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The Buried Pipeline Replacement Era: A Cost-effectiveness Analysis of Pipeline Replacement Strategies for the Santa Clara Valley Water District

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by

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INTRODUCTION

In August 2015, the Santa Clara Valley Water District (SCVWD) experienced a catastrophic failure on the Santa Clara Conduit, a 96-inch prestressed concrete cylinder pipeline (PCCP), which resulted in the loss of approximately 20 million gallons of water, and over $1.2 million in repair cost and property damage (SCVWD, 2015; SCVWD, 2016). The Santa Clara Conduit is part of the San Felipe system that delivers Central Valley Project water from the Sacramento-San Joaquin River Delta (Delta) to both San Benito and Santa Clara counties. The pipe failure impacted about 500 customers in San Benito County, who rely on the imported water as a significant source of their local supply (Kosmicki, 2015), while residents in Santa Clara County had to rely on water supplies coming through the South Bay Aqueduct (SBA), the other key route for water from the Delta (Rogers, 2016). A failure on the SBA at that time could have resulted in emergency water shortages to homes and businesses in Santa Clara County (Rogers, 2016).

In the wake of the pipeline failure, SCVWD was faced with reviewing pipeline replacement strategies and materials, to select the best-fit, right-cost solution to replace the failed pipe segment and to determine what pipeline replacement strategies and materials would be suitable for replacing future pipelines segments as they reach the end of their service life. SCVWD was also faced with revising its pipeline maintenance and operations strategies, in an effort to proactively identify distressed pipeline segments prior to their failure, and implement the best-fit, most cost effective pipeline replacement strategy for the distressed pipe segments. The intent of this study is to evaluate pipeline replacement strategies that would be most cost effective for SCVWD to implement. This study focuses on evaluating pipeline replacement strategies for SCVWD’s PCCP, since a majority of SCVWD pipelines are made of this material, and failures in PCCP often result in the highest water losses and involve mostly larger diameter pipelines (Grigg, 2013).

SCVWD Water Infrastructure Overview

SCVWD was created by an act of the California Legislature, and operates as a state of California Special District, with jurisdiction throughout Santa Clara County (SCVWD District Act, 2009). SCVWD's water infrastructure dates back to the 19th century, at a time when natural resources were able to sustain the early inhabitants of the Santa Clara Valley, and farming was the main activity in the Santa Clara Valley. The farmers at that time were able to use rainfall run off and some groundwater pumping, with the first noted well drilled in San Jose in 1854. The farmers also constructed the first sack dams in the Santa Clara Valley to help spread water around the valley for percolation. This was considered the farmers' first move towards the recharge of the groundwater basin; however, over pumping of the groundwater became an issue in San Jose in the 1920s and San Jose sunk by about 4 feet, prompting the need for countywide management of water resources (SCVWD, 2012).

In March 1921, a report to the Santa Clara Valley Water Conservation Committee (Tibbetts' Report) was released which outlined a plan to manage water in the Santa Clara Valley. The report recommended the construction of 17 reservoirs, local check dams, pump stations, and system conduits to convey water around the county for groundwater recharge. The construction of these improvements was estimated at $10.9 million. In order to raise funds for the recommended water infrastructure outlined in the Tibbetts' report, voters in the county passed the Water Conservation Act in 1929, and approved the creation of a local water conservation district to carry out the water conservation activities for the county, which included the construction of water infrastructure. The first projects included the construction of the Calero

Dam in 1935 to expand local water supplies, and by 1936, six new reservoirs had been built, which collectively allowed for the capture and storage of about 40,000 acre-feet of local water. In 1951 and 1952, Anderson and Lexington reservoirs were constructed, which nearly tripled the county's water storage capabilities, and raw water pipelines were installed to convey water to the recharge ponds around the county, for replenishment of the groundwater basin; however, local water supplies in Santa Clara Valley were still not able to meet the demands of the increasing population (SCVWD, 2012).

To increase the supply of water coming into the Santa Clara Valley, water was imported into the Santa Clara Valley in 1951, through the San Francisco Public Utilities Commission's (SFPUC) Hetch-Hetchy pipelines, and this supplied additional water to the communities in the south part of the bay area. As demands for water continued to increase in the county, water was imported through the SBA from the north part of Santa Clara County in 1965. The SBA is part of the State Water Project, and it conveys raw water from the Sacramento-San Joaquin Delta. Raw water pipelines were installed to convey water from the SBA into recharge ponds in the county, and these efforts were successful at halting the land subsidence in the county. These pipelines were made of PCCP and steel, and ranged in size from 66 to 78-inches in diameter. In 1987, large raw water pipelines were installed as part of the federally managed Central Valley Project's San Felipe Division, to convey water from the San Luis Reservoir to the Anderson Dam in the south county. These pipelines were made of PCCP and ranged in size from 96 to 120-inches in diameter. Additional PCCP raw water pipelines were installed to convey water from Anderson Dam to the Calero Reservoir, and into the Almaden Valley area (SCVWD, 2012).

To meet the drinking water needs of the Santa Clara Valley, water treatment plants were constructed in 1967 and 1974, along with the treated water pipelines needed to deliver water to the east and west portions of the Santa Clara Valley. These pipelines were made of steel and ranged from 30 to 84-inches in diameter. An additional treatment plant was constructed in 1989 in the Almaden Valley area, along with treated water pipelines, made of PCCP, which connected to existing treated water pipelines in the east part of the Santa Clara Valley. The final lengths of treated water pipelines were made of steel, and installed in 1992 to convey treated water to the Milpitas community and unify regional distribution of treated water between SCVWD and SFPUC (SCVWD, 2012).

Today, SCVWD provides wholesale water and groundwater management services to local municipalities and private water retailers, who maintain their own distribution system, utility billing, meter reading, and deliver drinking water directly to homes and businesses for approximately two million people, in seventeen municipalities in Santa Clara County (SCVWD Homepage, n.d.). SCVWD supplies over 121 billion gallons of water annually and effectively maintains and operates approximately 142 miles of raw and treated water pipelines (see Table 1), with pipeline diameters ranging from 30 inches to 120 inches, throughout the Santa Clara Valley (SCVWD Homepage, n.d.).

In addition to providing wholesale drinking water and groundwater management services, SCVWD manages flood protection and maintenance on more than 275 miles of streams in Santa Clara County, ten dams and surface water reservoirs, three water treatment plants, an advanced recycled water purification center, a water quality laboratory, and nearly 400 acres of groundwater recharge ponds (SCVWD Homepage, n.d.).

Table 1: SCVWD Pipeline Inventory Mileage

Material Type	Miles of Pipeline	Percent of Total
Prestressed Concrete Cylinder Pipe (PCCP)	78	55%
Welded Steel Pipe (WSP)	50	35%
Tunnel	8	6%
Others (RCCP, CPP, and other concrete pipe)	6	4%
Total	**142**	**100%**

Source: SCVWD, 2007, p. 2-2 and 2-3

The Buried Pipeline Replacement Era

Over a decade ago, the American Water Works Association (AWWA) announced that the U.S. was entering into a new era called the replacement era; where water utilities would need to begin to rebuild the water infrastructure that was passed down from earlier generations. AWWA issued a report which showed that significant investments would be needed in the coming decades in order to maintain the reliability of the buried pipeline infrastructure (AWWA, 2012). A majority of the water pipelines today were buried several years ago and these facilities are often out of the view of the public. A 2001 study conducted by AWWA noted that some water utilities have pipelines that are more than 100 years old, and patterns of growth in the United States indicate that there is currently a large national inventory of pipeline at around 50–60 years of age. As the water infrastructure continues to age, leaks and failures in the water infrastructure begin to compromise the reliability of the water system. This leads to an increased need to invest resources into the future replacement and reliability of the buried water infrastructure, since maintaining the reliability of the buried pipeline infrastructure is critical to protecting the health and safety of the general public.

Buried water pipes may carry raw water, irrigation water, treated drinking water, raw sewage, treated sewage effluent and recycled water, and are typically buried four to twelve feet below the ground. SCVWD's buried pipelines are primarily used to convey raw water and treated drinking water in Santa Clara Valley. Over sixty percent of SCVWD pipelines are 60 inches in diameter or larger, with most pipelines made of either PCCP, welded steel pipe (WSP), reinforced concrete cylinder pipe (RCCP), or concrete pressure pipe (CPP). SCVWD has some concrete tunnels as well. The majority of the SCVWD raw water pipelines are PCCP and most of these pipelines are over 30 years old. The majority of the SCVWD treated water pipelines are WSP, and most are over 40 years old (see table 2).

Table 2: SCVWD Pipeline Inventory Age

Material Type	Over 40 years old	30 to 40 years old	Under 30 years old
Prestressed Concrete Cylinder Pipe (PCCP)	26	32	20
Welded Steel Pipe (WSP)	32	10	8
Tunnels	2	6	0
Others (RCCP, CPP, other concrete pipe)	3	2	1
Total	**63**	**50**	**29**

Source: SCVWD, 2007, p. 2-2 and 2-3

SCVWD's water infrastructure has been fairly reliable, with ninety percent of the leaks occurring at appurtenances connected to the pipeline and not on the pipelines themselves. Reliability of water infrastructure can be measured by physical integrity indicators that include the rate at which buried water pipelines fail or leak (Grigg, 2013). When buried water pipelines fail, they often form craters in the ground ranging from twenty-four to fifty feet wide, which can cause damage to nearby structures from debris, and some of these craters are capable of swallowing cars and portions of roads (AWWA, 2012). While SCVWD has been fortunate to have a low rate of leaks and failures in its buried pipeline infrastructure, other water utilities in the United States have unfortunately experienced pipeline failures that have caused a range of impacts to the community. These failures in our water infrastructure highlight the fact that our systems are aging and in need of replacement, as most of our water infrastructure will reach the end of its service life in the next 25 to 40 years.

Social Implications of Water System Failures

Urban consumers rely on a community-based supply of potable water. SCVWD serves about two million people in seventeen municipalities (SCVWD Homepage, n.d.). Failure of a major water main could deprive households and businesses of water for hours to weeks. Leaking pipes can allow hazardous materials to leach into treated water, creating a public health threat. The delivery of tainted water to households in Flint, Michigan has heightened consumer awareness of water quality. Criminal charges against water and environmental officials in Flint demonstrate the social responsibility inherent in the water delivery sector (McLaughlin and Shoichet, 2016).

SCVWD is the special district entrusted with providing water in Santa Clara County. Loss of water service to consumers would damage the revenue stream of the district. Consumer confidence in SCVWD could be damaged, resulting in a political backlash against the elected Board of Directors of SCVWD. Damage to an agency's reputation and loss of public trust are hard to quantify, but difficult to repair. Forbes has called reputational value "irreplaceable," noting that reputations for quality and safety build consumer trust (Brigham and Linssen, 2010). When evaluating an investment in system reliability these social and political considerations must be included when valuing the cost effectiveness of repairs.

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METHODOLOGY

Using the Patton, Sawiki & Clark model for cost-oriented evaluations, this study analyzed the cost-effectiveness of pipeline renewal strategies that would meet SCVWD pipeline replacement objectives, and includes a recommendation to SCVWD on a cost-effective pipeline renewal strategy.

Cost-Effectiveness Analysis

A cost-effectiveness analysis is an alternative to the traditional cost-benefit analysis, and it is used to compare the relative cost of the outcomes for two or more alternatives used to resolve a particular problem or achieve a particular set of objectives, at the lowest cost (Kaplan, 2014; Levin, H. M., & McEwan, P. J., 2001). In a cost-benefit analysis, the outcome of implementing a particular alternative can be measured monetarily, whereas, in a cost-effectiveness analysis, cost and consequence are taken into account. Cost-effectiveness analyses often have restrictions with monetizing the benefits of a particular action; however, the outcomes of the alternatives themselves can be counted and compared (Kaplan, 2014; Levin, H. M., & McEwan, P. J., 2001).

Cost-effectiveness analysis was first developed in the 1950s by the United States Department of Defense, and was used as a means to justify the distribution of resources among the various branches of the armed services. By the 1960s, cost-effectiveness analysis had been adopted by other branches of the federal government, as a means of analyzing the efficiency of alternative government programs (Levin, H. M., & McEwan, P. J., 2001). The ratio of cost-effectiveness of a particular alternative is based on the measured effectiveness divided by the cost of a particular alternative, and the highest ratio is considered to be the most cost-effective option for implementation (Kaplan, 20014).

Measuring Cost Effectiveness

The basic techniques used in this study were derived from evaluation criteria and the identification of alternatives from pipeline renewal strategies used by comparable water utilities. This information was combined with cost data and the expected design life of each strategy. The steps used to complete this analysis are (1) selection of evaluation criteria, (2) identification and evaluation of renewal approaches, and (3) cost estimation. The steps for this analysis are explained as follows.

Selection of Evaluation Criteria

The evaluation criteria used to complete this research is a cost-effectiveness analysis and included the collection of pipeline inventory information from the SCVWD, information on pipeline renewal programs implemented by comparable water utilities, and a financial analysis of pipeline inspection, rehabilitation, and replacement cost. Information used in the financial analyses was obtained from a 2012 Water Research Foundation (WRF) industry survey.

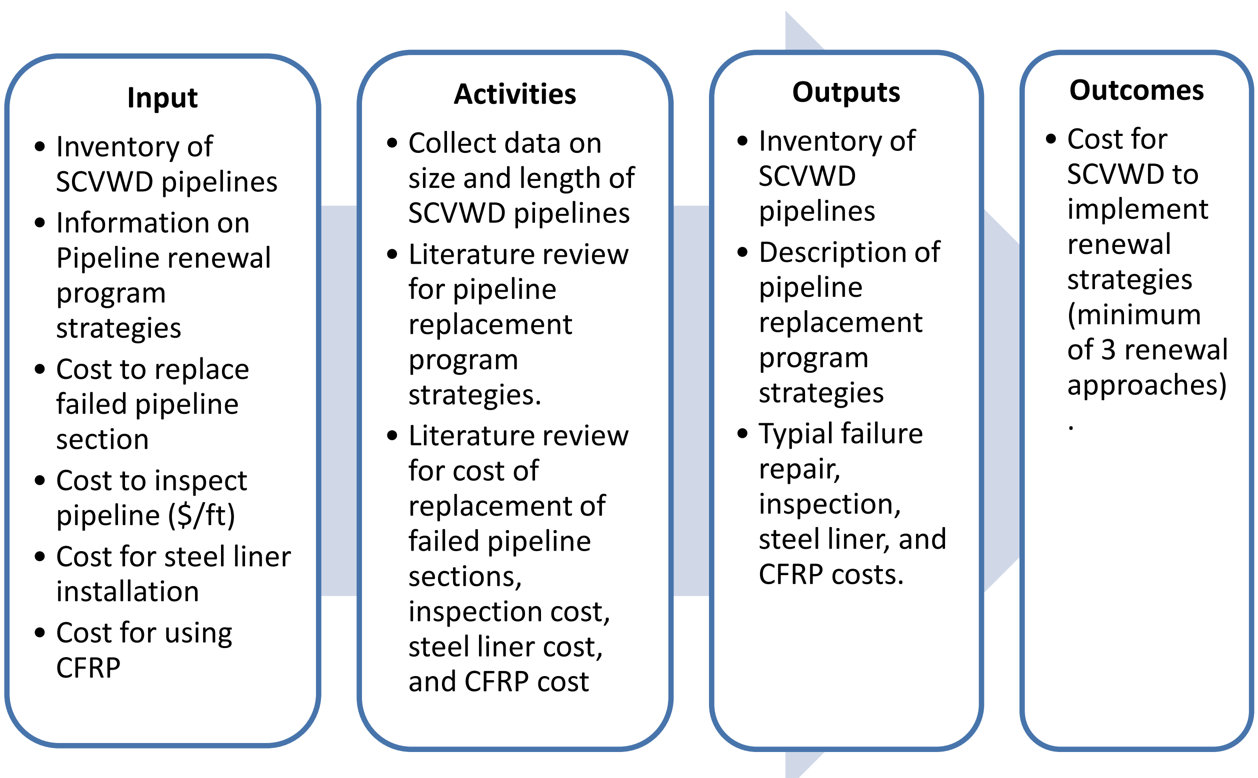
Identification and Evaluation of Repair Approaches

Evaluation of renewal approaches began with an analysis of the "No Action/Status Quo" approach. The evaluation of this approach required input on SCVWD's existing pipeline maintenance program and an assessment of the complete inventory of SCVWD pipelines. Additional repair approaches for this study came from the Washington Suburban Sanitary Commission and the Metropolitan Water District of Southern California, which are comparable water utilities to SCVWD and these agencies have implemented pipeline renewal programs. Information on the evaluation of the renewal approaches are outlined in the Literature Review, and include the cost to replace failed pipeline sections, pipeline inspection cost, steel liner installation cost, and the cost for the installation of carbon fiber reinforced polymer. Future cost for pipeline renewal strategies in this study were established using extrapolative forecasting.

Cost Estimation

The cost of a pipeline renewal strategy is defined as the value of the resources that are given up by SCVWD to achieve the objective of the pipeline renewal (Kaplan, 2014). The pipe renewal strategies identified in this study were analyzed based on SCVWD pipeline inventory, and the present value for each renewal approach was determined in order to measure the efficiency of each pipeline renewal strategy for SCVWD implementation. The methodology steps used in this study provided a comprehensive approach to determine the cost-effectiveness of implementing pipeline renewal approaches for SCVWD. Assumptions were made in order to complete the analysis and these assumptions are noted in the analysis section of this study.

Figure 1: Methodology for Analysis of Pipeline Replacement Strategies



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LITERATURE REVIEW

A majority of the water infrastructure in the United States was installed over a hundred years ago, and this infrastructure was often buried underneath community roadways. As the nation's water systems continue to age, the structural condition of the buried infrastructure has become compromised, which can impact the hydraulic capacity of the system and decrease the pipes' performance. The compromised water infrastructure has led to water being wasted from leaking pipes, and from complete pipe failures which have also caused damage to roads and adjacent infrastructure, such as buried utility lines.

Based on studies conducted by the ASCE and the AWWA, the nation's water pipe infrastructure will need to be replaced in the near future, as most of these buried pipelines are reaching the end of their designed service life (AWWA, 2012; ASCE, 2013). As noted in the ASCE and AWWA studies, the cost for replacements of these water pipes will be high; hence, it is important for water utility managers to analyze the condition of their water infrastructure and determine the proper timing of these inevitable pipeline renewals, and develop cost effective renewal strategies that account for and limit the burden of the replacement cost on the water rates paid by individual households.

A majority of the literature available on this topic emphasizes the need for utility managers to develop a sound understanding of the condition of their water infrastructure, so that timely repairs on the pipelines can be undertaken long before the complete failure of the system is realized. The literature also highlights the magnitude of the cost needed to renew the aging drinking water infrastructure, and cost savings from advanced engineering strategies that can be used for pipeline repair and replacement. The literature related to this study has been divided into the following three categories, which will be discussed in the order enumerated below: the need for increased rate of spending, alternatives to traditional replacement, and water infrastructure replacement value.

The Need for Increased Rate of Spending

This category answers the question of why so many American buried pipelines are in need of replacement and provides contextual understanding of key pipeline issues, such as the age of the drinking water infrastructure, impacts of water loss resulting from leaks and pipe breaks, and performance issues with PCCP. A large portion of the SCVWD pipeline inventory is made up of PCCP.

Aging Water Infrastructure and Risk

The potential consequence of failure for aging water infrastructure present risks that result in direct cost to rate payers from the cost of the breakage repair, cost of water lost, cost of direct damage to nearby properties, and liabilities from flooding. In addition to the direct costs, failure of aging water infrastructure also results in indirect and social costs which include the accelerated deterioration of roads and underground utilities, cost of service disruption, cost due to disruption of traffic and businesses affected by the location of the failed pipe, cost due to disruption of service to special facilities, and social costs due to adverse effects of pipe failures on water quality from the intrusion of contaminants into the pipeline (Makar & Kleiner, 2000). One of the most severe social costs impacts from a pipeline failure occurred in Chicago in 1933 where 1,409 people contracted amoebic dysentery from which 98 died (Anderson, 1981).

Often out of sight and out of mind since their installation, the potential risk from aging buried water infrastructure has started to come to the surface, as a number of these facilities begin to reach the end of their service life. In March 2013, a 60-inch PCCP failed in Chevy Chase, Maryland, causing water to gush over 30 feet in the air, and left a 20-foot-deep crater in the roadway. The break in the 33-year-old Chevy Chase pipe resulted in an estimated 60 million gallons of water lost (Shaver, 2013).

Another pipeline failure in the summer of 2014 on Sunset Boulevard, in Los Angeles resulted in the loss of about 20 million gallons of fresh water, and flooded out portions of the UCLA campus, underground parking garages, and drenched the wooden basketball floor of the storied Pauley Pavilion. Damages from this pipeline break are estimated at about $2.5 million from individual claims, and $13 million for damages to UCLA's Pauley Pavilion arena and other parts of the campus (Reyes & Stevens, 2014). At the peak of the pipe failure, about 75,000 gallons of water was lost per minute, which is equivalent to the amount of water needed to serve over 100,000 customers for a day. The water loss placed additional strain on customers, during a time where California was faced with one of its worst droughts in decades, due to diminished hydraulic capacity elsewhere in the system, especially in the hilly areas in and around the UCLA campus (Nicholson, 2014).

The EPA estimates that about 30% of the drinking water infrastructure, which delivers water to more than 100,000 people, is between 40 to 80 years old. Another 10% of these pipes are even older (Kosik, 2011). A large portion of the U.S. water infrastructure dates back to the Civil War era, with a majority of the pipelines installed in three distinct decades: 1880s, 1920s, and 1950s. Pipes installed in the 1880s were generally made from cast iron and had a 120 year design life, whereas, pipes installed in the 1920s were predominantly made of cast iron, and included some cast iron pipes with cement lining, and had a design life of 100 years. Pipes installed following the boom of infrastructure investment of post-World War II typically were predominantly made of cement lined cast iron and asbestos, and had a design life of 75 years (AWWA, 2012; Kail, 2004). Based on the design life of the pipelines installed in these three eras, America is approaching a period of time when three eras of installed pipes will be at the end of their design life at about the same time.

Every 4 years, the ASCE conducts an assessment of the nation's major infrastructure categories. The cumulative condition assessment grade for America's infrastructure in 2013 was a D+, and the water infrastructure category received a D grade (ASCE, 2013). In California, the water infrastructure condition assessment grade dropped from a C+ in 2006, to a grade of C in 2012. A 2012 ASCE analysis estimated that an investment of $4.6 billion would be needed in the water infrastructure through 2022 to raise the grade from a C to a B. Some of the most critical water infrastructure in California is part of the State Water Project, which is more than 40 years old, and the Federal Central Valley Project, which is more than 55 years old (ASCE, 2012). These facilities serve as the main water supply source for many California water agencies and are also critical to the agricultural industry in the State.

Pipeline Leaks and Breaks

The increased age and deteriorated state of the U.S. water infrastructure has brought about unexpected leaks and, at times, complete failures in some of the buried water infrastructure. A majority of the water infrastructure has not been inspected since its installation, and according to the ASCE, the U.S. has an estimated 240,000 water main breaks each year, which amounts to about 700 water main breaks each day. The water main breaks amount to about 7 billion gallons of lost water each day (ASCE, 2013).

SCVWD water infrastructure mostly consists of large diameter raw and treated water pipelines. Large diameter pipelines have a diameter of 36-inches and larger. Experts estimate that the number of large diameter water main failures in the U.S. is about 500 per year, and the average cost of failure is about $500,000 for each incident (Gaewski et al., 2007). In the Bay

Area, it is estimated that water utilities lose about 3 to 16 percent of water treated at drinking water treatment plants due to pipe leaks and breaks. 2010 data collected by the California Department of Water Resources, and analyzed by The Mercury News, estimates that leaks from the Bay Area water providers have resulted in a loss of about 23 billion gallons of water each year, which is enough to provide a year's worth of water to 71,000 families (Krieger, 2014).

Performance of Prestressed Concrete Cylinder Pipe (PCCP)

SCVWD operates and maintains approximately 78 miles of PCCP in its water infrastructure portfolio. PCCP was first used in the US in the early 1940s and was considered to be a viable alternative to welded steel pipe, due to its lower initial cost and the ability for the pipe to be designed for a multitude of internal pipe pressures, loads, and diameters. About 30,000 miles of PCCP were installed in the US and Canada between the 1960s and 1980s (Cromwell, 2002). A majority of the PCCP was produced between 1972 and 1978. There are two types of PCCP that are manufactured – lined cylinder type PCCP and embedded cylinder type PCCP. Embedded cylinder type PCCP is commonly used with most large diameter water transmission facilities (Roller, 2013).

Over time, water utilities began experiencing catastrophic failures with PCCP, due to breaks in the prestressing wires in PCCP that provide strength to the pipe. Multiple prestressing wire breaks in close proximity to each other reduces the pressure capacity that the pipe segment is able to handle, and can result in a catastrophic rupture of the pipe segment. Failures occur without warning and the impacts can include the interruption of service, costly emergency repairs, property damage, and at times threats to life and safety. As a result of these failures, water utilities have been implementing strategies to inspect and monitor the conditions of PCCP (Cromwell, 2002). Rajani, *et al*. (2006) in their study on PCCP emphasized the importance of using certain observed pipeline distress indicators, obtained from routine and scheduled pipeline inspections, to rate the aggregate condition of the pipeline's health. These distress indicators usually manifest themselves physically within the interior or along the surface of the pipeline and its associated appurtenances. Results from the inspections are used by water utilities to make decisions on the repair of distressed pipe sections, and repairs are completed for each pipe section identified. Rajani, *et al*. (2006) states that utilities have chosen to take a more aggressive approach, by choosing to replace several miles of PCCP each year, and have implemented rehabilitation strategies to provide full structural rehabilitation of the pipeline to eliminate the risk of failure.

Alternatives to Traditional Replacement

This category examines some of the advanced engineering repair and replacement strategies that have been developed, which offer water utilities a savings on the replacement cost, when compared to using traditional replacement methods.

The strategies discussed in this study include inserting steel cylinders as a liner inside existing pipe segments, and strengthening existing pipe segments by installing carbon fiber reinforced polymer (CFRP) lining. These strategies have been proven to provide full structural renewal of large diameter pipelines. When pipeline condition assessments find distressed pipe segments, decisions must be made by water utilities to repair or rehabilitate the pipeline to prevent failure of the water infrastructure. Large-diameter pipelines are typically more consequential when they break and therefore require a more proactive strategy to determine the condition of the main and an appropriate renewal strategy. Pipe renewal can be addressed through replacement using conventional open cut methods, repair of the existing pipe segment, or rehabilitation with fully structural pipelining solutions. Rehabilitation of pipelines offers a cost savings in that the excavation of the existing pipe is avoided, as the existing pipe becomes part of the renewal work. Carbon fiber-reinforced polymer (CFRP) and steel sliplining are commonly used rehabilitation methods for large diameter pipelines (Mathews, et al., 2012). Compared to open-cut pipe replacement methods, the potential cost savings for using alternative rehabilitation methods are dependent on how much site restoration activities are minimized, since the rehabilitation work is contained inside the existing pipeline (AWWSC, 2002).

Water Infrastructure Replacement Value

This category discusses the estimated water infrastructure replacement value for the U.S., based on EPA and AWWA studies.

The EPA estimates that 4,000 to 5,000 miles of pipe are replaced each year, but that number will quadruple by 2035, as more pipes reach the end of their design service life. A 2007 EPA needs assessment puts the U.S. water infrastructure replacement value at about $334.8 billion, for a 20-year capital investment need (ASCE, 2013).   A similar study conducted by the AWWA in 2012 concluded that the water infrastructure replacement value for more than 1 million miles of U.S. pipelines was about $2.1 trillion dollars. The AWWA replacement value is higher than the EPA estimate, since the AWWA estimate factors in an increase for water needs due to population growth. In California, the estimated water infrastructure investment need will amount to $126 billion by 2020. By 2040, the capital investment need would increase to $195 billion (ASCE, 2012).

Taken together, the literature highlights the fact that the drinking water infrastructure in the U.S. is reaching the end of its design life, as evidenced by the increased number of leaks and pipe failures that have occurred over the years. This means that significant investments are needed in the water infrastructure in order to inspect, repair, rehabilitate, and replace these aging facilities. The investment in American water infrastructure will require significant efforts by water utilities to analyze cost effective pipeline replacement strategies to help offset severe spikes to household water rates.

FINDINGS

History of SCVWD's Pipeline Management Program

SCVWD conducts routine maintenance on several miles of water conveyance pipelines in its systems. In the past, maintenance activities have been conducted on a case-by-case basis; however, SCVWD pipeline management strategies have been improved over the years, beginning with the first recorded major pipeline inspection and rehabilitation efforts in the 1990s.

1990s to the Mid 2000s

In the years prior to the 1990s, SCVWD pipeline maintenance consisted primarily of preventive maintenance work and the performance of miscellaneous repair activities as needed. Preventive maintenance activities included operating valves, and visual inspection of vaults and above ground appurtenances. These valves and appurtenances were often repaired by field staff if found to be in poor condition. In the late 1990s, SCVWD started to notice an increase in leaks on its appurtenances, which was the result of severe corrosion on threaded connections of the appurtenances. As a result of the increase in leaks, SCVWD expanded its pipeline maintenance program to include internal inspections of its pipelines (Pipeline Management Strategy Work Study Session, 2016).

In the early 2000s, SCVWD developed its first comprehensive strategy for internal pipeline inspections and rehabilitation of all its pipelines. The main objective of the projects that resulted from this effort was to establish a baseline condition for all SCVWD pipelines, to facilitate monitoring efforts over the years and SCVWD to measure the rate of decay of its pipelines, and allowing for the planning of rehabilitation projects for pipelines and appurtenances nearing the end of their useful life. The initial strategy established a schedule for inspecting and rehabilitating all pipelines based on the pipeline age and any known pipeline conditions that may have been noted by staff during routine inspections (Pipeline Management Strategy Work Study Session, 2016).

The first projects under the comprehensive strategy started in 2002, SCVWD's goal was to complete the inspection and rehabilitation of all its pipelines within 10 years; however, SCVWD inspection and rehabilitation efforts were limited due to water retailer system limitations and operational constraints, and it became evident that a complete inspection and rehabilitation of all SCVWD pipelines would take until at least 2017. In the mid-2000s, new technology, known as electromagnetic inspection became available for the inspection of PCCP, which allowed SCVWD to start measuring the number of broken prestressed wires in each segment of PCCP. Electromagnetic inspections use a transmitter to produce an electromagnetic field, and the prestressed wires in PCCP react to this transmission by amplifying the magnetic signal if the prestressed wires are in good condition, or by distorting the magnetic signal if the prestressed wires are broken. The emergence of this new inspection technology, coupled with the limitations SCVWD had experienced with the first few projects in the early 2000s, led SCVWD to revise its pipeline inspection and rehabilitation strategies. The inspection and rehabilitation strategies included developing a long-term program, which identified a large range of pipeline maintenance and rehabilitation activities, and provided protocols and procedures for carrying out pipeline inspection and rehabilitation (Pipeline Management Strategy Work Study Session, 2016).

2007 Pipeline Maintenance Program (PMP)

SCVWD developed a 10-year Pipeline Maintenance Program (PMP) in 2007, which was the first major comprehensive rehabilitation effort for many of SCVWD's raw and treated water pipelines since their construction and placement into service as far back as the 1950's. The PMP identified the inspection and maintenance process for SCVWD pipelines, listed activities, and defined several Best Management Practices (BMPs) aimed at protecting the environment during pipeline inspection and maintenance activities (SCVWD, 2007).

The goals of the program were to have each pipeline in the system inspected at least once, and to reduce the number of unplanned shutdowns and emergency repairs due to pipeline failures and severe corrosion of appurtenance connections. The preventive and remedial maintenance activities associated with the PMP address SCVWD's policies regarding asset management and protection, and also accounts for changes in design guidelines required by State regulatory agencies. Under the PMP, SCVWD has successfully completed the inspection and rehabilitation of over 100 miles of its large diameter raw and treated water conveyance pipelines. A typical pipeline inspection and rehabilitation project takes about a full year to complete, and consists of the following activities (SCVWD, 2007):

- Project definition, planning, and design
- Pipeline shutdown strategy development
- Valve, flowmeter, pipe, and parts procurement
- Environmental clearance and permitting
- Contractor procurement
- Dewatering, dechlorination, and BMPs
- Visual inspection and special inspections, such as electromagnetic inspections
- Maintenance and rehabilitation work
- Cathodic Protection Installation/Upgrades
- Disinfection, refill, and return pipe to service

- Leak inspection and project closure

Cathodic Protection/Corrosion Control and Monitoring

The incorporation of corrosion protection is part of SCVWD’s pipeline maintenance strategy and is aimed at prolonging the life of buried pipelines and vault infrastructure in SCVWD’s system. Corrosion control has been known as an effective method of protecting and extending the life of pipelines and appurtenances, thereby reducing pipeline breaks, associated water loss, and improving public safety. When used and managed properly, corrosion protection has the potential to offer significant savings by deferring replacement of pipe sections and appurtenances, since the pipeline remains in a safe and reliable condition (Pipeline Management Strategy Work Study Session, 2016).

SCVWD corrosion protection strategy uses a combination of good bonded coatings coupled with a well-managed cathodic protection system to protect SCVWD pipelines. Bitumen coal tar and leaded paint coatings have been observed on older pipelines constructed in the 1950s. In the 1960s, corrosion test stations were installed as part of pipeline construction projects. These early corrosion control test stations played a role in static monitoring of pipelines, looking for variations that might be interpreted as possible corrosion. SCVWD also began using non-conductive materials (insulating joints) to separate different pipelines into smaller sections, which helped minimize corrosion cells, and began systematically applying various coatings as an anticorrosion measure (Pipeline Management Strategy Work Study Session, 2016).

In the 1980s, SCVWD began placing large diameter pipelines and tanks under impressed current cathodic protection. The introduction of PCCP in SCVWD’s pipeline inventory presented a challenge, because too much impressed current can actually exacerbate breaks in the prestressed wires in PCCP. SCVWD routinely monitors the corrosion protection on its pipelines in accordance with National Association of Corrosion Engineers (NACE) standards. Each pipeline segment is analyzed to determine the effectiveness of the cathodic protection system, and adjustments and repairs are made to ensure that the cathodic protection systems for critical pipeline segments and tanks are functioning. The majority of the SCVWDs large diameter pipelines are under cathodic protection, with only a few short sections and valve yards remaining unprotected (Pipeline Management Strategy Work Study Session, 2016).

SCVWD PCCP Management Strategy

SCVWD's pipeline management strategy for PCCP currently emphasizes pipeline age, wire break data, and duration since the last pipeline inspection as the basis for decision making on the timing of inspection and renewal of PCCP. Before a pipeline can be inspected and renewed, the pipeline must be drained to allow access for personnel and equipment. Draining a pipeline can take many weeks to complete and presents the largest time constraint and scheduling issue for SCVWD. Scheduling of any inspection and renewal is also influenced by existing water supply agreements in place with SCVWD's water retailers as to the timing in the year and duration the pipeline can be out of service. Other capital projects and maintenance activities can also influence the timing of a pipeline being out of service, in order to avoid the shutdown of multiple SCVWD facilities at once. SCVWD currently conducts an inspection of its PCCP once every 10 years (visual, sounding, and electromagnetic inspection). Current repair and renewal strategies include installation of seals at leaking joints and structurally reinforcing severely distressed pipe sections (SCVWD, 2007).

Best Management Practices for PCCP

In 2012, the Water Research Foundation (WRF) evaluated technologies related to pipeline condition assessments, rehabilitation strategies, and monitoring strategies. The research included an industry survey of water utilities to determine what strategies and technologies were being used. The survey was sent out to 64 water utilities, 23 consultants, and 10 service providers (see Appendix A-1). Responses were received from 15 utilities, one consultant, and one service provider (Zarghamee et al., 2012). The results from the survey, along with literature reviewed for the WRF research, were used to develop a Best Practices Manual for PCCP (Manual). The Manual provides (1) guidance on the selection of pipeline sections for assessment, (2) a summary of the technologies used to identify distressed pipe sections, (3) and guidance on pipeline inspection frequencies.

Selection of Pipeline Sections for Assessment

Selection of pipelines for assessment is based on a ranking of the criticality of the pipeline section. According to the Manual, the criticality of a pipeline sections is determined based on the following (Zarghamee et al., 2012):

- Determine the Consequence of failure (CoF) – The consequence of failure analysis for a pipeline section looks at the impact a pipeline failure would have on public safety, interruption of service, political cost, and the cost to the water utility from a loss of public trust.
- Determine the Likelihood of failure (LoF) – The likelihood of failure is established using all available data on the pipeline section, which includes the pipeline age, design, and historical data, such as failure history and past performance.

- Determine System Constraints – System constraints are determined based on the redundancy of the pipeline system, the amount of time that the system can be taken out of service, and other system constraints such as pipeline dewatering, operational limitations, and access issues.
- Establish Criticality Ranking for Pipeline Sections – Ranking the criticality of pipeline sections can be accomplished using high, medium, and low categories.

Identifying Distressed Pipeline Sections

Results from the industry survey conducted during the preparation of the Manual indicated that the predominant condition assessment technologies used by water utilities are internal and sounding inspections, external visual and sounding inspection, electromagnetic inspection, and over the line corrosivity and corrosion surveys.

Internal Visual and Sounding Inspections

Internal visual inspection is used to identify cracks on the interior of the pipelines and at joints, which could be a sign of additional damage to the prestressing wires that provide strength to PCCP. Observations such as circumferential cracking and openings at joints are recorded during the inspection. In addition to visual inspection, sounding inspections are used to identify hollow areas in the core of the pipeline. Both inspections are performed at the same time and have been used by water utilities since the late 1980s (Zarghamee et al., 2012). SCVWD uses internal inspections on all pipelines in its system, and sounding inspections are only used on PCCP. Preparation efforts needed to allow for internal inspection and sounding include dewatering, identifying and establishing access points, and developing a rescue plan for pipe entry.

External Inspection of Pipe Surface

External pipe inspections can include visual and sounding inspections of the pipe surface. SCVWD also works with specialized consultants to conduct wire continuity test on its PCCP. Wire continuity testing is used as a direct method to detect wire breaks in PCCP. Results from the inspection are often used to verify results from other condition assessment technologies. Although this method requires excavation of the pipeline, the excavation often provides opportunities for collecting samples of the pipeline coating, soil, and concrete lining for laboratory analysis (Zarghamee et al., 2012).

Electromagnetic Inspection

Electromagnetic inspection is a nondestructive method used to identify distressed PCCP sections, by identifying the location and number of wires broken in a pipe section. This information is used to determine the amount of useful life remaining on a pipeline section, and used to make critical decisions regarding pipeline maintenance, repair, and renewal programs (Zarghamee et al., 2012). SCVWD works with specialized contractors to conduct electromagnetic inspections on its PCCP. SCVWD currently uses wire breaks as one of its main bases for the management of PCCP. A majority of SCVWD’s PCCP have been inspected with this method at least once over the past ten years, with the goal of completing a second round electromagnetic inspections in order to establish a rate of decay for SCVWD’s PCCP.

Over the Line Corrosivity and Corrosion Surveys

Over the line corrosivity is used to identify distressed pipe sections by identifying areas along the pipeline with high corrosivity. This method has been in use since the 1980s and although this method does not provide information on the level of distress in a pipe section, information from this survey can be used as an indicator of areas that might require additional attention (Zarghamee et al., 2012). SCVWD's use of this method has been limited thus far.

The costs associated with identifying distressed pipeline sections vary widely depending on the method selected by the water utility, length of pipe, diameter, access to the pipeline, environmental concerns, and many other factors. The costs listed in Table 3 reflect conditions that may vary significantly by regions and from typical projects (Zarghamee et al., 2012).

Table 3: Approximate Costs Associated with Identifying Distressed Pipeline Sections

Item	Unit	Approximate Cost
Internal visual and sounding inspection	Per mile	$2k to $3k
External visual and sounding inspection	Per pipe	$10k
Electromagnetic Inspection	Per mile	$12.5k to $56k
Over-the-line corrosion/corrosivity survey	Per mile	$0.5k to $3k
Acoustic Fiber Optic Monitoring	Per mile per year	$70k to $170k
Dewatering	Per mile per inch diameter	$300 to $500

Source: Zarghamee et. al., 2012, p. 30

Pipeline Inspection Frequencies

Pipelines must be inspected periodically in order to record the condition of individual pipeline sections and allow for decisions to be made on the renewal of any pipeline sections, if needed. SCVWD pipelines are typically inspected once every ten years. The Manual recommends that distressed pipelines or pipelines that were manufactured in the 1970s with Class IV wire and poor coating may need to be inspected more frequently (Zarghamee et al., 2012). On average, an inspection frequency of once every 5 years is recommended in the manual; however, highly distressed pipeline sections nearing the point of rupture could be inspected every 3 years (Zarghamee et al., 2012).

Renewal Strategies of Comparable Water Utilities

Pipeline renewal strategies have been developed over the years to increase the useful life of PCCP for water utilities. The 2012 Manual included a questionnaire with three open-ended questions regarding PCCP risk mitigation. The majority of the water utilities that responded to the survey employed the following three main strategies: (1) remove and replace entire sections of pipe with new pipe, (2) use CFRP to internally reline distressed pipe sections, and (3) sliplining distressed pipe with steel (Zarghamee et al., 2012).

Pipe Section Replacement

Pipe section replacement is used when there are limited to no restrictions to right-of-way or when there are a large number of distressed pipe sections that need to be repaired. This option has a high cost because the cost of excavating and replacing the distressed pipe section with new pipe presents the same challenges that are faced with new construction projects. The cost for this option is often higher when the work takes place in an urban environment. Welded steel pipe is typically used as the replacement pipe material whenever the pipe section replacement option is selected (Rahman et. al., 2012). The estimated cost of this option is $20 per linear foot per diameter based on responses received as part of the 2012 WRF questionnaire on engineering practices on PCCP (Zarghamee et al., 2012, p. 103).

Carbon-fiber-reinforced polymer (CFRP) Lining

The CFRP renewal option has been used since the late 1990s, and was first applied inside a PCCP line at a nuclear power plant in Arizona. Several water utilities have used this option to renew distressed pipe sections in their systems (Rahman et. al, 2012). CFRP liners are suitable for pipelines that are 30 inches in diameter or greater, because manned entry is required to apply the CFRP material inside the pipeline. CFRP liners typically consist of a primer, thickened epoxy, epoxy reinforcing fabric, and a top coat (Pridmore et. al., 2014). The greatest benefit of using CFRP liners is that all the installation work is performed internally, with little to no disruption to above-ground traffic, except at the man-way access point. Cure time for CFRP can take 24 hours or longer, based on how many layers of CFRP are applied to the distressed pipe section (Rahman et. al., 2012). The estimated cost of this option is $40 – $50 per linear foot per diameter based on responses received as part of the 2012 WRF questionnaire on PCCP engineering practices on PCCP (Zarghamee et al., 2012, p. 103).

Steel Sliplining

Steel sliplining involves the insertion of steel pipe to cover full sections of distressed pipelines, which serve as the host pipe. The installation process also involves filling the annular space between the steel sliplining and the host pipe with cement-grout. This renewal strategy is best suited for repairs on nearly straight sections of pipelines and when renewal is needed over long lengths of distressed pipe sections. Although this method has been proven to be simple and relatively inexpensive, this method does result in a reduction of the flow capacity in the pipeline. The estimated cost of this option is $14 per linear foot per diameter based on responses received as part of the 2012 WRF questionnaire on engineering practices on PCCP (Zarghamee et al., 2012, p. 103).

Table 4 provides a summarized comparison of the three renewal options discussed in the findings, and compares impacts related to traffic disruption, environmental and social impacts, and construction duration.

Table 4: Comparison of Renewal Strategies

Repair Method	Traffic Disruption	Environmental / Social Impact	Construction Duration
Pipe Section Replacement	High	High	High
Carbon-fiber-reinforced polymer (CFRP) Lining	Low	Low	Moderate
Steel Sliplining	Moderate	Moderate	Moderate

Source: Rahman et. al., 2012, p. 499.

Table 5 provides a summary of the renewal cost for each strategy discussed in this study. Cost data, along with the technical benefits and limitations for the three renewal options discussed in this study were obtained as part of the 2012 industry questionnaire and survey conducted by WRF (Zarghamee et al., 2012) (see Appendix A-2).

Table 5: Renewal Cost Data Based on 2012 WRF Industry Survey

Renewal Strategy	Technical Benefits	Technical Limitations	Comparative Cost
Pipeline Section Replacement	Effective for repair of pipeline sections. No reduction in internal diameter.	Requires excavation of the pipe. May require field welding of the closure piece. Requires an extensive work area along the pipeline alignment.	$$$ $20 per LF – inch diameter
CFRP Lining	Requires a limited work area. Minimal reduction of the internal diameter. Reduction of surface roughness.	Requires monitoring of CFRP installation.	$$$$ $40 to 50 per LF – inch diameter
Slip Lining of Pipe Section	Effective for repair of nearly straight sections of pipelines. Minimized welding inside the pipe.	Reduction of diameter may results in loss of flow capacity. Requires extensive work area and removal of several pipe sections.	$ $14 per LF – inch diameter

Source: Zarghamee et. al., 2012, p. 120

PCCP Management Strategies of Comparable Water Utilities

The risk of PCCP failures has prompted water utilities to begin implementing strategies to monitor, inspect, and repair or replace distressed PCCP sections. The strategies often consists of either a localized repair and/or a comprehensive replacement approach, based on the consequence of failure, risk of failure, and associated Lifetime Total Costs of the approach utilized (Coghill, 2013; Faber et al., 2012). Localized repairs consists of the removal and replacement of distressed sections of PCCP with steel pipe, or use of CFRP, while comprehensive replacement consists of the replacement of full sections of PCCP with collapsible steel cylinder reliners (Kenny & Rahman, 2014). Water utilities with PCCP management strategies now exist across the United States in agencies such as Washington Suburban Sanitary Commission on the east coast, to the Metropolitan Water District of Southern California on the west coast (Foellmi et. al., 2015).

Washington Suburban Sanitary Commission (WSSC)

Washington Suburban Sanitary Commission (WSSC) was established in 1918 and ranked as the 8th largest water and wastewater utility in the United States. WSSC pipeline network consists of nearly 5,600 miles of fresh water pipeline and over 5,400 miles of sewer pipeline. WSSC's service area spans nearly 1,000 square miles in Prince George's and Montgomery counties in Maryland, serving 1.8 million residents. WSSC operates approximately 145 miles of large-diameter PCCP equal to or greater than 36-inches in diameter (Pure Technologies, n.d.).

WSSC's PCCP management strategy consists of Geographic Information System (GIS) maps of the pipeline network, and a risk rating system, which assigns a score for each section of PCCP. The score is the result of an empirical formula, which accounts for a number of risk factors such as operational needs, known manufacturing defects, repair history, date last inspected, pipe diameter, and land use. The risk score is used to establish the order for future inspections. At the current schedule, WSSC inspects 18 miles of pipe per year, with each pipe section inspected once every 6 years. Pipe inspections consist of leak detection, pipe draining, visual and sounding inspection, and an inspection for wire breaks in the pipeline. WSSC utilizes a localized repair approach, where pipe sections found to be distressed are either replaced or repaired using CFRP. WSSC is also using continuous monitoring technology to monitor wire break activity in the pipeline until the next inspection. Less than 2 percent of WSSC's pipe segments have been found to be in need of replacement or renewal (WSSC, 2014). This percentage is in line with research conducted by Pure Technologies, a leader in the development of innovative inspection technology for pipelines, who have conducted extensive research and collected data on over 500 miles of PCCP, and found that the average distress rate is less than four percent, with about 1.4% in need of immediate repair. The study concludes that 98.6% of PCCP sections are found to have no damage or low levels of damage and low risk of failure (Higgins et. al., 2012).

Metropolitan Water District of Southern California (MWDSC)

The Metropolitan Water District of Southern California (MWDSC) was formed in 1928 and is a regional wholesaler that delivers water to 26 member public agencies – 14 cities, 11 municipal water districts, one county water authority – which in turn provides water to more than 19 million people in Los Angeles, Orange, Riverside, San Bernardino, San Diego and Ventura counties. MWDSC provides 40 to 60 percent of Southern California's water supply (MWDSC homepage, n.d.). MWDSC operates approximately 163 miles of PCCP in its system, ranging in diameter from 30 inches to over 200 inches (Metropolitan Water District General Obligation Refunding Bond, 2015).

The initial components of MWDSC's PCCP management strategy were established in 1996 and consisted of pipeline inspection, protection, evaluation, and repair. MWDSC inspects 35 to 40 miles of its pipelines each year for wire breaks, with inspections conducted on a 5-year cycle. In addition, MWDSC is using cathodic protection to protect its pipelines, and conducts corrosion surveys every 1 to 2 years. Repairs and replacements were completed on an individual basis, and through December 2014, MWDSC had spent $65.3 million, and had estimated that continued use of a localized repair approach could result in more than $5.5 billion in costs (Foellmi et. al. 2015).

MWDSC's revised long-term PCCP management strategy includes a system to rank and prioritize PCCP sections based on risk. The revised strategy utilizes a comprehensive replacement approach, which consists of the systematic replacement of the most at-risk pipelines from the ranking by relining the PCCP with steel cylinders. This approach was analyzed to be more cost effective than conducting periodic inspections and repairs (Foellmi et. al., 2015). The first stage of this effort would replace 30 miles of PCCP, over an 8 to 10-year period, and cost approximately $500 million. The estimated cost to reline all 100 miles of MWDSC's PCCP is about $2.6 billion (Metropolitan Water District General Obligation Refunding Bond, 2015). A similar approach has been undertaken by the San Diego County Water Authority (SDCWA), which has completed the relining of over 40 miles of the 83 miles of PCCP in its system. The SDCWA program is for 30 years, with a budget of $780 million (Northwest Pipe Company, n.d).

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ANALYSIS AND CONCLUSION

The intent of this study is to evaluate pipeline renewal strategies that would be most cost effective for SCVWD to implement. In addition, recommendations are provided for the improving of SCVWD's PCCP management strategies. The recommendations and analysis discussed below are based on identified gaps in SCVWD's current PCCP management strategy, based on a review of best management practices (BMPs) and PCCP management strategies currently being implemented by comparable water utilities.

PCCP Management Program

A major finding in this study is the need for SCVWD to establish a comprehensive program for the management of PCCP. The components of the management program would address (1) inspection to establish a baseline of the current condition of the pipe and record the rate of degradation, (2) evaluation to identify any areas in urgent need of repair and determine the approximate remaining life of the pipe section, and (3) repair or replacement methodologies. Achievement of these objectives would be gained through the use of strategies such as proper data management, risk rating, pipe inspections, use of appropriate assessment technologies, and the implementation of a cost-effective renewal approach.

A comparison of the findings of this study indicate that SCVWD is using some of the BMPs and strategies of comparable water utilities for PCCP management; however, there are certain strategies that would be beneficial for SCVWD to implement. The table below shows the strategies in use among the comparable water utilities reviewed for this study, as well as the BMPs developed as part of WRF's 2012 research for PCCP (Zarghamee et al., 2012).

Table 6: PCCP Management Strategies Comparison

	WSSC	MWDSC	SCVWD	BMPs
Data Management	Visual mapping of pipelines (GIS map) used for CoF. LoF from pipe age, wire breaks, and known pipe defects.		LoF determined based on pipe age and wire breaks.	Establish factors CoF, LoF, system constraints, and factors from condition assessment (wire breaks, failure analysis).
Established Risk Rating System	Empirical formula and risk rating system to prioritize inspections	Rank and prioritize PCCP sections based on established risk rating system.	None	Establish ranking criteria of critical pipeline sections (e.g. use high, medium, and low categories).
Pipeline Inspection Frequency	18 miles of pipe per year, 6 year inspection cycle.	35 to 40 miles of pipe per year, 5 year inspection cycle.	Varying lengths of pipeline per year, 10 year inspection cycle.	Once every 5 years or every 3 years for highly distressed pipeline sections
Inspection Technology Utilized	Leak detection, internal visual and sounding inspection, and EM inspection for wire breaks	EM inspection for wire breaks, and corrosion surveys every 1-2 years.	Internal visual inspections and EM inspections for wire breaks.	(1) Internal visual and sounding, (2) external visual and sounding, (3) EM inspections, and (4) over-the-line corrosion/ corrosivity survey
Renewal Strategies Implemented	Pipe sections are either replaced or repaired using CFRP	Systematic replacement of most at risk pipe sections by relining PCCP with steel cylinders.	Pipe sections are replaced with steel pipe, repaired with CFRP, or welded steel liners.	(1) Remove and replace entire sections of pipe with new pipe, (2) CFRP lining of distressed pipe sections, and (3) sliplining distressed pipe with steel.

Source: Data for WSSC from Pure Technologies, n.d., for MWDSC from Foellmi et. al., 2015, for SCVWD from SCVWD, 2007, and BMPs from Zarghamee et al., 2012.

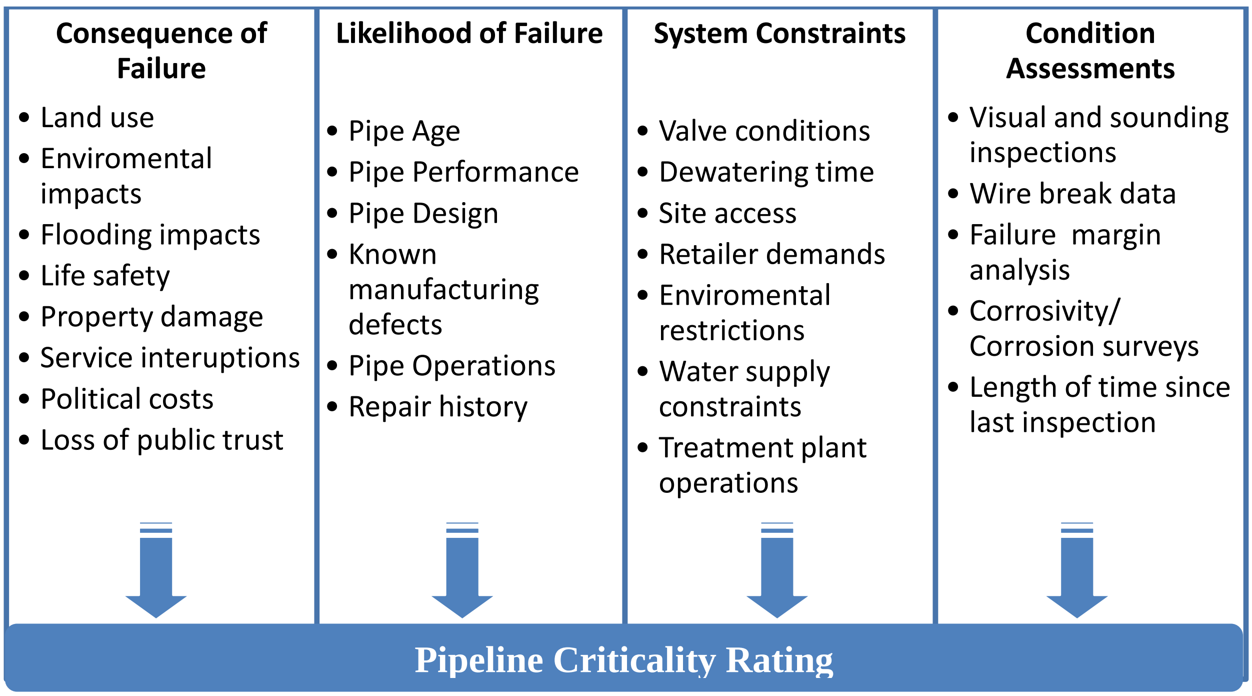
Data Management

To assist SCVWD's data management for PCCP, SCVWD should leverage the use of maps in GIS and use the maps to make determinations on the consequence of failure for each PCCP section in its system. If SCVWD leveraged the GIS mapping of the pipelines, it would assist them in understanding the relationship between the PCCP in the ground and the land above. Factors for the consequence of failure should include land use, environmental impacts, and potential impacts from flooding. In addition, factors beyond wire breaks, pipe age, and the duration since the last pipe inspection are needed in order to update SCVWD's pipeline management strategies for the likelihood of a PCCP failure. Repair history and known manufacturing defects such as the type of joints and class of the prestressing wire used, and system constraints should be documented for each pipe segment and used to determine the likelihood of failure for each section. System constraints and data from previous condition assessments should also be collected for each pipe section.

Risk Rating System

As shown in the Findings, SCVWD has not implemented a risk ranking system for PCCP management. A risk rating system should be developed using the likelihood of failure, consequence of failure, system constraints, and condition assessment factors collected from the data management efforts. WSSC uses a risk rating system to develop a safety analysis score, which is used for rating pipelines 36 inches in diameter and larger, and this model could be adopted by SCVWD. Alternatively, SCVWD could adopt a tool developed by WRF to provide water utilities with a method to integrate the cost of failure into decision making on asset management (Grigg et. al., 2013). The risk rating system should be performed for each section of pipe to identify any areas in urgent need of repair and determine each section's probability of failure. The development of a tool or empirical formula for calculating the rating for all PCCP would guide SCVWD decisions makers on prioritizing which pipe sections need to be inspected and renewed.

Figure 2: Risk Rating System Development Flow Chart



Pipeline Inspection Frequency

The pipeline inspection frequency for PCCP should be revised from 10 years to 5 years, to match the inspection frequency listed in the Manual (Zarghamee et al., 2012) and to be in line with comparable water utilities. This would require increasing the length of inspections each year from approximately 8 miles to 16 miles. Operational and budgetary considerations would need to be further explored in order to determine whether such an aggressive inspection schedule is feasible for SCVWD to implement for its PCCP.

Inspection Technology

The use of electromagnetic inspection for the identification of wire breaks in PCCP is a practice used by comparable water utilities and is a recommended BMP. SCVWD should continue to use electromagnetic inspections in order to identify wire breaks in PCCP. SCVWD should also include the use of leak detection and internal sounding of the pipeline with each inspection.

Renewal Strategies

Pipeline renewal strategies vary from one water utility to another and from one region to another. SCVWD has implemented CFRP, steel liners, and the removal and replacement of distressed and/or failed pipe sections in its system. Renewal strategies should be in accordance with a long term strategy to replace longer reaches of distressed pipe sections versus repairing pipe sections individually. The actual renewal strategy implemented would be based on the land use in the area of the pipe section, i.e. open land areas, urban areas, major roads, and similar features.

Cost-effectiveness Analysis

Cost-effectiveness analysis is used to determine "the least expensive" way to achieve a given objective; hence, the cost-effective analysis is used in this study since the benefits from pipeline renewal strategies are the same. For this study, a renewal strategy is cost-effective if, on the basis of the lifetime total cost analysis of competing strategies, it is determined to have the lowest costs expressed in present value terms. The cost-effective analysis in this study is based on direct cost to SCVWD, as indirect cost require much more effort to determine, and social cost are often difficult to quantify and would require more research (Makar & Kleiner, 2000).

Pipeline Dewatering and Inspection Cost

A cost estimate for dewatering and performing a complete cycle of inspections of the District's PCCP is shown in the table below. The cost estimate covers a five-year inspection period, and assumes all SCVWD PCCP pipelines would be inspected at least once during the five year timeframe. The cost estimate assumes SCVWD would need to mobilize two separate pipeline inspection teams per year, to complete the inspection of all PCCP in its pipeline network. Tables

7 and 8 show the dewatering and pipeline inspection cost estimate for SCVWD's PCCP. Unit cost data information for dewatering and pipe inspection were obtained from the 2012 WRF industry survey (Zarghamee et al., 2012, p.103).

Table 7: Pipeline Dewatering Cost Estimate

Pipe Diameter	Length	Unit Costs	Total
DEWATERING EXPENSES ($500/mile/inch diameter)			
60 inches	4.75 miles	$30,000	$142,500
66 inches	15 miles	$33,000	$495,000
72 inches	14.5 miles	$36,000	$522,000
78 inches	14.5 miles	$39,000	$565,500
96 inches	20.7 miles	$48,000	$993,600
120 inches	7.9 miles	$60,000	$474,000
SUBTOTAL DEWATERING EXPENSES			**$3,192,600**
Engineering Support and Administration (15%)			$478,890
TOTAL DEWATERING EXPENSES (2012 dollars)			$3,671,490
TOTAL DEWATERING EXPENSES (2016 dollars)			**$3,950,814**

Source: Data for dewatering cost per mile per inch from Zarghamee et al., 2012 and SCVWD pipe length and diameter data from SCVWD, 2007.

Table 8: Pipeline Inspection Cost Estimate

Description	Quantity	Unit Costs	Total
Leak Detection Inspection	77 miles	$11,000	$850,850
Internal Visual and Sounding Inspection	77 miles	$17,000	$1,314,950
Electromagnetic Inspection	77 miles	$25,000	$1,933,750
Mobilization and Reporting (assume 30% markup)			$1,229,865
SUBTOTAL PIPE INSPECTION EXPENSES			**$5,329,415**
Engineering Support and Administration (15%)			$799,412
TOTAL PIPE INSPECTION EXPENSES (2012 dollars)			$6,128,827
TOTAL PIPE INSPECTION EXPENSES for a 5-year cycle inspection program (2016 dollars)			**$6,595,102**

Source: Data for SCVWD pipe length and diameter data from SCVWD, 2007 and pipe inspection expense data from Zarghamee et al., 2012.

The cost estimate above would be applicable to any renewal approach implemented by SCVWD and includes an additional 15% of the total costs of the pipeline dewatering and inspection to account for contract administration and engineering support. In order to update the 2012 cost estimate to 2016 dollars, the 2012 cost estimate is multiplied by an inflation rate of 1.85%. The inflation rate used in this study was determined based on data from the United States Bureau of Labor Statistics, on the average annual inflation rates from 2012 to 2016 (see Appendix A-4). The cost estimate does not include items such as traffic control and permitting costs.

No Action/Status Quo Approach

Under the "No Action/Status Quo" approach, the frequency of PCCP condition assessments would remain on a 10-year cycle with distressed pipe section renewal occurring during each inspection. Under this approach, SCVWD would conduct no more than two pipeline inspections per year, on pipelines of varying lengths. Renewal of distressed pipe sections would be completed using a localized repair approach, and would involve open cut and replacement with steel pipe, repair with CFRP, or the use of welded steel liners, depending on the ease of access to the distressed pipe section. This approach is not consistent with BMPs, since the approach does not meet standards currently being used by comparable water utilities due to the 10-year cycle between pipe inspections.

Inspection and Localized Repair Approach

The "Inspection and Localized Repair" approach increases the frequency for the inspection of all PCCP in the system from a 10 year to 5-year cycle, with distressed pipe section renewal occurring during each inspection. The cost for implementing this approach includes the costs necessary to dewater, inspect the pipeline, and renew any distressed pipeline segments found during the inspection for the lifetime of the pipeline, based on the assumption that 98.6% of the pipelines inspected will be in a good condition, while 1.4% of the pipelines would require renewal (Higgins et. al., 2012). This approach also includes annual cost for a third party acoustic monitoring for the lifetime of the pipeline. The cost information used in this study to analyze this approach are based on 2012 WRF industry survey information collected (Zarghamee et al., 2012) and reflects water utility experiences that may differ from typical projects.

In addition to pipeline inspection and dewatering cost, this approach also includes cost for acoustic monitoring of the pipeline, which would be required for the lifetime of the pipeline. Installation costs for acoustic monitoring includes the cost for cables, hardware, and third party monitoring cost, estimated at $100,000 per mile of cable installation, $350,000 per computer for every 10 miles of cable installed, and annual third party monitoring costs of about $13,000 per mile (Litterski, 2013; Zarghamee et al., 2012). A breakdown of the acoustic monitoring costs is provided in Table 9.

Table 9: Acoustic Monitoring Cost Estimate

Description	Quantity	Unit Costs	Total
Installation Cost			
Fiber cable installation	77 miles	$100,000	$7,735,000
Monitoring Hardware	8 units	$350,000	$2,800,000
TOTAL INSTALLATION COST (2013 dollars)			$10,535,000
TOTAL INSTALLATION COST (2016 dollars)			**$11,130,577**
Monitoring Cost			
3rd Party Monitoring Cost per year (2013 dollars)	77 miles	$13,200	$1,021,020
ANNUAL 3rd Party MONITORING COST PER YEAR (2016 dollars)			**$1,078,742**

Source: Acoustic monitoring cost data for from Litterski, 2013 and Zarghamee et al., 2012. SCVWD pipe length and diameter data from SCVWD, 2007.

The pipeline renewal strategies analyzed under the inspection and localized repair approach includes open-cut replacement and CFRP. The analysis uses cost data from the 2012 WRF industry survey (Zarghamee et al., 2012). The unit cost obtained from the 2012 WRF industry survey data and used in this analysis for open-cut replacement and CFRP was $20 and $40 per linear foot – inch diameter respectively (Zarghamee et al., 2012). The analysis assumes a 50 year project lifecycle for the lifetime total costs of this approach. Table 10 provides cost estimates for the renewal strategies for this approach. The cost in the table includes an additional 15% of the total costs of the repair approach to account for contract administration and engineering support. Also, the 2012 cost estimate was updated to 2016 dollars, using a 1.85% inflation rate.

Table 10: Inspection and Localized Repair Approach Cost Summary

Diameter (inches)	Assumed Length of Distressed Pipe in feet	Open-cut Replacement	CFRP
60	352	$422,400	$844,800
66	1,109	$1,463,880	$2,927,760
72	1,072	$1,543,680	$3,087,360
78	1,072	$1,672,320	$3,344,640
96	1,531	$2,939,520	$5,879,040
120	584	$1,401,600	$2,803,200
SUBTOTAL LOCALIZED REPAIR APPROACH FOR ONE CYCLE OF 5 years		**$9,443,400**	**$18,886,800**
Engineering Support and Administration (15%)		$1,416,510	$2,833,020
TOTAL LOCALIZED REAPIR EXPENSES FOR ONE CYCLE (5 YEARS) IN 2012 dollars		$10,859,910	$21,719,820
TOTAL LOCALIZED REAPIR EXPENSES FOR ONE CYCLE (5 YEARS) IN 2016 dollars		**$11,686,121**	**$23,372,241**
TOTAL DEWATERING EXPENSES (2016 dollars)		$3,950,814	$3,950,814
TOTAL PIPE INSPECTION EXPENSES for a 5-year cycle inspection program (2016 dollars)		$6,595,102	$6,595,102
TOTAL LOCALIZED REPAIR COST OVER ONE 5 YEAR CYCLE		**$22,232,037**	**$33,918,157**
Acoustic Monitoring Installation Cost		$11,130,577	$11,130,577
Annual 3rd Party Acoustic Monitoring Cost		$1,078,742	$1,078,742
TOTAL LIFETIME COST OVER 50 YEARS		**$506,717,446**	**$718,640,011**

Source: Data for SCVWD pipe length and diameters from SCVWD 2007 and pipeline renewal cost data from Zarghamee et al., 2012.

Comprehensive Replacement Approach

The pipeline renewal strategy used for the comprehensive replacement approach is the use of steel sliplining. The analysis uses cost data from the 2012 WRF industry survey and estimates the costs for steel sliplining at $14 per linear foot – inch diameter (Zarghamee et al., 2012). Total lifetime cost for this approach assumes bond financing at a 5.5% interest rate and a 30 year lending period. The analysis includes the cost for one initial round of inspections, to prioritize the order of repairs, and dewatering in order to perform the required repairs. Table 11 provides cost estimates for the comprehensive replacement approach.

Table 11: Comprehensive Replacement Approach Cost Summary

Diameter	Length (miles)	Length (feet)	Steel Sliplining
60	4.75	25,080	$21,067,200
66	15	79,200	$73,180,800
72	14.5	76,560	$77,172,480
78	14.5	76,560	$83,603,520
96	20.7	109,296	$146,893,824
120	7.9	41,712	$70,076,160
COMPREHENSIVE REPLACEMENT APPROACH			$471,993,984
Engineering Support and Administration (15%)			$70,799,098
TOTAL COMPREHENSIVE REPLACEMENT APPROACH COST IN 2012 dollars			$542,793,082
TOTAL COMPREHENSIVE REPLACEMENT COST IN 2016 dollars at 1.85% inflation rate			**$584,088,206**
TOTAL DEWATERING EXPENSES (2016 dollars)			$3,950,814
TOTAL PIPE INSPECTION EXPENSES for a 5-year cycle inspection program (2016 dollars)			$6,595,102
TOTAL COMPREHENSIVE REPLACEEMNT APPROACH COST			$594,634,122
TOTAL LIFETIME COST OVER A 30 YEAR LENDING PERIOD			**$1,237,966,906**

Source: Data for SCVWD pipe length and diameters from SCVWD 2007 and pipeline renewal cost data from Zarghamee et al., 2012.

The cost in the table above includes an additional 15% of the total costs of the pipeline dewatering and inspection to account for contract administration and engineering support. In order to update the 2012 cost estimate to 2016 dollars, the 2012 cost estimate is multiplied by an inflation rate of 1.85%.

Economic Implications

The cost of a properly managed pipeline network is often less than the cost associated with pipe failures or the cost of implementing an unnecessarily conservative renewal strategy. The annual cost for the selected pipeline renewal approach would need to be funded by SCVWD through the cost per acre-foot of water consumed by SCVWD's municipal and industrial users. These costs would be passed on to the wholesalers, and ultimately to the consumers, who would need to understand the increased cost of water as an investment in system reliability and safety. In order to determine the revenue required to implement either pipeline renewal approach, the annual cost for each approach is distributed into the total water consumed by municipal and industrial water. For this study, the total volume of water used by SCVWD municipal and industrial users is about 201,000 acre-feet, based on data from SCVWD's FY 2015-16 Protection and Augmentation of Water Supplies report.

Table 12: Pipe Renewal Revenue Requirement per Acre-foot

Renewal Strategy	Lifetime Total Cost over 50 years	Equivalent Annual Expense over 50 years	Revenue Requirement per Acre-Foot
Localized Repair Approach			
Open-cut Replacement	$506,717,446	$6,246,838	$31
CFRP	$718,640,011	$8,859,430	$44
Comprehensive Replacement Approach			
Steel Sliplining	$1,237,966,906	$15,261,718	$76

Source: Data for pipeline renewal cost data from Zarghamee et al., 2012, dewatering costs, and pipe inspection expense data from Zarghamee et al., 2012.

The revenue requirements per acre-foot of water consumed represents the amount water rates would need to be increased in order to fund a PCCP renewal approach for SCVWD. For the purpose of this study, the total lifetime cost for implementing PCCP renewal approaches were spread out over a 50 year project period for cost comparison purposes, and assumes an inflation rate of 1.85%.

Conclusion and Recommendations

It is recommended that SCVWD leverage use of GIS mapping of its pipelines, to assist with understanding the relationship between the PCCP in the ground and the land use above the pipeline. This would help SCVWD with the decision making on the consequence of failure for each PCCP section in its system and the information could be used to and establish a risk rating system to guide decisions on what pipe sections are in need of urgent repair. It is also recommended that SCVWD revise its pipeline inspection frequency to a 5-year cycle on its PCCP to be in line with BMPs and comparable water utilities. The operational needs of the SCVWD system would need to be evaluated in order to determine the feasibility of implementing such an aggressive inspection schedule for PCCP.

The cost-effectiveness analysis found that the Localized Repair approach using open-cut replacement or CFRP would be the most cost effective strategy for SCVWD to implement. This approach would reduce the risk of pipeline failures and would be more sustainable in terms of lifetime total costs and economic implications to rate payers. In some areas, steel sliplining may also be installed, but as noted in the Findings, use of steel sliplining is most suited for straight sections of pipe, where there is enough area to establish access pits for the steel cylinders used for the slip lining, and in areas where there are multiple distressed pipe sections in close proximity.

The distress rate used for the cost-effectiveness analysis in this study assumes 1.4% of pipelines inspected would be in need of immediate repair. As SCVWD completes more cycles of inspections on its PCCP, an assessment of the pipe degradation rate would need to be completed, as an increase in the distress rate would influence whether it is most cost-effective to continue using a Localized Repair approach, or whether to switch to a Comprehensive Replacement approach for all PCCP in the system.

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APPENDIX A

Appendix A - 1: List of 2012 WRF Survey Respondents

Responding utility, consultant, and service provider

Responding Utilities	Abbreviation
The City of Calgary	Calgary
North Texas Municipal Water District	NTMWD
Cleveland Division of Water	CDW
Greater Cincinnati Water Works	GCWW
San Patricio Municipal Water District	SPMWD
Howard County Department of Public Works	HCDPW
San Diego County Water Authority	SDCWA
Metropolitan Water District of Southern California	MWDSC
Aurora Water	Aurora
Central Arizona Project	CAP
Halifax Water	Halifax
Calleguas Municipal Water District	Calleguas
Tarrant Regional Water District	TRWD
Greater Lawrence Sanitary District	GLSD
City of Montreal, Québec, Canada	Montreal
Chicago Department of Water Management	Chicago
Responding consultant	**Abbreviation**
Jason Consultants	Jason
Responding provider	**Abbreviation**
NDT Corporation	NDTC

Source: Zarghamee et al., 2012, 103

Appendix A - 2: 2012 Survey Response Regarding Cost/Benefit of Renewal Strategy

Part IV. c – What are the costs and benefits associated with each strategy used?		
Costs and benefits of pipe replacement	Replacement of two pipes at a time is very expensive, but easy to budget because we have very few high risk pipes.	Aurora
	Open cut replacement costs roughly $30,000 to $40,000 per spool.	HCDPW
	Pipe replacement: costly but we've very experienced in this method. Requires extensive work area and sometimes traffic control.	Calleguas
	Costs of steel replacement: Estimate: $20/(LF - in diameter); $1,920/LF for typical 96 in. PCCP	MWDSC
	Benefits of steel replacement: significantly reduce risk of failure and improve reliability of pipeline; provides opportunity to conduct full forensics on distressed pipe; no loss of ID.	MWDSC
	Replacement with steel pipe: Eliminates the need for replacing the entire pipeline and allows steel to be used in areas with soils with known high sulphate content.	Calgary
	The cost of a steel pipe replacement is approximately $100k to $200k depending on location and is for construction costs only. Benefit is long life expectancy to localized (single pipe) repairs. A section of pipe can be replaced in a short period of time, typically 6-10 days.	SDCWA
Costs and *benefits* of CFRP repair	Carbon fiber: most expensive but quick and easy to construction. Limited work area is required.	Calleguas
	The carbon fiber wrap is expensive, but it appears that it's working so far. Unfortunately a segment we didn't wrap failed in 2009. Did we prevent a segment from failing by wrapping it, most likely, but we still didn't prevent the main from failing.	CDW
	The cost of a carbon fiber reline is approximately $6,580/lf (based on 96 in. pipe). Benefit is minimal impact to communities or environment. Sections can be repaired in 3-4 days.	SDCWA
	Carbon fiber lining increases considerably the structural strength of the pipe and doesn't need a lot of subsequent maintenance, but it remains a costly method	Montreal
	Cost of carbon fiber liner: Estimate (6 layers): $40-50/(LF – in diameter); $4,800/LF for typical 96 in. PCCP.	MWDSC
	Benefits of carbon fiber liner: excavation not required, beneficial where excavation or steel liner is difficult; reduce risk of failure and improve reliability of pipeline.	MWDSC
	CFR in the past has costs $50,000 to $65,000 per spool.	HCDPW
	The cost for carbon fiber can be quite expensive and is only a reasonable repair solution when the added cost of disruption from replacement is considered.	Jason
Costs and benefits of steel lining repair	Steel liner installation: cheapest method but some work area is required.	Calleguas
	The cost of sliplining with steel is increasing yearly. In 2003, about $660/lf, in 2004, $830/ft2, in 2005, $915/ft2, and in 2006, $1,040/ft2. Current estimate is about $1,400/lf. The benefit is that it is the most long term solution for large section of a pipeline.	SDCWA

Source: Zarghamee et al., 2012, p. 120

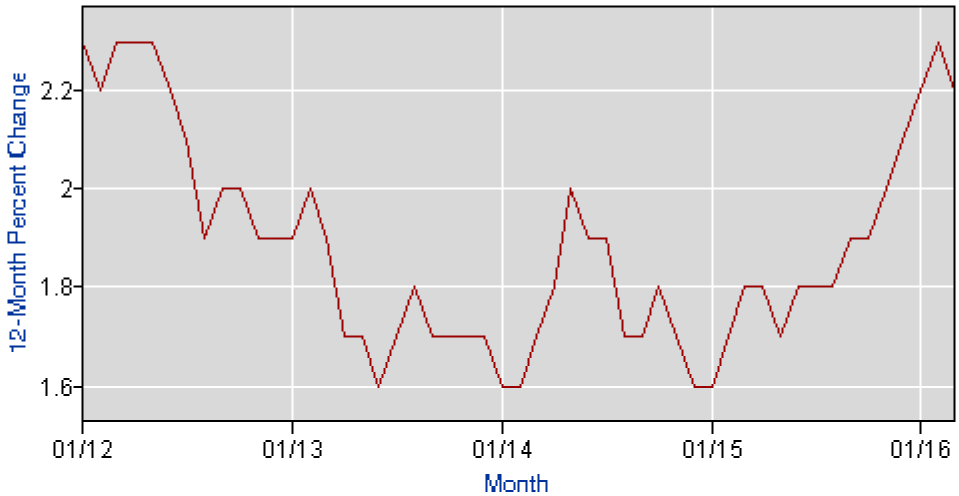
Appendix A - 3: Summary of Mitigation Strategies from 2012 WRF Survey

Subject of Response	Response	Author
Part IV. a – What strategies have you used for extension of service life?		
Pipe replacement	Pipe replacement	Calleguas
	Replaced 4.5 miles of 252-inch-diameter Agua Fria, New River, and Salt River siphons by 1997.	CAP
	Replace distressed pipe sections with steel	MWDSC
	Replacement of single "high priority" pipes.	Halifax
	Repair or remove damaged segments based on condition assessment	TRWD
	Replacement of high risk pipes with steel pipe.	Aurora
	Replaces PCCP with steel pipe on those sections deemed to be "severely" distressed.	SDCWA
	If the pipe location allows for open cut excavation, the pipe will be excavated and replaced.	HCDPW
	We are replacing 24-inch pipe with PVC after a service life of 57 years.	SPMWD
	Removing pipes with excessive wire breaks and replacing them with steel.	Calgary
Repair with steel liner	Highly distressed pipe have been sliplined with steel pipe	Jason
	Steel liner was applied to 1,000 ft of 252-inch diameter NCP	CAP
	Line distressed pipelines with steel	MWDSC
	Steel liner installation	Calleguas
	The Water Authority's preferred choice to extending PCCP service life is steel slip-lining. Of 82 miles of PCCP, approximately 27 miles have currently been slip-lined with the remaining to be lined by 2030. The remaining schedule for relining is based on the condition assessment reports, RFTC surveys, and acoustical monitoring.	SDCWA
Repair with carbon fiber reinforce polymer liner	Carbon fiber relining of PCCP to rehabilitate those sections of PCCP deemed "severe" in which replacement with steel sections is not feasible due to economic or environmental concerns.	SDCWA
	Carbon fiber lining	Calleguas
	Carbon fiber lining	Montreal
	Carbon Fiber Wrap	CDW
	Carbon Fiber Repairs	CAP
	If the pipe location does not allow for open cut excavation, the pipe will be carbon fiber repaired (CFR).	HCDPW
	Highly distressed pipe have been repaired using carbon fiber lamination	Jason
	Line distressed segments with carbon fiber	MWDSC

Source: Zarghamee et al., 2012, p. 117.

Appendix A - 4: Rate of Inflation for 2012 to 2016

12-Month Percent Change
Series Id: CUUR0000SA0L1E
Not Seasonally Adjusted
Area: U.S. city average
Item: All items less food and energy
Base Period: 1982-84=100



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Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	HALF1	HALF2
2012	2.3	2.2	2.3	2.3	2.3	2.2	2.1	1.9	2.0	2.0	1.9	1.9	2.1	2.2	2.0
2013	1.9	2.0	1.9	1.7	1.7	1.6	1.7	1.8	1.7	1.7	1.7	1.7	1.8	1.8	1.7
2014	1.6	1.6	1.7	1.8	2.0	1.9	1.9	1.7	1.7	1.8	1.7	1.6	1.7	1.8	1.7
2015	1.6	1.7	1.8	1.8	1.7	1.8	1.8	1.8	1.9	1.9	2.0	2.1	1.8	1.7	1.9
2016	2.2	2.3	2.2												

Source: United States Bureau of Labor Statistics.