Economic Analysis of Prestressed Concrete Cylinder Pipe Maintenance

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Acronyms and Abbreviations

$M	Millions of dollars
2020$	Dollar value reported at a 2020 price level
AF	Acre foot/feet
ASCE	American Society of Civil Engineers
CAP	Central Arizona Project
CCT	Reclamation's Construction Cost Trends index
CGB	DOI's California-Great Basin Region
CLIN	Contract line item number
CPN	DOI's Columbia-Pacific Northwest Region
DOI	United States Department of the Interior
EUAC	Equivalent uniform annual cost
FY2021 Planning Rate	Fiscal Year 2021 interest rate in the formulation and evaluation of plans for water and related land resources
Ft	Feet
HCDPW	Howard County Department of Public Works
LC	DOI's Lower Colorado Basin Region
LCC	Lifecycle cost analysis
LF	Linear foot/feet
MBA	DOI's Missouri Basin and Arkansas-Rio Grande-Texas Gulf Regions
mi	Mile(s)
M&I	Municipal and industrial water supply
MWDSC	Metropolitan Water District of Southern California
NPV	Net present value
Reclamation	Bureau of Reclamation
S&T	Science and Technology
sqft	Square foot (or feet)
TSC	Reclamation Technical Service Center
UC	DOI's Upper Colorado Basin Region
yr	Year(s)

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Executive Summary

The periodic costs associated with the condition assessment and maintenance of prestressed concrete cylinder assets represent an ever-increasing proportion of Reclamation's and/or a managing Water District's operation and maintenance budget. Using a least cost analysis, the goal of this research is to investigate the economics associated with performing periodic condition assessment and repairs throughout the service life of a Reclamation owned PCCP asset and compare those with the cost of a failure in the same asset. An analysis of three asset management scenarios was conducted and concluded the following:

- Both proactive asset management strategies were indicated to be more cost effective over the lifespan of an asset than the reactionary asset management approach
- Gradual implementation of high expense monitoring techniques is slightly more cost effective than wholesale early adoption
- Preponderance of literature indicates that CFRP is the most expensive replacement and lining technique. Replacement with steel sections and liners are indicated to be most cost-effective and commonly used, while still achieving a very long service life.
- Economic results are based on relatively conservative damages and lost benefits estimates, even for the high-cost iterations, indicating that the cost savings due to proactive management might be much higher.
- AFO DAQ ownership is more cost-effective than lease in all but a few situations. The payback period (years to breakeven) for ownership is highly dependent on the number of miles installed; the more miles installed, the shorter the payback period for ownership.
- Failure location and in turn, consequence of failure, largely impacts most economical asset management strategy due to end user water benefits as well as whether the debris results in property damages.
- The economic analysis indicates that proactive monitoring and repair saves nearly 50 percent on costs over the long-term, when using mid-range cost inputs

The economic analysis finds that proactive management scenario for a hypothetical PCCP asset modeled on the Santa Clara Conduit saves over $13 million over the period of analysis—an annualized savings of nearly $400,000. These savings would be multiplied many times over if applied to Reclamation's PCCP inventory. In summary, the study provides strong evidence that avoiding proactive monitoring and repair measures saves on upfront costs but can cost considerably more in the long run.

1 Introduction

Reclamation utilizes roughly 80 miles of mostly large diameter prestressed concrete cylinder pipe (PCCP) assets for water conveyance. The periodic costs associated with the condition assessment and maintenance of PCCP assets represent an ever-increasing proportion of Reclamation's and/or the managing Water District's operation and maintenance budget, including an ongoing program out of Reclamation's Office of Policy to conduct electromagnetic (EM) inspections on PCCP. EM inspection is the primary method of condition assessment able to quantify the distress of a given PCCP asset by determining the number and location of broken prestressing wires within the asset. Although many factors go into the need for a robust condition assessment plan, there is an outstanding question on the economics of conducting periodic inspections and repairs versus waiting for the pipe to fail and performing an emergency replacement.

The goal of this research is to investigate the economics associated with performing periodic condition assessment and repairs throughout the service life of a Reclamation owned PCCP asset and compare those with the cost of a failure in the same asset. The research will look at the cost of three PCCP asset management scenarios:

1) Baseline No Action: Operation of a PCCP asset without condition assessment or maintenance until eventual failure in service, prompting an emergency repair.
2) Gradual Implementation of Monitoring: Condition assessment with EM and gradual implementation of monitoring as well as maintenance of the PCCP asset at prescribed intervals throughout service life.
3) Early Implementation of Monitoring: An initial condition assessment with EM followed by complete implementation of monitoring and maintenance of the PCCP asset at prescribed intervals throughout service life.

Site-specific factors can vary widely and have a significant impact on the cost of both scenarios; some of those factors include:

- population density or geographic remoteness,
- proximity to civil infrastructure,
- special access requirements,
- system redundancy,
- impact of water loss to agricultural clients.

To narrow the scope of this case study, the investigation was limited to one regional site as a basis for assessment. The feature selected for investigation, the Santa Clara Conduit (SCC), was based upon having both a history of using EM inspections and having experienced a failure in 2015. Direct failure costs were provided by project partners at Valley Water; however, economic impacts and operation and maintenance costs were not included. Where information was either not provided or unavailable, additional information from the available literature was utilized for estimation.

2 Literature Review

2.1 PCCP Overview

PCCP is a composite pipe consisting of a concrete core helically wrapped by a pre-stressed wire that is covered with a layer of mortar. Frequently, a steel cylinder either lining the concrete core or embedded within it is used as an impenetrable membrane. Both types of PCCP containing cylinders can be seen in Figure 2-1. In either design, the compressive stresses generated by the pre-stressed wires wrapping the concrete core are utilized to offset the internal pressures generated in service. The mortar coating plays a critical role in providing corrosion protection to the wires.

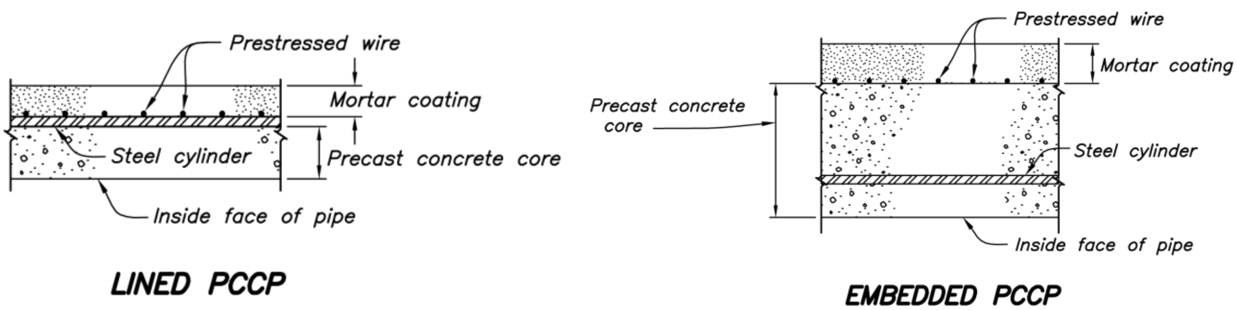

Figure 2-1. PCCP cross sections. Left: Lined cylinder type PCCP, Right: embedded cylinder type PCCP

PCCP was first installed in the United States in 1942; a steel scarcity due to World War II led to adoption of the techniques for prestressing concrete to be used in pressure pipes. It was estimated that from adoption in 1942 to 2007, over 100 million feet of PCCP had been produced, with peak production occurring in 1971 (Romer, Ellison, Bell, & Clark, 2008). Of the PCCP produced, nearly 72 percent was of the lined cylinder type between 16 and 60 inches while the embedded cylinder type was reserved for pipe greater than 32 inches in diameter. Over time, changes to design standards and materials have occurred which have impacted the performance of pipes. It has been noted that design standards were initially conservative and then were gradually changed to increase manufacturing efficiencies which also increased stress level in the pipe at working pressures and reduced the margin for error (Romer, Ellison, Bell, & Clark, 2008).

Eventually PCCP assets began to fail, frequently catastrophically. The cause of failure is typically the corrosion and failure of the prestressing wires after cracks develop in the mortar coating; the cracks allow an ingress of water which leads to the corrosion. As the wires corrode their ability to offset the internal operating pressure of the pipe is increasingly compromised until eventual failure occurs. The cracks can develop by any number of mechanisms such as improper handling during installation, improper bedding, excessive loading by the operation of heavy machinery over buried assets, and manufacturing defects, but the result is ultimately corrosion of the prestressing wires which then leads to failure.

2.1.1 BOR Assets

Reclamation's inventory of pipelines includes roughly 80 miles of PCCP which are summarized in Table 2-1 below. It can be seen in the table that the majority of PCCP was installed in the late 1980's to early 1990's in two projects: the Central Arizona Project, and the Central Valley Project. All sections of PCCP within these projects are in areas of low to medium population density and are of the embedded cylinder type PCCP. Roughly 15 percent of Reclamation's total inventory of PCCP lies within high density population regions.

Table 2-1. Reclamation PCCP Inventory

State	Project	# PCCP Sections	Length (miles)	Percent of Total (%)	Urban Density	Construction Year(s)
AZ	Ak-Chin Indian Water Rights Settlement	3	8.8	10.98	Low	1981
AZ	Central Arizona	20	25.3	31.66	Low-Medium	1980-1992
AZ	Salt River	3	5.5	6.85	Low-High	1992
CA	Central Valley	6	30.4	38.05	Low-Medium	1984-1987
CA	Ventura River	3	4.8	6.02	Low - High	1958
WA	Columbia Basin	1	1.1	1.41	Rural	1976
CO	Dolores	7	3.1	3.91	Rural – Low	1982-1992
UT	Central Utah	1	0.9	1.13	Rural	1987
	TOTAL:	**44**	**80**	**100**		

2.2 Asset Management

2.2.1 Risk Analysis

Reclamation employs a risk-based methodology as part of its approach towards PCCP asset management. For this approach, each section of pipe is given a specific risk rating based on the product of consequence of failure and likelihood of failure. Numerical values are assigned to each variable and where the result lies on a risk matrix determines both the overall risk and what actions, if any, should be taken. An example risk matrix can be seen in Table 2-2 where the actions required at each risk level are as follows:

- Monitor the pipe segment: Monitor the pipe segment by periodic visual, sounding, and EM inspections, as well as corrosivity testing, etc.
- Better understand the pipe segment: Better understand the pipe segment by increasing the monitoring and frequency of the segment, understanding soil resistivity, incorporating acoustic monitoring, perform data collection, finite element analysis, transient analysis, etc.
- Take Action: Take action by repairing or replacing the pipe segment, changing the loading conditions of the pipe segment, reduce the long-term risk of the pipe segment, etc.
- Take Immediate Action: Take immediate action on a pipe segment by procuring a replacement segment, restricting the flow and/or load on the pipe segment, communicate the risk and plan for rehabilitating the pipe segment, etc.

Table 2-2. Risk matrix

		Consequences of Failure				
		1	2	3	4	5
Likelihood of failure	5	Risk Ranking 4: Taking Action on the pipe segment may be appropriate	Risk Ranking 5: Take Action on the pipe segment	Risk Ranking 5: Take Action on the pipe segment	Risk Ranking 6: Take Immediate Action on the pipe segment	Risk Ranking 6: Take Immediate Action on the pipe segment
	4	Risk Ranking 3: Better Understand the pipe segment	Risk Ranking 3: Better Understand the pipe segment	Risk Ranking 4: Taking Action on the pipe segment may be appropriate	Risk Ranking 5: Take Action on the pipe segment	Risk Ranking 6: Take Immediate Action on the pipe segment
	3	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 2: Better Understanding of the pipe segment may be appropriate	Risk Ranking 3: Better Understand the pipe segment	Risk Ranking 3: Better Understand the pipe segment	Risk Ranking 3: Better Understand the pipe segment
	2	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 2: Better Understanding of the pipe segment may be appropriate	Risk Ranking 2: Better Understanding of the pipe segment may be appropriate	Risk Ranking 2: Better Understanding of the pipe segment may be appropriate
	1	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 1: Monitor the pipe segment	Risk Ranking 1: Monitor the pipe segment

Factors that go into the determination of the likelihood of failure include wire breaks, location of the breaks, design of wire spacing, internal pressure, reserve capacity based on demands and pipe capacity, external loading potential, local terrain, soil conditions, environmental factors, and structural characteristics such as year of pipe manufacture and wire class. Factors that go into the determination of consequence of failure include proximity to: existing structures, populations, powerlines, gas lines, other utility crossings, protected/sensitive environments, as well as system redundancy, end use, and temporary or current construction crossings. Design pressure class can be considered to both increase the likelihood of failure and have a more severe consequence of failure, especially when combined with proximity to densely populated areas.

Using a risk-based methodology is generally considered a cost-effective means of asset management. The methodology reduces unnecessary repairs, maximizes service life, and allows resources to be applied only where needed (Zarghamee, Ojdrovic, & Nardini, 2012).

2.2.2 Condition Assessment

An accurate determination of risk for each section of a PCCP asset relies upon condition assessment for informing the likelihood of failure. Numerous condition assessment techniques are available; however, the focus of this report will be limited to three of the most common: visual and sounding, EM inspection, and acoustic fiber optic (AFO) monitoring. For a more detailed overview of PCCP condition assessment technologies, the reader is directed to Torrey (2019).

2.2.2.1 Visual and Sounding Inspection

Typically used as an initial inspection, visual inspections serve to qualitatively describe the apparent condition of an asset and identify areas of concern for further investigation by more advanced, quantitative inspections. Areas of concern may include staining, corrosion, leakage, cracks, and spalling. While the inspection itself is simple in practice, dewatering and scheduled downtime, as well as safety precautions, are required for inspector access to the interior of the pipe. This can add complexity and cost to this technique (Torrey, 2019).

Sounding is commonly completed during the visual inspections to gain additional insight about the condition of an asset. At its most basic, sounding, is simply tapping the wall of an asset with a tool such as dead-blow hammer and listening for changes in sound; for example, a delaminated area may sound "hollow" or make a lower pitched thud. Instead of relying on human hearing, microphone type systems can also be incorporated that more quantitatively describe the response to the tapping. The simplicity of the examination makes it a cost effective and viable option for the initial inspection of long stretches of pipe. The expense of the inspection is more weighted by the activities outside of the inspection itself such as dewatering and shut down. An industry survey reported on by Zarghamee et al, indicates that visual inspections and sounding cost between $2,000-$3,000 2012$ per mile excluding outside costs (Zarghamee, Ojdrovic, & Nardini, 2012). It should be noted however, that while this cost is generally low, the expense and logistical complexity of dewatering and shutting down a section of pipeline for manned entry do not typically warrant a visual and sounding inspection alone. Typically, these inspections are scheduled during routine maintenance or alongside more advanced inspections.

2.2.2.2 Electromagnetic Inspection

EM inspection is widely used for quantitative condition assessment of PCCP assets. The inspection requires specialized equipment that trained personnel use to identify both the location and number of broken prestressing wires in an asset. For this technique, alternating current is applied to the asset that induces a current in the prestressing wire; that current can then be detected and analyzed to determine the state of distress in the prestressing wires (United States Patent No. US6127823A, 1997). Using this data to inform structural analysis, the overall condition of an asset can be estimated. The inspection can take place either in service using unmanned equipment, as shown in Figure 2-2, or manually, as shown in Figure 2-3.

Figure 2-2. EM inspection tool being lowered into Dolores siphon for unmanned EM inspection

Figure 2-3. EM inspection of Pleasant Valley Discharge Line

Typically, EM inspections are used to form a baseline condition assessment and are then regularly performed at scheduled intervals. Due to the high cost of such inspections, the scheduled intervals are usually on the order of years apart if the initial assessment of the asset is found to be in good condition. The frequency of inspections typically increases as the number of broken prestressing wires detected increases.

Both the specialized equipment and highly trained personnel required for EM inspection make the technique costly. Responses to the industry survey conducted by Zarghamee, et al. indicated that costs of inspection can range from $12,500-56,000 per mile (Zarghamee, Ojdrovic, & Nardini, 2012). Reclamation has experienced higher costs than those reported, the EM inspection cost of roughly 25 miles of PCCP of varying diameter across three separate sites averaged $99,000 per mile; however, a detailed breakdown of costs was not identified within the industry survey that would allow for direct comparison. For example, in addition to the EM inspection, Reclamation was also provided with visual and sounding inspection as well as structural and risk analysis within the same contract, these all contribute to an increased overall cost.

2.2.2.3 Acoustic Fiber Optic Monitoring

Acoustic fiber optic monitoring can be used to quantitatively monitor changes in asset condition. For this inspection, fiber optic cable is placed inside the asset to be monitored and connected to a data acquisition system. As prestressing wires break, the energy released causes vibrations that distort the fiber optic cable which causes changes in the reflected light within the cable. Those changes in reflected light are then detected by the data acquisition system and the wire break event is recorded (Higgens & Paulson, 2006). This inspection technique detects prestressing wire breaks as they occur, so in addition to the number and location of wire breaks, the rate of wire breaks can also be determined. This is valuable because it is frequently observed that the rate of prestressing wire breaks increases prior to failure; with an automated notification system, advanced warnings can be provided to appropriate personnel.

As part of an asset management program, AFO can be used to maximize service life. With a known baseline condition, such as after an EM inspection has been completed, the overall condition of an asset can be monitored in near real time. That condition assessment can then be used to update risk calculations on a continual basis and once the risk of failure for an asset reaches a pre-defined level, the asset can be taken out of service and repaired or replaced.

Capturing costs related AFO monitoring require consideration of both the initial capital investment of the system as well as ongoing costs for continuous monitoring by third party contractors. Data acquisition systems (DAQ) can be leased or purchased outright adding complexity to the analysis.

As of 2017, San Diego County Water Authority utilizes AFO to monitor over 36 miles of PCCP. Beginning in 2006 and up to 2013, SDCWA installed eight separate AFO systems and captured over 1,400 wire break events. The cost of the systems varied in part due to installation length; the overall average cost of all eight installations was $154,000 dollars per mile while the cost of installations greater than 4 miles averaged nearly half of that at $67,000 per mile. In addition to the baseline EM inspection, initial capital costs for the AFO system included: mobilization, installation labor, fiber optic cable, a DAQ that was purchased, cable splicing, system initialization while ongoing costs included: monitoring costs priced per foot per month for the purchased system, annual DAQ OM&R per unit, and telephone support billed annually. Initial capital costs for the DAQ systems averaged $365,000 per unit, a price that could be avoided by leasing, pipeline shutdown costs of $100,000 for the first mile and $55,000-$75,000 for each additional mile, and the baseline EM inspection of $20,000 per mile plus $35,000 for each mobilization. Ongoing costs were a monitoring fee of $0.20 per foot per month for an owned DAQ ($0.50 per foot per month for a leased system), annual DAQ OM&R of $21,525 per unit, and telephone supported billed annually (Faber, 2017).

As of 2019, the Washington Suburban Sanitary Commission (WSSC) has the largest AFO monitoring program in the United States with 100.5 miles of PCCP being monitored. WSSC serves over 1.8 million residents with a water system that includes 145 miles of 36 inch and greater PCCP. AFO monitoring is the final phase of a six-phase PCCP condition assessment program that cycles every five years. The program's phases are: prioritize, plan/prepare, collect data, evaluate data, replace/rehab, and monitor. Beginning around 2007, the amount of PCCP monitored by AFO has grown annually, averaging 20 additional miles installed and monitored per year between 2012 and 2018. Since 2009, WSSC's PCCP condition assessment program has cost a total of $122 million dollars. Of that, inspection and assessment were $44 million, pipe rehabilitation was $50 million, and AFO monitoring was $28 million. The warning provided by the AFO system was credited with preventing 20 failures saving an estimated direct cost of $32 million dollars at $1.6 million dollars per failure (Carpio, Acevedo, & Rodriquez, 2019).

2.3 Repair

Data obtained through condition assessments can be used to inform risk assessments. Once a predefined level of risk has been reached, intervention through repair or replacement becomes necessary. The most common repair and rehabilitation strategies for PCCP are the use of steel liners, carbon fiber reinforced polymer (CFRP), and full section replacement.

2.3.1 Steel liners

Steel lining of an PCCP asset can be achieved by either relining or sliplining with steel. The steel relining process requires cylinder halves, known as "collapsible cylinders" or "split cans," to be brought into the pipe section and welded together from within to form a continuous section of pipe. For the slip lining process, preconstructed sections of pipe are slid inside the existing asset. This requires that the preconstructed sections are of a smaller diameter to allow for clearance which results in a decreased capacity of the repaired pipe but simplifies installation. In both cases, welding is used to connect adjoining sections; however, the additional welding required in the relining process adds both time and labor to the process (Rahman, Smith, Mielke, & Keil, 2012). Because the repair can be completed from within the host pipe, excavation is not necessarily required at the site of the repair, although access to bring in the repair materials at some point along the length of the pipeline is still required. Steel lining is generally considered a long-term, cost-effective solution for the rehabilitation of long sections of PCCP. The repair is structurally independent and capable of achieving an internal burst strength equal to or greater than the PCCP being repaired for up to 100 years (Rahman, Smith, Mielke, & Keil, 2012).

In 2014, the city of Phoenix undertook the rehabilitation of 6,262 linear feet (LF) of 90-inch PCCP. The work was a construction manager at risk (CMAR) project on the Val Vista Water Transmission Main which delivers roughly 220 million gallons per day to upwards of 60% of the city's population. Steel relining with 87" split can pipe was selected for 3,812 LF of the rehabilitation, while the remaining 2,450 LF was repaired by slip lining with 84" solid can pipe. The work was constrained to take place during low demand months between November and April and to minimize impact on the community which also included minimizing traffic control issues. The final cost of the construction was $12.1 million dollars, roughly $1900 per LF of repair with all activities included (Market & Kratochvil, 2016).

2.3.2 Carbon Fiber Reinforced Polymer

CFRP linings have been used to restore the structural integrity of PCCP since the 1980's. (Zarghamee, Engindeniz, & Wang, 2013). For this repair, the lining is brought into the host pipe through standard manholes in rolls of carbon fiber sheets that are pre-impregnated with resin. These sheets are then adhered to the interior of the host pipe and built up by hand with several layers. After curing, the lining is structurally capable of meeting the internal stress demands of service operations. In addition to material costs, the process is labor intensive and results in an overall costly repair that currently limits industry wide adoption. Because the repair is manual, the minimum diameter for feasible repair is 24 inches (Zarghamee, Engindeniz, & Wang, 2013). The advantages cited for the technique are that existing manholes can be utilized, materials are flexible and easy to transport until applied and cured, work can be completed on a tight schedule and with a short lead time, the repair requires a minimum staging area and has minimal impact on traffic, the repair does not significantly affect water carrying capacity of the host pipe, and CFRP is resistant to corrosion (Pridmore & Ojdrovic, 2015). Cost data for CFRP is not readily available. In the industry survey reported on by Zarghamee, et al; representatives from SDCWA and Metropolitan Water District of Southern California (MWDSC) provided cost estimates of approximately $6,580 and $4,800 per foot of 96-inch PCCP (Zarghamee, Ojdrovic, & Nardini, 2012). Reclamation's experience on the SCC was significantly higher than this with the repair of two 24-foot sections of PCCP costing $445,000 equating to $9,270 per foot of repair, although it should be noted that this was for an emergency repair and expediting repairs usually comes at a higher expense.

2.3.3 Replacement

Full replacement of a PCCP section is necessary after catastrophic rupture but can also be an economically viable option under the right conditions, such for instances where the section can be readily excavated. The two options for replacing a section of PCCP are to replace with another like section of PCCP, or to replace with steel section of pipe. From an industry survey, the latter option was more frequently chosen (Zarghamee, Ojdrovic, & Nardini, 2012). Survey responses from MWDSC indicated that a typical steel replacement for a 96-inch section of PCCP costs approximately $1,920/ft while another from Howard County Department of Public Works (HCDPW) indicated open cut replacements cost between $30,000 and $40,000 per spool, which assuming an average spool length of 24 feet, works out to approximately $1,250 to $1,660 per foot. (Zarghamee, Ojdrovic, & Nardini, 2012).

2.4 Failures

As previously noted, the ability of a PCCP asset to withstand internal forces is dependent upon the compressive strength provided by the prestressing wires. As those prestressing wires corrode or break by other means, the compressive strength is lost, leading to eventual failure. Failures can be catastrophic due to the sudden loss of compressive strength associated with the wire breaks.

In an effort to establish if there were patterns in leaks and breaks of PCCP assets, Romer and Ellison compiled a database of 593 independent PCCP failures. It was noted that the largest percentage, 43%, of failures occurred in PCCP manufactured between 1972 and 1978 with the highest probability of catastrophic rupture occurring between 1992 and 2006. It was indicated in the report that pipes produced in this era by the manufacturer Interpace had the highest rate of catastrophic failures per sticks produced, primarily due to the high strength “class IV” wire used for manufacture. The database also showed that non-catastrophic failures of embedded cylinder type PCCP were reported five times more frequently than lined cylinder type PCCP; although it was noted in the report that the data could be skewed because lined cylinder type PCCP was primarily used for small diameter PCCP and may not have been reported as frequently as the higher profile large diameter PCCP (Romer, Ellison, Bell, & Clark, 2008). Considering both the number of catastrophic failures of PCCP and total amount of un-failed pipes produced for the manufacturing era between 1971-91, the probability of failure at 10 and 100 years was calculated to be just 2.18×10^{-3} and 7.81×10^{-3} percent (Romer, Ellison, Bell, & Clark, 2008). Most of Reclamation’s PCCP inventory was manufactured in this era, and while the numbers presented are statistically representative of the dataset analyzed, Reclamation’s own experience with failures does not align with this expected probability. Considering the experience of WSSC previously cited, the AFO system prevented what would have been 20 failures over the 100.5-mile total length of PCCP in 10 years (Carpio, Acevedo, & Rodriquez, 2019). This is roughly equivalent to 2 repairs, or potential failures, every 5 years for 20 miles of PCCP. Assuming a 24 ft PCCP section length, the percentage of the total pipeline that would have failed in a ten-year period is roughly 0.09 percent which provides an indication of variability between data sets.

Research recently conducted on behalf of Reclamation under Congressional Direction at Virginia Tech was completed that provided a comprehensive review of the United States’ national water pipeline infrastructure which included a database of PCCP assets. With the data grouped by manufacturing years prior to 1964, between 1964 and 1984, and after 1984, it was found in the national failure statistics that PCCP greater than 36 inches in diameter had an average time to failure of 36.8 years, 40.2 years, and 11 years for each respective grouping (Sinha, 2021). As well, it was determined that the mean service life for all PCCP greater than 36 inches was 65 years. Of the PCCP greater than 36 inches in diameter that is currently in service, it was found through qualitative and quantitative analysis that around 60 percent are about to reach the end of this service life. The optimal replacement time for this same group was found to be between 43 and 59 years of age (Sinha, 2021). Reclamation’s PCCP inventory has an average age of 37 years with a range between 29 to 63 years. The oldest of these PCCP assets were inspected by EM in 2020 and of the 1,569 pipe sections inspected, only 6 pipe sections had anomalies consistent with broken prestressing wires. Further, it was found that each of those six sections had only 5 wire breaks each. No remedial action was proposed; however, it was noted that in addition to the 1,569 pipe sections, there were three suspected non-PCCP replacement pipes. No additional information was available about these sections of pipe; however, assuming they were in fact replaced sections, the rate of failure for this section would be about 0.2 percent. Overall, the results of the inspection indicate that Reclamation’s experience does not align with the general statistics presented in the literature.

2.4.1 Economic Impacts

A key factor to deciding whether to proactively inspect and rehabilitate or replace an existing pipe is the direct economic cost in the event of a failure. A compilation and analysis of the costs associated with 30 large diameter pipe failures across North America was conducted by Gaweski et al. (2007). The primary type of pipe material for the 30 failures was cast iron (14), followed by pre-stressed concrete cylinder pipe (PCCP) (11), followed by steel (4) and one PVC pipe. The study examined total costs incurred in the event of a pipe failure. The results showed a range of approximately $6,000 to $8,500,000 with an average total cost $1.7 million (2006$). Due to the large range in total costs the geometric mean was calculated to be $500k per failure. The total cost of all 30 failures was $52 million (2006$). Of the $52 million total cost (2006$) ~75% of total failure cost was attributable to claims paid for property damage by utility, property damages paid by others (homeowners, insurance companies, etc.), traffic disruption, and customer water outage.

Gaweski et al. (2007) examined the various factors that impact total cost of pipe failures. Location of the failure, in terms of urban, suburban, or rural setting, was determined to be the most significant factor in total costs. Highly urban areas tended to have higher total costs due to factors such as property damage from flooding, traffic disruption and costs related to water outages. The next important factor in total cost was total gallons lost as a result of the failure. Of the 30 failures identified in the study, PCCP pipe failures lost an average of approximately 10 million gallons per break, compared to the second highest gallons lost, cast iron pipes, at ~3 million gallons per break (Gaweski, Peter E.; Tata and Howard Inc.; Blaha, Frank J.;, 2007).

In May 2016, the Navajo Nation's Navajo Agricultural Products Industry (NAPI) experienced a failure of the Kutz Siphon. The pipe failure discharged at a rate of about 1,000 cubic feet per second (cfs) into the San Juan River. There was approximately 75,000 acres of agricultural land that was without irrigation service; water was rationed to priority crops. NAPI estimated $17,500,000 in loss of crop revenue, plus additional impacts: reduced NAPI labor force (~100 jobs), reduced water access to community livestock needs, reduced contracted services to small businesses that rely heavily on crop output, reduced direct services provided by the Navajo Nation and its surrounding businesses (Duke, 2017).

3 Case Study – Santa Clara Conduit

3.1 Site Background

The SCC is part of the San Felipe Water Delivery System that conveys Central Valley Project water to Santa Clara and San Benito counties serving primarily municipal and industrial users. Construction of the SCC was completed in three sections by three different contractors between 1982 and 1987. Total construction costs, including the Coyote Pumping Plant, were just over $51.2 million dollars (Whynot & Simonds, 1994). The 21-mile conduit is composed of 24-foot long, 96-inch diameter sticks of embedded cylinder type PCCP that were installed beginning in 1984. The pipe uses class III pre-stressing wire covered in 1 inch of mortar to achieve a design pressure of 152 pounds per square inch (psi) and conveys roughly 100 cubic feet per second of raw water under normal operating conditions (Ndah & Crowley, 2016).

In 1991, of the 61,000 acre-feet (AF) of water delivered to end users, 46,000 AF went to non-agricultural users, while just over 15,000 AF went to agricultural customers. In 1991, the combined value of the crops grown by end users in San Benito and Santa Clara counties was $71.9 million for an average crop value per acre of $2,955 and $4,198 respectively (Whynot & Simonds, 1994).

3.2 Failure and Repair

On August 1st, 2015, a section of PCCP within the SCC ruptured resulting in an estimated loss of over 20 million gallons of water and impacting Santa Clara and San Benito Counties' water supply for over a month. The failure was located on private property within a mile of highway 152 near Casa de Fruta, California in a remote area without vehicle traffic. The pipe failed below its design pressure at an operating pressure of 125 psi (Keim, 2016). To provide perspective on the magnitude of this failure, the ruptured pipe section was originally buried 6 feet deep and debris from the failure was still found up to 200 feet away.

The failure occurred following the power failure of a nearby pump station leading to a transition from operating conditions to static head conditions after the power failure and subsequent valve closures. Investigation included metallography, tensile testing, and scanning electron microscopy on the broken prestressing wires as well as petrographic investigation of the concrete core and mortar coating. Reclamation's Technical Service Center (TSC) concluded that the failure was due to the service environment, the chain of events, and the condition of the pipe at the time of failure (Keim, 2016).

Prior to failure, in 2007, an EM inspection of the system had found 15 pipe sections with between 5 and 30 wire breaks. The ruptured pipe section was observed to have had 30 wire breaks. A follow up inspection was recommended 5 years later to monitor changes in condition; however, this testing was not completed due to operational constraints and concerns about the spread of zebra mussels. It was reported elsewhere that pipeline dewatering for inspection can require up to 6 weeks and is considered a risk on older pipelines that are more susceptible to failure when they are fully pressurized and depressurized (Ndah & Crowley, 2016).

Shortly after failure, an EM inspection (as well as sounding and visual inspection) was conducted on 3,661 feet of PCCP near the ruptured section and found one pipe section with 50 wire breaks and 30 wire breaks in another, up from 10 and zero wire breaks in these same sections from the 2007 EM inspection. The ruptured pipe section was replaced with a spare cement mortar lined steel pipe that was buried as part of the original 1984 installation and provided by Reclamation. The distressed sections found during the post failure condition assessment were also repaired at the time using CFRP (Ndah & Crowley, 2016).

Following the repairs, programs and policies were updated to prevent or minimize the impact of further failures. Steps taken included: increased inspections from every 10 years to every 5 years based upon condition, developing failure and structural analysis models as well as risk assessment tools, and the development of on-call service contracts for CFRP and other repair services to aid in prompt repair. As of 2021, no subsequent failures have occurred on the line.

3.3 Cost of SCC Failure

3.3.1 Direct Costs

The costs associated with the 2015 failure of the SCC were provided by Valley Water, formerly Santa Clara Valley Water District. The data collected is summarized in Figure 3-1.

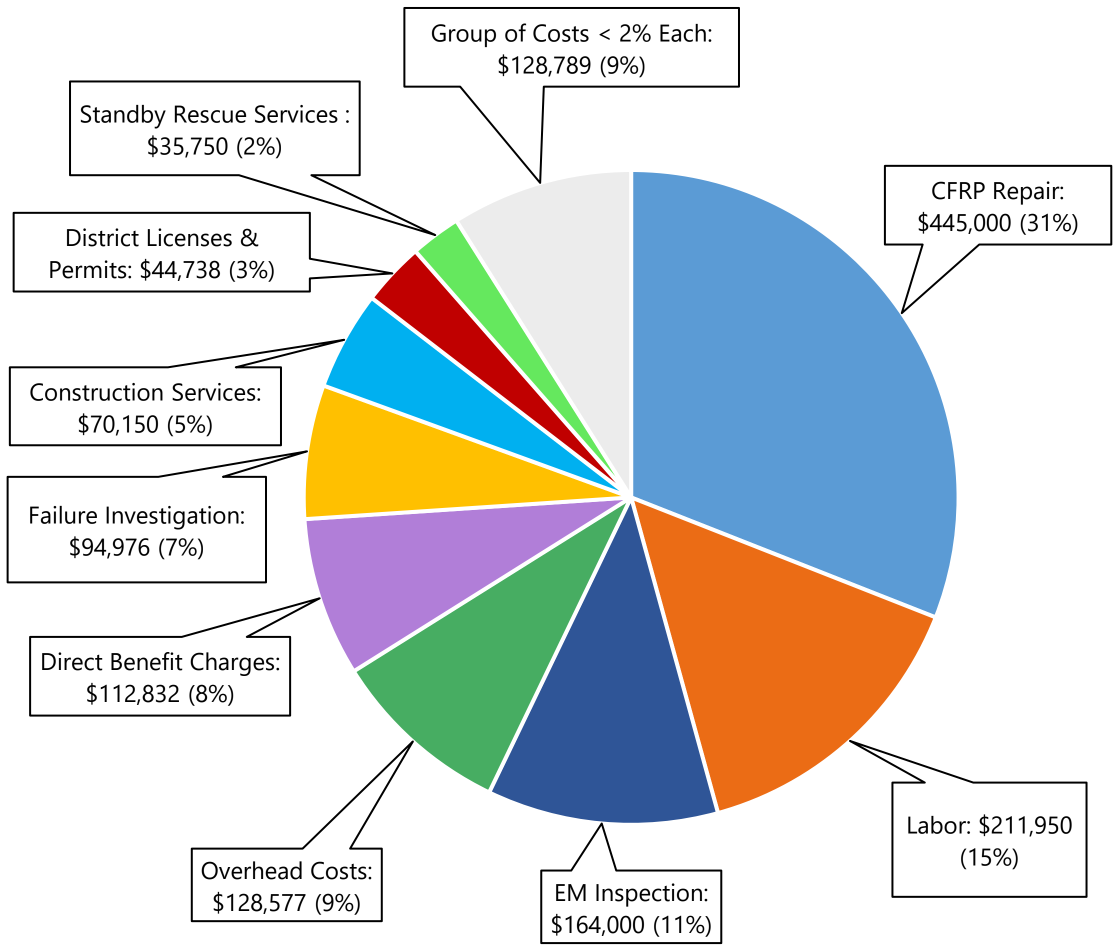

Figure 3-1 Summary of direct costs associated with the 2015 SCC failure

In total, the costs directly associated with the failure were $1.4 million dollars. Nearly one third of the costs associated with the failure were related to use of CFRP for repair of two of the damaged sections, and nearly twenty percent of the costs were attributed to the subsequent investigation and EM inspection.

Two notable exemptions in the cost breakdown were the cost of the section of PCCP used for the repair and the value of the water lost. The repair section used, a 96-inch cement mortar lined steel pipe, was constructed as spare pipe around the time of the SCC construction and buried for future use. Shortly after the SCC failure, the pipe section was retrieved, found to be in excellent condition, and utilized for the repair; no costs were incurred for this section of pipe. Overall, the direct costs of this failure were comparable to those observed in the literature. The location and timing of the failure greatly aided in a limited cost of failure.

3.3.2 SCC Economic Impacts

Economic impacts associated with the 2015 SCC failure were not provided by Valley Water. While the direct costs associated with the failure and subsequent repair efforts are easily quantifiable, economic impacts are more difficult to ascertain. The failure occurred in a remote area on private property that caused minimal damage and had a low societal impact due to the time of the season; all of which amount to economic impacts. According to literature, location of the failure was determined to be the most significant factor in total cost; highly urban areas tended to have higher total costs. Additionally, literature indicated the second largest contributor to total cost was total gallons lost as a result of the failure (Gaweski, Peter E.; Tata and Howard Inc.; Blaha, Frank J.;, 2007). Impacts incurred for this failure were 20 million gallons of lost water and the property damages. For this data, known aspects of the failure were used in conjunction with literature research to produce a meaningful estimate of impacts. For this study economic impacts consisted of lost water delivery benefits, lost value of spilled water during failure, and damages (costs related to property damage, traffic disruption, customer water outage, etc.)

4 Economic Decision-Making for PCCP Assets

Section 3 provided the details of an actual failure event for the SCC in 2015. A couple of questions can be posed regarding this failure from an economic standpoint:

1. Would it have been worth it to spend on monitoring and preventative maintenance of issues that monitoring might have identified?
2. What monitoring technologies and regimen are most cost-effective?

To answer these questions, an economic model was built to evaluate three scenarios for a PCCP asset based on the SCC using least-cost analysis (LCA). Scenario 1 serves as the no-action, or base case scenario. In summary, the pipe is run-to-failure and actions taken in this scenario are purely reactionary. Scenario 2 entails the gradual implementation of monitoring equipment and failure prevention measures. Low-cost monitoring (EM) is implemented on a regular basis to identify trouble sections. These sections are preemptively rehabilitated and higher-cost monitoring equipment (AFO) is installed proximate to these high-risk sections, as needed. Lastly, Scenario 3 evaluates the cost of wholesale early adoption of advanced higher-cost monitoring technology (AFO) upon the first detection of a problematic section. All subsequently identified problematic sections are preemptively rehabilitated. Costs for the actions entailed for each scenario can vary greatly depending on many variables. Therefore, each scenario is run with high-, low-, and mid-cost estimates.

The economic modeling presented here makes assumptions that may or may not be considered realistic by PCCP experts. However, the analysis serves as a demonstration of economic techniques that can be applied for alternative technology choice, cost, and timing assumptions. Ultimately, this analysis presents an economic framework for informing PCCP management decisions.

4.1 Choice of Least-Cost Analysis

For infrastructure as significant as a 21-mile long PCCP pipeline, a complete replacement is the (nearly) worst-case scenario from an economic standpoint. This would entail complete excavation of the existing pipeline and complete install with new material. Meanwhile, all end uses would be deprived of water deliveries (and society of the related economic benefits) for the construction duration. Therefore, it is assumed that water agencies would prefer to maintain the PCCP asset in perpetuity (at least for economic purposes), precluding a true lifecycle cost analysis. Rather, the economic objective is to maintain the asset in the most cost-effective manner. A least-cost analysis is a well-suited technique for this objective.

Reclamation economic analyses often look at a sequence of both benefits and costs over a given time period, i.e., a benefit-cost analysis (BCA). It is assumed, however, that the economic benefits accrued over any time period due to the existence of the pipeline are equivalent across alternatives. BCA would result in a benefit-cost ratio for each scenario sharing a common numerator (benefits), while the denominator (cost) would vary. In short, BCA could serve the needs of this study and would identify the same preferred alternative as LCA but is not the best tool for the job and could potentially introduce unnecessary confusion. LCA allows us to focus on the cost side through identification of the minimum cost to maintain the benefits provided by the pipeline.

4.2 Considerations for Time-Equivalent Economic Evaluation

The purpose of this section is to provide the reader an understanding of several economic concepts and techniques to accommodate the time-equivalent estimation of the costs and benefits across the evaluated scenarios. This section includes an overview of:

1. Determination of the period of analysis.
2. Specification of the base year for analysis.
3. Conversion of nominal dollars to real dollars.
4. Accounting for the time-value of money.

4.2.1 Period of Analysis (POA)

The period encompassing all modeled costs and benefits associated with the PCCP management scenarios is referred to as the *period of analysis* (POA). In accordance with Reclamation guidance, economic costs and benefits should be computed for the life of an asset not to exceed 100 years (DOI, 2015). As explained in Section 4.1, this analysis assumes that the PCCP asset should be maintained in perpetuity, and therefore uses the maximum recommended POA of 100 years. The POA encompasses the year following PCCP install through pipeline age 100.

4.2.2 Base year for analysis

The base year for analysis (base year) is the year in which all costs and benefits inputs are adjusted to and in which LCA results are reported. Generally, the base year is the most recent year for which inputs or appropriate indices are available. This analysis uses 2020 as the base year and is denoted in the POA as $t = 0$.

4.2.3 Conversion of Nominal Dollars to Real Dollars

Past expenditures reported in the year they were incurred are stated in *nominal* dollars. Objective comparison of costs requires that nominal dollars be adjusted to a common price level. Indexing is the technique used to convert nominal dollars to *real* dollars at a common price level based on empirical evidence (historical indices).

The proceeding LCA draws cost estimates from literature published from 1994 through 2019. All pre-2020 costs are indexed to "real" 2020 dollars[1] using appropriate indices. The shorthand "2020$" is used in some instances hereafter, denoting dollars reported at a 2020 price level. All costs are hereafter reported at a 2020 price level unless otherwise stated.

Useful resources for indexing past pipeline-related costs to real dollars are Reclamation's quarterly publication *Construction Cost Trends* (CCT) (Reclamation, 2021a), Reclamation's Operations and Maintenance (O&M) Index (Reclamation, 2019), and the Engineering News Record Construction Cost Index (ENR CCI) (Zevin, 2021). The Reclamation CCT consists of numerous categories and subcategories, including indices for steel pipelines and concrete pipelines—the most relevant for this work.

Figure 4-1 displays index values for the Reclamation O&M Index, the Reclamation CCT – Steel Pipelines index, the Reclamation CCT – Concreate Pipelines Index, and the ENR CCI for the years 1984 through 2020. The four indices are normalized to index value 100 in 1984 (the earliest common year among the four indices) to improve comparative visualization.

All costs used in this analysis are indexed to 2020$ using the ENR CCI. This is because the ENR CCI incorporates costs beyond materials prices (as opposed to the Reclamation CCT steel pipelines or concrete pipelines category indices) and is more inclusive of the types of costs that might be incurred for typical construction contracts, such as labor, mobilization, and equipment.

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[1] A "real dollar" value is an adjusted value that attempts to account for the impacts of inflation—the change in the purchasing power of a dollar. A real dollar value is used in this analysis to allow for better comparability of resource values across time. The estimated purchasing power of a dollar in year 2020 is used as the base value of a dollar (reference year).

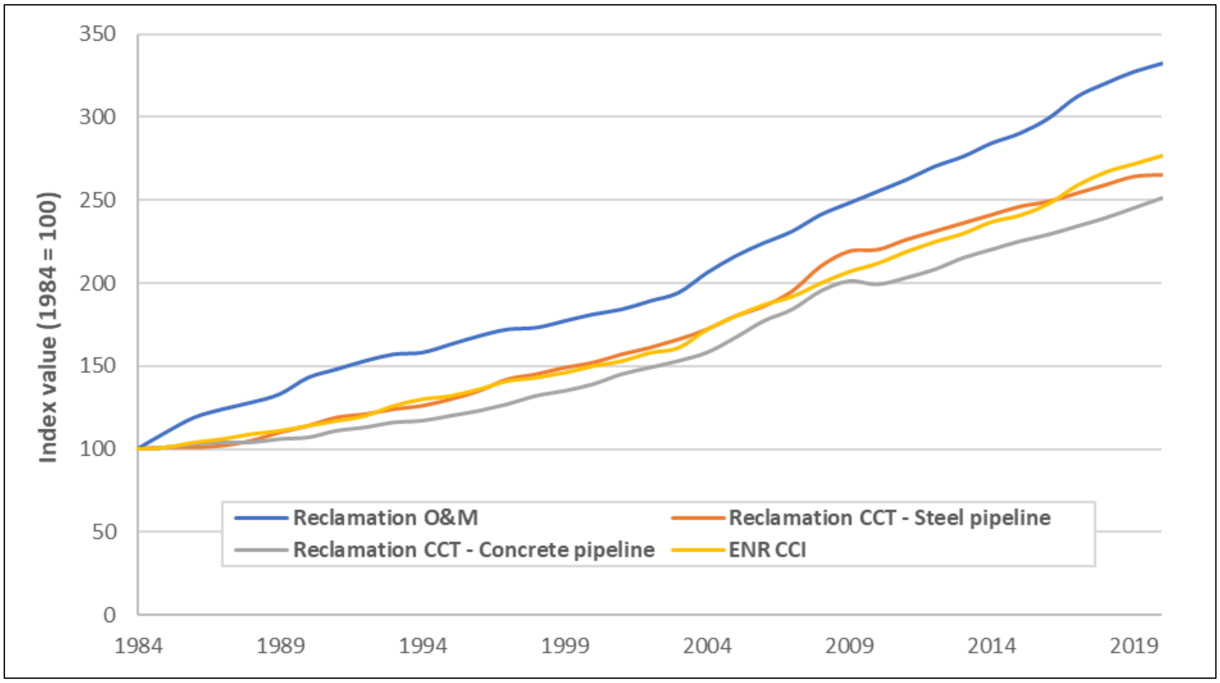

Figure 4-1. Comparison of four pipeline-related cost indices from 1984–2020

4.2.4 Accounting for the Time Value of Money

The timing of costs is central to economic analyses of investment decisions. Costs attributable to a given monitoring or rehabilitation technology are incurred at different times over long horizons. A fundamental concept in economics is that the timing of costs makes a difference in the attractiveness of an investment. All other things being equal, one would prefer to pay the costs of an investment as far out into the future as possible. Given the choice between paying out $100 today or one year from now, most of us would prefer the latter.

To be able to add and compare costs incurred at different times over the POA they must be made time equivalent. To make dollars time equivalent, they are converted to present dollars by compounding or discounting them to a common point in time—in this case the base year for analysis (2020)—a concept known as *present valuation*. Anticipated future costs and benefits are *discounted* back to their present value to account for the opportunity cost afforded by tying up those dollars in the investment.

The interest rate employed to calculate the present value of future dollars is referred to as the *discount rate*. The chosen rate can have a significant impact on the results of an economic analysis and its selection should therefore be made judiciously. For Reclamation economic evaluations, costs and benefits realized in anticipated in future years are converted to present dollars using the rate prescribed each fiscal year (FY) by the U.S. Department of Treasury for federal agencies in the formulation and evaluation of plans for water and related land resources (Federal Planning Rate). The Federal Planning Rate is employed as a real discount rate and Reclamation economic analyses therefore report results in real dollars (i.e., there is no assumption of inflation).The FY 2021 Federal Planning Rate of 2.500 percent is used for all present valuation in this analysis (U.S. Department of the Treasury, 2018).

4.3 Specific Assumptions for Modeled Scenarios

The scenarios are evaluated based on a hypothetical PCCP asset reflecting as closely as possible the SCC. All costs are therefore developed around a 21-mile long 96-inch diameter PCCP pipeline with an average flow rate of 100 cfs (approximately 6,150 AF per month). Beneficiaries of the water supply include M&I (75 percent of deliveries) and irrigated agriculture (25 percent of deliveries).

Initial install cost of the PCCP asset is not included in this analysis, as the LCA is strictly looking at the costs to preserve the economic benefits provided by the pipe. Inclusion of the initial install cost would scale the costs for all scenarios upward by a common value, having no relative differentiating effect, but diminishing the absolute cost differences.

Each scenario consists of a selection of event/action items and their related costs interspersed by specific intervals throughout the POA. Eight total event/action items were developed and fall into four general categories. The event/action items are presented by category in Table 4-1.

Table 4-1. Listing and categorization of event/action items

General category	Event/action items
Inspection/monitoring techniques	Electromagnetic (EM) inspection Acoustic fiber optic (AFO) monitoring
Rehabilitation techniques	Steel pipe section replacement Steel liner
Monitoring and rehabilitation associated actions	Dewatering
Economic damages and lost benefits	Economic damages Lost end-user benefits Lost benefits due to spillage

4.3.1 Description of Event/Action Items and Assignment of Costs

The event/action items are assigned an expected (mid), low, and high cost (in 2020$) based on literature review and expert input. All costs are indexed to 2020$ using the ENR CCI. Table 4-3 presents the cost ranges for each event/action item, while descriptions and additional context is provided below.

4.3.1.1 Inspection/Monitoring Techniques

The mid-range cost estimates for EM mobilization and monitoring are based on those provided in Faber (2017). EM mobilization is a fixed cost incurred per EM inspection event, regardless of pipe length inspected. Mobilization is estimated at $35,000—equal to $37,400 when indexed to 2020$ using the ENR CCI. EM variable costs are the costs incurred on a per-mile basis for the EM inspection, which is estimated at $20,000 per mile—equal to $21,400 per mile in 2020$. The high and low costs for mobilization and variable costs represent plus and minus 50 percent of the stated mid-range cost, which is consistent with the literature. Note that these costs are for a "dry" EM inspection and are stated exclusive of dewatering costs. Any EM inspection requires a dewatering event at additional cost. Additional information on EM is provided in Section 2.2.2.2.

AFO monitoring costs are broken out into two main categories: installation costs and monitoring costs. Installation costs include DAQ purchase (a per-system fixed cost) and contractor costs for cable installation (charged on a per-mile basis). Monitoring costs are all continuous annual costs and include contractor analysis (charged per-mile), DAQ O&M cost (charged per DAQ), and telephone fee (flat fee). AFO install contracting costs for one mile and four-plus miles, as well as DAQ purchase cost, are based on values provided in Faber (2017) and indexed to 2020$ using the ENR CCI. Contracting costs for two and three miles are interpolated from the one and four-plus mile costs. No cost range is estimated for AFO installation costs due to lack of alternative literature for these cost items. Mid-range for AFO monitoring costs are based on those provided in Faber (2017) and indexed to 2020$ using the ENR CCI. The high and low values for AFO monitoring costs represent plus and minus 50 percent of the stated mid-range cost, which is consistent with the literature. Note that a pipe must be dewatered for an AFO install, and the installation costs stated here are exclusive of dewatering costs. The continuous annual costs associated with AFO monitoring does not require dewatering. Additional information on AFO is provided in Section 2.2.2.3.

Note that this analysis assumes the purchase of a DAQ, rather than leasing. A cursory breakeven analysis indicates that for the scenarios modeled (and likely for most situations), ownership is more cost-effective than leasing. The payback period (years to breakeven) for ownership is highly dependent on the number of miles installed. Specifically, the more miles installed, the shorter the payback period for ownership. This is due to the higher per-mile charge for contractor analysis for a leased system compared to an owned system ($31,680 versus $12,672 per mile per year). The analysis indicates that for one mile of AFO installed, the payback period for DAQ ownership is 19 years, while for 20 miles installed it is 2 years. Table 4-2 shows the results of the breakeven analysis.

Table 4-2. Breakeven analysis for AFO DAQ ownership

Miles of AFO installed	1	2	3	4	5	10	15	20
Years to breakeven for DAQ ownership	19	9	6	4	3	3	2	2

4.3.1.2 Rehabilitation Techniques

The expected price per LF of steel liner is based on an estimate of $14 per inch diameter per LF, as provided by MWDSC and reported in Zarghamee et al. (2012). Applied to a 96-inch diameter pipe, this equals $1,344 per LF, or $1,700 per LF when indexed to 2020$ using the ENR CCI. The high and low values for steel liner represent plus and minus 50 percent of the stated mid-range cost, which is consistent with the literature. Steel liners are generally considered the most cost-effective long-term repair option. Note that after the 2015 SCC failure, multiple distressed pipe sections were repaired with CFRP liner, which by some indications costs an order of magnitude more per unit. Note that a pipe must be dewatered for a liner install, and the steel liner costs stated here are exclusive of dewatering costs. Additional information on steel liners is provided in Section 2.3.1.

The expected price per LF for steel replacement pipe is based on an estimate of $20 per inch diameter per LF, as provided by MWDSC and reported in Zarghamee et al. (2012). Applied to a 96-inch diameter pipe, this equals $1,920 per LF, or $2,400 per LF when indexed to 2020$ using the ENR CCI. The high and low values for steel replacement pipe represent plus and minus 50 percent of the stated mid-range cost, which is consistent with the literature. Like steel liners, steel replacement pipe is generally considered the most cost-effective long-term repair option. Note that a pipe must be dewatered for installation of a steel replacement section, and the steel replacement section costs stated here are exclusive of dewatering and excavation costs. Additional information on steel liners is provided in Section 2.3.3.

4.3.1.3 Monitoring and Rehabilitation Associated Actions

The dewatering cost range used in this analysis is based on the range of $300 to $500 per inch diameter per mile, as provided in Zarghamee et al. (2012). Applied to a 96-inch diameter, this equals $28,800 to $48,000 per mile ($35,500 to $59,100 per mile when indexed to 2020$ using the ENR CCI). The mid-range cost of $47,300 is the average of these values. Note that dewatering of all 21 miles of pipeline is required for any EM inspection, AFO install, liner installation, or pipe section replacement.

4.3.1.4 Economic Damages and Lost Benefits

Economic damages and lost benefits due to spilled water and interrupted water supply are only associated with an unexpected failure event. Unexpected pipe failures necessarily create an unplanned outage, which can have a significant economic impact on end-users dependent on water deliveries. Each failure therefore incurs a loss of economic benefits due to lost deliveries and spilled water.

Based on the 2015 SCC failure, an unexpected failure event interrupts deliveries for about one month. The modeled PCCP asset delivers an average of 6,150 AF per month of water supply to M&I and irrigated agriculture users. M&I users receive about 75 percent of deliveries, while irrigated agriculture receives the remaining 25 percent of deliveries. A one-month interruption translates to a loss of approximately 2,100 AF for M&I users and 1,050 AF for irrigated agriculture. Multiplying the unit value of this water (benefit per AF) by the AF of lost deliveries yields the lost economic benefits. Additionally, the value of the spilled water can be estimated using the same metrics in the same proportions.

The unit values for calculating lost economic benefits to end users are based on previous Reclamation irrigated agriculture and M&I economic studies conducted for the Southern California area. The economic value of irrigation water can vary drastically, depending on the cropping pattern, time of year, and availability of substitutes. Southern California grows some of the highest value crops in the country (notably fruits, nuts, and orchard crops), and often has few or no substitutes to surface water irrigation. Additionally, Southern California has an exceptionally long growing season, meaning that there is a low probability that an unexpected failure happens at a time when there is lesser agricultural demand. A conservative estimate for the economic benefit of irrigation water in Southern California is $600 per AF. The high and low values represent plus and minus 75 percent of the stated mid-range cost, which is consistent with the literature and economic studies conducted by the Reclamation Technical Service Center for the region.

Similarly, the economic value of M&I water supply can vary drastically, primarily depending on the availability of substitutes. Southern California has consistently faced increased demand and dwindling supply of water resources, which drives up the economic value of M&I water. A conservative estimate for the economic benefit of M&I water in Southern California is $1,200 per AF. The high and low values represent plus and minus 75 percent of the stated mid-range cost, which is consistent with the literature and economic studies conducted by the Reclamation Technical Service Center for the region.

Economic damages due to a catastrophic failure can vary widely. As discussed in Section 2.4.1, typical PCCP failures average $1.7 million in damages, but range from $6,000 to $8.5 million, with a geometric mean of $500,000. Damages can include homeowners insurance payments, traffic disruptions, and other property damages. A driving factor for this wide range is the location of the failure on the PCCP asset. Typical pipelines in the western U.S. have long runs though expansive rural areas, and then relatively short runs through populated areas. This means that there is generally a higher probability of failure in an area with less property and infrastructure impacts. However, when a failure happens in a populated area, the costs can multiply exponentially. The mid-cost value of $500,000 in economic damages per failure is supported by the literature, and the costs incurred for the 2015 SCC failure. The high and low values represent plus and minus an order of magnitude, which is consistent with the literature.

Table 4-3. Specific cost assumptions used in scenario modeling

		Cost range (2020$)			Used in Scenario		
Event/action	**Units**	**Low**	**Mid**	**High**	**1**	**2**	**3**
Inspection/monitoring techniques							
Electromagnetic (EM)[a]						X	X
Mobilization	$/EM event	$18,700	$37,400	$56,100			
Monitoring	$/mi/event	$10,700	$21,400	$32,100			
Acoustic fiber optic (AFO)[b]						X	X
AFO Installation							
Contracting – 1 mile	$/mi installed		$164,700				
Contracting – 2 miles	$/mi installed		$125,200				
Contracting – 3 miles	$/mi installed		$95,100				
Contracting – 4+ miles	$/mi installed		$71,700				
DAQ purchase	$/install event		$391,200				
AFO Monitoring							
Contractor	$/mi/yr	$6,800	$13,600	$20,400			
DAQ O&M	$/DAQ/yr	$11,500	$23,000	$34,500			
Telephone fees	$/yr	$500	$1,000	$1,500			
Rehabilitation techniques							
Steel liner[c]	$/LF	$850	$1,700	$2,550		X	X
Steel section replacement[d]	$/LF	$1,200	$2,400	$3,600	X		
Monitoring & rehab associated costs							
Dewatering ($/mi)[e]	$/mile	$35,500	$47,300	$59,100	X	X	X
Damages and lost economic benefits							
Lost end-user benefits[f]	$/failure event	$1,613,850	$6,455,400	$11,296,950	X		
Lost benefits of spillage[g]	$/failure event	$16,144	$64,575	$113,006	X		
Economic damages[h]	$/failure event	$50,000	$500,000	$5,000,000	X		

4.3.2 Scenario 1: Baseline No Action – Run-to-failure

Scenario 1 serves as the no-action, or base case scenario, and all actions taken in this scenario are purely reactionary. The PCCP asset is run to failure and actions taken are limited to rehabilitation of the failed section(s). Unexpected pipe failures necessarily create an unplanned outage, which can have a large economic impact on end-users dependent on water deliveries. Each failure therefore incurs a loss of economic benefits due to lost deliveries and spilled water. Additionally, there are direct damages associated with a failure.

Scenario 1 assumes 21 miles of PCCP are installed in year 0. There is no inspection or monitoring conducted and the first failure is in year 30. Repair costs for a catastrophic failure include dewatering of the 21 miles and replacement cost for three sections (72 feet) with steel pipe. An unexpected failure results in additional costs due to damages, spilled water, and lost benefits. Based on the 2015 SCC failure, 20 million gallons (61.5 AF) are spilled, and deliveries are interrupted for one month, translating to the loss of benefits associated with 6,210 AF of water supply. Economic damages include property damages, crop damages, and other infrastructure damage. After the initial failure in year 30, subsequent failures, and associated costs, are assumed every five years through the duration of the 100-year POA. Table 4-4 presents the cost items and associated time of incurrence for Scenario 1.

Table 4-4. Specific timing assumptions for Scenario 1

Year	Event	Result	Related cost item(s)
0	Install 21 mi of PCCP		Cost of initial install not included in LCA
30	Section failure	Emergency rehabilitation	1 month of lost end-user benefits Lost benefits of spilled water Damages due to catastrophic fail Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel replacement
35	Section failure	Emergency rehabilitation	1 month of lost end-user benefits Lost benefits of spilled water Damages due to catastrophic fail Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel replacement
…	…	…	…
100[a]	Section failure	Emergency rehabilitation	1 month of lost end-user benefits Lost benefits of spilled water Damages due to catastrophic fail Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel replacement

[a] Year 100 represents the final 5-year iteration of “Section failure” in the 100-yr POA.

4.3.3 Scenario 2: Gradual Implementation of Monitoring

Scenario 2 entails the gradual implementation of monitoring technologies and failure prevention measures. EM inspection is implemented on a regular basis to identify trouble sections, which are rehabilitated prior to failure. Rehabilitation of a pipe section is a planned event, and therefore the outage can be scheduled to avoid impacting water deliveries. This avoids the loss of economic benefits due to lost deliveries and spilled water. Upon any rehabilitation event, monitoring equipment (AFO) is installed proximate to high-risk sections.

This scenario assumes 21 miles of PCCP are installed in year 0. An EM inspection is performed in year 10, also requiring dewatering of the 21 miles pipe, with no issues identified. An additional EM inspection occurs in year 20 as well as the required dewatering. The year 20 EM inspection identifies minor issues and EM inspections are adjusted to 5-year intervals. The year 25 EM inspection identifies major issues, and a plan is developed to rehabilitate the section and proximate sections the following year with steel liner. Steel liner repair is performed on three sections (72 feet) in year 26, which requires dewatering. Additionally, in year 26, AFO is installed for one mile. AFO monitoring costs are now incurred annually for the mileage of installed AFO. This cycle occurs every 5 years throughout the duration of the 100-year POA. As a note, for each mile of AFO installed, that is one less mile for which EM inspections are conducted. However, for any mileage of EM inspection performed, the entire 21-mile pipe must be dewatered. Table 4-5 presents the cost items and associated time of incurrence for Scenario 2.

Note that for the 2015 SCC failure, deteriorated sections were lined with CFRP. However, this study assumes steel liner, which the consensus of literature indicates is much less expensive and has a very long service life.

Table 4-5. Specific timing assumptions for Scenario 2

Year	Event	Result	Related cost item(s)
0	21 mi of PCCP installed		Cost of initial install not included in LCA
10	EM inspection	No issues identified – follow-up EM scheduled for 10-years out	Dewatering for 21 mi of pipe EM inspection for 21 mi of pipe
20	EM inspection	Minor issues identified – follow-up EM scheduled for 5-years out	Dewatering for 21 mi of pipe EM inspection for 21 mi of pipe
25	EM inspection	Major issues identified – plan developed for section rehab 1-year out	Dewatering for 21 mi of pipe EM inspection for 21 mi of pipe
26	Rehab and AFO install	Steel liner and AFO installed as needed AFO monitoring costs are incurred annually based on mileage installed	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96" steel liner 1 mi of AFO installation 1 mile of annual AFO monitoring begins
30	EM inspection	Major issues identified – plan developed for section rehab 1-year out	Dewatering for 21 mi of pipe EM inspection for 20 mi of pipe
31	Rehab and AFO install	Steel liner and AFO installed as needed AFO monitoring costs are incurred annually based on mileage installed	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96" steel liner 1 mi of AFO installation 2 mi of annual AFO monitoring
…	…	…	…
96[a]	Rehab and AFO install	Steel liner and AFO installed as needed AFO monitoring costs are incurred annually based on mileage installed	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96" steel liner 1 mi of AFO installation 15 mi of annual AFO monitoring
100[b]	EM inspection	Major issues identified – plan developed for section rehab 1-year out	Dewatering for 21 mi of pipe EM inspection for 6 mi of pipe

[a] Year 96 represents the final 5-year iteration of "Rehab and AFO install" in the 100-yr POA. Note that beginning in year 96 there is 15 mi of AFO monitoring, as one mi of AFO has been installed every 5 years since year 26.

[b] Year 100 represents the final 5-year iteration of "EM inspection" in the 100-yr POA. Note that only 6 mi of pipe are inspected with EM in year 100, as 15 mi now have AFO installed by this time.

4.3.4 Scenario 3: Early Implementation of Monitoring

Scenario 3 models the costs associated with wholesale early adoption of higher-cost monitoring technology (AFO) upon the first detection of a problematic section. The continuous AFO monitoring identifies trouble sections early, which are rehabilitated prior to failure. Rehabilitation of a pipe section is a planned event, and therefore the outage can be scheduled to avoid impacting water deliveries. This avoids the loss of economic benefits due to lost deliveries and spilled water.

This scenario assumes 21 miles of PCCP are installed in year 0. An EM inspection is performed in year 10, also requiring dewatering of the 21 miles pipe, with no issues identified. An additional EM inspection occurs in year 20 as well as the required dewatering. The year 20 EM inspection identifies minor issues and AFO is installed for the entire length of the 21-mile pipe. With AFO installed on all 21 miles, EM inspections are no longer required and AFO monitoring costs are now incurred annually. In year 25 AFO identifies major issues, and a plan is developed to rehabilitate the section and proximate sections the following year with steel liner. Steel liner repair is performed on three sections (72 feet) in year 26, which requires dewatering. This cycle occurs every 5 years throughout the duration of the 100-year POA. Table 4-6 presents the cost items and associated time of incurrence for Scenario 3.

Note that for the 2015 SCC failure, deteriorated sections were lined with CFRP. However, this study assumes steel liner, which the consensus of literature indicates is much less expensive and has a very long service life.

Table 4-6. Specific timing assumptions for Scenario 3

Year	Event	Result	Related cost item(s)
0	Install 21 mi of PCCP		Cost of initial install not included in LCA
10	EM inspection	No issues identified – follow-up EM scheduled for 10-years out	Dewatering for 21 mi of pipe EM inspection for 21 mi of pipe
20	EM inspection	Minor issues identified – decision to install AFO for entire 21-mi pipeline	Dewatering for 21 mi of pipe EM inspection for 21 mi of pipe 21 mi of AFO installation 21 mi of annual AFO monitoring begins
26	AFO monitoring flags pipeline section	Section rehabbed with steel liner	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel liner Continued annual AFO monitoring
31	AFO monitoring flags pipeline section	Section rehabbed with steel liner	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel liner Continued annual AFO monitoring
…	…	…	…
96[a]	AFO monitoring flags pipeline section	Section rehabbed with steel liner	Dewatering for 21 mi of pipe 3 sections (72 ft) of 96” steel liner Continued annual AFO monitoring

[a] Year 96 represents the final 5-year iteration of “AFO monitoring flags pipeline section” in the 100-yr POA.

4.4 Computation of Present Valuation for Scenarios

As demonstrated in Section 4.3, the PCCP management scenarios incur a sequence of costs in multiple years over the 100-year POA. Equation (1) is used to compute the present value of the whole stream by summing the present values of the costs incurred in each year over the POA. The scenario with the lowest present value of costs over the POA is identified as the least-cost option, and therefore the economically preferred.

$$PV(Cost_{ScenX}) = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where:

$PV(Cost_{ScenX})$ = The present value of PCCP management costs under Scenario *X* over the POA.
C_t = The sum of all relevant costs occurring in year *t*
T = Period of analysis (POA) over which costs are evaluated for all scenarios
r = FY2021 Federal Planning Rate of 2.500 percent
t = Year of POA evaluated (t = 1, 2, …, T)

A second useful metric for comparing scenarios is the *equivalent uniform annual cost* (EUAC). Both present value and EUAC will always lead to the same conclusion in evaluation of alternatives (Boardman, Greenberg, Vining, & Weimar, 2006). The EUAC of a given scenario equals its present value divided by the *annuity factor* (a_r^T) that has the same term and discount rate as the given scenario, i.e., the present value of an annuity of $1 per year for the POA discounted at the rate used to calculate the present value. The EUAC is the amount which, if paid each year over the POA, would have the same present value as that scenario. EUAC and the annuity factor are defined below by Equations (2) and (3), respectively.

$$EUAC_{ScenX} = \frac{PV(Cost_{ScenX})}{a_r^T} \tag{2}$$

$$a_r^T = \frac{1-(1+r)^{-T}}{r} \tag{3}$$

where:

$EUAC_{ScenX}$ = Equivalent uniform annual cost
$PV(Cost_{ScenX})$ = The present value of PCCP management costs under Scenario *X* over the 100-year POA
a_r^T = Annuity factor
T = Period of analysis (POA) over which costs are evaluated for all scenarios
r = FY2021 Federal Planning Rate of 2.500 percent

Both metrics identified above are calculated for this analysis and reported in the results section of this paper (Section 4.5).

4.5 Case Study Results and Comparisons

The discussion of results focuses primarily on values calculated on the mid-range cost inputs. The mid-range cost estimates are those supported most strongly by the literature reviewed and expert opinion. The low and high values serve to bracket the expected costs but are much less likely to be realized by a PCCP management agency.

Table 4-7 reports the present value of costs under each scenario and cost inputs range based on the inputs and timing considerations specified in Section 4.3. Based on the mid-range cost inputs, the least-cost scenario is identified as Scenario 2—gradual implementation of monitoring and failure prevention measures. The two proactive management regimes (scenarios 2 and 3) are within $0.5 million of each other on a present value basis ($14.6 million and $15.2 million, respectively), while Scenario 1 (run-to-fail and reactionary rehabilitation) is nearly double the cost at $28.3 million.

Table 4-7. Present value of costs under each scenario

	Cost inputs range		
	Low	**Mid**	**High**
Scenario 1	$8,692,505	$28,328,229	$61,979,136
Scenario 2	$10,013,152	$14,606,913	$19,200,675
Scenario 3	$9,461,808	$15,172,358	$20,882,901

The cumulative present value over the POA for each scenario at the mid-range cost inputs is illustrated graphically in Figure 4-2. Note that Scenario 1 has the least costs through year 30, which is expected as no proactive measures are taken. However, after experiencing only two unexpected failures (in years 35 and 40) the cumulative costs exceed those for scenarios 2 and 3, and Scenario 1 costs continue to significantly outpace those under scenarios 2 and 3 for the duration of the POA. An important takeaway is that avoiding proactive monitoring and repair measures saves on upfront costs but can cost considerably more in the long run, even when adjusting for the time value of money.

Another interesting finding illustrated by Figure 4-2 is that Scenario 3 (wholesale early adoption of AFO) costs more than Scenario 2 (gradual implementation) throughout the duration of the POA. One of the effects of discounting is that large costs incurred relatively early in the POA disproportionately impact the present value compared to those incurred further into the future. The installation of 21 miles of AFO in year 20 under Scenario 3 therefore outweighs the impact of higher periodic costs under Scenario 2 for EM inspections and higher unit costs of short stretches of AFO installs, as they are spread over the POA rather than incurred as a lump sum.

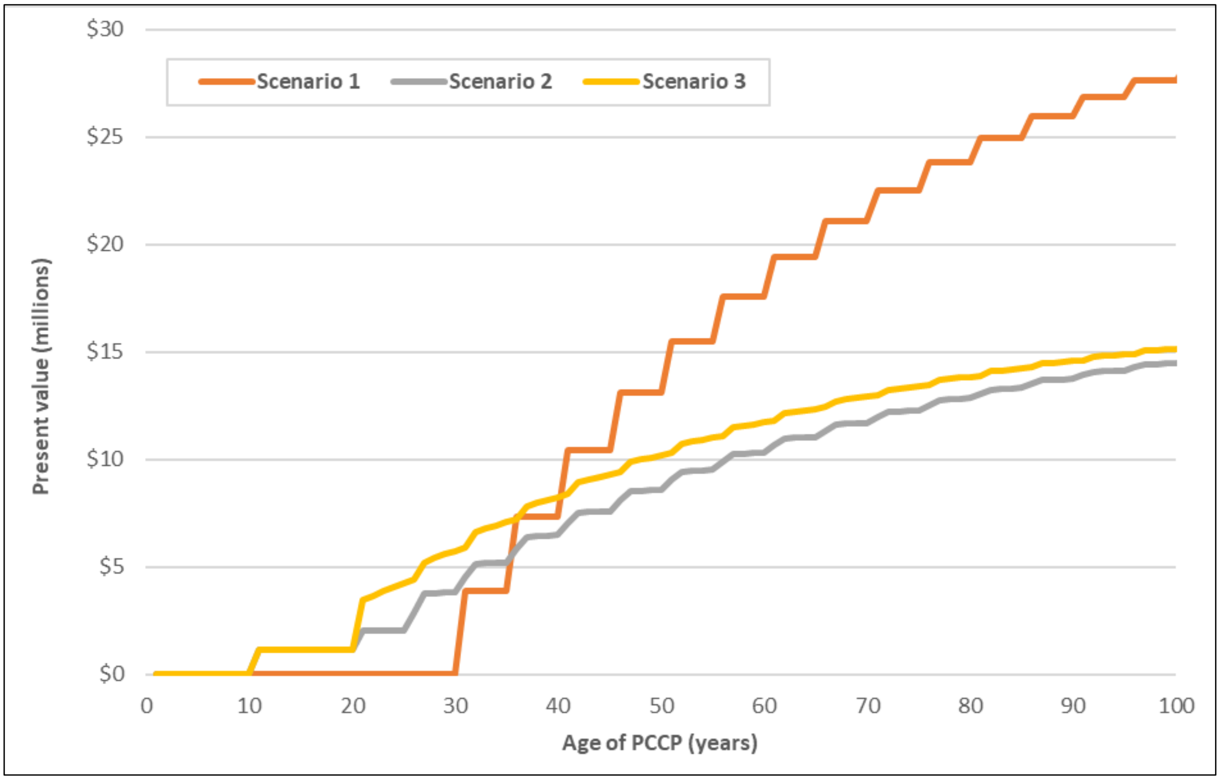

Figure 4-2. Cumulative cost under the three scenarios over the POA using mid-range cost inputs

The annualized cost under each scenario is reported as EUAC in Table 4-8. As explained in Section 4.4, the ranking of scenarios by least cost will always be the same, whether by present value or EUAC, but an annualized cost can provide a more tangible metric for comparison, and management strategizing purposes. As expected, the least-cost scenario identified by EUAC is Scenario 2, followed closely by Scenario 3, while Scenario 1 has an annualized cost nearly double the other two.

Table 4-8. EUAC under each scenario

	Cost inputs range		
	Low	**Mid**	**High**
Scenario 1	$237,409	$773,697	$1,692,767
Scenario 2	$273,478	$398,942	$524,407
Scenario 3	$258,420	$414,386	$570,351

Table 4-9 provides a comparison of the proactive management strategies (scenarios 2 and 3) using Scenario 1 as a no-action baseline. Analyzing the mid-range cost inputs results, we see that both Scenario 2 and 3 provide cost savings of nearly 50 percent (48 percent and 46 percent, respectively).

It is noteworthy that when comparing results for the low-range cost inputs that scenarios 2 and 3 both incur higher costs than Scenario 1 (15 percent and 9 percent higher). This is due primarily to the lost benefits and economic damages being minimized under the low-range cost inputs. The sensitivity analysis increases/decreases the unit value of water by 75 percent of the base value for the lost water deliveries for benefits estimation and increases/decreases economic damages by an order of magnitude. Comparatively, the cost items adjusted for scenarios 2 and 3 are adjusted by 50 percent for the sensitivity analysis. The significantly larger range for Scenario 1 is illustrated in Figure 4-3. This difference in cost ranges is realistic and expected, as the uncertainty surrounding potential economic damages and lost benefits is much higher than that surrounding constructions costs. According to the literature, location of failure and the total gallons lost because of the failure, were determined to be the most significant factors in total cost.

Table 4-9. Cost savings due to proactive PCCP management

Proactive management scenario	Savings metric[a]	Cost inputs range		
		Low	Mid	High
Scenario 2	Present value	-$1,320,647	$13,721,316	$42,778,461
	EUAC	-$36,069	$374,755	$1,168,360
	Percent savings	-15%	48%	69%
Scenario 3	Present value	-$769,303	$13,155,871	$41,096,235
	EUAC	-$21,011	$359,311	$1,122,416
	Percent savings	-9%	46%	66%

[a] Cost savings calculated as the difference between the proactive management scenario and Scenario 1, the no-action baseline.

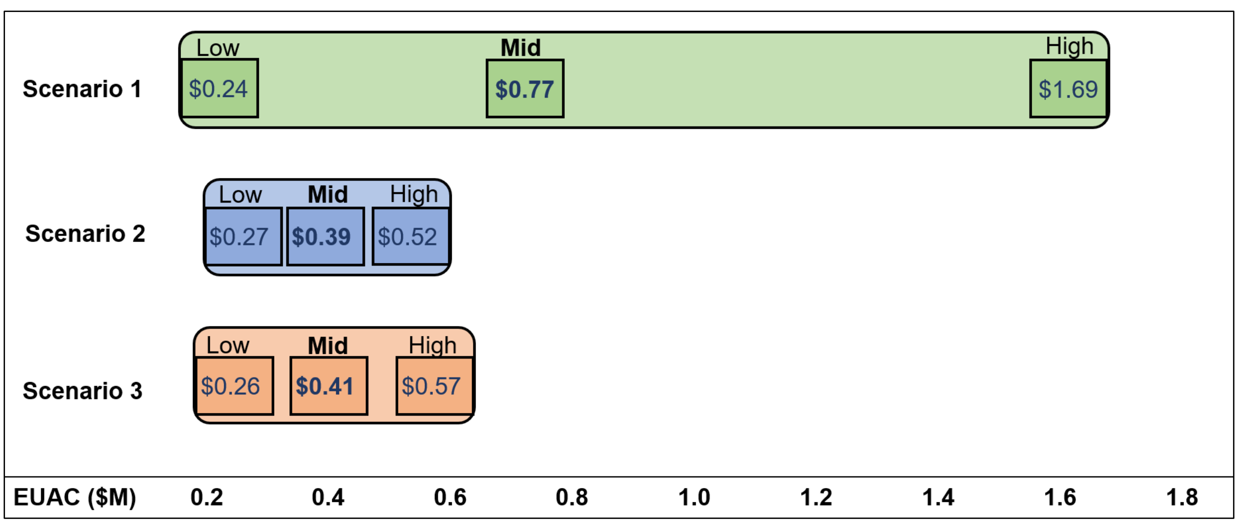

Figure 4-3. Comparison of EUAC across case study scenarios using low, mid, and high range cost inputs

5 Conclusions

Large diameter PCCP assets are used for water conveyance across many agencies. The condition assessment and rehabilitation of these assets continues to be an ever-increasing proportion of the managing Water District's operational budget and raised a question about the economics of this proactive approach. To answer this question, three hypothetical asset management scenarios were studied. One scenario was a no-action, reactive strategy towards asset management where emergency repairs are conducted only after eventual failure, the other two scenarios were gradual and early implementations of similar proactive strategies. Using a least cost analysis of these three asset management scenarios, this study concluded the following:

- Both proactive asset management strategies were indicated to be more cost effective over the lifespan of an asset than the reactionary asset management approach
- Gradual implementation of high expense monitoring techniques is slightly more cost effective than wholesale early adoption
- Preponderance of literature indicates that CFRP is the most expensive replacement and lining technique. Replacement with steel sections and liners are indicated to be most cost-effective and commonly used, while still achieving a very long service life.
- Economic results are based on relatively conservative damages and lost benefits estimates, even for the high-cost iterations, indicating that the cost savings due to proactive management might be much higher.
- AFO DAQ ownership is more cost-effective than lease in all but a few situations. The payback period (years to breakeven) for ownership is highly dependent on the number of miles installed; the more miles installed, the shorter the payback period for ownership.
- Failure location and in turn, consequence of failure, largely impacts most economical asset management strategy due to end user water benefits as well as whether the debris results in property damages.
- Gradual implementation of high expense monitoring techniques is slightly more cost effective than wholesale early adoption
- The economic analysis indicates that proactive monitoring and repair saves nearly 50 percent on costs over the long-term, when using mid-range cost inputs

Overall, the economic analysis finds that a proactive management scenario for a hypothetical PCCP asset modeled on the Santa Clara Conduit saves over $13 million over the period of analysis—an annualized savings of nearly $400,000. These savings would be multiplied many times over if applied to Reclamation's PCCP inventory. In summary, the study provides strong evidence that avoiding proactive monitoring and repair measures saves on upfront costs but can cost considerably more in the long run.

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