have the highest priority for replacement. Other factors influence the actual replacement schedule for pipes, including coordinating work on street repaving and work performed by other utilities to reduce costs and disruption to customers. Generally speaking,

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[9] Note again that here we are only examining pipes that broke more than once during the study period and were replaced, not all pipes that were replaced.

prioritizing pipes for replacement that break most frequently is a sound economic approach, because it results in replacement of pipes that are most costly to the utility. However, model results indicate that approximately half of the pipes replaced by the utility from FY05-FY09 had reached their threshold break rate. These results imply that the utility's current replacement policy may not consistently result in the replacement of pipes at an economically optimal time. This conclusion is based on the assumption that the threshold break rate is valid as applied to this data set, an assumption I will discuss later in this chapter.

5.3.3 Impact of external costs

Next, we examine the impact of external costs on both the threshold break rate equation and recommended pipe-replacement schedules. Table 5.7 outlines the threshold break rate estimates for an example 1,000-foot-length of pipe serving 30 customers, using average, upper-bound, and lower-bound estimates for external costs ($46.80, $55.80 and $37.80 per customer, respectively). Again, I hold the discount rate constant at 5%. These results demonstrate that external costs influence the threshold break rate estimate for a pipe. Including external costs results in lower threshold break rates and thus earlier replacement times.

Inputs	**Threshold break rate**
Internal costs only	1.95/year
Internal & external costs (mean)	1.28/year
Internal & external costs (upper-bound)	1.20/year
Internal & external costs (lower-bound)	1.37/year

5% discount rate

Table 5.7: Threshold break rate estimates for a 1,000-foot-length of pipe serving 30 customers, with varying external cost estimates

On a 1,000-foot-long, six-inch-diameter steel pipe serving 30 customers, including the average external cost of a water outage in the cost of a repair increases the cost of that repair by 53% (from $2,640 to $4,044). External costs have a smaller impact on threshold break rate estimates for shorter pipes, assuming that shorter pipes serve fewer customers (Table 5.8).

	Threshold break rate	
Pipe description	Internal costs only	Internal & external costs
1,000-foot-long pipe, 30 customers	1.95/year	1.27/year
500-foot-long pipe, 15 customers	0.99/year	0.78/year
100-foot-long pipe, 3 customers	0.22/year	0.21/year

5% discount rate, average external costs

Table 5.8: Threshold break rate estimates for pipes of varying lengths, serving varying numbers of customers

How big of an effect do external costs have on the decision of whether or not to replace pipes? Table 5.9 shows the number and percent of pipes recommended for replacement, including and excluding external costs. For simplicity, I focus here on existing six-inch-diameter steel pipes in the ABCWUA distribution system (i.e. pipes that were not replaced from FY95-FY09). I hold the discount rate constant at 5%.

Including external costs results in 4 (6%) more pipes being recommended for replacement. External costs do impact the selection of water pipes for replacement in the threshold break rate model. If we examine the upper and lower bounds of the willingness-to-pay estimate within a 95% confidence interval, we find little change to the number of pipes recommended for replacement. This gives us confidence in model prediction regarding the impact of external costs associated with water outages.

Including other external costs associated with pipe repair and replacement, such as those related to traffic delays, pressure loss, diminished water quality, fire-flow effects, and business losses, would likely impact these findings. A pipe-replacement decision-model would be more complete if it were to take into consideration, at the very least, external costs associated with traffic delays and business losses.

As Chapter 4 demonstrates, however, it takes time and resources to do a good job at estimating external costs. It would be possible to use values for these two costs from other economic-valuation surveys or to generate them using other methodologies, but the task of applying these estimates in a model requires careful thought. Taking traffic delays as an example, data on the "average annual daily trips," or the average number of vehicle trips during a 24-hour period, is routinely maintained by state and local transportation planners for roads. The traffic delays caused by water utility work on any given road could be estimated using this data, given certain assumptions regarding the relative impacts of pipe repairs and replacement. Cromwell et al. [2002] provide a review of the literature on calculating external costs associated with water main failure, including water outages, traffic delays, flooding, and human injury and mortality.

Cost inputs	**Percent of pipes recommended for replacement**
Internal costs only	38%
Internal & external costs (mean)	44%
Internal & external costs (upper-bound)	44%
Internal & external costs (lower-bound)	43%

Table 5.9: Percent of existing pipes recommended for replacement, with varying external cost estimates

5.3.4 Sensitivity of the threshold break rate to the discount rate

We now examine the effect of varying discount rates on model results. Table 5.10 shows threshold break rate estimates for the example 1,000-foot-long pipe serving

30 customers, using discount rates of 1%, 5%, and 10%. Low discount rates result in lower threshold break rates; high discount rates result in higher threshold break rates. In these calculations, I include the average external costs associated with water outages.

Discount rate	**Threshold break rate (breaks/year)**
1%	0.26
5%	1.28
10%	2.50

Average external costs

Table 5.10: Threshold break rate estimates for a 1,000-foot-length of pipe serving 30 customers, with varying discount rates

In Table 5.11, I report the percentage of existing six-inch-diameter steel pipes that are recommended for replacement at the current time, using varying discount rates. These estimates again use average external costs associated with water outages.

Discount rate	**Percent of pipes recommended for replacement**
1%	87%
5%	44%
10%	28%

Average external costs

Table 5.11: Percent of existing pipes recommended for replacement, with varying discount rates

Tables 5.10 and 5.11 illustrate the significant effect of the discount rate on pipe-replacement decisions. Higher discount rates result in less aggressive replacement policies; lower discount rates in more aggressive replacement policies. As discount rates increase, the future costs of repair and replacement decrease, so it is cost-effective to put off replacement until a later date.

5.3.5 Trends in pipe breaks over time

The threshold break rate is a cost-based method for determining the optimal economic life of pipe; its basic tenets are consistent with pipe-replacement decision-models that rely on break-even analysis. It distinguishes itself from other methods in that it does not require the explicit prediction of future break rates. It does so by relying on the assumption that the function representing the present worth of a pipe over time is unimodal.

Loganathan et al. [2002] presented an idealized example of a pipe's break history in their paper on the threshold break rate, which I have reproduced in Table 5.12. Given the acceleration of breaks in this example pipe, we can assume the pipe's total cost function is unimodal. The pipe's threshold break rate was estimated to be 1.844. Therefore, the ideal replacement time for the pipe is 47.8 years, following the 14^{th} break.

We can imagine a pipe in which pipe breaks do not uniformly accelerate over time. In this case, the pipe's total cost function would indeed be roughly U-shaped, with a global minimum - Even if pipe breaks do not uniformly accelerate over time, the cost of replacement still decreases due to discounting, and the (discounted) cost of repair increases as more pipe breaks occur. However, unlike the previous example, the total cost function of this pipe would also have local minima. The function might look something like Figure 5.2.

If the total cost function of a pipe is unimodal, it is possible to decide whether to replace a pipe based on data on two or more discrete breaks, because there will only be one instance in which the following holds true:

$$PV_{n-1} > PV_n < PV_{n+1} \tag{5.2}$$

where PV_n is the present value of the total cost of the pipe at break n, PV_{n-1} is the

Break number	**Break time**	**Time between breaks (years)**	**Break rate (breaks/year)**
1	10.0000	10.0000	0.1000
2	18.0000	8.0000	0.1250
3	24.4000	6.4000	0.1563
4	29.5200	5.1200	0.1953
5	33.6160	3.0960	0.2441
6	36.8928	3.2768	0.3052
7	39.5142	2.6214	0.3815
8	41.6114	2.0972	0.4768
9	43.2891	1.6777	0.5960
10	44.6313	1.3422	0.7451
11	45.7050	1.0737	0.9313
12	46.5640	0.8590	1.1642
13	47.2512	0.6872	1.4552
14	47.8010	0.5498	1.8190
15	48.2408	0.4398	2.2737
16	48.5926	0.3518	2.8422
17	48.8741	0.2815	3.5527
18	49.0993	0.2252	3.4409
19	49.2794	0.1801	5.5511

Break rate = 1/time between breaks

Table 5.12: Example pipe-break history (adapted from Loganathan et al. [2002])

present value of the total cost of the pipe at break $n-1$, and PV_{n+1} is the present value of the total cost of the pipe at break $n+1$.

However, if the total cost function is not unimodal, it is possible that a local minimum could be mistaken for a global minimum when only limited break data is available. In this section, we examine the validity of the assumption that the total cost curve of a pipe is unimodal.

Table 5.13 reports the mean, median, and standard deviation of the time between breaks of varying break intervals in the ABCWUA data set (e.g. 1^{st} to 2^{nd} break,

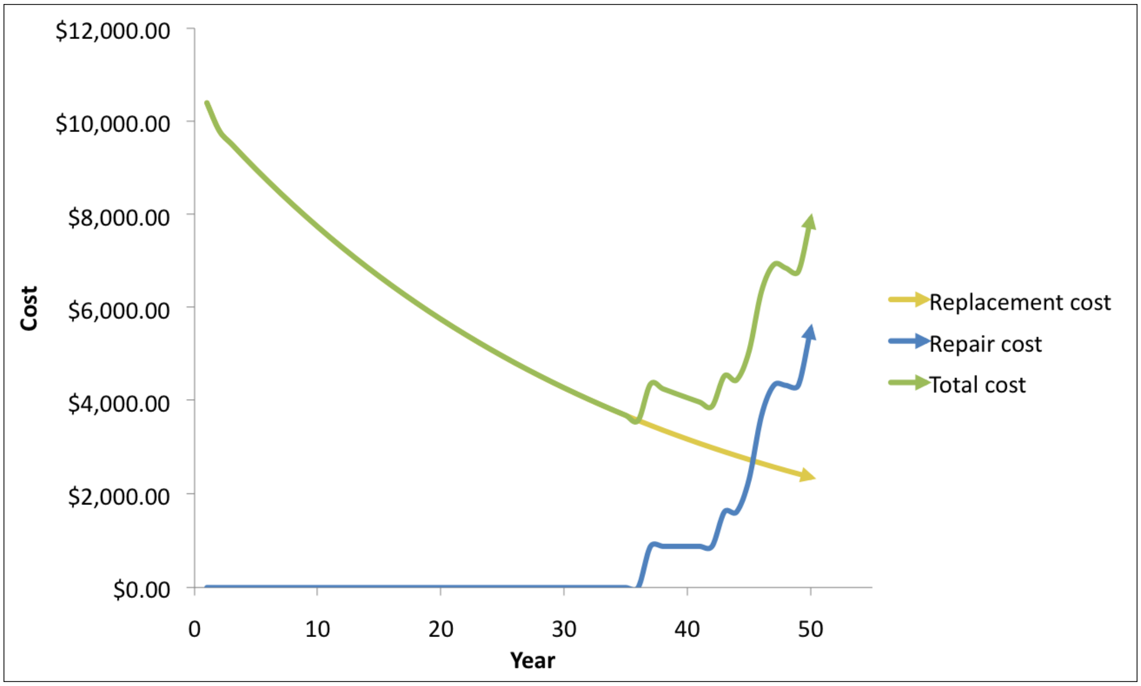

Figure 5.2: Example cost curves for a water pipe (2)

2^{nd} to 3^{rd} break).

As noted previously, all 114 pipes experienced at least two breaks. Of these, 65 broke at least 3 times, 38 broke at least 4 times, 27 broke at least 5 times, etc. The number of pipes that experience breaks diminishes as the total number of pipe breaks increases.

The mean and median time between breaks trend downward as the break intervals increase (e.g. 1^{st} to 2^{nd} break, 2^{nd} to 3^{rd} break). However, the downward trend is by no means consistent. For example, the average time between breaks 3 and 4 is 1.39 years, while the average time between breaks 4 and 5 is longer, 1.53 years. The median time between breaks 3 and 4 is 1.10 years, and between 4 and 5 is 0.82 years. Note that the median is less sensitive to outliers in the population than the mean.

The standard deviation is high among many of the break interval classes, indicat-

Break interval	**Number of pipes**	**Average time between breaks**	**Median time between breaks**	**Standard deviation**
1 to 2	114	3.26	2.71	2.74
2 to 3	65	2.11	1.40	1.86
3 to 4	38	1.39	1.10	1.01
4 to 5	27	1.53	0.82	1.53
5 to 6	16	1.49	1.10	1.32
6 to 7	11	1.12	0.95	0.67
7 to 8	7	1.20	1.08	0.86
8 to 9	5	1.08	0.97	0.61
9 to 10	4	1.18	1.06	0.67
10 to 11	3	1.03	1.28	0.50
11 to 12	2	1.71	1.71	1.33
12 to 13	2	1.13	1.13	1.09
13 to 14	1	0.62	0.62	n/a

Table 5.13: Mean, median, standard deviation of the time between breaks by break interval, all pipes

ing a high degree of variability in the data. The scatterplot in Figure 5.3 graphically illustrates this variation, as well as the downward trend in time between breaks as break intervals increase. In this figure, break interval "#2" refers to the interval between the 1^{st} to 2^{nd} break, "#3" refers to the interval between the 2^{nd} to 3^{rd} break, etc.

All this points to the possibility that pipe-break frequency does not consistently increase with time in six-inch-diameter steel pipes. To test this possibility, we can apply the Wilcoxon-Mann-Whitney rank-sum test.[10] Our null hypothesis (H_0) is that the mean time between breaks in one interval (e.g. 1^{st} break to 2^{nd} break) is the same as the mean time between breaks in a different interval (e.g. 2^{nd} break to 3^{rd} break). Our test hypothesis (H_1) is that the mean time between breaks in one interval is *not* the same as the mean time between breaks in a second interval:

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[10] The Wilcoxon-Mann-Whitney test is appropriate to test inferences about two small populations, where the assumption of a normal distribution is not reasonable for either of the two sets of data [Iman, 1994].

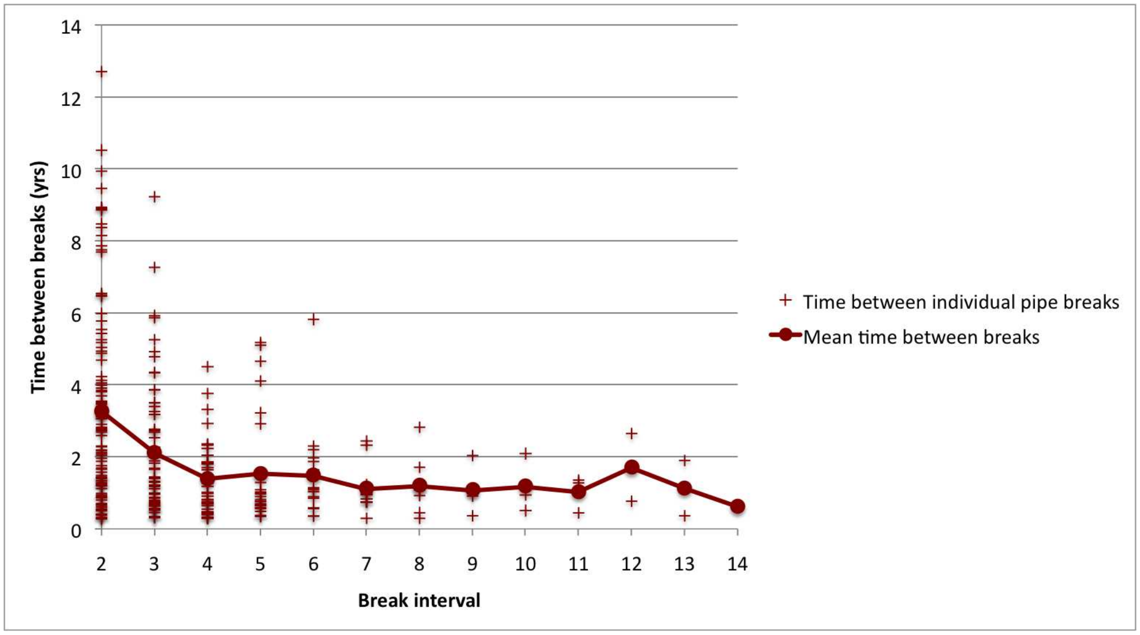

Figure 5.3: Years between breaks by break interval

$$
\begin{aligned}
&H_0 : \mu_x = \mu_y \\
&H_1 : \mu_x \neq \mu_y
\end{aligned}
\tag{5.3}
$$

Our decision rule is thus: Reject H_0 if $T_r > t_{1-\alpha,n_x+n_y-2}$ or $T_r < -t_{1-\alpha,n_x+n_y-2}$, where T_r is the test statistic and $t_{1-\alpha,n_x+n_y-2}$ is the $1-\alpha$ quantile of the Student's t distribution with $n_x + n_y - 2$ degrees of freedom.[11]

---

[11] The test statistic is: $T_r = \frac{\overline{R_x}-\overline{R_y}}{s_p\sqrt{\frac{1}{n_x}+\frac{1}{n_y}}}$, where $\overline{R_x}$ is the mean of the ranked values of population x, $\overline{R_y}$ is the mean of the ranked values of population y, n_x is the size of population x, n_y is the size of population y, and s_p is the pooled standard deviation of the ranks, computed as: $s_p = \sqrt{\frac{(n_x-1)s^2_{R_x}+(n_y-1)s^2_{R_y}}{n_x+n_y-2}}$, where $s^2_{R_x}$ is the variance of population x, $s^2_{R_y}$ is the variance of population y, and all else is as previously defined.

Letting $\alpha = .05$, we find that H_0 can be rejected at a 95% confidence level when comparing the mean time between the 1^{st} and 2^{nd} break to the 2^{nd} and 3^{rd} break (t=2.91), and the 2^{nd} and 3^{rd} break to the 3^{rd} and 4^{th} break (t=1.72), but not at any of the higher break intervals. This may, in part, be a function of the smaller sample sizes available at higher break intervals.

The test statistic for comparison of the means of each break interval is reported in Table 5.14. A test statistic greater than 1.65 or less than -1.65 indicates there is a statistically significant difference between the means of the two intervals at the 95% confidence level. Hence, it is safe to conclude that the mean time between the 1^{st} and 2^{nd} break is significantly different than the 2^{nd} and 3^{rd} break, and the mean time between the 2^{nd} and 3^{rd} break is different than the 3^{rd} and 4^{th} break. As indicated by the variation in the data set discussed previously, this may or may not be the case with individual pipes in the data set. In fact, pipe breaks accelerate over time in only 35% of pipes with greater than two breaks.[12]

Break interval 1	**Break interval 2**	**Test statistic**
1 to 2	2 to 3	2.91
2 to 3	3 to 4	1.72
3 to 4	4 to 5	0.34
4 to 5	5 to 6	-0.74
5 to 6	6 to 7	0.68
6 to 7	7 to 8	-0.35
7 to 8	8 to 9	0.08
8 to 9	9 to 10	-0.47
9 to 10	10 to 11	0.00
10 to 11	11 to 12	-0.52
11 to 12	12 to 13	0.71
12 to 13	13 to 14	n/a

Table 5.14: Wilcoxon-Mann-Whitney rank sum test results by break interval

---

[12] Only when pipes have broken more than two times can break intervals be compared.

5.3.6 Uncertainty in the pipe-break data set

It difficult to definitively determine whether pipe breaks accelerate over time because of the uncertainty regarding pipe and pipe-break associations, and the exact date of pipe breaks.

The rules used to define a pipe segment in this study were selected based on assumptions regarding the utility's replacement policies (see Appendix C for more detail on how pipes were defined during data processing). A typical pipe had cross-joints with intersecting pipes at each end (see Figure 5.4 from Mailhot et al. [2000] for an illustration). There were many instances in the GIS where pipe breaks were clustered around pipe cross-joints. Pipe and pipe-break associations in these cases were highly uncertain, given that there were typically four pipes near to the break location.

It could be the case that there are more breaks at pipe intersections, due to the presence of valves or higher external loads from the increase in traffic at intersecting streets. It could also be the case that field crews simply used the nearest intersection of streets to identify the pipe break location, even in cases when the pipe break occurred in the middle of the pipe.

The fact that pipe-break locations are not precise means that pipe breaks may not be associated with the pipe on which they occurred. In this analysis, fifty percent of pipe and pipe-break associations were determined to be uncertain. Table 5.15 reports the mean, median, and standard deviation of the time between breaks, with these pipes excluded. Ignoring the last three entries in the table where only one data point was available, data related to this subset of pipes performs somewhat better than data for the pipe cohort as a whole. Both the mean and median time between breaks display a more consistent downward trend, as pipe-break frequency increases. However, the standard deviation is still very high. In other words, variability remains

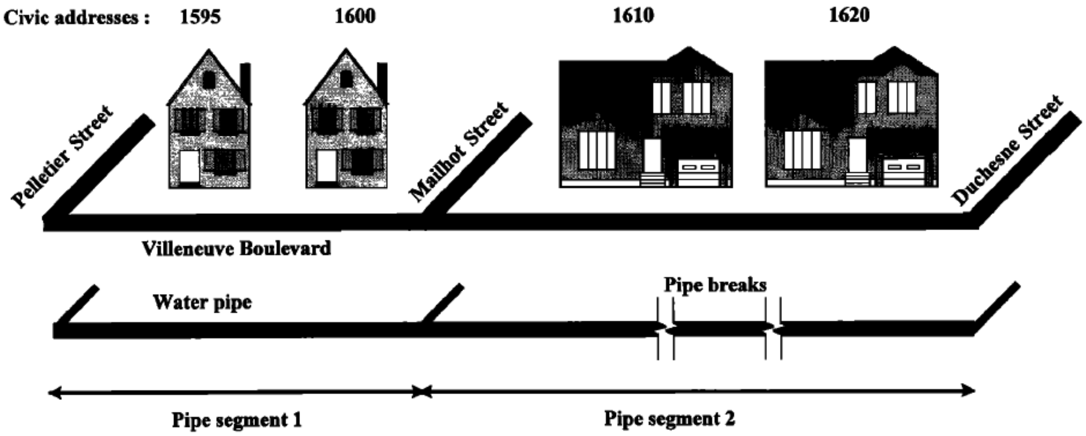

Figure 5.4: Example pipe segments (from Mailhot et al. [2000])

high even among individual pipes with high-quality data.

Another source of uncertainty in the data was the pipe break date. In the model, the date of a pipe break was taken to be the same as the date of a pipe repair. In fact, the pipe break could have occurred at any point prior to the repair; the repair date simply indicates when the break was identified. Identification of pipe breaks occurred through various means over the study period (e.g. the leak may have surfaced, or the

Break interval	Number of pipes	Average time between breaks	Median time between breaks	Standard deviation
1 to 2	59	3.15	2.69	2.75
2 to 3	35	2.08	1.42	1.79
3 to 4	21	1.64	1.26	1.20
4 to 5	14	1.80	0.93	1.68
5 to 6	8	1.55	0.99	1.80
6 to 7	5	1.00	0.97	0.15
7 to 8	3	0.77	0.92	0.43
8 to 9	1	0.97	0.97	n/a
9 to 10	1	1.19	1.19	n/a
10 to 11	1	0.44	0.44	n/a

Table 5.15: Mean, median, standard deviation of the time between breaks by break interval, subset of pipes with high-quality break data

break may have been identified through the leak detection pilot program). This is a source of uncertainty that is inherent to all water utility data on pipe breaks. Since the threshold break rate relies on a precise calculation of the time between breaks, this source of inaccuracy is significant and would be relevant to any utility applying this methodology.

5.4 Conclusions

The threshold break rate offers two key advantages. First, it can be applied even when the full history of breaks on a pipe is not available. This is a substantial benefit, given that most utility break data is left-truncated, i.e. data on pipe breaks is available only for recent years, not for the entire lifespan of pipes. Second, unlike other cost-based methods for determining the optimal time to replace a pipe, the threshold break rate method does not require projection of future break rates.

The method is appealing in its simplicity; it is easy for utilities to understand and apply. However, this simplicity is derived from the central assumption that the function representing the present worth of a pipe over time is unimodal. The threshold break rate provides a sound estimate of whether a pipe should be replaced, under the assumption that the first instance when the current break rate exceeds the threshold break rate is indeed the point when the total cost of the pipe begins to increase. The literature affirms that this assumption is a fair one, but evidence in this data set appears to contradict it. However, this finding is not conclusive because of uncertainty regarding both pipe break locations and dates. The uncertainty surrounding the location of pipe breaks is specific to the ABCWUA data set, but the uncertainty surrounding pipe-break dates would be characteristic of pipe-break data maintained by any utility.

The general approach of all cost-based methods for determining the optimal time to replace a pipe is to compare the cost of a new pipe to the future costs of continuing to repair the existing pipe, as a function of the year. The results of this and previous studies have shown that this type of economic analysis is very sensitive to model parameters that are often difficult to accurately determine.

Pipe-replacement decision-models should be used to prioritize pipes for replacement at the current time. They identify pipes that should be replaced in any given year, and, by extension, estimate how many pipes it is economical to replace in that year. It must be emphasized that model outputs should by no means be followed to the letter. There are many factors that should be taken into consideration when deciding when to replace an individual pipe. It is more cost-effective and less disruptive to customers and the community if projects are grouped geographically and scheduled to take place at the same time as other utility work.

I have focused on external costs in this application of the threshold break rate. Although I have identified potential issues with the application of the threshold break model to a real data set, we can still draw some conclusions about the influence of external costs on pipe-replacement schedules. Results of this project indicate that external costs do impact the rate of breaks per year at which it is economically optimal to replace a pipe. Loganathan et al. [2002] recommend replacement of a six-inch-diameter, 1,000-foot-long pipe at a break rate of 2 to 3 breaks per year, based on a threshold break rate estimates from their utility data. This estimate excludes external costs. The threshold break rate estimate from this study for the same example pipe is very similar. It is approximately 2 breaks per year considering only the utility's internal costs, and 1.25 breaks per year including external costs associated with residential customer outages. Accounting for these external costs produced a small but measurable impact on pipe-replacement schedules. Six percent more existing six-inch-diameter steel pipes were recommended for replacement at the current time, assuming a 5% discount rate.

Chapter 6

Conclusion

6.1 Summary of findings

This Professional Project had three research goals:

- Research goal 1: To estimate the external costs of pipe repair and replacement
- Research goal 2: To integrate external costs into a pipe-replacement model and demonstrate the effect of external costs on pipe-replacement schedules
- Research goal 3: To test the applicability of the pipe-replacement model for water utility use

I summarize here my findings related to each research objective.

6.1.1 Research goal 1

In Chapter 4, I described the design and implementation of an economic-valuation survey conducted among ABCWUA customers in 2009. The survey was administered in accordance with best practices outlined in the Tailored Design Method [Dillman, 2007]. The survey response rate was 45.8%. Comparison of the demographic data from the survey and the 2008 U.S. Census American Community Survey indicated that survey respondents were broadly representative of Albuquerque homeowners.

Survey results indicated that the external cost of a water outage to ABCWUA residential customers is \$46.80, with a 95% confidence interval of \$37.80 to \$55.80. The confidence interval is small and does not include zero, which provides confidence in the accuracy of the estimate.

These results indicate that stated-preference surveys provide a viable means to estimate utility external costs. However, it takes times and resources to conduct a valid economic-valuation survey.

6.1.2 Research goal 2

In Chapter 5, I demonstrated how the results of an economic-valuation survey can be integrated into the threshold break rate model, a pipe-replacement model that is consistent with asset management. I examined the impact of external costs on model outputs for the number of pipes recommended for replacement.

I found that external costs associated with residential customer water outages produced a modest but measurable impact on pipe-replacement schedules. Assuming a 5% discount rate, 6% more existing six-inch-diameter steel pipes were recommended for replacement when external costs were taken into consideration.

Results indicate that external costs make a difference in pipe-replacement models, and should be taken into consideration in water utility asset management.

6.1.3 Research goal 3

In Chapter 5, I also tested the applicability of the threshold break rate model for water utility use, by applying it to real data on six-inch-diameter steel pipes in the ABCWUA distribution system. I found that the threshold break rate is easy for water utilities to understand and apply. It is appealing because it does not require estimation of future pipe-break rates, and it can be used even when a full history of pipe breaks is not available.

However, pipe breaks in this data set appeared not to satisfy an underlying assumption of the model that the total cost function of a pipe is unimodal. Because of uncertainty in the data set associated with pipe break locations and times, this conclusion could not be made with confidence.

The ABCWUA can improve the accuracy of data on pipe-break locations in the future, but it cannot improve the accuracy of data on pipe-break dates. The exact date of a pipe break cannot be determined, and water utilities must always use the date when the break was discovered and repaired as a proxy. Since the threshold break rate model relies on a precise estimation of current pipe-break rates, this source of inaccuracy would be an issue for any utility seeking to employ the model.

6.2 Limitations of this analysis

The model employed in this analysis is limited in scope. It is a test case which is intended to demonstrate both how to integrate external costs into utility decision-making and why there is reason to do so.

I examined only a small number of water pipes (114). I focused only on six-inch-diameter steel water mains, under the assumption it was valid to group pipes by material and diameter. This assumption was based on the results of a 2010 NMEFC pipe-break analysis, which showed that different pipe types and sizes exhibit different break rates in the ABCWUA distribution system [NMEFC, 2010]. Finally, I included only external costs associated with water outages experienced by residential customers in the model.

Constructing a pipe-replacement decision-model is a task for utility personnel with expertise in the field and intimate knowledge of their water distribution system. This model relied on many assumptions, which I have tried to clearly delineate in this paper. A model is by definition a simplified version of reality; it is a problem-solving tool. As George P. Box famously stated, "All models are wrong; some models are useful."

6.3 Contributions of this research project and future work

This Professional Project contributes to research on how non-market valuation can be applied to benefit water utilities. There has been little work on this subject to date. The Water Research Foundation funded the larger research project of which this Professional Project is a part because of this deficit.

As a result, little primary data exists on external costs or willingness-to-pay for the water utility sector. Future studies will contribute to a better understanding of the value that customers place on water utility services.

Future studies will also demonstrate other ways that willingness-to-pay data can be used by water utilities. As I discussed in Chapter 2, willingness-to-pay data can assist water utilities in defining appropriate service levels. It can quantify the external benefits and costs of proposed utility projects, so that utilities can better assess project impacts. It can improve prioritization of investments and rate setting. These improvements can lead to more efficient service provision, and they support a utility's ability to provide sustainable levels of service to its customers over time.

Elicitation of customer preferences also provides a means for customers to play a greater role in how a water utility is managed. It educates customers about tradeoffs the utility is facing. It allows for greater utility accountability and transparency. All of these contributions are relevant to asset management.

This Professional Project also supports research aimed at improving water utility pipe-replacement decision-models. Pipe-replacement decision-models are a rich area of applied research. They hold much of interest to water resource professionals, given their interdisciplinary nature and the fact that they address a problem that is relevant to most U.S. water utilities.

As noted in Chapter 3, few pipe-replacement decision-models have been proposed, and fewer still are used by water utilities. Seattle Public Utilities in Seattle, Washington, is one of the few water utilities in the U.S. that has both a pipe-replacement decision-model and a long-range pipe-replacement-forecasting model. Both models incorporate triple-bottom-line costs (i.e. financial, social, and environmental), including costs associated with water outages, traffic interruption, water loss from leaking pipes, property-damage claims, fire-flow effects, and diminished water quality during construction. It is no coincidence that Seattle Public Utilities is also at the forefront of asset management in the U.S. Pipe-replacement decision-models are consistent with asset management, given that asset management requires utilities to make an economic case for expenditures on assets. Including external costs in pipe-replacement decision-models provides further justification for investment in pipe replacement.

Finally, this research project is also intended to explore both the possibilities and limitations associated pipe-break and economic-valuation-survey data that the ABCWUA already has in-hand. This study shows that it would benefit the utility to collect information in pipe-break work orders on the pipe type, pipe size, and precise pipe-break location. The basic building block of a pipe-replacement decision-model is an accurate database of failure data for all mains. There are many different ways that accurate pipe-break data can be applied to make better decisions about when to replace pipes. In asset management, improvements to utility management build on one another over time, an iterative process to which I hope this analysis has contributed.

Appendix A

Repair cost estimates

The NMEFC used information from 1997-1999 work order to generate mean and median repair costs for six-inch-diameter steel and cast-iron pipe [NMEFC, 2002]. The procedure used to generate these estimates was as follows:

1. From data entered, generate MS Access queries to create a listing that included the following:
    - Basic main repair = YES
    - Other work in addition to the basic main repair conducted = NO
    - Pipe Size = 6 inch
    - Pipe type = Steel or Cast Iron
    - CCN included enough information/documentation to determine man hours and cost = YES
2. Sort the resulting queries above in a chronological manner (i.e. by CCN).
3. Randomly select between 10-20 CCNs from FYs 97-99 to analyze cost and man-hour allocation. In some cases, all CCNs were analyzed for a FY while

in other cases; every other CCN was analyzed. The analysis performed was representative of main repairs occurring throughout the FY.

4. Analyze CCNs using MS Excel to determine the following:
    - Number of days between the open and close dates on the work orders
    - Number of activities (work orders) listed for the specific CCN/main repair
    - Number of man-hours allocated to the specific CCN/main repair
        - Assumptions for the man-hour allocations:
            (a) During a Check Leak activity of a complete CCN/main repair, if the time was undocumented, half an hour of actual work time (i.e. time on site) was assumed.
            (b) One-half hour of travel time to and from the job site was added to the actual work time of each individual crewmember dedicated to that activity of the CCN/main repair.
            (c) Supervisor time was not included in man-hour allocation.
    - Dollar costs for man-hours (crew and supervisor) allocated to each activity of a CCN/main repair
        - Assumptions for cost calculations:
            (a) Supervisor time was included in costs for man-hours by assuming an allocation of one-third of Supervisor time of the actual real time spent on a specific activity.
    - Dollar costs for the equipment allocated to the CCN/main repair
        - Assumptions for equipment costs:
            (a) Equipment was treated as a single item based on real time.
            (b) Equipment costs conveyed by the City in terms of dollars per day were converted to dollars per hour (based on an eight-hour day), to analyze costs.

- Dollar costs for replacement of asphalt, sidewalk, and curbstone excavated during the main repair (includes cost for obtaining an excavation permit)
- Dollar costs for barricades
  - Assumptions for barricades:
    (a) Cost of barricades was assumed to correlate with the start and end dates of the CCN/main repair minus one day.
- Dollar costs for materials
  - Assumptions for materials
    (a) Refill material not documented in the CCN/main repair was assumed to equal 50% of the excavation volume and cost was calculated using that assumption.

5. Generate values for the following:
   - Averages and the respective percentages based on all of the fields analyzed
   - Minimum, median, and maximum values based on all of the fields analyzed

Appendix B

Replacement cost estimates

Clark et al. [2002] used regression of USEPA [Gumerman et al., 1992] data on pipe replacement costs to develop cost estimates for the base installation costs of several pipe types, as well as optional, add-on costs for trenching, embedment, backfill and compaction, valves/fittings/hydrants, horizontal boring, sheeting and shoring, pavement removal and replacement, utility interference, traffic control, household service connections, cement mortar lining, sliplining, and corrosion control.

The general form of the cost models developed for the study is as follows:

$$y = a + b(x^c) + d(u^e) + f(xu) \tag{B.1}$$

where y is the cost of particular component (\$/ft), x is a design parameter (e.g. pipe diameter), u is an indicator variable, and a, b, c, d, e and f are coefficients estimated through regression techniques.

Full cost estimates for replacement of six-inch-diameter steel pipe with six-inch-diameter PVC pipe are presented in Table B.1.[1][2]

The City Engineer at the City of Albuquerque Planning Department periodically publishes estimated unit prices for contract items for use in estimating the construction cost of public infrastructure. The 2009 guide did not include prices that were specific enough for use in this study. In 2010 dollars,[3] it estimated the cost of removing and relaying a six-inch to fourteen-inch water line, including fittings, but excluding trenching and street removal and replacement to be \$114.85 per linear foot of pipe [Dourte, 2009]. Trenching, backfilling, and compaction for four-inch to fifteen inch pipe, 8 feet or less in depth, was estimated at \$19.94 per linear foot of pipe. Removal and replacement of residential pavement, including 2" extra asphalt thickness, with machine laydown, and with imported subbase or lime-stabilized material, any thickness, was estimated to cost \$23.40 per square yard. These estimates yield somewhat higher replacement costs than those provided by Clark et al. [2002], but they are reasonably close. More accurate estimates of pipe replacement and repair costs by the ABCWUA will yield more accurate estimates of the threshold break rates for pipes.

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[1] We assume: (1) steel lines will be replaced with PVC (150 pressure class) pipes of the same diameter; (2) the pipe depth is 4 feet; (3) the pipe trench is in sandy, gravel soil with 1:1 side slopes; (4) ordinary embedment; (5) backfill material is sandy, native soil; backfill compaction is 90%; (6) valve, fitting, and hydrant frequency is medium (i.e. fire hydrants every 500 feet); (7) pavement is concrete; and (8) traffic conditions are moderate.

[2] Replacement cost estimates were converted to 2010 dollars using the Municipal Cost Index.

[3] Albuquerque City Engineer cost estimates were converted to 2010 dollars using the Municipal Cost Index.

Expense	**y**	**x**	**u**	**a**	**b**	**c**	**d**	**e**	**f**
Base installed pipe	$7.18	6.0	150.0	-1.0	0.0008	3.59	0.011	1.0	0.0067
Trenching and excavation	$5.34	6.0	4.0	-24.0	0.32	0.67	16.7	0.38	0.0
Embedment	$1.76	6.0	0.0	1.60	0.0062	1.83	-0.2	1.0	0.07
Backfill	$3.16	6.0	4.0	-0.094	-0.062	0.73	0.18	2.03	0.02
Fittings, valves, hydrants	$10.3	6.0	4.0	9.8	0.02	1.8	0.0	0.0	0.0
Pavement removal & replacement	$20.58	6.0	2.0	-3.0	0.23	0.93	10.7	1.0	0.08
Traffic control	$0.10	6.0	n/a	0.088	0.0022	0.71	0.0	0.0	0.0
Total raw cost	$48.42								
Contractor overhead and profit (30%)	$14.53								
Engineering (15%)	$7.26								
Legal, fiscal, and administrative costs (5%)	$2.42								
Total capital cost (1997 dollars)	$72.63								
Total capital cost (2010 dollars)	$104.19								

Table B.1: Cost estimates for replacing six-inch-diameter steel pipe with six-inch-diameter PVC pipe

Appendix C

Pipe-break data-processing steps

1. Query all six-inch steel pipe breaks in FY95-FY09 work orders in ArcGIS. Work crews identified and documented the pipe type and material during each pipe repair from FY95-FY03. FY95-FY03 work orders are assumed to be more accurate than the pipe GIS, because pipe characteristics were field-checked. This assumption is consistent with the NMEFC pipe-break analysis [NMEFC, 2010]. Note cases where FY04-FY09 breaks are associated with pipes that have been corroborated FY95-FY03 data.

2. For each pipe break, identify and document the pipe (i.e. a representative pipe segment) to which it corresponds. Note whether the pipe and pipe-break association is uncertain. If the six-inch steel pipe has been abandoned in place, associate the break with the replacement pipe.

3. Join pipe segments (where only two pipe segments meet) of the same size, material, and install/rehab year to determine the pipe length. A pipe is therefore defined as a length of pipe that is consistent with respect to size, material, and install/rehab year. At each end a pipe a) joins to another pipe at a cross- or t-joint, b) joins to a pipe of a different size, material, or install/rehab year, or

c) terminates. This definition of a pipe is consistent with ABCWUA's current approach to prioritizing pipes for replacement.

4. Document the number of properties that are adjacent to the pipe.

Appendix D

Data set

Pipe ID	TBR: Internal costs, 1% discount rate	TBR: Internal costs, 5% discount rate	TBR: Internal costs, 10% discount rate	TBR: Avg external costs, 1% discount rate	TBR: Avg external costs, 5% discount rate	TBR: Avg external costs, 10% discount rate	TBR: High external costs, 1% discount rate	TBR: High external costs, 5% discount rate	TBR: High external costs, 10% discount rate	TBR: Low external costs, 1% discount rate	TBR: Low external costs, 5% discount rate	TBR: Low external costs, 10% discount rate	Uncertainty?	Number of customers	Pipe length (feet)	Material	Install year	Repair date	Break number	Time between breaks (years)	Break rate (years)
100	0.1849	0.9064	1.7706	0.1729	0.8480	1.6565	0.1708	0.8376	1.6362	0.1751	0.8586	1.6772	1	4	459	PVC	1994	11/6/95	1		
																		3/20/02	2	6.5337	0.1531
																		6/24/03	3	1.2949	0.7722
101	0.4110	2.0155	3.9373	0.2641	1.2947	2.5293	0.2472	1.2121	2.3677	0.2834	1.3898	2.7150	1	32	1036	PVC	2009	7/15/94	1		
																		5/13/00	2	5.9803	0.1672
																		11/16/00	3	0.5253	1.9037
																		7/30/01	4	0.7191	1.3906
																		4/4/02	5	0.6966	1.4355
																		7/1/04	6	2.3006	0.4347
																		3/24/05	7	0.7472	1.3383
102	0.1139	0.5584	1.0908	0.1139	0.5584	1.0908	0.1139	0.5584	1.0908	0.1139	0.5584	1.0908	1	0	278	PVC	2007	5/30/95	1		
																		7/16/98	2	3.2107	0.3115
																		8/21/01	3	3.1798	0.3145
																		4/7/02	4	0.6433	1.5546
																		8/31/03	5	1.4354	0.6967
103	0.3228	1.5830	3.0924	0.2125	1.0418	2.0351	0.1995	0.9781	1.9107	0.2273	1.1146	2.1774	1	30	811	STL	1950	11/20/95	1		
																		7/10/96	2	0.6545	1.5279
																		4/10/97	3	0.7697	1.2993
																		7/22/97	4	0.2893	3.4563
																		7/13/98	5	1.0000	1.0000
																		5/12/99	6	0.8511	1.1749
																		1/31/00	7	0.7416	1.3485
																		7/8/00	8	0.4466	2.2390
																		11/14/00	9	0.3624	2.7597
																		5/14/01	10	0.5084	1.9669
																		8/12/02	11	1.2781	0.7824
																		5/12/03	12	0.7669	1.3040
																		3/18/05	13	1.8989	0.5266

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104	0.1433	0.7026	1.3725	0.1190	0.5835	1.1399	0.1153	0.5653	1.1042	0.1230	0.6031	1.1781		12	353	STL	1964	9/30/95	1		
																		7/29/97	2	1.8764	0.5329
																		4/11/98	3	0.7191	1.3906
																		1/31/00	4	1.8539	0.5394
																		6/12/00	5	0.3736	2.6767
																		4/9/02	6	1.8708	0.5345
105	0.1374	0.6737	1.3161	0.1142	0.5597	1.0934	0.1106	0.5422	1.0593	0.1180	0.5784	1.1300	1	12	338	PVC	0	2/2/04	1		
																		5/19/09	2	5.4298	0.1842
106	0.1382	0.6776	1.3237	0.1359	0.6662	1.3014	0.1354	0.6641	1.2972	0.1363	0.6684	1.3056		1	340	STL	1950	1/4/07	1		
																		5/24/07	2	0.3933	2.5429
																		11/25/07	3	0.5197	1.9243
107	0.2244	1.1006	2.1499	0.1833	0.8989	1.7560	0.1771	0.8685	1.6966	0.1900	0.9316	1.8199	1	13	560	STL	1949	5/7/95	1		
																		8/3/96	2	1.2753	0.7841
																		5/12/02	3	5.9213	0.1689
108	0.2166	1.0621	2.0748	0.2166	1.0621	2.0748	0.2166	1.0621	2.0748	0.2166	1.0621	2.0748	1	0	540	STL	1956	9/15/94	1		
																		5/24/95	2	0.7051	1.4183
																		7/29/96	3	1.2135	0.8241
																		5/22/98	4	1.8596	0.5378
																		9/28/98	5	0.3624	2.7597
																		9/30/99	6	1.0309	0.9700
																		6/20/00	7	0.7416	1.3485
																		7/8/01	8	1.0758	0.9295
																		5/28/02	9	0.9101	1.0988
																		6/11/04	10	2.0927	0.4779
																		10/6/05	11	1.3539	0.7386
																		5/6/08	12	2.6489	0.3775
																		9/29/08	13	0.4101	2.7597
																		5/6/09	14	0.6152	1.6256
109	0.5259	2.5787	5.0374	0.3066	1.5035	2.9371	0.2840	1.3927	2.7207	0.3332	1.6338	3.1916		41	1329	PVC	2006	5/26/95	1		
																		10/18/96	2	1.4354	0.6967
																		4/7/99	3	2.5309	0.3951
																		7/25/01	4	2.3596	0.4238
																		7/5/02	5	0.9691	1.0319

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110	0.1464	0.7180	1.4025	0.1308	0.6413	1.2528	0.1282	0.6285	1.2278	0.1335	0.6547	1.2790		7	361	STL	0	7/23/02	1		
																		9/6/06	2	4.2303	0.2364
111	0.1351	0.6622	1.2936	0.1351	0.6622	1.2936	0.1351	0.6622	1.2936	0.1351	0.6622	1.2936	1	0	332	STL	0	7/6/94	1		
																		9/2/02	2	8.3708	0.1195
112	0.3495	1.7137	3.3478	0.2850	1.3973	2.7296	0.2752	1.3496	2.6363	0.2954	1.4486	2.8298		13	879	STL	1935	3/24/97	1		
																		2/12/01	2	3.9916	0.2505
																		10/5/02	3	1.6854	0.5933
																		5/11/04	4	1.6404	0.6096
																		5/1/09	5	5.1011	0.1960
113	0.2397	1.1755	2.2964	0.1985	0.9735	1.9018	0.1922	0.9426	1.8413	0.2053	1.0067	1.9665		12	599	STL	1946	11/19/95	1		
																		10/17/00	2	5.0393	0.1984
																		2/13/01	3	0.3343	2.9916
																		10/10/02	4	1.6966	0.5894
114	0.1217	0.5968	1.1659	0.1177	0.5772	1.1276	0.1170	0.5736	1.1205	0.1185	0.5809	1.1347	1	2	298	STL	1956	7/31/94	1		
																		10/24/95	2	1.2640	0.7911
																		4/29/96	3	0.5281	1.8936
																		7/3/98	4	2.2331	0.4478
																		12/23/98	5	0.4860	2.0578
																		7/30/00	6	1.6433	0.6085
																		12/16/02	7	2.4410	0.4097
																		8/16/04	8	1.7107	0.5846
																		8/11/06	9	2.0365	0.4910
																		7/12/07	10	0.9410	1.0627
115	0.0801	0.3929	0.7676	0.0801	0.3929	0.7676	0.0801	0.3929	0.7676	0.0801	0.3929	0.7676		0	192	PVC	2009	6/14/04	1		
																		7/2/07	2	3.1264	0.3199
																		11/13/08	3	1.4045	0.7120
116	0.4557	2.2346	4.3653	0.2660	1.3043	2.5478	0.2464	1.2084	2.3606	0.2890	1.4170	2.7681		41	1150	PVC	2006	9/5/98	1		
																		8/29/01	2	3.0590	0.3269
																		6/10/03	3	1.8258	0.5477
117	0.1386	0.6795	1.3274	0.1151	0.5645	1.1027	0.1115	0.5468	1.0682	0.1190	0.5834	1.1396	1	12	341	PVC	2009	9/28/94	1		
																		6/13/03	2	8.9326	0.1119
																		7/31/05	3	2.1882	0.4570
																		5/3/07	4	1.8006	0.5554

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118	0.1186	0.5814	1.1358	0.1147	0.5623	1.0985	0.1140	0.5588	1.0916	0.1154	0.5659	1.1055		2	290	PVC	2006	10/7/94	1		
																		6/17/03	2	8.9185	0.1121
119	0.5188	2.5441	4.9698	0.3610	1.7703	3.4582	0.3412	1.6729	3.2680	0.3834	1.8799	3.6723	1	25	1311	STL	1956	6/26/03	1		
																		6/24/05	2	2.0478	0.4883
																		2/2/07	3	1.6517	0.6054
120	0.1307	0.6411	1.2523	0.1186	0.5817	1.1364	0.1166	0.5716	1.1166	0.1208	0.5922	1.1569		6	321	STL	1961	7/4/94	1		
																		7/22/97	2	3.1292	0.3196
																		8/23/98	3	1.1152	0.8967
121	0.2876	1.4100	2.7545	0.2136	1.0473	2.0458	0.2036	0.9982	1.9500	0.2246	1.1015	2.1518		20	721	PVC	2003	7/6/94	1		
																		7/30/96	2	2.1208	0.4715
																		6/2/98	3	1.8876	0.5298
																		2/4/99	4	0.6938	1.4413
122	0.1476	0.7237	1.4138	0.1299	0.6368	1.2440	0.1270	0.6225	1.2161	0.1329	0.6518	1.2733	1	8	364	PVC	2003	7/24/94	1		
																		3/4/96	2	1.6545	0.6044
123	0.1107	0.5430	1.0607	0.1006	0.4931	0.9632	0.0988	0.4845	0.9465	0.1024	0.5019	0.9804		6	270	PVC	1998	7/25/94	1		
																		6/26/95	2	0.9438	1.0595
																		3/13/96	3	0.7331	1.3640
																		8/15/96	4	0.4354	2.2968
																		4/1/97	5	0.6433	1.5546
124	0.5173	2.5364	4.9548	0.3111	1.5252	2.9795	0.2891	1.4174	2.7689	0.3367	1.6512	3.2255	1	38	1307	STL	1950	8/1/94	1		
																		7/14/98	2	4.0534	0.2467
																		9/19/99	3	1.2135	0.8241
																		7/1/01	4	1.8287	0.5469
																		7/18/06	5	5.1770	0.1932
																		9/8/08	6	2.1994	0.4547
																		12/21/08	7	0.2921	3.4231

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125	0.4365	2.1405	4.1813	0.2835	1.3899	2.7152	0.2657	1.3027	2.5448	0.3038	1.4899	2.9105		31	1101	PVC	2000	8/5/94	1		
																		2/5/95	2	0.5169	1.9348
																		7/17/95	3	0.4551	2.1975
																		12/13/95	4	0.4185	2.3893
																		9/8/96	5	0.7584	1.3185
																		3/27/97	6	0.5618	1.7800
																		3/23/98	7	1.0140	0.9861
																		7/5/98	8	0.2921	3.4231
126	0.4604	2.2577	4.4104	0.2800	1.3730	2.6821	0.2605	1.2775	2.4956	0.3027	1.4842	2.8994		37	1162	STL	1952	8/7/94	1		
																		7/4/96	2	1.9579	0.5108
																		9/9/97	3	1.2135	0.8241
																		7/17/00	4	2.9270	0.3417
																		9/7/03	5	3.2219	0.3104
																		5/10/09	6	5.8202	0.1718
127	0.4036	1.9790	3.8659	0.2745	1.3462	2.6298	0.2587	1.2687	2.4784	0.2924	1.4340	2.8012		27	1017	PVC	2001	8/8/94	1		
																		2/6/95	2	0.5112	1.9560
																		1/26/96	3	0.9944	1.0056
																		7/9/96	4	0.4635	2.1576
																		7/31/97	5	1.0871	0.9199
																		12/5/97	6	0.3567	2.8031
128	0.3409	1.6715	3.2652	0.2466	1.2093	2.3622	0.2342	1.1486	2.2437	0.2604	1.2769	2.4943		22	857	PVC	1996	8/11/94	1		
																		4/8/95	2	0.6742	1.4833
																		2/6/96	3	0.8539	1.1711
129	0.1229	0.6026	1.1772	0.1169	0.5734	1.1201	0.1159	0.5681	1.1097	0.1180	0.5788	1.1306		3	301	PVC	2009	6/26/00	1		
																		3/13/04	2	3.8090	0.2625
130	0.1880	0.9218	1.8007	0.1704	0.8355	1.6320	0.1674	0.8207	1.6033	0.1735	0.8507	1.6619	1	6	467	STL	1951	2/16/95	1		
																		7/4/96	2	1.4157	0.7063
																		8/3/03	3	7.2640	0.1377
																		11/30/04	4	1.3624	0.7340
																		10/6/07	5	2.9213	0.3423
131	0.1092	0.5353	1.0457	0.1023	0.5014	0.9795	0.1010	0.4954	0.9678	0.1035	0.5076	0.9915	1	4	266	STL	1952	9/1/94	1		
																		9/18/99	2	5.1770	0.1932

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132	0.4326	2.1212	4.1438	0.3050	1.4953	2.9211	0.2887	1.4155	2.7651	0.3232	1.5849	3.0961		24	1091	STL	1983	10/15/94	1		
																		12/27/97	2	3.2837	0.3045
																		10/2/01	3	3.8624	0.2589
																		2/22/06	4	4.5056	0.2219
																		10/10/06	5	0.6461	1.5478
133	0.2797	1.3716	2.6794	0.1691	0.8292	1.6198	0.1573	0.7713	1.5068	0.1829	0.8968	1.7518	1	38	701	STL	1987	10/22/94	1		
																		2/9/01	2	6.4663	0.1546
																		8/25/01	3	0.5534	1.8071
																		2/11/02	4	0.4775	2.0941
134	0.4165	2.0424	3.9898	0.2867	1.4057	2.7460	0.2706	1.3267	2.5916	0.3049	1.4949	2.9203		26	1050	PVC	1998	10/26/94	1		
																		2/14/96	2	1.3371	0.7479
																		6/14/96	3	0.3399	2.9421
135	0.2778	1.3620	2.6606	0.2063	1.0118	1.9765	0.1967	0.9645	1.8840	0.2170	1.0641	2.0788		20	696	PVC	2009	8/20/94	1		
																		1/13/00	2	5.5393	0.1805
																		5/3/00	3	0.3118	3.2072
																		6/27/01	4	1.1798	0.8476
																		6/28/05	5	4.1067	0.2435
																		7/19/06	6	1.0843	0.9223
																		6/29/07	7	0.9691	1.0319
136	0.5871	2.8786	5.6232	0.2647	1.2979	2.5355	0.2397	1.1753	2.2960	0.2957	1.4498	2.8320		70	1485	PVC	2008	8/14/05	1		
																		8/24/08	2	3.1067	0.3219
137	0.1527	0.7487	1.4626	0.1200	0.5886	1.1497	0.1153	0.5655	1.1047	0.1251	0.6136	1.1987	1	16	377	STL	0	11/8/94	1		
																		12/21/96	2	2.1742	0.4599
																		9/2/99	3	2.7669	0.3614
																		8/29/00	4	1.0169	0.9834
138	0.1209	0.5930	1.1584	0.1209	0.5930	1.1584	0.1209	0.5930	1.1584	0.1209	0.5930	1.1584		0	296	PVC	2007	11/13/94	1		
																		12/28/99	2	5.2556	0.1903
																		5/29/03	3	3.5056	0.2853
139	0.2582	1.2659	2.4728	0.1417	0.6949	1.3575	0.1306	0.6404	1.2510	0.1550	0.7600	1.4847		48	646	PVC	2009	12/16/94	1		
																		3/18/05	2	10.5197	0.0951
140	0.3134	1.5369	3.0023	0.2214	1.0854	2.1203	0.2096	1.0278	2.0077	0.2345	1.1500	2.2465		24	787	PVC	2001	2/6/95	1		
																		2/20/97	2	2.0927	0.4779
																		4/15/98	3	1.1770	0.8496

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141	0.4706	2.3077	4.5080	0.2987	1.4649	2.8616	0.2793	1.3694	2.6751	0.3212	1.5750	3.0766		33	1188	PVC	2008	3/4/95	1		
																		7/21/07	2	12.7022	0.0787
142	0.5232	2.5653	5.0111	0.3082	1.5110	2.9517	0.2857	1.4011	2.7370	0.3344	1.6399	3.2035	1	40	1322	STL	0	12/2/06	1		
																		5/14/08	2	1.4860	0.6730
143	0.2021	0.9910	1.9358	0.1890	0.9270	1.8108	0.1867	0.9156	1.7886	0.1914	0.9386	1.8335		4	503	STL	1980	6/5/95	1		
																		8/14/96	2	1.2247	0.8165
																		4/9/97	3	0.6685	1.4958
																		8/26/97	4	0.3904	2.5612
																		5/28/98	5	0.7725	1.2945
																		7/1/99	6	1.1208	0.8922
																		4/22/00	7	0.8315	1.2027
																		5/21/01	8	1.1067	0.9036
																		5/2/02	9	0.9719	1.0289
																		6/29/03	10	1.1882	0.8416
																		12/4/03	11	0.4438	2.2532
144	0.1158	0.5680	1.1095	0.1120	0.5493	1.0731	0.1113	0.5459	1.0664	0.1127	0.5528	1.0799		2	283	PVC	1998	6/13/95	1		
																		8/23/96	2	1.2275	0.8146
145	0.3754	1.8406	3.5956	0.3294	1.6150	3.1549	0.3218	1.5779	3.0824	0.3373	1.6539	3.2309	1	8	945	STL	1968	6/17/95	1		
																		10/5/95	2	0.3090	3.2364
																		4/18/96	3	0.5506	1.8163
																		10/29/96	4	0.5449	1.8351
																		6/26/97	5	0.6742	1.4833
																		10/30/97	6	0.3539	2.8254
146	0.1049	0.5141	1.0043	0.1049	0.5141	1.0043	0.1049	0.5141	1.0043	0.1049	0.5141	1.0043	1	0	255	STL	1952	7/8/95	1		
																		6/5/96	2	0.9354	1.0691
147	0.1080	0.5295	1.0344	0.1080	0.5295	1.0344	0.1080	0.5295	1.0344	0.1080	0.5295	1.0344		0	263	PVC	2005	2/6/04	1		
																		7/4/05	2	1.4438	0.6926
148	0.5224	2.5614	5.0036	0.3549	1.7401	3.3993	0.3344	1.6396	3.2028	0.3781	1.8540	3.6218		27	1320	STL	1952	8/3/95	1		
																		10/29/98	2	3.3230	0.3009
149	1.0347	5.0735	9.9110	0.3886	1.9054	3.7222	0.3473	1.7029	3.3265	0.4412	2.1636	4.2265		95	2627	STL	1952	8/20/95	1		
																		1/7/99	2	3.4719	0.2880
150	0.3107	1.5235	2.9760	0.2194	1.0759	2.1018	0.2078	1.0188	1.9903	0.2325	1.1400	2.2269		24	780	PVC	1998	9/12/95	1		
																		11/17/96	2	1.2135	0.8241

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151	0.2813	1.3793	2.6944	0.2508	1.2297	2.4022	0.2457	1.2046	2.3532	0.2561	1.2558	2.4532		7	705	STL	1948	9/26/95	1		
																		12/14/04	2	9.4579	0.1057
																		5/5/06	3	1.4242	0.7022
152	0.5232	2.5653	5.0111	0.3082	1.5110	2.9517	0.2857	1.4011	2.7370	0.3344	1.6399	3.2035		40	1322	STL	1955	10/7/95	1		
																		5/10/96	2	0.6067	1.6481
																		7/28/98	3	2.2725	0.4400
																		11/2/00	4	2.3258	0.4300
																		5/17/05	5	4.6545	0.2148
																		4/19/07	6	1.9719	0.5071
																		7/1/08	7	1.2331	0.8109
																		5/26/09	8	0.9242	1.0821
153	0.6592	3.2322	6.3140	0.3518	1.7248	3.3694	0.3230	1.5839	3.0941	0.3862	1.8938	3.6995	1	50	1669	STL	1952	6/13/95	1		
																		11/6/95	2	0.4101	2.4384
																		7/13/98	3	2.7528	0.3633
																		4/30/99	4	0.8174	1.2234
																		4/29/00	5	1.0253	0.9753
																		6/10/01	6	1.1433	0.8747
																		9/15/03	7	2.3230	0.4305
																		6/16/06	8	2.8230	0.3542
																		7/17/07	9	1.1124	0.8990
154	0.1174	0.5757	1.1246	0.1117	0.5478	1.0701	0.1107	0.5428	1.0603	0.1128	0.5529	1.0802	1	3	287	STL	0	3/2/96	1		
																		10/20/04	2	8.8596	0.1129
																		7/11/05	3	0.7416	1.3485
155	0.1190	0.5834	1.1396	0.1190	0.5834	1.1396	0.1190	0.5834	1.1396	0.1190	0.5834	1.1396		0	291	PVC	0	8/22/95	1		
																		3/7/96	2	0.5562	1.7980
																		6/30/99	3	3.3989	0.2942
156	0.2966	1.4543	2.8408	0.2231	1.0939	2.1369	0.2130	1.0445	2.0403	0.2342	1.1484	2.2434	1	19	744	PVC	2004	3/30/96	1		
																		9/28/03	2	7.6910	0.1300
157	0.1276	0.6257	1.2222	0.1158	0.5678	1.1092	0.1138	0.5579	1.0899	0.1179	0.5781	1.1292	1	6	313	PVC	1998	7/6/95	1		
																		4/16/96	2	0.8006	1.2491

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158	0.5016	2.4595	4.8046	0.4539	2.2254	4.3473	0.4457	2.1855	4.2692	0.4623	2.2669	4.4283		6	1267	PVC	2002	5/20/96	1		
																		8/26/96	2	0.2753	3.6327
																		8/13/97	3	0.9888	1.0114
																		11/6/98	4	1.2640	0.7911
																		9/22/99	5	0.8989	1.1125
																		8/6/00	6	0.8961	1.1160
																		7/9/01	7	0.9466	1.0564
159	0.3640	1.7849	3.4867	0.2507	1.2294	2.4015	0.2367	1.1604	2.2668	0.2666	1.3072	2.5536	1	26	916	PVC	2000	5/24/96	1		
																		11/18/96	2	0.5000	2.0000
																		7/1/97	3	0.6320	1.5822
																		10/16/97	4	0.3006	3.3271
																		5/4/98	5	0.5618	1.7800
160	0.5067	2.4845	4.8534	0.3526	1.7290	3.3775	0.3332	1.6339	3.1918	0.3744	1.8360	3.5865		25	1280	PVC	2003	5/31/96	1		
																		11/9/99	2	3.5309	0.2832
																		10/16/00	3	0.9607	1.0409
161	0.1186	0.5814	1.1358	0.1076	0.5278	1.0311	0.1058	0.5187	1.0132	0.1096	0.5373	1.0496	1	6	290	STL	1950	6/13/96	1		
																		3/5/99	2	2.7949	0.3578
162	0.3354	1.6446	3.2126	0.3241	1.5891	3.1042	0.3220	1.5788	3.0842	0.3262	1.5994	3.1245	1	2	843	STL	1949	6/14/96	1		
																		5/24/04	2	8.1489	0.1227
																		12/11/04	3	0.5646	1.7711
163	0.1417	0.6949	1.3575	0.1177	0.5772	1.1275	0.1140	0.5591	1.0922	0.1217	0.5965	1.1652		12	349	PVC	2009	7/10/96	1		
																		10/12/04	2	8.4719	0.1180
164	0.4910	2.4076	4.7033	0.2893	1.4188	2.7715	0.2683	1.3157	2.5702	0.3140	1.5397	3.0077		40	1240	PVC	2006	7/10/96	1		
																		5/2/00	2	3.9101	0.2557
																		7/6/03	3	3.2584	0.3069
																		6/19/04	4	0.9803	1.0201
																		4/6/05	5	0.8174	1.2234
165	0.5553	2.7229	5.3190	0.3204	1.5711	3.0691	0.2965	1.4538	2.8399	0.3486	1.7094	3.3393		42	1404	PVC	2005	8/6/96	1		
																		5/8/00	2	3.8511	0.2597
																		10/5/03	3	3.4972	0.2859
																		8/23/04	4	0.9073	1.1022
166	0.1421	0.6968	1.3612	0.1330	0.6523	1.2742	0.1314	0.6444	1.2587	0.1347	0.6604	1.2900		4	350	STL	1952	9/12/96	1		
																		5/21/06	2	9.9382	0.1006

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167	0.1837	0.9006	1.7593	0.1746	0.8564	1.6729	0.1730	0.8483	1.6572	0.1763	0.8645	1.6888	1	3	456	PVC	2008	5/25/05	1		
																		9/19/08	2	3.4073	0.2935
168	0.1296	0.6353	1.2410	0.1194	0.5855	1.1438	0.1176	0.5768	1.1268	0.1212	0.5944	1.1612	1	5	318	STL	1957	9/17/06	1		
																		11/4/08	2	2.1882	0.4570
169	0.1300	0.6372	1.2448	0.1179	0.5782	1.1296	0.1159	0.5682	1.1099	0.1201	0.5887	1.1500	1	6	319	STL	1953	10/27/96	1		
																		7/29/99	2	2.8230	0.3542
																		5/8/00	3	0.7978	1.2535
170	0.4945	2.4249	4.7370	0.3071	1.5057	2.9414	0.2864	1.4041	2.7429	0.3311	1.6235	3.1714		35	1249	STL	1946	11/10/96	1		
																		7/18/99	2	2.7528	0.3633
171	0.1551	0.7603	1.4852	0.1406	0.6895	1.3469	0.1381	0.6774	1.3233	0.1432	0.7020	1.3714	1	6	383	STL	1970	11/18/96	1		
																		3/3/00	2	3.3736	0.2964
172	0.2574	1.2620	2.4653	0.1913	0.9380	1.8323	0.1824	0.8942	1.7468	0.2012	0.9864	1.9270	1	20	644	PVC	2009	7/13/96	1		
																		12/1/96	2	0.3961	2.5248
																		7/30/01	3	4.7809	0.2092
173	0.4169	2.0444	3.9936	0.2678	1.3131	2.5652	0.2507	1.2293	2.4013	0.2875	1.4096	2.7536		32	1051	PVC	2007	1/27/97	1		
																		9/3/00	2	3.6938	0.2707
																		10/18/05	3	5.2556	0.1903
																		7/11/06	4	0.7472	1.3383
174	0.2880	1.4120	2.7582	0.2060	1.0100	1.9730	0.1954	0.9580	1.8713	0.2178	1.0681	2.0866		23	722	STL	1964	1/29/97	1		
																		10/1/05	2	8.8961	0.1124
175	0.0186	0.0914	0.1786	0.0184	0.0902	0.1762	0.0183	0.0900	0.1757	0.0184	0.0904	0.1766		1	36	PVC	1997	5/3/96	1		
																		3/10/97	2	0.8736	1.1447
176	0.5549	2.7209	5.3153	0.2183	1.0703	2.0909	0.1958	0.9601	1.8756	0.2468	1.2099	2.3635	1	89	1403	STL	0	7/19/97	1		
																		7/26/01	2	4.1236	0.2425
																		3/22/04	3	2.7247	0.3670
																		7/29/05	4	1.3876	0.7206
177	0.2264	1.1102	2.1687	0.1684	0.8259	1.6133	0.1606	0.7874	1.5382	0.1771	0.8684	1.6963	1	20	565	STL	1963	9/16/97	1		
																		4/6/05	2	7.7500	0.1290
178	0.2346	1.1505	2.2475	0.2000	0.9809	1.9162	0.1946	0.9540	1.8636	0.2059	1.0094	1.9719		10	586	PVC	2007	1/21/98	1		
																		6/29/01	2	3.5253	0.2837
																		3/6/02	3	0.7022	1.4240

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179	0.2637	1.2928	2.5254	0.1935	0.9486	1.8531	0.1841	0.9028	1.7635	0.2038	0.9995	1.9525		21	660	STL	1951	3/28/98	1		
																		7/13/99	2	1.3258	0.7542
																		7/10/08	3	9.2275	0.1084
																		11/3/08	4	0.3258	3.0690
180	0.0911	0.4468	0.8728	0.0816	0.4001	0.7815	0.0800	0.3922	0.7662	0.0833	0.4082	0.7975		7	220	STL	1951	8/19/94	1		
																		12/28/95	2	1.3933	0.7177
																		8/10/98	3	2.6854	0.3724
																		5/21/99	4	0.7978	1.2535
																		12/16/99	5	0.5871	1.7033
181	0.1876	0.9198	1.7969	0.1453	0.7124	1.3916	0.1393	0.6830	1.3343	0.1518	0.7445	1.4543		17	466	STL	1951	11/4/98	1		
																		1/24/01	2	2.2809	0.4384
182	0.4734	2.3211	4.5343	0.2762	1.3543	2.6457	0.2559	1.2547	2.4511	0.3001	1.4715	2.8745		41	1195	STL	1936	12/5/98	1		
																		7/22/04	2	5.7753	0.1732
183	0.1868	0.9160	1.7894	0.1618	0.7933	1.5496	0.1577	0.7734	1.5109	0.1660	0.8142	1.5905		9	464	STL	1949	7/7/99	1		
																		3/23/01	2	1.7556	0.5696
184	0.0699	0.3429	0.6698	0.0677	0.3319	0.6484	0.0673	0.3299	0.6445	0.0681	0.3340	0.6524	1	2	166	PVC	2005	10/25/99	1		
																		5/20/04	2	4.6882	0.2133
185	0.1398	0.6853	1.3387	0.1161	0.5692	1.1120	0.1125	0.5514	1.0772	0.1200	0.5883	1.1492	1	12	344	STL	1955	11/1/99	1		
																		3/17/06	2	6.5393	0.1529
186	0.3381	1.6580	3.2389	0.2416	1.1848	2.3144	0.2291	1.1235	2.1948	0.2556	1.2532	2.4482	1	23	850	PVC	2007	12/16/99	1		
																		4/6/00	2	0.3146	3.1786
																		6/27/04	3	4.3343	0.2307
187	0.1029	0.5045	0.9855	0.1029	0.5045	0.9855	0.1029	0.5045	0.9855	0.1029	0.5045	0.9855	1	0	250	PVC	2007	2/24/00	1		
																		6/19/06	2	6.4803	0.1543
188	0.3981	1.9521	3.8134	0.2677	1.3126	2.5641	0.2519	1.2353	2.4131	0.2856	1.4004	2.7356		28	1003	PVC	1951	3/28/00	1		
																		10/9/01	2	1.5730	0.6357
																		7/15/05	3	3.8624	0.2589
189	0.2299	1.1275	2.2025	0.1778	0.8719	1.7033	0.1704	0.8358	1.6327	0.1859	0.9115	1.7805	1	17	574	STL	1970	6/6/00	1		
																		2/5/08	2	7.8652	0.1271

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190	0.2092	1.0256	2.0034	0.1619	0.7936	1.5503	0.1552	0.7608	1.4862	0.1692	0.8295	1.6204		17	521	PVC	2009	6/15/00	1		
																		7/18/01	2	1.1180	0.8945
																		8/22/04	3	3.1770	0.3148
																		4/22/08	4	3.7612	0.2659
																		8/23/08	5	0.3455	2.8943
191	0.1915	0.9391	1.8345	0.1588	0.7785	1.5209	0.1538	0.7539	1.4728	0.1642	0.8049	1.5723		12	476	STL	1951	6/23/00	1		
																		8/22/01	2	1.1938	0.8376
192	0.1986	0.9737	1.9021	0.1646	0.8071	1.5766	0.1594	0.7815	1.5267	0.1702	0.8344	1.6300	1	12	494	STL	1936	9/4/00	1		
																		6/6/05	2	4.8764	0.2051
193	0.1468	0.7199	1.4063	0.1154	0.5661	1.1058	0.1109	0.5440	1.0626	0.1204	0.5901	1.1528		16	362	PVC	2003	5/5/99	1		
																		12/27/99	2	0.6629	1.5085
																		11/2/00	3	0.8736	1.1447
194	0.3844	1.8848	3.6819	0.2679	1.3134	2.5658	0.2532	1.2415	2.4253	0.2844	1.3944	2.7238		25	968	PVC	2005	11/17/00	1		
																		8/4/03	2	2.7809	0.3596
195	0.2566	1.2582	2.4578	0.1837	0.9007	1.7595	0.1743	0.8545	1.6692	0.1942	0.9524	1.8606		23	642	PVC	2005	12/27/00	1		
																		7/6/01	2	0.5365	1.8639
196	0.1201	0.5891	1.1509	0.1201	0.5891	1.1509	0.1201	0.5891	1.1509	0.1201	0.5891	1.1509	1	0	294	STL	0	3/21/01	1		
																		8/2/01	2	0.3764	2.6567
197	0.3432	1.6830	3.2877	0.3261	1.5992	3.1240	0.3231	1.5841	3.0945	0.3293	1.6147	3.1542		3	863	STL	0	6/7/05	1		
																		12/16/07	2	2.5899	0.3861
																		5/12/09	3	1.4410	0.6940
198	0.2119	1.0390	2.0297	0.1662	0.8147	1.5916	0.1596	0.7825	1.5286	0.1733	0.8498	1.6601		16	528	STL	1950	8/7/01	1		
																		6/6/04	2	2.9045	0.3443
																		9/18/05	3	1.3174	0.7591
																		7/3/07	4	1.8343	0.5452
																		10/3/08	5	1.2865	0.7773
199	0.2256	1.1063	2.1612	0.2110	1.0347	2.0212	0.2084	1.0220	1.9964	0.2137	1.0477	2.0466	1	4	563	STL	1984	2/26/98	1		
																		8/12/01	2	3.5478	0.2819
																		5/1/07	3	5.8652	0.1705

Pipe ID	TBR: Internal costs, 1% discount rate	TBR: Internal costs, 5% discount rate	TBR: Internal costs, 10% discount rate	TBR: Avg external costs, 1% discount rate	TBR: Avg external costs, 5% discount rate	TBR: Avg external costs, 10% discount rate	TBR: High external costs, 1% discount rate	TBR: High external costs, 5% discount rate	TBR: High external costs, 10% discount rate	TBR: Low external costs, 1% discount rate	TBR: Low external costs, 5% discount rate	TBR: Low external costs, 10% discount rate	Uncertainty?	Number of customers	Pipe length (feet)	Material	Install year	Repair date	Break number	Time between breaks (years)	Break rate (years)
200	0.4530	2.2212	4.3390	0.2845	1.3950	2.7250	0.2656	1.3025	2.5444	0.3063	1.5018	2.9338		34	1143	STL	1960	8/26/02	1		
																		1/18/04	2	1.4326	0.6980
																		6/1/05	3	1.4045	0.7120
																		5/30/07	4	2.0449	0.4890
																		2/26/08	5	0.7640	1.3088
																		9/21/08	6	0.5843	1.7115
201	0.3189	1.5638	3.0549	0.2252	1.1043	2.1571	0.2132	1.0456	2.0426	0.2386	1.1700	2.2856	1	24	801	STL	1970	9/11/01	1		
																		12/9/03	2	2.3006	0.4347
																		9/25/08	3	4.9213	0.2032
202	0.5831	2.8593	5.5856	0.4209	2.0639	4.0317	0.3996	1.9595	3.8277	0.4446	2.1802	4.2590		22	1475	STL	0	11/4/01	1		
																		2/18/02	2	0.2978	3.3585
																		4/23/04	3	2.2331	0.4478
																		7/18/07	4	3.3174	0.3014
203	0.1068	0.5237	1.0231	0.1001	0.4906	0.9584	0.0989	0.4848	0.9470	0.1013	0.4967	0.9702		4	260	PVC	2009	5/19/99	1		
																		12/31/01	2	2.6882	0.3720
204	0.0954	0.4680	0.9141	0.0830	0.4068	0.7947	0.0809	0.3969	0.7754	0.0851	0.4172	0.8150		9	231	PVC	1991	1/8/02	1		
																		10/31/06	2	4.9354	0.2026
205	0.2805	1.3754	2.6869	0.2138	1.0485	2.0483	0.2046	1.0030	1.9593	0.2240	1.0985	2.1459	1	18	703	STL	1994	2/24/02	1		
																		10/22/04	2	2.7275	0.3666
																		6/7/05	3	0.6404	1.5614
206	0.4177	2.0482	4.0011	0.2776	1.3610	2.6586	0.2608	1.2790	2.4985	0.2966	1.4544	2.8410	1	29	1053	PVC	2004	9/17/02	1		
																		5/11/04	2	1.6910	0.5914
207	0.2527	1.2390	2.4203	0.1979	0.9705	1.8959	0.1901	0.9319	1.8205	0.2065	1.0125	1.9779		16	632	PVC	2009	6/8/07	1		
																		5/24/08	2	0.9860	1.0142
208	0.2629	1.2889	2.5179	0.2540	1.2456	2.4333	0.2524	1.2376	2.4177	0.2557	1.2537	2.4491		2	658	STL	1980	12/21/94	1		
																		5/9/98	2	3.4691	0.2883
209	0.1319	0.6468	1.2636	0.1216	0.5961	1.1645	0.1198	0.5873	1.1472	0.1234	0.6052	1.1822	1	5	324	STL	1955	6/1/01	1		
																		8/9/02	2	1.2191	0.8203
210	0.2127	1.0429	2.0372	0.1989	0.9754	1.9055	0.1965	0.9635	1.8821	0.2014	0.9877	1.9294		4	530	STL	0	1/10/01	1		
																		6/4/04	2	3.4860	0.2869
																		8/30/08	3	4.3483	0.2300
																		5/19/09	4	0.7360	1.3588

Pipe ID	TBR: Internal costs, 1% discount rate	TBR: Internal costs, 5% discount rate	TBR: Internal costs, 10% discount rate	TBR: Avg external costs, 1% discount rate	TBR: Avg external costs, 5% discount rate	TBR: Avg external costs, 10% discount rate	TBR: High external costs, 1% discount rate	TBR: High external costs, 5% discount rate	TBR: High external costs, 10% discount rate	TBR: Low external costs, 1% discount rate	TBR: Low external costs, 5% discount rate	TBR: Low external costs, 10% discount rate	Uncertainty?	Number of customers	Pipe length (feet)	Material	Install year	Repair date	Break number	Time between breaks (years)	Break rate (years)
211	0.0589	0.2889	0.5645	0.0589	0.2889	0.5645	0.0589	0.2889	0.5645	0.0589	0.2889	0.5645	1	0	138	PVC	2005	7/28/04	1		
																		5/31/05	2	0.8624	1.1596
212	0.3538	1.7349	3.3891	0.2381	1.1674	2.2805	0.2241	1.0988	2.1466	0.2540	1.2453	2.4327	1	28	890	STL	1982	8/16/04	1		
																		1/3/06	2	1.4185	0.7050
213	0.1468	0.7199	1.4063	0.1273	0.6241	1.2192	0.1241	0.6086	1.1890	0.1306	0.6404	1.2511		9	362	STL	1951	4/29/96	1		
																		3/13/97	2	0.8933	1.1195
																		7/3/97	3	0.3146	3.1786

Appendix E

ABCWUA economic-valuation survey design

		Alternative A						**Alternative B**					
Q	**V**	**O**	**L**	**N**	**R**	**G**	**C**	**O**	**L**	**N**	**R**	**G**	**C**
1	1	10	3	70	25	40	$0	0	3	20	65	20	$2
2	1	0	8	20	45	60	$6	10	15	70	25	20	$12
3	1	10	3	90	65	20	$15	5	15	70	45	40	$2
4	1	5	15	90	65	40	$12	10	8	20	45	20	$15
1	2	5	15	90	25	60	$15	0	8	20	65	40	$10
2	2	0	8	90	65	40	$12	5	3	70	25	20	$10
3	2	0	3	20	25	20	$0	10	15	20	45	60	$2
4	2	10	3	20	65	60	$10	10	15	90	45	40	$6
1	3	5	8	20	25	60	$0	10	3	90	65	20	$15
2	3	5	8	90	45	20	$10	10	15	20	65	40	$0
3	3	0	3	90	25	60	$6	5	3	20	45	40	$15
4	3	10	15	90	45	40	$6	0	8	70	25	20	$2
1	4	10	15	70	65	20	$15	0	15	20	45	60	$12
2	4	5	3	20	45	60	$12	10	8	90	25	40	$2
3	4	0	15	70	25	60	$10	5	3	90	65	40	$0
4	4	5	3	90	65	40	$0	10	15	70	25	20	$12
1	5	0	15	20	25	40	$15	10	3	20	65	60	$10
2	5	5	3	90	25	60	$2	0	15	90	45	20	$0
3	5	10	8	70	45	40	$10	0	15	90	65	20	$2
4	5	0	3	20	25	20	$0	0	8	90	65	40	$12
1	6	0	3	90	25	60	$6	5	8	20	65	40	$2
2	6	0	8	90	25	60	$15	10	3	90	45	20	$12
3	6	5	15	70	45	60	$0	10	3	20	25	40	$6
4	6	10	8	20	25	20	$12	0	15	70	65	40	$6
1	7	5	15	20	25	20	$6	0	3	70	45	40	$15
2	7	10	3	70	45	60	$2	5	15	20	65	20	$10
3	7	0	3	90	45	40	$10	10	8	70	65	60	$6
4	7	10	8	90	65	60	$0	10	3	20	25	40	$6
1	8	5	8	90	45	20	$6	0	15	20	25	40	$15
2	8	10	15	20	45	60	$2	5	8	70	25	40	$12
3	8	0	3	70	65	60	$12	0	15	90	45	20	$0
4	8	10	15	90	25	60	$10	5	3	70	65	20	$6

Q = Question
V = Survey version
L = Average length of outage
O = Number of outages
C = Additional monthly cost
R = Reuse water
N = Notify
G = Renewable Energy

Appendix F

Example ABCWUA economic-valuation survey

Investing in Albuquerque's Water System: What Is Important to You?

The Albuquerque Bernalillo County Water Utility Authority ('the water utility') provides water service to the majority of residents and businesses in Albuquerque.

The water utility is engaged in a long-term planning effort and would like customer input on the following potential, future investments:

- **Investment in water reuse**
- **Investment in renewable energy**
- **Investment in water pipe rehabilitation**

In this survey, we will ask whether you support these projects, given their benefits and costs. By expressing your opinion, you will help the water utility plan for the future.

UNM

Investment in Water Reuse

Most irrigation water in Albuquerque is currently treated to drinking-water-quality standards. However, for the last ten years, the water utility has used a blend of treated wastewater and river water (or *reuse water*) to irrigate some of Albuquerque's greenspace (e.g. parks, medians, and golf courses).

Currently, 25% of Albuquerque greenspace
is irrigated with reuse water.

Reuse water is treated to a clean and safe, but non-potable level. Although it is not suitable for drinking, it will not make a person sick if accidentally consumed.

Benefits of water reuse in Albuquerque include:

- It is cheaper to treat irrigation water to a safe, but non-potable level.
- Reuse water is an alternative to unsustainable groundwater and limited surface water supplies.

Reuse water requires a completely separate pipe distribution system. To make it more widely available, the water utility can invest in installing more reuse pipes and storage tanks.

1. How supportive are you of water reuse in Albuquerque? *Circle one.*

Not supportive	Somewhat supportive	Fairly supportive	Very supportive
1	2	3	4

Investment in Renewable Energy

Providing water and wastewater service to customers requires energy. Electricity from coal and natural gas produces carbon emissions that contribute to global warming. Renewable energy from sources like solar, wind, or biofuels produces very little, if any, carbon.

The water utility currently generates some electricity from renewable sources at the wastewater treatment plant. As a result:

Currently, about 20% of the energy used by the water utility is renewable.

The water utility can invest in additional renewable energy by signing a 5-year contract to purchase energy from a portfolio of renewable sources. At the end of the contract, the program will be evaluated to determine if it should be continued.

Each 20% increase in renewable energy would reduce the water utility's annual carbon emissions by about 26,000 tons. This is equivalent to the current, annual carbon emissions of about 6,000 Albuquerque households.

2. How supportive are you of the water utility's use of renewable energy? *Circle one.*

Not supportive	Somewhat supportive	Fairly supportive	Very supportive
1	2	3	4

Investment in Water Pipe Rehabilitation

In cities across the U.S., water pipes that were installed during population booms in the last century are reaching the end of their useful lives. As pipes deteriorate, they fail more frequently.

Some neighborhoods in Albuquerque are beginning to experience this problem. For example, you may have heard about or seen frequent pipe breaks in the Hoffmantown neighborhood.

The water utility can invest in rehabilitating old pipes. Rehabilitating pipes can involve replacing them, or extending their useful life using one of several renewal technologies.

Rehabilitating pipes at the first sign of deterioration will result in fewer impacts to customers, but it has a higher cost.

The decision of when to rehabilitate pipes affects you and other water utility customers in the following four ways:

- The number of outages (or disruptions in water service) at your home
- The average length of outages for water utility customers
- How often customers receive advance notification of outages
- The cost of your monthly water bill

Number of Outages

This survey will focus on outages that are caused by issues related to **utility water pipes**. Homeowners are responsible for maintaining the water pipes on their properties.

3. In the box below, please write the number of outages that you have experienced at your home here in Albuquerque **in the past 5 years**.

Number of outages at your home over 5 years: ________

Because pipes across Albuquerque are made of different materials and were installed at different times, they are deteriorating at different rates.

Although your neighborhood may not currently experience frequent outages, the pipes in your neighborhood will begin to deteriorate at some point in the future. Because the goal of this survey is to assist the water utility with long-term planning, we ask you to imagine that time when your neighborhood will be impacted by deteriorating pipes.

Depending on the water utility's level of investment in pipe rehabilitation, your current level of service could improve, worsen, or stay the same.

4. What is the **highest number of water outages at your home** that you consider acceptable (i.e. that would not make you think the water utility is doing its job improperly)? *Check one.*

☐ 1 0 outages every 5 years
☐ 2 1 outage every 5 years
☐ 3 3 outages every 5 years
☐ 4 5 outages every 5 years
☐ 5 7 outages every 5 years
☐ 6 10 outages every 5 years

Average Length of Outages

Currently, the average length of outages experienced by water utility customers is 3 hours.

5. How important do you think it is to **decrease the average length of an outage** from its current level of 3 hours? *Circle one.*

Not important	A little important	Somewhat important	Very important
1	2	3	4

Advance Notification of Outages

The water utility notifies customers in advance whenever planned outages are scheduled to occur. Planned outages generally take place during the middle of the day to minimize inconvenience to as many customers as possible. When outages occur because of a pipe failure, the water utility is not able to notify customers in advance.

Currently, the water utility gives customers advance notification of outages 70% of the time.

This means that 30% of the time, outages are unplanned.

6. How important do you think it is to achieve **a higher percentage of advance notification** than the current level of 70%? *Circle one.*

Not important	A little important	Somewhat important	Very important
1	2	3	4

Additional Amount Spent on Your Monthly Water Bill

Investing in reuse, renewable energy, or pipe rehabilitation would require additional funds. Because the water utility does not receive tax money or other significant sources of external funding, this project would need to be paid for by water utility customers through their water utility bills.

If these projects were fully funded, all customers would pay an additional amount on their water bills for the next 5 years. Similar to the San Juan Chama Project, the money generated from this charge would be placed in a dedicated Water Infrastructure Fund that could only be used for these three projects.

7. If the water utility were to increase your water utility bill by the amounts shown below, how much hardship would it cause you and your household? *Circle the appropriate number for each.*

	No hardship	A small hardship	Some hardship	A moderate hardship	A great hardship
Extra $5/month	1	2	3	4	5
Extra $10/month	1	2	3	4	5
Extra $15/month	1	2	3	4	5

Which Water Utility Investments Are Important to You?

On the following pages, we will present you with four different choices. With each one, we will show you two different water utility investment packages, and ask which of the packages you prefer. You may not like either of the investment packages presented. Nonetheless, please choose the one you like the best (or dislike the least). The following questions are very important, so please consider them carefully.

People often say they will pay money in a survey regardless of how they truly feel, because no money is actually involved. When you think about your answers to the following questions, we ask you to assume that you would **actually make the payments** presented in the scenarios. Please keep in mind both the benefits of the proposed projects and the impact they will have on your pocketbook.

On the next page, you see two different investment packages: Investment Package A and Investment Package B.

- **Investment Package A** results in greater use of renewable energy, more frequent advance notification of outages for all water utility customers, and no additional cost on your monthly water bill.
- **Investment Package B** results in greater use of reuse water and no outages at your home.

Which option do you prefer: Investment Package A or Investment Package B? You can assume that all other characteristics of water service are the same across all investment packages.

8. **Choice 1:** If these were the only two investment packages available, which would you choose: Investment Package A or Investment Package B? *Check one.*

	Investment Package A	**Investment Package B**
Percent of Albuquerque greenspace irrigated with reuse water	25% of greenspace	65% of greenspace
Percent of energy used by the water utility that is renewable	40% of renewable energy	20% of renewable energy
Number of outages you experience at your home	10 outages over 5 years	0 outages over 5 years
Average length of outages for water utility customers	3 hour outage	3 hour outage
Percent of time water utility customers receive advance notification of outages	Advance notification 70% of the time	Advance notification 20% of the time
Additional amount on your monthly water utility bill for the next 5 years	$0 per month	$2 per month
I would choose Package ⟶	☐ A	☐ B

9. Please tell us how you made your decision on Question 8. ______________________

____

10. **Choice 2:** If these were the only two investment packages available, which would you choose: Investment Package C or Investment Package D? *Check one.*

	Investment Package C	**Investment Package D**
Percent of Albuquerque greenspace irrigated with reuse water	45% of greenspace	25% of greenspace
Percent of energy used by the water utility that is renewable	60% of renewable energy	20% of renewable energy
Number of outages you experience at your home	0 outages over 5 years	10 outages over 5 years
Average length of outages for water utility customers	8 hour outage	15 hour outage
Percent of time water utility customers receive advance notification of outages	Advance notification 20% of the time	Advance notification 70% of the time
Additional amount on your monthly water utility bill for the next 5 years	$6 per month	$12 per month

I would choose Package ⟶ ☐ C ☐ D

11. **Choice 3:** If these were the only two investment packages available, which would you choose: Investment Package E or Investment Package F? *Check one.*

	Investment Package E	**Investment Package F**
Percent of Albuquerque greenspace irrigated with reuse water	65% of greenspace	45% of greenspace
Percent of energy used by the water utility that is renewable	20% of renewable energy	40% of renewable energy
Number of outages you experience at your home	10 outages over 5 years	5 outages over 5 years
Average length of outages for water utility customers	3 hour outage	15 hour outage
Percent of time water utility customers receive advance notification of outages	Advance notification 90% of the time	Advance notification 70% of the time
Additional amount on your monthly water utility bill for the next 5 years	$15 per month	$2 per month

I would choose Package ⟶ ☐ E ☐ F

12. **Choice 4:** If these were the only two investment packages available, which would you choose: Investment Package G or Investment Package H? *Check one.*

	Investment Package G	**Investment Package H**
Percent of Albuquerque greenspace irrigated with reuse water	65% of greenspace	45% of greenspace
Percent of energy used by the water utility that is renewable	40% of renewable energy	20% of renewable energy
Number of outages you experience at your home	5 outages over 5 years	10 outages over 5 years
Average length of outages for water utility customers	15 hour outage	8 hour outage
Percent of time water utility customers receive advance notification of outages	Advance notification 90% of the time	Advance notification 20% of the time
Additional amount on your monthly water utility bill for the next 5 years	$12 per month	$15 per month

I would choose Package ⟶ ☐ G ☐ H

13. How important were each of the following in making your choices over investment packages in Questions 8-12? *Circle the appropriate number for each.*

	Not important	A little important	Somewhat important	Very important
Percent of Albuquerque greenspace irrigated with reuse water	1	2	3	4
Percent of energy used by the water utility that is renewable	1	2	3	4
Number of outages you experience at your home	1	2	3	4
Average length of outages for water utility customers	1	2	3	4
Percent of time water utility customers receive advance notification of outages	1	2	3	4
Additional amount on your monthly water utility bill for the next 5 years	1	2	3	4

What Do You Think?

The water utility would like your input on three additional topics: water conservation, wastewater quality, and pipe maintenance on private property.

14. Please rate the acceptability of each of these methods for encouraging conservation. *Circle the appropriate number for each.*

	Not acceptable	Somewhat acceptable	Very acceptable
Water education programs	1	2	3
Higher rates for high levels of use	1	2	3
Rebates (e.g. for low water-use appliances)	1	2	3
Required conservation (e.g. watering restrictions)	1	2	3

15. How important are the following reasons for conserving water in Albuquerque? *Circle the appropriate number for each.*

To ensure a reliable water supply:

	Not important	A little important	Somewhat important	Very important
For my household	1	2	3	4
For my kids and grandkids	1	2	3	4
For people who move here	1	2	3	4
For economic development	1	2	3	4
For the environment	1	2	3	4

Wastewater is treated by the water utility and discharged into the Rio Grande. It currently meets or exceeds all federal and state water quality standards. However, there are very low concentrations of some substances in wastewater that are currently unregulated.

Some of these substances, such as pharmaceutical and personal care products, are introduced to wastewater by humans. If they are not removed at the wastewater treatment plant, they go back into the river, impacting river water quality and the drinking water supplies of cities downstream.

16. How concerned are you about unregulated contaminants in Albuquerque's treated wastewater going into the Rio Grande? *Circle one.*

Not concerned	Somewhat concerned	Fairly concerned	Very concerned
1	2	3	4

The water utility could invest in additional treatment technologies at the wastewater treatment plant to remove unregulated contaminants.

Investing in improved wastewater quality implies either lower investment in other projects or higher rates for customers.

17. Do you agree or disagree that the water utility should invest in additional treatment technologies at the wastewater treatment plant to remove unregulated contaminants? *Circle one.*

Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
1	2	3	4	5

The *water service line* from the water meter to the house and the *sewer service line* from the sewer main to the house are the homeowner's responsibility. Homeowner's insurance typically does not cover service line repairs.

The water utility is considering three optional plans to assist customers with pipe maintenance on their properties. Customers who sign up for a plan would pay the cost through their water bills. All plans would include an unlimited number of service calls or claims.

- The *water service line protection plan* would cover the repair of water service line leaks or breaks. The plan would cost $5 per month, and include a coverage limit of $5,000 per occurrence and a 12-hour contractor response time.
- The *sewer service line protection plan* would cover the repair of sewer service line blockages. The plan would cost $10 per month, and include a coverage limit of $8,000 per occurrence and a 24-hour contractor response time.
- The *in-home plumbing emergency plan* would cover emergency repair of leaks or breaks of internal water lines and blockages of internal sewer lines/drains. The plan would cost $5 per month, and include a coverage limit of $1,500 per occurrence and a 24-hour contractor response time.

18. How likely would you be to sign up for the following three optional plans? *Circle the appropriate number for each.*

	Very unlikely	Somewhat unlikely	Neutral	Somewhat likely	Very likely
Water service line protection	1	2	3	4	5
Sewer service line protection	1	2	3	4	5
In-home plumbing emergency	1	2	3	4	5

You and Your Household

Not all water utility customers will have the opportunity to complete this survey. Thus we need to know how similar you and other survey respondents are to all customers. Your answers to the following questions will help us to do this.

All the information collected in this survey will be kept completely confidential. No individual results will be reported.

19. In a typical summer month, what percentage of your property do you water? *Check one.*

☐ 1 0%
☐ 2 1% - 25%
☐ 3 26% - 50%
☐ 4 51% - 75%
☐ 5 76% - 90%
☐ 6 91% - 100%

20. How many years have you lived at your current address?: ____________________

21. How many years have you lived in New Mexico?: ____________________

22. Do you expect to still live in Albuquerque in 5 years? *Check one.*

☐ 1 Yes
☐ 2 No

23. How many people in the following age groups live in your household? *Please fill in the number of people in each category.*

Age 5 and under ______
Age 6 - 12 ______
Age 13 - 18 ______
Age 19 - 64 ______
Age 65 - 75 ______
Over age 75 ______

24. What is your age? ____

25. People may be affected differently by water outages at their homes. *Check **all** that apply.*

☐ 1 Someone in my household runs a business out of our home.
☐ 2 Someone in my household is a stay-at-home parent.
☐ 3 Someone in my household is a member of a sensitive subpopulation (i.e. a person with poor health or high health risk).
☐ 4 None of the above apply.

26. What is your gender? *Check one.*

☐ 1 Female
☐ 2 Male

27. What is the highest degree or level of school you have **completed**? *Check one.*

☐ 1 Less than 5th grade
☐ 2 5th - 8th grade
☐ 3 9th - 11th grade
☐ 4 12th grade, no diploma
☐ 5 High school diploma or GED
☐ 6 Some college, but no degree
☐ 7 Associate degree
☐ 8 Bachelor's degree
☐ 9 Master's degree
☐ 10 Professional degree (*e.g., MD, DDS, JD*)
☐ 11 Doctorate degree (*e.g., PhD*)

28. Are you Spanish/Hispanic/Latino?

☐ 1 Yes
☐ 2 No

29. The last question dealt with ethnicity, while this one deals with race. Please check the race(s) you consider yourself to be. These race categories may not fully describe you, but they are the standard categories used by the Census Bureau. *Check **all** that apply.*

☐ 1 White
☐ 2 Black or African American
☐ 3 American Indian or Alaska Native. Print tribe: ________________
☐ 4 Asian
☐ 5 Pacific Islander
☐ 6 Some other race. Print race: ____________________

30. What is the range that best describes your total household income before taxes in 2008? (Please include wages, interest, and any other income.) *Check one.*

☐ 1 Less than $19,999
☐ 2 $20,000 to $39,999
☐ 3 $40,000 to $59,999
☐ 4 $60,000 to $99,999
☐ 5 $100,000 to $149,999
☐ 6 $150,000 to $199,999
☐ 7 $200,000 or more

Thank you very much for your help!

If you have any additional comments, please write them below.

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