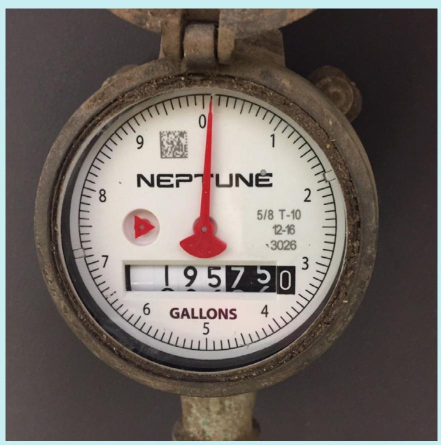
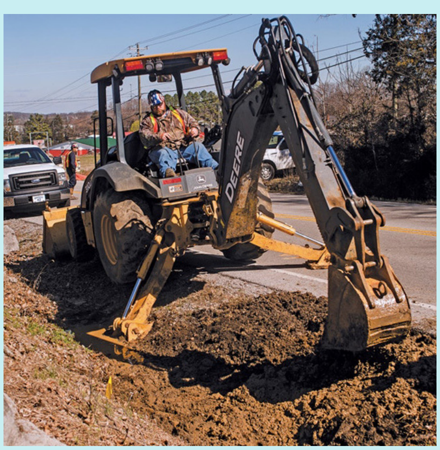
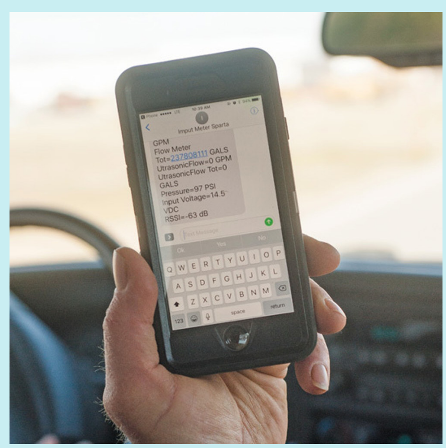
Hidden Reservoirs: Addressing Water Loss in Texas

Jennifer Walker, Alan Wyatt, Jonathan Seefeldt, Danielle Goshen, Meghan Bock, Ian Johnston, Maya Black







National Wildlife Federation
Texas Coast and Water Program

TEXAS LIVING WATERS PROJECT

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About the Authors

Jennifer Walker is the Deputy Director of the National Wildlife Federation's Texas Coast and Water Program. Jennifer has 20 years experience focusing on water policy/resources issues in Texas with an emphasis on water planning, water conservation and bay and estuary protection. She serves on the Water Conservation Advisory Council of Texas and is Chair of Austin's Water Forward Task Force. She also serves on the Board of Directors of the Alliance for Water Efficiency and the Colorado River Alliance. Jennifer has a BS in Ecology, Evolution and Conservation Biology from the University of Texas at Austin.

Alan Wyatt has over 40 years of experience in water supply, non-revenue water, utility performance assessment, benchmarking, economics and finance, and related fields, including field work in 25 countries. He has a Dual Bachelor's Degree in Mechancial Engineering and History from Cornell University (USA) and a Masters Degree in Water Resource Engineering from the University of North Carolina at Chapel Hill (USA). He is a member of the IWA Specialists Groups on Water Loss and on Benchmarking and Performance Assessment. He is an active member of AWWA and its Water Loss Control Committee. He specializes in utility / water loss performance assessment, performance indicators, planning water loss mitigation programs, economic optimization, uncertainty analysis and regulation of water loss performance.

Jonathan Seefeldt, Ph.D. is the Senior Communications Manager of the National Wildlife Federation's Texas Coast and Water Program. Jonathan has over a decade of experience in environmental and educational communications. He has researched and published on the history of large-scale water infrastructure in semi-arid environments with a particular focus on the long-term impact of climate infrastructure projects. Jonathan has an Ph.D. in Environmental History from the University of Texas at Austin.

Danielle Goshen is a Policy Specialist/Counsel at the National Wildlife Federation's Texas Coast and Water Program. Danielle's interest in environmentalism and curiosity on how natural systems function inspired her to attend the University of Toronto for her undergraduate degrees in environmental geography and environmental studies. Later, she continued her studies at the University of Georgia School of Law. During her time at Georgia Law, Danielle interned at the Environmental Protection Agency's Region 4 office and served as a Georgia Sea Grant Legal Fellow working on coastal resiliency projects.

Meghan Bock is a Solution Architect at Aiqueous. Meghan is driven by her passion to positively impact the world around her. She seeks opportunities to deliver outcomes that will benefit the environment, especially when it comes to water conservation, energy efficiency, and electrification. Meghan translates this passion to her work at AIQUEOUS by helping utilities and third-party implementers conceive and deploy their programs on the WaterWays and POWERPATH platforms. Meghan holds an M.S. in Community and Regional Planning from the University of Texas at Austin.

Ian Johnston is a Technical Project Manager at Aiqueous. Ian brings a myriad of experience within the water-energy field — from building green and affordable homes, to an education in community and regional planning, to his work in the development of a stormwater management program in Austin, to three years of data driven projects at AIQUEOUS. This diverse background not only represents a passion for water conservation and energy efficiency but is also well utilized in his current position as Technical Project Manager. Ian holds an M.S. in Community and Regional Planning from the University of Texas at Austin.

Maya Black is a Research Analyst at Aiqueous. Maya has a passion for protecting and sustaining the environment, with experience in healthcare sustainability, climate change ecology and data analysis. She researches and engages water and energy utilities to help them improve their delivery of customer programs and services. Maya holds a B.S. in Environmental Science from the University of Wisconsin-Madison.

Executive Summary

Texas urgently needs to address water loss. The state's population is growing at an unprecedented rate and Texas' water supply is finite. Increasing climate extremes threaten longer and deeper drought periods. In order to have sufficient water to meet the needs of both our communities and the environment, we need to make sure that efficient use is made of all Texas water resources.

If Texas utilities take action to address water loss in their systems, the need for many supplemental water supply projects can be mitigated, delayed, or eliminated. It is therefore critical to understand the potential for mitigating water loss in Texas.

The following report explores this potential by analyzing the extent of water loss in Texas public water systems, outlining how much water could be saved with cost-effective approaches, collating the many available avenues for funding water loss projects, and recommending next steps for the Texas Legislature, Texas Water Development Board, and utilities.

HOW MUCH WATER IS BEING LOST?

Our analysis of 2019 water audits concludes that Texas utilities are losing about 572,000 acre-feet per year, corresponding to an average of about 51 gallons of water per service connection every day. The total water losses are enough water to meet the total annual municipal needs of the cities of Austin, Fort Worth, El Paso, Laredo, and Lubbock combined.[1] That amount of water is also about the same as the average flow in the San Antonio River and about 88% of the average flow in the Rio Grande.[2]

Water losses include both real and apparent losses. While real loss encompasses all forms of physical leakage, apparent loss refers to water which is actually consumed but not properly tabulated or billed. We include both components not only to align our analysis with the 2022 State Water Plan (which includes apparent and real water loss in its water supply projections and water loss control strategies) but also because accounting for both gives a true picture of future municipal needs and helps facilitate accurate planning.

572k af/yr

Texas utilities are losing at least 572,000 acre-feet of water per year — more than the total 2020 annual water needs of the cities of Austin, Fort Worth, El Paso, Laredo, and Lubbock combined.

51 gallons/conn/day

Each service connection in Texas loses an average of 51 gallons of water every day. Utilities serving populations over 100,000 have an even higher average loss of 55 gallons per connection per day.

249k af/yr potential

Achieving a 75th percentile performance level — i.e. achieving water loss performance equivalent to or better than 75% of peer utilities — could save Texas about 249,000 acre-feet per year. A 90th percentile performance could save about 359,000 af/yr.

Meets municipal needs

The water savings from utilities achieving a 75th percentile performance level would provide a significant amount of the municipal water needs outlined in the 2022 State Water Plan.

$ cost-efficient

The cost of many loss mitigation technologies compares very favorably to various supply-side water management strategies such as seawater desalination and new major reservoirs.

1 2020 Municipal Water Demands for Lubbock 46,775 afy, Fort Worth 189,110 afy, El Paso Water 110,572 afy, Austin 181,661 afy and Laredo 42.028 afy. Total 2020 water demand for these utilities is 570,146 afy. 2022 Interactive State Water Plan, https://texasstatewaterplan.org/statewide.

2 San Antonio River average flow per year is 562,700 afy and the Rio Grande's average flow is 645,500 afy. TWDB River Basins, https://www.twdb.texas.gov/surfacewater/rivers/river_basins/index.asp.

Estimated Total Water Loss and Potential Savings

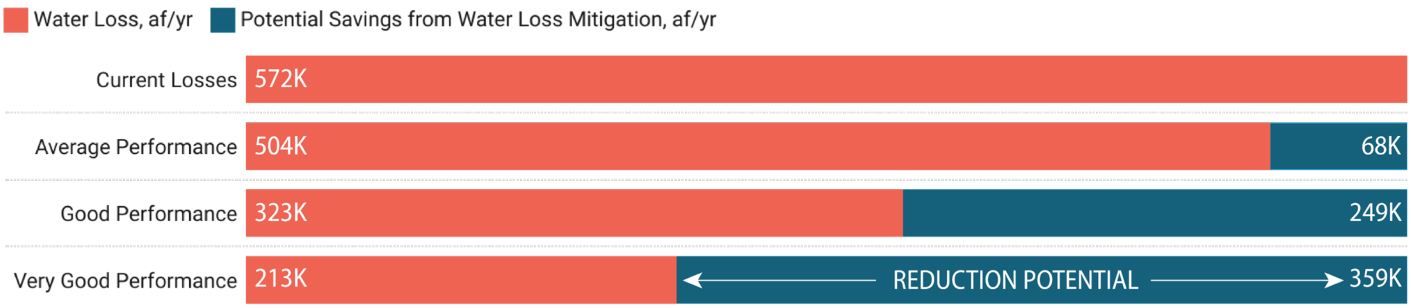


Figure 1. Estimated Total Loss and Potential Savings (in acre-feet/year). *Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.*

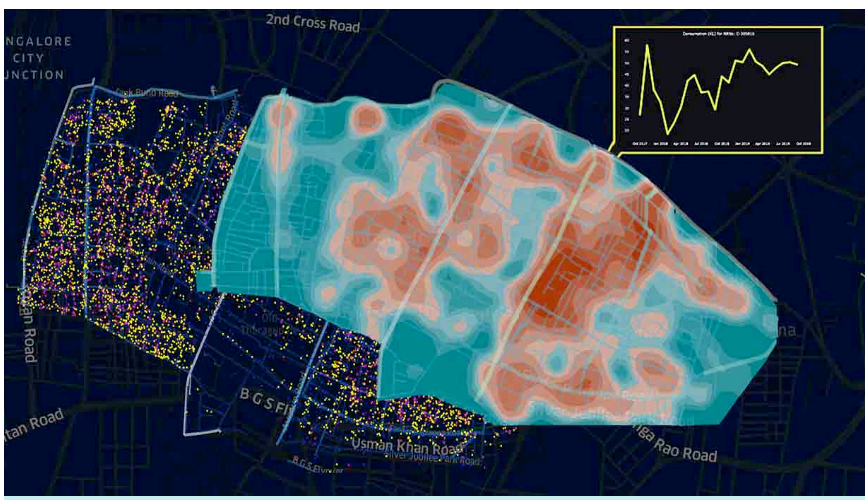
HOW MUCH WATER COULD BE SAVED?

Because the water savings potential per utility varies significantly based on a variety of factors, we use a 'Frontier Analysis' (FA) methodology. Under this method, a mathematical model predicts the best, average and worst possible water loss performance of any (and each) water utility, based on attributes such as miles of pipe, connections per mile of pipe, water consumption per connection per day and the variable cost of water production. When actual performance is compared to this predicted range the potential for reduction can be estimated.

The FA results show that if each utility reduced its losses to the current Average Performance Level for their set of attributes, the total water loss would decrease from about 572,277 acre-feet per year to about 504,472 acre-feet per year — a modest savings of 67,806 acre-feet per year. If each utility mitigated losses to a Good Performance Level (i.e., achieving water loss performance equivalent to or better than current water losses of 75% of peer utilities), the savings would be much larger – 248,851 acre-feet per year. Mitigation to a Very Good Performance Level, (i.e., achieving water loss performance equivalent to or better than current water losses of 90% of peer utilities), the savings would be about 358,856 acre-feet per year. Overall, Texas could significantly mitigate total water loss in the state by achieving water loss levels already realized by the better-performing utilities in Texas.

HOW DOES THIS COMPARE TO THE WATER TEXAS NEEDS?

Our analysis indicates that if all water utilities achieve the Good Performance Level, the aggregate water savings across the state would be greater than the increase in municipal water needs identified in the 2022 State Water



Water loss distribution matters!

Although savings from water loss mitigation can be significant in terms of volume, they are not necessarily evenly distributed within and across regions.

Savings in a region or one part of a region may exceed the local increase of municipal water needs in that location, but may not meet the needs in other regions or in other parts of the region.

While our analysis indicates total savings could often exceed the overall needs of a region, certain areas will still have unaddressed needs.

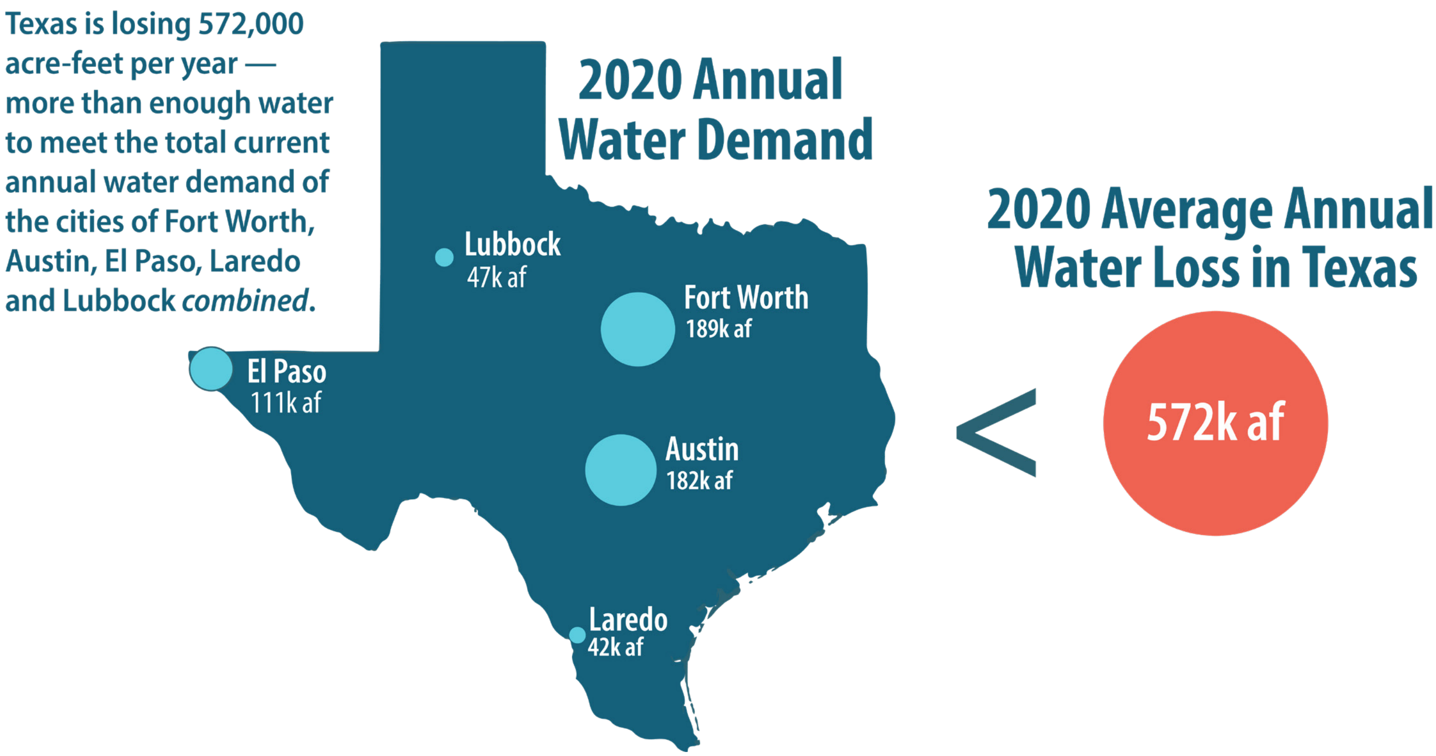


Figure 2. Annual Water Loss vs Annual Water Demand.
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

Plan for the 2020 decade — although it is important to remember savings and needs are not evenly distributed (see *Water loss distribution matters!* on page 6). These comparisons provide an order-of magnitude signal on the contribution water loss mitigation could make in the water demand and water supply gap. In some cases, the results are quite compelling. For example, achieving the Good Performance Level could provide about *double* the municipal needs for Very Large utilities for the 2020 decade.[3] This is especially noteworthy given that this size class represents almost 50% of the Texas population.

HOW EXPENSIVE IS WATER LOSS MITIGATION AND HOW CAN WE PAY FOR IT?

The cost of water loss mitigation varies greatly from utility to utility, and is often not discretely tabulated or publicly disclosed. Nonetheless, mitigation methods that focus on the "root causes" of water loss, and address the largest components of water loss are usually very cost effective.

Any water loss mitigation project will involve a mix of different approaches, such as acoustic active leak detection, pressure management, small meter replacement, large meter replacement, and selective pipe replacement. The cost of each approach depends on the condition of the infrastructure and equipment, the level of water losses, the network attributes and the scale of operations. Our analysis of empirical data on various water loss mitigation approaches concludes that the unit costs of water loss mitigation activities often follow a classic "economies of scale" curve. A small program will have a relatively high unit cost, compared to a large one. The overall cost of a water loss mitigation project in a given location will depend on the mix of approaches used to address the levels of apparent and real losses.

The cost of many water loss mitigation approaches compares favorably to various supply-side water management strategies (e.g., aquifer storage and recovery, direct potable use, groundwater or seawater desalination and new major reservoirs) in the 2022 State

3 For more on these and other size categories, see Table 1 on page 10 and Table 3 on page 19.

The City of Houston could save about 40,000 acre-feet per year by reaching the midpoint between the Good and Very Good Performance Levels. This is more than *double* the additional Municipal Water Needs for the 2020 decade in all of Region H (18,500 acre feet per year).

Water Plan. For example, our detailed analysis of multi-year records of acoustic active leak detection and repair in three large US cities, showed a range of $73 to $239 per acre foot saved (lower and upper quartile). Data from other sites on advanced pressure management showed a cost range of $151 to $252 per acre foot saved over the same time span, and large meter replacement programs had a cost range from $112 to $202 per acre foot saved over the same span. Small meter replacement programs and full-scale infrastructure overhaul projects cost more.[4]

In contrast, supply-side projects in the Texas State Water Plan range in cost from $391 to $1724 per acre foot.[5] The unit costs of water loss reduction are also comparable to or lower than the unit costs of agricultural, municipal and industrial conservation in the State Water Plan.[6]

From an integrated resource planning perspective, the cost-effectiveness of water loss mitigation, compared to other strategies, suggests that water loss mitigation should be among the first strategies implemented by water utilities to meet future demand.

Fortunately, there are many federal, state, local, and private funding sources available for projects that mitigate water loss. We outline existing and emerging options in Chapter 3.

WHAT ARE OUR NEXT STEPS?

We recommend utilities — with the strong support of the Texas Legislature and state agencies — work to aggressively mitigate water loss and achieve the highest practicable level of water loss performance.

Specifically, we recommend the Legislature create a program to prioritize financial assistance for utilities with the highest water losses, make the funding programs accessible across size classes, and provide additional funding for TWDB conservation and water plannning staff.

We recommend the Texas Water Development Board (TWDB) prioritize data accuracy, transparency and accountability. TWDB should also ensure that all entities applying for financial assistance for new water supply projects from the Board meet or exceed water loss standards or have plans and/or programs in place to do so. TWDB also needs to prioritize technical assistance and increase accessibility to financial assistance for utilities pursuing water loss mitigation projects.

In addition, the state and regional water planning process should include water loss as a water management strategy.

Finally, utilities can also play a critical role in prioritizing water loss. Utilities need to accurately evaluate the financial impact of water losses, continuously invest in resilient infrastructure, and make regular investments in addressing water loss with the goal of staying ahead of water loss to prevent compounding losses over time.

As Texas' finite water resources strain under the growing pressures of population growth, economic development, and climate variability, we urgently need to shore up our water supply by investing in water loss mitigation. We have the evidence, the methods, and the funding to address water loss in a strategic, cost-effective manner. It's time for Texas to get serious about water loss.

4 All cost figures are in $2020. More details and the methods used to compute these units cost are provided in Chapter 2 and Appendix B.
5 See Table 7-6 of the 2022 State Water Plan, Indirect use is listed as $391/af and conjunctive use is listed as $1724/af.
6 *Ibid*. The weighted average cost for industrial conservation in the 2020 planning decade is $680/af, the municipal conservation weighted average for the same period is $675/af, for agricultural conservation it is $284/af.

Water Loss Mitigation as a Supply Strategy

1

How much water is being lost in Texas and how much could be saved?

- Texas utilities are losing at least 572,000 acre-feet of water loss per year.
- Texas could save at least 249,000 acre-feet per year if utilities achieve a 75th percentile water loss performance level compared to peers.
- Nine Texas water planning regions could meet a significant amount of municipal needs by achieving a 75th percentile in water loss mitigation.

INTRODUCTION

Water is an essential resource for Texans. Water utilities treat and distribute drinking water directly to our homes, businesses, institutions and industrial facilities. Texas water distribution systems are composed of over 165,000 miles of pipes, enough to reach from El Paso to Houston more than 220 times. Those pipes degrade over time due to aging, corrosion, pressure, vibrations, ground movement, traffic loads, and other forces, causing various types of fractures and leaks.[7] As a result, water distribution systems leak and lose treated drinking water, with a small but significant fraction never arriving at the intended destination.

The 2022 State Water Plan identifies water demands, available supplies, and municipal needs for each of Texas' 16 planning regions. Each of the planning groups identify water management strategies necessary to fill the predicted water supply gap. If Texas utilities take actions to address the water loss in their systems, the need for many supplemental water supply projects can be mitigated, delayed, or eliminated. It is therefore critical to understand the potential for mitigating water loss in Texas. With this in mind, we used data from the 2022 State Water Plan and 2019 water loss audits to project the potential water supply which could be derived from mitigating water loss.[8]

This chapter:

- defines water loss,
- estimates how much water is being lost in Texas,
- estimates how much water can be saved if we focus on addressing water loss,
- compares that to water needs identified for each region in the 2022 State Water Plan.

What is a water loss audit?

A water loss audit is a tabulation of all categories of water losses and components of water losses using a standard format. Water loss audits help a utility understand where and how much water is being lost from the distribution system and provide a baseline from which to track and improve water loss mitigation efforts. All retail public water systems with more than 3,300 connections or a financial obligation to TWDB are required to complete and submit a water loss audit annually. All other retail public water suppliers are required to submit a water loss audit to the agency every five years.

7 https://www.waterworld.com/home/article/14070145/nonrevenue-water-loss-its-causes-and-cures
8 The 2019 water loss audits were based on 2019 data submitted to the Texas Water Development Board in May 2020.

WHAT IS WATER LOSS?

Water loss encompasses both real physical loss through leakage and apparent loss through consumed water that is not accurately tabulated or billed.

To understand how much water is being lost in Texas it is important to understand the key components of water loss. All water distributed by a utility system can be categorized as either **revenue water** or **non-revenue water**. Revenue water is the volume of water which the utility bills to end users. Non-revenue water, however, is the volume of water which is distributed but is not billed by the utility. Non-revenue water consists of unbilled authorized consumption (e.g., flushing and firefighting) and water losses.

Water loss is broken down into two categories: apparent losses and real losses.

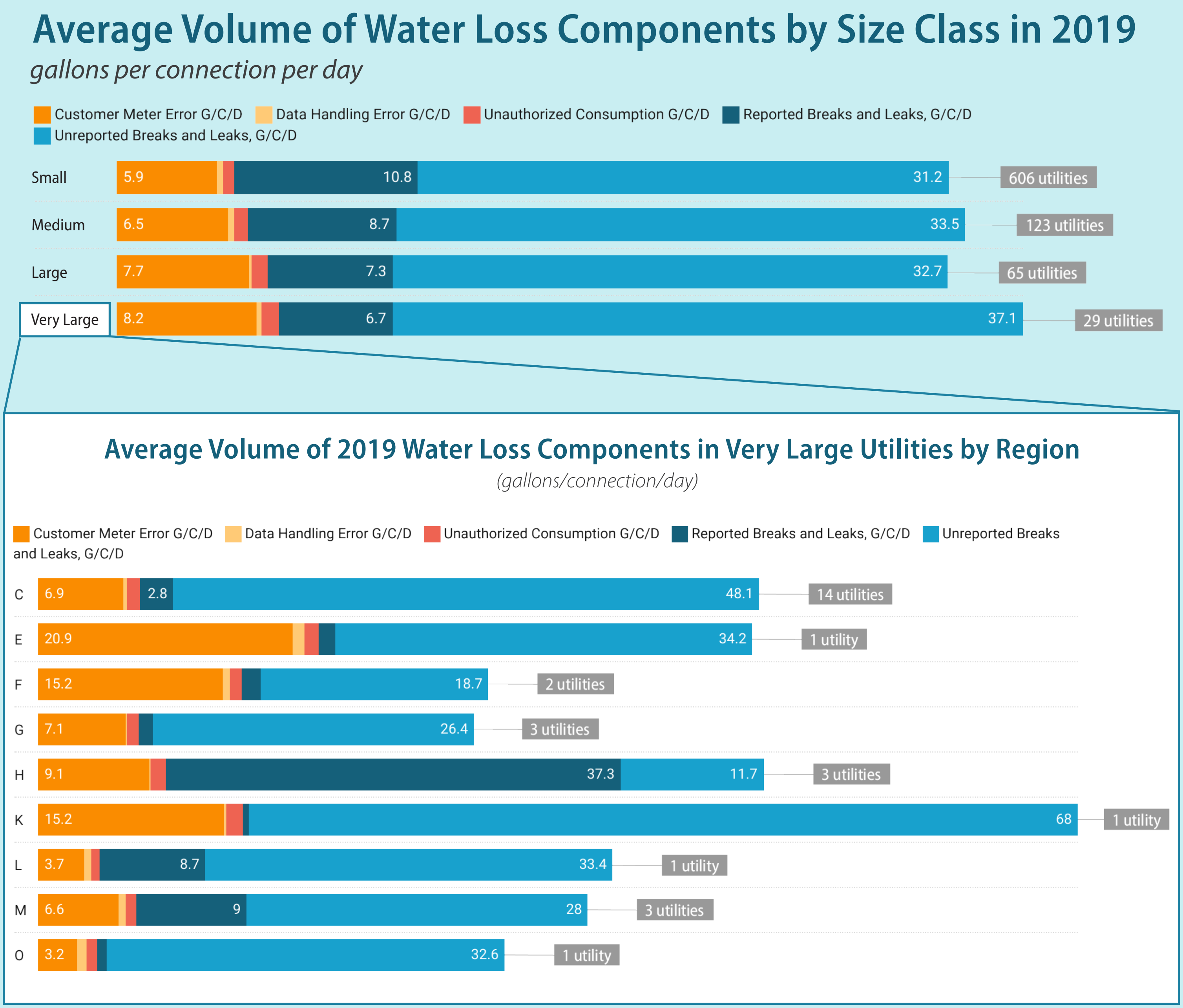


Figure 3. Average Volume of Water Loss Components by Size Class in 2019 (in gallons/connection/day).
Source for analysis: Texas Water Development Board, Water Loss Audit Data, 2019. Note: Figure 3 does not necessarily represent all Texas utilities, it is the result of an analysis of a filtered sample of utilities that demonstrates the average proportions of water loss components amongst utilities.

- **Real losses** are physical water losses (leakage) from the water distribution system which can range from small yet constant leaks throughout a water distribution system to the losses from catastrophic main breaks. The principal consequences of real losses are water resource depletion and excessive water pumping and treatment costs.
- **Apparent losses** represent non-physical losses — water which is actually consumed, but not properly tabulated or billed. These losses are the result of meter inaccuracies, billing system errors and water theft (unauthorized consumption). The principal consequence of apparent losses is lost revenue for the utility.

For this report, we focus on both apparent and real losses. We do this because the total water supply projections in the 2022 State Water Plan include apparent and real water loss, and the water loss control strategies in the State Water Plan address both apparent and real water loss. Accounting for both gives a true picture of future water needs and helps facilitate accurate planning.

Figure 3 shows the average volume of the various components of water loss in gallons/connection/day for utilities in Texas in 2019 using data from a sample of 823 water audits (filtered down from a larger dataset to remove outliers, see Appendix A for filtering criteria). The chart shows three components of apparent loss in orange/red, and two components of real losses in blue. Real losses dominate the proportion of water losses. The proportion of losses across size classes has low variation because the large number of utilities in each class tends to smooth out the variations. The inset chart in Figure 3 provides a closer look at the same components for the 29 Very Large (>100,000 pop.) utilities by region. Considerable variations, especially in the real losses, are evident.

HOW MUCH WATER IS TEXAS LOSING?

Texas utilities are losing about 51 gallons of water per service connection every day, which adds up to at least 572,000 acre-feet of water loss per year.

Texas has robust programs for reporting water use and water loss data. All retail public water suppliers in Texas are required to submit a water loss audit once every five years to the Texas Water Development Board (TWDB). Additionally, any water supplier with either more than 3,300 service connections or financing from TWDB must submit an annual water loss audit. Since 2017, every utility that submits a report is required to attend a

Estimated Water Loss in 2020 by Size Class

Size Category	Population Served	# of Utilities	Total Retail Population	% of Population	Total Retail Connections	% of Connections	Estimated Total Water Losses (af/yr)	% of Water Losses	Estimated Avg Water Losses (g/c/d)
Very Large	Greater than 100,000	41	14.2M	49%	4.5M	45%	277K	48%	55
Large	Between 25,000-100,000	105	5M	17%	1.8M	18%	96K	17%	47
Medium	Between 10,000-25,000	228	3.5M	12%	1.2M	12%	70K	12%	50
Small	Less than 10,000	3.6K	6.5M	22%	2.4M	24%	129K	23%	47
All		4K	29.2M		10.1M		572K		51

Table 1. Utility Attributes & Estimated Water Loss in 2020 by Size Class.
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

water loss audit training administered by TWDB prior to submitting the report.

For this report we obtained water audits submitted to the TWDB over the period 2015-2019, representing 2,871 utilities. We found the 2019 data points to be statistically consistent with the 2015-2018 data. Given the consistency of both datasets, we chose to base our analysis on only 2019 data as this was the most recent publicly available data at the time the analysis was performed.

We continued our analysis by establishing baseline calculations of total water loss using the 2019 data for a filtered sample of water audits submitted by Texas utilities, with 823 observations in the sample. We then extrapolated the sample results to a state-wide level, using specific utility infrastructure attributes for 4,021 Texas utilities. Table1 provides state-wide estimates of water utility attributes by size category, including number of utilities, population served, and number of retail connections served.

Many factors contribute to water loss; no one indicator can tell the complete story of water losses. However, indicators generally fall into two categories:

- **Total Water Loss** allows a comparison to water resource availability, total water needs, potential supplies or mitigations in demand from other water management strategies.
- **Unit Water Loss** is found by dividing the total water losses by a scale factor, such as the number of miles of pipe or the number of connections. An accurate unit water loss allows comparison of losses from place to place and between different time periods. However, comparisons must be done carefully because differences in utility attributes, listed below, may interfere with accurate comparisons.

Water loss levels are a function of many factors such as the total number of service connections, distribution system age and condition, total system miles or pipe, pipe material, system pressure, pressure variations, the type of soil (corrosion), water consumption per connection, as well as type and age of water meters. In addition, fluctuations in water loss levels may or may not reflect investments in water loss mitigations. Improvements in reported data quality, changes in total system water use, and extreme weather events can also drive water loss indicators.

One of the indicators for water loss most recommended by the American Water Works Association is the number of gallons of water lost per service connection per day. Unlike the commonly-used percentage indicator, gallons per connection per day is not dependent on the amount of water sold by a utility and is less prone to annual fluctuations due to weather and other factors.[9] As shown in Table 1, our analysis indicates Texas is losing approximately 572,000 acre-feet per year which equates to about 51 gallons per service connection every day. The total water losses are enough water to meet the total annual municipal needs of the cities of Austin, Fort Worth, El Paso, Laredo and Lubbock combined. It's a lot of water.

Water is a limited resource and we cannot afford to lose such volumes — and water utility revenue — through leaking infrastructure or inaccurate measurements.

Water loss is not distributed evenly across the state. Our largest water utilities — those that serve 100,000 people or more — account for only 1.0% of all water utilities but serve 49% of the state's population, have 45% of service connections, and incur 48% of Texas' total water loss. Conversely, our smallest water utilities account for 91% of all water utilities but serve only 22% of the population, 24% of service connections, and contribute to 23% of the state's total water loss.

9 Committee Report: AWWA Water Loss Control Committee – Non-Revenue Water Key Performance Indicators: AWWA's 2020 Position. In the Committee Report this indicator is referred to as the normalized water loss.

HOW MUCH WATER COULD WE SAVE BY REDUCING LOSSES?

Given the total amount of water loss occurring in utilities across Texas, how much water could we potentially save if those water losses are mitigated?

Analysis Methodology

To estimate the potential water savings from water loss mitigation, we used a statistical performance assessment tool referred to as a "Frontier Analysis" (FA) which is described in detail in Appendix A.

In short, The Frontier Analysis uses regression analysis to predict the water losses in any utility based on the miles of pipe, connection density, unit authorized consumption, and the variable production cost of water. The regression produces a formula for the average water losses for any utility with any set of inputs. That level of losses is known as the predicted losses. The actual (observed) water losses are compared to the predicted losses to assess water loss performance of each utility.

Some utilities will have observed loss higher than the predicted — indicating poorer than average performance; and some will have lower observed losses than predicted — indicating better than average performance. This concept is illustrated in Figure 4.

The strongest performer creates a "low frontier" which is essentially the best possible performance. For any water utility, the difference between the actual water loss and the "low frontier" represents the maximum water loss savings potential. The low frontier is equivalent to the 100th percentile toward best possible performance. Other percentile levels, such as the 75th percentile, or the 90th percentile create alternate performance levels.

As discussed in more detail in Appendix A, setting targets at the best possible performance (100th percentile) is not realistic nor economically sensible. The absolute best performance is likely to be a special case or has attributes not captured in the Frontier Analysis model. A target range between the 75th and 90th percentiles has been found to be close to the economic level of water

Conceptual Framework of Frontier Analysis

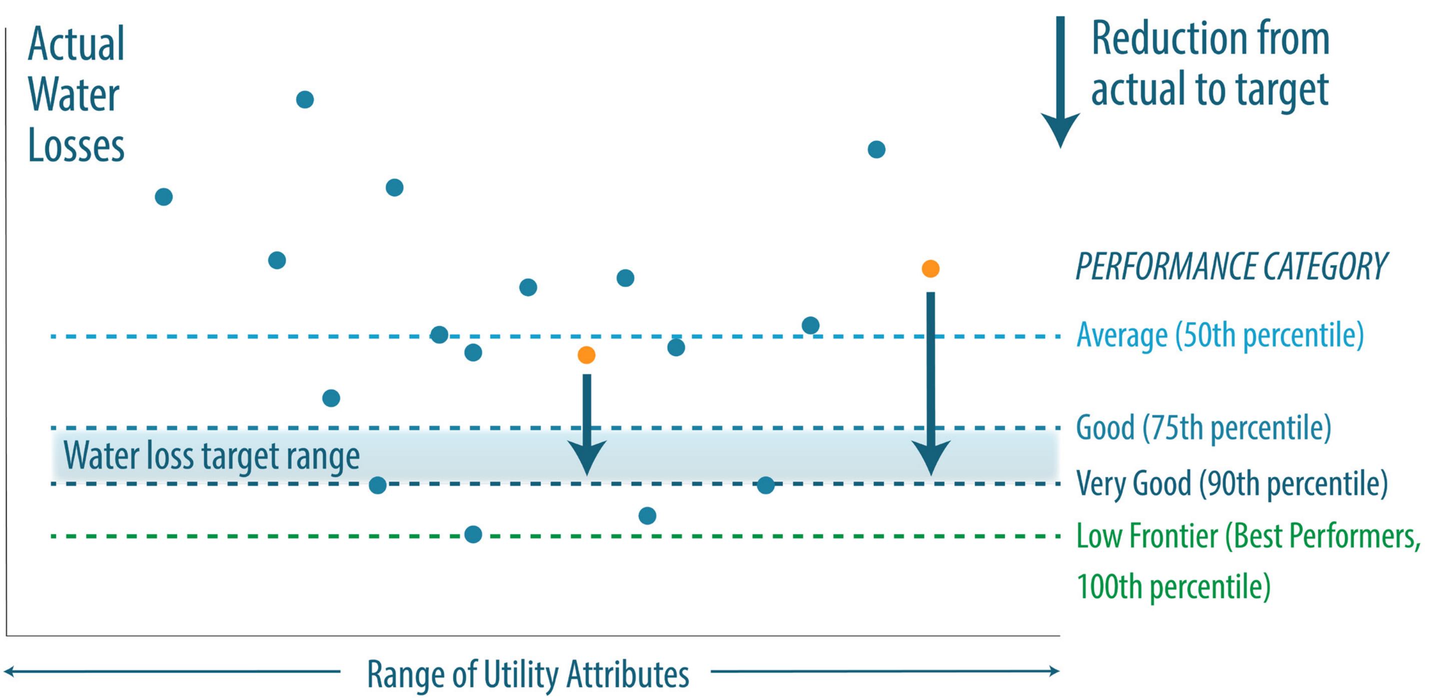


Figure 4. Conceptual Framework of Frontier Analysis. This report uses Frontier Analysis to estimate the potential water savings from water loss mitigation at different performance levels.

AVERAGE	Water loss in gallons / connection / day is lower than **50% of TX utilities with similar attributes**
GOOD	Water loss in gallons / connection / day is lower than **75% of TX utilities with similar attributes**
VERY GOOD	Water loss in gallons / connection / day is lower than **90% of TX utilities with similar attributes**

Figure 5. Water Loss Mitigation Performance Standards

losses and appropriate for a rapid assessment of water loss mitigation potential.[10] There are utilities in Texas that currently perform in this range. In addition to this 'Very Good' 90th percentile performance standard, we chose a 'Good' 75th percentile standard, and an 'Average' 50th percentile standard to quantify savings potential associated with average water loss performance across the state.

Since the objective is to decrease water loss, achieving a higher percentile in terms of water loss performance is the preferred outcome.

For ease of reference and to avoid confusion, we have labeled the 50th, 75th, and 90th percentiles as Average, Good, and Very Good Performance standards, respectively, and refer to them as such throughout our subsequent analysis.

The Frontier Analysis was conducted on a filtered sample of 823 water loss audits from 2019. The sample provided the most accurate starting point for estimating the water loss level and savings potential. However, there are over 4000 retail public water suppliers in the state. Therefore, we obtained a complete dataset of the retail population and number of retail connections from each retail public water supplier for the year 2020 from the TWDB. This data and the results of the Frontier Analysis results on the sample (gallons per connection per day for each size category, in each region, at each performance standard) were used to estimate the statewide water losses in the year 2020 by region, size class and performance standard. More information on this "scale-up" calculation is provided in Appendix A.

Analysis Results

The final results are provided in Table 1, as well as Figures 6 and 7. Figure 6 provides the estimated total water loss and potential savings in 2020 by utility size category. The Frontier Analysis results show that if each utility reduced its losses to the current Average Performance Standard the total water loss would decrease from about 572,000 acre-feet per year to about 504,000 acre-feet per year for a modest savings of about 68,000 acre feet per year and a reduction of about 12%. A reduction in water loss to the Good Performance Standard would save much more — about 249,000 acre-feet per year or about 43%. Adherence to the Very Good Performance Standard would save about 359,000 acre-feet per year, or almost 63%. Figure 7 provides a similar tabulation of results, but on the basis on unit water losses (and savings) in gallons per connection / day. Overall, Texas could significantly mitigate total water loss in the state by achieving water loss levels already realized by the better-performing utilities in Texas.

10 As described in Appendix A, the Frontier Analysis method was "tested" by comparing it to other methods of water loss performance assessment. A paper by Dr. Tim Loftus of Texas State University published in 2019 estimated the economically recoverable water losses on Regions C and K, using audits from 2014. After making adjustments for time period, the economic water loss level was found to correspond closely to the average of the Good and Very Good Performance Standards from the Frontier Analysis. In addition Appendix A shows a comparison of the FA Performance Standards (for real loss only) to the results of an Optimal Real Loss Model, for the case of the State of Parana in Brazil. The economic levels at all 25 sites analyzed fell between the Good and Very Good Performance Standards. Loftus (2019) Economically Recoverable Water in Texas: An Underappreciated Water Management Strategy?, Texas Water Journal, Vol 1o No. 1, July 2019, pps 60-74.

Estimated Total Water Loss and Potential Savings

acre-feet/year

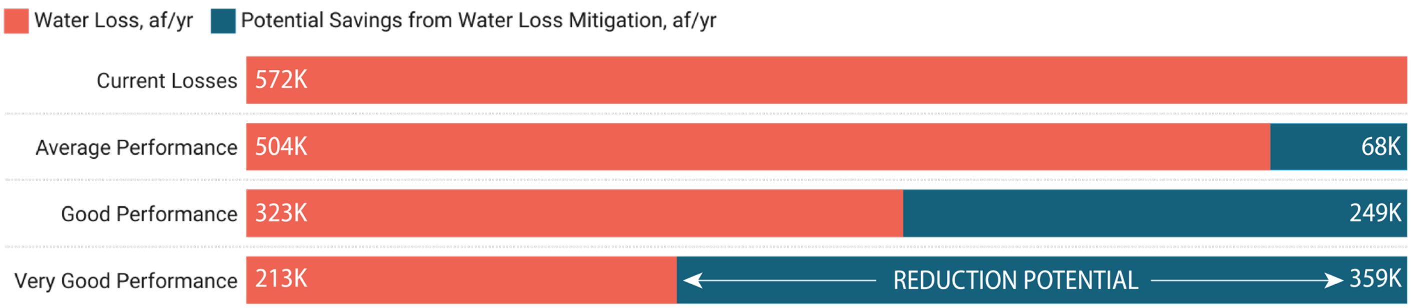


Figure 6. Estimated Total Loss and Potential Savings (in acre-feet/year). *Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.*

Average Water Losses at Improved Performance Levels

gallons/connection/day

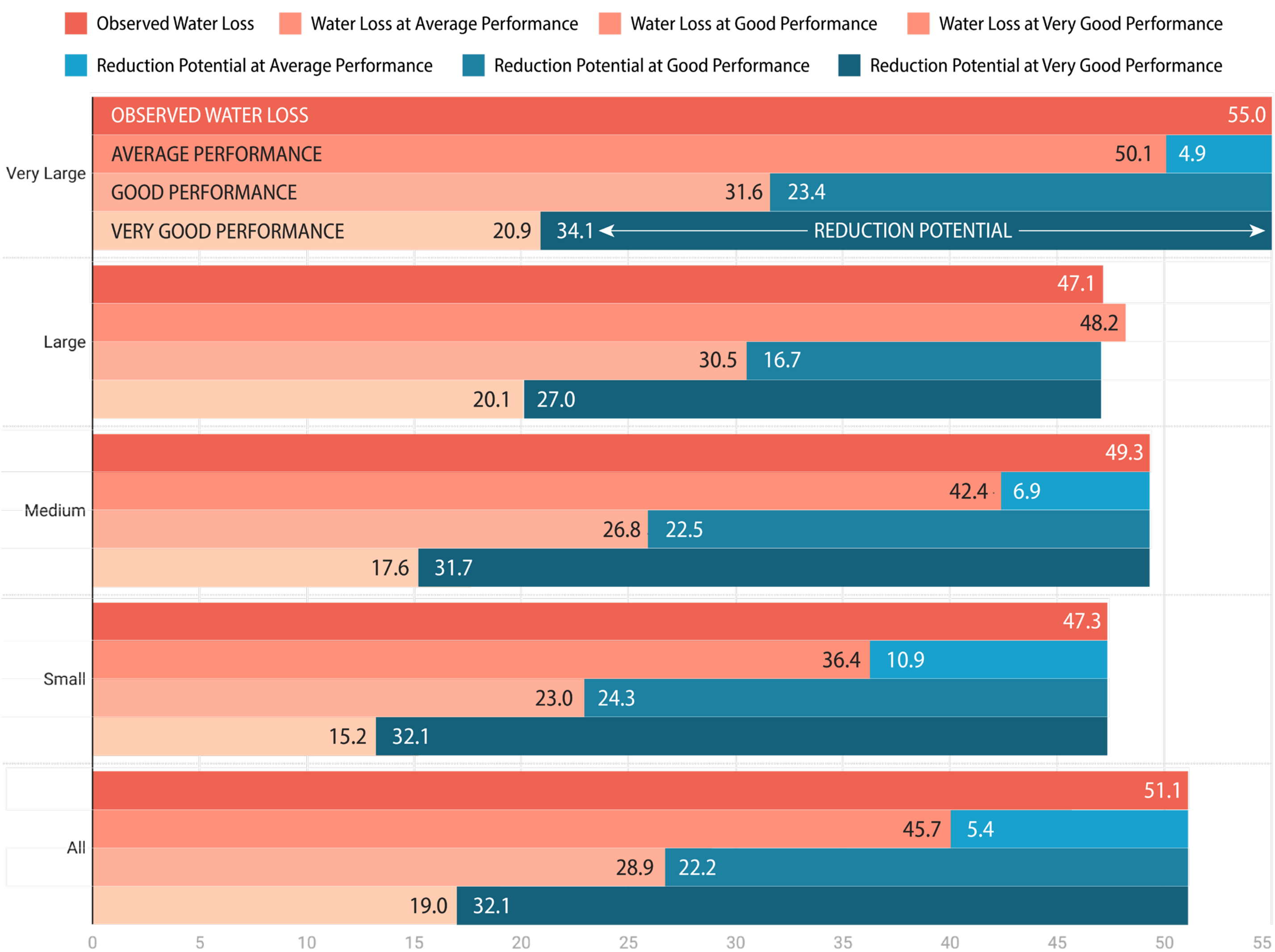
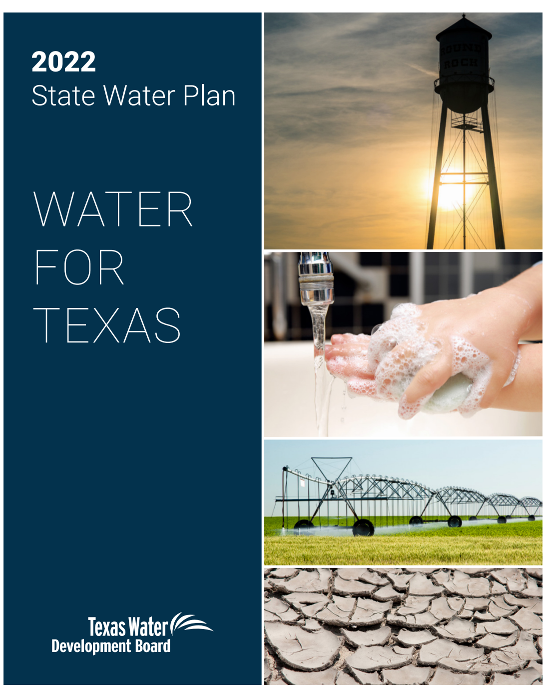


Figure 7. Average Water Losses at Improved Performance Levels (gallons/connection/day). *Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; Texas Commission on Environmental Quality, 2020 Water Utility Data.*

HOW DO THESE SAVINGS COMPARE TO WATER LOSS RELATED STRATEGIES IN THE 2022 STATE WATER PLAN?

After determining 2019 baseline water loss levels and estimating the water savings potential for each performance standard, we then consulted the 2022 State Water Plan to identify the recommended water management strategies (WMSs) that specifically targeted mitigating municipal water loss. In the course of each region's efforts to develop their plans, each region considers water loss mitigation as a potential strategy and if that strategy is selected, the planning group will quantify the amount of water supply that will result from implementing that strategy across each planning decade. The following municipal WMSs were considered "water loss mitigation" for the analysis:

- Water audit and leak repair
- Advanced metering / meter infrastructure (AMI) or AMI project
- Water loss control
- Water loss audit and main-line repair
- Water loss mitigation
- Water audits and leak
- Water meter and water line replacement



The 2022 State Water Plan includes some water loss mitigation in the recommended water management strategies of certain individual water planning regions. Our analysis shows further mitigation is cost-effectively achievable in each region.

The objective of this step is to determine the amount of water Regional Water Planning Groups (RWPG) are planning to save through implementing water loss mitigation strategies (aka water loss related WMS). By cross-referencing the supplies from these WMSs, we are able to allocate future water loss mitigation accurately by showing water loss mitigation goals set by each RWPG and additional projected savings potential based on our analysis. If RWPGs did not indicate their planned water loss mitigation efforts via one of the WMSs listed above, those efforts were not accounted for in this analysis. We note that some RWPGs included water loss mitigation as part of the Municipal Water Conservation WMS included in those plans. However, those groups did not provide details about the quantity of water that would be saved through implementing water loss apart from the other strategies listed. Eleven Regional Water Planning Groups included municipal WMSs aimed at water loss mitigation.

Figure 8 and Table 2 provide a comparison of the estimated 2020 water losses with water savings potential from both the FA and recommended water-loss-related WMSs from the 2022 State Water Plan. Two important observations can be made. First, the "supplies" from the recommended water loss related WMS are concentrated in the regions with high current, observed losses, such as Regions C and H. Yet there are other regions, G and L for example, where water loss related WMS are small. If utilities in those regions mitigated losses to the Good or Very Good Performance levels, major mitigation of water losses could be achieved. Second, and overall, the supply from the recommended water loss WMS are small — especially when compared to the water loss mitigation potential.

Figure 9 shows the estimated water savings in acre-feet per year that can be achieved by meeting the performance targets outlined in Figure 5, as well as the water savings from municipal WMSs that target water loss in the 2022 State Water Plan. In each row, the four categories build on top of one another. The left-end of each row represents supplies from WMSs and stacked on top of this are the incremental savings for each performance standard. The length of each row represents the total savings potential associated with the most aggressive performance target. Figure 10 presents the same results in gallons per connection per day instead of acre feet per year.

Estimated Water Savings by Region
(acre-feet per year)

Region	# of Retail Connections	Observed Water Loss (acre-ft/yr)	Supplies from Water Loss WMSs (from 2022 SWP)	Average	Good	Very Good
A	137.1K	8.6K	3.9K	1.4K	4.1K	5.6K
B	70.4K	4K	0	425	1.7K	2.5K
C	2.5M	146.3K	29.1K	14.6K	63.1K	91.5K
D	304.1K	17.1K	0	1.5K	7.3K	10.6K
E	260.2K	17K	5.3K	680	6.7K	10.2K
F	228.7K	15.4K	330	2.8K	7.5K	10.2K
G	832K	45.6K	698	3K	18.7K	27.9K
H	2M	104.2K	5.9K	10.8K	45.2K	65.3K
I	389.1K	28.5K	2K	9.2K	16.3K	20.5K
J	34.9K	2K	245	350	974	1.3K
K	479.6K	36K	12.9K	5.6K	16.8K	23.3K
L	1.2M	61.9K	426	7.8K	27.8K	39.4K
M	547.9K	29.9K	1.6K	0	9.8K	16.7K
N	190.5K	10.8K	0	935	4.6K	6.7K
O	156.4K	7.7K	0	0	2.3K	4.1K
P	14.6K	843	0	182	426	568

Table 2. Estimated Water Savings by Region.
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

Our analysis of the 2022 State Water Plan indicates that municipal water loss WMS included in the plan will reduce water loss by one to seven gallons per connection per day. However, going beyond what is in the State Water Plan and achieving the 75th percentile performance (Good Performance) can reduce water loss by 16 to 24 gallons per connection per day, while achieving 90th percentile performance (Very Good Performance) will yield savings ranging from 26 to 34 gallons per connection per day.

In short, our analysis indicates that more water can be saved through water loss mitigation than is recommended in the 2022 State Water Plan. Making a strong investment in mitigating water loss can defer or replace major supply-side investments such as reservoirs and desalination. This is especially important when water loss mitigation is a less expensive supply strategy. Chapter 2 analyzes the cost-effectiveness of water loss mitigation compared to supply-side strategies.

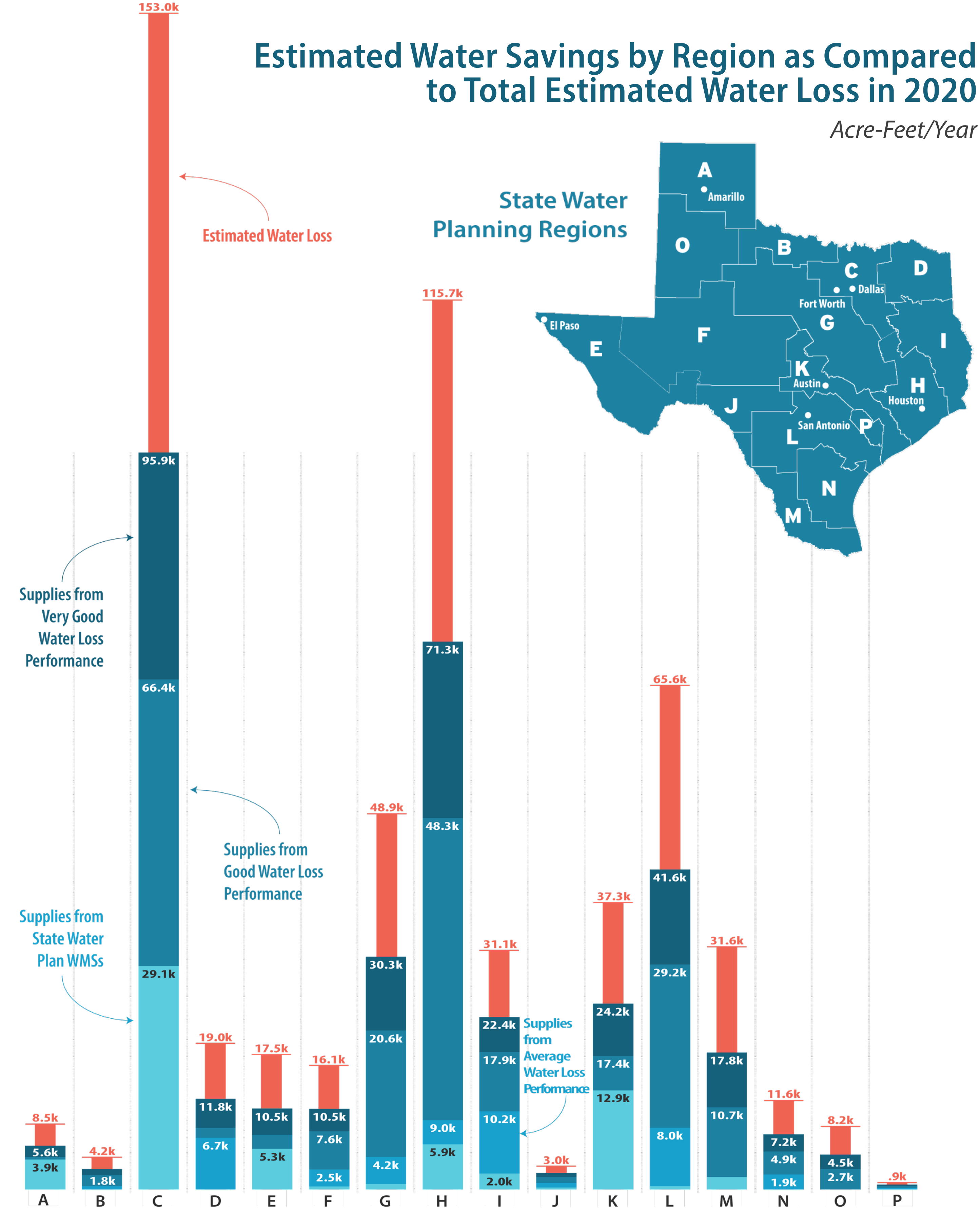


Figure 8. Estimated Water Savings by Region as Compared to Estimated Water Loss in 2020.
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

Estimated Water Savings from Water Loss Mitigation by Utility Size

Acre-Feet/Year

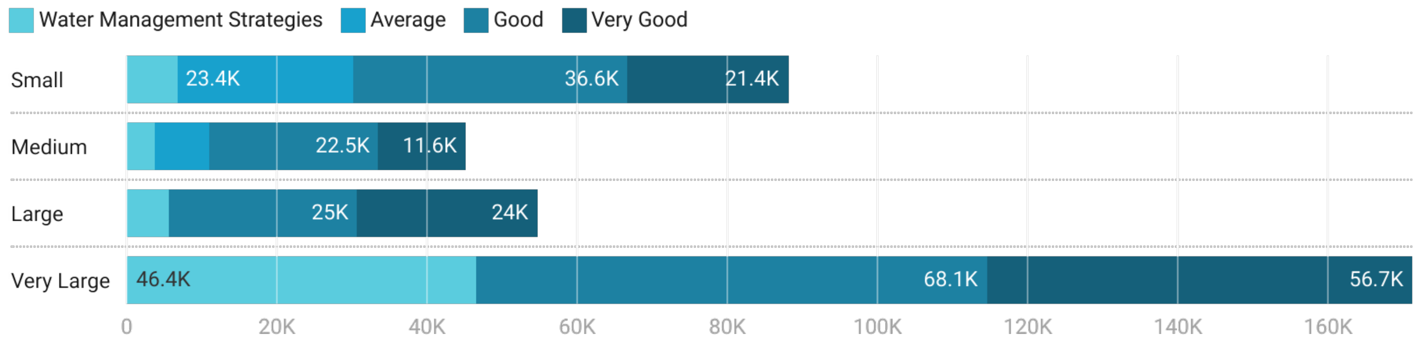


Figure 9. Estimated Water Savings From Advanced Water Loss Strategies by Utility Size (acre-feet/year).
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.an.

Gallons per Connection per Day

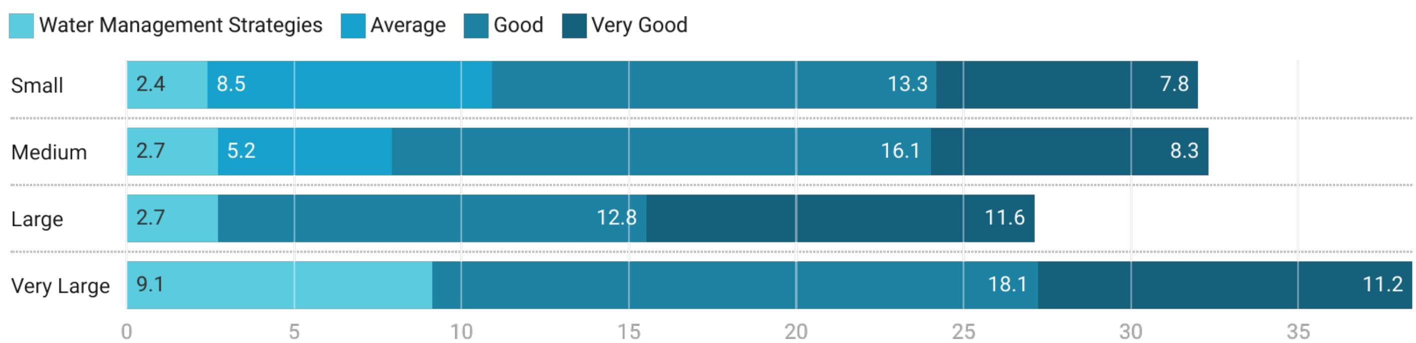


Figure 10. Estimated Water Savings from Water Loss Mitigation by Utility Size (gallons/connection/day).
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

HOW DOES THIS COMPARE TO THE WATER WE NEED?

Our analysis shows significant water supply potential from mitigating water loss, which will greatly improve water utilities' ability to meet future needs without having to develop new water supplies.

The Texas State Water Plan calculates "need" for each planning decade by estimating "demands" (population multiplied by per capita water demand) and then subtracting the "supplies" (the projected water supply available). Simply put, the result represents the water demands that existing water supplies cannot meet.

We compared the municipal water needs for each of Texas' 16 planning regions against the savings potential estimated for each performance standard. These estimates account for the municipal water loss WMSs recommended in the Regional Water Plans. The results of the analysis for the 2020 planning decade for the four size categories are shown in Table 3.

The table shows that if water utilities achieve Good Performance, (75th percentile), the water savings could provide 100% of State's increased municipal water needs. Importantly, achieving the 75th percentile could meet 100% of needs for both the Very Large and Small utilities for the 2020 planning decade. This is especially noteworthy given that these two size classes represent the largest share of the Texas population at a combined 70%.

Table 4 and Figure 11 present the same analysis by region. The table demonstrates significant contributions to meeting increased municipal water supply needs can result from investment in water loss mitigation. For the 2020 planning decade, nine regions could have 100% of their water needs met by achieving a Good Performance Standard (75th percentile) in water loss mitigations, including Regions C, H, K, L and M which have high demands.

It is important to recognize that if 100% is shown in a particular Size Class or Region, it does not necessarily mean that all water user groups in those regions will have 100% of needs satisfied. For example, a large utility in a particular "location" may be able to mitigate losses to cover its needs, or in many cases more than cover its needs, allowing reserve for growth. But another city in the same region may not be able to meet all of its needs through water loss mitigation. Utilities within the same region are generally not physically interconnected and may not be in the same river basin. Sharing supply from water loss mitigation is therefore not usually feasible. Nonetheless, a utility that mitigates water loss can use the saved water to meet water demand for many years to come and incurs substantial benefits, such as delaying or reducing the need for water supply expansion and enhancing water resource security and resilience.

The 2022 State Water Plan forecasts demands, supplies, and needs out to the 2070 planning decade. While long term planning is important in general terms, it is difficult to plan for future decades when water loss mitigation programs are being recommended. For example, significant water loss mitigation WMS are recommended in Regions C and H in the 2020 and 2030 decades. If utilities adopted these WMS their water losses would be significantly mitigated, and utilities could maintain the water losses at the lower levels at relatively low cost — which could help meet additional needs from growth in population and water demand. If the utilities in Regions C and H implemented those WMS, the potential for further

Projected Water Savings Compared to 2022 State Water Plan Municipal Needs

(by Size Category)

Utility Size	2020 Decade Municipal Needs (af/yr)	Potential Water Savings from Water Loss Reduction as a Percent of Needs: Supply from Water Loss WMSs	Average	Good	Very Good
Very Large	65.4K	71% *(46.4k af/yr)*	35% *(22.6k af/yr)*	>100% *(116.5k af/yr)*	>100% *(171.2k af/yr)*
Large	65.9K	8% *(5.6k af/yr)*	6% *(4.2k af/yr)*	50% *(33.2k af/yr)*	83% *(54.6k af/yr)*
Medium	37.7K	10% *(3.8k af/yr)*	29% *(11.0k af/yr)*	86% *(32.6k af/yr)*	>100% *(45.1k af/yr)*
Small	45.7K	14% *(6.6k af/yr)*	66% *(30.1k af/yr)*	>100% *(66.7k af/yr)*	>100% *(88.0k af/yr)*
Total	214.6K	29% *(62.4k af/yr)*	29% *(62.4k af/yr)*	>100% *(248.9k af/yr)*	>100% *(358.9k af/yr)*

* Note: Water loss distribution is not uniform. A region with >100% needs met does not neccessarily mean all Water User Groups will have 100% of needs met. See '*Water Loss Distribution Matters!*' on page 6.

Table 3. Projected Water Savings Compared to 2022 State Water Plan Municipal Needs (by Size Category).
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

Projected Water Savings Compared to 2022 State Water Plan Municipal Needs

(by region)

Region	2020 Municipal Needs (af/yr)	Potential Water Savings from Water Loss Reduction as a Percent of Needs			
		Supply from Water Loss WMSs	Average	Good	Very Good
A	1.4K	>100% *(3.9k af/yr)*	>100% *(1.6k af/yr)*	>100% *(4.2k af/yr)*	>100% *(5.7k af/yr)*
B	263	0% *(0k af/yr)*	>100% *(426 af/yr)*	>100% *(1.8k af/yr)*	>100% *(2.6k af/yr)*
C	42.7K	68% *(29.1k af/yr)*	37% *(15.8k af/yr)*	>100% *(66.4k af/yr)*	>100% *(95.9k af/yr)*
D	17.5K	0% *(0k af/yr)*	38% *(6.7k af/yr)*	46% *(8.0k af/yr)*	67% *(11.8k af/yr)*
E	4.1K	>100% *(5.3k af/yr)*	67% *(2.7k af/yr)*	>100% *(7.1k af/yr)*	>100% *(10.5k af/yr)*
F	14K	2% *(330k af/yr)*	18% *(2.5k af/yr)*	54% *(7.6k af/yr)*	75% *(10.5k af/yr)*
G	31.1K	2% *(698k af/yr)*	13% *(4.2k af/yr)*	66% *(20.6k af/yr)*	97% *(30.3k af/yr)*
H	18.5K	32% *(5.9k af/yr)*	49% *(9.0k af/yr)*	>100% *(48.3k af/yr)*	>100% *(71.3k af/yr)*
I	501	>100% *(2.0k af/yr)*	>100% *(10.2k af/yr)*	>100% *(17.9k af/yr)*	>100% *(22.4k af/yr)*
J	5.1K	5% *(245 af/yr)*	15% *(785 af/yr)*	32% *(1.6 af/yr)*	41% *(2.1k af/yr)*
K	4.9K	>100% *(12.9k af/yr)*	>100% *(5.8k af/yr)*	>100% *(17.4k af/yr)*	>100% *(24.2k af/yr)*
L	24.5K	2% *(426 af/yr)*	33% *(8.0k af/yr)*	>100% *(29.2k af/yr)*	>100% *(41.6k af/yr)*
M	35.5K	5% *(1.6k af/yr)*	0% *(-1.5k af/yr)*	30% *(10.7k af/yr)*	50% *(17.8k af/yr)*
N	10.2K	0% *(0k af/yr)*	19% *(1.9 af/yr)*	48% *(4.9k af/yr)*	70% *(7.2k af/yr)*
O	4.3K	0% *(0k af/yr)*	0% *(-592k af/yr)*	61% *(2.7k af/yr)*	>100% *(4.5k af/yr)*
P	0	0% *(0k af/yr)*	>100% *(184 af/yr)*	>100% *(451 af/yr)*	>100% *(568 af/yr)*

Table 4. Projected Water Savings Compared to 2022 State Water Plan Municipal Needs (by Region).
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

Estimated Water Savings as a Percentage of 2022 State Water Plan Municipal Needs (by Region)

Potential Water Savings from Water Loss Mitigation as a Percent of Needs

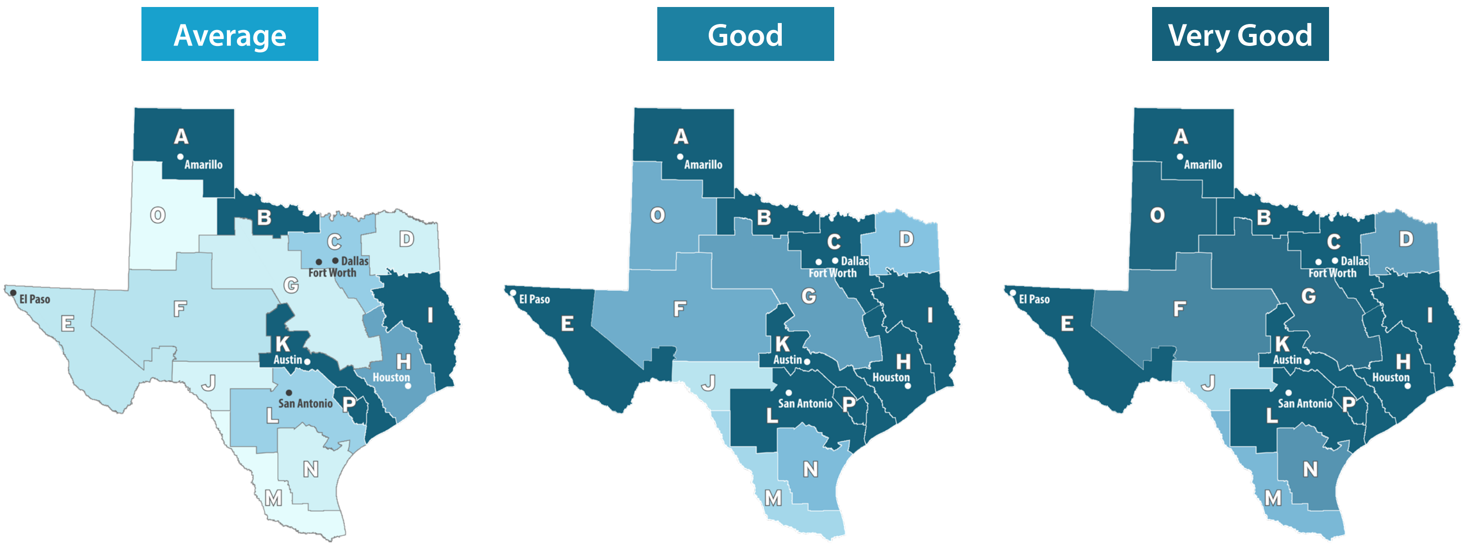


Figure 11. Estimated Water Savings as a Percentage of 2022 State Water Plan Municipal Needs (by Region).
Sources for analysis: Texas Water Development Board, Water Loss Audit Data, 2019; 2022 State Water Plan; Texas Commission on Environmental Quality, 2020 Water Utility Data.

loss mitigation could be small. However, it is not known, without considerable analysis, if each of those WMS to mitigate water losses will bring the losses down to the Average, Good or Very Good Standard. In addition, it is not certain that the recommended water loss mitigation programs included in the Regional Water Plans will be implemented. Given these uncertainties and the scope of this report, the analysis of water loss mitigation in future decades was not analyzed.

CONCLUSIONS

Our analysis demonstrates that mitigating water loss will benefit Texans. Investments in this water management strategy will help close the gap between water demands and water supplies. Ensuring that all utilities are mitigating and controlling water loss at the good to very good performance level is an important strategy to ensure a resilient water future.

Investing in water loss mitigation programs is more cost-effective than developing new water supplies. Texas communities should prioritize investment in water loss control. The following chapter reviews the costs and benefits of water loss control programs.

Cost-Effectiveness

How much do water loss mitigation activities cost and how do those costs compare to other water management strategies?

2

- Mitigation methods that focus on root causes and address the largest components of water loss are usually very cost effective.
- Water loss mitigation activities often follow a classic economies of scale curve— unit costs decrease as projects increase in scale.
- The cost of many water loss mitigation approaches compare favorably to various supply-side water management strategies (e.g. reservoirs, seawater desalination) in the Texas State Water Plan.

INTRODUCTION

We've seen that there is a significant amount of water that can be saved in Texas by mitigating the amount of water utilities lose due to water losses. To make the economic case for water loss mitigation as a Water Management Strategy, this section reviews the basics of water loss mitigation practices and focuses on their cost effectiveness by addressing:

- **The main components of, the principal drivers of and best management practices for mitigating apparent loss.**
- **The main components of, the principal drivers of and best management practices for mitgating real loss.**
- **How much these practices cost per unit of water savings.**

Before reviewing water loss components and associated mitigation practices, two fundamental precepts should be highlighted — good management and data quality.

Good Management: The Continuous Improvement Cycle. A water loss mitigation program cannot produce results and be cost effective if it is not data-driven, well planned and effectively managed. Figure 12 shows a continuous planning and implementation cycle, which begins with a validated audit and other data, to water loss assessment, activity planning and implementation and re-assessment and refinement of the program.

Data Quality: Water Audits and Validation. The critical foundation of an efficient and cost-effective water loss mitigation and control program is accurate, thorough, validated water audits. Such audits will identify the largest components of water loss and provide some information on their causes, especially if combined with component analysis. With that knowledge, effective programs can be designed and implemented and refined to mitigate the priority components.

Table 6 outlines water balance components, the "drivers" associated with water waste and water loss, and practices for water savings in each component. It is common for components to involve similar drivers and be addressed through similar practices. For example, the mitigation of all three components for real loss have overlapping drivers and practices. In addition, some of the practices which address water loss also address water saving through conservation, such as the Advanced Metering Infrastructure (AMI). Savings from water conservation and water loss mitigation are similar Water Management Strategies in that they both benefit future water supplies through reducing demand. If customers use less water and utilities lose less water through leaky infrastructure, there will be more water supply.

Figure 12. The Continuous Planning and Implementation Cycle

BENEFITS OF MITIGATING APPARENT AND REAL LOSS COMPONENTS

Reducing real losses is critical for two main reasons. First, mitigating infrastructure leakage reduces the overall amount of water needed to meet customer needs (system input volume). This, in turn, reduces energy costs for pumping water from source to customer, reduces energy chemical and related costs for water treatment, water purchases, and where relevant, reduces the need for additional water supplies. Second, a reduction in system input volume requirements will ease the withdrawal of water from wells tapping pumped aquifers, can delay the construction of, and/or cost of expansion of water treatment plants, pumping stations, dams and other surface water delivery infrastructure, and even reduce the need for additional water supplies. Avoiding expansions or new facilities can represent major capital savings.

Reducing apparent water loss is important for three main reasons. First, if there is a large amount of apparent loss, the actual water needs may be under-measured and water planning will be conducted on an under-estimated basis. Second, reducing apparent loss through accurate metering may increase water utility revenue. This increased revenue can support the costs of real loss mitigation. Third, reducing apparent loss creates an incentive for efficient use of water by customers. For example, if older water meters under-register consumption, customers under-pay for their water use and do not receive price signals to conserve water.

COST EFFECTIVENESS OF WATER LOSS MITIGATION

Water loss mitigation activities are highly variable from any public water system to another. Key factors which influence the amount of reduction obtained from an activity and its cost effectiveness include:

- **Scale of the water loss mitigation program** — replacing 1000 meters will generally be more expensive on a per meter basis, or on a per gallon of apparent loss reduction basis, than replacing 10,000 meters or 100,000 meters.
- **The baseline level of water loss** — in general, water systems which are in poor condition and have high water loss can make substantial reductions at a lower cost than water systems with low losses could achieve.[11]

11 See *Guidance on Implementing an Effective Water Loss Control Plan*, Report #4695, Water Research Foundation, 2019.

Water Loss Components, Drivers, and Water Savings Activities

		Components	Drivers	Water Saving Activities
System Input Volume	Authorized Consumption	Metered Billed Authorized Consumption Unmetered Billed Authorized Consumption Metered Unbilled Authorized Consumption Unmetered Unbilled Authorized Consumption	• Lack of awareness of the strain on water resources, and cost of water production, • Lack of awareness of the waste associated with old plumbing fixtures and household appliances • Lack of water price signals to encourage lower water consumption • Policy of not charging municipal departments and other institutions • Poor estimates of consumption for unmetered customers	• Awareness raising activities, • New, efficient, plumbing fixtures and household appliances, • Low water-use landscaping, • Customer monitoring of water use with AMI, • Customer side leak detection with AMI, • Water use reduction from pressure reduction • Customer water budgets, • Water rate-design-based incentives, • Voluntary restrictions, • Involuntary restrictions, • Universal metering and billing
	Apparent Losses	Losses from meter under-registration	• Meter error from age and high water volume throughput	• Customer meter testing • New, consistent, high accuracy meters
			• Low flow error	• Correct meter sizing
		Losses from data transfer, handling & billing error Losses from unauthorized consumption	• Meter reading error • Faulty data transfer to billing system • Out-of-date customer records • Billing system errors • Unauthorized consumption hard to find	• AMR/AMI meter reading & data transfer systems • Advanced customer management & billing database / system • Periodic database scrutiny • Surveillance & enforcement at points of interest
	Real Losses	Reported Losses Unreported Losses Background Losses	• Long runtimes on unreported leaks • Slow repair response on reported and unreported leaks • Excessive and variable pressure • Storage tank overflows • Corrosion • Pipe, appurtenances and service connections beyond useful life	• Improved speed and quality of repairs • Leak detection & repair on all assets • District Metered Areas • Network sensor / monitoring systems • Advanced pressure management • Corrosion control • Pipe, appurtenance & connection replacement

Table 5. Water Loss Components, Drivers, and Water Savings Activities.
Note: System Input Volume accounts for water produced, water imported, water exported, and adjustments for all bulk meters.

- **Environmental, technical, and economic factors** — factors such as soil conditions, local topographic variations leading to high or variable pressure, raw or finished water quality, the cost of skilled labor and materials, etc.
- **Suitability of the water loss mitigation strategies** — has the utility collected and analyzed sufficient reliable data to select appropriate technologies / strategies, and institute systematic, recognized, best practices?

Partly due to the great variability in site conditions and water loss mitigation needs, there are no commonly-accepted, standardized, methods to estimate water loss mitigation costs. Many articles are published every year on the inputs and outputs of water loss mitigation efforts. Most of these documents describe the context and outline the actions undertaken and the results achieved in terms of water loss volume, energy use, variable costs, pipe leak rates or meter accuracy. But few publications address project cost, usually for confidentiality reasons.

Nevertheless, the costs of water loss mitigation practices can be compared to supply side alternatives to help utilities select the appropriate mix of Water Management Strategies. Appendix B provides the methodology used to analyze cost of several water loss mitigation practices based on empirical data from actual water utility experiences.

Unit Cost of Annual Survey Leak Detection & Repair Surveys
$2020 per AF saved

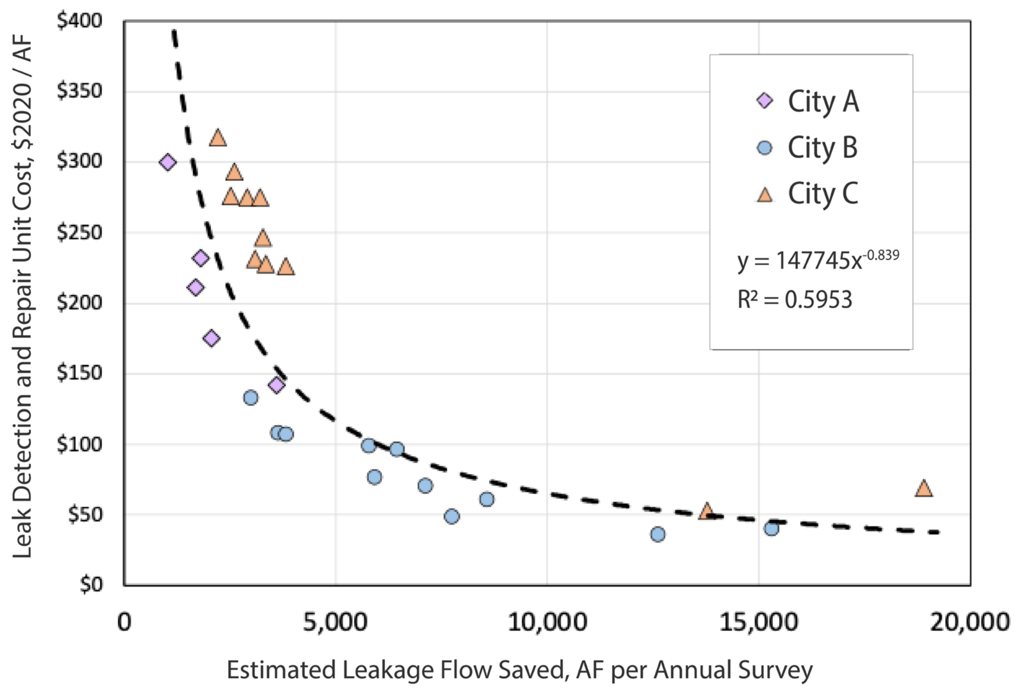


Figure 13. Unit Cost of Annual Survey Leak Detection & Repair Surveys, $2020 per AF saved.

This report provides data on four specific practices and programs:

- active leak detection and repair
- replacement of small customer water meters
- replacement of large customer water meters
- integrated water loss mitigation programs, which often combine the three practices listed above and some more expensive mains replacement.

The first three practices are generally considered short term activities — because the time frame over which they are conducted is short, and to a certain extent the benefits extend over the short to medium horizon. These are usually funded from utility operating budgets. This is especially true for active leak detection and repair. Large integrated water loss mitigation programs will usually involve longer term interventions which provide large benefits over a longer time horizon and at a higher unit cost. These are usually funded from utility capital budgets. For example, such an integrated program would commonly include the sectorization of the network, creation of District Metered Areas (DMAs), installation of advanced pressure management which both reduces pressure and reduces pressure variations, and selective replacement of service connection and mains pipes and appurtenances.

Figure 12 presents a summary of the analysis of the cost effectiveness of conventional acoustic active leakage detection and repair programs in three large US cities, where ample, high-quality data could be obtained. The programs consist of annual surveys of portions of a network ranging from surveys of 10% of the network to annual surveys of the entire network. Program data collected includes the miles of pipe surveyed, leaks found, leak flow, annual water savings, the leak detection cost and the leak repair cost. This leakage mitigation activity is very similar to that described in the case study on Nashville, Tennessee in Chapter 5.

Figure 12 shows the unit cost in $2020 per AF. First, it can be immediately seen that the data points for different surveys in different places (with different leakage levels) fall on a noticeable, clear curve.

It can also be seen that a program which saves a small amount of water in a year will have a relatively high unit cost. But a program which saves a lot of water will have a much lower unit cost. The curve shape represents a classic example of "economies of scale."

It should be noted that the points shown include a variety of situations and program "scenarios". Some of the data points represent:

1. surveys with a low number of miles surveyed in very leaky areas,
2. surveys with a high number of miles surveyed, in less leaky areas, and
3. cases in between.

Yet all the points tend to fall on the same curve. Note that situation 1 above will have a lower detection costs because there would be less miles "walked", but a higher repair costs because more leaks are found. Situation 2 is the opposite — higher detection cost and lower repair costs. Appendix A presents more information on these tendencies.

Other water loss mitigation practices show economies of scale. For example, Figure 14 shows the units costs for a program of replacing 100 large meters, extrapolated from actual large meter tests and new large meter replacement program costs in US utilities.[12] First there are economies of scale of large meter costs, but the unit cost of savings will also decline with the "correction" of larger under-registration at larger flow rates (larger meters), leading to more savings and additional revenue.

12 These data were adapted from data provided in *Guidance on Implementing an Effective Water Loss Control Plan*, Report #4695, Water Research Foundation, 2019.

Unit Cost vs Total Water Loss Savings for Large Meter Replacement

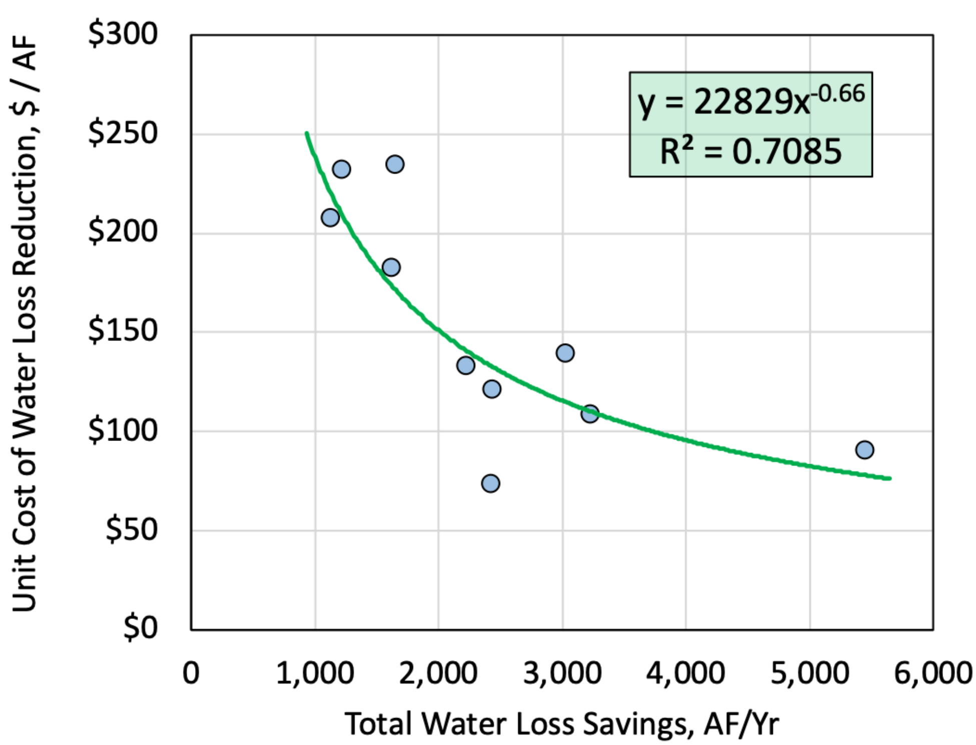


Figure 14. Unit Cost vs Total Water Loss Savings for Large Meter Replacement (100 Meters).

Unit Cost of Water Loss Mitigation Strategies

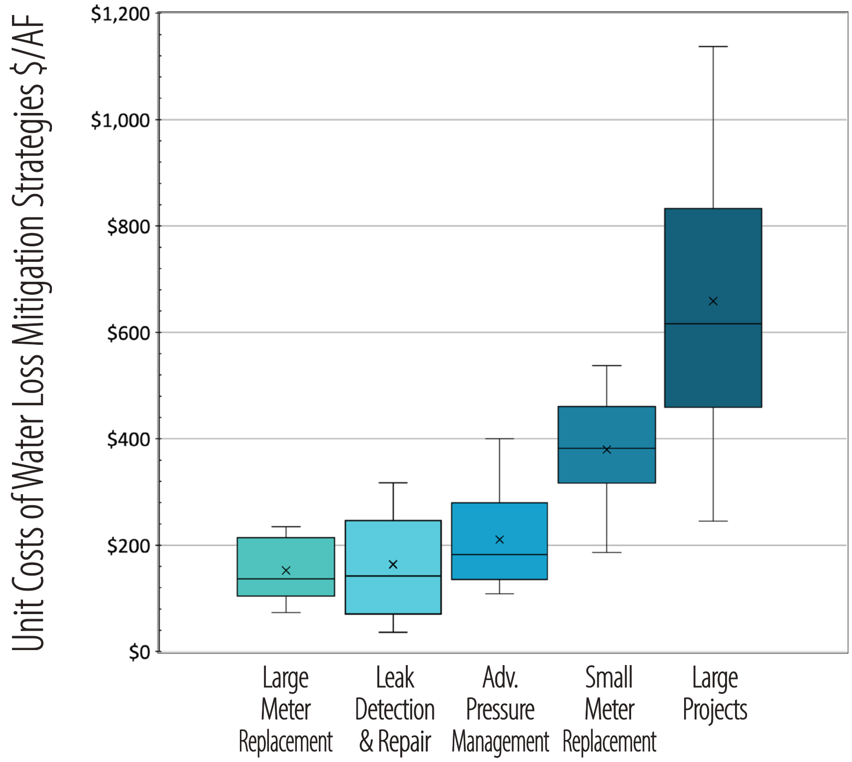


Figure 15. Unit Cost of Water Loss Mitigation Strategies (in $2020).

Integrated water loss mitigation programs tend to have less economies of scale, due to the presence of significant infrastructure components, whose cost is not so closely linked to the water loss savings. The costs of these programs are discussed more in Appendix B.

Figure 14 shows a summary comparison of the range of unit costs, in $2020/AF of the five water loss mitigation practices/programs, in the form of a box and whisker plot.

Each practice / program has a range of costs, depending on technical parameters at the utility. Advanced pressure management, replacement of large meters, and active leak detection and repair in general have lower costs and a smaller range of costs. In general, the higher costs tend to occur at smaller scale. For those practices, costs range from about $75 to $240 per AF (by lower and upper quartiles). Small meter replacement programs tend to cost more. The cost of larger integrated projects with significant mains replacement is considerably higher with an average of about $600/AF, with the lower to upper quartile costs ranging from about $300 to $800 per AF.

A recent study by University of California at Davis (Ruppier et al, 2022) arrives at similar cost figures for several water loss mitigation practices and other sources of supply (see Figure 15). Pressure reduction is by far the lowest cost. Leak detection and repair costs about $250 per acre-foot, and other “sources” (including conservation) are considerably higher. The study also applied the costs and reduction benefits of pressure reduction and leak detection to almost 900 locations in California, Georgia, Tennessee and Texas. The cost for the

Left: A leak detection crew at work with acoustic leak detection equipment in New Braunfels, Texas. Photo: Peter Kenter. *Below, clockwise starting from top left:* a small customer meter, large customer water meter, electronic controller, and a pressure reducing valve.

median utility size came to approximately $277 acre-foot.[13]

The analyzed cost of water loss mitigation, between $75 to $800 per acre-foot compares very favorably to various supply side water management strategies (e.g., aquifer storage and recovery, direct potable reuse, groundwater or seawater desalination and new major reservoirs) in the 2022 State Water Plan, which have a weighted average of $695 per acre foot in 2020.[14] These costs of water loss control are also lower than the average costs of municipal and industrial conservation in the 2022 State Water Plan.[15] The cost-effectiveness of water loss mitigation (compared to other strategies) suggests that this should be among the first strategies considered by water utilities to meet future demand.

While this discussion has focused on the range of unit costs of several water loss control practices, it does not provide a complete perspective on the water loss control program priorities and associated costs. Chapter 5 of this report provides three detailed case studies to illustrate what water loss control programs could look like across various utilities in Texas.

13 Untapped potential: leak mitigation is the most cost-effective urban water management tool, Ruppier, A. et al Environmental Research Letters, Vol 17, No 3, 2022.
14 See Tables 7-3 and 7-6 of the 2022 State Water Plan. The weighted average of the cost per AF of all WMS is found by weighting the unit cost of each supply side WMS (in the 2020 Decade) by the amount of acre feet recommended in the 2022 State Water Plan. For example, Table 7-3 of the 2022 SWP shows that aquifer storage and recovery has 152 recommended projects, which would "produce" 18,868 AF/yr in the 2020 decade. The 2020 unit cost for aquifer storage and recovery $437/AF (from Table 7-6) resulting in a total cost of $8,245,316. The total cost of all WMS Projects for the 2020 decade $ 531 million with a water supply of 764,551 AF/yr leading to a weighted average cost of all WMS projects of $695/AF.
15 Ibid. A similar calculation for Industrial and municipal conservation yields a weighted avergae unit cost of water savings of $675 / AF. If agricultural conservation is added into the calculation, the weighted average drops to $404/AF. However, agricultural conservation may not be applicable in urban areas where water losses are highest.

3

Funding and Financing

Where and how can utilities secure funding for water loss mitigation?

Water supply is a pressing issue in Texas and it is essential that water providers mitigate their water losses to shore up future supply. While investing in water loss mitigation projects makes both economic and environmental sense, utilities may struggle with financing projects. Fortunately, many federal, state, local, and private funding sources are available for projects that mitigate water loss. Table 7 provides a list of funding sources available to eligible entities for water loss mitigation projects.

If water loss mitigation projects are delayed or ignored, the water utility infrastructure will grow older over time, and water losses will rise. This is true for both water meters and water distribution pipes. Therefore, it is imperative utilities understand the universe of funding and financing opportunities available to help continuously invest in projects that mitigate water losses.

Federal and state loans and grants are available for utilities seeking additional financing opportunities outside of user charges. Overall, more loan opportunities are available than grants, although recent federal funding opportunities are increasingly emphasizing grant opportunities especially for disadvantaged communities. Utilities may find federal and state loan opportunities attractive to finance large water loss mitigation projects. However, well-situated utilities may find it more attractive to take on additional debt via the bond market instead of seeking loans from federal or state sources.

Utilities that are less able to take on debt may need to rely on grants to support investment in water loss mitigation projects. For eligible entities, the Green Project Reserve under the Clean Water State Revolving Fund (CWSRF), Drinking Water State Revolving Fund (DWSRF), Economic Development Administration's Public Works and Development Facilities Grants Programs, and the Community Development Block Grant Program for Rural Texas may be attractive grant options. In addition, the Bipartisan Infrastructure Law (BIL) is sending nearly $3 billion to Texas under the DWSRF and CWSRF to invest in essential water infrastructure projects, and is requiring at least 49% of the funds to be spent as grants or forgivable loans with a focus on disadvantaged communities.[16]

Even with these programs, utilities may still face hurdles in accessing funds or financing. Utilities that have low unemployment and high per-capita income within their jurisdiction, such as the Water and Wastewater Authority of Wilson County described in our case studies (Chapter 5), may be reluctant to take out loans and may have difficulty accessing grants. Other entities have expressed a reluctance to take out additional loans in order to not impact bond ratings. Further, technical assistance may be required to help utilities apply for and receive loans and grants – especially when trying to navigate lengthy state or federal application processes.

When the hurdles to accessing funding and financing are too high, utilities are often left with few other options than user charges. As discussed in the case studies in Chapter 5, each utility interviewed for this report relied on user charges to finance water loss mitigation projects. However, for many utilities, these user fees are usually insufficient to pay for all needed water loss projects — resulting in continued escalation of water loss issues.

While user charges may be the best option for many utilities with a sufficient revenue stream to regularly finance water loss mitigation projects, future changes to grant and loan opportunities will be essential to adequately and continuously address water loss in Texas — especially for underperforming utilities, rural utilities, and utilities in economically distressed areas. Greater access to funding and financing for water loss projects in these areas will help alleviate water supply demands before investing in other expensive supply strategies. The cost effectiveness of water loss projects is discussed in Chapter 2 above.

It should be noted that retail public water utilities in Texas seeking financing from the TWDB that have water losses above a threshold determined by the TWDB must either spend a portion of the financing received from the board to mitigate water losses or obtain a waiver. Therefore, utilities should be encouraged to proactively mitigate water losses before being required to implement multiple projects at once to receive assistance from the Board.

As the ongoing pressures of development, climate variability, and the realities of living in a state with limited water resources continue to place strain on our water resources, investments in water conservation and water loss mitigation are vitally important. We have shown that infrastructure investments in water loss mitigation projects are economically sound — when compared to other water supply projects. Since the cost of water losses will only get higher the longer they go unaddressed, utilities should draw on the many available state and federal funding sources to invest in water loss projects.

16 Public Law 117-58 (Nov. 15, 2021).

Table 6. Funding Sources for Water Loss Mitigation Activities

	Name	Administered By	Match Requirements	Grant or Loan	Eligible Applicants	Eligible Projects
Federal	Rural Utility Service, Water and Wastewater Loan/Grant Program[17]	U.S. Department of Agriculture		Mostly loans but grants may be combined with a loan if necessary to keep user costs	Public and nonprofit water utilities serving up to 10,000 people that cannot find private funding	Meters, leak detection, and control equipment
Federal	Community Development Block Grant Program for Rural Texas	U.S. Department of Housing and Urban Development (HUD)	Additional project points for leveraging local funds	Grants	Cities with population below 50,000 and counties with non-metropolitan population below 20,000	Planning and management efforts and all kinds of activities. Structural measures can include meters, leak detection and control equipment, etc.
Federal	Water Conservation Field Services Program/ Efficiency Incentives Program[18]	U.S. Bureau of Reclamation	Applicant must be willing to share a minimum 50% total activity costs[19]	Grants	Water systems that contract for water supplies through the Bureau of Reclamation	Water conservation measures such as meters; leak detection and control equipment; etc.
Federal	Resource Conservation and Development	National Resources Conservation Service (NRCS)	RC&D grant assistance (up to 25 percent not to exceed $50,000 of the total project cost) may be provided for a project[20]	Grants and Loans	State or local governments and certain nonprofit organizations	Resource conservation and development

17 https://www.rd.usda.gov/programs-services/water-waste-disposal-loan-grant-program.
18 https://www.epa.gov/sites/default/files/2017-03/documents/appendix-e-federal-funding-sources-for-water-conservation.pdf
19 https://www.federalgrantswire.com/water-conservation-field-services-program-wcfsp.html#.YQQrZjZKhpQ http://ftp.weat.org/stormwater/20132014SW_Water_Conservation_Field_Services_Program.pdf
20 https://www.federalgrantswire.com/resource-conservation-and-development.html#.YQQrpTZKhpQ

Federal

Name	Administered By	Match Requirements	Grant or Loan	Eligible Applicants	Eligible Projects
Economic Development Administration's Public Works and Development Facilities Grants Programs	Economic Development Administration, U.S. Department of Commerce	Between 50-80% non-federal funding match[21]	Grants	Mostly rural communities	Public works infrastructure and development facilities, including improvements to drinking water systems including meters, leak detection and control equipment.
WaterSMART Water and Energy Efficiency Grants	U.S. Bureau of Reclamation	50% non-federal funding match[22]	Grants	Irrigation and water districts, tribes, states, and other entities with water or power delivery authority	Projects that conserve and use water more efficiently, with a focus on projects that can be completed in two years
Water Infrastructure Finance and Innovation Act Program	Environmental Protection Agency		Loans	Corporations, partnerships, joint ventures, trusts, Federal, State, or local government, tribal government or consortium of tribal governments, and State infrastructure financing authority	Projects eligible for Clean Water and Drinking Water SRFs, energy efficiency projects at water facilities, drought prevention, desalination
DWSRF – Green Project Reserve	Environmental Protection Agency / Texas Water Development Board		Loans and principal	Publicly and privately owned water systems; nonprofit water supply corporations; nonprofit, non-community public water systems	Planning, design, acquisition and construction to: correct water system deficiencies; upgrade or replace water systems; and implement green projects.
CWSRF – Green Project Reserve	Environmental Protection Agency / Texas Water Development Board		Loans and principal	Political subdivisions including water supply corporations that are designated management agencies (DMAs)	Water quality projects can include meters, plumbing fixture retrofits or replacements if tied to water-quality projects

21 https://seneca-llc.com/funding/economic-development-administration-public-works-grants/
22 https://www.usbr.gov/watersmart/weeg/

	Name	Administered By	Match Requirements	Grant or Loan	Eligible Applicants	Eligible Projects
State	SWIFT	Texas Water Development Board		Loans	Any political subdivision or nonprofit water supply corporation with a project included in the most recently adopted State Water Plan.[23]	Recommended water management strategy projects with an associated capital cost in the most recently adopted State Water Plan. Projects include conservation.
	Rural Water Assistance Fund	Texas Water Development Board		Loans	Rural political subdivisions or nonprofit water supply corporations serving a population of 10,000 or less; counties in which no urban area has a population exceeding 50,000	Planning, design, acquisition for water projects
	Texas Water Development Fund	Texas Water Development Board		Loans	Political subdivisions; nonprofit water supply corporations	Planning, design, acquisition and construction projects for conservation
Local	Municipal revenue bonds	-	-	-	-	-
	User charges	-	-	-	-	-
Private	Communities Unlimited Water and Wastewater Loan Fund	Communities Unlimited		Loans	Low income communities with population below 20,000	Improve drinking water and wastewater systems
	NADB Community Assistance Program	North American Development Bank	10% of the project must be contributed in cash	Loans	Public entities and projects must be within 100km of the US-Mexico border	Water, wastewater, and water conservation projects, construction, equipment purchases, and project management

23 https://www.h-gac.com/getmedia/606ab6b9-d9bc-44eb-a309-91a732b87444/TWDB%20Hand-Outs%20and%20Resources.pdf

4

Recommendations to Address Water Loss in Texas

Texas urgently needs to address water loss. The state's population is growing at an unprecedented rate and Texas' water supply is finite. Increasing climate extremes threaten longer and deeper drought periods. In order to have sufficient water to meet the needs of both our communities and the environment, we need to make sure that efficient use is made of all Texas water resources.

The following recommendations can move the state closer to addressing these issues and will help promote the wise and efficient use of Texas' limited water resources now and for future generations.

When compared to other water supply strategies, meeting Good and Very Good performance levels for water loss can be a cost-effective approach to meeting future municipal needs, and many funding opportunities are available to help utilities pay for these projects.

We recommend that utilities — with the strong support of the Texas Legislature and state agencies — work to mitigate water loss to achieve the highest practicable level of water loss performance. Specifically, we recommend the following strategies be prioritized:

LEGISLATIVE RECOMMENDATIONS

Prioritize Financial Assistance for Utilities with the Highest Water Losses

The Legislature should direct TWDB to better enable utilities to mitigate water losses. This could be accomplished by placing a short-term priority on utilities with above-average water losses (50th percentile) for financial investments, followed by emphasis on investments in utilities above the Good Performance Standard (75th percentile). With these actions the TWDB can continuously help move Texas utilities towards lower water losses.

Provide Additional Funding for TWDB Conservation and Water Planning Staff

The Legislature should approve and appropriate funds for additional TWDB water conservation and water planning staff to better equip the agency to meet the growing needs of Texas utilities. Additional staff would allow greater emphasis on data accuracy, technical assistance for utilities, and continued outreach on water conservation best practices.

TEXAS WATER DEVELOPMENT BOARD RECOMMENDATIONS

Further Prioritize Data Accuracy

TWDB should require Level 1 Validation of Water Loss Audits to improve accuracy of those audits. Utilities need to have accurate data to make effective decisions about the best methods to address system water loss and Level 1 Validation, the process of examining water audit inputs to improve their accuracy and document the uncertainty associated with water audit data, will help with this. Accurate Water Loss Audits inform utility decision making and can lead to better water loss mitigation programming. TWDB has begun work in this direction by conducting a Level 1 Validation pilot study and has included a Level 1 Validation program in the 2023 DWSRF Intended Use Plan.

Update Water Loss Thresholds and Report on HB 3605 Implementation

TWDB should update water loss thresholds used to determine compliance with HB 3605 (83R) every 5 years using water loss audit data. TWDB should also report amounts invested in water loss mitigation and the projected water savings ensued from grants or loans consistent with HB 3605 implementation. HB 3605 requires communities to invest in mitigating water loss in excess of the threshold set by TWDB when seeking state funding for water supply projects, making it an important tool for addressing water loss.

Further Prioritize Transparency and Accountability

Policy makers and the public are often not aware of the volumes of water being wasted each year as the result of water loss in utility distribution systems. When water loss data is available, the extent and effect of that water loss is often obscured by the technical nature of the metrics used and the lack of context for the information provided.

TWDB should provide a report to the Legislature and Governor every five years on the results of the most recent water loss audits submitted to the Board by the state's public water utilities. The report should include: (1) information on the total volume and g/c/d of water loss incurred by Texas utilities, (2) steps the Board has taken or is taking to assist water utilities in mitigating water loss, (3) information on financial assistance from TWDB to mitigate water loss and (4) any recommendations for additional state action to curb water loss.

Increase Technical and Financial Assistance for Utilities for Water Loss Projects

TWDB should provide more grants or principal loan forgiveness for underperforming and low-income utilities; provide loans at a lowered interest rate; or provide other financial incentives to utilities with above-average water loss in their size category.

Texas needs modern and reliable water infrastructure to thrive and our funding needs are immense. All Texas communities — especially economically disadvantaged, rural, and minority populations — are feeling the effects of decades of under-investment in water infrastructure. Ongoing state-administered programs and new federal funding initiatives combine to present unprecedented opportunities to tackle these issues, including water loss, and better prepare Texas for a more resilient water future in the face of climate change.

Provide Regional Water Planning Groups Tools to Develop Water Loss WMS

The TWDB should provide guidance and support on how to use water loss data to inform the development of water management strategies to mitigate water loss in the Regional Water Planning process. Regional Water Planning Groups develop water management strategies to address municipal needs though the regional water planning process. It is imperative that strategies be developed around mitigating water loss. These should be considered in advance of supply-side strategies where appropriate and should include be quantified and called out specifically rather than folded into general water conservation water management strategies.

Develop Accurate Costs for Water Loss in Regional Water Planning

TWDB should update the costing tool regional water planning groups are required to use for water management strategy analysis, as implementation costs for strategies included in the State Water Plan help drive decision-making for water supply investments.

STATE AND REGIONAL WATER PLANNING RECOMMENDATIONS

Include Water Loss as a Water Management Strategy

Regions that have not recommended water management strategies to mitigate water loss should do so in the upcoming 2026 Regional Water Plans. Strategies included in the State Water Plan help drive decision making for water supply investments and water management strategies and must be included in the State Water Plan in order to be eligible for SWIFT financing. Water loss mitigation is a cost-effective tool to ensure the water we already have is reaching its intended destination and should be considered by each planning group as a water management strategy. This could reduce, eliminate, or delay the need for expensive and contentious water management strategies. Regions that have not recommended water management strategies to mitigate water loss should do so in the 2026 Regional Water Plans. Currently 11 of 16 regions include water loss mitigation as a strategy in their plans.

UTILITY RECOMMENDATIONS

Properly Value Water Losses

Utilities should thoroughly evaluate the financial impact of water loss and consider the near- and long-term costs of not addressing losses when planning for and making investments. When weighing the cost/benefit of investing in water loss mitigation, utilities should account for the predicted financial benefits of deferring or even eliminating future water supply projects.

Continuously Invest in Resilient Infrastructure

Utilities should make regular on-going investments to address water loss and access financial assistance programs, including new federal funding opportunities, to do so. These investments should be guided by data-driven water loss program planning informed by regular water audits, validation, and program refinement.

Water losses compound over time when continuous infrastructure investments are not made. In order to ensure losses are adequately addressed over time, proper financial planning is necessary to make infrastructure investments. Because traditional rate increases can be challenging, prohibitive, or insufficient for communities to meet investment demands, state and federal funding and financing opportunities can often fill the gap.

Case Studies

5

To help provide an "on the ground" picture of what it might look like for a water utility to start, implement and measure the results of a water loss mitigation program, we analyzed a number of loss mitigation programs from water utilities across the country. We present below in-depth case studies from the following utilities:

Wilson County, Tennessee

Nashville, Tennessee

San Antonio, Texas

While Wilson County and Nashville are geographically adjacent, they are of contrasting size and adopted differenct technical approaches. Both utilities have excellent data available allowing for a more in-depth analysis.

	Wilson County, TN	Nashville, TN	SAn Antonio, TX
Why did you address water loss?	Financial drivers due to high cost of purchased water	Water loss kept rising over time and an "enough is enough" decision was reached, study identified major leaks	Part of San Antonio Water System's (SAWS) integrated water management plan for past 25 years
What were your system vulnerabilities?	Poor installation contributed to most losses; start / stop pump operation creating pressure transients	Aging infrastructure, high operating pressure in certain areas and surge / water hammer events	Aging pipes
How did you quantify and track water loss?	District meter areas (DMAs) quantified by new meters, focused on nighttime flows	Acoustic tests and leak identification on every mile of main, DMAs,	Started with water audits, brought in outside consulting firm, investment in data tracking technologies
How did you address water loss?	Permanent electromagnetic meters, valve isolations, Pipe replacement, pipe collars	Annual water loss audit, ongoing leak detection program, mapping and understanding pressure fluctuations	Collaring, clamps, pipe replacement (shifting to HDPE pipes for main and service lines), cross-departmental coordination and collaboration
What were your results and challenges?	Now better than Tennessee on average, saving 100 million gallons per year and $230,000 per year	800 - 2,100 million gallons per year in savings	Estimating 4,000-6,000 acre feet per year (1,300 - 1,950 million gallons per year)
What were your costs and funding mechanisms?	$210,000 in capital costs, paid out of operating budget	$1M per year for subconsultant and about $300,000 per year in labor for fixing leaks. Operating expenses but stopped funding when budget was unavailable.	Funding has been part of SAWS' capital improvement plan, estimate $8 million per year
What were your primary lessons learned?	Focus DMAs in the "easier" areas of the system, technology and software implementation is critical to success, and don't get discouraged	Staff must be willing to adapt, alter or change approaches as data becomes available. This isn't just about aging infrastructure, it's about understanding root causes.	Initial data collection usually points to bad data which need to be corrected; there is no "one and done" in water loss control, leaks are guaranteed to reappear

Table 7. Key Takeaways from Case Studies

WILSON COUNTY, TENNESSEE: A SMALL RURAL UTILITY'S SUCCESS IN WATER LOSS MITIGATION PROGRAM

The Water and Wastewater Authority of Wilson County (WWAWC) lies just east of Nashville and serves a population of 21,000. It's a rural utility, with 7,725 service connections and only 22 connections per mile. WWAWC pays for all the water that runs through their 345 miles of 100% PVC pipe, which comes from three surface water and one groundwater supplier.

WWAWC launched a water loss mitigation program in 2006. The Authority purchases all of their water, so the cost of loss is much higher for them. Their initial audit of the system in 1988 showed they were losing over 70 million gallons of water per year in potential leakage, when they had 129 miles of distribution main and 1,923 service connections. The distribution system nearly tripled in size since 1988 and water losses continued to rise to unacceptable levels. After acoustic metering proved difficult with their 100% PVC distribution system, they began monitoring nighttime flow data in 15 district metered areas (DMAs) as a benchmark to prioritize the DMAs with the highest leakage.[24] WWAWC also switched out their mechanical meters measuring DMAs to electromagnetic meters and installed telemetry.

The real time data mitigates the run time of leakage, which helps improve water loss, and initially helped WWAWC get to an ILI below 1. They also look for ways to reuse water. On the wastewater side, they have 43 State Operating Permits for wastewater treatment facilities which are all for decentralized STEP systems serving outside of the city limits. These systems are all soil-based with dispersal of treated effluent via drip irrigation into approved soils areas. They also provide reuse water to a golf course for spray irrigation. These decentralized systems serve residential subdivisions and increase the growth in more rural areas which are farther away from their drinking supply locations.

Over the last 15 years WWAWC has saved nearly 100 million gallons per year with remaining losses in the 75

Chris Baenziger checks the ultrasonic flow meter at a storage tank in Wilson County, Tennessee. *Photo: Peter Kenter*

Because WWAWC purchases all their water, the retail rate of water was the main driver of their water loss mitigation program. WWAWC does not have access to typical grant funds because of the low unemployment rate and high per-capita income in the county. To fund water loss mitigation programs, they charge sufficient rates to maintain financial stability to cover all expenses such as operating costs, depreciation, and debt coverage. The rates also supply the funds to build the sites for the DMAs which are then depreciated over their useful life. They do accumulate some additional debt from bond funding, which they used to expand service to unserved areas.

The Water and Wastewater Authority of Wilson County has spent around $210,000 on capital costs for the DMAs. This amount was solely for capitalized equipment, which does not includes any parts for repairs such as repair clamps or a section of pipe to repair a main break or replace a leaking service. The typical repair costs are part of their operating expenses. The $210,000 does not include the labor cost that's involved. However, the technology that's been implemented has allowed WWAWC to detect leaks before they become catastrophic has saved lots of time and money. They are planning

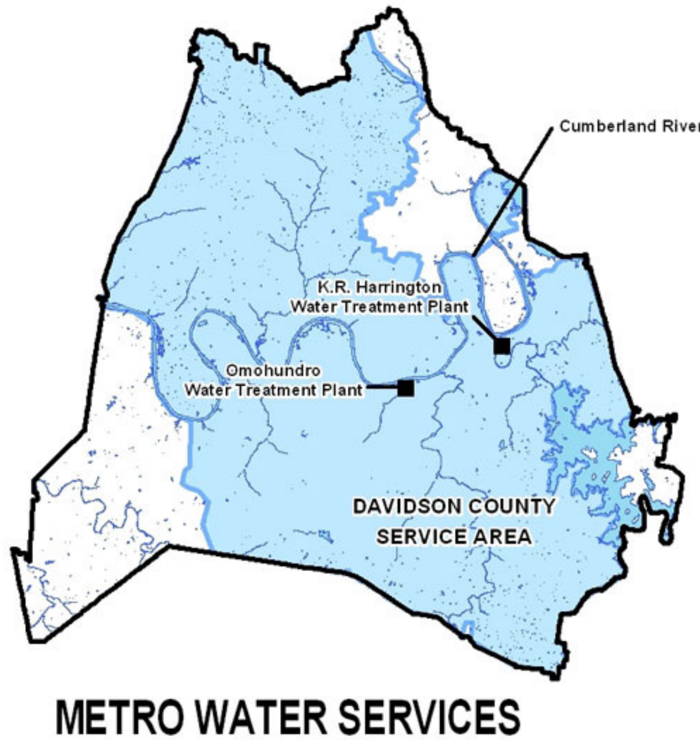
24 District Metered Area measurements record the water flow into a small section of the network in order to investigate the amount of leakage. If ongoing measurements show a spike on a particular day, then it is likely a leak has occurred within the DMA.

the implementation of an AMI system which will bring additional equipment costs. WWAWC is spending around $2.5 million for all equipment, installation, and implementation. They expect approval to proceed in October 2021, and the implementation will be completed by October 2022.

An analysis calculated that the WWAWC has a payback period of around 9 months when looking at the $210,000 investment divided by the savings based on their ILI performance compared to the state of Tennessee median ILI. WWAWC proves that even for smaller rural utilities, water loss mitigation programs can be successful and economically viable.

NASHVILLE, TENNESSEE: WALKING THE LINES

Nashville Metro Water Services (NMWS), located in Nashville Tennessee, provides water, wastewater and stormwater services to over 250,000 customers in the Metro area. NMWS draws their water supply from the Cumberland River and has two water treatments plants which can treat up to 180 million gallons of water per day. NMWS delivers drinking water through over 3,000 miles of water main.



Nashville Metro Water Services provides water, wastewater and stormwater services to over 250,000 customers in the Nashville metro area. *Image: Nashville Metro Water Services*

With non-revenue water loss rising over time, it was decided internally within NMWS, that “enough was enough”, and an outside consultant was brought in to get a better understanding of why and where this water loss was occurring. The WSO study revealed major leaks in the NMWS system. Because the cost of water supply has been low, NMWS’s water loss mitigation program was driven by dedicated staff, who wanted to not only ensure that public trust in the utility would be maintained, but also that work towards supplying water would be done in an environmentally conscious and efficient manner.

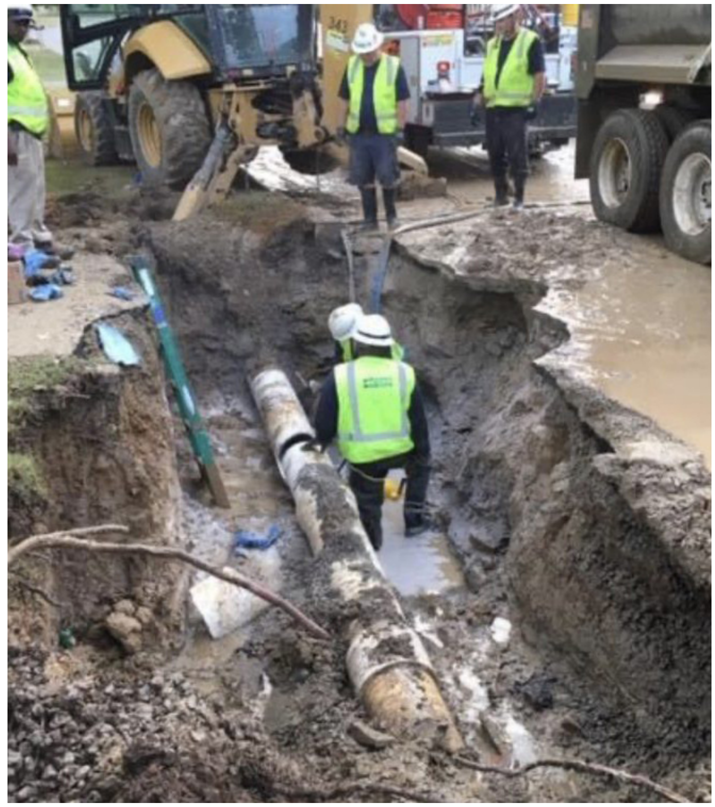
With the assistance of the contractor, NMWS became an early adopter of the IWA/AWWA water audit methodology in the US, performing their first water audit in 2003. That first audit established the long-running strategies they have been actively pursuing since to mitigate losses. These management strategies have included many of the best practices established with the M36 methodology, including annual water audits, DMA measurements, and proactive leak detection. As a result, NMWS has been able to supply an increasing population over time without a significant increase in water production. The work of the contractor has focused on real loss, but NMWS has mitigated apparent losses (through a water meter replacement program) and decreased unbilled authorized consumption through tighter control of the use of fire hydrants by building construction contractors.

Following NMWS’s initial audit, they have conducted an annual water audit following the same methodology, which they have used to continually evaluate and adjust their water loss control program. Some of the more important best practices implemented have included M36 methodology (i.e. annual audits), DMA measurements, and proactive leak detection. Proactive leak detection specifically, has been a valuable tool and particularly early on. To do this leak detection, initially WSO was contracted to walk every mile of main annually, to perform acoustic tests and identify leaks. These efforts alone led to the discovery of 12 to 16 inch pipes that were discovered fully open and releasing into storm sewers. Leak estimates were then tracked and trued up by NMWS once leaks were found. While there was and still is dedicated internal staff responsible for proactive leak detection, with over 3,000 miles of pipes to maintain, NMWS retains the services of WSO for support. Working with WSO, NMWS has been able to eliminate a backlog of leakage and stop increasing trends in real losses through their proactive leak detection program. Based on results of the proactive leak detection program, NMWS vulnerabilities have been identified as primarily a result of aging infrastructure, high operating pressure in areas, and surge / water hammer events.

Since NMWS began addressing water loss almost 20 years ago, they have realized great progress. In the last 6 years alone, NMWS has performed leak detection on their system annually (over 18,000 miles of main surveyed total) and recovered between 1,500 and 4,000 gpm of leakage annually as a result of leaks identified and addressed with this program. Since 2010, NMWS has found and stopped a total estimated 50 MG of water loss.

NMWS identified their primary costs to be Capital. Namely, the need to hire a sub-consultant to locate leaks – which amounts to an estimated $1M annually. The other significant cost identified was internal personnel costs and repair costs breaks / leaks on mains and service connections. For those employees dedicated solely to fixing those leaks found by the consultants and called in by customers – a cost of approximately $300K/yr could be estimated. Finding the funding to pay for these costs over time was in fact identified as the biggest challenge in addressing water loss. Because NMWS is a rate payer funded entity, they have also had to endure periods of austerity – which has been a hurdle in program implementation. As of today, they have been able to raise rates and do have adequate funding, however it may be that they would consider alternative funding sources in the future, should austerity measures be enacted once again.

Moving forward NMWS continues to evaluate emerging technologies for leakage management. Currently, they are in their "next phase of detection and tracking", which includes implementing temporary DMAs to gauge incoming and outgoing water. In the next five years, the focus will be to transition into a permanently based DMA methodology that enables them to monitor their system in 24/7 real time. This will also entail installing additional AMI meters – to reach 100% of customers versus the 40% currently. NMWS also plans to maintain the annual water audit following IWA/AWWA methodology – which will continue to assist them in evaluating and adjusting their water loss control program as necessary over time. NMWS shows how a conservation ethos and bit of outside help can help reign in water losses for a large utility, and how a successful water loss mitigation program can help defer new supply projects, despite growing service population.



Nashville Metro Water Department employees repair a broken water main in September 2019. *Photo: Nashville Metro Water Services*

SAN ANTONIO, TEXAS: BETTER DATA EQUALS BETTER MITIGATION

San Antonio Water System (SAWS) provides water and wastewater services to 1.9 million people in the greater San Antonio area. SAWS has a complex system, integrating water from 15 different supplies and 9 different water sources. The primary groundwater source, the Edwards Aquifer, has 125 active production wells, and where San Antonio previously depended on this aquifer, it now only provides about 55 percent of the water supply. Substantial elevation changes across a large service area mean that there are approximately 65 pressure zones with 110,000 plus valves. An Aquifer Storage and Recovery system acts as a "water bank" to store water during wet periods so it is available during drought. While all of this infrastructure translates into resiliency for water services, it introduces a great deal of complexity in tracking water produced, water stored and water sold. As of August 2021, SAWS' potable distribution system includes nearly 7,500 miles of mains.

SAWS started completing water loss audits nearly 20 years ago. The results from data then available made it appear that SAWS total water losses might only be in the single digits. At the time this type of audit result was not uncommon. Current water loss experts seeing a result like this today would point out this was so "remarkably low" that something about the data needed improvement.

Like many utilities across the country, SAWS found that its production data was inaccurate and making the water loss calculation misleading. For many years, Edwards Aquifer well production was estimated using run time constants calculations. While this was an accepted industry standard at the time, an upgrade to more accurate production meters was illuminating. The newer meters made it clear that run-time constants had under-estimated production by 4 to 6%. When more accurate production data was used in a water loss audit, it became clear that water losses were higher than previously believed. Once SAWS understood that water losses were not as low as previously thought, they responded by investing more time and energy into water loss auditing, meter management, and leak detection.

To aid with efforts, an outside consultant firm was selected and hired under a two-year extendable contract in 2012 to conduct Level Three Validation of SAWS Water Audit processes. One area of focus for the consultants was customer meter accuracy because this is a critical input for all water loss audits. SAWS had a customer

Charles Crawford, data collection supervisor at the Edwards Aquifer Authority, measures the water height of a well at the authority's Field Research Park in far north San Antonio. *Photo: William Luther*

meter testing program, operated a calibrated bench test to assess meter accuracy and had specialty trucks to test large meters in the field. The consultants encouraged SAWS to look at sampling methods, brands of meters and other data points SAWS had not considered. By focusing on meter accuracy, SAWS began to see the need to address more real losses. SAWS initiated a proactive acoustic monitoring program with an estimated savings of 4,000-6,000 acre feet of water per year from this effort. It is key to note that because leaks will return in new areas, the savings won't be fully retained without continual monitoring.

A big part of SAWS' water loss program has been utilizing systems already in place, such as the billing database, Supervisory Control And Data Acquisition (SCADA) database, enterprise work order capture systems and the AWWA water audit software methodology. SAWS has also used machine learning and Artificial Intelligence software to classify risks on the potable distribution system.

In 2015 through 2019 SAWS worked with the Edwards Aquifer Authority to fund a massive leak detection and repair effort. The funding allowed for an acceleration of normal leak detection and repair schedules. The investment of $18.9M is estimated to have saved 13,000 acre-feet of water. The most common method to control water loss has been point repairs using collaring or clamps. High Density Poly Ethelene (HDPE) is a product that can be installed with seamless joints and has more flexibility, but an open trench is still needed in many areas, and the material may react with surrounding elastic soil or material. Main and service line replacement continues to be an important part of water loss control, and SAWS is looking to newer materials such as HDPE because it has lower leakage and corrosion potential than metallic mains and service lines.

SAWS showed commitment to a continuous water loss mitigation program in 2015 when executive leadership decided that water loss auditing was not a part-time job or a side assignment. A full-time staff person was assigned to coordinate Water Loss Audits; interfacing with nearly every department in the company. This has helped to improve data SAWS collects every day, which is used to compare against quarterly known rates to monitor and asses the water balance and communicate internally about any irregularities or patterns. SAWS' most effective strategy to mitigate water loss has been understanding the recurrence of leakage and using their resources efficiently, such as using the AI process to pinpoint leaks and managing the workload of both internal and contracted staff. SAWS background infrastructure leakage has been staying flat according to analysis, but could increase as existing infrastructure ages. This makes maintenance over time a key part of planning.

Since 2013, San Antonio Water System has doubled its investment in water loss, although it's tricky to give an exact budget amount because the investments fall into many department budget line items. Spending at least eight million dollars across multiple program areas per year is a conservative estimate for annual water loss investments, but the total depends on circumstances for each year and which program efforts are counted. In a year with a lot of soil movement due to drought, the expenses will be higher due to the need for more pipe repair. Money to pay for water loss management comes largely from rate payers, although SAWS was successful in funding their acoustic monitoring program with funds from the Edwards Aquifer Authority as part of the Habitat Conservation Program.

Currently, SAWS has an Advanced Meter Infrastructure (AMI) pilot program. Once SAWS goes to full deployment, AMI will provide daily information on total customer consumption. We can compare this with daily production information. Further, SAWS is also looking at efficient options for repair of aging water pipes. There are a lot of point repairs addressed with collaring or clamps. Trenchless repairs like pipe bursting technology may also have promise. While this is not a common practice for the water side of the business, SAWS is interested in it to mitigate the need for expensive trenching and the associated disruption of streets and other areas. SAWS shows us that good data can help utilities properly understand their system and develop sufficient programs to address water losses.

CASE STUDY CONCLUSIONS: KEY FINDINGS AND LESSONS LEARNED

These case studies have shown the potential savings from water loss mitigation are significant — ranging from hundreds to thousands of millions of gallons per year.

The case studies also reveal there are financial, cultural and practical drivers for water loss mitigation, and decisions to invest in water loss mitigation programs often are influenced by all three drivers.

In addition, system vulnerabilities are consistent across the case studies, and include aging infrastructure, high pressure and pressure transients.

Good data — both system-wide and smaller-scale — is critical to an effective water loss mitigation program. The utilities studied above have paired district metered areas with software packages to proactively identify areas with potential leaks, followed up by walking the main lines and pinpointing leaks.

Finally, the case studies underline the importance of defining the goals for a water loss mitigation program and indicate that adaptive management can ensure flexibility as teams respond to changing conditions as more information becomes available.

Appendix A:
The Use of Frontier Analysis to Estimate the Water Loss Mitigation Potential in Texas

Alan Wyatt

1. INTRODUCTION

Effective and efficient Water Management Strategies (WMS) for both water demand and water supply are critical for managing a scare and precious resource in Texas — where demand is high and supply is often constrained by drought and climate change. Texas' recently approved 2022 State Water Plan (SWP) identifies water demands, available supplies, and needs for each of Texas' 16 planning regions. Each of the planning groups identify water management strategies necessary to fill the predicted water supply gap.

An "underappreciated" WMS (Loftus 2019) is the mitigation and control of water losses. Texas' public water distribution systems include over 193,000 miles of pipe, and over 10 million water meters, which naturally create significant water losses. If Texas utilities take sufficient action to address the water loss in their systems, the need for many supplemental water supply projects can be mitigated, delayed, or eliminated. It is therefore critical to improve the estimates of the current water loss volume and the potential for mitigating water loss in Texas. In fact, the TWDB has undertaken a water loss validation study that oulines the need for more accurate data in water loss audits

This paper presents a compilation of the water losses based on a sample of 2019 water audits, and uses a recognized methodology — Frontier Analysis — to estimate the water loss mitigation potential in utilities in 4 Size Classes and in the 16 regions across the state. Using a dataset of 2020 utility attributes, the results are scaled-up to provide estimates for 2020.

This appendix is organized into four main sections. The first section explains the concepts and mathematics of FA for the assessment of water utility efficiency, focusing on the application of FA to water losses. The second section focuses on the 2019 sample dataset used to apply FA in Texas, and the results of the associated regression modeling. The next Section provides results on observed water losses and water loss mitigation potential for utilities in four size classes and 16 regions across the state. Next, the scale-up process and results are discusssed. Before the conclusions of the appendix, a brief section shows how the FA results can be used in water management planning in Texas.

2. FRONTIER ANALYSIS: BASIC CONCEPTS AND ANALYSIS STEPS

2.1 Basic Concepts

Various forms of Frontier Analysis (FA) have been used for over 50 years to measure the efficiency or productivity of private firms or public services. (Filipinni et al. 2008, Ferro et al. 2014, Akimov et al, 2018, Estruch-Juan et al., 2020) For the non-expert the following definition, by Blank (2010) is useful: To put it simply, this technique is essentially a multivariate regression technique, but instead of drawing a graph through the "middle of all data points", the graph envelopes them. By doing so the graph does not represent production or cost of the average firm but that of the best performing firms (with highest production or lowest cost, conditional on all other variables).

FA has been applied specifically to water loss performance in WRc (2008), Pearson & Trow (2012), Wyatt et al (2015), Molinos-Senante et al (2021), Wyatt (2021), and Wyatt (2022) For water utilities and water loss, key concepts concerning behind FA are:

1. The water loss performance of a water utility depends on a combination of 1) a set of situational conditions or external variables over which the utility has little control in the short to medium term (such as number of connections, mains pipe length, water consumption, cost of water production), and 2) a set of practices it uses (or doesn't) use to manage water losses).

2. Utilities with identical situations and identical practices would (in theory) have identical water loss volumes and, by our terminology, identical performance. But, utilities with very similar situational conditions often have different practices and therefore different performance. Measuring the relative difference in performance is the key to fully understanding the water loss at a given utility, and determining for estimating the potential water savings with water loss mitigation.

3. Excellent performers delineate a "frontier" of excellent performance (known as the "low frontier" to indicate low water losses); very weak performers delineate a "frontier" of weak performance (known as the "high frontier" to indicate high water losses).

4. The mathematical "distance to the frontier" (also called the distance function) in volumetric terms is an indicator of performance, and water loss mitigation potential. A utility which is "far" from the low frontier has weak performance and high mitigation potential, and one close to the low frontier has good performance and low mitigation potential.

2.2 Preliminary Analysis Steps

In practice, a FA consists of the following major steps and considerations:

1. Assemble water audit data to construct a dataset with observed annual water loss volume, and situational parameters such the number of connections, miles of mains, billed water use, variable production cost of water, retail price of water, operating pressure, etc.

2. Use multi-variate regression to predict an annual average water loss volume, for each utility, based solely on the situational variables, such as connection density, miles of mains, authorized consumption, etc., which are not under control of the utility (at least in the short term). Care must be taken to avoid multi-collinearity of the independent variables.

3. Graphically compare the observed and predicted water losses, as shown in Figure 1. Utilities with observed water losses higher than their predicted losses will be above the trend line (weaker performers), and those with observed water losses lower than their predicted water losses will be below the trend line (stronger performers). As shown in Figure 1, lines can be drawn for the low frontier and high frontier.

4. Experience in the application of FA to water loss in several countries (UK, Brazil and several States in the USA) has shown that the low frontier could be defined by exceptional, excellent performers, or utilities which have particular characteristics not captured in the regression model. This issue is reviewed in Wyatt et al 2015, and Wyatt 2021. A mitigation to a range between the 75th percentile line and the 90th percentile line of the distance function appears to be appropriate choices for a rapid assessment of water mitigation potential.

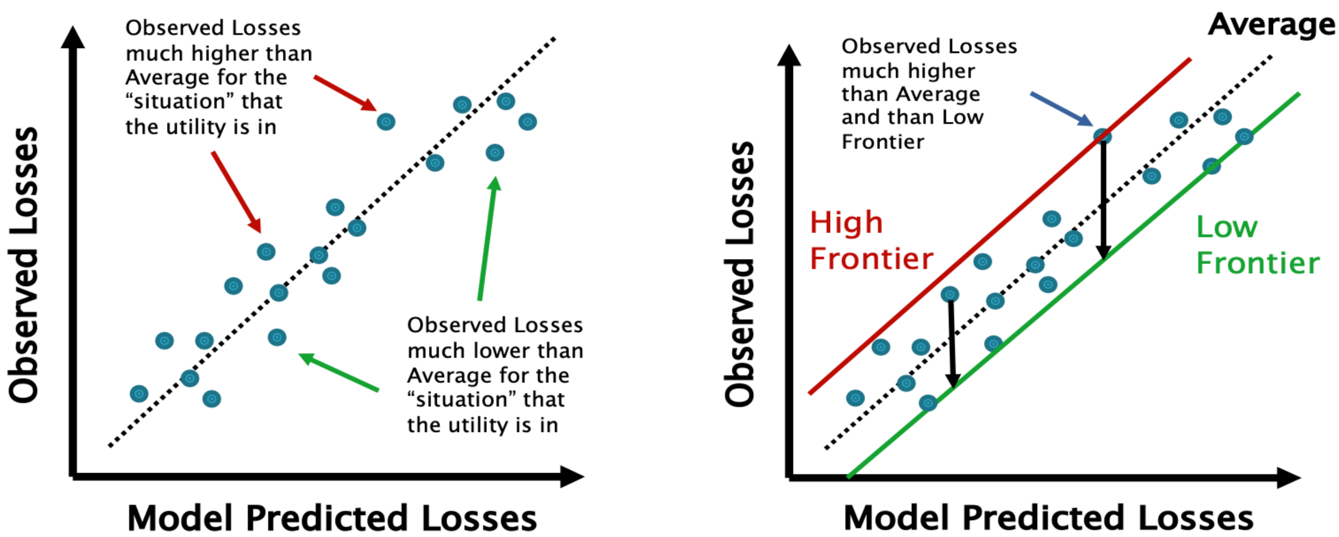
For purposes of this report, three performance levels, or standards were defined:

a. **Average Performance**: Water losses at the average line, which is equivalent to the 50th percentile line of the distance function;

b. **Good Performance**: Water losses at a level equivalent to the 75th percentile of the distance function;

c. **Very Good Performance**: Water losses at a level equivalent the 90th percentile of the distance function.

Figure 1. Basic FA Cross-Plot



2.3 Calculation of Water Loss Performance and Potential Water Loss Mitigation

As described above, the relative water loss performance for any utility can be assessed by using the distance function to the low frontier. The formulas and diagrams below illustrate the method of calculating the current water loss performance for any given utility, and the volume of mitigation required to reach a selected performance standard. For the calculations we define:

1. A water loss performance indicator which is the ratio of the Observed (current) water losses to the Predicted water losses, symbolized as O/P. Any given utility, i, will have its own value for this ratio, O_i/P_i. A utility with good performance will have a lower current annual volume of water losses, O_i, than its Predicted annual volume of water losses, P_i. Then, the ratio will be less than 1. A utility with poor water loss performance will have a higher annual volume of water losses, O_{ii}, than its Predicted annual volume of water losses, P_{ii}. Then the ratio O_{ii}/P_{ii} will be greater than 1. While most values of O/P are between 0.5 and 1.5, much higher or lower ratios do occur.

2. The annual water loss volume at the performance levels specified above — Average, Good, and Very Good. This is most easily explained with an example, shown in Figure 3. Consider a hypothetical water utility - site #22. Its annual water loss volume at the Good Performance level, LG22, can be calculated from the Predicted Losses (P22) and the associated percentile, using the following formula:

LG22 = P22*
(25th percentile of the range of values of O/P across the dataset)

And the annual water loss volume at the Very Good Performance level LVG22, can be calculated using the formula:

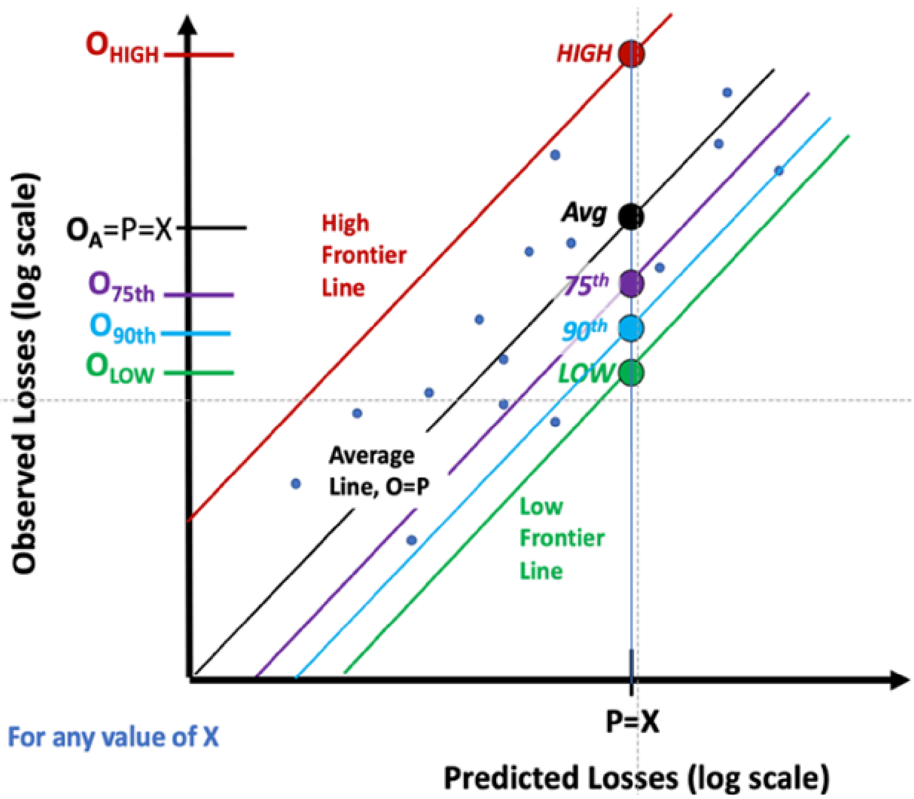
LVG22 = P22*
(10th Percentile of the range of values of O/P across the dataset)

3. The mitigation in annual water loss volume from the observed level to any of the Performance levels specified above – Average, Good, and Very Good (known as RG, RVG, etc.). As before, an example, for RG22 simplifies the derivation:

RG22 = O22 - LG22
Where O22 is the observed water losses for Site #22

So, the annual water losses for each site for each performance category can be calculated, as well as the water loss mitigation required for each site for to reach each performance standard. These water losses

Figure 2. Distance to the Low Frontier



A note on the use of percentiles: in this analysis, percentiles of two parameters are referred to, as outlined in the table to the right.

Performance Category	Relative Water Loss	Percentile of the Distance to the Low Frontier	Percentile of the Value of the Ratio O_i/P_i
Average	**Moderate**	**50th**	**50th**
Good	**Low**	**75th**	**25th**
Very Good	**Very Low**	**90th**	**10th**

can be added across the dataset, to find the total water loss mitigation required to move from the observed total water losses to the total water losses volume for a selected performance standard.

Figure 3 shows an alternate visualization of the elements of the Frontier Analysis approach, for a selected value of P including the distribution of points on either side of the Average Performance line – where O/P = 1. Experience with FA in various U.S. States and countries, including Texas shows that the utility points on the plot of the observed water oss volume versus the predicted water loss volume, do not conform to a normal distribution. There is a long "tail" in the distribution caused by a small number of very poor performers. However, Figure 4 uses a curve shape similar to a normal distribution to simplify the example. The right hand graphic in Figure 4 provides a conceptual diagram for the example site #22, with an indication of the level of Water Losses at the Good Performance Category, for Site#22 (LG22) and mitigation of water losses to achieve Good Water Loss Performance (RG22).

Figure 3. Example Performance Calculation

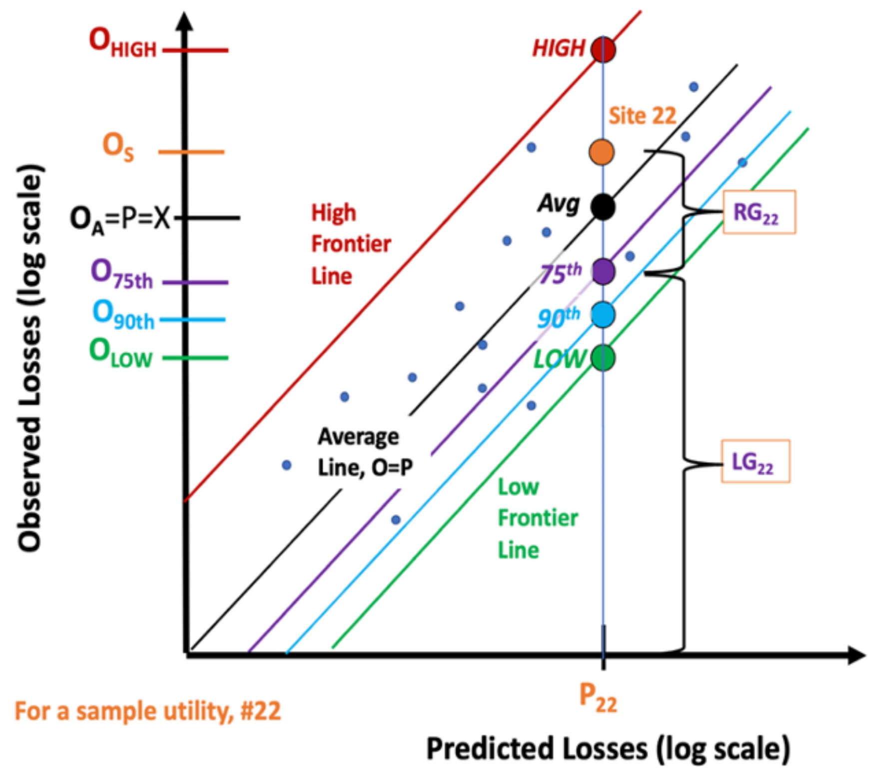
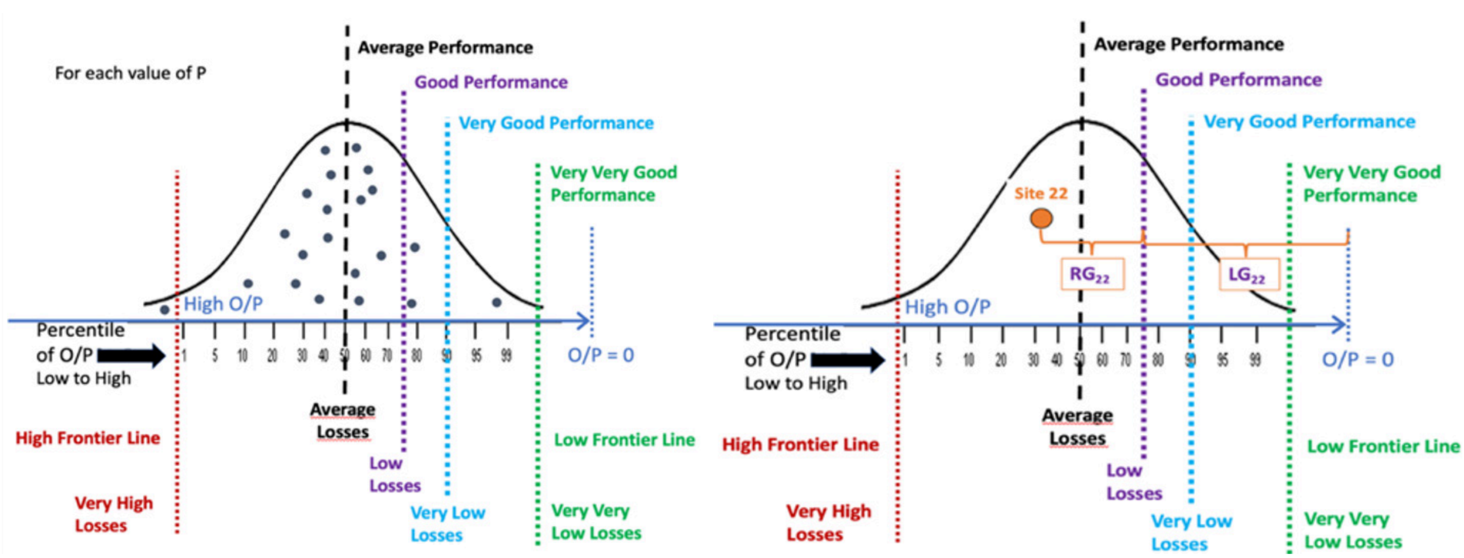


Figure 4. Example Performance Calculation



3. FRONTIER ANALYSIS OF WATER UTILITIES IN TEXAS

3.1 Dataset Utilized -Sample of Utilities from 2019 Audits

The initial step in preparing a dataset for analysis was to obtain all the water audits submitted to the TWDB over the period 2015-2019, which included audits for 2,817 water utilities. We found the 2019 data points to be statistically consistent with the 2015-2018 data. Given the consistency of both datasets, we chose to base our analysis on only 2019 data as this was the most recent publicly available data at the time the analysis was performed. Next the audits were filtered, using a two-step process, first using criteria established by the TWDB, similar to the AWWA recommended filtering criteria (Sturm et al. 2015 and Trachman et. al. 2019) and second, additional filters to remove outliers. The first set of filters included:

1. Negative or Zero Values for Total Water Loss, Total Apparent Loss, Total Unreported Loss, Total Real Loss
2. Customer Meter Accuracy < 90%
3. ILI outside of range of 1 to 10
4. Produced + Purchases – Wholesale (Exports) < = Billed Metered Consumption
5. Billed Metered Consumption < 1000 Gals / connection / month
6. Unusual or outlier values for population, # of connections, length of mains, service connection density or pressure

The second set of filters included the following:

7. An “over-riding” criterion ILI outside of range of 0.5 to 15.0
8. Total Water Loss Percentage > 50%
9. Customer Retail Unit Cost (CRUC) <$500/MG, >$50,000/MG or No Data
10. Variable Water Production Cost (VPC) < $100/MG, >$50,000/MG or no Data
11. Ratio CRUC / VPC <1 for greater than 100
12. Connection Density (Connections / Mile) < 4 or > 250
13. Total Authorized Consumption <50 G/C/D, or >1000 G/C/D
14. Real Loss < 3/G/C/D
15. Water Loss < 5/G/C/D or > 200 G/C/D

Table 1. Water Loss in Sample Dataset Utilities - by Size Class, 2019

Size Category	# of Utilities	% of Utilities	# of Retail Connections	% of Connections	Total Water Losses, AF/Yr	% of Total Water Losses
Very Large	29	4%	3.8M	61%	285K	68%
Large	65	8%	1.1M	18%	60.3K	14%
Medium	123	15%	730K	12%	41.1K	10%
Small	606	74%	600K	10%	35.9K	8%

Size Category	Average Retail Connection Density (Conns / Mile)	Average Operating Pressure, psi	Average Authorized Consumption, Gals/Conn/Day	Average Variable Water Production Cost, $ / AF	Average Water Losses, Gals/Conn/Day	Average Apparent Losses, Gals/Conn/Day	Average Real Losses, Gals/ Conn/Day
Very Large	77	69	356	$598	54	10	44
Large	58	65	337	$469	49	9	40
Medium	63	63	284	$510	50	8	42
Small	42	59	235	$621	49	7	42
Average	48	60	255	$591	49	7	42

Table 2. Water Loss in Sample Dataset Utilities — by Region, 2019

Region	Number of Utilities	Retail Population Served	Retail Connections Served	Average of Daily Authorized Consumption, Gals / Conn / Day	Total Observed Water Losses, AF / Yr	Average of Water Losses, Gals / Connection / Day
A	14	83.4K	33.87K	302	2.5K	68
B	6	27.2K	13.02K	218	815	45
C	143	5.8M	1.98M	259	135.5K	42
D	50	253.3K	97.77K	209	6.5K	46
E	4	747.3K	215.08K	370	14.3K	66
F	21	331.6K	122.42K	282	8K	83
G	125	1.2M	466.39K	214	25.9K	58
H	190	4M	1.09M	272	98.2K	40
I	62	379.9K	156.24K	193	13K	62
J	15	69.1K	30.2K	180	1.9K	25
K	56	1.5M	376.71K	310	31.3K	45
L	65	2.7M	1.07M	277	56.3K	51
M	32	1.1M	371.18K	300	20.1K	61
N	14	120.1K	43.39K	282	2.1K	51
O	21	334.7K	117.47K	283	5.4K	54
P	5	26.8K	11.08K	247	754	51
Total	823	18.7M	6.2M	255	422.7K	49

The resulting sample dataset used in the FA analysis consisted of audit data from 823 water utilities for 2019, including utilities in each regional water planning area (region) and in each of the four size categories (based on population served). This sample dataset, being based on the double filtering, is considered to be the most accurate available at this time. The results in any region, or for any size category, or for the whole sample can be "scaled up" according to service connections, on a pro-rata basis, to estimate regional or state-wide water losses and water loss mitigation potential.

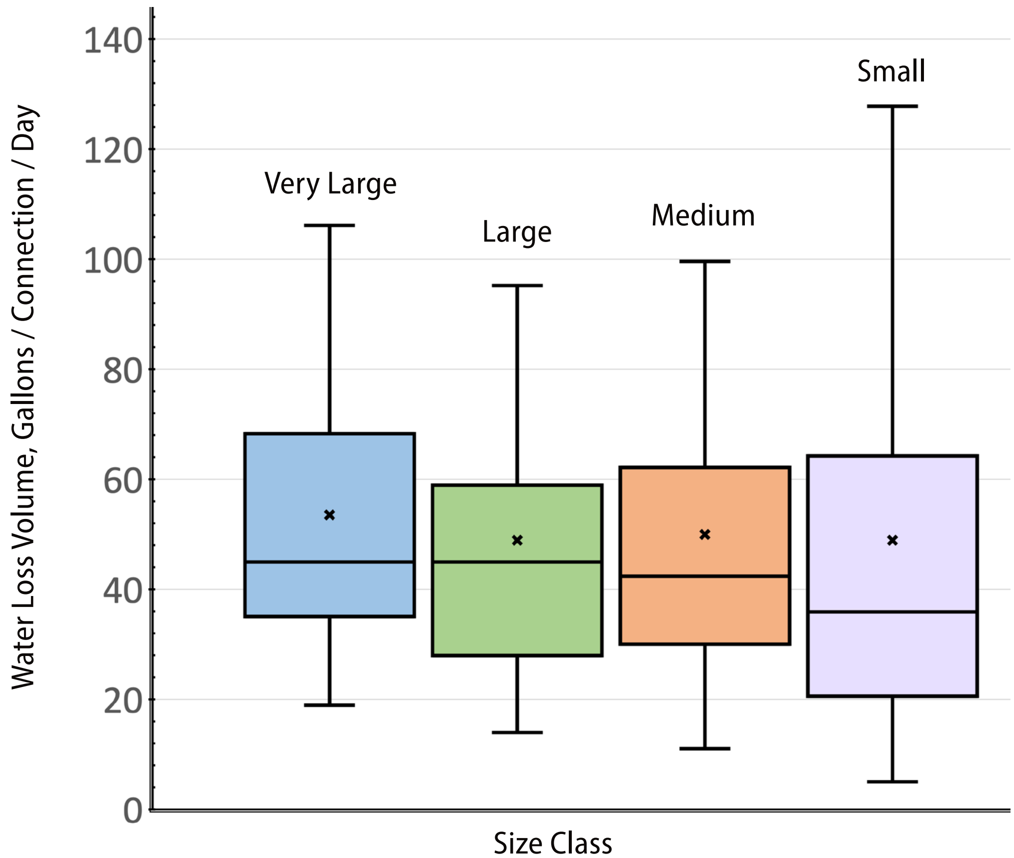
It should be stressed that, as is the case across Texas, the water audits from which the dataset was prepared, are not validated water audits according to the AWWA recommended practice. Therefore, these data, and the results of their analysis should be considered as approximate only, and as preliminary.

3.2 Observed Water Loss Performance from 2019 Sample

Water loss statistics from the sample dataset are provided in Tables 1 and 2.

Obviously, the Very Large utilities make up the bulk of the water losses, due to their size. But on the basis of volume per connection, the water losses are very close. Behind those similar numbers is a wide variation, as shown in the box and whisker charts in Figure 5. The small water systems have a wider span of values of water losses in gallons/connection/day.

Figure 5. Box and Whisker Plots by Size Class and Region, 2019



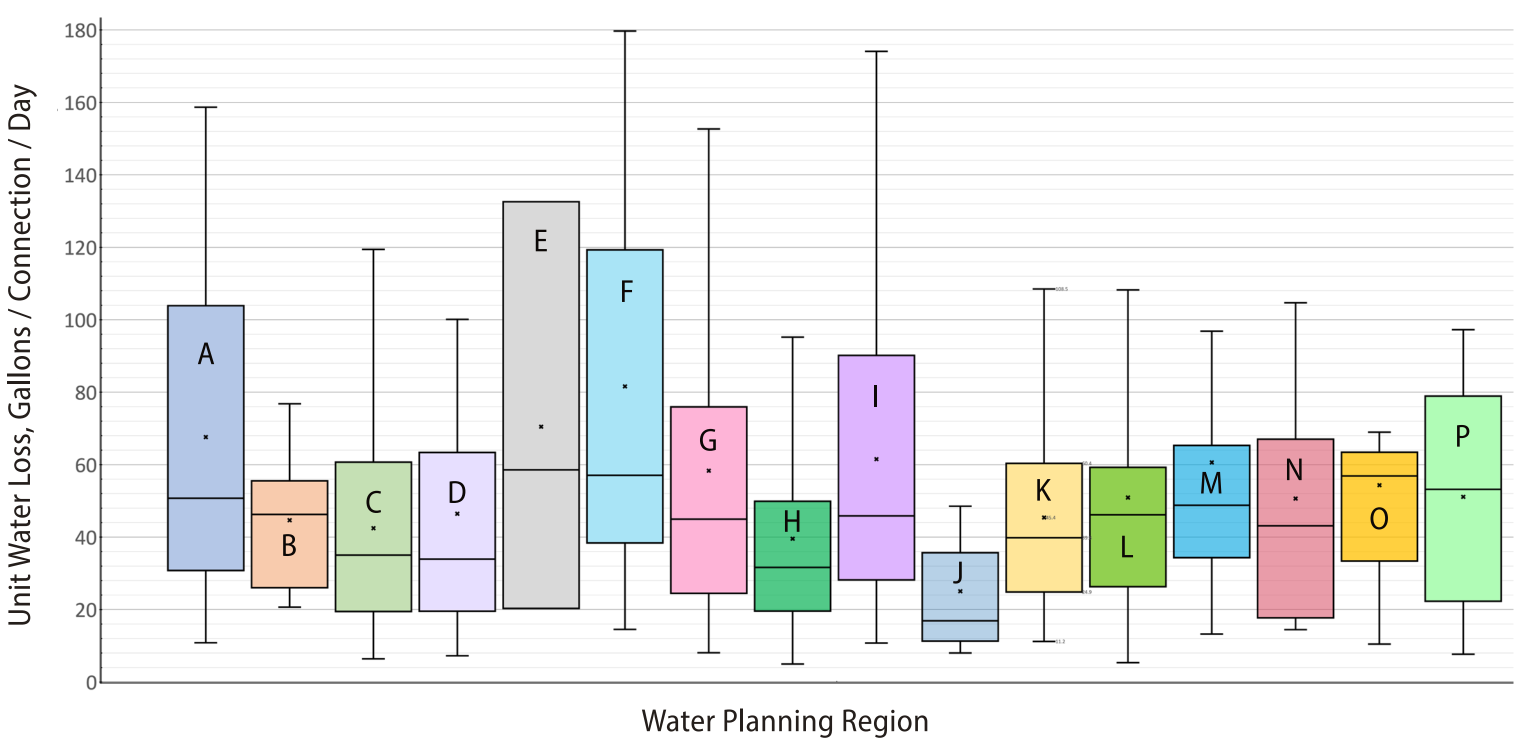


Table 2 shows the regional breakdown of water losses. Regions C, G, H, K and L have the largest number of utilities, retail population served, and retail connections served, and total water loss (AF/yr), due to the presence of big cities like Dallas, Fort Worth, Houston, Austin and others. In fact, these regions have 80% of the connections across the State, and 82% of the total water losses. The average water losses in G/C/D vary considerably from region to region, ranging from 25 G/C/D to 68 G/C/D.

3.3 Regression Model for the Frontier Analysis

Table 3 provides the model form, the independent variables and the dependent variable of the multivariate regression model used to predict water losses. The model is in the Cobb-Douglas form, which is generally used in frontier analyses, (Filippini et al 2008). An earlier version of the model included both average operating pressure and unit water price, but these variables were found to be statistically insignificant, and dropped from the model.

It is also important to note that this model is deterministic, rather than stochastic. A deterministic model does not account for any randomness in the inputs and produces the same result if used many times with the same inputs. A stochastic model, with more sophisticated techniques, can account for randomness in inputs to give a range in outputs.

Table 4 shows the regression model statistics, including overall fit, analysis of variance and the values of the coefficients and their statistical significance as explanatory variables. Overall, the regression model is of very high quality, with an adjusted r^2 of 0.902, and Fstat of 1886. The parameter coefficients have the expected signs (positive or negative), and very good P-values for the intercept and four independent variables (>99th confidence level).

Table 4 also provides the Pearson Correlation Coefficients showing pair-wise correlations of the independent variables. The results show low correlations, indicating little multi-collinearity.

3.4 Frontier Analysis Plots for Texas

Figure 6 compares the Observed Water Losses to the Predicted Water Losses, including the Low Frontier, High Frontier, the Average line, and the Good Performance and the Very Good Performance levels. The data points have an even spread across the Average line over the full range of the values of P. Figures 7-9 provide FA plots for different groups of utilities. One graph highlights Region C and another Region K. The data seem evenly spread around the Average line and line over the full range of the values of P. Figure 9 provides a plot with data points colored by size class. The location of the data points seems plausible and exhibit a balanced spread.

Overall, these plots indicate a robust data set which can be used to assess the annual water loss volume at the Good Performance and Very Good Performance levels and determine the water loss mitigation required to reach those standards.

Table 3. Mathematical Form of the Regression Model

Dependent Variable	WL= Total Water Loss, AF/Year
Independent Variables	N_m= Length of Mains pipes, miles
	D = Connection Density = Number of Retail Connections / Length of Mains, # / mile
	C = Unit Authorized Consumption, Gallons / Connection / Day - (Billed and Unbilled)
	VPC =Variable Water Production Cost, $/MG
Model Forms	$WL = A * L^b * D^c * C^d * VPC^e$ *Note: in this formulation, the exponents, b, c, etc are elasticities of the corresponding independent variables with respect to the dependent variable.*
	Ln (WL) = LN A + *b**Ln (L) + *c**Ln (D) + *d**Ln (TAC) + *e**Ln(VPC)

Table 4. Multi-variate Regression Model Parameters

Regression Statistics	
Multiple R	0.949840042
R Square	0.902196105
Adjusted R Square	0.901717847
Standard Error	0.662455891
Observations	823

CORRELATIONS	Mains Length	Connection Density	Authorized Cinsumption	Var Production Cost
Mains Length		0.03664	0.16735	-0.02241
Connection Density	0.03664		0.23128	0.03159
Authorized Consumption	0.16735	0.23128		-0.06976
Var Production Cost	-0.02241	0.03159	-0.06976	

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	3311.402977	827.8507443	1886.418778	0
Residual	818	358.9775063	0.438847807		
Total	822	3670.380483			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-4.882701069	0.332414135	-14.68860845	1.59562E-43	-5.535186235	-4.230215903
LN Miles of Mains	1.075567672	0.014524539	74.05176008	0.00E+00	1.047057915	1.104077429
LN Connection Density	0.810779182	0.030240767	26.81080065	3.9558E-114	0.751420539	0.870137825
LN Unit Authorized Consumption, G/C/D	0.460099605	0.058466048	7.869517733	1.12701E-14	0.345338452	0.574860757
LN Variable Production Cost, $ / MG	-0.059976205	0.024111529	-2.487449275	0.013064491	-0.10730396	-0.012648449

Figure 6. Frontier Analysis Cross Plot for Water Loss in Texas Utilities, 2019

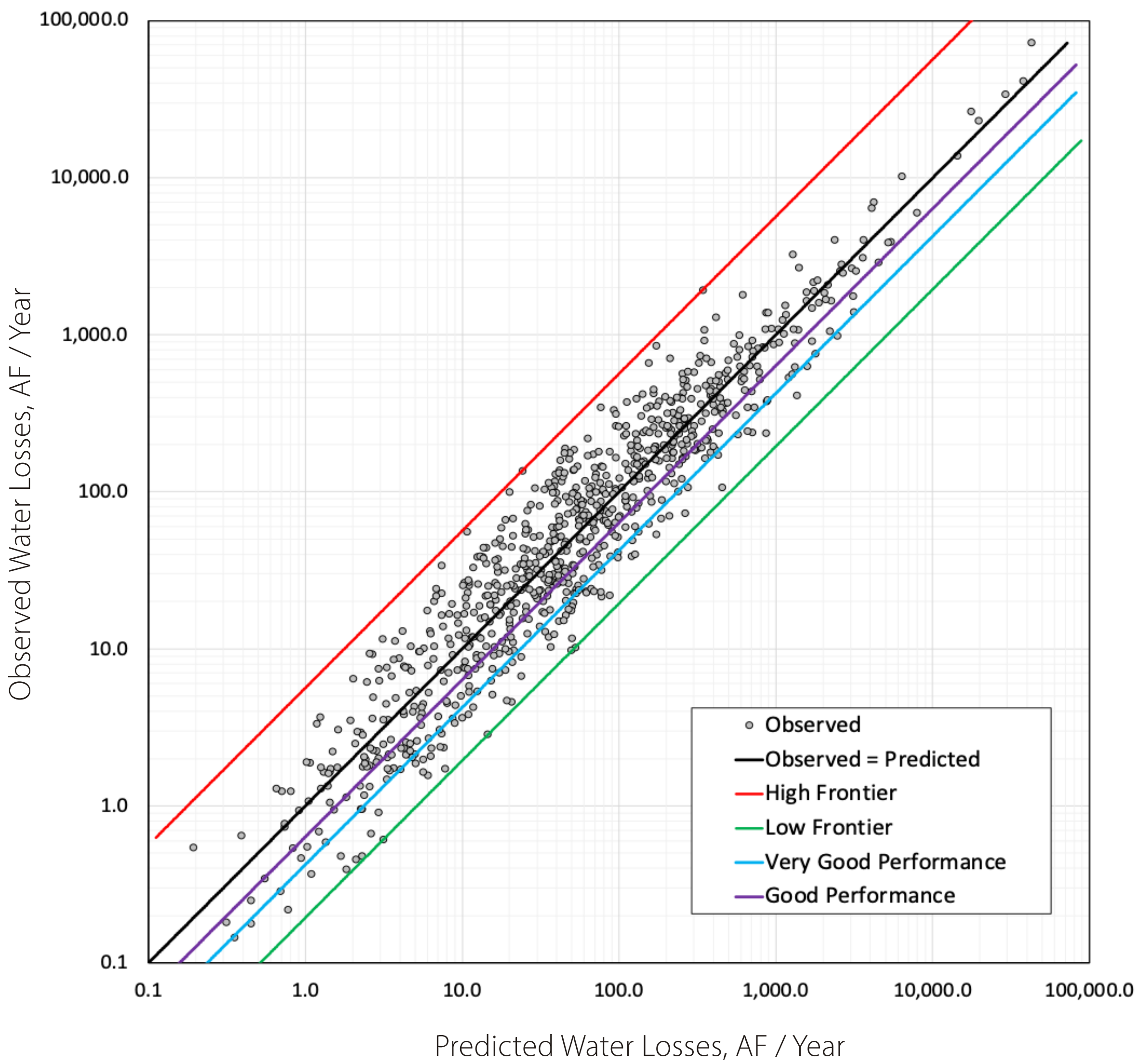


Figure 7. Frontier Analysis Cross Plot for Water Loss in Region C, 2019

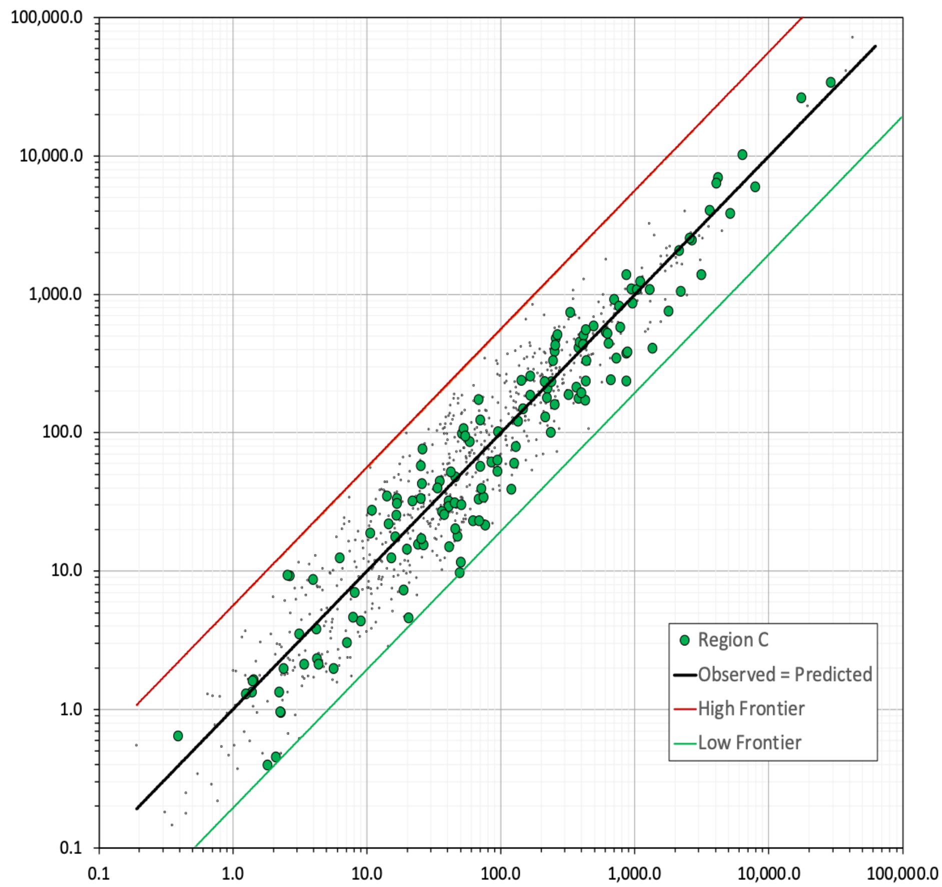
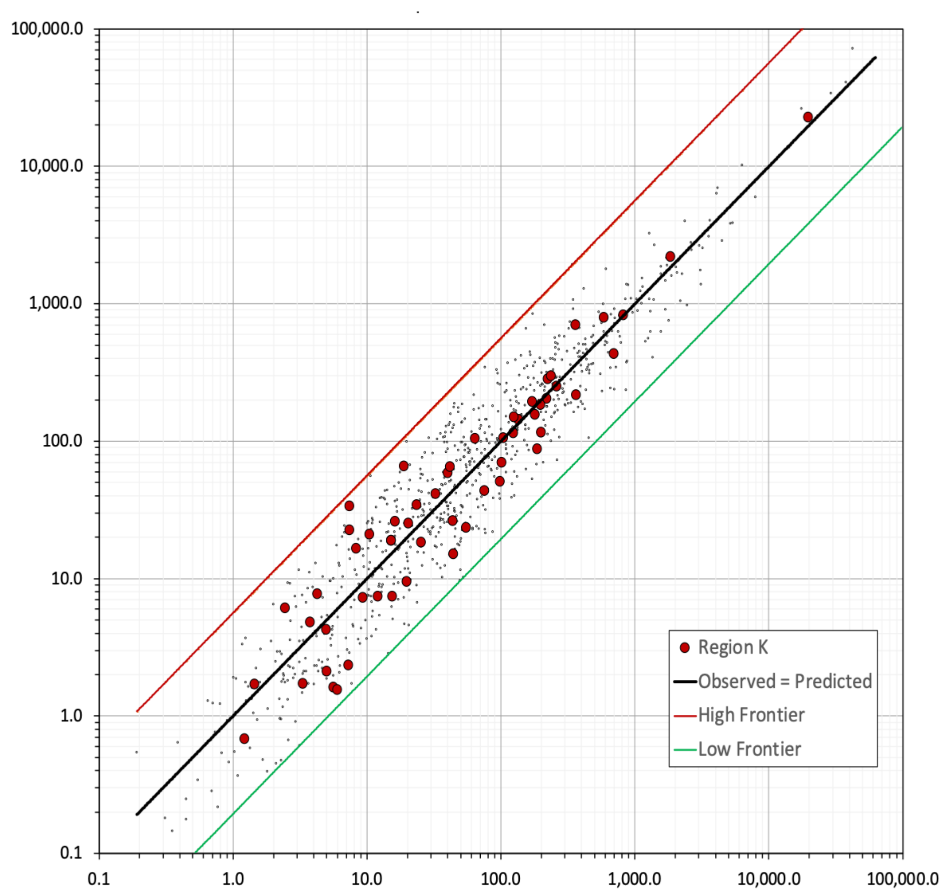


Figure 8. Frontier Analysis Cross Plot for Water Loss in Region K, 2019



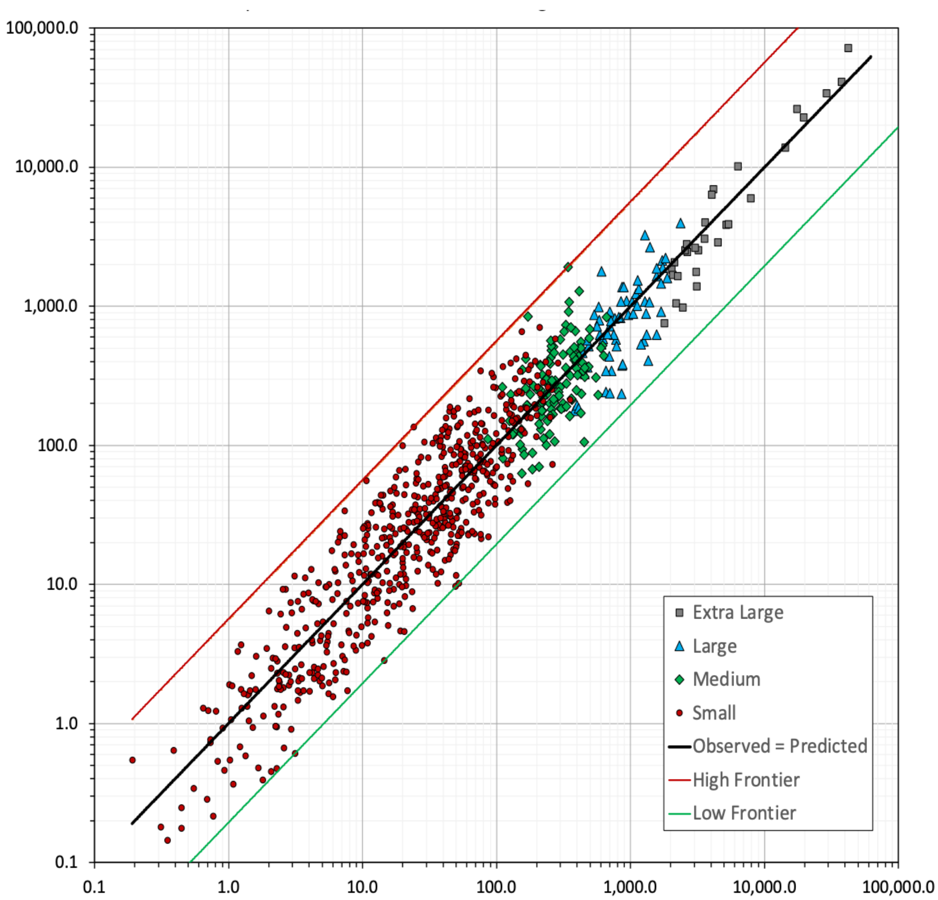


Figure 9. Frontier Analysis Cross Plot for Water Loss in Very Large Utilities, 2019

It is important to note that the FA results allow a calculation of the range of mitigation potential of any utility in the state, by using the equation of the regression model in Table 3, the coefficients in Table 4 and the performance formulae for Good and Very Good Performance from the FA. A target range for water losses can be found from utility characteristics with a poor quality audit or no audit at all. This capability can speed up water loss mitigation planning.

4. ANALYSIS OF FA RESULTS FOR WATER UTILITIES IN TEXAS

4.1 Water Loss and Mitigation Potential by Performance Level by Size Category

Table 5 and Table 6 provide observed water loss performance levels and potential water loss mitigation (possible water savings) for the sample dataset, organized by size category.

Note that the mitigation potential at a given standard is the difference between the observed water losses in a size category, minus the water loss associated with the given standard in that size category. For example, for Large water systems, the observed water loss is 60,365 AF/Yr, and the water losses at the Good Performance standard is 42,368 AF/Yr, so the potential water loss mitigation is the difference, or 17,878 AF/Yr. The same logic holds true for unit water loss in Gallons / Connection / Day.

The Very Large utilities account for about 67.5% of the observed water losses, but as shown in Table 3, they only represent 60% of the connections, so the unit losses for Very Large utilities in Table 8 are higher than utilities in the other size categories.

Mitigation to the Good Performance Standard would result in a savings of about 41% across all size classes. A more aggressive, or longer-term mitigation to the Very Good Performance level would lead to a larger savings, of approximately 61%. So reaching the midpoint between Good and Very Good Performance is very close to cutting the Water Loss in half.

The complementarity of water loss performance standard and the water loss mitigation potential can be seen in Figure 10. Logically, the sum of the water loss performance level and water loss mitigation potential is equal to the observed water losses.

4.2 Water Loss Performance Level and Mitigation Potential by Region

Table 7 provides estimated levels of water losses for the utilities in the sample, by region, denominated in AF/Year and in Gallons / Connection / Day as noted above. The variation of total observed water losses varies greatly across Regions, more so than variation by Size Class. Regions C, H, L, G, M, and K have large populations, larger cities, higher number of connections and higher water losses. Region C contains approximately 30% of the observed water losses.

4.3 Comparison of FA Results to Texas State University Water Loss Study

In 2019, the Texas Water Journal published a paper on the economically recoverable water losses in Regions C and K, based on water audit data from 2014 (Loftus 2019). The paper used a combination of two methods to estimate the economically recoverable water losses — one involving the ILI and a second method previously used by George Kunkel in a paper on the economically recoverable water losses in Pennsylvania (Kunkel 2017).

Table 5. Water Loss Performance Levels and Reduction Potentials by Utility Size Class 2019, Sample, AF/Year

Size Class	Observed Water Losses	WATER LOSSES Average	WATER LOSSES Good	WATER LOSSES Very Good	REDUCTION POTENTIALS Average	REDUCTION POTENTIALS Good	REDUCTION POTENTIALS Very Good
Very Large	285.4K	241.1K	163.6K	107.3K	44.2K	121.8K	178K
Large	60.4K	62.6K	42.5K	27.9K	-2.3K	17.9K	32.5K
Medium	41.1K	36.2K	24.6K	16.1K	4.9K	16.5K	25K
Small	35.9K	27.4K	18.6K	12.2K	8.3K	17.1K	23.5K
Total	422.7K	367.4K	249.3K	163.5K	55.1K	173.3K	259K

Table 6. Water Loss Performance Levels and Reduction Potentials by Utility Size Class 2019, Sample, G/C/D

Size Class	Observed Water Losses	WATER LOSSES Average	WATER LOSSES Good	WATER LOSSES Very Good	REDUCTION POTENTIALS Average	REDUCTION POTENTIALS Good	REDUCTION POTENTIALS Very Good
Very Large	54	51	32	21	3	22	33
Large	49	49	31	20	0	18	29
Medium	50	43	27	18	7	23	32
Small	49	37	23	15	12	26	34
Total	49	39	25	16	10	25	33

Table 7. Water Loss Performance Levels and Reduction Potentials by Region, 2019, Sample, AF/Year

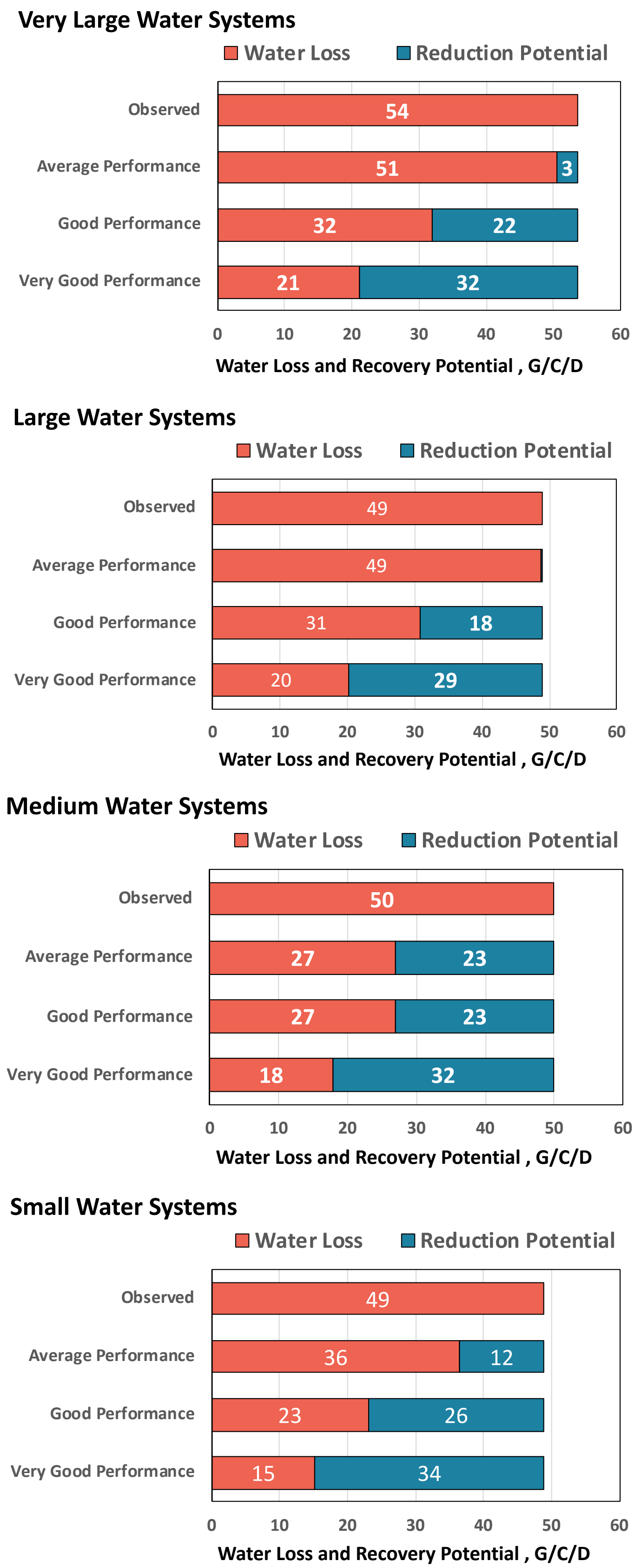
Size Class	Observed Water Losses	WATER LOSSES			REDUCTION POTENTIAL		
		Average	Good	Very Good	Average	Good	Very Good
A	3K	2K	1K	730	882	1K	2K
B	815	535	363	238	280	452	577
C	136K	121K	82K	54K	15K	54K	82K
D	7K	6K	4K	3K	883	3K	4K
E	14K	15K	10K	6K	-318	4K	8K
F	8K	7K	5K	3K	698	3K	5K
G	26K	25K	17K	11K	418	9K	15K
H	98K	70K	47K	31K	28K	51K	67K
I	13K	8K	6K	4K	5K	8K	9K
J	2K	2K	1K	703	364	872	1K
K	31K	28K	19K	12K	4K	13K	19K
L	56K	53K	36K	23K	4K	21K	33K
M	20K	22K	15K	10K	-2K	5K	10K
N	2K	2K	1K	901	114	765	1K
O	5K	7K	5K	3K	-2K	617	2K
P	754	552	375	246	202	379	508
Total	423K	367K	249K	164K	55K	173K	259K

The comparison of the economic results obtained by Loftus to the results of the FA provides a useful perspective on the FA results.

The Loftus analysis was based on water audits for 2014, using a sample of 106 water utilities in Regions C and K with approximately 6,800,000 population and with approximately 2,260,000 connections. The total water losses in the sample were approximately 147,000 AF / Year, or 58.1 Gallons / Connection / Day. The analysis of the economically recoverable water losses led to an estimate of 65,000 AF/Year, or 25.7 Gallons / Connection / Day.

It is important to note that the proportion of Very Large, Large, Medium and Small water utilities in the Loftus sample is different than the proportion for regions C and K in the sample used in the FA; therefore, the calculation of the Good Performance Standard and the Very Good Performance Standard used 1) unit mitigation potential volumes in G/C/D for each size slass, each region and each performance standard and the number of connections in the sample for each region and size category. This calculation led to a result of a Good Performance Level of 30.3 Gallons / Connection / Day and the Very Good Performance Standard of 20.0 Gallons / Connection / Day. The midpoint of the two Levels is 25.1

Figure 10. Water Losses & Water Loss Reductional Potential by Size Class



Gallons / Connection / Day, which is remarkably close to the Loftus result.

It is possible that the current level of economically recoverable losses in 2019 is different from that 2014. A change in the economically recoverable level, in general, is dependent on the change in the variable cost of water, the retail price of water, in relation to the change in the cost of water loss mitigation and the balance between apparent losses and real losses. Such a complex recalculation of the economically recoverable level in 2019 is beyond the scope of this report.

Another comparison was made recently between the results of an FA and an economic water loss model, in Brazil (Depexe 2021 and Wyatt 2021). The study conducted an FA for real losses in 59 water systems in the State of Parana, operated by a regulated private company – SANEPAR. The modeling computed the Good Performance and Very Good Performance water loss levels. The same 59 sites were analyzed to determine the economically optimal level of real losses, using an analytical technique known as the Economic Level of Leakage (ELL). That type of model determines the optimal level of real loss by balancing the marginal cost of real loss mitigation with the marginal value of the water savings. The Brazil ELL Model was based on Wyatt (2010), but adapted and customized to conditions in Brazil. The comparison of the FA results and the ELL results showed that the economic level or real losses for nearly all of the utilities was between the real losses at Good Performance and Very Good Performance.

Overall, it appears that the range between the Good Performance Standard and the Very Good Performance Standard, is close to the economically recoverable, or economically optimal level, although this preliminary finding merits further study.

4.4 Scale-up from the Sample to the State of Texas

The analysis and results presented so far are all based on the sample of 823 water loss audits from 2019. However, there are over 4000 retail public water systems in the state (see Table 9). The sample included 70% of the Very Large water systems, about 60% of the Large ones, about

Table 8. Observed Water Loss by Region and Size Class, G/C/D

Region	Very Large	Large	Medium	Small
A	53.5	48.9	40.8	74.9
B	53.5	48.9	76.8	38.2
C	59.1	37.7	51.9	38.3
D	55.7	48.9	66.6	42.6
E	58.6	48.9	50.0	68.7
F	36.9	48.9	98.1	81.1
G	35.7	47.4	53.9	60.5
H	59.5	44.5	35.6	39.5
I	53.5	84.5	70.5	59.0
J	53.5	82.0	35.7	19.8
K	85.3	68.7	40.1	43.2
L	47.1	45.9	48.2	52.9
M	45.1	43.0	66.7	69.5
N	53.5	48.9	33.8	63.3
O	38.2	48.9	42.4	55.8
P	53.5	48.9	53.2	50.6
Avg	53.5	48.9	50.0	48.9

Table 9. Comparison of Sample Dataset to State-wide Dataset

Size Class	SAMPLE DATASET 2019			STATE-WIDE DATASET 2020		
	# of Utilities	Population Served	# of Connections	# of Utilities	Population Served	# of Connections
Very Large	29	12,060,602	3,759,320	41	14,200,378	4,540,688
Large	65	3,083,718	1,114,008	105	4,994,168	1,843,316
Medium	123	1,998,855	730,422	228	3,500,658	1,248,915
Small	606	1,561,315	594,050	3647	6,544,906	2,448,192
TOTAL	**823**	**18,704,490**	**6,197,800**	**4021**	**29,240,110**	**10,081,111**

half of the Medium ones, but only about 17% of the Small Water Systems. This situation is caused by two factors: 1) many small systems have not submitted audits, and 2) the filtering process removed many audits.

Therefore, we obtained a dataset from TWDB which contained the 2020 retail population and retail connections at each of the 4021 retail public water systems in the state. The actual origin of the data is the TCEQ water quality monitoring database, but this dataset is used by TWDB. The "scale-up" process from the sample to statewide estimates for water loss became, in simple terms, a combination of the number of connection in the TWDB/TCEQ database and the water loss in gallons per connection per day from the sample. The 2019 sample had very accurate information on unit water loss, and the 2020 dataset had the full roster of water systems. The fact that the dataset were one year apart was deemed to be satisfactory for an extrapolation to get arrive at an estimated assessment of statewide water loss.

The calculations were conducted for each size class and each region (64 "cells") to obtain the number of connections and total water loss in each cell. These could added up into regional or size class tables. The results if the frontier analysis on the sample were used to determine the total water loss and the potential water mitigation in each "cell".

It is important to note that figure for the gallons per connection per day was drawn from the sample. However, there were cells, where the sample had no data. In this case the data in Table 8 was used. For example, if there were two large water systems in the full water system database for a given cell, but no water systems in the sample in that cell, the average gallons per connection per day was used as an approximation, to obtain total water loss data for the cell.

4.5 Statewide: Performance Levels and Mitigation Potentials by Size Class

Table 10 presents the estimated statewide water loss performance levels and mitigation levels. The total estimated water loss is 572,000 AF/Yr. It is not known if there have been any previous estimates of this large potential water resource. The mitigation potential ranges from 248,900 to 358,900 AF/Yr, whose average is 303,900 AF/Yr, which is over half the current losses.

4.6 Statewide: Water Loss Performance Levels and Mitigation Potentials by Region

Table 11 provides the scaled-up FA results, water loss performance levels and mitigation potentials by region. Note there are some rounding error differences from Table 10.

Table 10. Statewide Water Loss Performance Levels and Reduction Potentials by Utility Size Class, AF/Yr

Size Class	# of Connections	Est. Water Losses	ESTIMATED WATER LOSSES			REDUCTION POTENTIALS		
			Average	Good	Very Good	Average	Good	Very Good
Very Large	4.5M	277.2K	254.6K	160.8K	106K	22.6K	116.5K	171.2K
Large	1.8M	96.1K	91.9K	62.9K	41.5K	4.2K	33.2K	54.6K
Medium	1.2M	69.6K	58.7K	37K	24.6K	11K	32.6K	45.1K
Small	2.4M	129....	99.3K	62.7K	41.3K	30.1K	66.7K	88K
Total	10.1M	572.3K	504.5K	323.4K	213.4K	67.8K	248.9K	358.9K

Table 11. Statewide Water Loss Performance Levels and Reduction Potentials by Region, AF/Yr

Region	# of Connections	Est. Water Losses	ESTIMATED WATER LOSSES			REDUCTION POTENTIALS		
			Average	Good	Very Good	Average	Good	Very Good
A	133.7K	8.5K	6.9K	4.3K	2.9K	1.6K	4.2K	5.7K
B	75.2K	4.2K	3.8K	2.4K	1.6K	426	1.8K	2.6K
C	2.6M	153K	137.2K	86.6K	57.1K	15.8K	66.4K	95.9K
D	344.3K	19K	12.3K	11K	7.2K	6.7K	8K	11.8K
E	270.5K	17.5K	14.8K	10.4K	7K	2.7K	7.1K	10.5K
F	255.5K	16.1K	13.6K	8.6K	5.7K	2.5K	7.6K	10.5K
G	903.1K	48.9K	44.7K	28.2K	18.6K	4.2K	20.6K	30.3K
H	2.3M	115.7K	106.7K	67.4K	44.4K	9K	48.3K	71.3K
I	427.7K	31.1K	20.9K	13.2K	8.7K	10.2K	17.9K	22.4K
J	46.2K	3K	2.2K	1.4K	925	785	1.6K	2.1K
K	495.7K	37.3K	31.6K	19.9K	13.1K	5.8K	17.4K	24.2K
L	1.2M	65.6K	57.5K	36.3K	24K	8K	29.2K	41.6K
M	573.1K	31.6K	33.1K	20.9K	13.8K	-1.5K	10.7K	17.8K
N	200.7K	11.6K	9.6K	6.7K	4.4K	1.9K	4.9K	7.2K
O	164.8K	8.2K	8.8K	5.6K	3.7K	-592	2.7K	4.5K
P	15.8K	909	726	458	302	184	451	607
Total	10.1M	572.2K	504.4K	323.4K	213.4K	67.8K	248.9K	358.9K

Table 12. Water Savings from Water Loss-Related WMS recommended in the 2022 SWP for the 2020 Decade, AF/ YrRegion, AF/Yr

Region	Extra Large	Large	Medium	Small	Total
A	3,562		289	12	3,863
B					
C	24,426	2,733	968	925	29,052
D					
E	4,950	197		176	5,323
F				330	330
G	698				698
H	4,273	778	152	689	5,892
I	2,027		7		2,034
J		12	134	99	245
K	4,910	1,870	1,835	4,289	12,904
L	426				426
M	1,140		370	88	1,598
N					
O					
P					
Total	46.4K	5.6K	3.8K	6.6K	62.4K

5. APPLICATION OF THE FA RESULTS TO WATER LOSS PLANNING IN TEXAS

The results of the FA, including the estimated level of water losses, the water loss performance levels and the potential water loss mitigation amounts were used to review two aspects of the 2022 State Water Plan (SWP) in conjunction with the TWDB staff. These reviews allowed an assessment of the current and potential role of water loss mitigation in the revisions to the 2022 SWP and in future plans.

5.1 Review of Recommended Water Loss-Related WMS in the 2022 State Water Plan

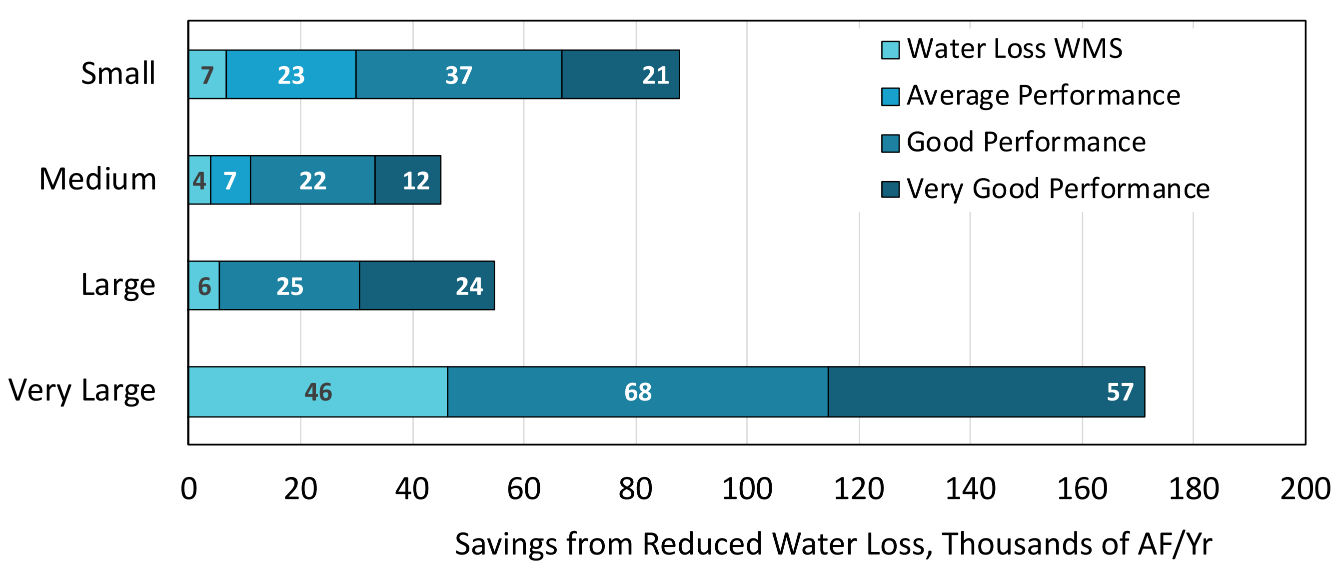
The first review consisted of a comparison of the water-loss-related water management strategies (WMS) in the 2022 SWP (see Table 12) to the observed water losses and the mitigation potentials by size class and region. The recommended WMS emphasize water loss mitigations in the Extra Large size class utilities, especially in Region C, but also in Regions E, H and K.

Table 13 compares the WMS savings from the SWP to the Mitigation Potential by Region. It can be seen that, as

Table 13. Comparison of WMS Water Savings to Water Loss Reduction Potential Volumes by Region, AF/ Yr

Region	2022 SWP Water Loss Related WMS 2020 Decade	POTENTIAL WATER SAVINGS AT THREE PERFORMANCE STANDARDS		
		Average	Good	Very Good
A	3,863	1,638	4,174	5,654
B		426	1,821	2,636
C	29,052	15,799	66,372	95,882
D		6,695	8,009	11,753
E	5,323	2,745	7,128	10,528
F	330	2,541	7,550	10,473
G	698	4,167	20,647	30,264
H	5,892	9,019	48,340	71,285
I	2,034	10,183	17,892	22,391
J	245	785	1,604	2,082
K	12,904	5,754	17,391	24,181
L	426	8,022	29,233	41,610
M	1,598	-1,507	10,686	17,801
N		1,948	4,899	7,177
O		-592	2,655	4,533
P		184	451	607
Total	62.4K	67.8K	248.9K	358.9K

Figure 11. Savings from Improved Water Loss Performance (Cumulative), Thousands of AF/Yr



noted before that, Regions C, G, H, L and K have relatively high savings potential compared to other regions, especially Region C. So, the allocation of resources toward water loss mitigation are basically being placed in the regions with higher potential. However, it is also clear that the magnitude of the water savings from the WMS recommended in the plan are small compared to the mitigation potentials. These WMS will not make much of a mitigation, and do not contribute substantially to the water needs in Texas. It should be added that the 2022 SWP calls for water loss-related WMS in the 2030 Decade to be about twice that of the 2020 Decade. Nonetheless, a doubling will be small compared to the mitigation potential.

The review also compared the WMS water loss to mitigation potential by Size Class. Figure 11 shows the SWP savings and additional, cumulative, potential water savings from more water loss mitigation. As with the regional perspective, the emphasis on water loss mitigation in the SWP is small.

5.2 Comparison of Water Loss Mitigation Potential to Municipal Water Needs

The second review compared the expected increase in municipal water needs to the water loss-related WMS in the 2022 SWP and to the observed water losses and the water loss mitigation potentials. Table 14 lists the municipal needs in the 2020 Decade by region. Regions C, D, G, H, L, M, and N all have municipal needs in excess of 10,000 AF/Year. The total increased municipal needs in the 2020 decade exceeds, 200,000 AF/Year.

The recommended water loss-related WMS in Regions E and K could provide sufficient water to meet municipal needs, but not in other regions. However, higher levels of water loss mitigation appear to meet these needs in many regions. The Good Performance water loss level could meet 100% of municipal needs in many regions, and the Very Good level appears to meet nearly all the municipal needs.

However, the numbers above must be seen carefully. For example, in Region H, the water savings potential for the Good Performance level is over 45,000 AF/Year, which is more than twice the municipal needs. But probably most of the water loss mitigation would be in Houston and could even exceed the municipal needs in Houston. But other towns and cities in Region H may have municipal needs that cannot be met by water loss mitigation.

6. CONCLUSIONS

This analysis has pioneered the use of an innovative methodology to estimate the total water losses in the state of Texas, and a range of potential mitigation of water losses, that could make a significant contribution to meeting future water supply needs in Texas.

More specifically, the study demonstrated that a combination of filtered water audits and Frontier Analysis can provide what appears to be a robust method for estimating the total water losses and the mitigation potential. The regression fit and graphical presentation of the FA results appear very plausible, and not subject to large scatter or bias in terms of scale or location. The FA analysis provides a range of mitigation potential from “Good Water Loss Performance to Very Good Performance”. A previous, published estimate of the economically recoverable water losses was found to be very close to the midpoint between Good and Very Good Performance. FA can be used despite some uncertainty in the water audits, largely because it indicates a range of mitigation rather than a narrow target. In addition, the FA method has low data requirements and can be performed rapidly.

The estimated statewide water losses are 572,000 AF/Year and the mitigation potential is within the range of 249,000 to 359,000 AF/Year. These results were reviewed in the context of the 2022 State Water Plan, which showed that increased efforts on water loss would be beneficial for water management in Texas.

This is a preliminary study and more work is needed on a variety of related topics, including 1) refining and validating water audits to improve the baseline data used in a FA and 2) conducting an FA on one or more regions in Texas to take a “closer look” at observed water loss levels and mitigation potentials which would facilitate better planning.

Table 14. Comparison of Municipal Needs to Water Loss Related WMS and to Water Loss Reduction Potential

Region	2020 Municipal Needs (af/yr)	Potential Water Savings from Water Loss Reduction as a Percent of Needs			
		Supply from Water Loss WMSs	Average	Good	Very Good
A	1.4K	>100% *(3.9k af/yr)*	>100% *(1.6k af/yr)*	>100% *(4.2k af/yr)*	>100% *(5.7k af/yr)*
B	263	0% *(0k af/yr)*	>100% *(426 af/yr)*	>100% *(1.8k af/yr)*	>100% *(2.6k af/yr)*
C	42.7K	68% *(29.1k af/yr)*	37% *(15.8k af/yr)*	>100% *(66.4k af/yr)*	>100% *(95.9k af/yr)*
D	17.5K	0% *(0k af/yr)*	38% *(6.7k af/yr)*	46% *(8.0k af/yr)*	67% *(11.8k af/yr)*
E	4.1K	>100% *(5.3k af/yr)*	67% *(2.7k af/yr)*	>100% *(7.1k af/yr)*	>100% *(10.5k af/yr)*
F	14K	2% *(330k af/yr)*	18% *(2.5k af/yr)*	54% *(7.6k af/yr)*	75% *(10.5k af/yr)*
G	31.1K	2% *(698k af/yr)*	13% *(4.2k af/yr)*	66% *(20.6k af/yr)*	97% *(30.3k af/yr)*
H	18.5K	32% *(5.9k af/yr)*	49% *(9.0k af/yr)*	>100% *(48.3k af/yr)*	>100% *(71.3k af/yr)*
I	501	>100% *(2.0k af/yr)*	>100% *(10.2k af/yr)*	>100% *(17.9k af/yr)*	>100% *(22.4k af/yr)*
J	5.1K	5% *(245 af/yr)*	15% *(785 af/yr)*	32% *(1.6 af/yr)*	41% *(2.1k af/yr)*
K	4.9K	>100% *(12.9k af/yr)*	>100% *(5.8k af/yr)*	>100% *(17.4k af/yr)*	>100% *(24.2k af/yr)*
L	24.5K	2% *(426 af/yr)*	33% *(8.0k af/yr)*	>100% *(29.2k af/yr)*	>100% *(41.6k af/yr)*
M	35.5K	5% *(1.6k af/yr)*	0% *(-1.5k af/yr)*	30% *(10.7k af/yr)*	50% *(17.8k af/yr)*
N	10.2K	0% *(0k af/yr)*	19% *(1.9 af/yr)*	48% *(4.9k af/yr)*	70% *(7.2k af/yr)*
O	4.3K	0% *(0k af/yr)*	0% *(-592k af/yr)*	61% *(2.7k af/yr)*	>100% *(4.5k af/yr)*
P	0	0% *(0k af/yr)*	>100% *(184 af/yr)*	>100% *(451 af/yr)*	>100% *(568 af/yr)*

REFERENCES

Akimov, A., P. Simshauser, (2018) Performance measurement in Australian water utilities: Current state and future directions, Griffith University, Griffith Business School, Mount Gravatt, Queensland, Australia

Blank JLT. Measuring the performance of local administrative public services. BRQ Business Research Quarterly. 2018;21(4):251-261. doi:10.1016/j.brq.2018.09.001

Depexe, M. (2021) Aplicação De Um Modelo Econômico Para Perdas De Água Distribuída Em Empresas De Saneamento, Presented at the Congresso Brasileiro de Engenharia Sanitaria e Ambiental, Curitiba Brasil, Octorber 2021

Estruch-Juan, E.; Cabrera, E., Jr.; Molinos-Senante, M.; Maziotis, A. (2020) "Are Frontier Efficiency Methods Adequate to Compare the Efficiency of Water Utilities for Regulatory Purposes?" Water 2020, 12, 1046. https://doi.org/10.3390/w12041046

Ferro, G., Lentini, E., Mercadier, A. Romeroa, C. Efficiency in Brazil's water and sanitation sector and its relationship with regional provision, property and the independence of operators, Utilities Policy 28(2014) 42-51. https://doi.org/10.1016/j.jup.2013.12.001

Filippini, M., N. Hrovatin & J. Zoric (2008). "Cost efficiency of Slovenian Water Distribution Utilities: An application of Stochastic Frontier Methods". Journal of Productivity Analysis. Vol. 29, No. 2, 169-182.

Kunkel, G (2017) Report on the evaluation of water audit data for Pennsylvania Water Utilities (Contract report prepared for Natural Resources Defense Council). New York: Natural Resources Defense Council;

Loftus, T. (2019) Economically Recoverable Water in Texas: An underappreciated Water Management Strategy?, Texas Water Journal, Vol10, No. 1 pages 60-74 July 19, 2019

Molinos-Senante, M.; Villegas, A. Maziotis, A. (2021) Measuring the marginal costs of mitigating water leakage: the case of water and sewerage utilities in Chile Environmental Science and Pollution Research, Published Online: 25 February 2021 https://doi.org/10.1007/s11356-021-13048-9

Pearson, D., Trow, S., 2012, Comparing Leakage Performance using the Frontier Approach, Proceedings of the IWA Water Loss Conference, Manila, Philippines

Sturm, R. Gasner, K. Andrews L., Water Audits in the United States: A Review of Water Losses and Data Validity, Water Research Foundation, 2015

Trachtman, G.B., J. Cooper, S. Sriboonlue, A. Wyatt, S. Davis, and G. Kunkel, (2019), Guidance on Implementing an Effective Water Loss Control Plan. Project 4695. Denver, CO, USA., The Water Research Foundation.

TWDB Texas Water Development Board. 2022. Water for Texas: 2022 State Water Plan. Austin (Texas): Texas Water Development Board;

WRc - Water Research Centre, plc (2008) Leakage Target Setting – A Frontier Approach – Final Report, prepared for OFWAT and the UK Environment Agency, WRc Report UC7733, Swindon, England

Wyatt, A.S. (2010). Non-revenue water: Financial Model for Optimal Management in Developing Countries. RTI International, Research Triangle Park, NC, RTI Press.

Wyatt, A., Jones, P., Pearson, D., Trow, S. (2015). Leakage Performance Assessment using Frontier Analysis: Application to Water Utilities in North America, Proc of the IWA Efficient Water Conference, OH, USA.

Wyatt, A.S., (2021). Tools for Water Loss Performance Assessment, Presented at the Segundo Seminário Internacional de Gestão de Perdas de Água e Eficiência Energética, ABES, Sao Paulo, Brasil (Virtual Presentation).

Wyatt, A.S., (2022). The Use of Frontier Analysis to Estimate the Water Loss Reduction Potential in Texas, Proceedings of the IWA Water Loss Specialists Group 2022 Conference, Prague, Czech Republic.

Appendix B:
The Cost of Water Loss Reduction: Recent Empirical Evidence

Alan Wyatt

1. INTRODUCTION

The benefits of water loss reduction differ considerably depending on the type of water loss involved. Table B-1 outlines the key benefits of reduction of real and apparent losses.

Water loss reduction activities vary greatly from one public water system to another, in terms of the potential reduction, and the time and cost to achieve that reduction. Key factors which influence the amount of reduction obtained from an activity and its cost effectiveness, include:

- **Scale of the water loss reduction program** — replacing 1000 meters will generally be more expensive on a per meter basis, or on a per gallon of apparent loss reduction basis, than replacing 10,000 meters or 100,000 meters.
- **The baseline level of water loss** — in general, water systems which are in poor condition and have high water loss can make substantial reductions at a faster rate and at a lower cost than water system in good condition can achieve.
- **The local context in terms of environmental, technical, and economic factors** — such as soil conditions, pipe installation practice, pipe material and age, pipe replacement rate, pressure and pressure variations, raw or finished water quality, water consumption, water meter installation practice, and water meter type and size, and finally the cost of skilled labor and materials, etc.

Table B-1. Benefits of Reduction of Components of Water Losses

Components	Benefits of Reduction
Apparent Loss	Better estimates of true water demand, leading to more accurate planning of future supply and demand.
	Increased utility revenue.
	Incentive for customers to reduce water consumption, reducing overall demand and also, to a small extent, decreasing apparent loss.
Real Loss	Reduction of amount of water resources needed to meet customer water demand.
	Reduction of the total variable cost of water production, including energy, water treatment chemicals and the cost of water purchases.
	The delay or cancellation of new water supply projects, which can lead to large capital savings.

- **The suitability of the water loss reduction strategy undertaken** — a strategy which is not focused on the mains sources or "root causes" of water loss will generally be less costs effective. A utility which collected and analyzed sufficient reliable data to select appropriate technologies / strategies, and instituted systematic, recognized, best practices.

Despite the multi-faceted variability of cost effectiveness of various water loss reduction and control strategies, this study collected and analyzed empirical data on the context, program inputs and outputs and the cost effectiveness of several common water loss reduction strategies. However, the scope and extent of the research was limited, in keeping with the depth and detail of a report of this type. A definitive, comprehensive study of the cost effectiveness would involve a large research and analysis effort. Nonetheless, the results presented here give reasonable approximations of the unit costs of various water loss reduction strategies. They can be compared to the cost of both "demand side" and "supply side" WMS, such as those in the State Water Plan.

2. WATER LOSS REDUCTION STRATEGIES

Table B-2 provides a full list of water loss reduction strategies – including both the Driver of loss (essentially the "problem" and the activities and strategies to mitigate the drivers.

The project gathered empirical information on the rate of reduction of water losses and cost per unit of reduction of water losses of the most common loss reduction strategies, including:

1. Advanced pressure management systems, which both reduce pressure and reduce diurnal pressure variations;
2. Acoustic leak detection and repair surveys of a distribution network to detect unreported leaks and repair them;
3. Testing, and when appropriate, replacement of large customer meters;
4. Small customer meter replacement programs,
5. Multi-year, multi-faceted, network-wide programs, usually involving significant replacement of network piping.

3. METHODOLOGY

Important methodological considerations for this data collection and analysis effort include:

- The tabulation of the water loss reduction only considered the "observed" reduction in water losses – not the observed reduction plus the "natural rise" in water losses that would have occurred over the period being analyzed.

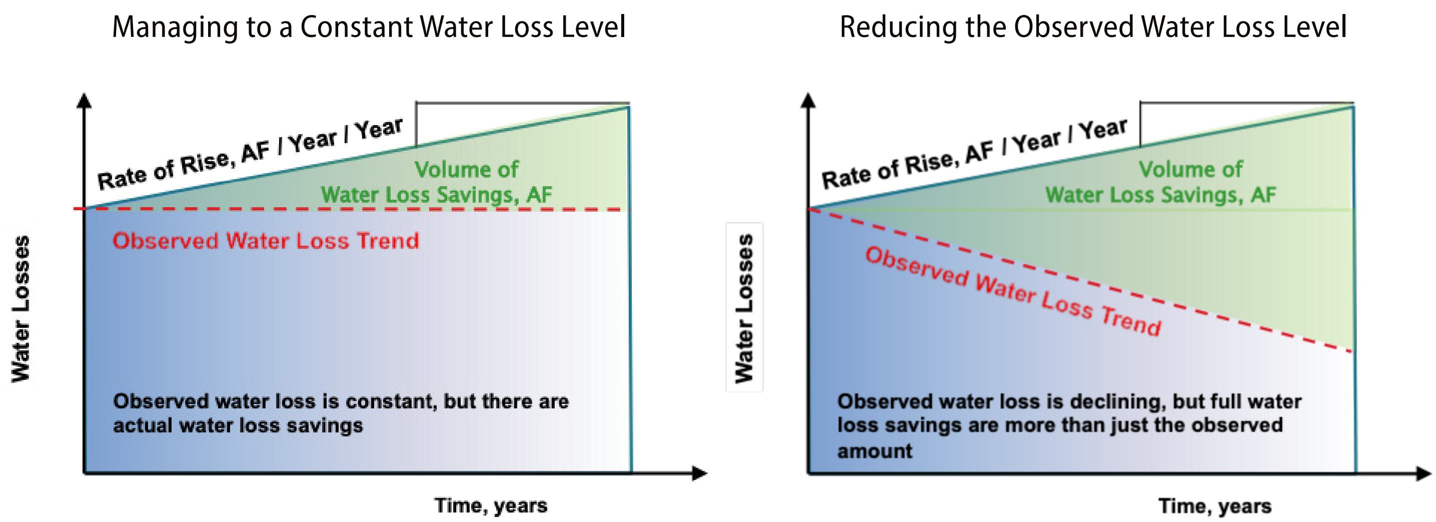
  The simplest explanation of the "natural rise" in water losses is to understand that water loss increases naturally, as water supply infrastructure ages. The condition of pipes deteriorates over time, leading to higher losses, and water meters lose accuracy over time, also increasing water losses. Therefore, a water utility which works on water loss reduction (or control) and maintains its total water losses at a constant observed amount has only eliminated newly appearing "natural" rate of rise (as shown in the figure on the left). A utility which decreases the observed level of losses has "saved" more losses than the observed change – it has also eliminated the natural rise.

  Including the natural rise gives the most accurate assessment of cost effectiveness of an activity, but its

Table B-2. Water Loss Components, Drivers and Mitigation Strategies / Activities

	Component	Drivers	Water Saving Activities
Apparent Losses	Losses from meter under-registration	• Meter error from age and high water volume throughput	• Customer meter testing • New, consistent, high accuracy meters
		• Low flow error	• Correct meter sizing
	Losses from data transfer, handling & billing error	• Meter reading error • Faulty data transfer to billing system • Out-of-date customer records • Billing system errors • Unauthorized consumption hard to find	• AMR/AMI meter reading & data transfer systems • Advanced customer management & billing database / system • Periodic database scrutiny • Surveillance & enforcement at points of interest
	Losses from unauthorized consumption		
Real Losses	Reported Losses	• Long runtimes on unreported leaks • Slow repair response on reported and unreported leaks • Excessive and variable pressure • Storage tank overflows • Corrosion • Pipe, appurtenances and service connections beyond useful life	• Improved speed and quality of repairs • Leak detection & repair on all assets • District Metered Areas • Network sensor / monitoring systems • Advanced pressure management • Corrosion control • Pipe, appurtenance & connection replacement
	Unreported Losses		
	Background Losses		

Figure B-1. Tabulation of Water Loss Reduction



inclusion in the calculation is highly complex because the natural rise is very site specific and difficult to estimate. For this report the "natural rise" was not included in the calculations due to the additional complexity and to be consistent with the State Water Plan which determines loss reduction based on the observed level of water losses at different time periods.

- While many "anecdotal" cost effectiveness data are available in the literature, but many sources do not provide the contextual information (infrastructure condition, pressure, water consumption etc) that is necessary to compile data for trend analysis, to avoid comparing "apples and oranges". Therefore, only cases where the necessary contextual information, reduction information and cost information were available in a logical, consistent and comprehensive manner were used in the study.

- Some water loss reduction strategies have costs which are so site specific that it is close to impossible to develop a cost-effectiveness guideline. For example, the costs of District Metered Areas (DMAs) are very site specific, depending greatly on the configuration of the pipe network. In some utilities in Tennessee (such as WWAWC in Chapter 5) the cost of establishing DMAs was very low - a chamber, inlet meter and often a pressure reducing valve and controller. In many other utilities major network reconfiguration would be needed, so the cost, including mains replacement, would be high. So, a general cost effectiveness trend (in $/AF) or trend based on one or two context parameters is essentially impossible to determine. For these reasons the cost effectiveness of DMAs was not analyzed or presented in this report, despite the fact that they can be among the most cost effectiveness water loss reduction interventions available, in many cases. The Case Study in Chapter 5 on Water and Wastewater Authority od Wilson County (WWAWC) in Tennessee has ample information on DMAs.

- There are also new leak detection technologies including satellite leak detection, and systems using acoustic, pressure or temperature sensors spread throughout the network, with real time monitoring. Unfortunately, complete data on more than just a few such systems could be found, so these technologies were not analyzed, despite growing interest in these innovations.

- Many water loss reduction efforts involve a mix of CAPEX and OPEX, some over a short period, some over a longer one. Activities such as acoustic leak detection are conducted on an annual basis, usually funded from the utility Operating Budget, while other activities such as a program of full scale replacement of customer meters would typically funded through the utility Capital Budget, or a Bond issue or Loan. Therefore, in this analysis, with the exception of acoustic leak detection, the CAPEX costs of implementing a program were added up and converted into an annualized cost ($ / year), using the capital recovery factor (at 3% over 5, 10 or 20 years depending on the useful life of the equipment). That annualized cost ($/Year) was then divided by the average annual observed water loss savings (AF/Year), to arrive at a figure for cost effectiveness ($/AF).

- Program costs from different years are brought to a standard 2020 $US basis using US CPI-U tables.

4. ADVANCED PRESSURE MANAGEMENT

Advanced pressure management is and approach to reduce pressure, but more than that to "manage" pressure to reduce daily pressure variations and "calm the pipe network. This approach will reduce leakage by reducing break frequency and the flow rate of breaks. Ian addition advanced PM will extend pipe asset life, delay pipe replacements, reduce customer water consumption. While there have been concerns about sufficient pressure for fire flows, this concern can be addressed through bypass valves and proper PM system design.

There are several types of pressure management approaches as shown in Table B-3. The first item in the Table, the "fixed outlet" PRV is actually ordinary pressure reduction, and is not really advanced pressure management. The following three approaches involve the addition of sensors and controllers to adjust pressure based on time of day, water demand, or to keep the minimum pressure at a desired level.

The paragraphs below provide field data on the real loss reduction and the cost per AF of real loss reduction from a dozen Advanced PM installations in British Columbia, California, Georgia, North Carolina, Nova Scotia, Ontario, Quebec, and Tennessee. A sample PRV is shown in Figure B-2.

Figure B-2. Sample Pressure Reducing Valve (PRV)

Table B-3. Types of Basic and Advanced Pressure Management

Form of Pressure Control	Description	Cost	Water Loss Reduction Efficiency	Complexity to Maintain and Operate
Fixed Outlet Pressure	Basic PRV	Lower	Lower	Lower
Time Modulated	PRV outlet pressure varied according to time	Moderate	Moderate	Moderate
Flow Modulated	PRV outlet pressure varied according to in zone demand	Higher	Higher	Higher
Remote Node Pressure Control	PRV outlet pressure varied according to monitored pressure in the zone	Higher	Higher	Higher

Figure B-3.
Adv Pressure Management: Total Cost

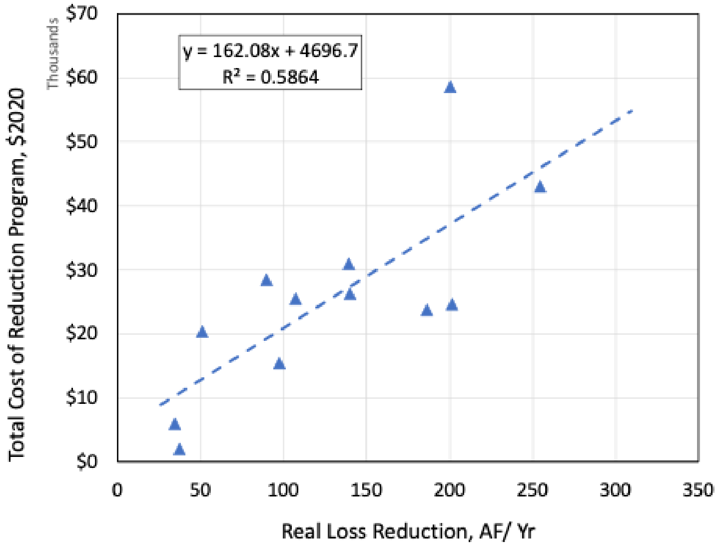
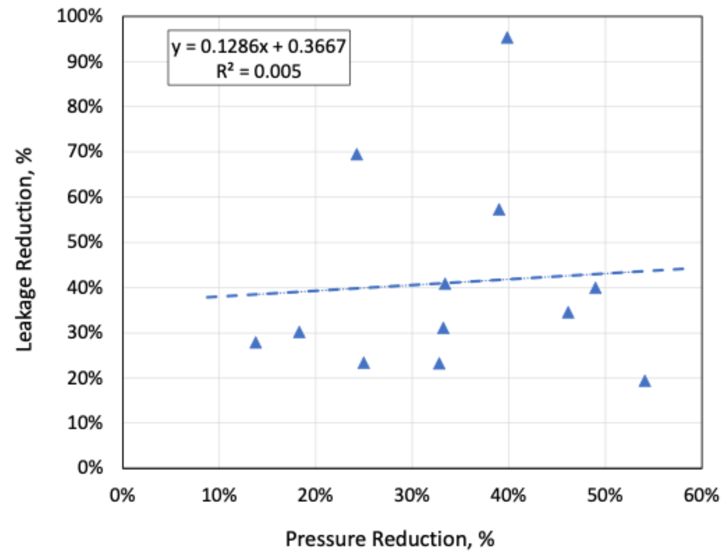


Figure B-4.
Adv Pressure Management: Leakage & Pressure



The installations managed pressure in small zones or DMAs with 500 to 8,000 connections, creating pressure reductions ranging from 14% to 54%, with an average of 33%, resulting in leakage reductions ranging from 19% to 95%, and also an average of 33%. Generally, the change in leakage depends on the change in pressure with the ratio of the change depending the pipe material.

Figure B-3 shows the Total Cost of installations in relation to the AF/Year of real loss reduction – with a fairly clear trend. Installations which produce more reduction, cost more Figure B-4 shows the impact of pressure change on leakage. There is a wide scatter which can be attributed to pipe material and other local conditions.

A look at unit costs of reduction ($/AF) show considerable scatter due to the different conditions in the different places, but there are some rough trends. Figure B-5 shows a roughly flat trend of unit cost at approximately 200 $/AF. Figure B-6 shows that installations with higher pressure reduction have a lower unit cost of leakage reduction.

Figure B-5.
Adv Pressure Management: Unit Cost

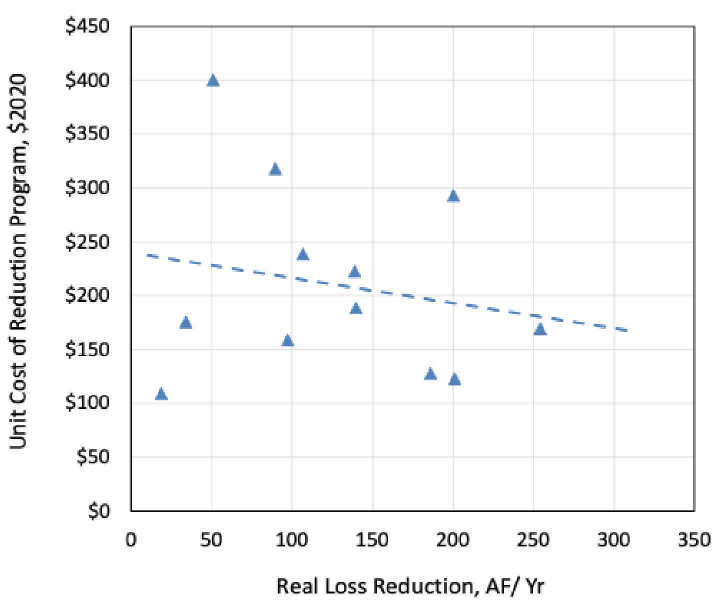
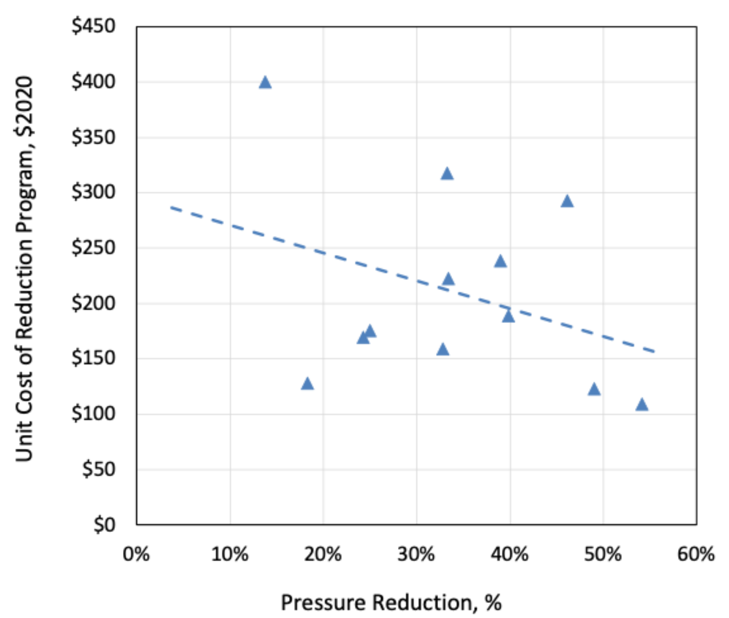


Figure B-6.
Adv Pressure Management: Leakage & Pressure



Overall, the range of unit costs for advanced pressure management is from $109/AF to $400/AF with the lower quartile at $151/AF, the median at $182/AF an upper quartile at $252/AF. It should also be emphasized that while pressure management can have significant effect on leakage it also reduces pipe break rates and extends the useful life of distribution hardware, and can even reduce water consumption.

5. ACOUSTIC LEAK DETECTION AND REPAIR

Acoustic leak detection and repair surveys have been the main strategy, for over 100 years, for finding and fixing unreported leaks - those which remain hidden underground. The technology has changed from simple iron rods used as listening sticks, to ground microphones and leak correlators which use sound waves to pinpoint leaks. Figure B-7 shows a modern leak detection crew at work in Texas.

The analysis of the efficiency and cost effectiveness of active acoustic leak detection and repair is somewhat complex due to the many contextual parameters, and many input and output variables. Therefore, the framework in Figure B-8 was adopted to ensure accuracy and consistency of the analysis and results.

Figure B-7. B.J. Baugus uses an Aqua-Scope leak detector to help pinpoint a leak in the Wilson County water system. Photo: Peter Kenter, *Municipal Sewer & Water*

Figure B-8. Annual Leak Detection and Repair Survey Analysis Framework

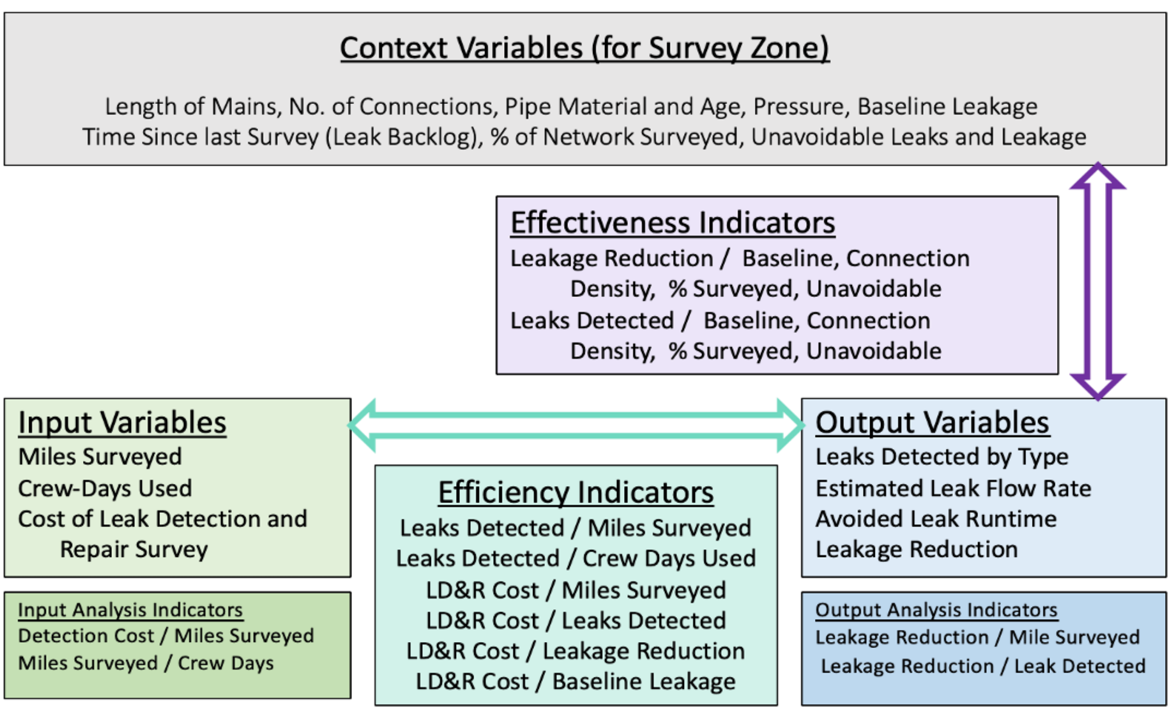


Table B-4. Contextual Information, Inputs and Summary Results of Leak Detection and Repair Surveys in Three US Cities

Average Annual Parameter Value	City A	City B	City C
Survey Years	2002-2013	FY02-FY16	FY11-FY16
LD&R Implementor	In-house staff	Contractor	Contractor
Connections (1000)	530	175	218
Total Miles in Network	3133	2880	3720
Connection Density	165	61	58
Average Operating Pressure, psi	58	84	77
Infrastructure Leakage Index	10.5	5.8	3.0
Baseline Leakage, AF / Mile/ Year	23	8.4	3.7
Average Pipe Age, Years	70-85years	65% > 40years	30-50years
Principal Pipe Material(s)	CI	DI	DI, CI, PVC
Miles Surveyed / Year	1134	1764	600
Crew Days / Year	753	NA	NA
Miles Surveyed / Crew Day	1.5	NA	NA
% of Network Surveyed / Year	36%	61%	18%
Breaks and Leaks Detected / Year	181	216	154
Breaks & Leaks / Crew Day	0.24	NA	NA
Breaks & Leaks / 100 Miles Surveyed	16	12	27
Mains Breaks / 100 Miles Surveyed	3.0	3.2	2.0
Mains Breaks / UARL Break Frequency	3.0	3.2	2.0
Connection Leaks / 1000 Connections	0.8	1.3	4.8
Connection Leaks / UARL Leak Freq.	1.0	1.7	6.4
Leakage Saved, AF / Year	7,276	5,425	2,345
Leakage Saved, AF / Mile Surveyed / Year	6.4	2.0	3.6
Leak Detection Cost / Mile Surveyed	$415	$365	$307
Repair Cost / Mile Surveyed	$78	$120	$378
Total LD&R Cost / Mile Surveyed	$493	$485	$686
Leak Detection Cost / AF Saved	$78	$194	$105
Repair Cost / AF Saved	$13	$71	$125
Total LD&R Cost / AF Saved	$91	$266	$230
Leak Detection Cost / Leak	$3745	$3940	$1,504
Unit Cost of Repairs	$340	$147	$1200

In brief, the relationship between outputs and inputs would seem to be quite straight-forward – for example – the more miles surveyed, the more leaks found. While that is generally true, contextual variables influence the outputs produced for a given set of inputs. For example, if it has been a long time since a zone was last surveyed, there will be a "backlog" of leaks and more leaks will be detected per mile surveyed. Since the inputs are related to costs and the outputs related to water loss reduction, contextual variables will influence the cost effectiveness of acoustic leak detection and repair, producing a wide range of unit costs per AF saved.

Table B-4 presents a summary of the data and results of an analysis of the cost effectiveness of acoustic active leakage detection and repair programs in three large

US cities, where ample, high-quality, year-on- year data could be obtained. The table includes context variables, input and output variables as well as efficiency and effectiveness variables, in keeping with the framework outlined above.

The programs consisted of annual surveys of portions of a network ranging from surveys of 10% of the network to annual surveys of the entire network. Program data collected includes the miles of pipe surveyed, leaks found, leak flow, annual water savings, the leak detection cost and the leak repair cost. This leakage reduction activity is very similar to that described in the case study on Nashville, Tennessee.

A few examples of results in the table above provide some understanding of the multi-faceted way in which context influences both efficiency and cost effectiveness. City C has relatively low baseline leakage, high pressure, "younger" mains pipes, and less frequent surveys. This combination of factors leads to a higher number of breaks per mile surveyed, and relatively fewer mains leaks, and relatively high leaks on connections. Given the dominance of connection leaks, the AF saved per year is relatively low. But the repair costs in City C are high, so in the end the total cost per mile is higher. Given all these various consideration, the unit cost of the surveys is relatively high. In contrast, City A has relatively high baseline leakage, low pressure, older mains pipes, and more frequent surveys. The leaks per mile is lower, but the mains leaks are high and connections leaks low. In the end, the leakage saved is high, the cost per mile of surveys is moderate, and the unit cost is lower. This complexity can be "boiled down" to the simplified classification below.:

1. surveys with a low number of miles surveyed in very leaky areas,
2. surveys with a high number of miles surveyed, in less leaky areas, and
3. cases in between.

Situation 1 above will have lower detection costs because less miles would be "walked", but a higher repair costs because more leaks are found. Situation 2 is the opposite — higher detection cost and lower repair costs. Yet, as shown below Unit cost values tend to form a relatively consistent curve.

Figure B-9. Unit Cost of Annual Leak Detection & Repair Surveys, $2020 per AF saved

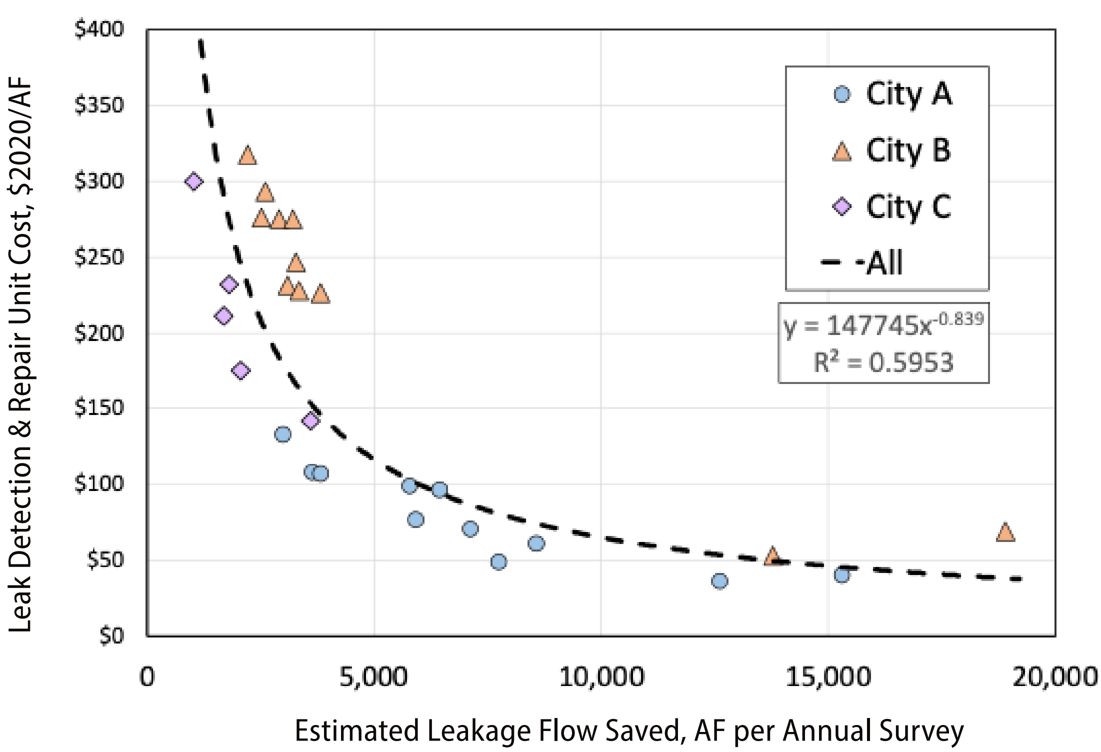


Figure B-10. Unit Cost of Annual Surveys, $2020 per AF saved (per mile surveyed)

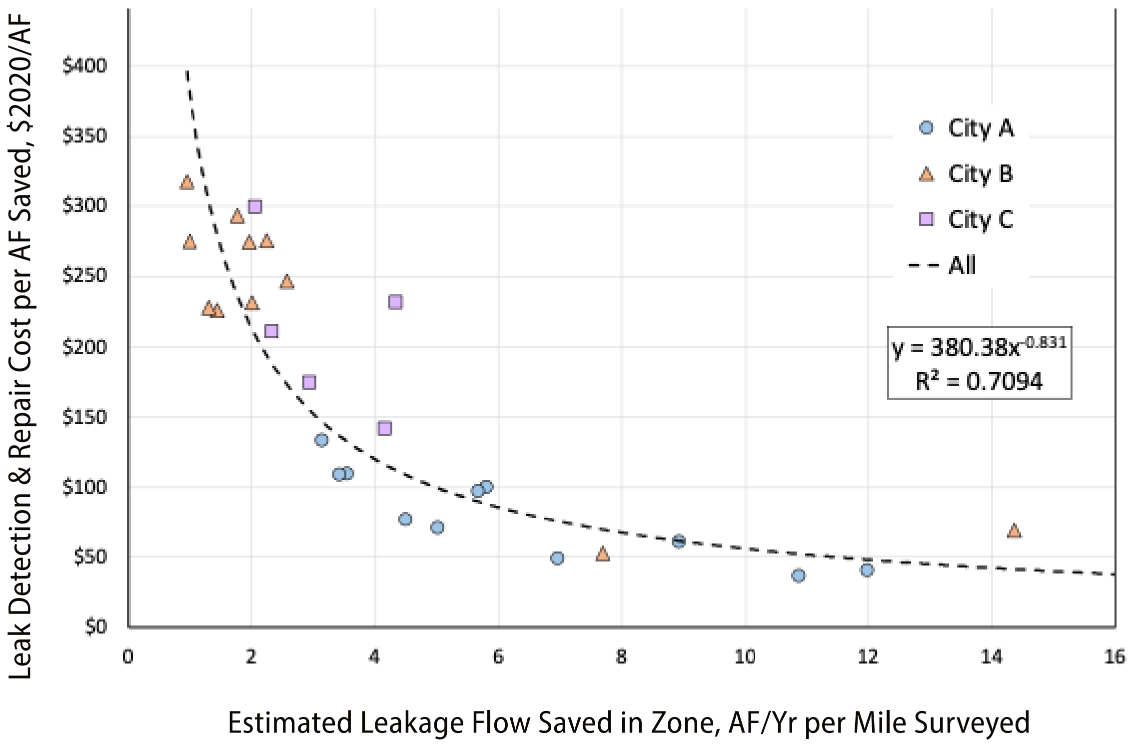


Figure B-11. Unit Cost of Annual Surveys vs Baseline, $2020 per AF saved

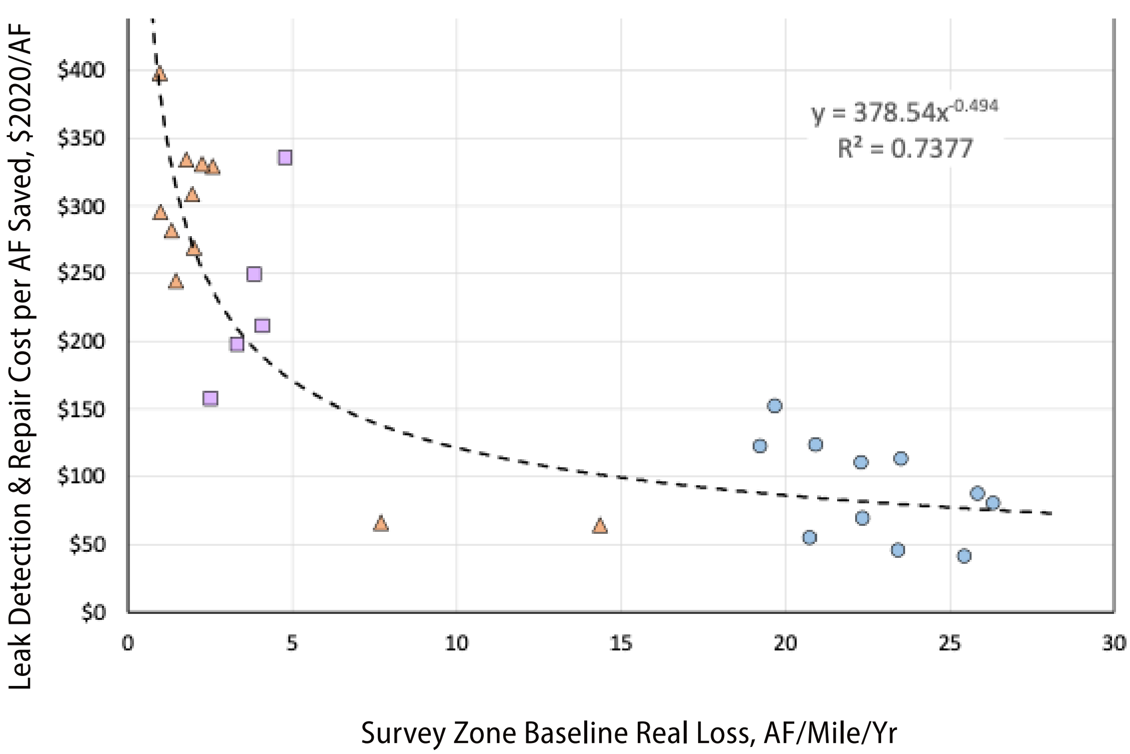


Figure B-9 shows the unit cost in $2020 per AF. First, it can be immediately seen that the data points for different surveys in different places (with different leakage levels) fall on a noticeable, clear curve.

It can also be seen that a program which saves a small amount of water in a year will have a relatively high unit cost. But a larger program will have a much lower unit cost. The curve shape represents a classic example of "economies of scale."

Figures B-10 and B-11 show similar unit costs curves, but in relation to leakage savings per mile, and in relation to the baseline leakage. Once again, the points tend to form a consistent curve. Despite the complex influences of different factors, the unit cost of leak detection and repair surveys tend to fall on useful curve. More research would be useful to "test" this finding.

Overall, the range of unit costs is from $36/AF to $317/AF with the lower quartile at $73/AF the median at $142/AF an upper quartile at $239/AF.

6. REPLACEMENT PROGRAMS FOR SMALL CUSTOMER WATER METERS

One of the most common water loss reduction strategies is the replacement of small customer meters, often 5/8 inch or ¾ inch. These meters under-register over time and or with accumulating water "throughput".

The data analysed here is derived from water loss reduction and control cost data from the USEPA Green Reserve Project data (2012), and data in the Water Research Foundation Project 4695 Report (Trachtman et al, 2019.) Adjustments were made to provide estimates in $US 2020. The EPA Green Reserve Project provides grants to small and medium size utilities, for various water projects, including small (residential) meter replacement programs. These data are for replacement of manually read meters to AMR meter, which have an electronic, Radio" transmitter which can be read by personnel in a passing truck. These are not as sophisticated or costly as meters used in AMI infrastructure.

Costs include including the meters themselves, installation and any procurement or administrative costs.

Figure B-12. One of the most common water loss reduction strategies in the replacement of small customer meters, often 5/8 inch or ¾ inch. An AMR meter is pictured above.

The programs ranged from 100,000 meters down to 1000 meters, in the States of Georgia, New York, North Carolina, Oklahoma, Pennsylvania, and Tennessee. The overall set of programs included close to 425,000 meters and a cost very close to $90 million (2012 data). The water loss reduction was estimated assuming the new meters were replacing old manually read meters (20 years or more) incurring an under-registration of 15%.

Figure B-13 shows the total cost of each program in relation to the number of meters provided. The programs ranged in cost from about $17 million down to about $400,000 in $2020. The exponent of the cost curve (0.8265) indicates there is moderate economies of scale.

Figures B-14 to B-16 show the unit costs of the meters, with a range of unit cost of about $350 down to a unit cost of about $140, which also indicates economies of scale, which can be attributed to be attributed to some fixed costs in administrative and procurement functions as well as the benefits of bulk purchases.

The range of unit cost in $/ AF of savings is from $186/AF to $538/AF, with the lower quartile at $326/AF, median at $382/AF an upper quartile at $455/AF.

Figure B-13. Total Cost - Small (AMR) Meter Replacement Programs

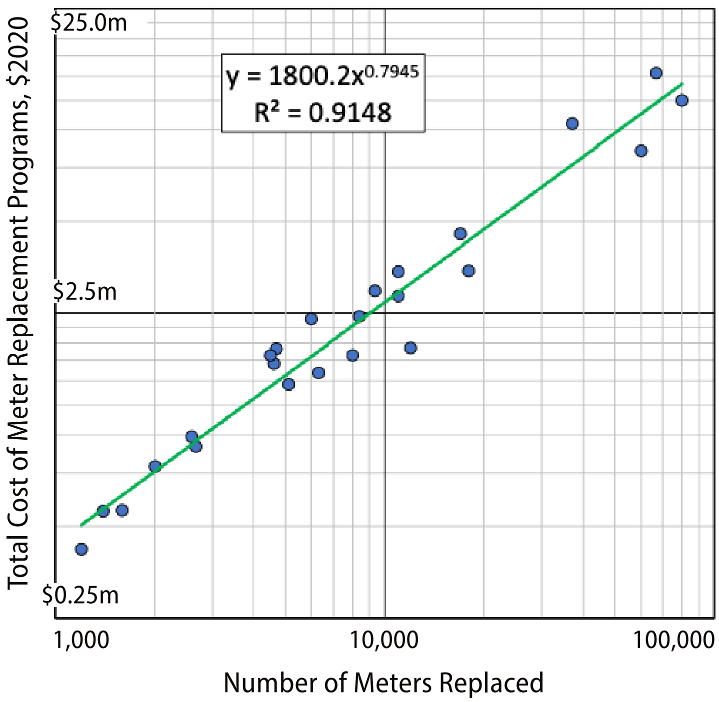


Figure B-14. Unit Cost - Small (AMR) Meter Replacement Programs

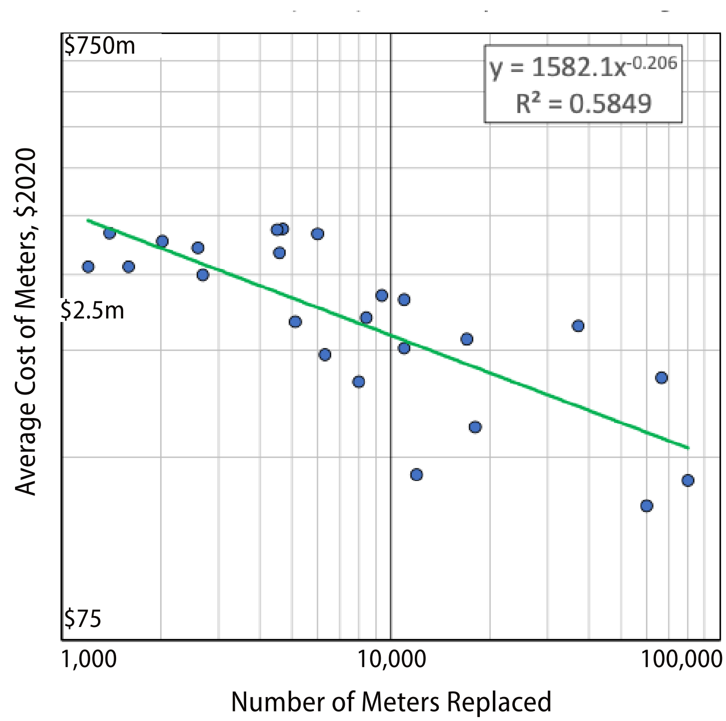


Figure B-15. Unit Cost Water Savings from Small (AMR) Meter Replacement, $/AF

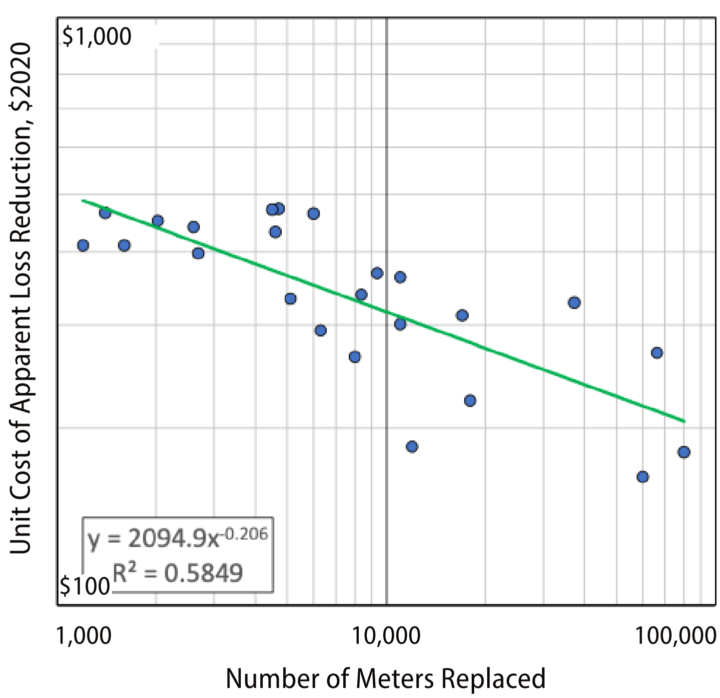
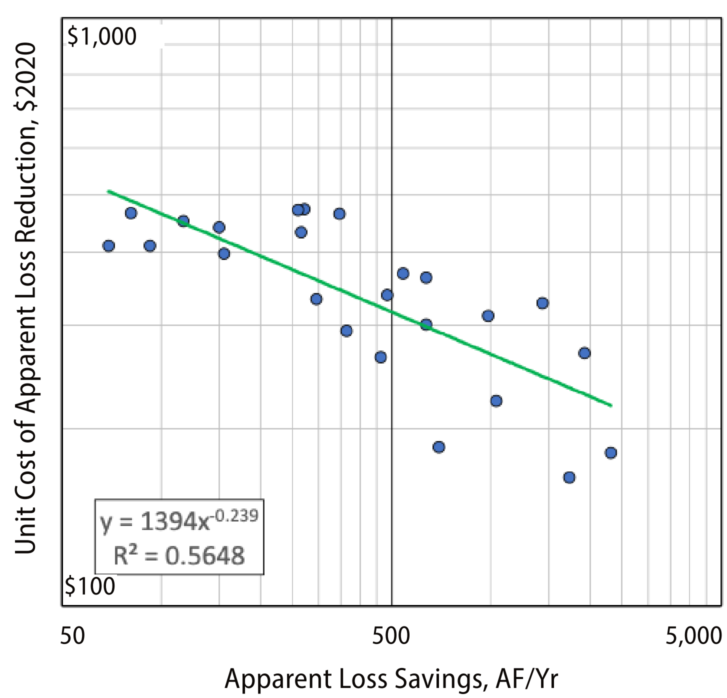


Figure B-16. Unit Cost Water Savings from Small (AMR) Meter Replacement, $/AF



7. REPLACEMENT OF LARGE CUSTOMER WATER METERS

The testing, and where appropriate, replacement of large customer meters is an important water loss reduction control strategy. The large water flow and overall consumption, often combined with higher rates for large users, means that even a small meter under-registration will lead to a cost-effective water loss reduction strategy. Figure B-17 provides pictures of a typical 3 inch meter and a typical 6 inch meter.

Figure B-17. A typical three-inch and six-inch meter.

Data was assembled on fifteen large meter replacement programs in ten US cities in California, Georgia, Indiana, Kentucky, New York, North Carolina, Pennsylvania, and Texas including meter test results, apparent loss saved, and program cost. Meter sizes ranged from 1.5 inch to 8 inch, but most were 3 inch or 6 inch meters. For a consistency, programs were scaled to replacement of 100 large meters

Figure B-18provides results on the total cost of the programs in relation to the total apparent loss reduction, in AF/ Year and Figure B-19 provides the unit cost of apparent loss reduction ($/AF) in relation to the total apparent loss savings. Both graphs exhibit very strong economies of scale, which can be explained by consideration of two factors. The cost of the program for a given size meter will be roughly constant (at 100 meter scale), but higher consumption or higher meter error will lead to more loss reduction and lower unit cost of water loss reduction.

Figure B-18. Total Cost Large Meter Replacement (100 meters)

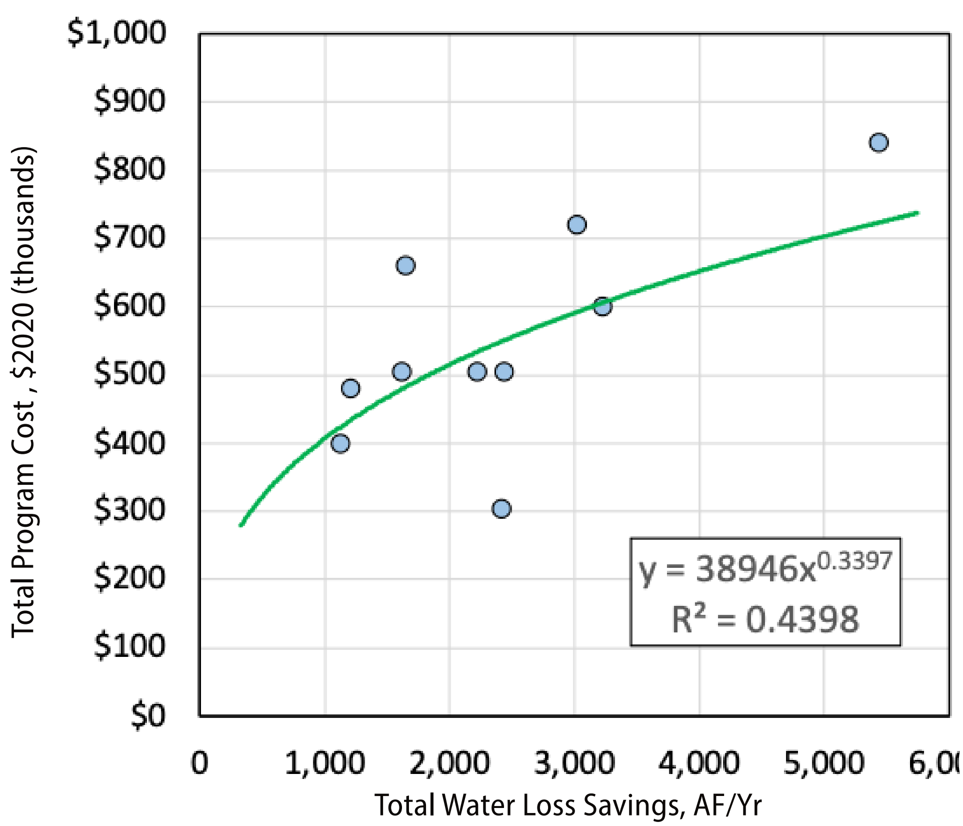
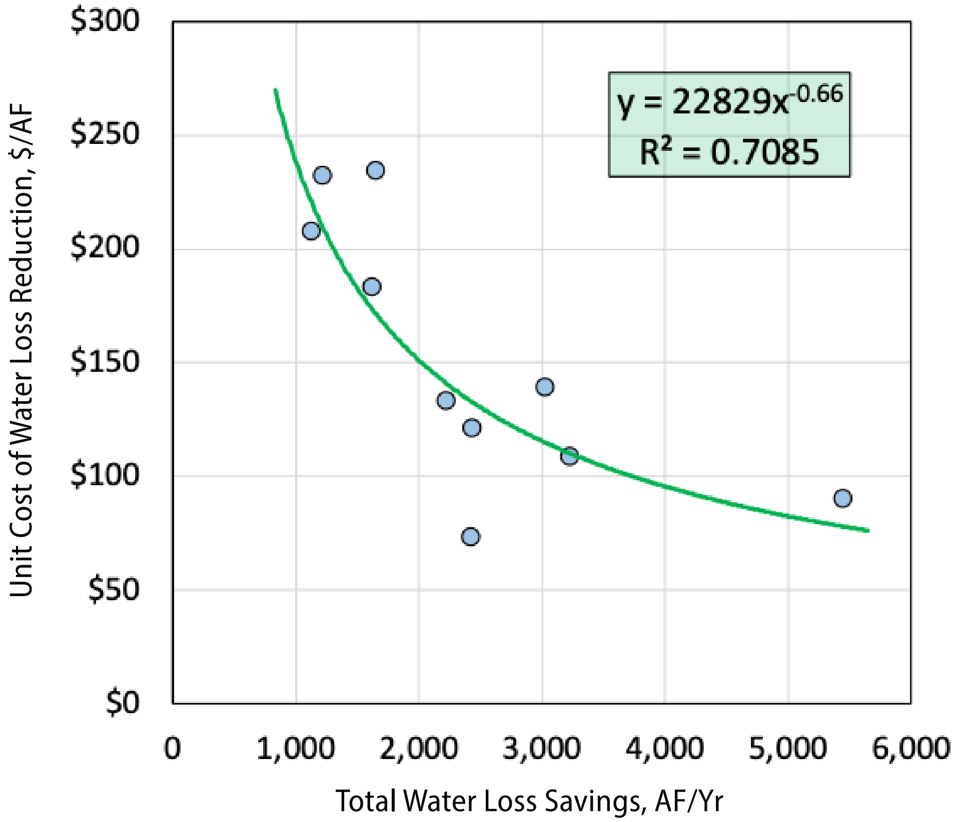


Figure B-19. Unit Cost of Water Loss Reduction



The range of unit cost in $/ AF of savings is from $73/AF to $235/AF, with the lower quartile at $112/AF, median at $136/AF an upper quartile at $2020/AF. Large meter testing and replacement is generally regarded as usually the most cost-effective water loss reduction activity, and the results shown here confirm that understanding.

8. LARGE SCALE MULTI-YEAR WATER LOSS REDUCTION PROGRAMS

These projects represent major muti-year projects which combine the practices listed above as well as replacement of mains and service connections, which adds considerably to the cost. They can be thought of as an "overhaul" of the distribution system (including metering,), which are required when the infrastructure has not been maintained and water losses have been left to run and run, rising all the while. While a larger project can benefit from economies of scale, the need for pipe replacement and in some cases rearrangement / sectorization of the piping network will "counteract" the economies of scale effect to some extent.

Data was assembled on 21 projects in British Columbia, California, Georgia, Ontario, Pennsylvania, North Carolina, and Tennessee. The data set also included one project from the Bahamas, one from Belize and one from Jamaica. Given their use of US hardware and international consultants, these projects were viewed as similar to projects in the US or Canada.

The duration of the projects ranged from 2 years to 11 years with a total cost from $500,000 to $50 Million. This rather broad range can be attributed to the very broad range of size of the project locations – from about 3,500 to 450,000 connections.

Given the multi-year nature of the projects, the Annualized Capital Cost (using the capital recovery factor) and the reduction of Water Losses on AF/ Year per year of the Project were used as the main analysis variable. Figure B-20 provides the annual cost in relation to the average water loss reduction per year. The curve (on log scales) shows a clear trend, but rather low economies of scale (exponent at about 0.9).

Figure B-20. Annual Cost of Large Multi-Year Projects

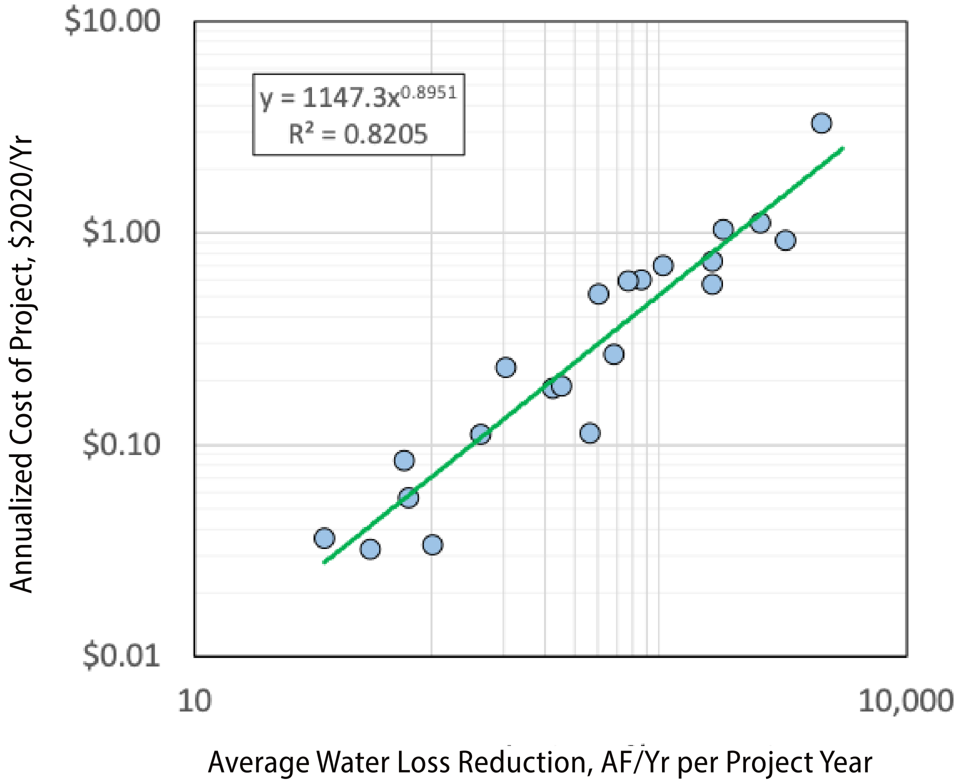


Figure B-21. Unit Cost of Water Savings vs Average Water Loss Reduction

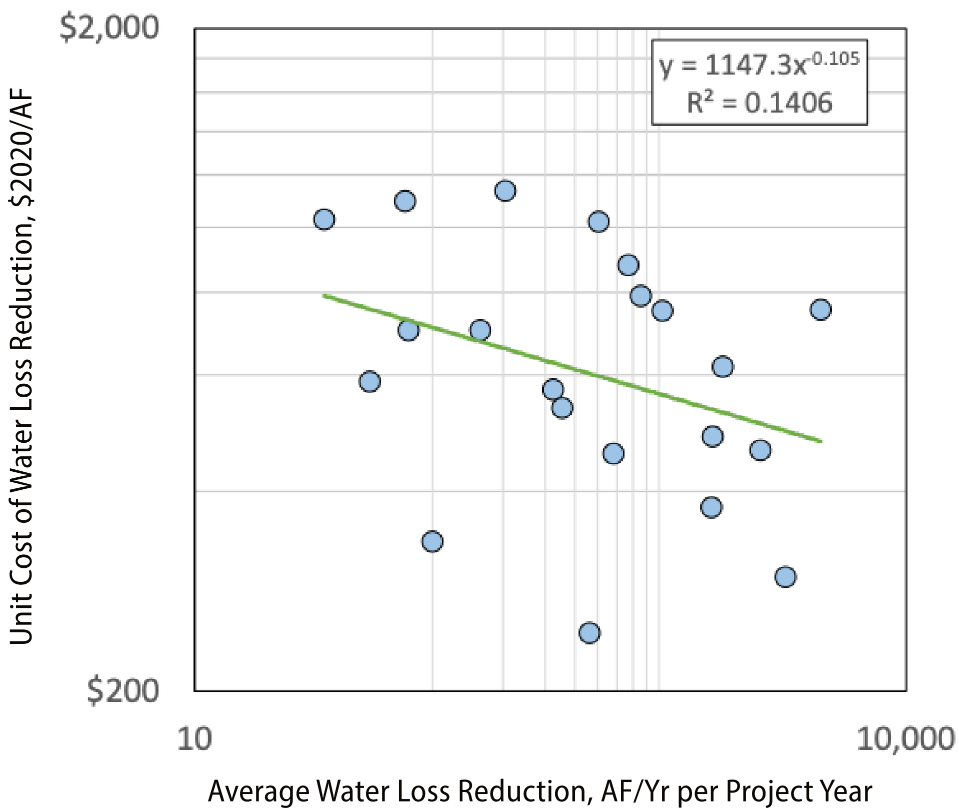


Figure B-22. Unit Cost of Water Savings vs Total Water Loss Reduction

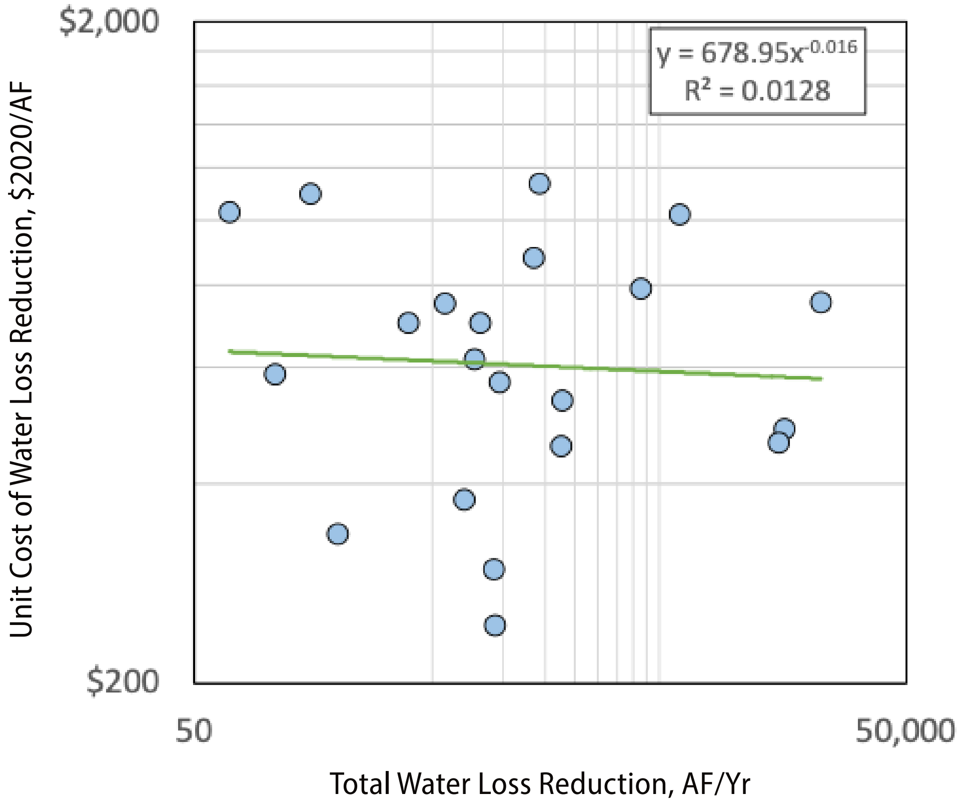


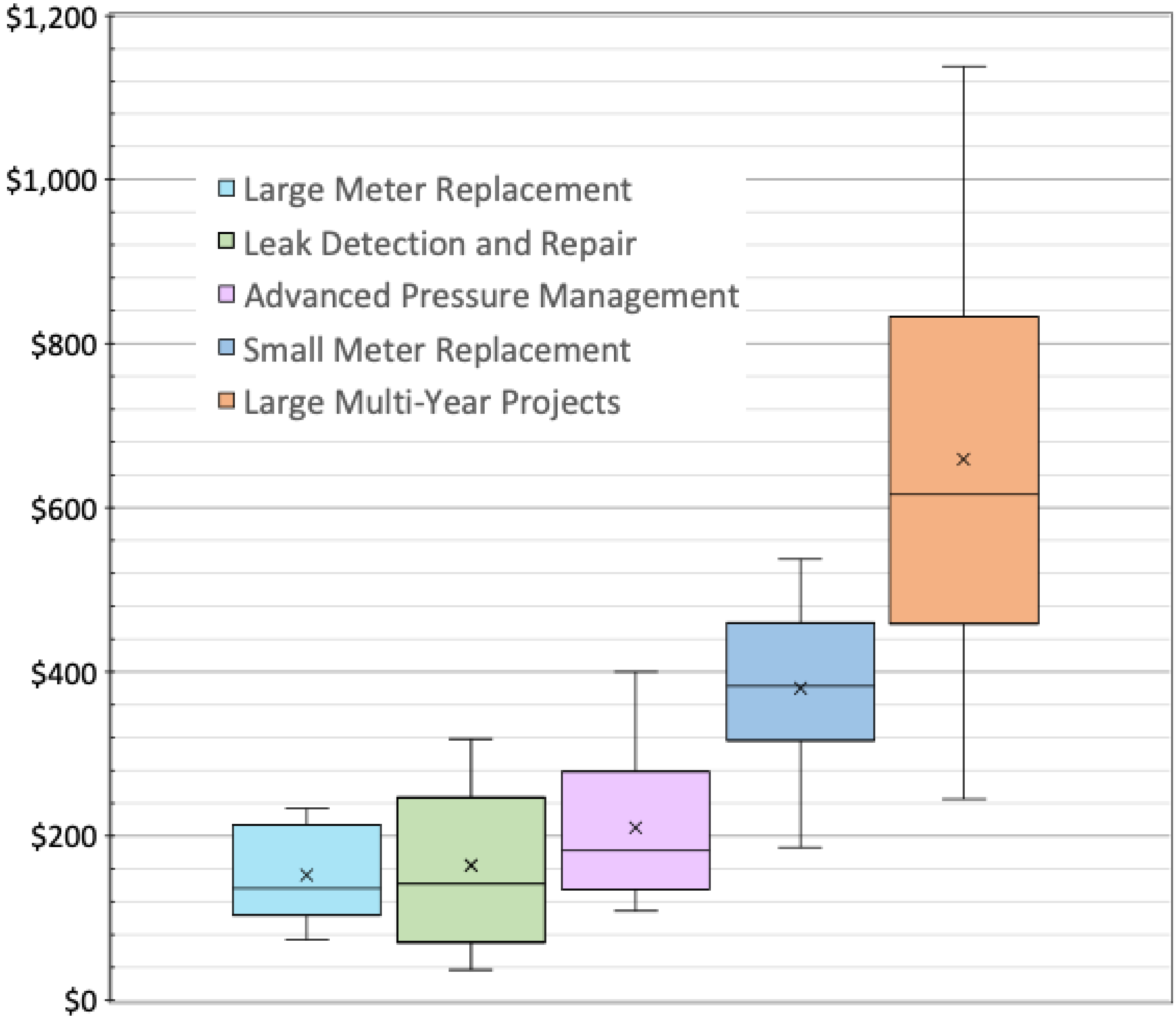
Figure B-21 provides the unit cost of water loss reduction ($/AF) in relation to average water loss reduction per year. The curve (on log scales) shows a general trend (reflecting some economies of scale), but significant scatter. Figure B-22 provides the unit cost of water loss reduction ($/AF) in relation to total water loss reduction (AF/Yr) over the course of the project. The curve (on log scales) shows a general trend but significant scatter. The "flat" trend is interesting, despite the scatter.

The range of Unit Cost in $/ AF of savings is from $245/AF to $1138/AF, with the lower quartile at $468/AF, median at $616/AF an upper quartile at $789/AF.

9. SYNTHESIS OF DATA ANALYZED IN THIS REPORT

Figure B-23 provides a summary of the unit costs of water loss reduction, in $2020 / AF, in the form of a Box and Whisker chart. The diagram shows the average, median, upper quartile and lower quartile of cost for each water loss related WMS.

Figure B-23. Unit Costs of Water Loss Reduction Strategies, $/AF



Unit Costs, $ / AF (2020)	Large Meter Replacement	Leak Detection and Repair	Advanced Pressure Management	Small Meter Replacement	Large Multi-Year Projects
Min	$73	$36	$109	$186	$245
10th	$89	$51	$123	$274	$336
25th	$112	$73	$151	$326	$468
50th	$136	$142	$182	$382	$616
Average	$153	$164	$210	$380	$659
75th	$202	$239	$252	$455	$789
90th	$233	$283	$315	$472	$1,031
Max	$235	$317	$400	$538	$1,138

Table 7-6. Statewide weight-averaged unit costs (dollars per acre-foot)* of strategy water supplies by strategy type 2020–2070

Water management strategy type	2020	2030	2040	2050	2060	2070
Agricultural conservation	$284	$273	$202	$188	$186	$181
Aquifer storage & recovery	$437	$666	$904	$609	$509	$664
Conjunctive use	$1,724	$1,729	$1,986	$1,147	$903	$814
Direct potable reuse	$1,321	$1,456	$1,402	$1,587	$1,590	$1,504
Drought management**	$70	$119	$168	$168	$169	$169
Groundwater desalination	$920	$1,618	$1,430	$899	$994	$1,080
Groundwater wells & other	$599	$659	$592	$523	$439	$402
Indirect reuse	$391	$697	$541	$391	$266	$297
Industrial conservation	$680	$597	$513	$339	$311	$292
Municipal conservation	$675	$607	$503	$498	$519	$515
New major reservoir	$114	$598	$818	$678	$521	$511
Other direct reuse	$962	$892	$865	$483	$559	$630
Other strategies	$10	$2,128	$2,016	$1,073	$1,055	$1,066
Other surface water	$744	$1,037	$986	$581	$550	$523
Seawater desalination	na	$2,402	$2,394	$1,440	$1,383	$1,371

** Unit costs include a mixture of projects, some of which will be beyond their debt service period by 2070.*

*** Unit costs for drought management strategies represent possible costs to municipal water users from foregone consumer surplus of imposed reduced water use rather than capital expended to produce water supply.*

na = not applicable or not available.

Source: "Water for Texas," 2022 State Water Plan, Texas Water Development Board.

10. REVIEW OF COST EFFECTIVENESS DATA IN THE TWDB 2022 STATE WATER PLAN

The results of the compilation of the unit costs of water loss reduction were compared to Water Management Strategies (WMS) in the 2022 State water Plan, including comparisons to "Supply Side" WMS and to "Demand Side" WMC, such as conservation. The unit costs for the full range are provided in Table 7-6 of the SWP. We compared the unit costs complied above to the unit costs in Table 7-6 for the 2020 Decade. Many of the unit costs are considerably higher than the unit costs of water loss reduction.

To make a more thorough comparison, we located data in the SWP on the volume of Recommended Projects for each WMS in the 2020 Decade (Table 7-3). With those volumes and the corresponding unit cost we computed a weighted average of the cost of Supply Side WMS and Demand Side WMS.

The results from Table B-5 show that the Supply Side WMS have a weighted average of $695 / AF, and the Demand Side WMS have a weighted average of $406 / AF (in $2020). However, in most urban areas where water losses are highest, the potential for agricultural conservation is low, such that the cost of Municipal and Industrial Conservation is $675 / AF. The Water Loss Related WMS have much lower unit costs – with the exception of the large scale multi-year projects, whose costs are relatively close to the Supply side and Demand side WMS. Overall we can conclude that water loss reduction is highly cost effective, especially with regard to WMS that are now in the Texas 2022 SWP.

Table B-5. Comparison of Water Loss Reduction Unit Costs to Supply- and Demand-side Water Management Strategies

Category of WMS - Supply Side	Number of Recommended Projects	Associated Volume (AF/Yr) in 2020 Decade	Unit Cost (from Table 7-6)	Total Cost
Aquifer Storage and Recovery	153	18,868	$437	$8,245,316
Conjunctive Use	131	5,787	$1,724	$9,976,788
Direct Potable Reuse	18	14,147	$1,321	$18,688,187
Groundwater Desalination	29	19,374	$920	$17,824,080
Groundwater Wells and Other	625	257,179	$599	$154,050,221
Indirect Reuse	550	61,808	$391	$24,166,928
Other Direct Reuse	93	48,459	$962	$46,617,558
Other Surface Water	1225	338,929	$744	$252,163,176
TOTAL	**2824**	**764,551**		**$531,732,254**
Weighted Average Unit Cost for Supply Side WMS =			$695	
Category of WMS - Demand Side	Number of Recommended Projects	Associated Volume (AF/Yr) in 2020 Decade	Unit Cost (from Table 7-6)	Total Cost
Agricultural Conservation	155	534,840	$284	$151,894,560
Industrial Conservation	141	23,042	$680	$15,668,560
Municipal Conservation	1877	219,644	$675	$148,259,700
TOTAL	**2173**	**777,526**		**$315,822,820**
Weighted Average Unit Cost for Demand Side WMS =			$406	
Without Agricultural Conservation in Urban Areas, Unit Cost =			$675	
Water Loss Reduction WMS Unit Costs	25th Percentile	Median	Average	75th Percentile
Large Meter Replacement	$112	$136	$153	$202
Leak Detection and Repair	$73	$142	$164	$239
Advanced Pressure Management	$151	$182	$210	$252
Small Meter Replacement	$326	$382	$380	$455
Large Multi-Year Projects	$468	$616	$659	$789
Unweighted Average	$226	$292	$313	$387

Bibliography

Ahopelto, S. R. Vahala (2020) Cost–Benefit Analysis of Leakage Reduction Methods in Water Supply Networks Water 2020 Vol 12 doi:10.3390/w12010195

American Water Works Association (2016) M36 - Water Audits and Loss Control Programs, Fourth Edition: American Water Works Association, Denver, CO, 405 p

American Water Work Association Research Foundation. (1987), Water and Revenue Losses: Unaccounted For Water, American Water Work Association Research Foundation, Denver CO, 182p

Arregui, F. et al, (2018) Calculation Proposal for the Economic Level of Apparent Losses (ELAL) in a Water Supply System, Water 2018 Vol 10 1809

Arregui, F. (2010). "Calculating the Optimum Level of Apparent Losses Caused by Water Meter Inaccuracies." In Proc. of International Water Association Conference. Sao Paulo, Brazil.

Arregui, F., E. Cabrera Jr, R. Cobacho, (2006) Integrated Water Meter Management, IWA Publishing, London, UK, 272p

Barfuss, S. L., M. A., Neilsen, and M. C. Johnson. (2011). Accuracy of In-Service Water Meters at Low and High Flow Rates. Project #4028. Denver, CO: Water Research Foundation.

Blackwelder, B., P. Carlson (1982), Survey of the Water Conservation Programs in the Fifty States – Model Water Conservation Program for the Nation, Bureau of Reclamation, Washington, DC

Burgers, K., P. Johnson (2015), Comprehensive Water Loss Control Program in Nashville, TN, In Proc. of North American Water Loss 2015 Conference, Atlanta. GA

Cabrera, E. M. Andres F. Planelis, (1985) Network maintenance through analysis of the cost of water, Journal of the American Water Works Association, July 1985, pages 86-98

Campbell, R. 2010. "Advanced Pressure Management at Halifax Water: Issues and Challenges." In Proc. of the Global Water Leakage Summit, London, England.

Campbell, R., and G. MacDonald. 2013. "Pressure-Reducing Strategy Tackles Mains Breaks and Leakage Problems." Water, 21 (August): 39-40.

Cobacho, R. et al., (2003) The Repair and Maintenance Costs Curve: Ways to Calculate it for a Medium Size Utility, Chapter in Pumps, Electro-mechanical Devices and Systems – Applied to Urban Water Management , pps 219-227, A.A. Balkema Publishers, Lisse, FA

City of Austin, (2015), Meter Management Evaluation, City of Austin TX, Austin, TX, 89p

City of Austin, (2015), Water Loss Management Audit, Austin, TX, 10p

City of Fort Worth, (2019) Water Conservation Plan Fort Worth, TX, 87p

Cooley, H., R. Phurisamban, (2016) The Cost of Alternative Water Supply and Efficiency Options in California, Pacific Institute, Oakland, CA, 30p and 2 Appendices

D'Andrea, M. (2011). "Water Loss Reduction Strategy: City of Toronto." In Proc. of the Global Water Leakage Summit, London, England

Davis, S. E., and C. Hill. (2005). "Economics of Domestic Residential Water Meter Replacement Based on Cumulative Volume." In Proc. of American Water Works Association Annual Conference and Exposition. San Francisco, CA.

Earth Tech, (2008) Water Loss Study – Leakage Management Strategy (for West Virginia American Water), Earth Tech, Inc, Stevens Point, WI Earth Tech Project 103939 45p

EC (European Commission). 2015. EU Reference Document: Good Practices on Leakage Management. Brussels, Belgium.

Fanner, P. et al. Evaluating Water Loss and Planning Loss Reduction Strategies (2007) American Water Work Association Research Foundation, Denver, CO, 289p

Fanner, P. et al. Leakage Management Technologies (2007) American Water Work Association Research Foundation, Denver, CO, 345p

Fanner, P., and J. Thornton., (2005). "The Importance of Real Loss Component Analysis for Determining the Correct Intervention Strategy." In Proc. of International Water Association Conference. Halifax, NS.

Fantozzi, M., A. Lambert, and M. Petroulios, (2013). "Latest Developments in Predicting and Validation Benefits of Pressure Management." In Proc. of 1 st EWaS-MED International Conference, Improving Efficiency of Water Systems in a Changing Natural and Financial Environment. Thessaloniki, Greece.

Farley, M., S. Trow, (2007), Losses in Water Distribution Networks, IWA Publishing, London, UK

Folkman, S. (2018) Water Main Breaks in the USA and Canada: A Comprehensive Study, Buried Structures Laboratory Utah State University, Buried Structures Laboratory, Logan UT, 48p

Friedman, M., G. Kirmeyer, M. LeChevallier, J. Lemieux, and S. Seidl. 2010. Criteria for Optimized Distribution Systems. Project #4109. Denver, CO: Water Research Foundation and Partnership for Safe Water.

Green, N. (2017). "Practical Application of Pressure Management within a Water Distribution System." In Proc. of the Kentucky – Tennessee American Water Professionals Conference 2017. Lexington, KY.

Green, J., P. Gagliardo, (2020) Satellite Data Complement Traditional Leak Detection and Repair Programs, Opflow, Vol 46 No.1 January 2020, American Water Works Association, Denver, Colorado

Hamilton, S.; B. Charalambous (2013) Leak Detection: Technology and Implementation; IWA Publishing: London, UK

Hamilton, S.; R. McKenzie. Charalambous (2014) Water Management and Water Loss; IWA Publishing: London, UK, 192p

Hardeman, Shawn. (2008) A Cost-Benefit Analysis of Leak Detection and the Potential of Real Water Savings for New Mexico Water Systems, University of New Mexico, Albuquerque, NM https://digitalrepository.unm.edu/wr_sp/101

Koeller, J. (2010). Evaluation of Potential Best Management Practices - Distribution System Pressure Management. Sacramento, CA: The California Urban Water Conservation Council.

Kunkel G., R. Sturm, Reducing Apparent Losses and Recovering Revenue for Large Customer Meters, - Philadelphia Water Department Proceedings of the AWWA ACE Conference, 2012

Kunkel, G. (2017), Report on the Evaluation of Water Audit Data for Pennsylvania Water Utilities

Lalonde, A. (2005). "Use of Flow Modulated Pressure Management in York Region, Ontario, Canada." In Proc. of the IWA Water Loss Conference, Halifax, Nova Scotia.

Lambert A O and M. Fantozzi M (2005) Recent Advances In Calculating Economic Intervention Frequency For Active Leakage Control, And Implications For Calculation Of Economic Leakage Levels Water Science and Technology, Vol 5, pps 263–71.

Lausten, L. (2017). "Water Loss Control Program – Trabuco Canyon Water District." In Proc. of North American Water Loss 2017 Conference, San Diego, CA.

Leauber, C. (2017). "DMAs – A Must for PVC Systems." In Proc. of North America Water Loss Conference, San Diego, CA.

LeChevallier, M., J. Yang, M. Xu, D. Hughes, and G. Kunkel. (2014). Pressure Management: Industry Practices and Monitoring Procedures. Project #4321. Denver, CO: Water Research Foundation.

Levine, B., J. Lucas, P. Cynar, T. Hildebrand, and W. Morgan. (2005). "Pressure Management in the Pittsburgh Area: A Working and Economical Solution." In Proc. of the IWA Water Loss Conference, Halifax, Nova Scotia.

Loftus, T. (2019), Economically Recoverable Water in Texas: An Underappreciated Water Management Strategy? Texas Water Journal, Vol 10, No 1, pps 60-74

Magda, M., and K. Sikaitis. 2015. “Pressure Reducing Valves Optimize Detroit Water’s Distribution System.” Flow Control Magazine, November 2015.

Male, J.W., R. Noss, I., C. Moore, (1985) Identifying and Reducing Losses in Water Distribution Systems, Noyes Publications, Park Ridge New Jersey, 156p

Malm, A.; Moberg, F.; Rosén, L.; Pettersson, T.J.R. (2015) Cost-Benefit Analysis and Uncertainty Analysis of Water Loss Reduction Measures: Case Study of the Gothenburg Drinking Water Distribution System. Water Resources Management. 2015, Vol 29, 5451–5468.

Molli, K. 2017. “The Silent Thief – Large Meter Accuracy Degradation Findings and Impacts.” In Proc. of North America Water Loss Conference, San Diego, CA.

Molli, K., and C. Horner. 2017. “LADWP Large Meter Operations Initiatives - Optimizing Revenue Impact and Maintenance.” In Proc. Of AWWA Annual Conference and Exposition, Philadelphia, PA.

Molli, K., D. Mijatovic, and W. C. Liebold. 2015. “NYC’s Large Meter Replacement Program improving Revenues and Lowering Costs.” In Proc. of North America Water Loss Conference, Atlanta, GA.

Moyer, E. et al, (1983) The Economics of Leak Detection and Repair – A Case Study, Journal of the American Water Works Association, January 1983, pages 29-34

Powers, M. (2017). “A Break with Convention: Reducing Apparent Losses Through Meter Testing and Volume Based Capacity Classes.” In Proc. of North America Water Loss Conference, San Diego, CA.

Puust R, Kapelan Z, Savic D A and Koppel T (2010) A Review of Methods For Leakage Management In Pipe Networks, Urban Water Journal. Vol. 7 25–45

Ruppier, A. et al (2022) Untapped potential: Leak Reduction Is the Most Cost -Effective Urban Water Management Tool, Environmental Research Letters 2002, Vol 17 No. 3 https://doi.org/10.1088/1748-9326/ac54cb

Rye, S. (2017) – A Tale of Two Cities Urban Leak Sensors and Rural DMAs for Water Loss Management, Proceedings of the North America Water Loss Conference 2017, San Diego, CA

Skipworth, P. et al. (2002) Whole Life Costing For Water Distribution Network Management , Thomas Telford Publishing, London,UK, 203p

Shriver, P., (2017), Adding the Dimension of Loss Control, Proceedings of the North America Water Loss Conference 2017, San Diego, CA

Shriver, P. (2015) From Average to Optimized in San Antonio, Texas, Proceedings of the North America Water Loss Conference 2015, Atlanta, GA

Smith, L.A., et al., (2000), Options for Leak and Break Detection and Repair of Drinking Water Systems, Battelle Press, Columbus, Ohio, 163p

State of California, Department of Water Resources, Office of Conservation, (1983), An Examination of the Benefits of Leak Detection, State of California, Department of Water Resources, Office of Conservation, Sacramento, CA, 50 p

Sturm, R. et al. (2014) Real Loss Component Analysis: Tool for Economic Water Loss Control Report 4372a, Water Research Foundation, Denver, CO, 147p

Texas Water Development Board, (2022) State Water Plan 2022 TWDB, Austin, TX

Texas Water Development Board, (2008) Water Loss Audit Manual for Texas Utilities, TWDB Austin, TX, 50p

Texas Water Development Board, (2007) An Analysis of Water Loss as Reported by Public Water Suppliers in Texas, TWDB Austin, TX, 130p

Texas Water Development Board, (1991) A Guidebook for Reducing Unaccounted For Water , TWDB, Austin TX, 32p

Thornton, J. et al. (2008) Water Loss Control, Second Edition, McGraw Hill, New York, NY, USA, 623p

Thornton, J., and A. Lambert. (2007). “Pressure Management Extends Infrastructure Life, and Reduces Unnecessary Energy Costs.” In Proc. of International Water Association Conference, Bucharest, Romania.

Thornton, J., and A. Lambert. (2005). “Progress in Practical Prediction of Pressure, Leakage, Burst Frequency and Pressure, Consumption Relationships.” In Proc. of

International Water Association Conference, Halifax, Nova Scotia, Canada.

Trachtman, G., S. Davis, A. Wyatt, (2019) Guidance on Implementing an Effective Water Loss Control Plans, WRF Project 4695, Water Research Foundation, Denver, CO, p291. https://www.waterrf.org/research/projects/guidance-implementing-effective-water-loss-control-plan

UK Water Industry Research, (UKWIR), (2019) Measuring the Efficiency of Active Leakage Control, Report 19/WM/08/69, UKWIR, London, UK

United States Environmental Protection Agency, (2010) Control and Mitigation of Drinking Water Losses in Distribution Systems, US EPA, Washington, DC

Wagoner, T. 2015. "Is There Any Relief? A Case Study in Pressure Optimization." In Proc. of North American Water Loss 2015 Conference. Atlanta, GA.

Wagoner, T. 2017." Pressure Optimization as a Tool to Manage Leakage." In Proc. of the IWA Efficient 2017 Conference. Bath, UK.

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CONTACT US:

Jennifer Walker: walkerj@nwf.org
Jonathan Seefeldt: seefeldtj@nwf.org

National Wildlife Federation
505 E. Huntland Dr., Suite 485
Austin, Texas 78752

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