December 2023

A COMPREHENSIVE ASSESSMENT OF THE DELAWARE RIVER BASIN COMMISSION'S WATER AUDIT PROGRAM (2012-2021)

Technical Report No. 2023-7

Managing, Protecting and Improving
the Water Resources of the
Delaware River Basin since 1961

Delaware River Basin Commission
DELAWARE • NEW JERSEY
PENNSYLVANIA • NEW YORK
UNITED STATES OF AMERICA

Suggested Citation:

Thompson, M.Y., Sayed, S.C., & Pindar, C.E. (2023). *A Comprehensive Assessment of the Delaware River Basin Commission's Water Audit Program (2012-2021).* (DRBC Report No. 2023-7) Delaware River Basin Commission.

A Comprehensive Assessment of the Delaware River Basin Commission's Water Audit Program (2012-2021)

DRBC Report No: 2023-7

Prepared by Michael Y. Thompson, Sara C. Sayed, and Chad E. Pindar

Authorization

This work is being conducted in accordance with Article 3 Section 3.6(c) of the Delaware River Basin Compact (PL 87-328, 75 Stat. 688). More specifically, the project is outlined in Section 2.2.1.3 (Water Supply Management: Conservation, Special Area Management, and Permitting) of the DRBC Water Resources Program FY2024-2026 (DRBC, 2023).

Acknowledgements

First and foremost, the authors express gratitude to all utilities and staff who have been completing the AWWA Free Water Audit Software reports over the past decade. Thank you for your coordination year after year, and for working with DRBC to get the best data feasible. As the adage goes, you cannot manage what you do not measure – and because of your efforts, it is possible to perform analyses such as this to help plan for a sustainable future.

The authors express their gratitude to: Allan Lambert and Kate Stanton-Davies (Water Loss Research & Analysis Ltd) for sharing valuable knowledge of the industry's history, reviewing the draft report, and for assistance related to their ongoing research on System Correction Factors; to George Kunkel (Kunkel Water Efficiency Consulting) and Gary Trachtman (Arcadis US, AWWA WLCC) for their discussions on meter testing/accuracy, and for providing valuable insight after reviewing a draft report; and to Margaret Hunter (New Jersey American Water) for her assistance in compiling the additional data needed for the pilot study on System Correction Factors. Additionally, the authors would like to acknowledge the help and expertise of the DRBC Water Management Advisory Committee (WMAC).

Scope and Organization

The purpose of this study is to perform a comprehensive assessment of the ten years of data collected though the Delaware River Basin Commission's water audit program (Delaware River Basin Water Code §2.1.8). A detailed background on water system efficiency is presented, with a specific focus on how the industry has arrived at its current practices (i.e. top-down approaches to water balances with standardized terminology). A review of the most recent year of data (CY2021) summarizes specific metrics measured by the AWWA Free Water Audit Software, followed by assessments of observed trends (2012-2021). Investigations are performed to estimate possible reductions of real water loss (i.e., leakage) across the Delaware River Basin. Multiple recommendations are made at the end of this report to help move the water audit program in the Delaware River Basin from monitoring progress, to promoting progress.


WATER

Executive Summary

The Delaware River Basin provides drinking water for an estimated 14.2 million people (approximately 4% of the of the total population of the United States), while only draining 0.4% of the total continental United States land area. Although the Basin supplies roughly half of the water for the largest city in the United States (New York City), the majority of the population served resides within the Basin boundary – estimated in 2020 to be 8.629 million people. Of that in-Basin population, about 85% (7.366 million people) are served by hundreds of public water supply systems. It is a remarkable feat of engineering that has woven together 29,000 miles of water mains, which is long enough to circle the globe. Home to two of the fourteen water supply systems built before the Declaration of Independence was adopted in 1776, public water supply in the Delaware River Basin is rooted in the country's history.

The Delaware River Basin Commission (DRBC) has a history of water loss control efforts, notably adopting a resolution which set out an official statement of policy on the conservation of water in 1976. The DRBC has since taken many actions that include but are not limited to implementing requirements on source and service metering, requirements on plumbing standards and leak detection practices, promoting and supporting retail water pricing that encourages conservation, and notably, beginning in 2012, requiring regulated water utilities (public and private) to complete the AWWA Free Water Audit Software (Delaware River Basin Water Code §2.1.8). Since that time, DRBC has collected reports from nearly 300 systems on an annual basis and published three assessments of the data—for 2012, 2014 and 2016. Note that data collected by DRBC have not been "Level 1 Validated" according to the AWWA recommended practice. This study is the first comprehensive look at the data collected through the water audit program, specifically assessing trends and progress, and evaluating the room left for improvement.

Data collected for CY2021 is generally consistent with prior data. Public water supply systems withdrew an estimated average of 779 million gallons per day (MGD) from their own water supply sources. As many systems are interconnected, cumulative exports (60 MGD) and imports (76 MGD) suggest a net import of about 16 MGD (major Basin exports to New York City and New Jersey under the 1954 Supreme Court Decree are out of the scope of this study). Therefore, the total volume of water supplied by these systems is estimated to average 795 MGD. Based on the calculation methods utilized by the AWWA FWAS, it is estimated that these systems register an average of 585 MGD in authorized consumption, and experience 209 MGD in water losses. The total estimated real loss volume is 182 MGD, which can be subdivided into estimated unavoidable annual real losses (41 MGD) and avoidable real losses (141 MGD). The total estimated apparent loss volume is 27 MGD. The public water supply water balance for the Delaware River Basin has been provided for reference as Figure ES-1. Not shown in the water balance is the concept of "data validity", which reflects the overall level of trust in the audit results. The AWWA data validity score generated for each report ranges from 0-100. These scores are grouped into five "tiers" (Tier I – Tier V), with Tier V being the most reliable data. Regarding the data submitted for 2021, it is shown that 53% of the water supplied is accounted for in 77 reports with high data validity (Tiers IV and V); 37% is accounted for in 125 reports with moderate data validity (Tier III); and 10% is accounted for in 98 reports on the low end of data validity (Tiers I and II).

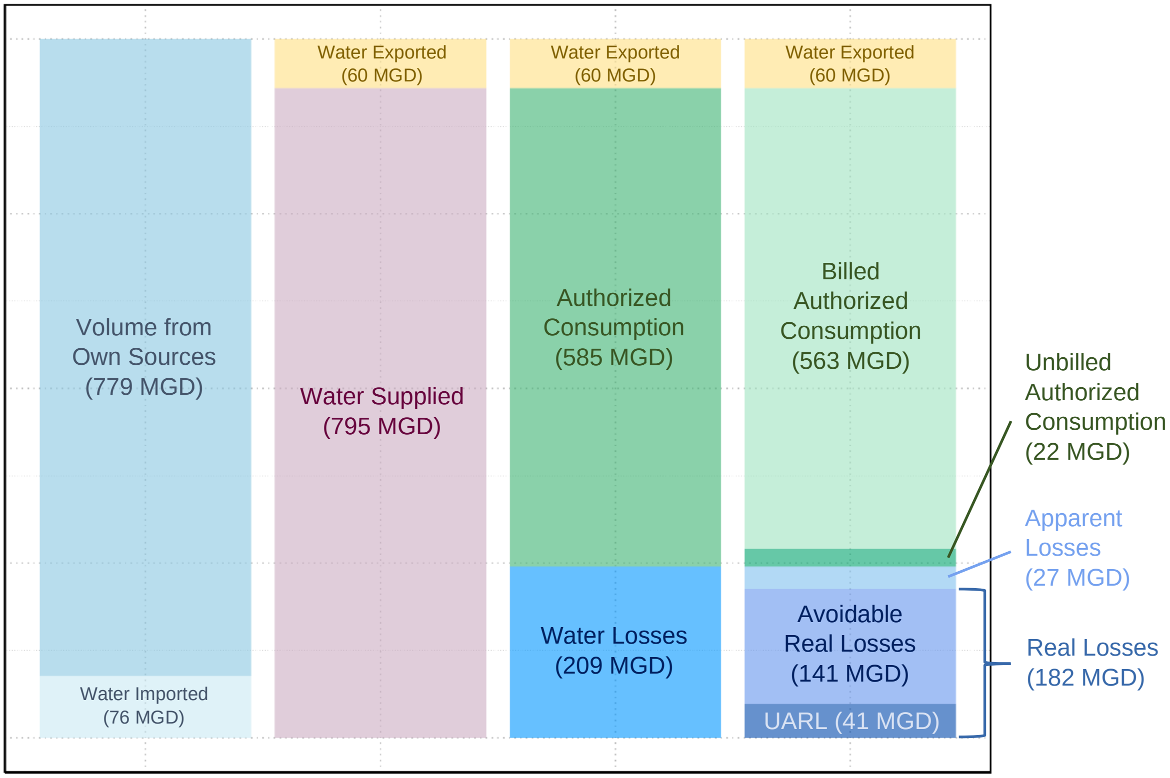


Figure ES-1: Aggregate water balance for 300 systems reporting water audit data to DRBC for CY2021. Note that the totals in the 3rd and 4th columns are 1 MGD less than the 1st and 2nd due to rounding when the data is disaggregated.

Assessment of the data between 2012-2021 is primarily done in two forms: (1) volumetric trends for the entire Delaware River Basin, and (2) trends of Key Performance Indicators (KPIs). Overall, the volume of water withdrawn has remained relatively constant over the decade, which was consistent with withdrawal data reported to respective state agencies. Volumetric assessments of trends in the three components of non-revenue water (real losses, apparent losses, unbilled authorized consumption) show only one significant trend, an increase in real losses in the years 2020 and 2021. Hypotheses for these increases are offered, including the possibility that the COVID-19 pandemic resulted in a redistribution of water consumption from non-residential to residential properties, or hindered utilities' ability to perform necessary maintenance. KPIs such as unit real and apparent losses (gallons per connection per day), even by system class, did not show any significant trends in either direction.

Select analyses of real loss reduction potential (RLRP) are performed for the entire Delaware River Basin. A frontier analysis (FA) is performed by developing a multivariate model for real loss and comparing the performance of systems against each other. A separate analysis is performed considering the Infrastructure Leakage Index (ILI), which is a measure of a system's current annual real loss (CARL) compared to the unavoidable annual real losses (UARL). Assuming that system performance increases (e.g., a system reduces losses and moves from ILI=8 to ILI=7), a volume of water saved can be calculated Basin-wide by applying the method to all systems. It is shown that the results of the two analyses are similar, and that the ILI methodology is preferred

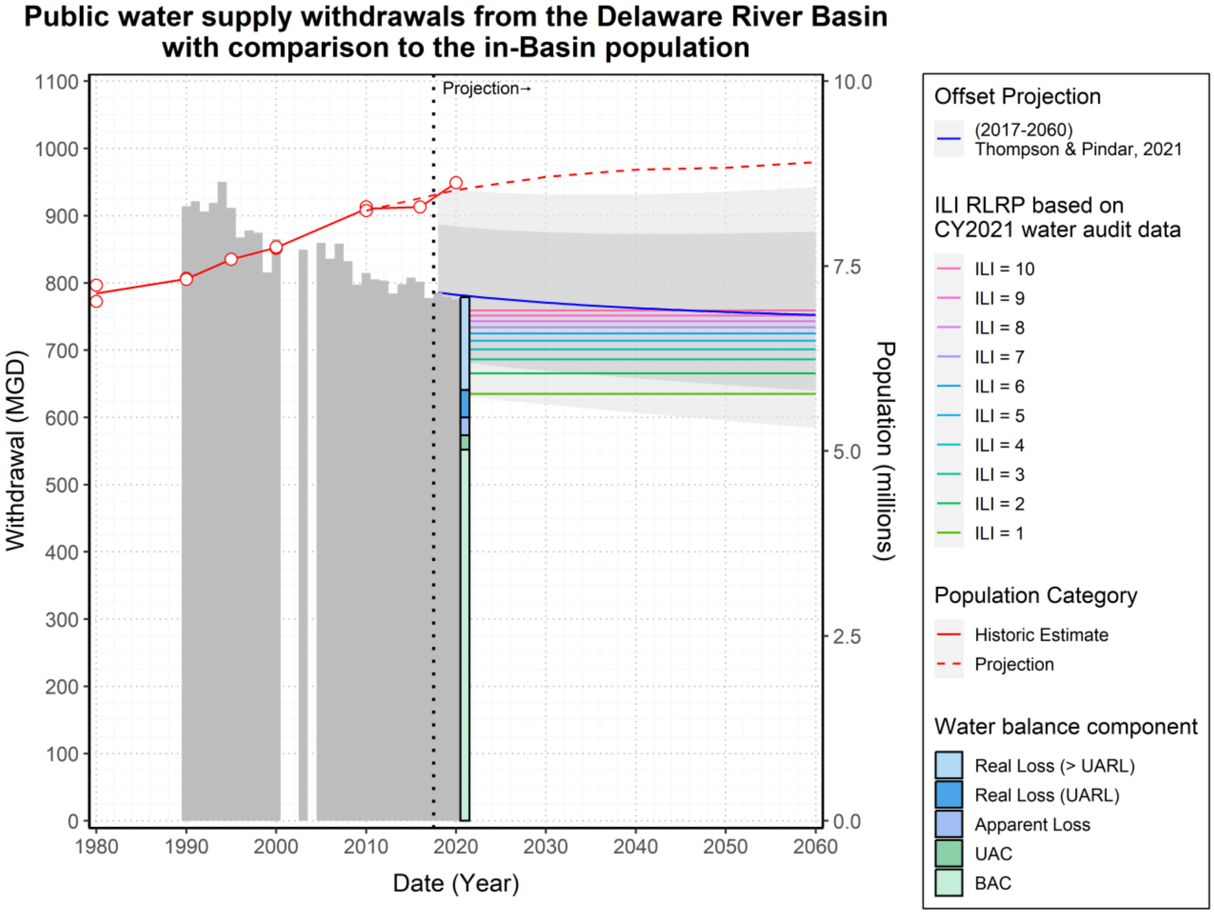


Figure ES-2: *The projections from Thompson & Pindar, 2021 have been offset by about 33 MGD, equal to the error between the model and reported withdrawals in CY2017. Horizontal lines representing the ILI frontiers have been calculated for each ILI based on applying the real loss reduction potential (RLRP) to the CY2021 VOS.*

because (1) it is based on a theoretical lower limit to water losses, and (2) the calculation involved is simpler than that for a frontier analysis. The ILI analysis shows that further reductions in real losses within the Delaware River Basin could range between about 20 MGD (those above ILI=10 reaching ILI=10) and 144 MGD (those above ILI=1 reaching ILI=1). However, it is noted that expecting all systems to reach an ILI=1 is not realistic, and that incorporation of Economic Level of Leakage analyses could help improve accuracy and set more realistic expectations. These ILI frontiers are compared against previous public water supply withdrawal projections (offset to meet recent data) and show that current trends in reduced withdrawal by 2060 are equivalent to those above ILI=9 reaching ILI=9 (Figure ES-2).

It is evident from Figure ES-2 that water withdrawals by public water suppliers in the Delaware River Basin have decreased by about 100 MGD on average over the last 30 years (1990-2020) while the in-Basin population is estimated to have increased by about 1.3 million people in the same timeframe. Overall, these statistics suggest a good deal of success regarding water conservation and are related to a variety of factors. However, assessment of the water audit data collected over the past 10 years as presented in this report highlights that there is still much room for improvement. Specifically related to data for CY2021, 47% of the water supplied in the Basin is accounted for in 223 reports which have data validity in Tier III or less.

This report provides a brief discussion on topics related to pressure management, with a specific focus on commonly cited shortfalls/challenges associated with the term average operating pressure (P_{AO}), such as not accounting for (1) the causes and effects of high transient pressures and (2) the spatial variation of pressure within a system. While it is recognized by the authors that P_{AO} may have a certain elegance in its simplicity, it is important to recognize its shortcomings and strike a balance between a data burden and oversimplification. To this end, P_{AO} is referenced and used throughout this report as it is the data which is available to us. The authors recognize that research is warranted investigating additional pressure related parameters, and how they might be used to better analyses such as this.

Three additional analyses are included in this study as they are applicable to the water audit program and data:

1. A pilot study has been conducted to calculate and apply system correction factors (SCF) to the standard UARL equation for five small public water supply systems. Specifically, for one system, the results show that the corresponding ILI is raised from below 1 (suggesting lower than theoretical limits of real losses are being reported), to slightly above 1 (suggesting efficient operation).
2. Data on sourcewater designation (i.e., groundwater, surface water, or both) is not collected through the AWWA FWAS and has not previously been assessed by DRBC with respect to water audit data. The results presented in this study using CY2021 audit data suggest that systems relying only on groundwater sources had lower unit real loss rates than those reliant on surface water, or combined surface water and groundwater. One hypothesis is presented related to temperature fluctuation of sourcewater. It is shown that median monthly groundwater temperatures range between 51-61°F in the southern portion of the Basin (<1,000 ft. amsl) and range between 47-54°F in the northern portion of the Basin (>1,000 ft. amsl). Surface water temperatures show a consistent trend across the entire Basin with median temperature values between 36°F (January) and 71°F (July). Additional research is determined to be necessary to draw specific conclusions, although it seems possible that system infrastructure subjected to larger temperature fluctuations of raw water may correlate with increased leakage.
3. An analysis is performed assessing the elevation differential within system service areas (based on digital elevation maps and GIS shapefiles), as they relate to average system pressure and real losses. It is found that the service area elevation differential (SAED) varies largely based on physiographic region of the system, with higher differentials in the northern (mountainous) portion of the Basin. The SAEDs show a correlation with average system pressure and unit real loss rates, and linear models are developed to help quantify the relationship.

Overall, the data and analyses in this report show that good progress has been made within the Delaware River Basin, particularly when looking at the trends in water withdrawals over the past 30 years. However, it has also highlighted that there is room for improvement of performance, and room for growth as a program. Numerous recommendations are made at the end of the report which will hopefully help move the water audit program in the Delaware River Basin from monitoring progress, to promoting it.

Fairmount Water Works
in Philadelphia, Pennsylvania.
Credit: Partnership for the Delaware Estuary
Used with permission

List of Acronyms/Abbreviations

AWWA	American Water Works Association
AWWA WLCC	AWWA Water Loss Control Committee
AwwaRF	American Water Works Association Research Foundation (now WRF)
BABE	Bursts and Background Estimate
BMP	Best management practice
CADWR	California Department of Water Resources
CDF	cumulative density function
CPCN	Certificate of Public Convenience and Necessity
CY	Calendar year
DEM	Digital elevation map
DHSS	Delaware Health and Social Services
DMA	District metered area
DOE	Department of the Environment (in the United Kingdom)
DRB	Delaware River Basin
DRBC	Delaware River Basin Commission
ELL	Economic Level of Leakage
FAVAD	Fixed and Variable Area Discharges
FPPI	Financial percentage performance indicator
FWAS	Free Water Audit Software
GIS	geographical information system
GW	groundwater
GWAC	Ground Water Advisory Committee
IQR	Inner-quartile range
IRC	International Residential Code
ITA	Instituto Tecnológico del Agua
IWA	International Water Association
IWSA	International Water Supply Association
KPI	Key Performance Indicator
NEWWA	New England Water Works Association
NJDEP	New Jersey Department of Environmental Protection
NLCI	National Leakage Control Initiative
NRC	National Research Council
NWC	National Water Council (in the United Kingdom)
NYCDEP	New York City Department of Environmental Protection
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
OFWAT	Office for Water Services (in the United Kingdom)
PADEP	Pennsylvania Department of Environmental Protection
PIPEiD	Pipeline Infrastructure Database
PDF	probability density function
PWSID	Public Water System Identification
SCADA	Supervisory control and data acquisition

SDWIS	Safe Drinking Water Information System
SW	surface water
UKWIR	United Kingdom Water Industry Research
USBR	United States Bureau of Reclamation
USCB	U.S. Census Bureau
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VPPI	Volumetric percentage performance indicator
WADI	Water Audit Data Initiative
WARD	Water Audit Reference Dataset
WCAC	Water Conservation Advisory Committee
WMAC	Water Management Advisory Committee
WRF	Water Research Foundation (previously AwwaRF)

Variables

AC	Authorized consumption
AL	Apparent loss
BAC	Billed authorized consumption
BF	Burst frequency
BMAC	Billed metered authorized consumption
BUAC	Billed unmetered authorized consumption
CARL	Current Annual Real Loss
CMI	Customer metering inaccuracies
CRUC	Customer retail unit charge
DVS	Data validity score
DVT	Data validity tier
ICF	Infrastructure Condition Factor
ILI	Infrastructure Leakage Index
L_c	Total length of customer service piping (miles)
L_m	Length of mains (miles)
L_p	Average length of customer service connection piping (feet)
MMEA	Master meter error adjustment
N_c	Number of connections (active and inactive)
NRW	Non-revenue water
O/P-ratio	Observed / predicted ratio
P_{AO}	Average operating pressure (psi)
PMI	Pressure Management Index
Q	Flow rate
RL	Real losses
RLRP	Real loss reduction potential
RW	Revenue water
SAED	Service area elevation differential
SCD	Service connection density
SCF	System Correction Factor

SDHE	Systematic data handling errors
TAOC	Total annual operating cost
TIRL	Technical Indicator for Real Losses
UAC	Unbilled authorized consumption
UARL	Unavoidable Annual Real Losses
UC	Unauthorized consumption
UFW	Unaccounted-for water
UMAC	Unbilled metered authorized consumption
UUAC	Unbilled unmetered authorized consumption
VOS	Volume from own sources
VPC	Variable production cost
WE	Water exported
WI	Water imported
WL	Water loss
WS	Water supplied
WSEA	Water supplied error adjustments

Units

°F	degrees Fahrenheit
amsl	above mean sea level
CFS	cubic feet per second
con	connection
ft	feet
gal	gallon
gcd	gallons per connection per day
gmd	gallons per mile of main per day
km	kilometer
m	meter (or meter of water pressure)
MG	million gallons
MGD	million gallons per day
MGY	million gallons per year
mi	mile
MM	million
psi	pounds per square inch

Table of Contents

Water supply towers in Pennsauken, NJ.
© Merchantville-Pennsauken Water Company.
Used with permission.

1. INTRODUCTION

1.1. Scope and authorization

The purpose of this study is to analyze trends from 10 years of self-reported water audit data by public water supply systems in the Delaware River Basin. The primary source of data used in this study are the annual reports generated using American Water Works Association's (AWWA) Free Water Audit Software (FWAS). These annual water audit reports ("audits" or "reports") have been submitted to the Delaware River Basin Commission (DRBC) by public and private utilities ("utilities") for approximately 300 public water supply systems ("systems") over the course of 10 years (calendar years 2012 through 2021). The results of this work will support the ongoing water conservation goals of the DRBC by providing a quantitative data-based foundation to guide future practices, decisions and policies related to water conservation. This work is being conducted in accordance with Article 3 Section 3.6(c) of the Delaware River Basin Compact (PL 87-328, 75 Stat. 688).

1.2. A primer on water efficiency

When studying public water supply systems and data on operational efficiency, a helpful primer may be the quote often attributed to Benjamin Franklin's publication "*Poor Richard, 1746. An Almanack For the Year of Christ 1746"* (Franklin, 1746), but perhaps more accurately attributed to Thomas Fuller's 1732 publication "*Gnomologia: Adages and Proverbs, Wise Sentences, And Witty Sayings*" (Fuller, 1732) as entry number 5451:

> *We never know the Worth of Water, till the Well is dry.*

This widely referenced adage aptly captures the importance of studying and planning for the availability of water resources. Because it is essential to put forth best efforts to reach a sustainable balance between the various demands on a water resource (human and environmental), water users should strive to use the resource as efficiently as possible. resources as efficiently as possible.

1.3. The Delaware River Basin Commission water audit program

The DRBC water audit program was established by Resolution No. 2009-1 on March 11, 2009 by unanimous vote of the Commission's five members. The program is codified at Article 2, "*Conservation, Development and Utilization of Delaware River Basin Water Resources,*" Sections 2.1.2 C.1.e., 2.1.6, 2.1.8, and 2.50.3 A.1.b.ii., of the Delaware River Basin Water Code which is incorporated by reference at Title 18, Part 410 of the Code of Federal Regulations. Although the final regulation requiring the submission of water audit reports is contained in Section 2.1.8 of the Delaware River Basin Water Code, several important elements of the DRBC's water conservation program preceded it, as follows:

- In 1976, the Commission adopted a resolution to "*undertake a long-range continuing program to reduce water use throughout the Basin*". Additionally, it specifies that the

Commission should undertake research and planning programs needed to give effect to the policy (Resolution No. 76-17).

- In 1977, the Commission adopted a resolution which directed an investigation of the groundwater conditions in the Delaware River Basin (Resolution No. 77-3). The funding became available by 1979, and the associated study was completed in 1982 (Resolution No. 82-25). From the study's inception in 1979, it had been guided by a steering committee, and following the final report in December 1982, the steering group was renamed the Ground Water Advisory Committee (GWAC) and retained to assist in the implementation phase (DRBC, 1982).
- In 1983, the Commission adopted a resolution to establish a Water Conservation Advisory Committee (WCAC) (Resolution No. 83-5).
- In 1986, the Commission adopted resolutions establishing requirements for entities withdrawing water at rates above the DRBC review thresholds to meter the sources of withdrawal (Resolution No. 86-12; Resolution No. 86-13), based on recommendations of the Commission's GWAC.
- In 1987, it was determined that public water suppliers meeting DRBC review thresholds must conduct service level metering based on a recommendation of the Commission's WCAC, as it was determined that "*both source and service metering are needed to determine unaccounted-for water in a public water supply system, which is necessary for leak detection and repair*" (Resolution No. 87-7 Revised). Additionally, a separate resolution was adopted at the recommendation of the WCAC to require owners of public water supply systems meeting DRBC thresholds to institute leak detection and repair practices that included reporting on levels of "unaccounted-for water" (UFW) (Resolution No. 87-6 Revised).
- In 1998, the Commission adopted a resolution to dissolve the WCAC and the GWAC, and to establish the Water Management Advisory Committee (WMAC) (Resolution No. 98-21).

By the year 2000, a water loss accountability structure known as a "Top-down Water Audit" had been developed by the International Water Association (IWA) (Alegre et al., 2000; Lambert et al., 1999; Lambert & Hirner, 2000). This methodology rapidly became regarded within the water industry as superior to existing methods for tracking what was now referred to as "Non-revenue water" for the following reasons, among others: (1) it is based upon precise definitions and rational accounting procedures that result in a clearer understanding of the causes of water loss; (2) it facilitates more consistent tracking and reporting and thus helps utility managers and regulators target their efforts to improve water supply efficiency; and (3) the above benefits would potentially lead to reduced water withdrawals.

Between May of 2004 and early 2005, the Commission's WMAC, whose members represent a diverse group of public and private sector organizations, reviewed the IWA water audit methodology and the current Delaware River Basin Water Code provisions and recommended that the methodology be adopted within the Basin. With the express support of the Commission, DRBC staff participated in an effort led by the AWWA Water Loss Control Committee (WLCC) to develop new software for implementing the water audit approach, and with the assistance of the WMAC, engaged a half-dozen water utilities within the Basin in a nation-wide pilot study that led to improvements in the software.

In March of 2006, the software was approved by the AWWA WLCC and was posted on the AWWA website, where it is available at no charge to users.

In July of 2007 the Commission directed the Executive Director to proceed with rulemaking on a set of proposed amendments to the DRBC Water Code and DRBC Comprehensive Plan for implementing the water audit methodology Basin-wide. Because the approach was relatively new in a regulatory context, the proposed amendments provided for voluntary use of the approach by utilities through CY2011 and mandatory annual water audits conforming to the IWA/AWWA methodology, specifically using the AWWA FWAS, beginning in CY2012.

The Commission conducted an informational meeting on the proposed amendments on September 10, 2008, and a public hearing on September 25, 2008, both in West Trenton, New Jersey, and accepted written comment on the proposed amendments through October 3, 2008. The Commission received one letter and no oral testimony on the proposed amendments. On March 11, 2009, the Commission adopted Resolution No. 2009 – 1, which amended the Commission's DRBC Water Code and DRBC Comprehensive Plan to implement an updated water audit approach to identify and control water loss in the Basin.

During CY2009 through CY2011 the Commission undertook extensive outreach efforts to engage with the regulated entities, and offered workshops and training on the water audit software. Specifically, in April 2011, DRBC partnered with the Philadelphia Water Department (PWD), New Jersey American Water Company (NJAWC) and Aqua Pennsylvania (Aqua PA) to present a day-long workshop on water auditing (DRBC website). In 2012, extensive database preparation took place in order to track, store and analyze incoming water audits.

Water audit submittals for CY2010 and CY2011 were voluntary. In December 2012, the first mandatory reporting year, the Commission notified impacted entities that the first water audit would cover CY2012 and must be submitted to DRBC by March 31, 2013, with subsequent reporting required annually thereafter. An important aspect of the new DRBC water audit requirement was an emphasis on electronic reporting and processing of water audit reports using a consistent format (the AWWA FWAS).

In March 2015, DRBC conducted a survey of regulated entities regarding the water audit program and the results were shared with WMAC in June 2015 (WMAC web pages). In September 2018, DRBC partnered with the Pennsylvania Department of Environmental Protection (PADEP) and Kunkel Water Efficiency to host a series titled, "Hands on Training in Water Loss Auditing" at Bucks County Community College. DRBC has published reports on water audit submittals, which focused on yearly "snapshots" and were prepared using data from CY2012 (Sayers et al., 2015), CY2014 (Najjar & Barr, 2016), and CY2016 (Najjar et al., 2018).

1.4. Public water supply in the Delaware River Basin

1.4.1. Public water supply service areas

Public water supply systems in the Delaware River Basin perform a basic, yet essential service: providing potable water for people. A map showing the distribution of population across the Basin, as well as the location of public water supply service areas, is shown in Figure 1. It is similar to a figure presented in Thompson & Pindar, 2021, which estimated that the 2010 in-Basin population was approximately 8.252 million people, of which approximately 86% (7.106 MM people) were residing within public water supply service areas. While the population data in Figure 1 are the same as were used in Thompson & Pindar, 2021, there have been minor updates to the service area boundaries within the State of Delaware.

Due to the availability of statewide data, Thompson & Pindar, 2021 used CPCN (Certificate of Public Convenience and Necessity) boundaries as a proxy for public water supply service areas in Delaware. It is noted that these boundaries are similar to water supply service areas, but not necessarily the same. Therefore, this study improves service area mapping within the Delaware portion of the Basin by (1) contacting private utility companies directly to obtain accurate service area boundaries, (2) only using CPCN boundaries where it is known that municipal water works are in operation (based on permits or water audits), and (3) in one circumstance the actual municipal boundary is used as the service area. As a result, the addition of one municipal service area not covered by the CPCN dataset offset the removal of CPCN areas not matching active water supply service areas. The revised estimate for the 2010 in-Basin population of the Delaware River Basin residing within public water supply service areas is 7.157 MM people (approximately 87% of the estimated 8.252 million Basin residents).

Based on this figure, two things are apparent: (1) public water supply systems are most densely located in the megalopolis corridor near Philadelphia, coinciding with the highest population density areas in the Basin; and (2) the majority of people living in the Basin rely on public water supply. Beyond the major population centers, public water supply systems become more isolated and localized, for example, in the Pocono Mountains in Pennsylvania and the Catskill Mountains in New York. In these areas, smaller population centers such as towns, villages, and hamlets were historically formed in the valleys along waterways and have consequently established smaller public water supply systems. It is assumed that all populations living outside of the public water supply service areas rely upon self-supplied domestic groundwater withdrawals and are not assessed in the context of this study.

1.4.2. Current water demand and population

The most recent DRBC estimate of water withdrawals by public water suppliers is based on data that utilities have reported to respective state agencies for CY2020. These show an average of 775 million gallons per day (MGD) were withdrawn (DRBC, 2021). Based on 2020 U.S. Census Bureau (USCB) data, DRBC estimated that the 2020 in-Basin population has reached 8.629 MM people (DRBC, 2021). These data are shown on Figure 2, which presents a historical time series of withdrawals by public water supply systems in the Delaware River Basin (1990-2020), as well

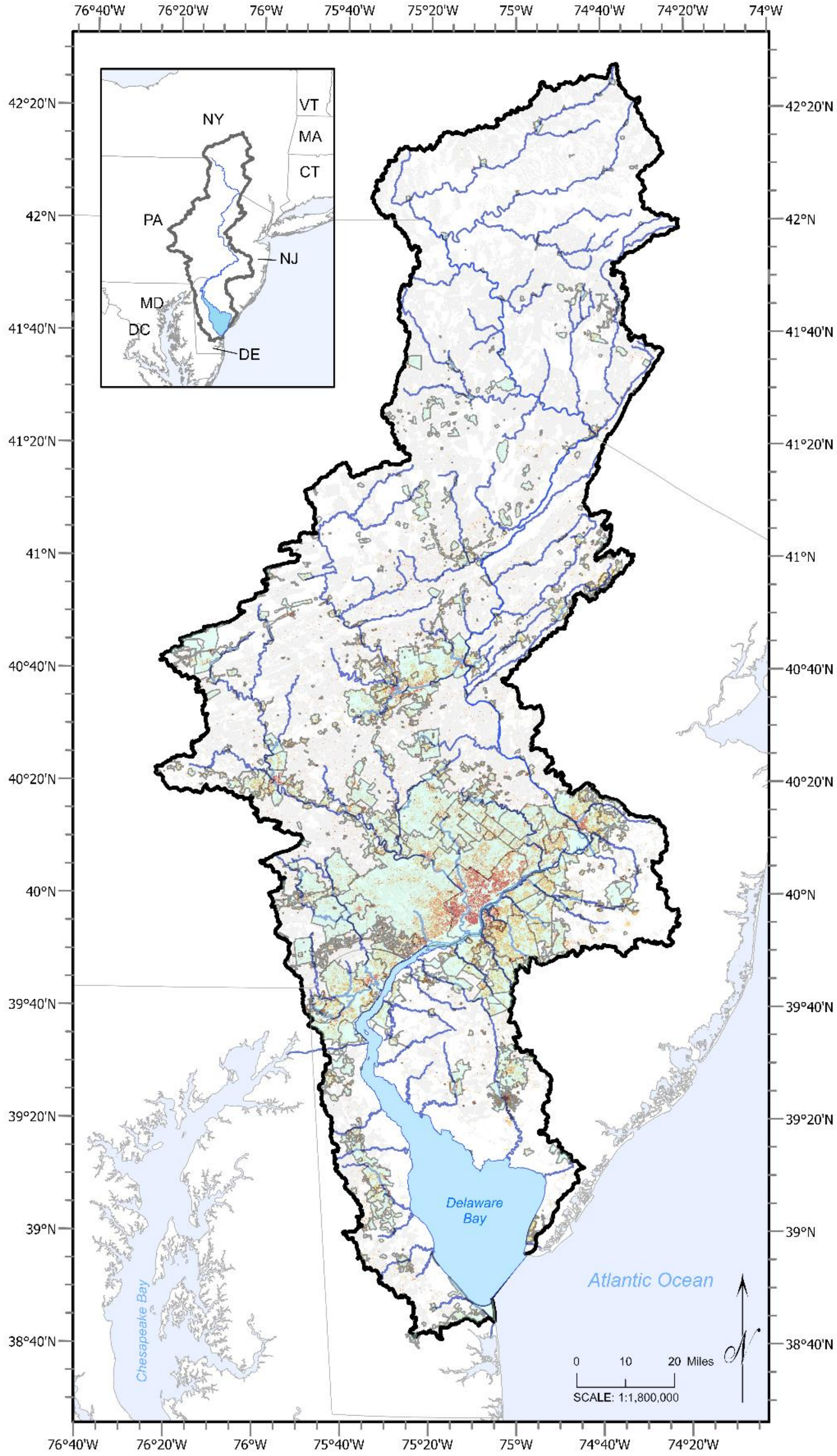


***Figure 1**: A map comparing population distribution and public water supply service areas in the Delaware River Basin. The population dataset is the 2010 U.S. Census Bureau data, dasymetrically mapped for the USEPA EnviroAtlas (USEPA, 2016). The public water supply service areas overlay the population raster as a semi-transparent layer for DE, NJ (NJDEP, 2019), NY (NYSDOH, 2021), and PA (PADEP, 2020). Note that service area files for DE are a combination of CPCN areas (DE PSC, 2021), shapefiles from private utilities, and one municipal boundary. Population values represent the number of people per 30x30 meter area (pixel), evaluated at an accuracy of 0.001 prior to rounding.*

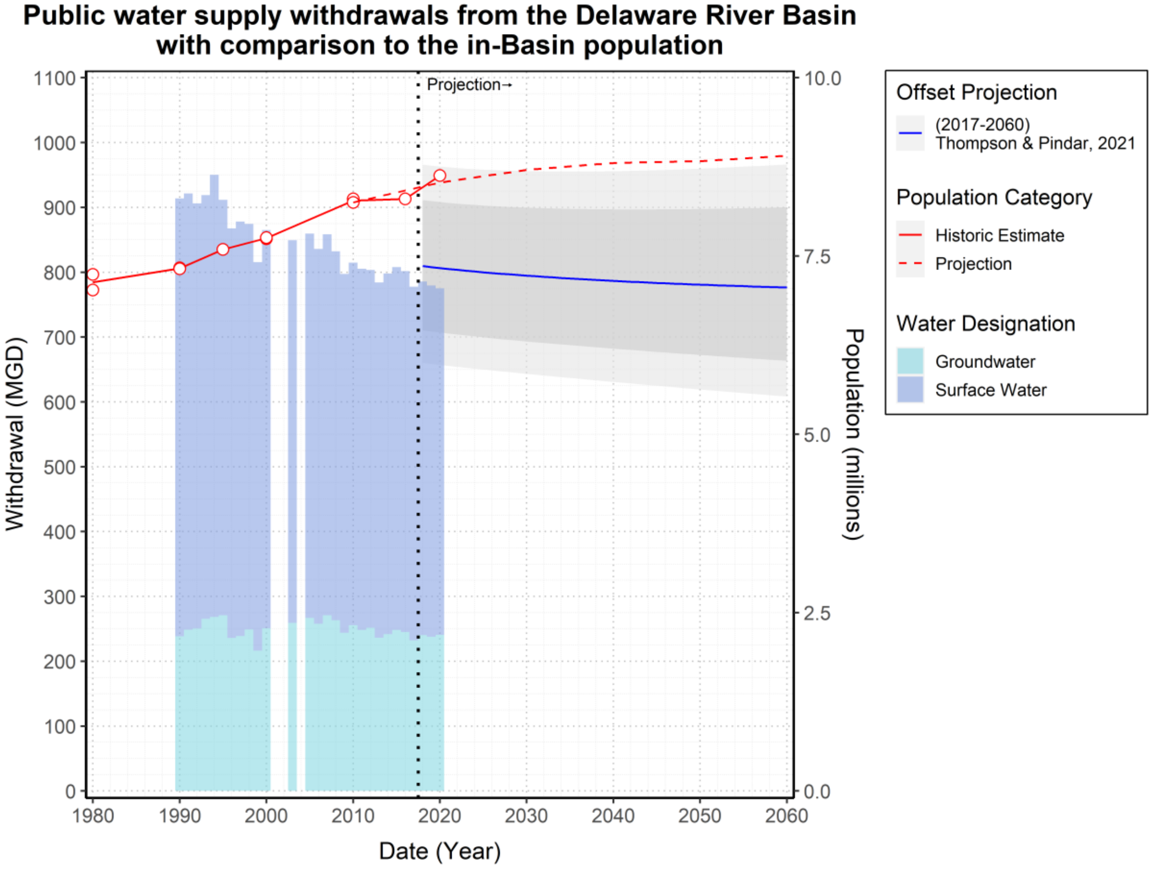


***Figure 2**: Withdrawals by public water supply systems in the Delaware River Basin 1990-2020. Known data gaps exist for 2001, 2002 and 2004. The population values projected from 2010 through 2060 are reflective of the population residing within the Basin boundary as presented in Figure 1. Projected withdrawals by public water suppliers and project population values are adapted from Thompson & Pindar, 2021.*

***Table 1**: Population estimates for the Delaware River Basin, corresponding to the data shown in Figure 2.*

Population Year	Population Estimate (million people)	Data Source	Reference study
1980	7.24	U.S. Census Bureau	(DRBC, 1981)
1980	7.022	U.S. Census Bureau	(DRBC, 1994)
1990	7.335	U.S. Census Bureau	(DRBC, 1994)
1990	7.322	U.S. Census Bureau	(DRBC, 2008)
1995	7.591	--	(DRBC, 2008)
2000	7.742	U.S. Census Bureau	(USACE & DRBC, 2008)
2000	7.759	U.S. Census Bureau	(DRBC, 2008)
2010	8.3	U.S. Census Bureau	(DRBC, 2013)
2010	8.252	U.S. Census Bureau	(Thompson & Pindar, 2021)
2016	8.3	American Community Survey	(Byun et al., 2019)
2020	8.629	U.S. Census Bureau	(DRBC, 2021)

as historical population estimates (adapted from Thompson & Pindar, 2021). Details on the historical population estimates are provided in Table 1.

A key observation highlighted in Figure 2 is the inverse relationship between the volume of water withdrawn by public water suppliers and the population residing within the Delaware River Basin. The annual average water withdrawal by public water suppliers has decreased by over 100 MGD in the past 30 years, while the population of the Delaware River Basin has grown by about 1.3 million people. Projections of water withdrawals and the in-Basin population were published by Thompson & Pindar, 2021, and are also shown in Figure 2. While the projection for withdrawals provides a slight overestimate, the projection trend of continued decreases has seemingly been realized in recent years. Additionally, it appears that the Thompson & Pindar, 2021 population projection was reasonable in suggesting growth of 0.278 MM people since 2010, in light of the more-recent estimated growth of 0.377 MM people based on 2020 USCB data.

There are approximately 900 public water supply systems within the Basin. The number of systems was determined by a count of the Public Water System Identification (PWSID) numbers in the U.S. Environmental Protection Agency's (USEPA) Safe Drinking Water Information System (SDWIS), that have a service area footprint within the Delaware River Basin. The Safe Drinking Water Act of 1974 defined the term "public water supply system" as "*a system for the provision to the public of piped water for human consumption, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals*" (Pub. L. No. 93-523, 88 Stat. 1660). This definition has largely been accepted by state agencies:

- PADEP Safe Drinking Water Regulations (25 Pa. Code §109)
- NJDEP Safe Drinking Water Act Rules (N.J.A.C. 7:10)
- DHSS Public Drinking Water Regulations (16 Del. Admin. C §4462)
- NYSDOH Drinking Water Supplied Regulations (N.Y.C.R.R. tit. 10)

Not all public water supply systems are subject to Commission regulations. Thompson & Pindar, 2021 indicated that there were 335 public water supply systems subject to Commission regulations, and that these systems accounted for 99% of the total Basin-wide withdrawals by public water suppliers. As of 2021, 300 of those systems are required to comply with Sections 2.1.6 and 2.1.8 of the Delaware River Basin Water Code and must annually submit a water audit using the AWWA FWAS. For the vast majority of the withdrawals by public water suppliers in the Basin, DRBC has been collecting data on infrastructure and operational performance for ten years (2012-2021).

1.4.3. Population served by public water supply

A common variable reported to the USEPA SDWIS is the population served by each system registered to a PWSID number. While population served has been added as a data input field for the newest version of the AWWA FWAS (v6.0 update), DRBC has found that it has not been completed with a high degree of accuracy as it is relatively new (v5.0 of the software did not include this field). Therefore, population served data has been retrieved for public water supply systems using the USEPA SDWIS via the R package {echor} (Schramm, 2020). At the time of this study, the most recent SDWIS data were retrieved on May 25, 2023. In total, data for 911

PWSID numbers were retrieved, of which 328 are associated with the 300 systems required to submit water audits to DRBC in 2021. The included systems, with key characteristics of each, are identified in Appendix A.

The population served for each PWSID number has been adjusted by the percentage of the appurtenant service area within the Delaware River Basin, based on a GIS analysis. This method estimates that the total population within the Basin served by public water supply systems is 7.366 million people, and is assumed to reflect the same general time-frame as the 2020 USCB population estimate of 8.629 million people (DRBC, 2021). Therefore, these findings suggest that in 2020, about 85% of the Basin population was served by public water supply. It is interesting to note that entirely different methodologies yield comparable percentages for the population served by public water supply, notwithstanding that one methodology is based on 2010 data and the other on 2020 data. A breakdown of the population data retrieved from SDWIS is presented in Figure 3.

The most recent year of data analyzed in this report (CY2021) indicates that 300 systems are required to submit water audits (328 PWSIDs). These involve over 29,000 miles of water main and 2.5 million service connections (active and inactive). The systems range in size from very small (e.g., a village in upstate New York with under four miles of water mains and about 185

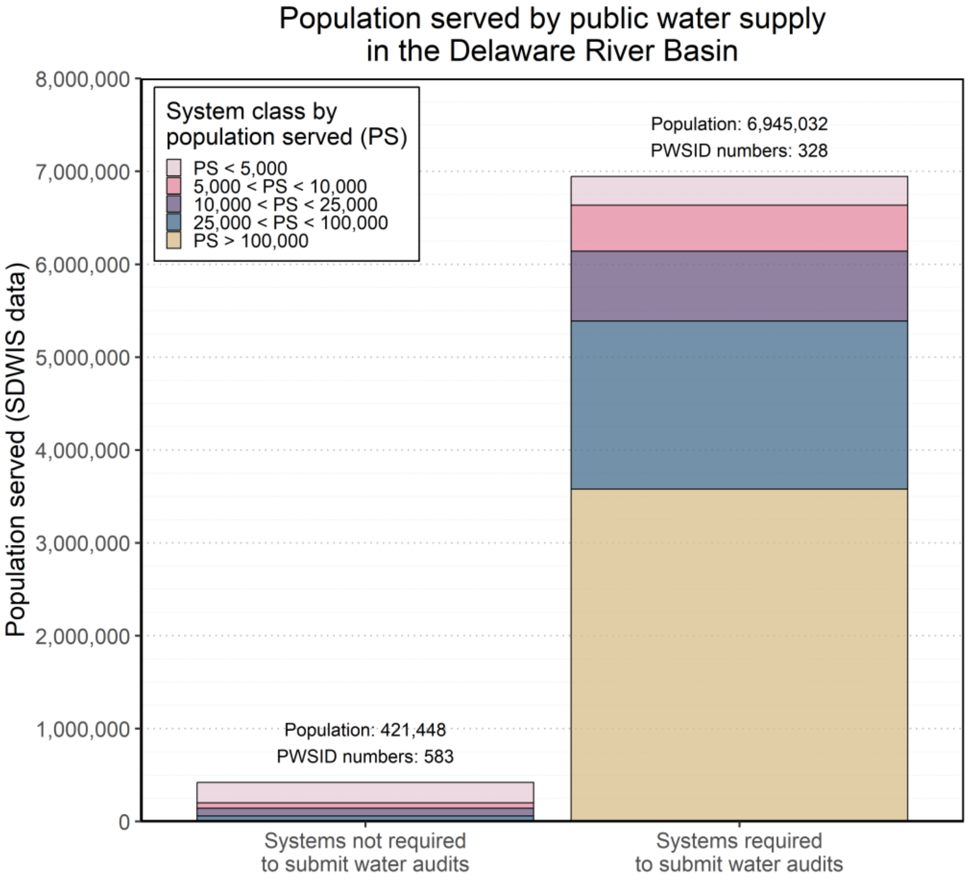


Figure 3*: Population served by public water supply systems within the Delaware River Basin. Population served data obtained from USEPA SDWIS for PWSID numbers with at least a partial service area within the Delaware River Basin boundary. Population served data is adjusted for each PWSID based on the percent of service area within the Delaware River Basin boundary.*

connections), to the 6th largest city in the United States – the City of Philadelphia (with over 3,000 miles of water mains and over 500,000 connections). Therefore, it is appropriate to classify each system by size. In this report, classification by size is based on the number of connections within the system, as defined in Table 2. The need for such a schema is illustrated by Figure 4. These subplots highlight the two extreme scenarios:

1. 15 Very Large systems within the Basin, roughly, have a combined 1.430 million connections and 13,500 miles of mains, and serve an estimated 4.115 million people.
2. 94 Very Small systems, roughly, have a combined 0.048 million connections and 960 miles of mains, and serve an estimated 0.155 million people.

1.5. System infrastructure and asset condition

There is a long history of waterworks (i.e., water supply systems) within the boundary of the Delaware River Basin. In fact, two of the fourteen water supply systems built before the Declaration of Independence was adopted in 1776 are within the Basin boundary: (1) the Bethlehem Water Works, built in 1754, now operating as Bethlehem Authority and serving the City of Bethlehem and (2) the Nazareth Water Works, built in 1773, now operating as the Blue Mountain System owned by Pennsylvania American Water (Pierce, 2022). Furthermore, seven of the ten Very Large systems operated by local governments (“public systems”) in this analysis are cities for which the average year of establishing a waterworks is 1801. While infrastructure gets replaced over time (as illustrated by the fact that all wooden mains in Philadelphia were taken out of service by 1859 (WEF, 2017)), it is a process that utilities must balance with external factors such as financial constraints, competing priorities, feasibility, regulatory requirements and societal needs.

As part of the NJDEP Asset Management Policy Program, a survey of both community public drinking water systems and permitted wastewater utilities (handling residential waste) was conducted in 2016 and serves as a baseline assessment of the current state of asset management in New Jersey (NJDEP, 2016). Responses from 443 drinking water systems indicated that 70% had some form of asset tracking and, while some use enterprise software, most rely on either spreadsheets (such as Microsoft Excel) or paper records. It was also reported that only about 40% of systems incorporate the use of Geographical Information Systems (GIS) to provide electronic mapping, the remainder relying on things like blueprints or schematics. As might be expected, a general trend can be observed that the larger utilities more frequently reported use of more advanced asset management methods (such as software, or GIS). AWWA performed similar surveys at a national scale in 2015 (AWWA, 2015) and 2020 (AWWA, 2023).

The concept of asset condition is not quantifiably considered within the context of this study (e.g., data on pipe material and age). The data in this report are based largely on the AWWA FWAS, which collects only high-level data on system infrastructure (such as the number of connections, or the length of mains). The AWWA FWAS does not require more detailed information such as the percentage of mains which are made of particular materials, or the percentage which are within particular age brackets. Some ongoing work has attempted to compile data nationally, such as the National Water Pipeline Infrastructure Database (PIPEiD), which is a project led by a

***Table 2**: System size class definitions.*

System size class	Abbv.	Active/Inactive Connections
Very Small	VS	< 1,000
Small	S	[1,000, 5,000)
Medium	M	[5,000, 10,000)
Large	L	[10,000, 20,000)
Very Large	VL	≥ 20,000

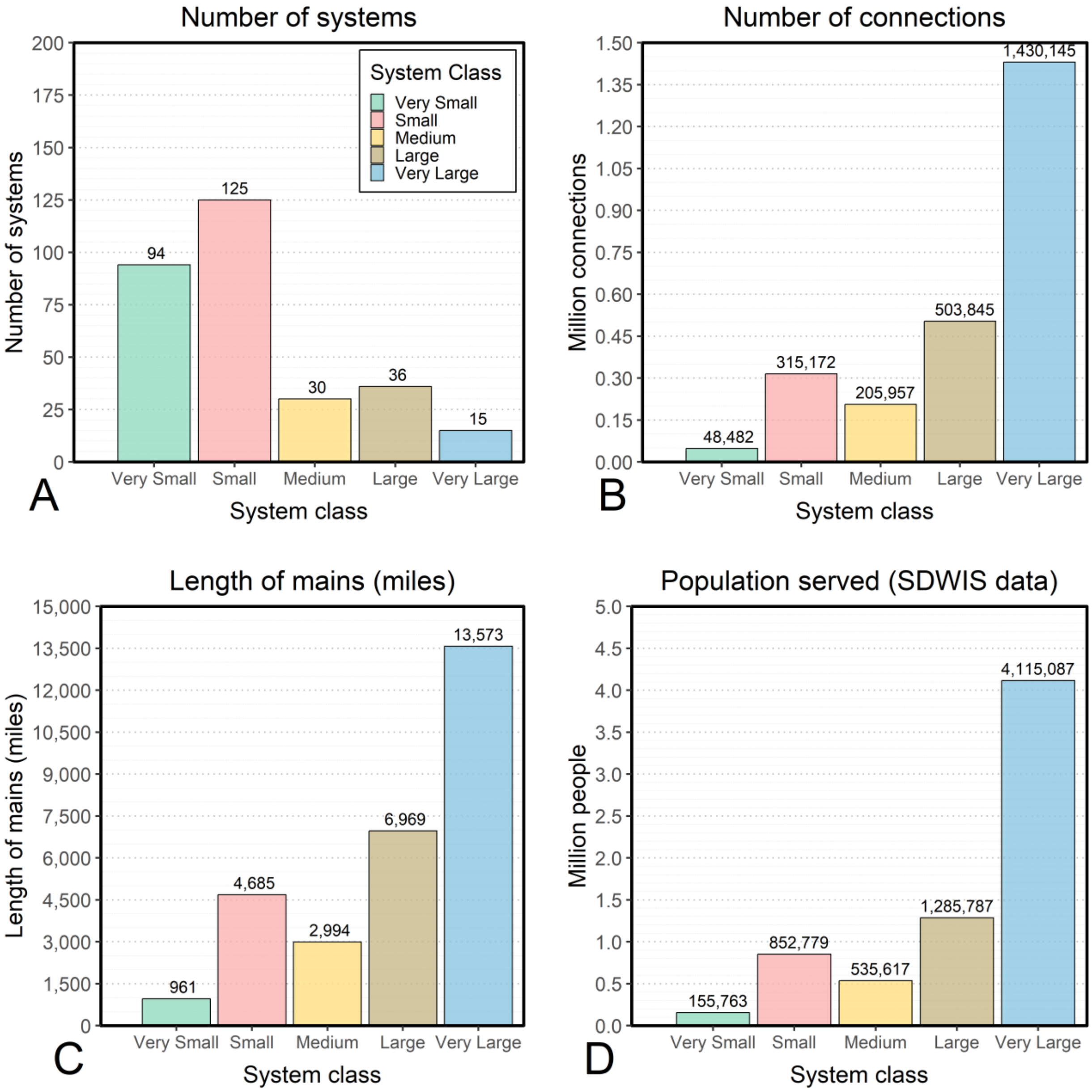


***Figure 4:** Data for the 300 systems meeting DRBC water audit requirements for the year 2021, comprised of 328 PWSID numbers.*

research team at Virginia Tech, funded by the United States Bureau of Reclamation (USBR) (Virginia Tech, 2017). However, at the time of this study, the PIPEiD project is still ongoing and is not comprehensive across the Delaware River Basin. Additional work in this area of asset condition data, specific for systems within the Delaware River Basin, may offer additional benefits for future planning studies. While challenging, it may also benefit the reader to qualitatively consider concepts such as system age or asset condition while reviewing this report.

1.6. Out of scope

In addition to public water supply serving populations largely within the Delaware River Basin, significant withdrawals for export from the Basin are made by two of the Decree Parties pursuant to a 1954 U.S. Supreme Court Decree (347 U.S. 995, 1954). This decree authorizes:

1. The withdrawal of up to 100 MGD from the Delaware and Raritan Canal and export to northern New Jersey primarily for public water supply.
2. The withdrawal of up to 800 MGD from three reservoirs in New York (Cannonsville, Neversink, and Pepacton) and export to New York City for public water supply.

Because these exportations are not subject to DRBC audit requirements, it is unclear whether all withdrawals associated with them are audited using the AWWA FWAS. Therefore, they are not addressed in this report. However, it can be noted that New York City Department of Environmental Protection (NYCDEP) publishes a Water Demand Management Plan every five years, most recently in 2023 (NYC DEP, 2023b), as well as annual updates to this plan. The 2022 Demand Management Annual Update (NYC DEP, 2022) provides a summary of results from a water audit of the NYCDEP system in CY2021 (done with AWWA FWAS v5.0), which indicate that water losses were approximately 58,251 MGY (about 160 MGD). Additionally, the real losses were estimated to be 41,926 MGY (about 115 MGD) at a unit rate of about 137 gallons per connection per day (gcd). NYCDEP has previously estimated that water from the Delaware River Basin comprised between 45-50% of the New York City water supply (DRBC, 2023). Note that the AWWA FWAS water audit typically does not include the conveyance of raw water to treatment facilities within the scope of calculation. An audit by NYCDEP would therefore not include water lost in transit via the City's aqueduct system. For example, the City's Delaware Aqueduct, which conveys Delaware Basin water to the Hudson River Basin, has been leaking upwards of 30 MGD since the 1990s. A repair is planned to commence in 2024 after nearly a decade-plus of coordinated technical study, engineering, planning, and modeling (NYC DEP, 2023a).

1.7. Closing introductory remarks

It has been ten years since annual submissions of a water audit became required for many public water supply systems in the Delaware River Basin. This study analyzes the data and lessons learned over the course of the decade to compile a current view of water conservation by public water supply systems in the Basin. Additionally, it offers an opportunity to look back and analyze historical data to assess the trend of water conservation by these systems. The analyses performed in this study will provide information for both the Delaware River Basin as a whole, and for the classes of systems defined in Table 2.

2. BACKGROUND

As stated in AWWA's M36 Manual for Water Audits and Loss Control Programs, "*Community water supply systems around the world have been instrumental in improving the human condition by providing essential water to promote public health and safety and to serve as a basis for economic development"* (AWWA, 2016b). Within the Delaware River Basin, over 900 public water supply systems advance public health, safety, and economic objectives. Based on data from the 300 systems that are subject to the DRBC's water audit program requirements, these systems collectively involve over 29,000 miles of water mains, 2.5 million service connections, and likely over 12,000 miles of service lines (based on the number of connections multiplied by service line length). Such expansive infrastructure does not come without its challenges. As stated in an AWWA whitepaper on the state of water loss control in drinking water utilities, it is a hard truth that "*All drinking water utilities have water losses, however, the extent varies from system to system*" (AWWA, 2016a). Therefore, monitoring and collecting the data necessary to evaluate system performance is a critical step in water conservation planning. This section of the report discusses what water loss is, the history of tools developed to collect data, water conservation programs that use such tools, and landmark water audit datasets.

2.1. Unaccounted-for water

The reality that all water put into a distribution system does not reach its final destination is not a novel conclusion. However, it has only been possible to quantify such water losses when data collection via metering began. As early as 1904, this concept was proven by Mr. Dexter Brackett (chief engineer of the Metropolitan Water Works of Boston) who delivered a Report On The Measurement, Consumption and Waste of Water Supplied to the Metropolitan Water District to the New England Water Works Association (NEWWA) (Brackett, 1904). In this report, Brackett provided data on towns that had 100% of the service connections metered, allowing for a quantification of the water losses via meter calculations. Specifically for two of the eighteen towns served by the Metropolitan Water Works (Milton, MA and Belmont, MA), he compared the total water supplied to individual takers (metered customers) to the total quantity supplied to the towns. These two towns were selected because "*In the Metropolitan District in the town of Milton the water supplied to every taker is metered, including that used for street watering and other public purposes. In Belmont all supplies are metered, and a careful record is kept of the number of loads of water used for street watering.*" Additionally, Brackett noted that the meters had only been used in the town "but a few years" such that the error could not be more than 2-3%. He calculated a percent of water that was "unaccounted for" as the ratio of (1) the difference between the volume of water supplied to the town and the volume metered to customers, to (2) the total volume supplied to the town. He then provided data from seven towns and cities not served by Metropolitan Water Works, but which were substantially metered (upwards of 85-100%) and concluded that "*a large percentage of water delivered into the mains from the reservoir or pumps is unaccounted for by the meters*." This study was expanded upon by Johnson, 1907, who compiled data from 1905 for 21 systems (12 of which were >90% metered) and presented a range of calculated values for unaccounted-for water as a percentage of the total quantity of water pumped.

By 1912 the NEWWA Committee of Water Consumption had accounted for leakage as a major component of the water budget, stating that the four "uses" were: (1) domestic uses, (2) industrial uses, (3) public uses (e.g. firefighting, street cleaning, schools, municipal buildings), and (4) leakage and unaccounted-for water (Metcalf et al., 1912). At this point, it was a seemingly common practice that the difference between water supplied and the total measured by service meters be compared to the total supplied as a percent unaccounted-for water (%UFW). Given the increase in newly available data from systems which had become substantially metered, the %UFW variable had already become (unknowingly or not) a performance indicator. – as shown by the discussions later in the 1912 report from the Committee of Water Consumption:

> *In general, it may be said that if, in a well-metered system, the water-unaccounted-for does not exceed 25 per cent, of the total pumpage, the practice is good. If, on the other hand, as is often the case, the leakage or water-unaccounted-for amounts to 40 per cent, or more of the pumpage, the practice is not good and it is probable that measures taken to reduce the amount of this leakage will effect a substantial saving in leakage and consequent reduction in expense of operation.* (Metcalf et al., 1912)

In 1916, the NEWWA Committee on Meter Rates was charged with and provided an analysis on the "*amount of water not accounted for*", in which it assessed 35 systems across the country which were "completely metered, or nearly so" (Hazen et al., 1916). In total, 29 of the systems had the data necessary to estimate the water not accounted for, and the study concluded that "*The water not accounted for averaged 27.0 per cent. of the total output.*" This statistical methodology to obtain a representative indicator of system performance continued to be used by Howson, 1928 (surveyed 85 completely metered systems in the country, obtaining a usable dataset of 44 systems, concluding an average %UFW of 26.5%, or approximately 31 gallons per capita per day unaccounted for), Mabee, 1928 (sent questionnaires to "*several hundred cities, large and small, and widely spread*", and based on 121 of the cities, concluded an average %UFW of 24.72%) and Whitman, 1932 (estimated the average %UFW of 12 American cities at 25%).

Beyond quantifying unaccounted for water, Hazen et al., 1916 also classified how water may be lost, stating four possibilities as (1) leakage from the mains in the streets, (2) leakage from the service pipes between the mains and the meters, (3) under-registration of meters (sometimes referred to as "slippage"), and (4) water used for various purposes, not registered or estimated, as, for instance, water used for flushing sewers. Notably, in the preceding year, the Journal of the American Water Works Association Hill, 1915 noted that water unaccounted for could also include (5) failure to account for pump slippage when measuring system inputs via pump displacement, a view shared by Chester & Bankson, 1924 (although this factor is mostly no longer relevant, as public water supply systems more than likely have installed master meters).

In 1926 the American Water Works Association (AWWA) published its first edition of a comprehensive manual titled Water Works Practice (AWWA, 1926). This manual appears to have adopted the terminology %UFW, and provides one of the older formal textbook definitions:

> *Water unaccounted for is that portion of the water flowing into a distribution system which is not delivered to the consumers*.

2.2. Accounting for the water

It was highlighted by Thornton et al., 2002 that "*Compiling a reliable water audit or water balance is the critical first step in managing losses in public water supplies*." Yet at the time it was published, the practice of performing an annual audit of the water balance within a water supply system had been fairly uncommon. Thornton et al., 2002 notes that "*Throughout the 1990s, efforts were made to develop a rational, standardized water audit methodology and water loss performance indicators*."

2.2.1. Developments in the United States

The term unaccounted-for water and the corresponding performance indicator %UFW had become accepted within the United States as early as 1912 (Metcalf et al., 1912). While less consistent and usually presented in combination with %UFW, the total UFW had also been expressed as a volume per mile of pipe (Brackett, 1904; Hill, 1915), per service connection (Hazen et al., 1916; Metcalf et al., 1912), per capita (Howson, 1928), or per meter unit (Hazen et al., 1916). However, by as early as 1939 it was recognized that the term "unaccounted-for water" may not be the most appropriate phrase ascribed to its definition. As stated in an article titled Increasing the Efficiency of Water Systems, Cook, 1939 wrote the following:

> *The term "unaccounted for water" means but little, as it is too easy, with present day methods, to account for water… . Therefore it is the writer's opinion that in discussing the question of system efficiencies… the subject matter should include all water supplied by a system for which direct revenue is not received.*

This concept was proposed again in 1947, when Haydock, 1947 suggested:

> *Unaccounted-for water means different things to different people; to the author it represents the water introduced into the distribution system and not recorded on customers' meters. In a completely metered system, unaccounted-for water can therefore be described as nonrevenue-producing water.*

In 1950, Egbert D. Case (president of the then Pitometer Company) notably wrote an article with an opening statement challenging the usefulness of %UFW as a benchmarking performance indicator:

> *No specific percentage of unaccounted-for water can be regarded as satisfactory for all water systems… . Many factors must be considered before it can be said that the unaccounted-for figure is too high or too low.* (Case, 1950)

Case, 1950 explains that the factors requiring consideration include: (1) master meter accuracy; (2) large consumption connections (e.g. industry) and the effect on percentage calculations; (3) estimates of unmetered usage; (4) meter under-registration and testing frequencies; and (5) unavoidable leakage (which was defined as "*underground leaks which exist in every system and which would cost more to locate and repair than to permit to exist*"). Studies as early as 1897 estimated such unavoidable leakage using methods based on the number of joints and connections, and found results ranging from 2,500 to 3,000 gpd per mile of main (Kuichling, 1897), which led The Pitometer Company to adopt a value of 3,000 gpd per mile of main (a standard value previously referenced by Myers, 1946, when discussing "*permissible underground leakage*").

To move beyond UFW, and consequently, %UFW, would require a methodology to quantify the water entering and exiting a system at all phases of the water supply process, and as Cook, 1939 stated, the methods to do such water accounting were seemingly present in the 1930s. Yet while the method may have been understood, obtaining reliable data required by the method is another challenge in and of itself. Coincidentally in the 1940's, AWWA embarked on a landmark series of studies to collect national scale data from hundreds of water works systems and to provide statistical analyses on the data, which it called A Survey of Operating Data for Water Works. These surveys and associated analyses were performed for 1945 (AWWA, 1948; Schroepfer et al., 1948), 1950 (AWWA, 1953; Seidel et al., 1953), 1955 (AWWA, 1957; Seidel & Baumann, 1957), and 1960 (AWWA, 1964; Seidel & Cleasby, 1966). A single analysis was performed for surveys in 1965 and 1970 (AWWA, 1974; Seidel, 1978), followed by another for surveys in 1976, 1978 and 1980 (Seidel, 1985). A major focus of this series became an analysis of system production and distribution, for which each category had a suite of data parameters. In many of the surveys, this data could provide an indicator of a system's efficiency in terms of water losses.

- The initial 1945 survey was limited and only collected data on the total water produced (own sources and imports), and the total sales; by 1950, the survey was expanded to calculate the performance metric of "% production sold".
- In 1955 the sales number was replaced by "distribution" which was comprised of both "sales" (in current terms, billed metered, billed unmetered, or both) and "free service" (in current terms, unbilled metered, unbilled unmetered, or both). The 1955 survey also replaced the metric "% production sold" with "% production unaccounted for".
- The 1960 survey analysis grouped total sales to all categories (retail, public, wholesale) under the heading "revenue-producing water", and a metric was provided as % revenue producing water, which was likely a function of adopting terminology from Revenue-producing Versus Unaccounted-for Water (E. S. Cole et al., 1957). Notably, water provided for free was considered separately. The remaining water volume was considered distribution system losses and was referred to as unaccounted for water. The survey for 1965 was carried out in a similar manner.
- In 1970 an additional change to the survey was performed to remove unmetered water (i.e. flat rate water [billed unmetered] and unmetered free service), which inherently was then included in the UFW value.

A noteworthy observation from the AWWA series A Survey of Operating Data for Water Works is that data on some widely known factors of UFW were not captured by the survey (such as meter inaccuracy, unauthorized use estimates and unavoidable leakage estimates). While some took a step to quantify "sales" (billed metered and/or billed unmetered) and "free service" (unbilled metered and/or unbilled unmetered water), no survey collected enough data to confidently eliminate the term unaccounted for water – and may have simply been a function of the availability of data and scale of the study at that time in history.

In 1970, AWWA published a Survey Form for Evaluating Water Utility Operations which was intended to serve as a standardized form for utility managers to assess a system's distribution performance (E. S. Cole, 1970). Similar to some of the AWWA surveys conducted between 1945-1981, the form includes data inputs for what are now referred to as billed metered, billed unmetered, unbilled metered, and unbilled unmetered water; however, the focus remained on calculating a ratio between metered consumption and the system inputs ("metered ratio"). In a review titled Accounting for Unaccounted-for Water, Bennevelli, 1978 discussed the major components understood to comprise UFW and how to accurately account for them (which included meter inaccuracies and unavoidable leakage). Furthermore, Bennevelli, 1978 suggested that an annual "audit" of the UFW components should be performed – the form published by E. S. Cole, 1970 was referenced, however, it still did not account for all the components of UFW outlined by Bennevelli, 1978 (e.g. meter inaccuracies, unavoidable leakage). And while it appeared to be common knowledge that UFW is most appropriately broken down into more detailed quantifiable components, most studies addressing system performance still held a primary focus on reducing unaccounted for water (AWWA, 1987; Hudson, 1978; Moyer, 1985).

In 1987, concepts of water loss prevention took a step forward in a study published by the American Water Works Association Research Foundation (AwwaRF)[1], titled Water and Revenue Losses: Unaccounted-for Water (Wallace, 1987). Among the recommendations made in this study, three are specifically worth highlighting in the context of this report:

> 1. *Because of the deep seated allegiance to existing, conflicting definitions of "unaccounted-for water", it is recommended that both existing definitions no longer be used. In their place, it is recommended that all water for which there is a metered account be called "account water" and all other water can be labeled "non-account water".*

This first recommendation stems from an observation that there was wide inconsistency in how UFW was defined among different utilities. Notably, it pre-dates the same observation made internationally by Cheong, 1991 which served as the impetus for standardizing water loss definitions in Lambert & Hirner, 2000. And while the terminology proposed by Wallace, 1987 did not take hold, the terms are conceptually similar to "revenue water" and "non-revnue water," which became the industry standard after Lambert & Hirner, 2000.

> 2. *The most comprehensive method to determine water loss is to conduct a complete water audit. A comprehensive water audit can reveal the true operational efficiency of a utility and the magnitude of specific water and revenue losses.*

Specifically, Wallace, 1987 recommended use of the water audit methodology developed by the California Department of Water Resources (CADWR), and the AWWA California-Nevada Section (Carr & Pike, 1986). Ultimately, the method was adopted in whole as the first AWWA Manual M36: Water Audits and Leak Detection (AWWA, 1990).

---

[1] The AWWA Research Foundation (AwwaRF) formally changed its name to the Water Research Foundation (WRF) in 2009.

> 3. *Unavoidable Leakage includes water from all underground leaks which, due to the small amount of actual water lost, would cost more to locate and repair than the value of the water saved over a reasonable amount of time."*

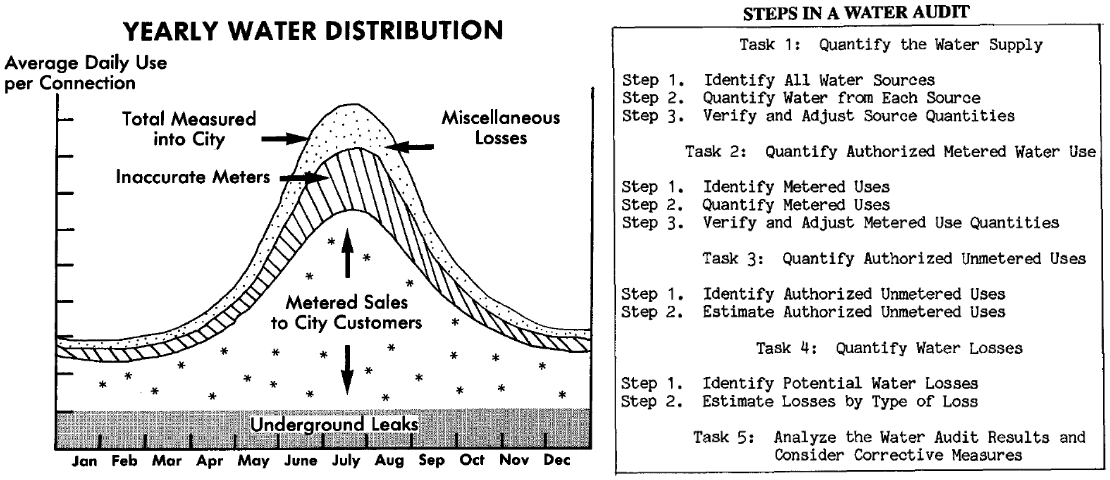
This was the recommended definition of unavoidable leakage provided by Wallace, 1987, who included an entire appendix on the subject, which discussed the work of Kuichling, 1897. As a part of the AwwaRF study, a master's thesis at Brigham Young University attempted to develop an emperical equation for an "Unavoidable Leakage Index Equation" based on parameters such as pipe age, pipe diameter, the number of joints, hydrants, valves, and service connections, as well as pressure (J. C. Smith, 1987).

2.2.1.1. (1986) Water Audit and Leak Detection Guidebook

A significant step in water conservation analytics was made in 1986 when Water Audit and Leak Detection Guidebook was published jointly by the State of California Department of Water Resources (CADWR) Water Conservation Office, and the AWWA California-Nevada Section (Carr & Pike, 1986). This guidebook introduced a method for performing a comprehensive survey of a water supply system in order to better understand and quantify where water went once it passed through a system's master meter. The method was called a "Water Audit" and was defined as "*a thorough examination of the accuracy of water agency records and system control equipment… to identify, quantify, and verify water and revenue losses.*" Under this methodology, the difference between the master meter(s) and the total water delivered to customers was referred to as "unmetered water" (as opposed to unaccounted-for water). The method quantifies many components of the unmetered water, and by process of elimination quantifies what the guidebook's authors assumed to be water system leakage. Some of the primary components of data analyzed include:

- **Total Water Supply**
  (corrected for errors in meter accuracy and other areas)
- **Authorized Metered Water**
  (corrected for meter inaccuracies and meter reading lag time)
- **Authorized Unmetered Water**
  (such as firefighting, system flushing, storm drain flushing, sewer and street cleaning, unmetered municipal connections, water system testing)
- **Identified Water Losses**
  (including accounting procedure errors, illegal connections, malfunctioning system controls, reservoir seepage and leakage, evaporation, reservoir overflow, discovered leaks and theft)
- **Potential Water System Leakage**

A schematic was presented which details the components of annual water delivery from a typical water system (reproduced as Figure 5), and it is clear how the steps in the water audit help quantify each component. The second portion of the guidebook focused on leak detection and leak detection surveys.



STEPS IN A WATER AUDIT

Task 1: Quantify the Water Supply

Step 1. Identify All Water Sources
Step 2. Quantify Water from Each Source
Step 3. Verify and Adjust Source Quantities

Task 2: Quantify Authorized Metered Water Use

Step 1. Identify Metered Uses
Step 2. Quantify Metered Uses
Step 3. Verify and Adjust Metered Use Quantities

Task 3: Quantify Authorized Unmetered Uses

Step 1. Identify Authorized Unmetered Uses
Step 2. Estimate Authorized Unmetered Uses

Task 4: Quantify Water Losses

Step 1. Identify Potential Water Losses
Step 2. Estimate Losses by Type of Loss

Task 5: Analyze the Water Audit Results and Consider Corrective Measures

Figure 5: *Adopted from Carr & Pike, 1986, (left) a figure showing the yearly water distribution (courtesy of Community Consultants Inc.) and (right) the steps in a water audit as were presented in Table 1 of the guidebook.*

2.2.1.2. (1990) AWWA M36 Manual

The guidebook (Carr & Pike, 1986) was ultimately adopted in whole as the first AWWA Manual M36: Water Audits and Leak Detection (AWWA, 1990). This marks one of the first times in the United States that a comprehensive methodology for assessing leak detection was published, notably without reference to unaccounted-for water. Instead, water entering a distribution system was quantified as one of: authorized metered or unmetered water, water losses (both physical and administrative), or system leakage. Notably, the M36 manual relayed an estimate from Carr & Pike, 1986 (who stated that 75% of leakage could be recovered) and suggested that "recoverable leakage" be calculated accordingly. Today, this approach would be considered outdated, as many more rigorous analytical methods exist for estimating possible leakage reductions.

2.2.1.3. (1996) Performance Benchmarking for Water Utilities

Between 1994-1995, the Stroud Water Research Center completed a study titled Performance Benchmarking for Water Utilities, published by the AwwaRF (Kingdom et al., 1996). A major focus of the study was "metric benchmarking," which was defined as the quantitative measurement of performance in terms of inputs, outputs, outcomes and the relationships between them (although more recently, the IWA Specialist Group of Benchmarking has strongly recommended using the term "performance assessment" instead of metric benchmarking (Cabrera Jr. et al., 2011). Kingdom et al., 1996 noted that the performance assessment process begins with the determination of appropriate "performance measures" (synonymous with "performance indicators"). Twenty-one organizations, including water utilities, water authorities, government agencies and commissions (DRBC among them), participated in project meetings and helped to develop comprehensive lists of performance measures. These 267 performance measures were grouped into four levels, and measures in Levels 2 through 4 were grouped into categories such as "Water Resources," "Water Treatment," and "Water Distribution", as shown in Table 3.

***Table 3**: A summary of efficiency performance measures defined in Kingdom et al., 1996. The number in each box represents the number of performance measures defined in each category.*

Performance Measure Group	Adequacy	Customer Service	Reliability	Quality	Expense	Revenue	Financial	Resource Utilization	Managerial	Operational	Maintenance	Asset Management	Capital Efficiency	Others	**Subtotals**
Level I	2	6			15	5	19	10	2	1		5			65
Level II-IV - Water resources	9		3	1	15			5	2						35
Level II-IV - Water Treatment	2		2	5	20			10	3		5			3	50
Level II-IV - Water Distribution	2	1	3		12			6	2		6			5	37
Level II-IV - Planning Function	10	2			3			1	2				4	2	24
Level II-IV - Support Function	11		3	9	14			9	10						56
Subtotals:	36	9	11	15	79	5	19	41	21	1	11	5	4	10	267

Of note as it relates to water conservation and efficiency, water losses were primarily captured by one performance measure within Level I under the heading "Operational" as the "*Level of unaccounted for water*". While not as detailed as components of water loss proposed by (Carr & Pike, 1986), it was noted that the metric could be reported as either a percentage or as gallons per day per mile. Other metrics associated with water loss and leak detection were presented within Level II-IV - Water Distribution, such as main breaks per mile of pipe, the speed of response to customer requests for repair of a leak, leakage operation and maintenance (O&M) costs as a percentage of the total O&M costs, and meter accuracy as a percentage (to name a few). While not capturing the methodological shift away from UFW to more detailed assessments of water loss, Kingdom et al., 1996 did provide a comprehensive framework for future studies assessing water utility performance metrics.

2.2.2. Developments in the United Kingdom

As discussed in OFWAT, 2006, in 1945 England and Wales had more than 1,000 entities involved in the supply of water and 1,400 responsible for sewerage and sewage disposal. Since most of these were local authorities, water resource planning was often localized. Post-World War II legislation related to water resources culminated in the Water Resources Act 1963, which created a new class of authorities beyond water and sewer authorities. Specifically, the 1963 act created 27 river authorities, each with a role to conserve, redistribute and augment water resources in England and Wales on a regional basis. For the first time, groundwater and surface water abstractions had to be licensed by the river authorities. The legislation also created a new Water Resources Board, which was a national agency designed to advise the government and river authorities on water resource conservation.

By the early 1970s, Parliament recognized a need for change and passed the Water Act 1973. This legislation defined the boundaries of ten authorities, which were charged with the responsibilities formerly performed by public water, sewer and river authorities. (The legislation did not consolidate privately owned statutory water supply companies.) The 1973 act also established the National Water Council (NWC) as an independent statutory body to act as a link between the central government and the water authorities on general issues.

When over time problems related to capital investment and increasing customer rates developed within each of the ten authorities created by the Water Act 1973, Parliament passed the Water Act 1983, which changed the organizational structure of the authorities to allow a more “business-like” operation, with the idea that a more efficiently run utility would help curb customer rate increases. The 1983 legislation also abolished the NWC.

Following years of continued planning, the Water Act 1989 provided a mechanism for privatizing the industry, transforming the ten authorities into new water and sewerage companies. It also maintained 29 statutory companies that became registered “Water Only Companies.” and also created the National Rivers Authority (NRA) to manage pollution and environmental control, and to license water abstractions.

In short order, four Acts of Parliament—the Water Industry Act 1991, Water Resources Act 1991, Statutory Water Act 1991, and Land Drainage Act 1991—codified all past legislation still in force. Notably, the Environment Act 1995 created the Environment Agency which became fully operational in 1996, assuming responsibility for the functions of the NRA.

2.2.2.1. (1980) Leakage Control Policy and Practice

Before the NWC established by Water Act 1973 was disbanded by Water Act 1983, the organization produced a report on leakage for the water industry of England and Wales. Published in 1980, *Leakage Control Policy and Practice* (known as “Report 26”) noted:

> *A figure representing the level of leakage within an undertaking may be required for purposes other than leakage control but the only practical way of obtaining an acceptable figure is by making an estimate of unmetered consumption (either total daily consumption or night consumption). (DOE & NWC, 1980)*

The DOE & NWC, 1980 proposed two methods for estimating leakage: (1) the "total integrated flow" method, and (2) the "total night flow" method. In discussing which terms should be used to express leakage, the report notes that although percentages are the most common expression, they are not recommended. Instead, the authors propose the use of two different metrics—liters/property/hour for urban areas, and liters/km of main/hour for rural areas (DOE & NWC, 1980).

2.2.2.2. (1991-1994) National Leakage Control Initiative

Following four years of drought (1988-1992), the Department of the Environment (DOE) Welsh Office published a 1992 consultation paper titled "Using Water Wisely." The paper noted how the drought highlighted the importance of working with environmental forces, stating, "*This is a time to take stock of our attitude to water, to see whether we are using it in the wisest way.*" (DOE, 1992). The paper presented key data and information related to the evolving priorities within the UK's water industry at the beginning of the 1990s, dedicating much of the discussion to the reduction of leakage. It mentions that the privatized water companies (the Water Services Association and the Water Companies Association) had formed a Joint Leakage Control Steering Group to produce a series of technical reports to update the "code of practice" on leakage used at the time (Report 26, DOE & NWC, 1980). This effort, initiated in 1991, was referred to as the National Leakage Control Initiative (NLCI). The NLCI was comprised of nine project groups consisting of over fifty water industry professionals. In 1994, its findings were published nine reports on different topics under the common title "Managing Leakage." Some of the more significant features of the NLCI study are described here:

(1) Recognition of inconsistent definitions, and the resulting inclusion of a glossary of terms, produced a structure similar to that of current day water budgets.

(2) Report B, "Reporting Comparative Leakage Performance," focused on performance metrics for reporting purposes, and how to equitably compare systems. It recognized that Report 26 had suggested a measure of liters/property/hour for urban areas and liters/km of main/hour for rural areas, but the NLCI study noted that liters/property/hour had become the commonly accepted measure. With considerable debate as to what the correct measure might be, Report B recommended (m^3/km of distribution system/day) (NRA, 1995). However, within five years it was recognized by the 1st IWA Water Loss Task Force that both 'per service connection' and 'per mile or per km of mains' should be retained, the choice being influenced by the number of connections per mile of mains (A. Lambert, personal communication, 2023).

(3) Report C, "Setting Economic Leakage Targets," outlined two possible basic approaches for the optimum level of leakage, updating the method set forth in Report 26.

(4) The study introduced the "Bursts and Background Estimate" (BABE) concept. In North America, this concept is oftentimes referred to as a component analysis of leakage.

2.2.2.3. (1994) Bursts and Background Estimate (BABE)

The Bursts and Background Estimate (BABE) methodology developed to support the NLCI is a method for estimating annual real losses considering the major categories of real losses and the system infrastructure components. The former are identified as reported bursts, un-reported bursts, and background leakage, while the latter include, for example, trunk mains, distribution mains, and supply piping (Lambert, 1994). The model was built as a Microsoft Excel spreadsheet, using component data in three categories: (1) standard components (e.g. pressure), (2) auditable local data (e.g. burst data), and (3) company policies. The BABE model also later served as the foundation for development of an equation describing the Unavoidable Annual Real Losses (UARL) for distribution systems (Lambert et al., 1999), discussed in Section 2.2.3.2 of this report.

2.2.3. (1996-2000) International Water Association

Similar to what had been discussed at a national scale in the United States in Wallace, 1987, a 1991 International Water Supply Association[2] (IWSA) report titled *Report on Un-accounted for Water and the Economics of Leak Detection* highlighted particular problems and unnecessary misunderstandings which arose due to differences in the definitions used for describing and calculating unaccounted-for water (Cheong, 1991). In part to address such findings, the IWA Operation and Maintenance Committee set up a Task Force in 1996 to review existing methodologies for international comparisons of Water Losses from water supply systems. The Task Force was comprised of representatives from the United Kingdom, France, Japan, Germany, and on behalf of North American countries, the AWWA. The two primary goals of the Task Force were to:

(1) Prepare a recommended standard terminology for calculation of real and apparent losses.
(2) Recommend preferred performance indicators for international comparison of losses.

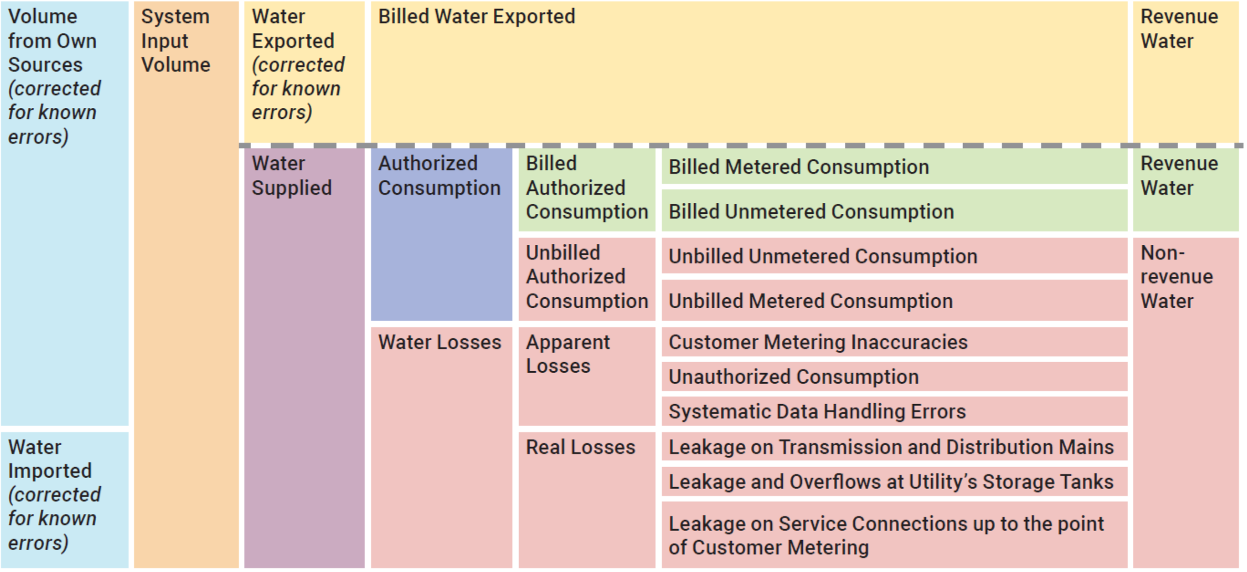
2.2.3.1. Standard water balance and terminology

The first goal was addressed in Lambert & Hirner, 2000, which proposed standardized international terminology and definitions for parameters of a water distribution system's "Water Balance," presented graphically in Figure 6. (Note that Figure 6 presents the current schema used by AWWA, which varies slightly from the original published by Lambert & Hirner, 2000). The recommendations and findings of Lambert & Hirner, 2000 were incorporated into a publication in 2000 titled Performance Indicators for Water Supply Services (Alegre et al., 2000). As AWWA was a major contributor to the Task Force, it is not surprising that in 2003 the AWWA Water Loss Control Committee (WLCC) recommended that "*the IWA methodology for water audit (balance) and performance indicators should be recognized as the current BMP for quantitatively monitoring water use and water loss in drinking water systems*" (Kunkel, 2003). Upon publication of the third edition of the AWWA Manual M36 (AWWA, 2009), AWWA aligned with the IWA to adopt the standardized water balance as the new methodology for performing water audits, thereby superseding the methodology proposed by the first edition of the manual (AWWA, 1990).

The water balance methodology is based on the principle of mass balance. As a result, the IWA water balance does not include the term "unaccounted-for water" because all of the water on the left side of the balance is accounted for on the right side (Figure 6). Similar to the initial thinking of Cook, 1939 and Haydock, 1947, IWA proposed that once water enters the distribution system,

---

[2] Discussions between the International Water Supply Association (IWSA) and the International Association on Water Quality (IAWQ) begun in 1996 and culminated in a formal merger of the two organizations (Reiter, 2022).



Volume from Own Sources *(corrected for known errors)*	System Input Volume	Water Exported *(corrected for known errors)*	Billed Water Exported			Revenue Water
		Water Supplied	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption	Revenue Water
					Billed Unmetered Consumption	
				Unbilled Authorized Consumption	Unbilled Unmetered Consumption	Non-revenue Water
					Unbilled Metered Consumption	
			Water Losses	Apparent Losses	Customer Metering Inaccuracies	
					Unauthorized Consumption	
					Systematic Data Handling Errors	
Water Imported *(corrected for known errors)*				Real Losses	Leakage on Transmission and Distribution Mains	
					Leakage and Overflows at Utility's Storage Tanks	
					Leakage on Service Connections up to the point of Customer Metering	

Figure 6: *The water balance as presented in AWWA M36 (AWWA, 2016b). Adopted from (AWWA, 2016a).*

It will ultimately become either "revenue water" (RW), or "non-revenue water" (NRW). The primary calculations supporting the water balance as defined by the AWWA FWAS are presented on the next page. This introduced two important concepts: (1) as noted by Farley & Trow, 2003, it is required to differentiate between the terms "water loss" and "leakage", as water losses include both real losses (e.g., leakage) and apparent losses (e.g. meter under-registration) and (2) the term non-revenue water can be defined by Equation 7, where terms related to the right hand side of the equations are defined below referencing the AWWA FWAS (AWWA, 2021a). Additionally, there are many other terms standard to the water balance that are defined in Appendix B via reproduction of the definitions worksheet in the AWWA FWAS (AWWA, 2021a).

> **Real Losses:** Physical water losses in the pressurized system (water mains and customer service connections) and the utility's storage tanks, up to the point of customer consumption. Examples include all types of leaks, breaks and overflows. The annual volume lost depends on frequencies, flow rates, and average duration of individual leaks, breaks and overflows.
>
> **Apparent Losses:** This includes all types of inaccuracies associated with customer metering (worn meters as well as improperly sized meters or wrong type of meter for the water usage profile) as well as systematic data handling errors (meter reading, billing, archiving and reporting), plus unauthorized consumption (theft or illegal use).
>
> **Unbilled Authorized Consumption:** All consumption that is unbilled, but still authorized by the utility. This includes authorized consumption of water, which is both metered and unmetered (and therefore either tracked or estimated by system operators).

Equation 1........... $WS = VOS + WI - WE$
WS = Water Supplied
VOS = Volume from Own Sources
WI = Water Imported
WE = Water Exported

Equation 2........... $AC = BMAC + BUAC + UMAC + UUAC$
AC = Authorized Consumption
BMAC = Billed Metered Authorized Consumption
BUAC = Billed Unmetered Authorized Consumption
UMAC = Unbilled Metered Authorized Consumption
UUAC = Unbilled Unmetered Authorized Consumption

Equation 3........... $WL = WS - AC$
WL = Water Losses (total)
WS = Water Supplied
AC = Authorized Consumption

Equation 4........... $AL = UC + SDHE + CMI$
AL = Apparent Losses
UC = Unauthorized Consumption
SDHE = Systematic Data Handling Errors
CMI = Customer Metering Inaccuracies

Equation 5........... $RL = WL - AL$
RL = Real Losses
WL = Water Losses (total)
AL = Apparent Losses

Equation 6........... $RW = BAC = BMAC + BUAC$
RW = Revenue Water
BAC = Billed Authorized Consumption
BMAC = Billed Metered Authorized Consumption
UMAC = Unbilled Metered Authorized Consumption

Equation 7........... $NRW = WL + UMAC + UUAC$
NRW = Non-Revenue Water
WL = Water Losses (total)
UMAC = Unbilled Metered Authorized Consumption
UUAC = Unbilled Unmetered Authorized Consumption

2.2.3.2. Unavoidable annual real losses (UARL)

The second goal of the Task Force was addressed in part by Lambert et al., 1999, which reviewed traditional performance indicators and local factors which affect them, recommended a Technical Indicator for Real Losses (TIRL),[3] developed an equation to quantifiably estimate a system's Unavoidable Annual Real Losses (UARL), and introduced the concept of the Infrastructure Leakage Index (ILI). It was highlighted in Lambert et al., 1999 that although they are still widely used as performance indicators throughout the world, percentage based indicators are flawed as they do not account for key local factors and the difference per-unit demand in the system. Consequently, other metrics had been proposed within the UK by studies such as Report 26 which recommended gal/property/hour (DOE & NWC, 1980), and the "Managing Leakage" reports which recommended m^3/km of distribution system/day (NRA, 1995).

In assessing which performance indicators might be recommended, Lambert et al., 1999 noted:

> "*Leakage management practitioners recognise that it is impossible to eliminate real losses from a large distribution system. There must therefore be some value of `unavoidable annual real losses' (UARL) which could be achieved at the current operating pressures if there were no financial or economic constraints. If the UARL volume for any system can be assessed, taking into account key local factors, then the ratio of technical indicator real losses (TIRL) to UARL offers the possibility of an improved performance indicator for real losses.*"

This echoes back to the opinions of Case, 1950, who argued that many factors affect what might be considered acceptable levels of unaccounted for water, including "unavoidable leakage". Case, 1950 had also noted that studies as early as 1897 estimated such leakage using methods based on the number of joints/connections, and found results ranging from 2,500 to 3,000 gpd per mile of main (Kuichling, 1897), which led to the author's company (The Pitometer Company) to adopt a value of 3,000 gpd per mile of main (a standard value previously referenced by Myers, 1946 when discussing "permissible underground leakage").

However, instead of using a single value, Lambert et al., 1999 developed an equation for UARL on a "*rational yet flexible basis… for a wide range of distribution systems.*" The empirical equation is based on physical and operational characteristics of a particular system and is shown below in its most basic form, adjusted to standard units as used in the AWWA FWAS. Lambert et al., 1999 then proposed a nondimensional performance indicator which allows for an overall assessment of infrastructure management which is independent of operating pressure, termed the Infrastructure Leakage Index (ILI), defined as the ratio between a system's current real losses, and the estimated unavoidable real losses. Therefore, the more a system's calculated ILI exceeds a value of 1.0, the more potential there is for further management of real losses (leakage).

---

[3] The accepted term is now Current Annual Real Loss (CARL).

Equation 8........................ $UARL = (5.41\ L_m + 0.15\ N_c + 7.5\ L_c) \times P_{AO} \times 365$

Equation 9... $L_c = N_c * L_p$

Equation 10... $ILI = CARL\ /\ UARL$

where,

$UARL$ = unavoidable annual real losses .... gallons per year
$CARL$ = current annual real losses .... gallons per year
ILI = infrastructure leakage index .... dimensionless
L_m = length of mains... miles
L_p = average length of customer service connection piping* .... feet
N_c = number of service connections.. dimensionless
L_c = total length of customer service piping .... miles
P_{AO} = average operating pressure .... psi

** excluding above ground lengths of service connections*

2.2.3.2.1. An economic level of leakage

Beginning in 1995, the England & Wales Economic regulator OFWAT required Utilities to begin to calculate Economic Level of Leakage. This concept is based on the fact that active leak detection and repair as a method of reducing real losses has a financial cost, that the cost increases with the level of effort, and that the level of effort increases as the losses become smaller (e.g., diminishing returns). The broad ELL concept states that as leak detection and repair efforts increase and real losses decrease, there is a financial inflection point where the cost of loss prevention starts to outweigh the cost of water saved. Notably, a paper published in the proceedings of the IWA Conference "Leakage 2005" focuses on ELL as combination of a range of leakage management activities, comprised of (in priority), pressure management, repair time, intervention policy and investment in infrastructure (Pearson & Trow, 2005). It has been noted that the economic benefits of actions such as pressure management extend beyond the cost of water saved, considering but not limited to simple concepts such as extending asset life.

2.2.3.2.2. Target setting for ILI

Shortly after the ILI was introduced in 1999, the AWWA's Water Loss Control Committee's (WLCC) published the report Applying worldwide BMPs in water loss control, which adopted use of both the ELL and the ILI. The guidance indicated that while a system-specific ELL is the best option, a table of ILI ranges was developed to offer preliminary "*general guidance to establish a long-term target ILI for utilities that have not determined an ELL*" (Kunkel, 2003). These concepts were incorporated by AWWA into their M36 manual and have been updated over the years to include notes from current research (Table 7-2, p.191), and is reproduced in Table 4.

2.2.3.2.3. Limits for calculating UARL (and ILI)

AWWA M36 states that UARL (and subsequently ILI) should not be calculated for (L_m + 32) + N_c < 3,000 or for systems where P < 35 psi (AWWA, 2016b). This is based on a recommendation made in Lambert, 2009, which has since been superseded by the research and recommendations presented in (Lambert, 2020). The current recommendation is that if the system has parameters outside of the range of data used in developing the UARL equation, i.e., a small number of connections (N_c < 5,000) or an average operating pressure outside of a "normal range" (about 65 psi < P < 85 psi), a dimensionless "System Correction Factor" (SCF) should be applied to the UARL. These SCFs are discussed more in depth in Section 7 of this report, including a pilot study of five systems from within the Delaware River Basin.

2.2.3.3. Performance Indicators for Water Supply Services

A final comprehensive deliverable from the IWA Operation and Maintenance Committee Task Force was a publication in 2000 titled Performance Indicators for Water Supply Services (Alegre et al., 2000). This reference formally adopted the standardized nomenclature and water balance methodology proposed by Lambert & Hirner, 2000, and incorporated the findings on performance indicators[4] from Lambert et al., 1999. The text defined a total of 133 performance indicators, categorized in six groups (1) water resources, (2) personnel, (3) physical, (4) operational, (5) quality of service and (6) financial. These indicators were then also binned into three levels of importance as management tools. As was demonstrated by the equation for UARL, performance indicators are typically calculated values which use specific pieces of input data (variables). Sometimes performance indicators are calculated using other performance indicators (e.g., ILI), and variables may be calculated using other variables (e.g., L_c). For standardization, Alegre et al., 2000 also defined 227 variables which were categorized in the same six groups as the performance indicators, plus one additional group of 'Demography and consumer data'.

The current version of this text is the third edition Alegre et al., 2017, to which additional performance indicators and variables have been added and the three levels of importance have been removed. Therefore, a breakdown of the current 170 performance indicators and 232 variables are presented in Table 5.

---

[4] The initial publication (Alegre et al., 2000) incorrectly specified the UARL equation, which was corrected in subsequent editions.

Table 4: *Adopted from AWWA M36. Guidelines for Use of the Infrastructure Leakage Index as a Preliminary Leakage Target-Setting Tool (in lieu of having a determination of the system-specific economic level of leakage).*

Target ILI Range	Water Resources Considerations	Operational Considerations	Financial Considerations
Less than 1.0	In theory, an ILI value less than 1.0 is not possible for most systems.* If the calculated ILI is just under 1.0, excellent leakage control is indicated. If the water utility is consistently applying comprehensive leakage management controls, this ILI value validates the program's effectiveness. However, if strict leakage management controls are not in place, the low ILI value might be attributed to error in a portion of the water audit data, which is causing the real losses to be understated. If the calculated ILI value is less than 1.0 and only cursory leakage management controls are used, the low ILI value should be considered preliminary until it is validated by field measurements utilizing the bottom-up approach.		
1.0–3.0	Available resources are greatly limited and are very difficult and/or environmentally unsound to develop.	Operating with system leakage above this level would require expansion of existing infrastructure and/or additional water resources to meet the demand.	Water resources are costly to develop or purchase. Ability to increase revenues via water rates is greatly limited due to regulation or low ratepayer affordability.
3.0–5.0	Water resources are believed to be sufficient to meet long term needs, but demand management interventions (leakage management, water conservation) are included in the long-term planning.	Existing water supply infrastructure capability is sufficient to meet long-term demand as long as reasonable leakage management controls are in place.	Water resources can be developed or purchased at reasonable expense. Periodic water rate increases can be feasibly effected and are tolerated by the customer population.
5.0–8.0	Water resources are plentiful, reliable, and easily extracted.	Superior reliability, capacity, and integrity of the water supply infrastructure make it relatively immune to supply shortages.	Cost to purchase or obtain/ treat water is low, as are rates charged to customers.
Greater than 8.0	While operational and financial considerations may allow a long-term ILI greater than 8.0, such a level of leakage is not an effective utilization of water as a resource. Setting a target level greater than 8.0—other than as an incremental goal to a smaller long-term target—is discouraged.		

*An ILI value less than 1.0 can be achieved in small, stand-alone systems of less than 3,000 service connections, and in flexible pipe (such as plastic) systems with high N1 values at pressures less than 40 psi (Lambert et al., 2014).

***Table 5**: Summary of performance indicators published in IWA's "Performance Indicators for Water Supply Services", 3rd edition (Alegre et al., 2017).*

PI and/or Data Group Name	Group Code	Performance Indicators	Variables
Water resources (volume data)	*WR*	4	22
Personnel	*Pe*	26	26
Physical	*Ph*	15	25
Operational	*Op*	44	65
Quality of service	*QS*	34	23
Financial	*Fi*	47	58
Demography and customer			11
Time			2
	Totals:	170	232

2.3. The Water Audit: a top-down water balance

Presently, water audits are typically calculated using a standardized water balance to guide the calculations (e.g. Figure 6). One of the most common ways to approach the water balance calculations is termed a "top-down approach", meaning that the analysis starts at a high/broad level of data, and becomes more refined as the analysis progresses (as opposed to something such as the BABE methodology, which begins by assessing detailed data at a fine resolution, e.g. the number of line breaks, and works up to a total loss volume). In the case of the AWWA water balance (Figure 6), data input and calculations generally move from the left-hand side to the right. It was discussed previously how efforts such as Carr & Pike, 1986, which led to the first AWWA M36 manual, used this top-down approach. However, specific procedures and terminology do not seem to have been successfully standardized until IWA published a report in Blue Pages (Lambert & Hirner, 2000) which was ultimately adopted by the IWA Manual of Best Practice Performance Indicators for Water Supply Services (Alegre et al., 2000). Notably, this text also came with free software on a CD-ROM, called SIGMA Lite (which was developed by Instituto Tecnológico del Agua (ITA), Valencia Polytechnic University, Spain as a simplified version of their professional performance indicator software SIGMA) (ITA, 2000).

Following the publication of Alegre et al., 2000, the standardized top-down water balance methodology was widely adopted and alternative free water balance software was developed by third parties. In fact, there have been numerous publications since the early 2000s which have summarized available software related to assessing non-revenue water, in the context of a water balance analysis (Al-Washali et al., 2020; McKenzie & Seago, 2005; Sjøvold et al., 2005; Sturm et al., 2014). Expanding primarily on the analysis of Sturm et al., 2014 for the purposes of this study, a summary of top-down water audit software developed since 2000 is included as Table 6. This table provides a brief summary as to who developed the software, why it was developed and possibly how it has continued to be improved. Additional information can be found for any of the free water audit software by accessing the respective references. As DRBC has required and receives data using the AWWA FWAS, discussion related to software for data collection in this report is limited to the AWWA FWAS.

***Table 6**: Summary of top-down water balance software.*

Software	Initial Year	Recent Year	Recent Version	Environ.	Comments	References
SIGMA Lite	2000	2015	v3.4.0.0	Windows Application	SIGMA Lite was initially published as a CD-ROM accompanying the IWA Manual of Best Practice "Performance Indicators of Water Supply Services". Successive iteration SIGMA Lite 2 was developed in 2006, and SIGMA Lite 3 was developed in 2009 (seemingly last updated in 2015).	(ITA, 2000) (ITA, 2006) (Rochera et al., 2009)
BENCHLEAK *(superseded by AquaLite)*	2000	2000	v1.0	Microsoft Excel	Developed by WRP Consulting Engineers (Dr. Ronnie McKenzie and Allan Lambert) for the South Africa Water Research Commission (WRC) in 2000, and includes benchmarking and target setting based on data from systems in South Africa.	(McKenzie, Lambert, et al., 2002) (McKenzie, Bhagwan, & Lambert, 2002)
BENCHLOSS	2000	*NA*	*NA*	Microsoft Excel	BENCHLOSS was an Australian version of BENCHLEAK with minor differences, written by McKenzie and Lambert for Australian Water Services Association. It was replaced in 2009 by WATER BALANCE developed for WSAA by Wide Bay Water and ILMSS Ltd.	(Carpenter et al., 2003)
BENCHLOSSNZ	2002	2008	v2A	Microsoft Excel	BENCHLOSSNZ V1a was a version of BENCHLEAK which allows for some unmetered consumption, written by McKenzie and Lambert for New Zealand Water and Waste Association. Version 2a (2008) was updated by McKenzie and Lambert; a shorter free CheckCalcs NZ was also provided by ILMSS Ltd.	(McKenzie & Lambert, 2008)
AquaLite	2007	*NA*	v4.5	Windows Application	Developed to replace BENCHLEAK. The manual supports V2.01 which was released in March 2007.	(McKenzie, 2007)
AQUALIBRE *(superseded by WB-EasyCalc)*	2003	*NA*	*NA*	Microsoft Excel	This software is longer supported and the software no longer publicly available - it has been replaced by WB-EasyCalc.	(Liemberger & McKenzie, 2003)
WB-EasyCalc	2006	2021	v6.17	Microsoft Excel	Developed to replace AQUALIBRE, WB-EasyCalc was created by Liemberger & Partners and is currently available in 23 languages.	Liemberger and Partners (website)
WB-PI Calc-UTH	2010	*NA*	v2.2	Microsoft Excel	Uses a modified water-balance chart, which includes an additional loss parameter specific to water pricing practices adopted by Greek water utilities.	(Tsitsifli & Kanakoudis, 2010)
CheckCalcs	2002	2020	*NA*	Microsoft Excel	Leakage Evaluation and Assessment Know-How Software LEAKS Suite software programs in Excel developed by Allan Lambert (ILMSS Ltd) and Water Loss Research & Analysis Ltd (WLR&A Ltd). CheckCalcs is a free introductory software, while PIFastCalcs was more comprehensive. More than 1000 copies and versions were issued in many countries and languages, but it is no longer available as WLR&A now produce online software.	Water Loss Research and Analysis Ltd (website)
PI Fast Calcs	2002	2018	*NA*	Microsoft Excel		
CheckCalcsNZ	2013	2013	v4a	Microsoft Excel	CheckCalcsNZ was designed to be complimentary to 2008 version of BENCHLOSSNZ by providing a quicker/ streamlined version of the Water Balance and PI calculations.	(ILMSS Ltd, 2013)
AWWA Free Water Audit Software (FWAS)	2006	2021	v6.0	Microsoft Excel	First developed following the AWWA M36 Manual publication in 2003, the initial software was released in 2006. There have been multiple subsequent updates which are outlined in the latest version of the software. Key Performance Indicators (KPIs) are compared against a Water Audit Reference Dataset (WARD). A separate "compiler" software can extract data from multiple reports.	(AWWA, 2021a) -- (website)

2.4. Key Performance Indicators (AWWA)

2.4.1. (2000-2019) Previous recommended practices

As is shown in Table 5, the most recent suite of performance indicators defined by Alegre et al., 2017 are for a system's performance as a whole, which may not be or may only be tangentially related to water losses (e.g. personnel indicators, quality of service indicators). This makes sense as Alegre et al., 2017 notes that the IWA Performance Indicator system was developed for all stakeholders playing a role in the water utility and was designed to be as universal as. Consequently, it was highlighted by Alegre et al., 2017 that it is important to have an objective-oriented performance assessment system, in which an entity performing the assessment can select the most pertinent performance indicators for its specific situation. Oftentimes, the performance indicators of most importance to a utility, agency or group may be referred to as "Key Performance Indicators", or KPIs.

Upon publication of the third edition of the AWWA Manual M36 (AWWA, 2009), the AWWA Water Loss Control Committee had reviewed performance indicators presented in Alegre et al., 2000 and endorsed/adopted six of them for use in the text and the AWWA FWAS:

- (Fi36) Volume of non-revenue water as a percentage of system input
- (Fi37) Valuation of non-revenue water as a percentage of the annual cost of running the system
- (Op23) Apparent losses (gal/connection/day)
- (Op24) Real losses (gal/connection/day), (gal/connection/day/psi) or (gal/mi of mains/day/psi)
- UARL, Unavoidable Annual Real Losses, as in Lambert et al., 1999
- (Op25) ILI (dimensionless) = CARL / UARL

These six endorsed KPIs remained consistent upon publication of the 4th edition of the AWWA M36 Manual (AWWA, 2016b), which is the current edition at the time of this study. However, it is worth noting that AWWA is in the process of updating this manual and the update will likely include changes in recommended KPIs since the 2016 publication. These changes were summarized in the recent AWWA WLCC report titled Key Performance Indicators for Non-Revenue Water (Jernigan et al., 2019), and provides findings based in part on the Committee's 2018 project titled Assessment of Performance Indicators for Non-Revenue Water Target Setting and Progress Tracking (Trachtman & Wyatt, 2019).

2.4.2. (2020) AWWA WLCC's 2020 Position

In the 2018 project Trachtman & Wyatt, 2019, the authors were tasked with conducting research to assess non-revenue water performance indicators and recommend those which utilities and regulators should consider when evaluating and addressing water loss, including those which might be used to set water loss control targets. Performance indicators were vetted for being: (1) technically rigorous, (2) understood by various stakeholders, (3) suitable for use in target setting, progress monitoring and motivating NRW reductions and (4) suitable for the state of readiness for North American water utilities and regulatory agencies. Ultimately Trachtman & Wyatt, 2019 recommended nine volumetric performance indicators and three financial performance indicators; notably, it was determined that a VPPI (volumetric percentage performance indicator, indicator *Fi36*) and an FPPI (financial percentage performance indicator, indicator *Fi37*) were both nonrigorous indicators and not-recommended. The recommendations were reviewed by the AWWA WLCC, and a formal position on performance indicators was outlined in Jernigan et al., 2019 as the **AWWA WLCC 2020 Position** – adopting six volume indicators and two financial indicators. Two primary changes are the agreement that a VPPI and FPPI are not technically rigorous and were therefore no longer recommended, and that UARL is considered an attribute rather than a performance indicator. Therefore, in addition to the KPIs remaining on the list from M36 (Op23, Op24, Op25), three additional KPIs were added:

No longer recommended
- (Fi36) Volume of NRW / system input
- (Fi37) Valuation of NRW / cost of running the system

Additional KPIs recommended
- Unit Water Loss (volume / connection / day)
- Real Loss Cost Rate ($ / connection / year)
- Apparent Loss Cost Rate ($ / connection / year)

The final list of KPIs supported by AWWA is reproduced for reference as Table 7. Furthermore, AWWA stated: "*To this end, AWWA is removing all percentage indicators from its water loss publications and tools, including the next edition (5th) of the M36 guidance manual and the next version (6.0) of the AWWA Free Water Audit Software (Jernigan et al., 2019).*"

Table 7: *Water audit outputs and key performance indicators recommended for use by the AWWA Water Loss Control Committee as summarized by (Jernigan et al., 2019).*

Type	Indicator	IWA Code (3^{rd} Ed.)	Units
Attribute	Apparent Loss Volume	--	Volume
	Apparent Loss Cost	--	$
	Real Loss Volume	--	Volume
	Real Loss Cost	--	$
	Unavoidable Annual Real Loss (UARL)	--	Volume
Volume	Unit Apparent Losses	--	volume / connection / day
	Unit Real Losses	Op27	volume / connection / day
	Unit Real Losses (pipe length)	Op28	volume / pipeline length / day
	Unit Water Losses	Op23	volume / connection / day
	Real Losses by Pressure	--	volume / connection / day / pressure unit
	Infrastructure Leakage Index (ILI)	Op29	Dimensionless
Value	Apparent Loss Cost Rate	--	$ / connection / year
	Real Loss Cost Rate	--	$ / connection / year
Validity	Data Validity Tier (DVT)	--	Dimensionless

2.5. Pressure management

When discussing system operational data as it relates to real losses, a recurring concern identified by some interested parties is that the industry is "stuck" using average operating pressure (P_{AO}) as it is the best information available. Inevitably, the argument is made that average operating pressure as a single annual value for a distribution system does not capture what could be very useful information related to real losses, such as (1) the causes and effects of high transient pressures and (2) the spatial variation of pressure within a system. The ensuing sub-sections of this report respectively address these arguments. While it is recognized by the authors that P_{AO} may have a certain elegance in its simplicity, it is important to recognize its shortcomings and strike a balance between a data burden and oversimplification. To this end, P_{AO} is referenced and used throughout this report as it is the data available to the authors, but the authors recognize that research is warranted into the additional pressure related parameters, and how they might be used to better analyses such as this.

2.5.1. Transient high pressure

It has been well established that transient high pressure conditions (i.e. a pulse or wave of water pressure caused by some external factor, such as a valve closing) can play a role in main breaks, and subsequently in the amount of real losses per year (for example, rupturing a pipe directly through excessive pressure, or exploiting an existing weakness to damage the pipe indirectly) (Karney & McInnis, 1990). While transient pressures are usually most severe at particular areas in a system (e.g., pump stations, high elevation areas, areas of low static pressure), Boulos et al., 2005 aptly notes that "*all systems will at some time be started up, switched off, or undergo flow changes, and so on, and will likely experience the effect of human errors, equipment breakdowns, earthquakes, or other risky disturbances.*"

Notably, a 2006 National Research Council (NRC) study assessing risks in drinking water systems ultimately recommends that one of the most important parameters for utilities to consider monitoring for is transient pressure using high-speed electronic pressure data loggers, as high pressure transients can pose a risk to a system's physical integrity, whereas low pressure transients can compromise a systems hydraulic integrity (e.g., inadequate supply, or even contaminant intrusion) (NWC, 2006). Consequently, the 2010 WRF Project No. 4109 titled *Criteria for Optimized Distribution Systems* (Friedman et al., 2010) defined five performance goals for the optimization of pressure management, one of which was to maintain system pressure within ±10 psi of the average pressure (average pressure calculated on a 96-hour basis, seasonally) for more than 95% of the time. Friedman et al., 2010 further suggested that pressure be measured at two key locations in each pressure management zone (areas representative of high and low pressure). However, a 2014 survey of 36 systems in 22 states found that such stringent pressure management goals were not largely practiced by responding utilities and about 40% of respondents had no specific goal to control pressure variations (LeChevallier et al., 2014).

Consider the recent WRF project No. 4917, which presents results from a pilot study performed at the Water and Wastewater Authority of Wilson County (WWAWC) located in central Tennessee in which they investigated the effectiveness of pressure transient monitoring technology (Karl et al., 2022). It found that the technology can detect high pressure transients, be useful in determining the cause and identifying potential mitigation alternatives, and be helpful in determining the general area of large or catastrophic main breaks. However, it also emphasized that the ability to do so is system-specific and dependent upon variables such as topology, break size, location of pressure monitors in reference to the break and the reporting frequency. These findings are promising, but the data collected are largely geared toward system-specific operation and management.

One other notable study investigates historical failures at a utility in the UK (48 district metered areas serving 100,000 people) and suggests some positive correlation between daily/weekly pressure variations and the rate of historical pipe failures (Rezaei et al., 2015). However, the daily/weekly pressure variations were based on modeled pressure at the failure points, which may not lend this methodology to broad application, especially when considering smaller systems with limited resources. Rezaei et al., 2015 does recommend that additional research investigating the impacts of high pressure transients on main failures be conducted; however, at this point in time it seems difficult to conclude what data, if any, could be collected and reported at the scale necessary for regional planning studies while quantifiably describing the occurrence of high transient pressure events in individual systems. Therefore, it is recommended that such an investigation would be worthwhile, to assess if there are relatively simply data parameters which can measured (or calculated from measurements) and quantifiably describe the occurrence of high transient pressure events in individual systems. In combination with P_{AO}, perhaps such data parameters would enhance the accuracy of estimated real losses, specifically, the possible reductions based on changes in pressure management.

2.5.2. Spatial variation of average pressure

While the argument that P_{AO} neglects the possibility that transient high pressure events are largely a question of temporal data resolution, there is also an argument on the validity of average annual P_{AO} as only one value intended to represent pressures over an entire system. More often than not, a single system likely has several pressure management zones (PMZs), which are monitored by either permanent or portable devices. Regarding the recent survey on pressure management practices which received responses from 36 systems in 22 states, LeChevallier et al., 2014 noted that the median number of pressure zones per system was 5-6, yet only about half of the systems surveyed had permanently installed pressure monitors system-wide. Additionally, while the AWWA FWAS v6.0 includes data collection via the interactive data grading questions related to how pressure is measured and how the P_{AO} is calculated (AWWA, 2021a), perhaps there are more quantifiable data parameters that can be collected to help describe the pressure management of individual systems. Some such variables might include data on the number of PMZs, the number of PMZs with a permanent real-time pressure monitoring device(s), the average size of a PMZ (per some unit of measure), the P_{AO} of the PMZ with the highest average pressure, and the P_{AO} of the PMZ with the lowest average pressure.

2.6. Data validity

2.6.1. Water audit data validity score

When it comes to the reliability of data being reported or used in modelling/decision making processes, the adage which rings in our ears is "*garbage in, garbage out*." The AWWA FWAS addresses this concern via the use of individual "grades" for each input variable which are intended to reflect the data's "trustworthiness"; in version v6.0 of the software, these grades are determined by answering "interactive data grading" questions for each data input. AWWA's M36 manual indicates that the grading scale ranges from 1 (equivalent to a "wild guess") to 10 (very reliable data which is based upon a measured and verifiable data source which is routinely reviewed and corrected if necessary). The individual grades of all data inputs are aggregated into a comprehensive "data validity score" (DVS), which spans a range between 0-100 and reflects the overall level of trust in the audit results. AWWA has defined five ranges of scores, referred to as Data Validity Tiers (DVT) which are used for guidance in suggesting areas of focus to improve data reliability (AWWA, 2016b). Notably, the "Loss Control Planning" worksheet of the AWWA FWAS states that for a DVS<50 (Tiers I and II), target setting and benchmarking should not be areas of focus until more reliable data is achieved.

In 2016, the United States Environmental Protection Agency (USEPA) published a guidance document titled Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion (USEPA, 2016a). There are numerous recommendations in the report regarding KPIs such as the ILI and unit real losses; however, the specific recommendation often changes based on whether or not the system has a DVS≥71 (which would put the system in the DVT "Tier IV"). One example provided for ILI and unit real losses, if the DVS is less than 71 the guidance is "*the utility should work on improving its Data Validity Score in order to have greater confidence in the data on which to base water resource planning, non-revenue water management interventions, and financial decisions*." Whereas if the DVS is greater than 71, USEPA, 2016a provides a benchmark of ILI between 1.0-3.0 (the lowest AWWA target ILI range, Table 4), and guidance on what a utility should do if it is above 3.0.

While slightly dated at this point, it is worth noting that adjacent to the portion of the report where USEPA, 2016a discusses selection of the target DVS≥71, USEPA, 2016a provided descriptions of how certain states had been implementing regulatory targets on data validity.

- The California Urban Water Conservation Council Memorandum had published (updated as of 2016) a Memorandum of Understanding, which required agencies to achieve data validity Level IV (DVS≥75) by the fifth year of reporting (CUWCC, 2016).
- In Tennessee, the Utility Management Review Board and the Water and Wastewater Financing Board developed and adopted a phase-in schedule related to the definition of excessive water loss. As of 2020, this is a DVS≤80 and NRW≥20% by cost of operating system cost (TNCT, 2020).

2.6.2. Water audit validation

Water audit validation was defined in AWWA's Level 1 Water Audit Validation: Guidance Manual as "*the process of examining water audit inputs in order to (1) identify and appropriately correct for inaccuracies in water audit data and application of methodology, and (2) evaluate and communicate the uncertainty inherent in water audit data.* (Andrews et al., 2016)". As part of an assessment Water Audits in the United States: A Review of Water Losses and Data Validity, Sturm et al., 2015 noted that the accuracy of audit data sets must be addressed in concert with analyses of water loss performance. The research team defined five levels of data validation, noted below; however, the most recent guidance (2nd edition) only speaks to Levels 1-3 (Sturm et al., 2021a). The 2nd edition of the guidance manual was published in 2021 because the AWWA FWAS update to v6.0 resulted in many changes to the data grading process (primarily, introduction of "interactive data grading"). This study being performed by DRBC will rely on "filtered audits" as the level of effort to perform Level 1 validation for the existing dataset is too great.

Self-reported audits	have not been subject to an in-depth review, and data grading has been completed by the reporting entity based on their best understanding.
Filtered audits	have been checked for technical plausibility by a research team based on simple, broad criteria.
Level 1 validated audits	have been subject to third-party "desktop review" of data that is immediately available (such as supply reports, consumption reports and testing reports). This level of validation is intended to (1) confirm the accurate application of the AWWA M36 water audit methodology to the utility-specific situation, (2) identify and correct inaccuracies where realistic, and (3) verify the answers selected to the interactive data grading (v6.0).
Level 2 validated audits	have been third-party reviewed with a deeper "desktop" analysis and may include the review of items such as a production database, SCADA system reports, billing system information, and meter test results. No field testing or new data gathering efforts are performed.
Level 3 validated audits	have been third-party reviewed using both "desktop analysis" (as described in level 2 validation) and field investigations.

Notably, a second portion of WRF Project 5057 (which developed the 2nd edition of the validation guidance manual) reviewed existing "certification" programs for audit validators (Sturm et al., 2021b). This document provides a high-level comparison for the certification programs in Georgia, California and Indiana (as well as the Canadian province of Quebec).

2.7. Water audit programs in the United States

Across the United States, many utilities are faced with aging infrastructure and with a changing climate, which may impact supply and quality of drinking water. To overcome these challenges, states and regional water agencies across the United States have begun implementing policy or regulations to reduce water loss among their utilities. Water loss reduction can help preserve water supply and help suppliers gain a better understanding of their physical water system. There have been numerous studies which assess the status of state regulations with respect to water audits as a conservation practice, such as the Alliance for Water Efficiency's scorecards in 2017 and 2022 (Burke et al., 2022; L. Smith et al., 2019), AWWA's most recent 2022 publication Governmental Policies for Drinking Water Utility Water Loss Control (Blackwell et al., 2022) and it's 2016 predecessor The State of Water Loss Control in Drinking Water Utilities (AWWA, 2016a), the "Task 3" memorandum as part of AWWA's recent publication on revised validation requirements (Sturm et al., 2021b), as well as the National Resource Defense Council's interactive web report based on 2020 information (NRDC, 2020). A synthesis of the information readily available to DRBC has resulted in Figure 7, which provides a picture of the current regulatory requirements across the United States, by state.

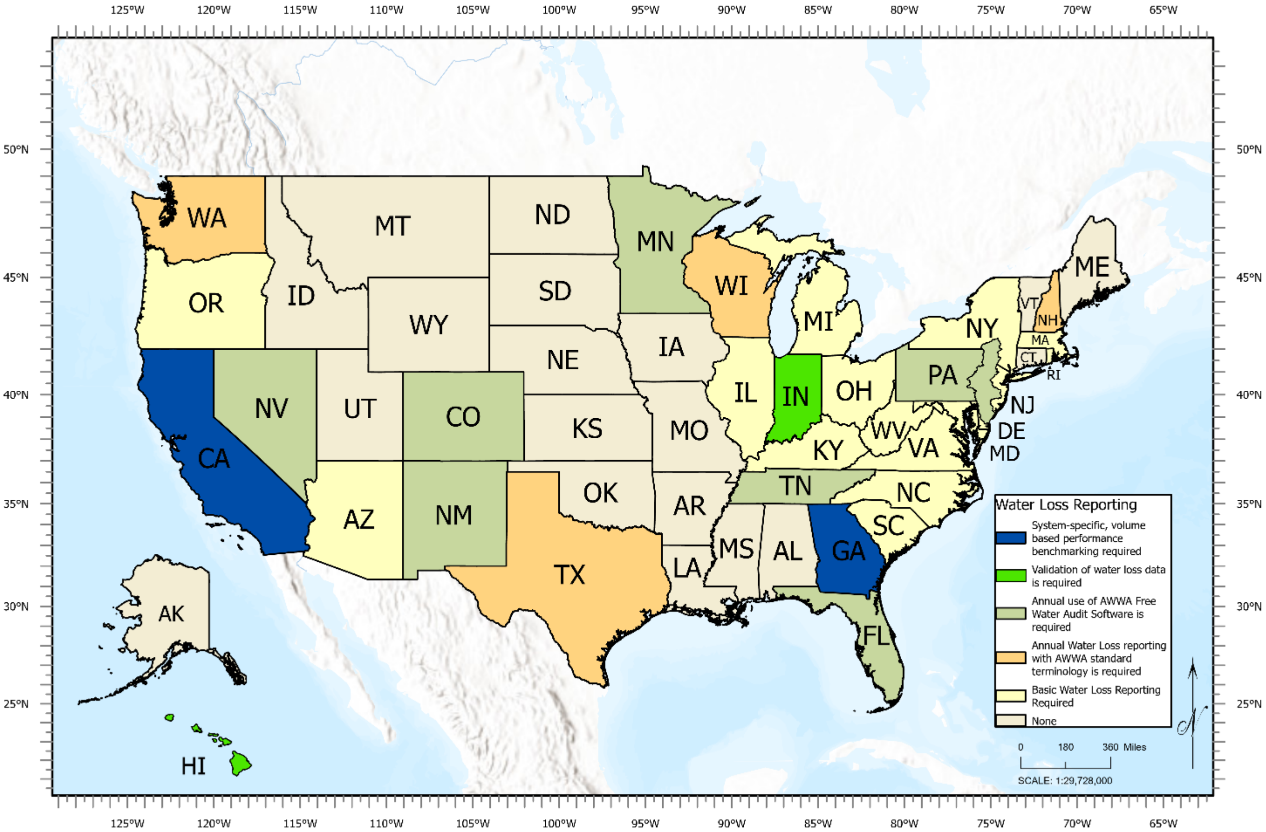


Figure 7: *National Map of State Water Loss Programs (Adapted from (NRDC, 2020)).*

2.8. Reference datasets

2.8.1. Water Audit Data Initiative (WADI) and WADI Plus (WADI+)

The AWWA launched the Water Audit Data Initiative (WADI) in 2011 to demonstrate AWWA FWAS implementation practices and improve the understanding of water loss issues by providing reliable examples of the audit data in North America (AWWA, 2011). The initial year of 2011 included 21 utilities in the dataset, providing validated data; although a specific level was not defined at the time, the methods used served as the framework for the Level 1 validation process (Sayers et al., 2016). Data was collected and reviewed by AWWA through 2017, when the program was sunset. A comprehensive assessment of WADI data at the five-year mark was provided in Sayers et al., 2016, presenting research on trends in water audit data; however, it was noted that trends could have been affected by “extra scrutiny” given the audits.

In 2018 as part of a larger project on the assessment of KPIs, an AWWA study was initiated under WRF Project No. 4695, Guidance on Implementing an Effective Water Loss Control Plan (Trachtman et al., 2019). To support the project goals, additional data was incorporated into the WADI dataset, including two additional utilities from the group of six participating utilities in this project (which had been validated) as well audits from sites in California, Georgia, Wisconsin, and Washington. Comprehensively, this dataset was called WADI Plus (WADI+), and includes 223 audits from 68 utilities, spanning the years 2009-2017. The WADI+ dataset is referenced later in this report for comparisons to data collected by the DRBC.

2.8.2. Water Audit Reference Dataset (WARD)

The Water Audit Reference Dataset is a product compiled by the AWWA Water Loss Control Committee which includes Level 1 validated water audits for CY2018 from 1,124 utilities in Quebec (Canada), California and Georgia. The intent of creating WARD was to establish the “*largest repository of high-quality North American water audit data*” (AWWA, 2021b). Additionally, the dataset has been used to calculate multiple percentiles of various performance indicators which appear as “speedometer” charts in the AWWA FWAS v6.0.

2.9. Basin state conservation programs

Many old, large water systems exist in the Delaware River Basin. It is estimated that over $500 billion will be needed nationally to replace failing and aging infrastructure (EPA, 2022). Across the United States, many states have implemented water conservation programs to reduce water loss and conserve water. In the Basin, each basin state takes a slightly different approach when it comes to water conservation, which is discussed in the following section. While each state has varying approaches, for entities in the Delaware River Basin, they are required to adhere to DRBC's water conservation regulations if they meet the conditions set forth in the regulations (Resolution No. 2009 – 1, 2009).

2.9.1. Delaware

Delaware does not require water audits to be conducted and uses the 2021 International Plumbing Code requirements, which do contain some water conservation measures (4 Del. Admin. C §4455-2.0). Water allocation permit applicants must show the existence of a water conservation program as a condition of their application. Additional water conservation requirements include:

1. Implementation of a water usage monitoring program
2. Creation of a systematic leak detection and control program
3. Utilization of Best Management Practices (BMPs) to conserve water
4. Development of a drought management plan
5. Evaluation of alternative water supplies, including use of treated wastewater
6. Implementation of price schedules that accurately reflect the actual costs of water (7 Del. Admin. C §7303-4.3)

2.9.2. New Jersey

New Jersey Department of Environmental Protection (NJDEP) required water utilities who serve over 500 people to determine their percentage of unaccounted for water. If the %UFW exceeds 15 percent, then it may trigger compliance action (N.J.A.C. 7:19-6.4). Generally, water audits submitted using AWWA methodology are considered optional by NJDEP. About 30 private water companies are regulated by the New Jersey Board of Public Utilities (N.J.A.C. 7:19-6.4). In 2022, the Appliance Standards law was passed which established efficiency standards for certain categories of household or commercial appliances. The law went into effect on January 18th, 2023 (NJ. Stat. §464, 2022).

Water supply allocation permits in New Jersey come with three requirements related to water conservation:

1. Public community water systems should monitor and aim to reduce leakage, if possible
2. Public community water systems must implement a water conservation program for their system
3. Public community water systems must create a water conservation and drought management plan, that is submitted to NJDEP every two years (N.J.A.C. 7:19-6.4)

2.9.3. New York

As of January 1989, all water withdrawal permit holders in New York must have a water conservation program as a permit condition (NYSDEC, 2021). Although there is no specific prescribed method for permit holders to follow in implementing this requirement, the New York State Department of Environmental Conservation (NYSDEC) has developed a manual that outlines various approaches to develop a water conservation program. In January 1989, as part of the New York's Statewide Water Resources Management Strategy, the NYSDEC was directed to assist municipalities with developing a water conservation program. In addition to a water conservation program requirement, New York also enforces plumbing fixture requirements, which are part of its Environmental Conservation Law. On December 28, 2022, the New York State Energy Research and Development Authority adopted appliance and equipment efficiency standards which took effect on June 26, 2023 (N.Y. ENG § 11-104). There is no statewide water audit requirement.

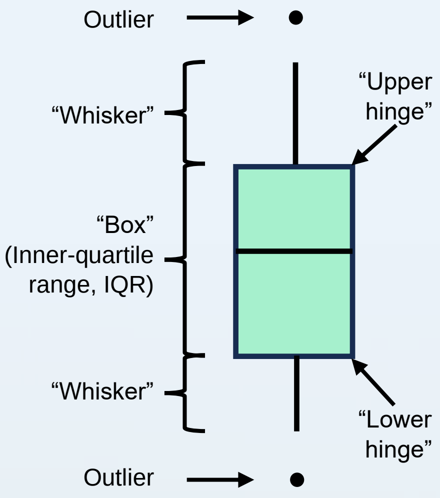
2.9.4. Pennsylvania

A proposed regulation by the Pennsylvania Public Utility Commission would establish water conservation measures for all public water utilities, and require reporting of unaccounted water for Class A, B & C utilities using a form developed by the Pennsylvania Utility Commission. Furthermore, it would require all Class A public water utilities to submit water audits annually using the AWWA audit software or a similar form (52 Pa. Code 65.20a). Pennsylvania follows the plumbing standards set forth in the 2018 International Residential Code (PHRC, 2021).

Pennsylvania requires its public water systems to meet seven criteria related to water conservation in its state code. These criteria include:

1. Education initiatives
2. Mandatory water audits for large users (as defined by the Pennsylvania Public Utility Commission)
3. Incorporation of efficient plumbing fixtures in new construction
4. Limiting unaccounted for water to below 20% for water utilities
5. Use of a leak detection system within the system
6. Installation of a metering system in the water system
7. Development of a water conservation plan for each utility. (25 Pa. Code §65.20)

Interpreting boxplots



Boxplots in this report are generated using the R package {ggplot2} (Wickham, 2016). Therefore, there are some default settings which hold true unless otherwise stated:

1. The middle line across the box represents the median of the data.
2. The upper and lower hinges represent the 1st and 3rd quartiles, or the 25th and 75th percentiles, respectively.
3. The whiskers extend from the hinge to the largest (or lowest) value, but no further than 1.5*IQR (where IQR is the inner-quartile range).
4. Values outside the range of the whisker(s) are plotted as outliers.

IBM PC 5150 Color
Reprint Courtesy of IBM Corporation
© Used with permission.

3. DATA MANAGEMENT AND REVIEW

3.1. Reporting compliance & software version

The Commission's water audit program began voluntarily in 2011, and was made mandatory for specific systems beginning in 2012, as required by the Delaware River Basin Water Code (discussed in Section 1.3 of this report). Based on a review of regulatory requirements and a review of reports received by the DRBC, it is possible to understand how many reports are expected in a given year, how many were received, and a general compliance rate for the water audit program. A summary of data related to compliance with the water audit program are provided in Table 8. On a few occasions, there may be several dockets for one system (and therefore one audit covering multiple dockets), a single utility may choose to submit multiple reports for multiple systems covered under one docket, and over time some dockets/systems may become combined. Therefore, a tracking system was established to understand how many water audits might be expected in a given year, considering scenarios such as:

- A new system increases above the review threshold or is constructed, and a new report is expected in that particular year ("First Year")
- A system was decommissioned, combined with another system, or falls below the review threshold and is no longer expected to submit reports ("Last Year")

Note that the numbers contained in Table 8 do not represent dockets or other IDs such as PWSID – but merely how many water audit reports are expected by the DRBC each year. This total does not include about a dozen systems which meet the reporting requirement, but which do not have customer meters thereby rendering the water audit report unusable. By 2016, compliance with the reporting program had increased to above 90% and has remained there ever since. DRBC staff continue to coordinate with docket holders on an annual basis in order to obtain the highest compliance rate within reason based on staffing and time limitations. Note that data collected by DRBC have not been "Level 1 Validated" according to the AWWA recommended practice.

Table 8*: Summary of compliance statistics for the DRBC water audit program. Values represent a number of reports and are not necessarily reflective of the number of systems, PWSIDs or dockets.*

Year	First Year	Last Year	Expected	Missing	v4.1	v4.2	v5.0	v6.0	Received	Compliance
2012	306	2	306	62	3	240	1	0	244	80%
2013	0	2	304	44	2	255	3	0	260	86%
2014	0	2	302	43	1	95	163	0	259	86%
2015	0	0	300	35	0	6	259	0	265	88%
2016	0	0	300	11	0	1	288	0	289	96%
2017	1	0	301	8	0	0	293	0	293	97%
2018	2	5	303	8	0	0	295	0	295	97%
2019	5	3	303	19	0	1	283	0	284	94%
2020	1	1	301	17	0	0	150	134	284	94%
2021	0	0	300	18	0	0	4	278	282	94%

3.2. Data validity

The AWWA FWAS has undergone several updates and changes since its release. Perhaps the most pronounced change came with the update to v6.0 – which included an improved method for determining a data validity score (DVS), and the shift towards referencing a data validity tier (DVT, which are simply ranges of DVS). In previous versions of the AWWA FWAS, data inputs were graded on a scale of 1-10 by the person completing the report (1 indicating low-quality data and 10 indicating high-quality data). This method of grading inherently presents the opportunity for subjective grading of data, and a likely scenario of over-stating confidence in data accuracy. The AWWA FWAS v6.0 attempted to normalize this process by introducing questions with standardized answers, which in turn generate a score for each data input. Importantly, it was noted in a 2020 memorandum regarding the version release that (1) the default value in v5.0 for an input variable would yield a grade of 5 for that variable, but now yields a grade of 3 in v6.0, and (2) the overall weighting of scores to calculate a DVS was slightly re-shifted due to the elimination of one grade (AWWA, 2020). A summary of data validity scores for reports received by DRBC are grouped by system class and AWWA FWAS version in Figure 8. Not surprisingly, it is evident that completing the audit using AWWA FWAS v6.0 reduced the DVS for systems across all categories. It is also apparent that decreases in scores were most pronounced in smaller systems, which may be logical given the resources available to larger systems. Consequently, there now appears to be a very slight trend in DVS where median DVS is lowest for Very Small systems, increasing to being the highest for Very Large systems; again, this may be reflective of resources available to respective systems.

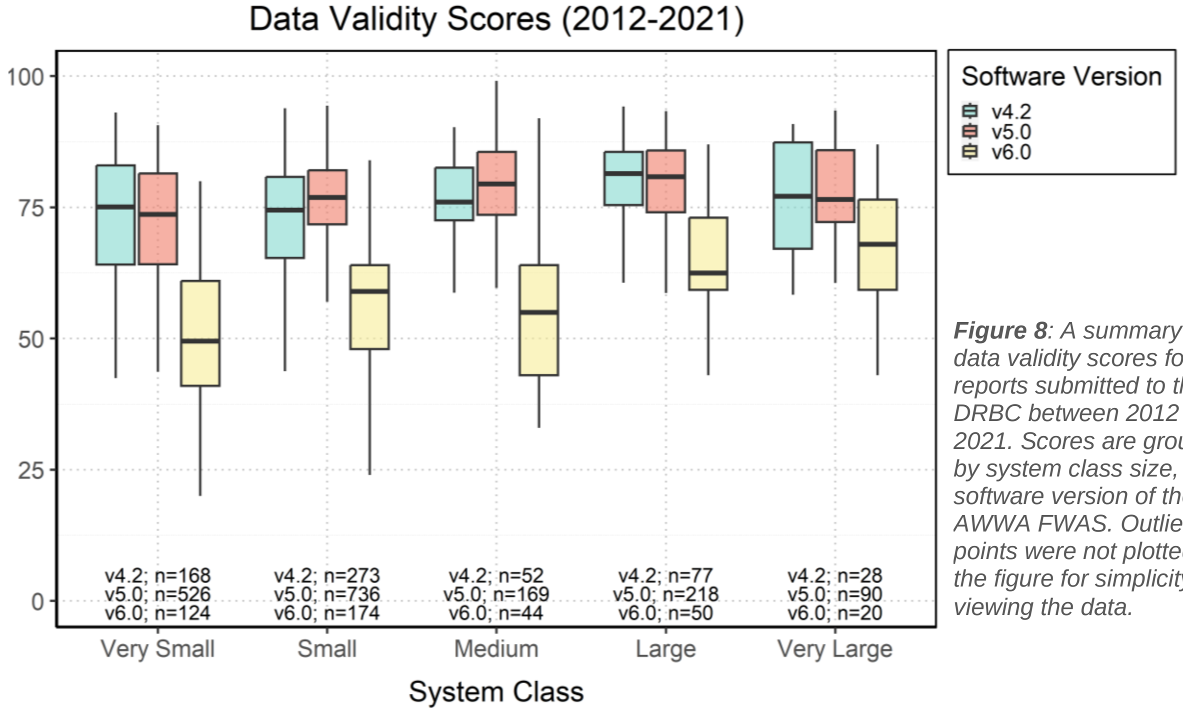


***Figure 8**: A summary of the data validity scores for reports submitted to the DRBC between 2012 and 2021. Scores are grouped by system class size, and software version of the AWWA FWAS. Outlier data points were not plotted on the figure for simplicity of viewing the data.*

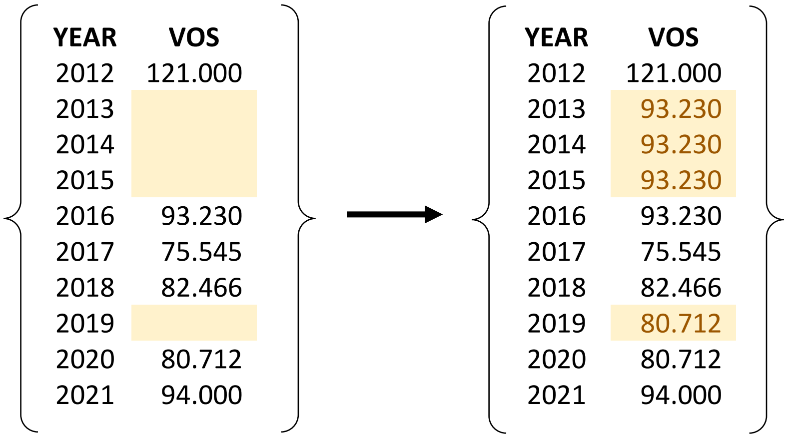
3.3. Data Quality Assurance and Quality Control (QAQC)

3.3.1. General data entry error

DRBC staff reviewed the dataset for what might be called general data entry errors, and manually made corrections while retaining a record of the original value. The primary focus was on fields which a person completing the report would enter data related to the water balance calculations. The most common error was data entered in incorrect units, resulting in an order of magnitude error (for example, a report where volumes were entered in gallons instead of million gallons). On a few occasions, water withdrawal and transfer data were retrieved for a system from respective state agencies and replaced what was entered in the report. Regardless of modifications to data based on QAQC procedures, all resulting calculations from the AWWA FWAS were carried forward using the modified dataset.

3.3.2. Missing data (un-reported)

It was shown in Table 8 that there are several reports not submitted each year, which poses a challenge for volumetric trend analyses. If missing data is not resolved, missing data may be mis-interpreted as data trends or hamper the ability to see trends in data. Therefore, a simple solution was selected to backfill missing reports with neighboring data for the same system. This was done in *R* with the package {tidyr} using the function “fill” (Wickham et al., 2023). As described by the function, it “*fills missing values in selected columns using the next or previous entry.*” The options selected in the function were such that any missing value in a particular system’s dataset was backfilled with the closest “more current” data point. An example of filled data is presented below:



YEAR	VOS
2012	121.000
2013	
2014	
2015	
2016	93.230
2017	75.545
2018	82.466
2019	
2020	80.712
2021	94.000

YEAR	VOS
2012	121.000
2013	93.230
2014	93.230
2015	93.230
2016	93.230
2017	75.545
2018	82.466
2019	80.712
2020	80.712
2021	94.000

3.3.3. Data filtering

While it is important to backfill missing data for analyses which analyze the total volume of a parameter, other analyses such as those which assess the statistics of KPIs will not benefit from backfilling missing data. In fact, it is preferrable that the data be screened (or filtered) such that the calculated statistics are not skewed by potentially less accurate data. Therefore, some analyses in this report may use "filtered data", as described in Section 2.6.2 of this report, as defined in Sturm et al., 2015. Similar to steps used in other studies (Sturm et al., 2015; Walker et al., 2022), the following criteria were used to filter data for inclusion in the filtered dataset. A summary of the total number of reports received each year is provided in Table 9, as well as the number of backfilled reports (which were missing), the number of reports in the total dataset, and the number of reports passing the filter criteria and therefore present in the filtered dataset.

1. Cannot be backfilled report data
2. Total Water Loss, Apparent Loss, Real Loss ....>= 0
3. Customer Metering Inaccuracy (CMI) ....< 25% of Total Water Loss
4. Infrastructure Leakage Index (ILI) ....1 < ILI <20
5. Billed Metered Authorized Consumption (BMAC) ....> 1,000 gal/connection/month

Table 9: *An annual summary of the reports received, reports backfilled, reports available for analysis and those which pass the filter criteria to be included in the "filtered dataset".*

Year	Received	Missing (i.e. backfilled)	Full Dataset	Filtered Dataset
2012	244	62	306	174
2013	260	44	304	182
2014	259	43	302	191
2015	265	35	300	192
2016	289	11	300	202
2017	293	8	301	202
2018	295	8	303	168
2019	284	19	303	187
2020	284	17	301	199
2021	282	18	300	209

3.4. Apparent loss component normalization

The components of apparent losses are defined by Equation 4, and include unauthorized consumption (UC), systematic data handling errors (SDHE) and customer metering inaccuracies (CMI). The methods used in the AWWA FWAS to calculate the components of apparent losses have changed over time, primarily between software versions updates as summarized in Table 10. This poses a challenge when assessing multiple years of data, especially as the assumptions made in calculating these components in turn affect the calculation of key parameters such as real losses (i.e., Equation 5).

3.4.1. Unauthorized Consumption and Systematic Data Handling Errors

Since the methods for calculating UC and SDHE changed over time, it was determined necessary to adjust historical data to match the current methods of calculation. However, when assessing the means of calculation, it is important to consider how someone completing the AWWA FWAS report could have entered the data. If a person does not choose to enter system specific data, a "default" percentage-based value is used as indicated in Table 10 and applied using the respective equations. If a system specific value is entered, the person completing the report only has an option to enter it as a volume in million gallons per year. Additionally, note that for SDHE there were no default values for software versions v4.1 or v4.2, and therefore calculations could involve zero values whereas that is not the case in later versions. Ultimately, two issues were addressed during the QAQC process:

a. Inconsistent calculations: Based on how data is input to the AWWA FWAS, UC and SDHE are only calculated using percentages when the default values are used (otherwise it is a manually entered volume). Notably, the software collects data on whether or not a default value is used. Therefore, for the entire 10 years of data, any record which used a default value had UC and SDHE recalculated using the most recent equation, and all subsequent calculations carried through. Any record which manually input data had the same value carried through in million gallons.

b. No default SDHE for v4.1 & v4.2: To address the issue of having no default values for SDHE in v4.1 or v4.2, the data was assessed and backfilled with default values where SDHE was indicated to be zero. Calculations of SDHE volumes were then performed using the most recent equation, and subsequent calculations carried through.

Table 10: *Summary of calculation methods for the components of apparent losses as used by the AWWA FWAS.*

Software Version	Unauthorized Consumption (UC)		Systematic Data Handling Errors (SDHE)		Customer Metering Inaccuracies (CMI)	
	Equation	Default	Equation	Default	Equation	Default
v4.1	WS * % [1]	0.25%	--	--	(BMAC+UMAC)/(1-%)-(BMAC+UMAC)	--
v4.2	WS * %	0.25%	--	--	(BMAC+UMAC)/(1-%)-(BMAC+UMAC)	--
v5.0	WS * %	0.25%	BMAC * %	0.25%	(BMAC+UMAC)/(1-%)-(BMAC+UMAC)	--
v6.0	BMAC+BUAC * %	0.25%	BMAC+BUAC * %	0.25%	(BMAC+UMAC)/(1-%)-(BMAC+UMAC)	--

Notes:

[1] The definitions in the software indicate that the calculation was performed using VOS; however, the actual calculations in the workbook appear to have referenced WS.

3.4.2. Customer Meter Inaccuracies

As the methodology for calculating CMI volume has never changed, the primary issue considered is that there has never been a default value (i.e., the ability for reporting zero error exists). According to a study in 2011, approximately 85% of all utility billing flow meters sold in the United States are of the positive displacement design and 15% are of the multi-jet design, while remaining meter technologies are estimated at 1-2% (Barfuss et al., 2011). The same study performed endurance testing on various meter designs (single-jet, multi-jet, piston, turbine, propeller, nutating disc, fluidic oscillator) of various sizes (⅝×¾ inch, ¾ inch, 1 inch, 1 ½ inch and 2 inch) at various throughputs (¼-life, ½-life, ¾-life, full-life). Considering mechanical meters such as the positive displacement or multi-jet designs, the data shows that not only did accuracy often decrease at low flows, but that over time the median accuracy further under-registers at any given flow. Note that errors tending to skew toward under-registering likely would not happen to meters without moving parts (such as electromagnetic, or ultrasonic).

The most recent AWWA M36 manual notes that errors with customer meters come not only from wear over time, but also from things such as improper meter sizing, improper installation, and decreased accuracy at low flow rates (AWWA, 2016b). As meter accuracy can vary with flow rate, AWWA's M36 suggests that a weighted meter accuracy be calculated based on the percentage of time flow is expected to pass through a meter at low, medium and high flow rates. For small residential water meters, the profile was suggested to be {Low: 15%, Med: 50%, High: 35%} and for large meters (industrial/commercial) the profile was suggested to be {Low: 15%, Med: 60%, High: 25%}. Additionally, the AWWA M6 Manual 2018 addendum (AWWA, 2018) notes that test requirements for new, rebuilt and repaired cold-water displacement meters should have the following accuracy limits {Low: 95-101%, Med: 98.5-101.5%, High: 98.5-101.5%} and multi-jets should have {Low: 97-101%, Med: 98.5-101.5%, High: 98.5-101.5%}.

As it has been understood that most customer meters are likely mechanical displacement meters which experience wear over time and likely skew towards under-registering, DRBC has calculated a "default" CMI accuracy using the AWWA M36 suggested weighting for residential meters and the lower accuracy limits of displacement meters from AWWA M6:

$$(0.15)(95\%) + (0.50)(98.5\%) + (0.35)(98.5\%) \ = \ 97.975\%$$

Therefore, DRBC has conservatively selected 98% accuracy (under-registering by 2%) as a default value, understanding that under-registration of customer meters results in higher apparent losses and lower real losses. Records in the DRBC dataset which report zero CMI were recalculated using a default value specified by the DRBC as 2% under-registration.

3.5. Master Meter Error Adjustments (MMEA) default values

Error associated with a master meter, especially on the volume from own sources (VOS) can have a significant effect on the overall results of the AWWA FWAS. As such, it is notable how many systems routinely leave this field for master meter error adjustment (MMEA) blank, or report that there is zero error associated with the data (consistently about half of reports, or more). It has even been noted in the AWWA M36 that "*The MMEA should be at least 0.25 percent of the Water Supplied volume. This represents accuracy of 99.75 percent, and most flowmeters in use are less accurate than this level*" (AWWA, 2016b).

A summary of the reported VOS MMEA percentages is presented in Figure 9, where the number of systems reporting an MMEA value versus those which don't (or report zero) are indicated at the bottom of the figure. The change in data which occurs with the change of AWWA FWAS to v6.0 is striking, although again one needs to consider human interaction with the software:

1. In v5.0 users are prompted to enter a percentage, with instructions that a negative value represents under-registration, while a positive value represents over-registration. Entering a positive value of 0.02 yields over-registration of 2%.
2. In v6.0 users are prompted to enter a percentage, but then need to also choose from a separate drop-down menu whether it represents under- or over-registration (the default being under-registration). Therefore, if a user enters 0.02 as in v5.0 and does not pay attention to the drop-down, it now becomes under-registration of 2%.

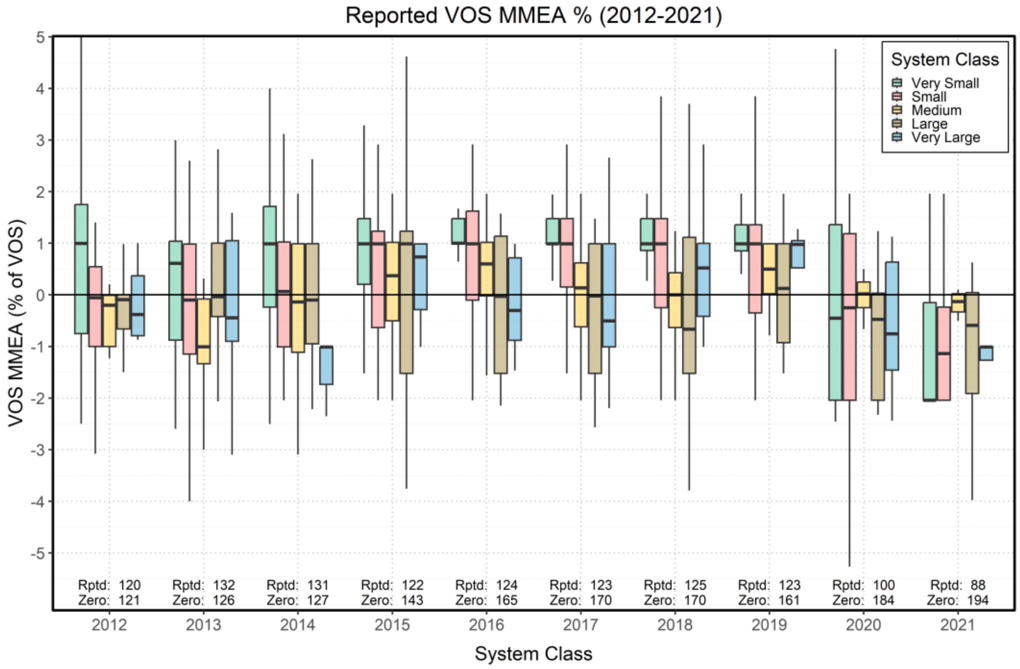


Figure 9*: A summary of the reported master meter error adjustments (MMEA) applied to the volume from own sources (VOS) for all systems which reported an MMEA each year, by system class. The total number of systems which reported a master meter error are listed below each series of boxplots as "Rptd", whereas the total number of systems which reported zero or did not report any error are listed as "Zero". Outlier data points were not plotted on the figure for simplicity of viewing the data.*

In order to address the issue of consistency regarding the VOS MMEA, the concept of replacing any missing or zero error values with a “default” error percentage was considered (conservatively proposed as under-registration). The question was posed to the AWWA Water Loss Control Committee (WLCC), who responded that it is not advisable to enter an assumed error for two reasons: (1) in case the zero value is indeed correct and representative of the measured error, and (2) over-registration is more common than one might think, especially considering the larger non-mechanical meters (e.g., clogging on a venturi meter may lead to over-registration).

The opinions of the AWWA WLCC were reviewed and certainly not dismissed; however, DRBC elected to proceed with a default under-registration for two reasons: (1) the “compiler” software which extracts data from individual AWWA FWAS reports (in this case, near 3,000) does not currently have a way to differentiate between whether a VOS MMEA was entered as zero, or left blank, as both scenarios are compiled as a numeric zero, and (2) it was determined that the benefit to this analysis from applying the adjustment and being more conservative (i.e. over-estimating the potential loss volume) outweighed the desire to keep the data as-is with the understanding that many if not most systems may simply not be reporting any VOS MMEA data.

Therefore, the bias of the default error in this study is under-registration as it is the more conservative option. Based on an assessment of the absolute value of meter errors reported to DRBC (Figure 10), the mean of the entire set of reported errors is 2.06%, and the median value is 1.01%. However, it is also clear that reporting organizations have favored three values; of the 1,154 times a percentage was reported, it was between (0.95%-1.05%) 271 times or 23%, (1.45%-1.55%) 123 times or 11%, and (1.95%-2.05%) 132 times or 11%. Considering the mean, median and mode of the data, DRBC elected to set a default VOS MMEA value at 1.5% under-registration. Wherever a default value was entered instead of zero, all necessary calculations were carried forward.

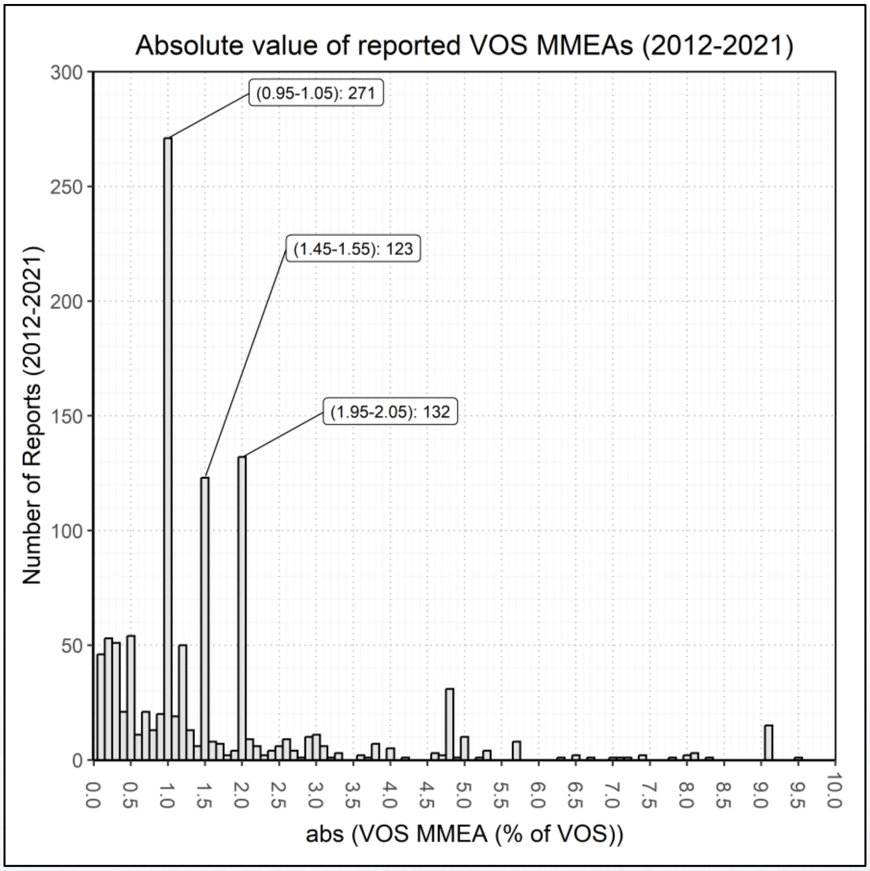


***Figure 10**: The absolute value of the reported errors associated with master meters for the measurement of volume from own sources (VOS), as reported to the DRBC. The total number of reported values is 1,188 (approximately 32 values above 10% are not shown on the figure).*


kg/cm2
psi
lb/in2
kPa
Bar

4. WATER AUDIT ANALYSIS (2021)

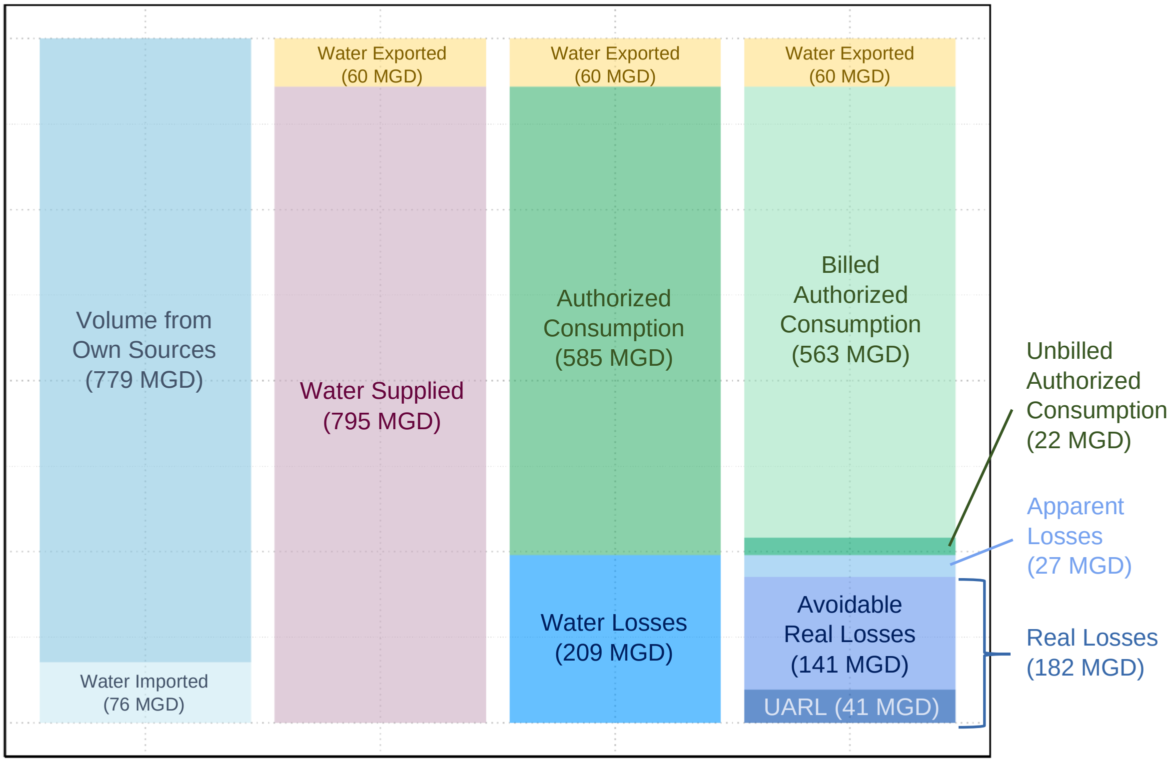


Figure 11: Aggregate water balance for 300 systems reporting water audit data to DRBC for CY2021. Note that the totals in the 3rd and 4th columns are 1 MGD less than the 1st and 2nd due to rounding when the data is disaggregated. Note that the UARL=41 MGD summation includes UARL calculations for all 300 systems, some of which return ILI<1; if those systems' UARL value are replaced with the smaller reported real loss volume, the numbers change to UARL=38 MGD, and Avoidable Real Losses=144 MGD.

In CY2021 there were 282 water audits submitted to DRBC, and therefore 18 reports were backfilled from 2020 (per Table 8) resulting in a total of 300 reports being included in this analysis. The above graphic, Figure 11, summarizes the cumulative data reported by all systems as a water balance for the Delaware River Basin. Starting at the left-hand-side of Figure 11, these systems withdrew an estimated average of 779 million gallons per day (MGD) from their own water supply sources. As many systems are interconnected, cumulative exports (60 MGD) and imports (76 MGD) suggest a net import of about 16 MGD. Therefore, the total volume of water supplied by these systems is estimated to average 795 MGD. Based on the calculation methods utilized by the AWWA FWAS, it is estimated that these systems register an average of 585 MGD in authorized consumption, and experience 209 MGD in water losses. The overwhelming majority of authorized consumption is billed (563 MGD), while a much smaller portion of unbilled authorized consumption (22 MGD) may be attributed to uses such as firefighting, flushing of mains and sewers, public fountains or any unbilled customers such as municipal buildings. Considering water losses, the majority is estimated to be real losses such a leakage (182 MGD), which can be subdivided into estimated unavoidable annual real losses (41 MGD) and avoidable real losses (141 MGD). A much smaller component is attributed to apparent losses (27 MGD) such as data handling errors, meter inaccuracies and unauthorized uses.

4.1. Water supplied

To better understand findings in the dataset, each system was assigned a classification from Very Small to Very Large based on the number of service connections (Table 2). As shown in Figure 4, there are 15 systems classified as Very Large ($N_c > 20,000$). These fifteen systems have a cumulative water supplied volume of 513 MGD, which is approximately 65% of the total 795 MGD highlighted in Figure 11. Notably, the largest water supplier in the Delaware River Basin is the Philadelphia Water Department, which reported an average of about 229 MGD (which is approximately 29% of the total 795 MGD). The second largest system serves the area surrounding the City of Philadelphia and reported an average of about 76 MGD (which is approximately 9.5% of the total 795 MGD). The remaining Very Large systems all reported individually supplying between about 7 – 27 MGD. In order to show how the water supplied by all 300 systems is distributed, Figure 12 limits the y-axis to an average of 10 MGD. This shape of data distribution is considered normal based on previous analyses performed by DRBC. There are 101 systems which reported an average rate of WS≥1 MGD, accounting for 92% of the total water supplied. Conversely, it is perhaps more striking to state the same observation by noting that 199 systems had a system input of less than 1 MGD accounting for only 8% of the total water supplied.

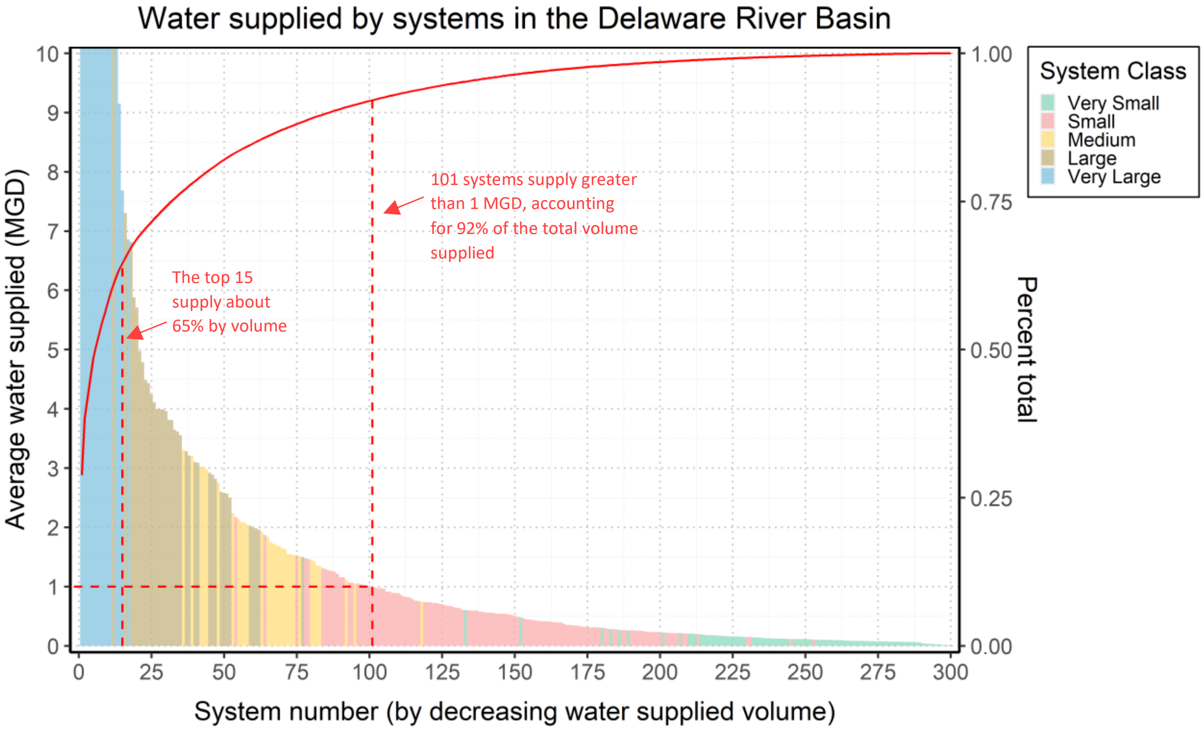


Figure 12: All reported water supplied volumes for CY2021 (n=300), ranked by decreasing volume of water supplied. A percent of the running total water supplied is indicated by the red line, compared to the secondary axis. The y-axis of this plot has been limited to 10 MGD, although some data plots above that value.

4.2. Data validity grades and scores

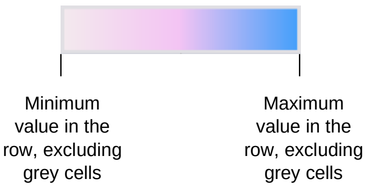
The AWWA FWAS uses individual grades for each input variable which are intended to reflect the data's "trustworthiness". In version v6.0 of the software, these grades are determined by answering "interactive data grading" (IDG) questions for each data input (AWWA, 2021a). AWWA's M36 manual indicates that the grading scale ranges from 1 (equivalent to a "wild guess") to 10 (very reliable data based upon a measured and verifiable data source which is routinely reviewed and corrected if necessary). In reviewing the input data grades for CY2021, this section only considers the 278 reports submitted using AWWA FWAS v6.0 for consistency (as indicated in Table 8). The individual data grades for all input parameters of all 278 reports were grouped into five "grade ranges", as summarized in Table 11. Each row has been color-coded using the same color ramp; however, the scale in each row is adjusted to the maximum and minimum value of that row (excluding greyed out cells). A grade of "NA" represents a scenario where grading was not applicable and a grade of zero indicates that the questions were unanswered. Some noteworthy observations regarding the summary of individual data grades are:

- Where water is either imported or exported, the confidence in the input data generally appears to be less than equivalent VOS data.
- The category of "Metering and Data" appears to have the least reliable inputs (compared to other categories) although the BMAC variable subcomponent of this category appears to have among the most reliable inputs.
- Data related to system infrastructure ("Physical") generally appear to have higher scores, aside from some uncertainty in L_p, and some related to P_{AO}.

Table 11: *A summary of the individual grades for each AWWA FWAS input variable for the n=278 reports which submitted a report using AWWA FWAS v6.0 in CY2021.*

Gp.	Variable	NA	0	1-2	3-4	5-6	7-8	9-10
Volume	VOS	*1*	*8*	17	93	47	72	40
	VOS MMEA	*17*	*8*	0	76	0	93	84
	WI	*15*	*169*	15	34	9	19	17
	WI MMEA	*28*	*170*	0	43	8	4	25
	WE	*24*	*191*	10	22	12	12	7
	WE MMEA	*28*	*191*	0	39	5	2	13
Metering & Data	BMAC	*0*	*0*	20	2	40	183	33
	BUAC	*18*	*216*	28	1	10	0	5
	UMAC	*11*	*114*	35	29	14	42	33
	UUAC	*0*	*0*	6	197	24	23	28
	UC	*0*	*0*	3	260	6	7	2
	CMI	*0*	*3*	87	76	59	40	13
	SDHE	*0*	*0*	3	250	14	3	8
Physical	L_m	*0*	*0*	26	9	53	78	112
	N_c	*0*	*0*	8	1	124	53	92
	L_p	*0*	*0*	85	0	36	28	129
	P_{AO}	*0*	*0*	0	18	106	120	34
$	CRUC	*0*	*19*	23	0	73	36	127
	VPC	*0*	*0*	32	77	3	19	147

Table color scheme:



The individual data validity grades are then weighted (via proprietary AWWA percentages) and summed to yield a final data validity score (DVS) (out of 100). The water audit DVS serves as a measure of confidence in the data provided by the utility. Low DVS indicate a high degree of estimation in the data, while higher scores indicate a higher degree of confidence in the data. A summary of DVS distribution by system class is presented in Figure 13A, based on data from all systems for CY2021 (n=300, i.e., includes backfilled missing data). While there is a good degree of spread within each system class, in general, it appears that larger systems tend to have a higher degree of confidence in the reported data (which is likely a function of available resources for producing the underlying data and performing the water audit). It should be noted that the KPI recommended by the AWWA are the data validity tiers (DVT), which are based on a DVS range as indicated on the “Loss Control Planning” worksheet of the AWWA FWAS; these thresholds are indicated on Figure 13A by horizontal lines. Notably, the AWWA FWAS uses DVT to provide suggestions of how to improve validity score based on the specific tier a system falls within.

Additionally, Figure 13B groups the total water supplied by DVT and color codes the data by system class. It is noteworthy that 53% of the water supplied by volume is captured in reports with high data validity (Tiers IV and V), however, it is skewed by the fewer larger systems, only accounting for about 25% of the reporting systems. There is a large contingency of systems within the middle range of Tier III (37% by volume, 42% of systems), and a smaller group on the low-end including Tiers I & II (10% by volume, 33% of systems).

Data validity scores and tiers for all systems, CY2021 (*n*=300)

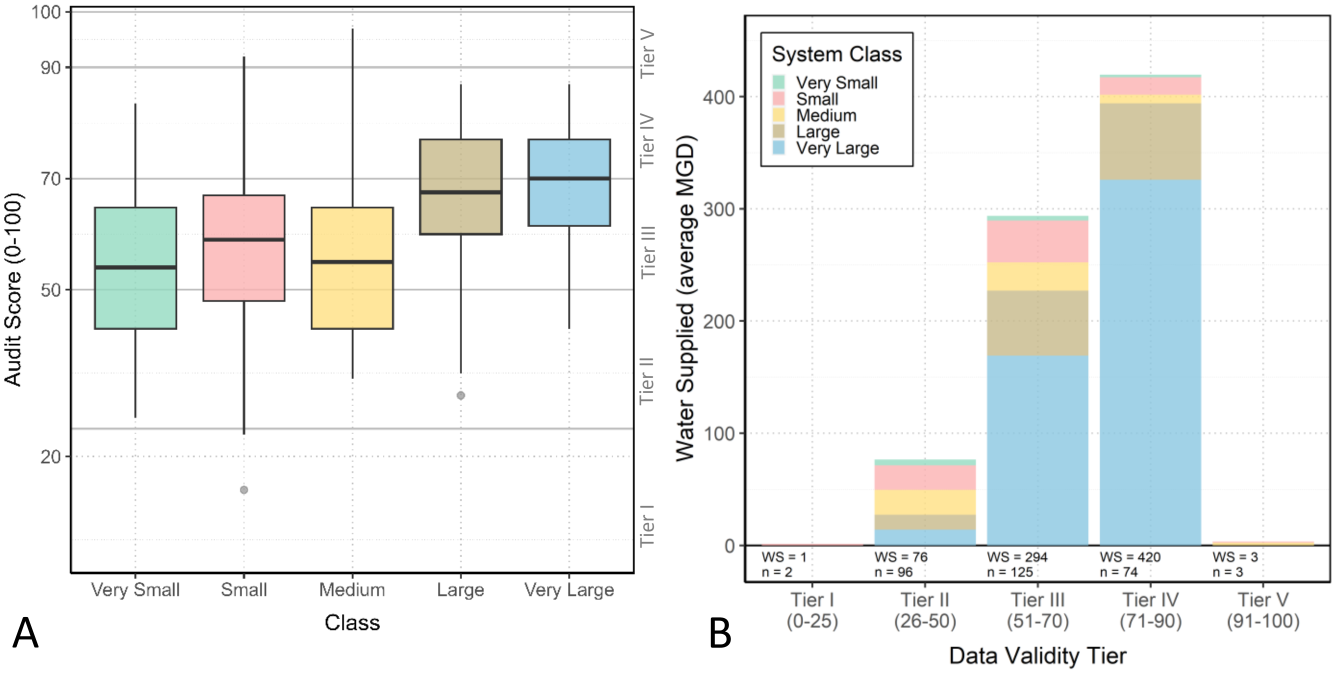


Figure 13: *Water audit data validity scores by system class for CY2021. (A) The distribution of DVS within each system class. (B) The average rate of water supplied by systems reporting data within each DVT, color coded by system class (the number “n=” represents the number of reports within a DVT).*

4.3. Priority areas for improvement

Once the interactive data grading is completed and a DVS/DVT generated, the AWWA FWAS provides feedback on how data validity could be improved by suggesting three “priority areas” where attention should be given by the organization completing the report to improve the confidence of the input data. Considering only the 278 systems which submitted reports in CY2021 using AWWA FWAS v6.0, the resulting 834 priority area suggestions have been tallied as a summary in Figure 14. Collectively, the three top priority areas account for 593 of the 834 recommendations made for CY2021, which is roughly 71% of all recommendations made. In total, 252 of the 278 reports had at least one of these three (91%), 185 reports had two of the three (67%), and 72 had these three exactly (26%). Notably, these top three priority areas are large components of the water balance, including the treated water volume input to the system (VOS), the distributed water which has been metered and billed (BMAC), and a large component of apparent loss (CMI). The following subsections of this report investigate further the specifics of data validity for each of the top three priority areas.

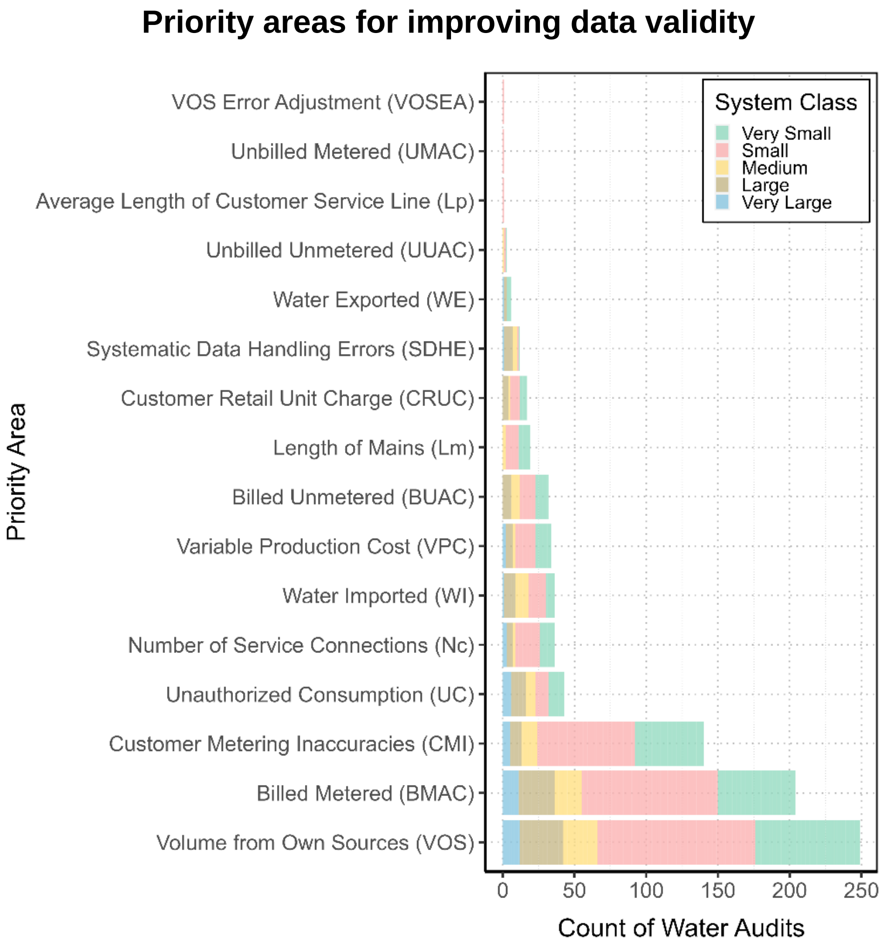


***Figure 14**: Parameters identified as a priority area for attention to improve the water audit data validity score (CY2021).*

4.3.1. IDG: Volume from own sources

As net imports and exports are relatively small in comparison to the total volume supplied from the systems' own sources, it is worthwhile to assess how the reported VOS data are generated. There are ten questions for a person completing the AWWA FWAS to answer regarding the VOS, if water utility supplied any water from its own sources during the audit year (listed below).

vos.0 – Did the water utility supply any water from its own sources during the audit year?
vos.1 – What percent of own supply volume is metered?
vos.2 – What is the frequency of electronic calibration?
vos.3 – What level of data transfer errors are checked as part of the electronic calibration process?
vos.4 – Is the most recent electronic calibration documentation available for review?
vos.5 – What is the frequency of in-situ flow accuracy testing?
vos.6 – Is the most recent in-situ flow accuracy testing documentation available for review?
vos.7 – What are the total volume-weighted average results of in-situ flow accuracy testing (during or closest to audit year)?
vos.8 – Have testing and calibration procedures been closely scrutinized for compliance with procedures described in the AWWA M36 and/or M33 Manual(s)?
vos.9 – Which best describes the frequency of finished water meter readings?
vos.10 – Which best describes the frequency of data review for anomalies/errors? These can include numbers that are outside of typical patterns, and zero or 'null' values that may reflect a gap in data recording.

Questions 2-10 apply to systems whose meters measure >90% of the finished water volume.

Considering the subset of reports submitted in CY2021 using AWWA FWAS v6.0 (n=278, per Table 8), 269 reported having withdrawn volumes of water from their own sources (answer "yes" to *vos.0*). Once a report is completed and the grade generated for VOS, the AWWA FWAS v6.0 indicates which answer (or combination of answers) to the IDG questions is limiting the grade – termed the limiting criteria. A summary of which IDG questions for VOS were the most commonly identified as limiting is presented in Figure 15 (n=421 data points). From the results, it is clear that *vos.2*, *vos.3*, *vos.5 and vos.10* are the most frequently cited as limiting grades from being higher. It is noticeable that *vos.3* and *vos.10* both deal with the manual checking of data, whereas *vos.2* and *vos.5* are more related to the frequency of calibration and testing.

A summary of answers to *vos.2* by all 269 systems in the dataset is presented in Figure 16, with the number of responses color coded by whether or not the answer was the limiting criteria to the data grade for VOS. It becomes clear from the average grade of reports associated with each answer that getting to a point of calibrating finish water meters annually yields the biggest impact on data reliability. In a similar fashion, Figure 17 presents a summary of answers to *vos.5* which asks about the frequency of in-situ flow testing on finished water meters. Then, Figure 18 summarizes answers to *vos.7,* which asks about the results the accuracy testing, this time color coded by system class. Additionally, the VOS (average MGD) attributed to the systems in each bar of Figure 18 is noted below the bar, as well as the percentage of all VOS it represents for CY2021. It is noteworthy to observe that even though the frequency of in-situ accuracy testing may be considered limiting in many cases, the results of in-situ testing suggest meter accuracy within ±3% for almost 75% of the VOS volume in CY2021 (779 MGD).

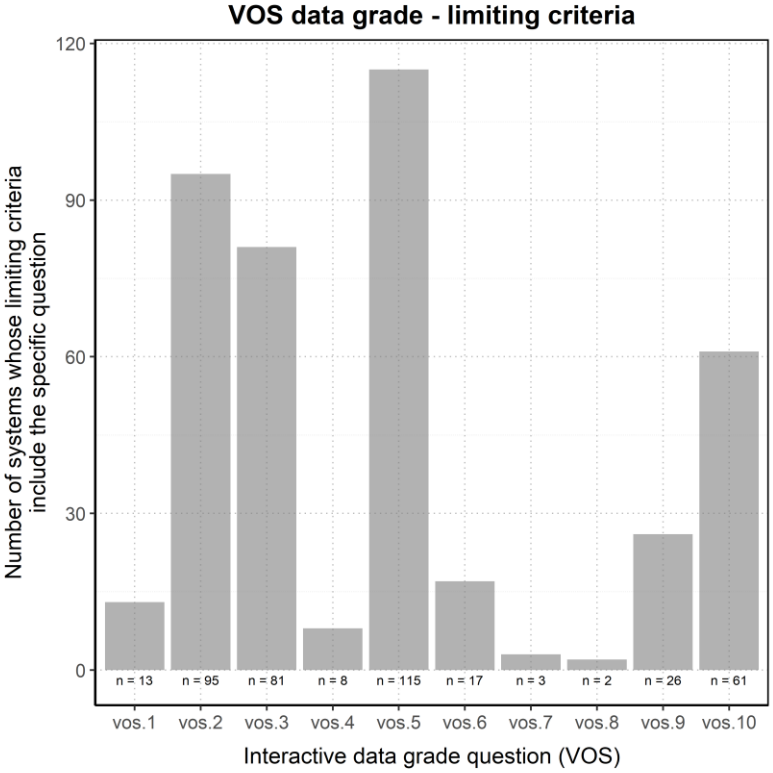


Figure 15: *A summary of the limiting data grading question for the Volume from Own Sources (VOS). There are 267 reports included in this figure (i.e., submitted in CY2021, AWWA FWAS v6.0, reported to have VOS). Note that limiting criteria may include a combination of questions, and therefore the total number of data points tallied is n=421.*

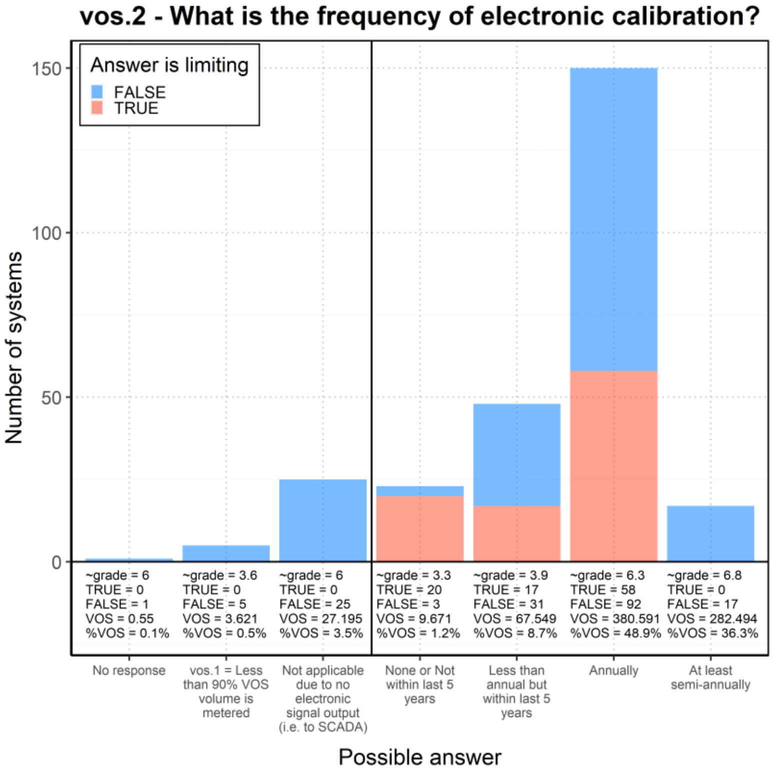


Figure 16: *A summary of answers to vos.2 for all 269 systems, color coded by whether or not that answer was flagged as a limiting criterion for the overall VOS data grade. Note that "~grade" represents the mean VOS data validity grade for reports in each column. Additionally, the VOS (average MGD) attributed to the systems in each column is noted below each column, as well as the respective percentage of all VOS for CY2021 (779 MGD).*

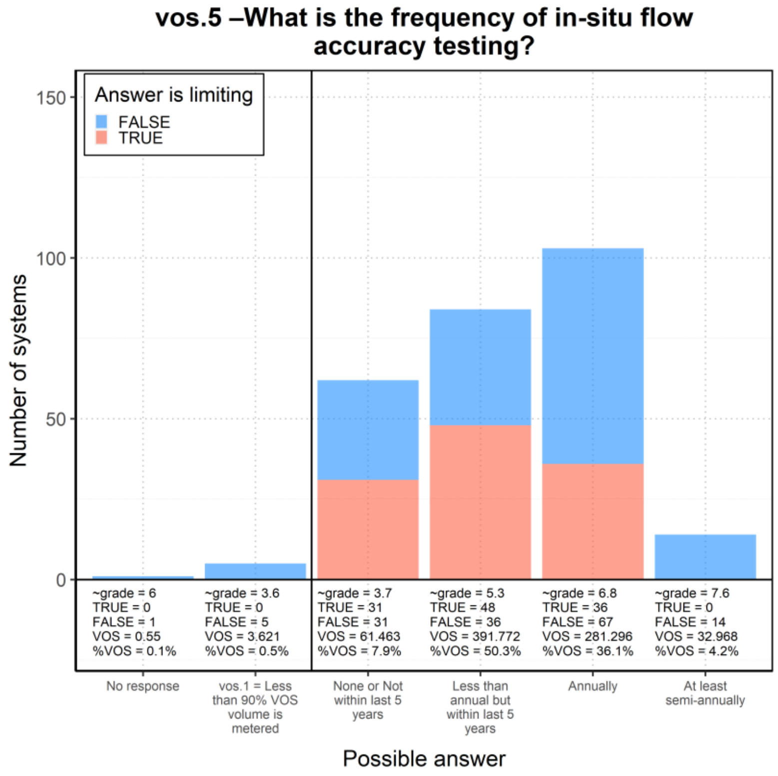


Figure 17: *A summary of answers to vos.5 for all 269 systems, color coded by whether or not that answer was flagged as a limiting criterion for the overall VOS data grade. Note that “~grade” represents the mean VOS data validity grade for reports in each column.*

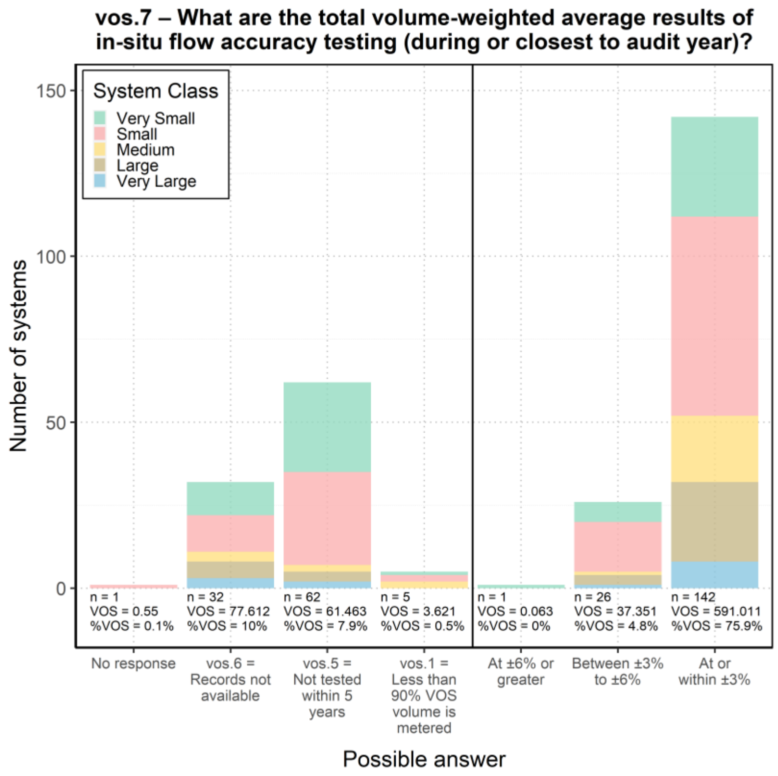


Figure 18: *A summary of answers to vos.7 for all 269 systems, color coded by system size class. Note that the ability to answer vos.7 depends on answers to vos.1, vos.5 and vos.6. Additionally, the VOS (average MGD) attributed to the systems in each column is noted below each column, as well as the respective percentage of all VOS for CY2021.*

4.3.2. IDG: Billed metered authorized consumption

The second most highlighted priority area for attention to improve the overall water audit data validity score (per Figure 14) is the input data for billed metered authorized consumption (BMAC). This finding is a bit surprising based on the distribution of data validity grades for BMAC shown in Table 11, which indicated that about 78% of reports had a data grade ≥7 for BMAC. Understandably, it is one of the more decisive components to the overall water balance and therefore likely holds more weight in generating the overall data validity score for the report. Nonetheless as it was identified as limiting, it is worth investigating the responses to the grading questions. There are seven questions for a person completing the AWWA FWAS to answer regarding the BMAC, if any customers were metered in the audit year (listed below).

bmac.0 – Were any customers metered in the audit year?
bmac.1 – For billed metered accounts, what % of bills are estimated in a typical billing cycle?
bmac.2 – How often does the utility read its customer meters? For systems with multiple read frequencies, select the reading frequency that describes the majority of your customers.
bmac.3 – Is the BMAC volume pro-rated to represent consumption occurring exactly during the audit period?
bmac.4 – How frequently does internal review by utility staff of the BMAC volumes occur?
bmac.5 – What level of detail is examined in the internal review of BMAC volumes?
bmac.6 – When was the most recent billing data review by someone who is independent of the utility billing process?
bmac.7 – What level of detail was examined in the review by someone who is independent of the utility billing process?

All reports submitted in CY2021 using AWWA FWAS v6.0 (n=278, per Table 8) reported having metered customers (answer “yes” to *bmac.0*). These 278 reports account for 549 MGD of BMAC, which is approximately 97.8% of the total 561 MGD (Figure 11) that is calculated when including missing reports in the analysis. Once a report is completed and the grade generated for BMAC, the AWWA FWAS v6.0 indicates which answer (or combination of answers) to the IDG questions is limiting the grade – termed the limiting criteria. A summary of which IDG questions for BMAC were the most commonly identified as limiting is presented in Figure 19 (n=349 data points). From the results, it is clear that *bmac.2* is the most frequently cited as limiting grades from being higher, which is related to the frequency of customer meter reading.

A summary of the responses selected to *bmac.2* is presented in Figure 20, color coded by whether or not the answer to *bmac.2* was the limiting criteria for the overall BMAC grade. Quite clearly, the most selected answer was that meters are read quarterly, which in most cases ended up limiting the grade. However, it is notable that the average BMAC grade for these responses was still 6.2, whereas the average grade increases to only 7.5 for systems reading data more frequently than monthly. Considering all BMAC for CY2021 (561 MGD), 153 systems reading data quarterly account for about 31% of the total volume, 105 systems reading data monthly account for about 42% of the volume, and 13 systems reading data more frequently than monthly account for about 26% of the volume.

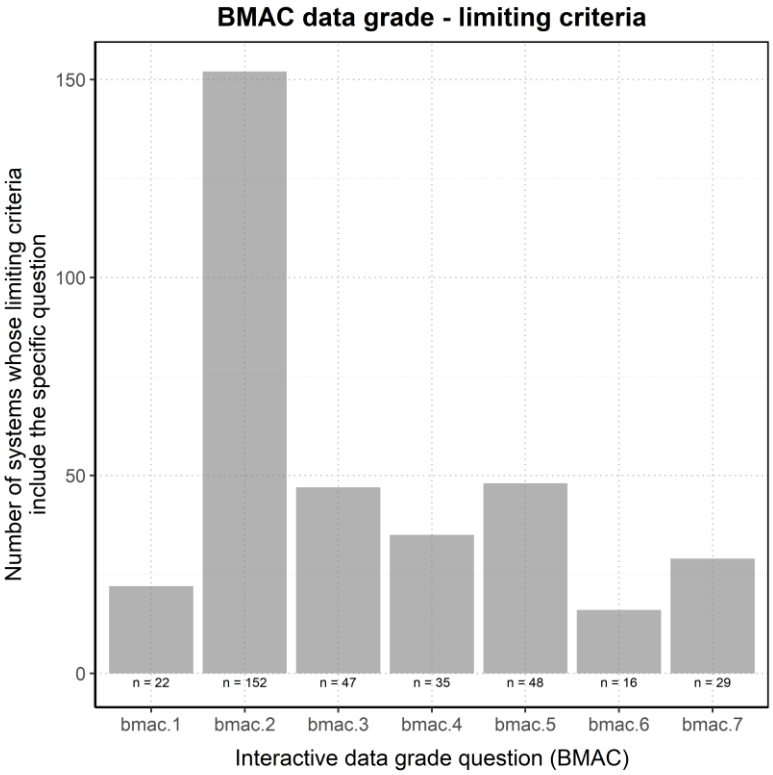


Figure 19: *A summary of the limiting data grading question for the billed metered authorized consumption (BMAC). There are 278 reports included in this figure (i.e., submitted in CY2021, AWWA FWAS v6.0, reported to have BMAC). Note that limiting criteria may include a combination of questions, and therefore the total number of data points tallied is n=349.*

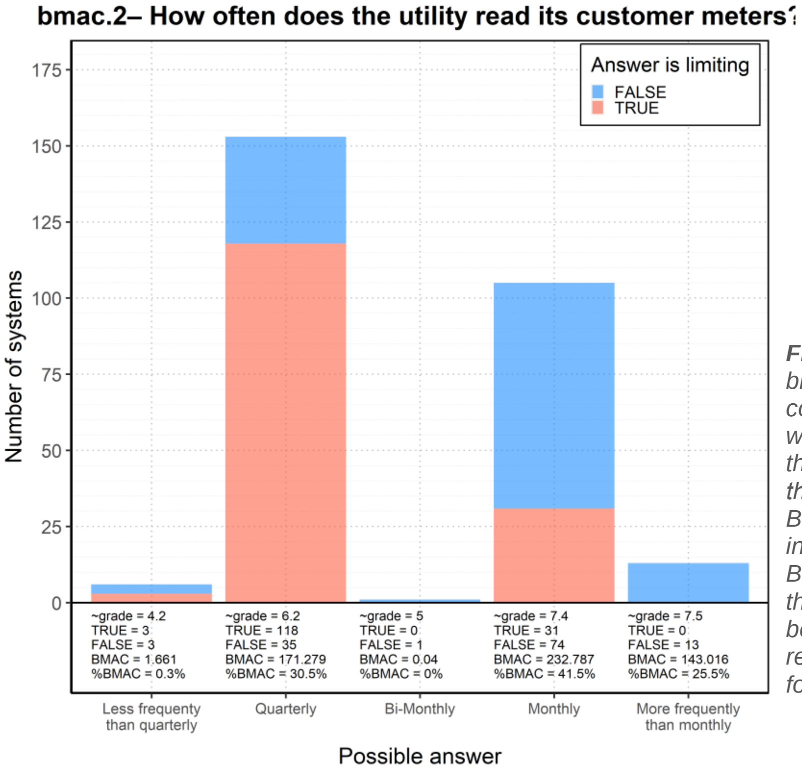


Figure 20: *A summary of answers to bmac.2 for the 278 systems, color coded by whether or not that answer was flagged as a limiting criterion for the overall BMAC data grade. Note that "~grade" represents the mean BMAC data validity grade for reports in each column. Additionally, the BMAC (average MGD) attributed to the systems in each column is noted below each column, as well as the respective percentage of all BMAC for CY2021.*

4.3.3. IDG: Customer meter inaccuracies

The third most highlighted priority area for attention to improve the overall water audit data validity score (per Figure 14) is the input data for customer meter inaccuracies (CMI). This finding is not very surprising based on the distribution of data validity grades for CMI, shown in Table 11, demonstrating that grades are heavily skewed toward the lower ranges. There are nine questions for a person completing the AWWA FWAS to answer regarding the CMI, if there was any metered customer usage in the audit year (listed below).

cmi.0 – Was there any metered customer usage during the audit period?
cmi.1 – Do you test meters reactively (when triggered by customer complaint or billing/consumption flag)?
cmi.2 – For small size customer meters, which best describes the frequency of proactive testing (effort beyond when triggered by customer complaint or billing/consumption flags)?
cmi.3 – Which best describes what meters are included in the proactive small size customer meter testing activities?
cmi.4 – For mid and large size customer meters, which best describes the frequency of the proactive testing program?
cmi.5 – Which best describes what meters are included in the proactive mid- and large customer meter testing activities?
cmi.6 – Which best describes how the input was derived?
cmi.7 – Has the input derivation been reviewed by someone with expert knowledge in the M36 methodology?
cmi.8 – To what extent does meter replacement occur and for which meters?
cmi.9 – Which best describes the reliability of meter installation records?

Of the subset of reports submitted in CY2021 using AWWA FWAS v6.0 (n=278, per Table 8), three answered "No" to question *cmi.0* but reported a value for BMAC, suggesting inconsistent data; therefore, these systems are identified as "No response" and the dataset remains at n=278. These 278 reports account for 549 MGD of BMAC, which is approximately 97.8% of the total 561 MGD (Figure 11) that is calculated when including missing reports in the analysis. Once a report is completed and the grade generated for CMI, the AWWA FWAS v6.0 indicates which answer (or combination of answers) to the IDG questions is limiting the grade – termed the limiting criteria. A summary of which IDG questions for CMI were the most commonly identified as limiting is presented in Figure 19 (n=328 data points). Questions *cmi.2* and *cmi.4* are similar in that they both ask about proactive meter testing, but distinguish between small and large meters, respectively.

The IDG question most frequently cited as limiting the CMI grade is *cmi.6*, which inquires as to how the input data is generated. A summary of the responses to that question are presented in Figure 22, color coded by whether or not the answer to *cmi.6* was the limiting criteria for the overall CMI grade. It is notable that input data on CMI is "guesstimated" by 75 systems associated with about 11.5% of the total BMAC for CY2021. The average CMI grade for systems reporting that this value was "guesstimated" is 1.8, logically leading this to be classified as a limiting response. An additional 80 systems associated with about 29% of the total BMAC for CY2021 input CMI data having referenced manufacturer specifications or meter test results, but without using the information in a calculation.

Based on the information gleaned from an investigation such as this, the notion that there are difficulties which CMI data is reinforced. It was previously discussed in Section 3.4.2 of this report

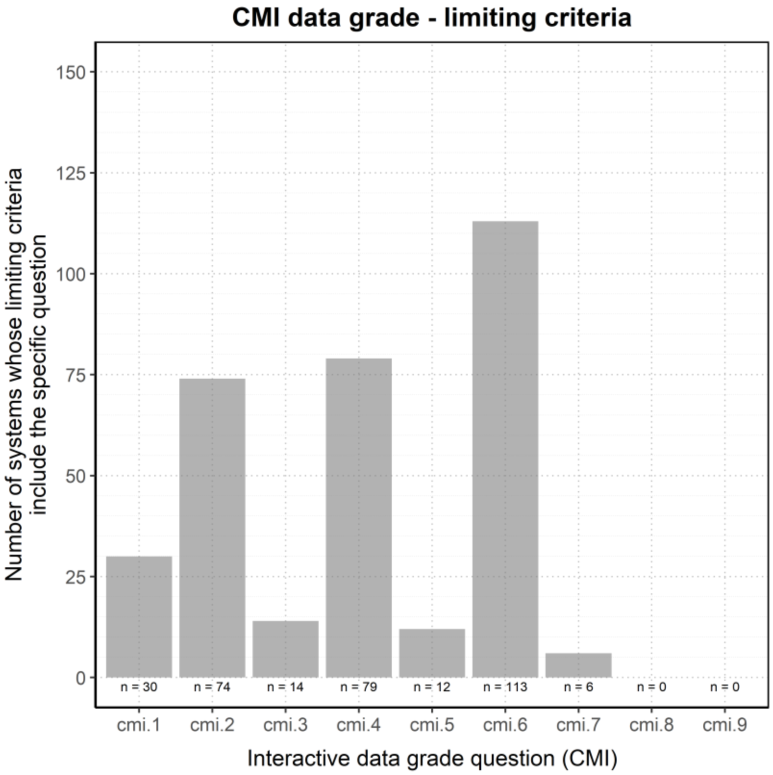


Figure 21: *A summary of the limiting data grading question for the customer metering inaccuracies (CMI). There are 278 reports included in this figure. Note that limiting criteria may include a combination of questions, and therefore the total number of data points tallied is n=328.*

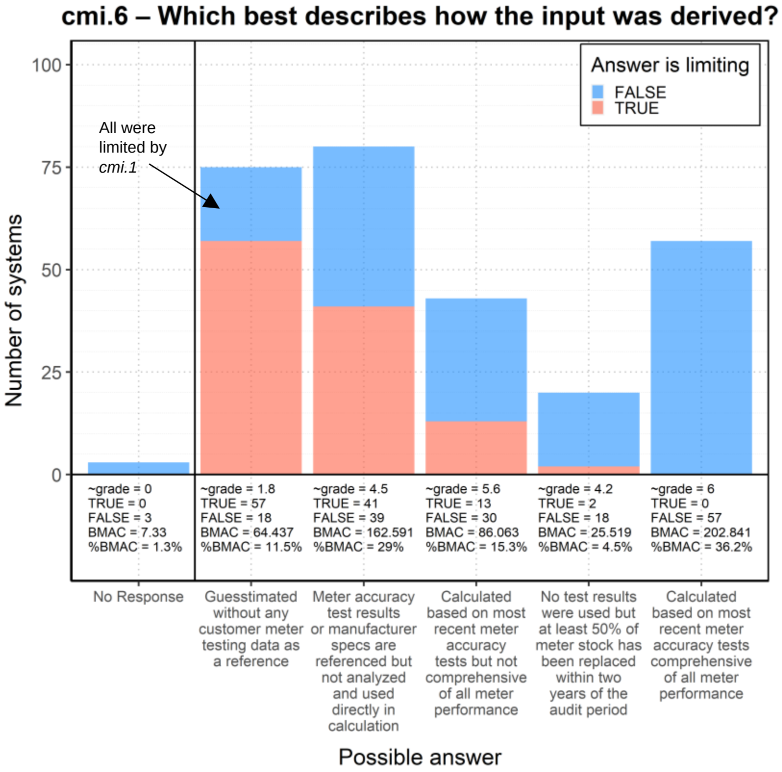


Figure 22: *A summary of answers to cmi.6 for the 278 systems, color coded by whether or not that answer was flagged as a limiting criterion for the overall CMI data grade. Note that "~grade" represents the mean CMI data validity grade for reports in each column. Additionally, the BMAC (average MGD) attributed to the systems in each column is noted below each column, as well as the respective percentage of all BMAC for CY2021.*

that one downfall to the input field for CMI in the AWWA FWAS is that there is no option for a default value to be selected, possibly forcing users into the camp of inputting data which is “guesstimated,” or which loosely references manufacturer specifications. There was discussion about the prevalence of CMI data input as a zero value or as 0% of the BMAC+UMAC, and to this end, a summary of data has been provided in Figure 23. This is the same number of reports and categories as Figure 22, only the color scheme has been changed to indicate which reports have input zero versus non-zero values of CMI. It is striking that many systems, even with more accurate derivations of the input, report 0% error of customer meters. Notably, the average reported CMI (as a percent of BMAC+UMAC) for systems not entering a zero value is listed below each column, ranging between 1.50% and 2.46% under-registration.

For the purposes of this study, it is worthwhile to reiterate that reports which included the input of CMI=0% had the value replaced with 2% under-registration, and all calculations carried forward; the rationale behind the specified value was provided in Section 3.4.2 of this report. This was done for all reports regardless of the answer to questions such as cmi.6, for two primary reasons (1) to be conservative in estimates of CMI erring on the side of more water loss, and (2) to be consistent with efforts to correct previous years of data which do not have the benefit of IDG questions and answers that AWWA FWAS v6.0 has. For other or future analyses which only include data from AWWA FWAS v6.0, there are likely more intricate ways to address concerns of inaccurate CMI values than are utilized in this analysis.

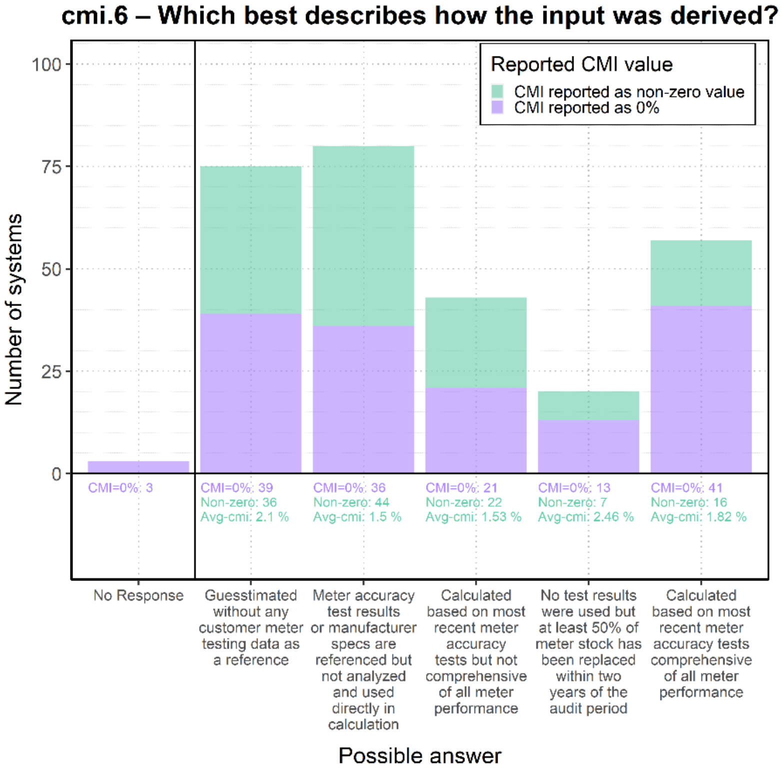


Figure 23: *A summary of answers to cmi.6 for the 278 systems, color coded by whether or not the report included a CMI value of 0%. Note that the number of reports in each category for each column is presented below the column. The “Avg-cmi” value represents the mean reported CMI percentage for reports retuning non-zero values (positive indicates under-registration).*

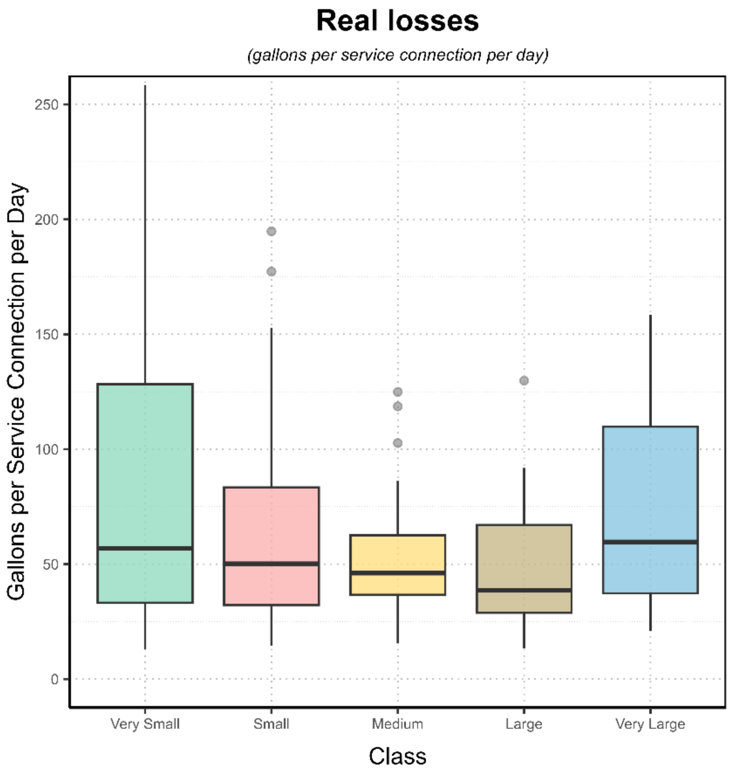


***Figure* 24:** *Real losses (gallons per service connection per day), by system class (n=209). Note that while it has been suggested that this performance indicator is a poor metric for systems with low average service connection density (less than 32 connections per mile), there are only 8 Very Small systems and 2 Small systems below that threshold in this analysis.*

4.4. Real water losses

The AWWA FWAS does not account for the transmission of raw water from sources to the treatment facilities – i.e., it begins the water balance at the master meter for finished water. Therefore, real losses are physical water losses which leave the pressurized system (water mains and customer service connections) and the utility's storage up to the point of customer consumption. As was discussed in the seminal paper which introduced the Burst and Background Estimates (BABE) methodology for estimating water loss (Lambert, 1994), it is understood that these real loss values contain a combination of losses from (1) reported bursts, (2) unreported bursts, and (3) background leakage. While all forms are influenced by system pressure, the bursts in particular (including service reservoir overflows) are dependent upon the frequency, flow rate and leak duration (e.g., the time to become aware, locate and repair the leak).

The unit real losses (in gallons per connection per day) are presented in Figure 24 by system class. The highest median unit real loss rate occurs in Very Large systems, inclusive of several larger, generally older, urban areas. While typically having higher data validity scores (Figure 13), these systems appear to encounter challenges in replacing and/or upgrading respective water infrastructure. While Very Large systems had the highest median, there are several systems in all categories that have high unit real loss rates and are outliers among their class. There are two systems that have a real loss rate of less than 0.3 gallons/service connection per day, which is unlikely and indicates that the data from those systems is possibly flawed.

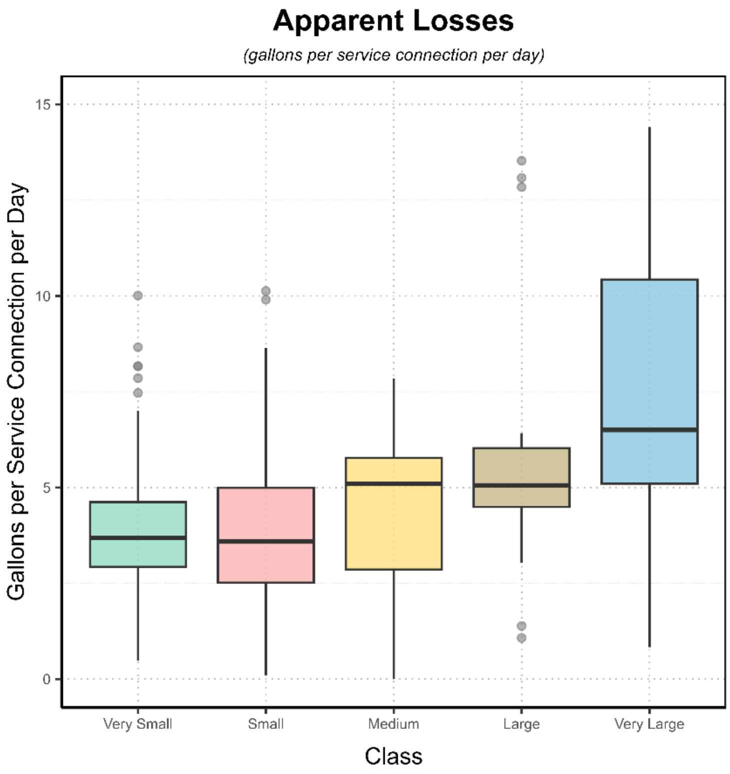


Figure 25: *Apparent losses (gallons per connection per day) by system class (n = 209).*

4.5. Apparent water losses

Apparent losses include data inaccuracies which are associated with customer metering (old meters, improperly sized meters, etc.), systematic data handling errors (meter reading, billing archiving, and reporting) and unauthorized consumption (theft or illegal use). As a unit metric, apparent loss can be used to compare systems of different sizes. As shown in Figure 25, Very Large systems had the highest median unit apparent loss rate of 6.8 gallons/connection/day (gcd). The average unit apparent loss rate for the entire dataset is 4.1 gcd.

Apparent losses are valued at the customer retail unit cost, which means that this water makes it to the end user (customer), but it is not accurately billed or metered. Thus, systems which reduce apparent losses may not see a decrease in water withdrawals but may see an increase in revenue collected by the utility. Additional revenue increases the potential for utilities to invest in their system to reduce real losses, as well as apparent losses through meter maintenance and replacement programs.

4.6. Average operating pressure

It was discussed previously in this report how the value of annual operating pressure poses challenges (Section 2.5), in that it is a single value representing the variable pressures of an entire system throughout the year. A benefit of AWWA FWAS v6.0 is that the interactive data grading requires users to answer questions about the P_{AO} input data in order to generate a data validity score. Of specific interest are the answers to question *aop.5*, which asks "*How was the input data derived?*". The possible answers to choose from are presented in Table 12, along with the total number of systems choosing each answer; the distribution of associated pressures for each system class and answer is presented in Figure 26. Note that only systems which submitted reports using v6.0 in CY2021 (n=278) have the answers shown, consistent with Table 8. The following bulleted points highlight some interesting observations from the interactive data grading responses:

- Perhaps unsurprisingly, a significant number of systems have calculated P_{AO} using a simple average of field data (n=120, 43%), while a much smaller contingent use the methods suggested in AWWA M36, which provide specific guidance on how to perform a weighted average (n=16, 6%).
- There is a clear increasing trend in the likelihood for a system completing the AWWA FWAS to be either "guesstimating" or "loosely estimating" the P_{AO} input data.
- Many systems make use of hydraulic models to calculate P_{AO} (n=83, 30%), including systems from every size class. However, based on survey results from 36 systems in 22 states, LeChevallier et al., 2014 reported that 92% of the systems had developed hydraulic models, suggesting that hydraulic models have been accepted as a common engineering and planning tool. The smaller percentage using hydraulic models reported to DRBC could be attributed to: (1) while 300 water utilities were invited, only 36 (12%) completed the survey put out by LeChevallier et al., 2014, and perhaps those who responded skew towards having more advanced management practices, and/or (2) not all who have developed hydraulic models used them to calculate P_{AO} in the reports submitted to DRBC.

Table 12: *Summary of the responses to interactive data grading question aop.5 for reports submitted in CY2021 using AWWA FWAS v6.0.*

aop_5: How was the input data derived?	VS	S	M	L	VL	TOTAL
Guesstimated	10	6	2	0	0	18
Loose estimate inferred from field measurements but no analysis nor calculations performed	16	16	4	4	1	41
Calculated from field data as a simple average	29	58	14	16	3	120
Calculated from field data as a weighted average compliant with methods described in the M36 Manual	5	7	3	0	1	16
Derived from hydraulic model where model has not been field calibrated in the last 5 years	4	3	1	2	0	10
Derived from hydraulic model where model has been field calibrated in the last 5 years	16	29	5	14	9	73
TOTAL	80	119	29	36	14	278

By class, the percentage of systems using hydraulic models to calculate P_{AO} is 25% (Very Small), 27% (Small), 21% (Medium), 44% (Large) and 64% (Very Large). It seems as though broadly classifying hydraulic models as a common engineering and planning tool may be applicable to larger systems (in this case $N_c \geq 10{,}000$), but may be less broadly utilized in smaller systems.

Now considering the actual P_{AO} that was reported by each system, the data can be presented by both system class and the response to *aop.5*, as shown in Figure 26. As the data have been parsed into 30 categories, there are many categories that have small sample sizes and do not provide much distribution information. The minimum P_{AO} is 42 psi, which was reported by five systems (4 Small, 1 Large); the Small systems used loose estimates and both forms of averaging, while the Large system used a calibrated hydraulic model. The maximum P_{AO} is 200, which was reported by two systems (1 Very Small, 1 Small), both of which calculated the value as a simple average. It is difficult to draw many conclusions from Figure 26, although it is possible that Small systems "guesstimated" P_{AO} on the higher side class-wide, whereas Large systems loosely estimated P_{AO} on the low side class-wide.

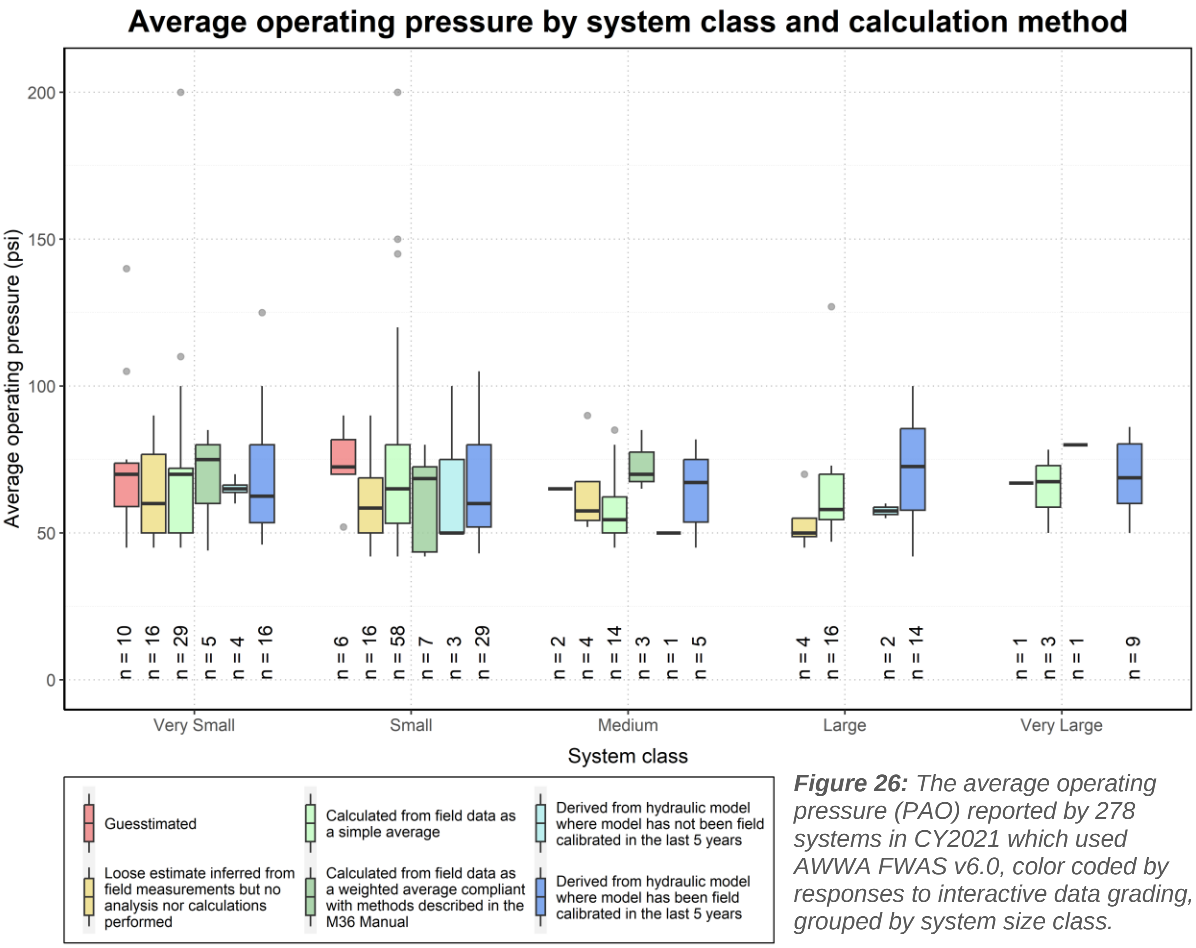


Figure 26: *The average operating pressure (PAO) reported by 278 systems in CY2021 which used AWWA FWAS v6.0, color coded by responses to interactive data grading, grouped by system size class.*

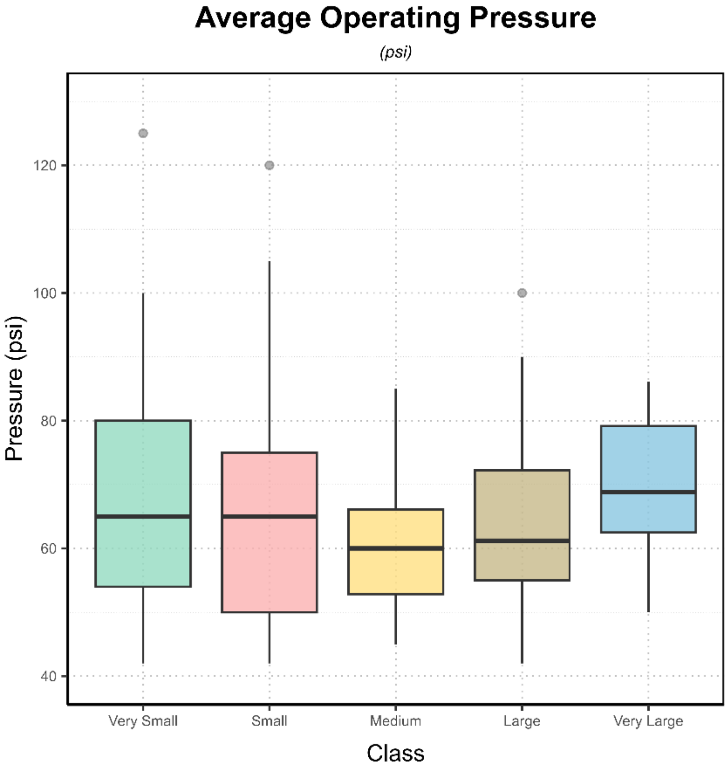


Figure 27: *Average operating pressure in pounds per square inch (psi), by system class (n = 209)*

The average operating pressure (P_{AO}) as reported by the 300 systems is presented in Figure 27. Visually, it appears as though the range of P_{AO} increases as the system class size decreases. The smaller range in P_{AO} that comes with the larger systems may be attributed to stronger pressure management practices and availability of system capital and operating resources; however, it is difficult to hypothesize exact reasons for pressure increases based solely on the pressure values. It is noteworthy that many of the Very Small and Small systems are located in the northern portion of the Delaware River Basin, which has much more variable topography. The relationship between the topography of a system's service area (i.e., elevation differential) and the P_{AO} is investigated in this report in Section 9: Physiographic Analysis.

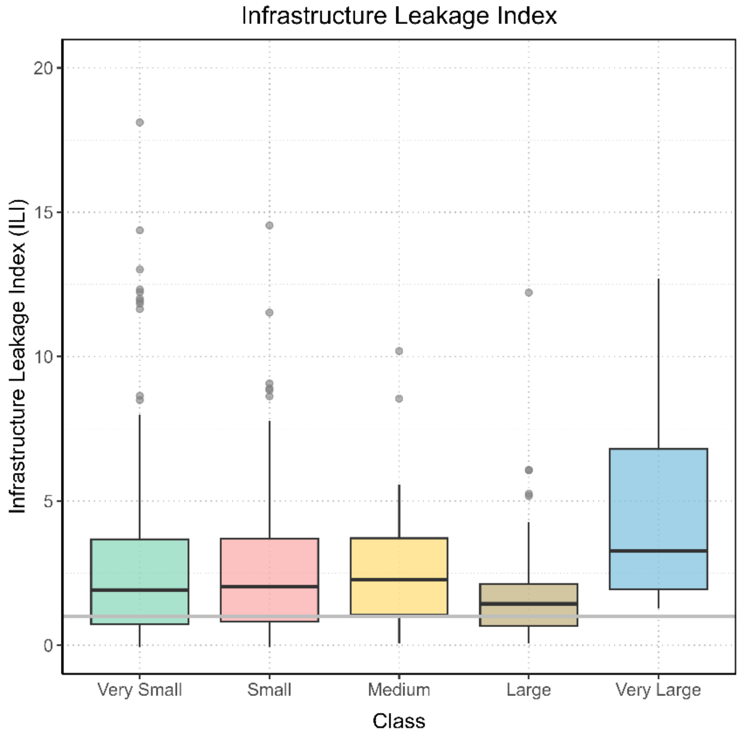


Figure 28: *Infrastructure Leakage Index (n = 300). Note that the current recommendation for the standard calculation of UARL is that systems with N_c < 5,000 or about 65 psi < AOP < 85 psi are recommended to have a "System Correction Factor" applied to the UARL value. Note that one outlier plots above the y-limit for the Very Small and the Small system classes, but the viewing pane has been restricted for clarity).*

4.7. Infrastructure Leakage Index

The Infrastructure Leakage Index (ILI) is the ratio of the current annual real losses (CARL) to the Unavoidable Annual Real Losses (UARL), as noted by Equation 10. The UARL is a theoretical reference value representing the technical low limit of leakage that could be achieved if the best technology and concepts available in 2000 could be successfully applied to well maintained systems with infrastructure in good condition. The ILI is consequently a highly effective performance indicator for comparing (benchmarking) the performance of utilities in operational management of real losses. The current recommended limits for calculating ILI were discussed in Section 2.2.3.2.3, and additional information on System Correction Factors (including a pilot study) are provided in Section 7. With this information in mind Figure 28 presents calculated ILI values for all 300 systems in this study; an assumption being made that *most* ILIs for small systems are *likely* to be underestimates based on the results of Section 4.4. Initially, it is recognizable that some ILIs have been calculated to be less than 1, which has the potential to be corrected if the system has a small number of connections, or pressure outside the recommended range for using the equations. Beyond this observation, it is evident that the Very Large systems have the highest inner-quartile range and median ILI; again, it is also known that some of the systems in this class include older urban areas which may deal with a large amount of aging infrastructure.

According to AWWA, striving to reduce system leakage to a level close to the UARL is usually not needed unless the water supply is unusually expensive, scarce, or both (Table 4 was adapted from AWWA M36 and provides general guidelines on target ILIs in the absence of a calculated system specific Economic Level of Leakage, ELL). Note that the USEPA's Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion (USEPA, 2016a) recommends that systems with strong data confidence (DVT "Tier IV") should target an ILI ≤ 3, or provide an ELL analysis demonstrating that the ILI ≥ 3 is justified. An analysis investigating the "Real Loss Reduction Potential" based on all systems meeting particular ILI thresholds is presented in this report in Section 6.2.

5. WATER AUDIT DATA TRENDS (2012-2021)

5.1. Volume from own sources

The volume from own sources is the primary input component to the Basin-wide water balance, as previously shown in Figure 11. As has been discussed, this data is collected from about 300 systems annually via the AWWA FWAS, which provides one annual VOS number per system. Additionally, all of these systems (and more below DRBC water audit thresholds) are required to submit withdrawal data to respective state agencies, typically at a source-level with monthly data points. A comparison between these datasets is provided in Figure 29 and shows that the data collected through the AWWA FWAS is in strong agreement with data reported at a much finer scale to state agencies. Data compiled for CY2021 from state agencies was not available at the time of this assessment. Typically, the aggregate AWWA FWAS VOS is about 96-100% of the aggregate withdrawal data from sources within the Basin. It is not expected for the two datasets to match exactly for a few reasons: (1) there are small systems withdrawing water within the Basin not required to submit water audits, (2) the state data only includes sources from within the Basin, while the water audit may include sources outside for systems on the Basin boundary, and (3) state data is measured at the source, whereas VOS is theoretically what leaves the treatment facility, and there may be small losses of raw water. Ultimately, the comparison adds additional confidence to the validity of the AWWA FWAS dataset. Over the last 10 years the trend in VOS has been largely stable, hovering around a mean value of about 772 MGD.

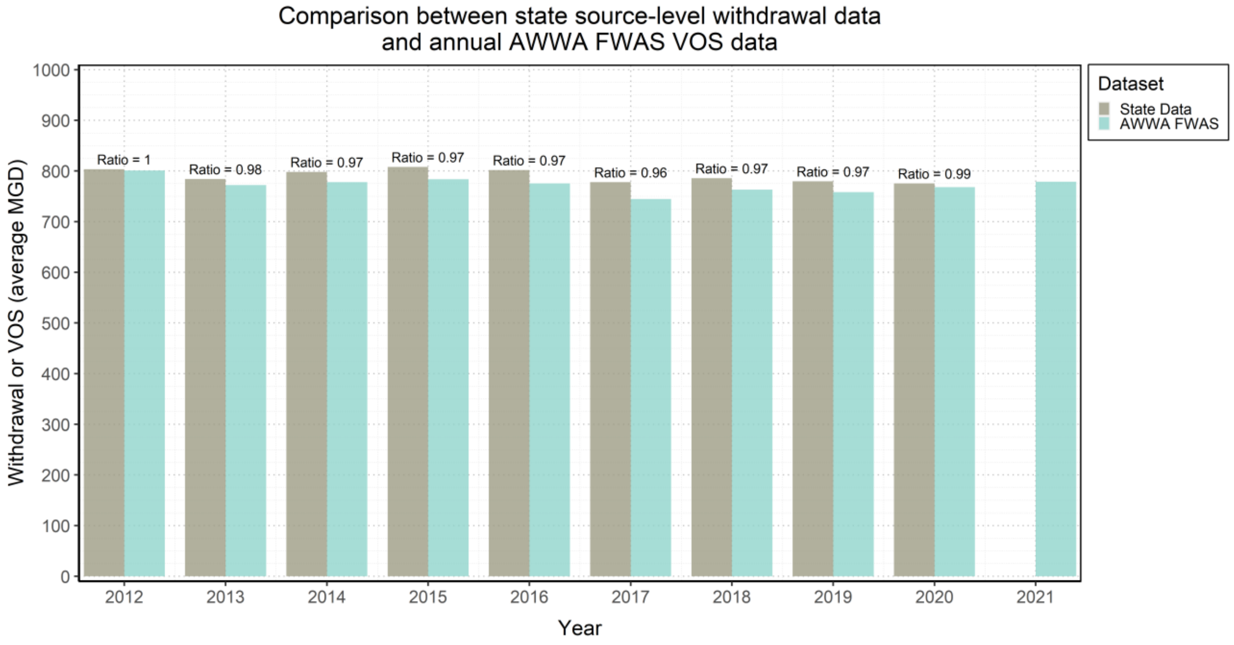


Figure 29: *A comparison between the total water withdrawals from sources within the Delaware River Basin as reported to state agencies (compiled by DRBC), to the volume from own sources (VOS) from the approximately 300 audited systems in the Delaware River Basin, as collected via the AWWA FWAS. Note that the state withdrawal data is the same as Figure 47, simply zoomed to the same extent of data available from the audit program. Note the analysis had not been updated past 2020.*

5.2. Real water losses

The real losses of a system can vary greatly depending on multiple factors such as the age, size and how well maintained the physical water system is. In the Delaware River Basin, there is a significant range in size from the small villages in Catskill Mountains of New York, to the sixth most populous city in the United States, the City of Philadelphia. Furthermore, many of the larger systems in the Basin were established in the 1800's and may still have older infrastructure in service, not that this is necessarily the sole indicator of performance. For example, in 2015 the Philadelphia Water Department reported that the average age of their water lines was 78 years old with some pipes dating back to 1824 (PWD, 2015), and the City of Bethlehem is one of 14 water systems in the country constructed prior to the United States Declaration of Independence in 1776 (the Bethlehem Water Works was built in 1754) (Pierce, 2022). For public water supply systems in the Delaware River Basin subject to the water audit reporting requirements, the total real water loss over time is presented graphically in Figure 30, color coded by system class, and has the corresponding annual totals presented in Table 13. The annual totals for water loss by system class are then unit by respective 10-year mean values, and color coded in Table 14.

Volumetric real losses appear to have slightly increased; however, a closer examination shows that it has remained around 150-175 MGD, with slight increases in the past two years. CY2020 reported on average about 15% higher water loss than the 10-year mean (ranging by class between +1% to +22%), and CY2021 reported on average about 8% higher water loss than the 10-year mean (ranging by class between -9% to +11%). Conversely, the prior eight-year period (2012-2019) averaged about 3% lower water loss than

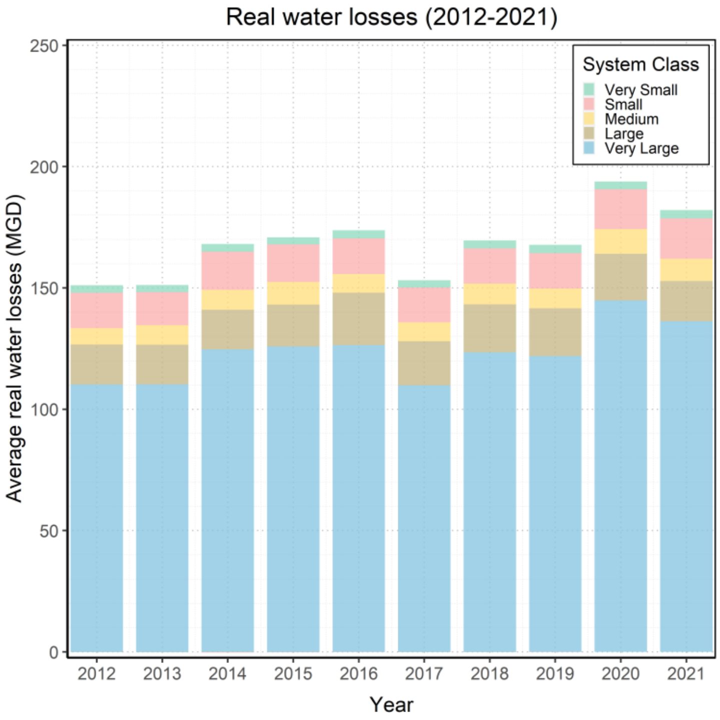


Figure 30: Real water loss as reported by water supply systems in the Delaware River Basin which are subject to water audit reporting requirements.

Table 13: *Real water loss summary data related to Figure 30, values are annual averages presented in units of million gallons per day (MGD).*

Year	Very Small	Small	Medium	Large	Very Large	Total
2012	3.153	14.558	6.734	16.461	110.165	151.072
2013	2.908	13.620	8.088	16.199	110.266	151.081
2014	3.157	15.558	8.290	16.164	124.691	167.860
2015	2.901	15.419	9.349	17.120	125.899	170.689
2016	3.299	14.580	7.748	21.596	126.422	173.644
2017	2.933	14.311	7.821	18.159	109.820	153.044
2018	3.251	14.459	8.603	19.666	123.496	169.474
2019	3.357	14.575	8.132	19.730	121.904	167.697
2020	3.176	16.390	10.240	19.204	144.845	193.855
2021	3.382	16.691	9.186	16.534	136.281	182.073
Mean	3.152	15.016	8.419	18.083	123.379	168.049

Table 14: *The annual real water loss volumes by system class previously presented in Table 13, normalized by the 10-year mean and color coded such that values above the mean are red (>1), and values below the mean are blue (<1).*

Year	Very Small	Small	Medium	Large	Very Large	Total
2012	1.00	0.97	0.80	0.91	0.89	0.90
2013	0.92	0.91	0.96	0.90	0.89	0.90
2014	1.00	1.04	0.98	0.89	1.01	1.00
2015	0.92	1.03	1.11	0.95	1.02	1.02
2016	1.05	0.97	0.92	1.19	1.02	1.03
2017	0.93	0.95	0.93	1.00	0.89	0.91
2018	1.03	0.96	1.02	1.09	1.00	1.01
2019	1.07	0.97	0.97	1.09	0.99	1.00
2020	1.01	1.09	1.22	1.06	1.17	1.15
2021	1.07	1.11	1.09	0.91	1.10	1.08

the 10-year mean (total ratios ranging between -10% and +3%). We have presented a few possible explanations for such an observation, although confirming these hypotheses currently is very difficult to near impossible:

1. It is possible that the implementation of v6.0 software requirements (beginning in 2020, per Table 8) affected the total amount of water loss being calculated, although it does not seem likely to have had such a significant effect as is being observed.
2. Many of the precautionary measures and governmental restrictions related to the COVID-19 pandemic were in place by March/April 2020. There have been numerous research studies which investigate water use patterns before/after this timeframe, although currently, published results seem to have relatively limited datasets (data not extending into 2021). While no studies seem to have investigated leakage directly, a brief literature review suggests that redistribution of water consumption between residential and non-residential properties, typically increased residential use and decreased non-residential,

was commonly observed at least during a period of time following the March 2020 timeframe:

- A study of the water consumption data from six urban water utilities in the United States focusing on a period of "stay-at-home" orders compared data from January-May 2020 to the same timeframe in prior years (2018 and 2019) found an increase in residential demand by 11.80% and 13.65%, and a change in non-residential property demand by -22.53% and -45.08%, respectively (Nemati & Tran, 2022).
- A study of the impacts of social distancing policies on water use in the City of Austin, Texas presented water consumption data for the system's nine zones of varying residential/non-residential composition for all of 2019 and 2020 (Bakchan et al., 2022) found only marginal changes as the system level but highlighted a "*spatial redistribution of water demand after the stay home-work safe order*" at the sub-system level.
- A study on the Polish city of Wroclaw showed that April 2020 registered a 13.2% increase in water to housing buildings as compared to a -17.2% decrease in water to commercial as compared to the prior month (Kazak et al., 2021).
- A study of 395 water retailers in California focused on urban water use comparing April 2020 to April 2019 found a decrease in overall use of about 7.9%, due to a an -11.2% decrease in the commercial, industrial and institutional (CII) sectors which was not offset by the +1.4% increase in the residential sector (Li et al., 2021).

It is evident that the exact magnitude and duration of COVID-19 related impacts on water consumption will vary by region, utility and even DMA or system zone. However, it is interesting to note that in the Delaware River Basin the volume from own sources remained relatively consistent (on an annual scale, Figure 29). If this same volume of water were to be broadly redistributed from portions of the CII sectors to residential customers (for example, instead of water being sent though a 2" pipe to a commercial building it would be sent through many ¾" single residential service lines), it is not unreasonable to assume it may affect leakage rates (background and/or burst frequency). The temporal extent impacts related to consumption redistribution is again unclear; however, it is clear that a culture of remote and hybrid working has remained to some extent (Hansen et al., 2023). Exacerbating these effects (at least during the height of impacts in 2020) may have been reduced staffing available for repairing leaks, supply chain issues, and difficulty notifying customers about possible leaks. With these considerations in mind, it seems reasonable to hypothesize COVID-19 related impacts (such as the redistribution of water consumption to residential customers, speed of leak detection/repair and supply chain issues) may have contributed to the increased real losses in 2020 and 2021; however, additional research would be needed to appropriately investigate.

3. Another consideration which was also studied in some literature, is temperature. At the time of this study, daily historical temperature data across the Delaware River Basin was available from 1950 through 2022, summarized into ninety-three (93) 22km^2 grid cells which cover the Basin (DRBC in prep, 2024). This would indicate that for any given day, there are 93 values for temperature to describe the

***Table 15**: A summary of the daily minimum temperature as registered in 93 grid-cells which cover the Delaware River Basin. The percentages shown are the fraction of total cell-days below the specified temperature threshold.*

Year	Total cell-days	Cell-days < 32°F		Cell-days < 0°F	
		Count	%	Count	%
2012	34,038	9,603	28.2%	54	0.2%
2013	33,945	11,824	34.8%	118	0.3%
2014	33,945	11,815	34.8%	837	2.5%
2015	33,945	10,615	31.3%	904	2.7%
2016	34,038	10,627	31.2%	193	0.6%
2017	33,945	9,975	29.4%	149	0.4%
2018	33,945	11,265	33.2%	406	1.2%
2019	33,945	11,238	33.1%	371	1.1%
2020	34,038	9,529	28.0%	52	0.2%
2021	33,945	10,458	30.8%	51	0.2%

Basin; therefore, in any given year there should be approximately 33,945 “cell-days” of data (and leap years have 34,038 cell-days). Using a dataset of the minimum daily grid-cell temperature in degree Fahrenheit (°F), Table 15 presents a summary showing the number of cell-days in each year below 32°F (cold) and 0°F (very cold). This brief analysis was only done at a very high level to assess broadly whether or not CY2020 or CY2021 may have been abnormally cold, presenting a qualitative indication towards possible increased pipe burst rates and therefore higher real loss volumes. However, the data Basin-wide for CY2020 and CY2021 indicate that if anything, it may be considered warmer than the majority of previous years in the range of this study. Of course, more localized research could improve the accuracy of conclusions drawn here, or even limiting the grid cells to focus on particular regions of the Delaware River Basin.

Using the filtered dataset as described in Section 3.3.3, it is possible to analyze some statistics regarding the unit real loss rate (i.e., the volume lost per connection per day), summarized in Figure 31. This presentation of the data, which allows for comparison of system performance, does not immediately show that there was anything substantially different occurring in 2020 or 2021, as compared to the analysis of total volume. Consider a scenario where a Very Large system and a Very Small system change places in a given year, the mean unit real loss rate will remain the same, but the total volume will not. The median value across all system classes for the entire time-series has remained between 49-56 gal/con/day. To further assess the trends using the filtered dataset, the unit real loss rates are presented by system class in Figure 32, subplots A-E. An increase in total volume can be attributed to increased per-connection rate for any of the fifteen Very Large systems; as shown in Figure 32E, CY2020 and CY2021 are the only times where a Very Large system has registered over 150 gal/con/day in real losses. Overall, there do not appear to be any apparent trends in the unit real loss rate performance for any system class.

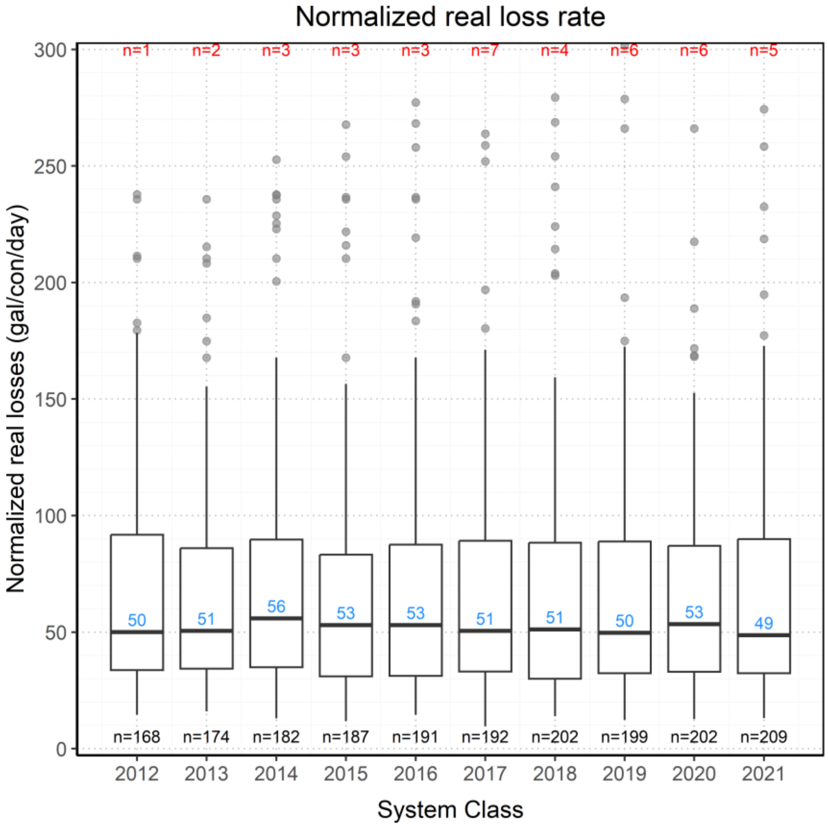
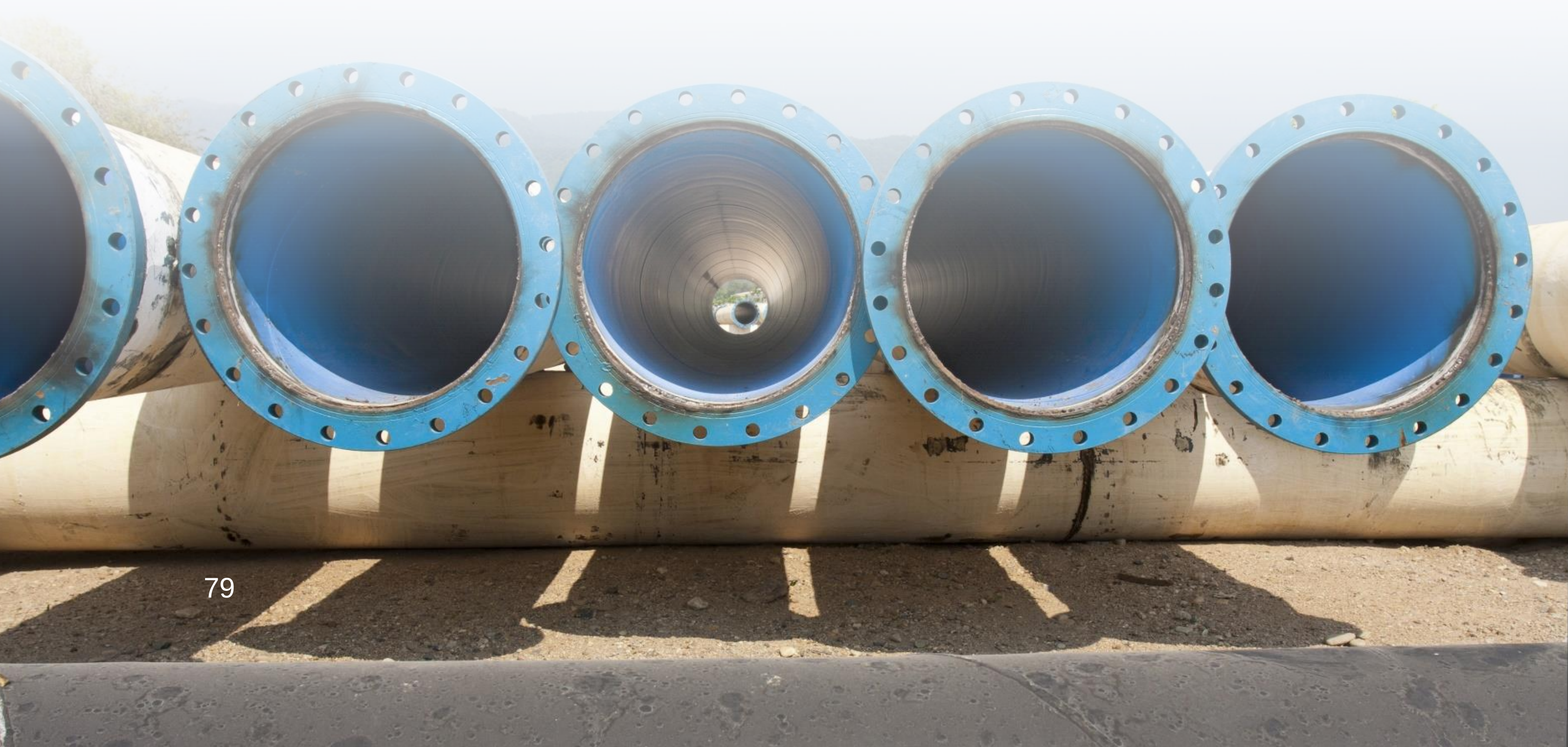


***Figure 31**: Unit real water loss rate calculated using the filtered dataset for systems in the Delaware River Basin subject to water audit reporting requirements. The black "n=123" label at the bottom is the total data points for each bar, whereas the red "n=123" at the top of the frame is the total number of points plotting beyond the y-axis limit. The blue number in the middle of each box is the median value (unit real loss rate).*



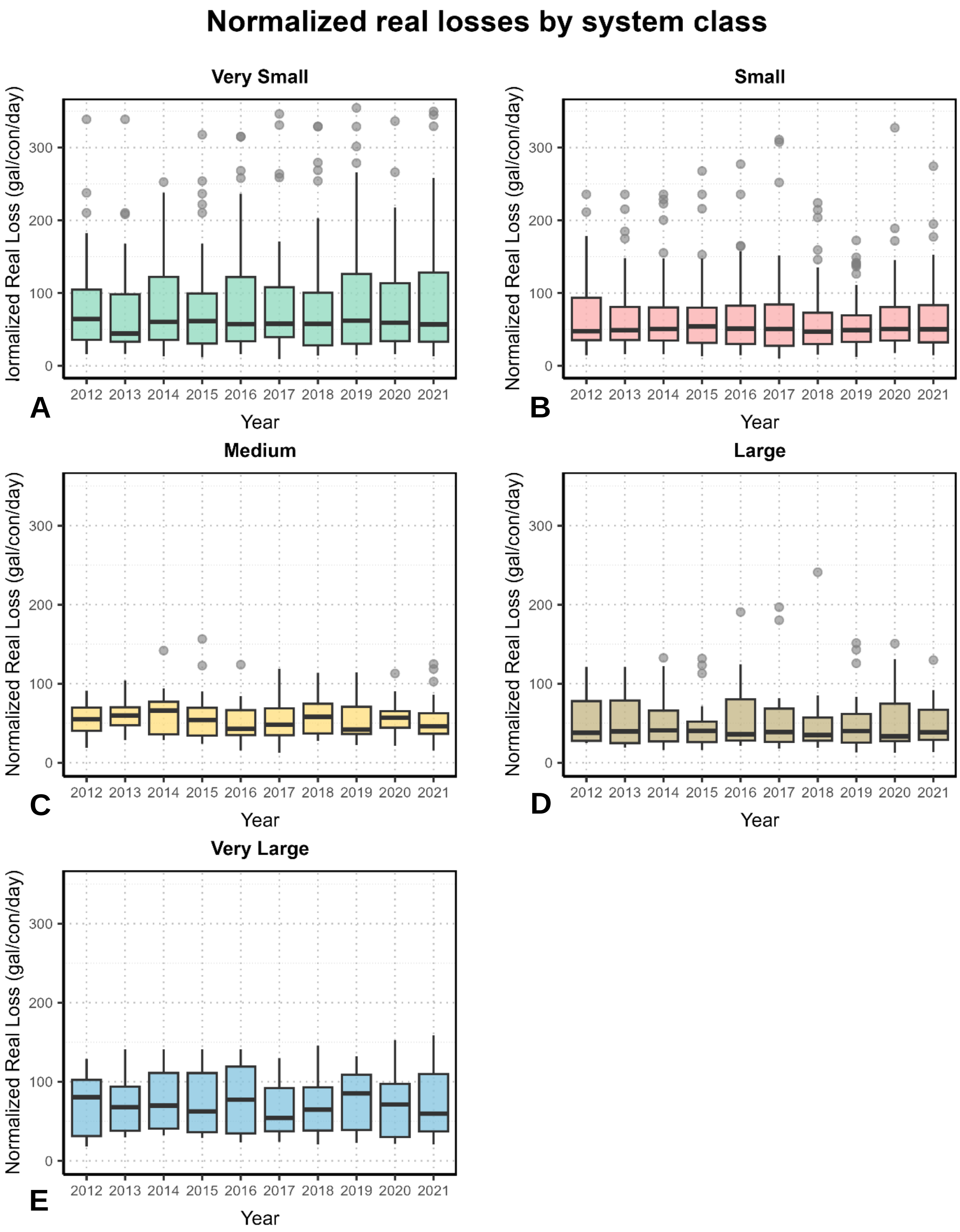


Figure 32:Unit real water loss rates in the Delaware River Basin (CY2012-CY2021).

5.3. Apparent water losses

For public water supply systems in the Delaware River Basin subject to the water audit reporting requirements, the total estimated apparent loss over time is presented graphically in Figure 33, color coded by the three components of apparent loss: customer metering inaccuracies (CMI), system data handling errors (SDHE) and unauthorized consumption (UC). A summary of the annual values for each component are presented by system class in Table 16. The aggregated data shows a decreasing trend in the volume of apparent losses; however, it is important to consider the way in which these numbers are calculated in the AWWA FWAS. As discussed in Section 3.4 of this report, the use of default values and the methods for calculating resulting volumes of the apparent loss components has changed over time with the different versions of the AWWA FWAS. Therefore, it is appropriate to present each component of apparent losses separately and investigate which portion of the total number is attributed to reports using default values, as in Figure 34 (A-C). In each subplot, the primary color has been split between TRUE (the reports used the default methods for calculation) and FALSE (a user value was input); the text above each color "n=123" represents the number of reports falling in each category.

The majority of decreases in apparent losses are attributed to SDHE, and that the majority of the reduction happens near 2015 (Figure 34B). It is not a coincidence that a default method for calculating SDHE was introduced in v5.0 of the AWWA FWAS (Table 10), which became mandatory for reporting to DRBC in 2015 (Table 8). As there was no option for default calculation prior to v5.0, there is a much higher rate of user-entered data prior to 2015 than after 2015 when v5.0 was required, and the default option was available. As discussed in Section 3.4 of this report, DRBC updated all default apparent loss component calculations using consistent current formulas; however, this does not address a shift between user-entered data and default calculation.

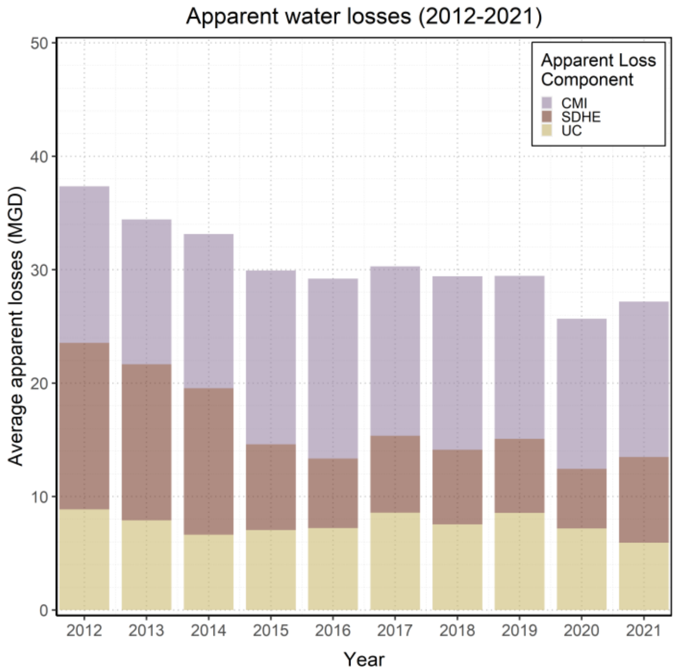


***Figure 33**: Apparent losses reported by public water supply systems in the Delaware River Basin, color coded by the three components of apparent losses as recorded in the AWWA FWAS. The values for each component are summarized by system class in Table 16.*

Table 16: *Total apparent loss summary data related to Figure 33, values are annual averages presented in units of million gallons per day (MGD).*

Class	Comp.	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
Very Small	CMI	0.163	0.167	0.143	0.152	0.161	0.168	0.164	0.143	0.146	0.148	0.155
	SDHE	0.075	0.074	0.024	0.021	0.018	0.017	0.017	0.018	0.018	0.018	0.030
	UC	0.034	0.042	0.034	0.020	0.022	0.019	0.021	0.021	0.020	0.019	0.025
	Total	0.272	0.283	0.201	0.192	0.201	0.204	0.202	0.182	0.185	0.185	0.211
Small	CMI	1.401	1.204	1.298	1.253	1.180	1.299	1.150	1.144	1.058	1.136	1.212
	SDHE	0.564	0.454	0.329	0.160	0.143	0.157	0.151	0.135	0.133	0.131	0.236
	UC	0.165	0.162	0.159	0.141	0.140	0.133	0.136	0.133	0.138	0.138	0.145
	Total	2.130	1.819	1.786	1.554	1.463	1.588	1.437	1.412	1.329	1.405	1.592
Medium	CMI	1.382	1.178	1.187	1.092	1.069	0.950	0.849	0.874	0.798	0.846	1.022
	SDHE	0.290	0.222	0.190	0.163	0.151	0.155	0.112	0.108	0.108	0.111	0.161
	UC	0.114	0.109	0.112	0.112	0.109	0.106	0.105	0.107	0.106	0.111	0.109
	Total	1.785	1.509	1.489	1.367	1.329	1.211	1.066	1.088	1.012	1.069	1.292
Large	CMI	2.462	2.258	2.360	2.130	2.099	2.226	2.257	1.984	2.123	2.491	2.239
	SDHE	0.532	0.531	0.400	0.412	0.422	0.369	0.300	0.265	0.293	0.269	0.379
	UC	0.275	0.277	0.266	0.281	0.276	0.267	0.262	0.259	0.269	0.277	0.271
	Total	3.269	3.067	3.026	2.823	2.797	2.862	2.819	2.508	2.684	3.037	2.889
Very Large	CMI	8.394	7.962	8.603	10.696	11.357	10.304	10.875	10.227	9.097	9.078	9.659
	SDHE	13.199	12.478	11.968	6.790	5.399	6.069	6.004	5.995	4.709	7.016	7.963
	UC	8.291	7.316	6.064	6.505	6.674	8.061	7.020	8.045	6.651	5.393	7.002
	Total	29.884	27.757	26.635	23.991	23.430	24.434	23.899	24.266	20.458	21.488	24.624

Note that the volumes of SDHE attributed to default calculation prior to v5.0 are the result of reports leaving blanks and DRBC's QAQC algorithm backfilling the data for consistency in comparing years. Almost 2/3 of reporting agencies began using default values for SDHE as it became available in v5.0 (2014/2015). It is now apparent that prior to the option of default values, self-reported estimates may have been higher or over-estimated. Consequently, the majority of the reduction in apparent losses seems to be attributed to a change in reporting methods for the parameter SDHE. While possibly yielding more representative results, it should not be confused with actual progress in reducing systematic data handling errors across the Delaware River Basin and is likely more akin to increased data validity.

Regarding CMI, as there is no default value in the AWWA FWAS, these volumes are reflective of DRBC's QAQC efforts to replace those reporting zero error with a default 2% under-registration (as discussed in Section 3.4.2). While the overall volume has remained relatively constant, it is noteworthy that there has been an increase in the number of reported 0-error instances since the requirement of v6.0, as shown by the n=171 reports in CY2021 which were replaced with a default.

Regarding UC, the default calculation method used for all years was (BMAC+BUAC) * 0.25%. The majority of the systems reported UC using the default method; however, there is not much change between years. The slight decrease over time is mainly attributed to user-reported values of UC, and may reflect improvement in understanding, data management, or actual reduced unauthorized consumption.

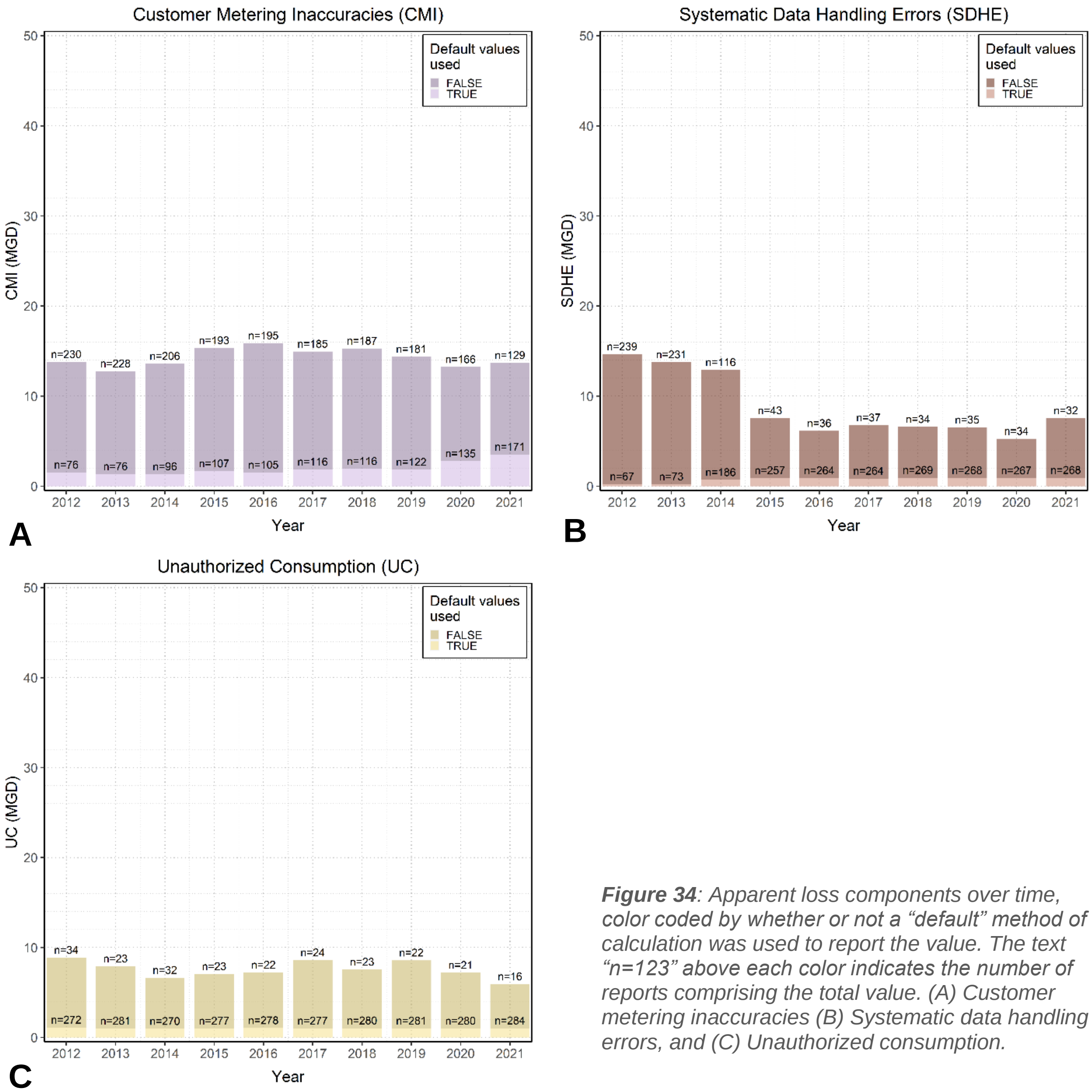


***Figure 34**: Apparent loss components over time, color coded by whether or not a "default" method of calculation was used to report the value. The text "n=123" above each color indicates the number of reports comprising the total value. (A) Customer metering inaccuracies (B) Systematic data handling errors, and (C) Unauthorized consumption.*

Lastly, a Key Performance Indicator (KPI) recommended for use by AWWA is the unit apparent loss in gallons per connection per day (Table 7). As opposed to the total volume of apparent loss, this KPI seeks to normalize differences in the physical characteristics of systems and is a useful tool to compare system performance. The annual unit apparent loss rates are presented by system class as a series of subplots Figure 35(A-E). Notably, the median value for all system classes has been consistently around 5 gcd. There has not been much change in the median among any class over time, aside from a seemingly anomalous year (2017) observed for Very Large systems. The distribution deviation (length of box and whiskers) seem generally consistent among Very Small systems, has decreased slightly in Small, Medium and Large systems, and has been variable for Very Large systems. Overall, it is not possible to conclude that any significant Basin-wide trends are occurring regarding unit apparent loss rates.

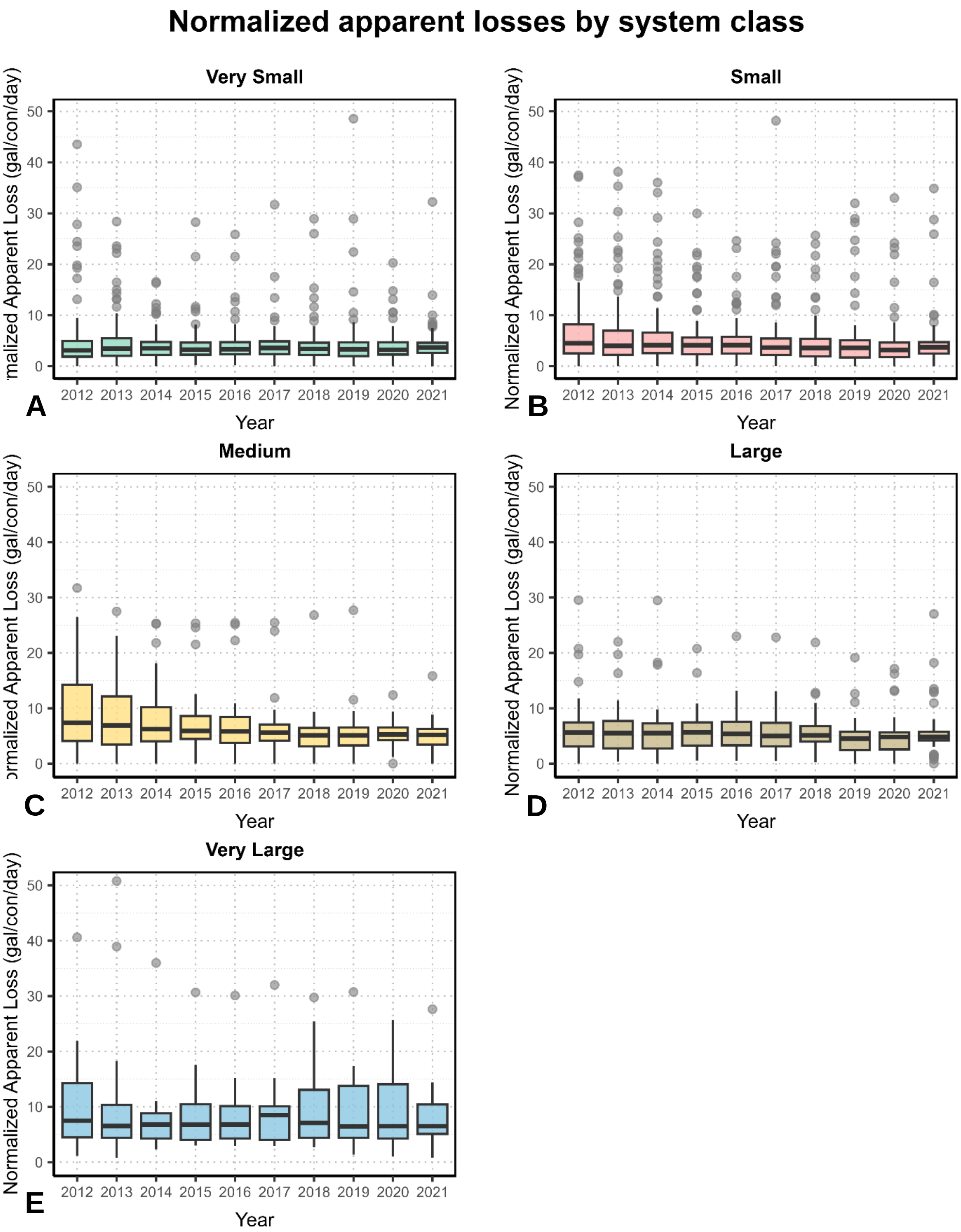


***Figure 35**: Unit apparent water loss in the Delaware River Basin (CY2012-CY2021).*

5.4. Unbilled consumption

Concerning the components of unbilled consumption, trends are shown for unbilled metered authorized consumption (UMAC) in Figure 36A and for unbilled unmetered authorized consumption (UUAC) in Figure 36B. No significant trend is observed for the UMAC, while UUAC shows a clear increase in reported average rates. The default value for the data input to UUAC in AWWA FWAS v5.0 was 1.25% of the total water supplied, whereas in v6.0 the default is set to 0.25% of the billed authorized consumption volume (BMAC + BUAC). As v6.0 moved to a smaller percent of a smaller number, it would suggest that if all data stayed the same the UUAC would decrease; however, this is not the trend observed in Figure 36B. Assessing the data with consideration to whether or not a default value was used confirms that this was not a contributing factor. The increase appears to be attributed to a small collective increase in reported values between 2016-2019 (about 2 MGD), plus large increased reported values from one Very Large system (~1.5 MGD) and one Large system (~1.25 MGD) beginning in 2019.

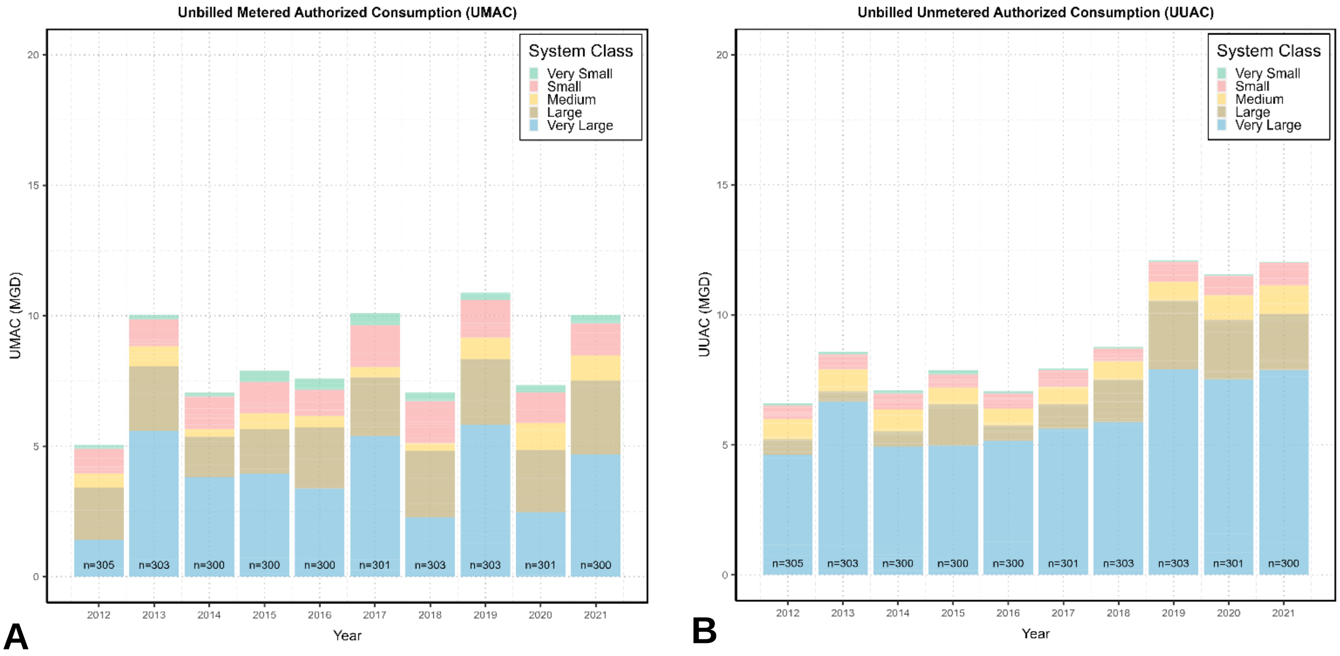


Figure 36: *Reported data for the components of unbilled consumption (CY2012-CY2021).* ***(A)*** *Unbilled Metered Authorized Consumption (UMAC).* ***(B)*** *Unbilled Unmetered Authorized Consumption (UUAC).*

5.5. Non-revenue water

Non-revenue water is water that has been treated and pressurized by the system but provides no revenue for the utility; this includes water lost as either as a real or apparent losses, as well as any authorized consumption which is unbilled. Understanding changes in the volume of non-revenue water may provide a simple method for utilities to understand how much monetary value treated water could have if it was not lost from the system. Average rates of non-revenue water over time are presented in Figure 37. The overall volume between CY2012 and CY2021 has slightly increased from 200 MGD in CY2012 to about 225 MGD in CY2021. A closer look into the components of non-revenue water shows that while specifically apparent losses are slightly declining, real losses are increasing, as seen in Figure 30. The increase in non-revenue water is related to the increase in Real Loss. Overall, there is some room for improvement to reduce non-revenue water among utilities in the Delaware River Basin.

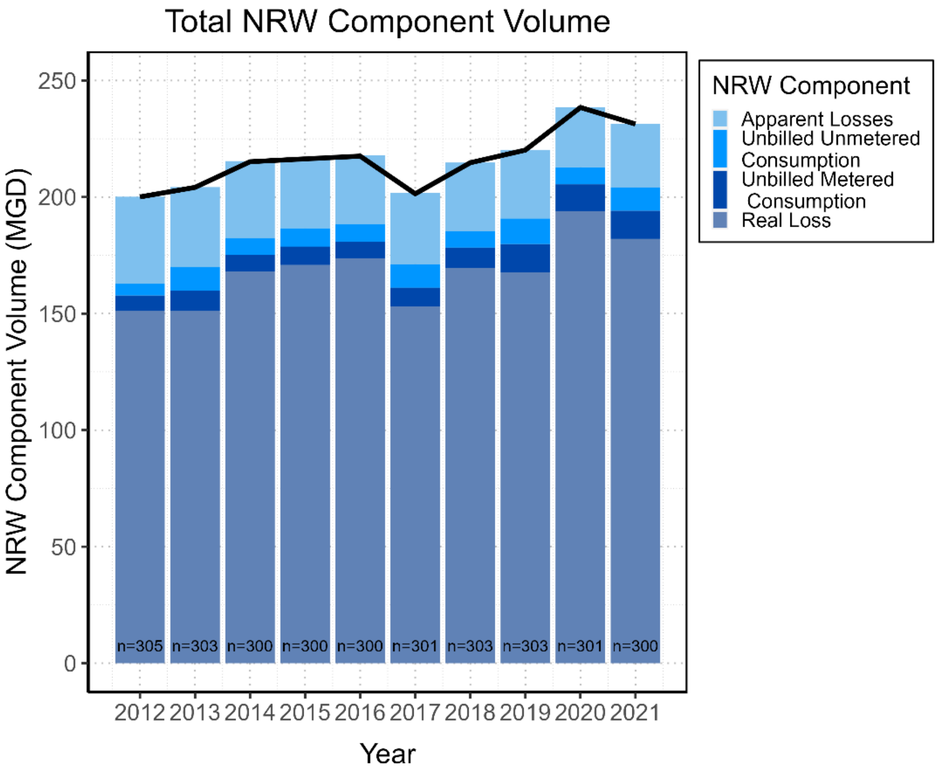


***Figure 37**: Non-revenue water component average volumetric rates (CY2012-CY2021).*

5.6. Rate of reduction analysis

To better understand the rate of water loss change, an additional analysis was conducted to look at the rate of change among the class sizes by comparing the water loss in CY2012 to the water loss in CY2021. Using the unit total loss, volume was plotted against the initial water loss to show the change over the last ten years (Figure 38). Many systems among all the classes had a rate of change of 0, indicating that total loss volume was the same as CY2012. But there were quite a few that showed decreases, specifically a decrease of 20 gallons/connection/day in the Very Small and Small system classes. The utilities with the highest total loss decease in the classes includes the City of Port Jervis, NJAW Logan and Blythe Township. In the same system classes, there were some systems that showed increases of more than 20 gallons/connection/day. Among the larger system classes, results were more uniform, most systems did not have significant changes in their water losses, but a few systems showed an increase of 10 gallons/connection/day. Among Very Large systems, there was little to no change in water loss between CY2012 and CY2021. An analysis like this helps Commission staff better understand if systems have reduced their water loss over the past ten years, as well as determine if the Commission should take further steps to encourage water loss reduction.

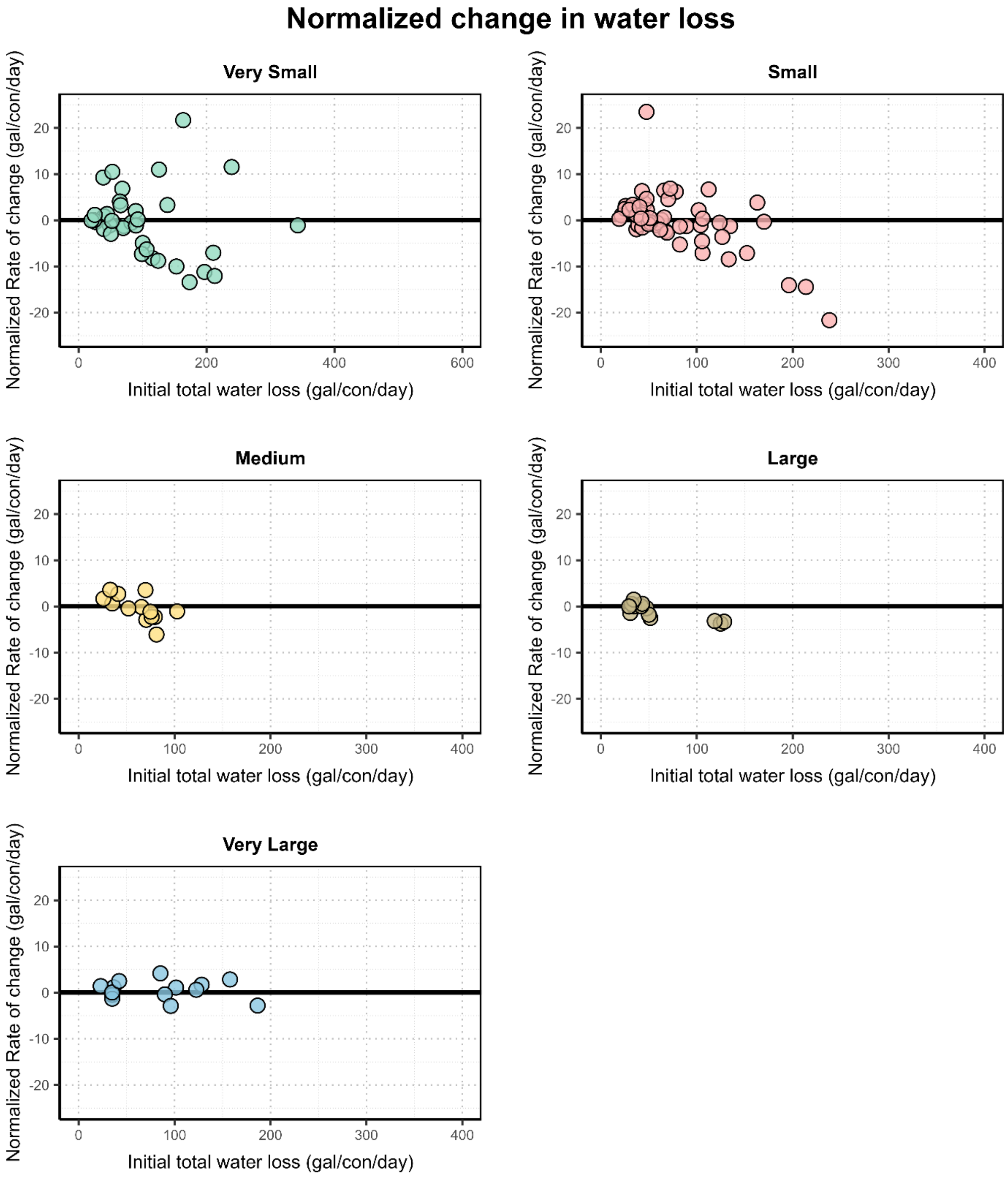


__Figure 38:__ Change in Water Loss in the Delaware River Basin by Class (CY2012-CY2021).

6. REAL LOSS ANALYSES

6.1. Frontier analysis for real loss reduction potential

Beyond summarizing the data within the most recent year of submitted audits, multiple analytical methods have been shown to be effective tools for water conservation planning and management. One of these is termed a “frontier analysis”, which compares the performance of an individual within a group to percentiles calculated from the group. As it applies to the water industry, Walker et al., 2022 recently performed a frontier analysis for water systems in Texas – starting with a multivariate model to predict total water loss. Considering each system in the analysis, the observed total loss as compared to the respective predicted value (O/P ratio) was used to classify performance (e.g., systems operating at a fraction of the predicted value were said to be performing well [O/P < 1], whereas a system operating at a multiple of the predicted value would be performing poorly [O/P > 1]). Considering all systems in the analysis, the distribution of O/P ratios defined performance “frontiers” as Average (50th percentile), Good (25th percentile) and Very Good (10th percentile). Reduction potentials (or the amount of potential water loss reduction) could then be computed if a system with a high O/P were to reduce total water loss such that it reached one of the established frontiers.

One shortcoming of the frontier analysis is that it inherently compares the performance of a system with the performance of a group of systems, and not against fundamental/theoretical limits of operational performance. For example, if an analysis is performed using data for 2021 and all systems improve to the calculated 2021 average performance by the following year, another frontier analysis using 2022 data will suggest that those systems no longer meet average performance as the recalculated 2022 average will be lower than the 2021 average. Therefore, this study has chosen to develop the multivariate regression using variables which allow for a comparison against theoretical limits on real losses (i.e., the UARL). The unique variables of the UARL equation include the number of connections (N_c), the length of mains (L_m), the average length of customer service connection (L_p) and the average operating pressure (P_{AO}).

6.1.1. Data filtering

To develop an accurate model describing total water losses, the input data must be screened (or filtered) such that the modeled frontiers are not skewed by potentially inaccurate data. Therefore, this analysis of 2021 data from the Delaware River Basin (DRB-2021) uses the “filtered dataset” as described in Section 3.3.3. Applying the filters to DRB-2021 (n=300) reduces the filtered dataset to 209 audits, termed DRB.f-2021. Additionally, it was confirmed that none of the variables intended for use in the multivariate modelling were missing from any of the reports.

6.1.2. Comparison to reference dataset (WARD)

To generally assess the quality of data within DRB.f-2021, it was compared to data from the Water Audit Reference Dataset (WARD) (AWWA, 2021b). Scatter plots of total water loss versus c(N_c, L_m, Psi, L_p) were generated for WARD data (Level 1 validated data), and points from DRB.f-2021 were added to visually assess consistency, shown in Figure 39. From this comparison, it is evident that the relationships between total water loss and the independent variables within the filtered

DRB-2021 water audits are fairly consistent with the relationships present in the WARD dataset. Of the three WARD datasets, only data from Quebec utilities spanned the range of system sizes present in DRB.f-2021. Most data from California and Georgia systems either reported L_p=0, or did not report any data, as shown in Figure 39d (often times because meters are located at the street curb in warmer climates). This process of filtering the data and comparing against Level 1 validated data has supported DRBCs use of the data in developing a model for performing a frontier analysis.

6.1.3. Frontier analysis: establishing frontiers

The form of the multivariate regression used in this frontier analysis considered four variables which are based on the formulation of the equation for Unavoidable Annual Real Losses (Lambert et al., 1999). The UARL equation is based on a method for calculating different components of real losses, termed the background and bursts estimates (BABE) model (Lambert, 1994), which considers the different components of physical infrastructure within a system where leaks are likely to occur as (1) background losses, (2) losses from reported leaks and bursts, and (3) losses from unreported bursts. An analysis assessing multicollinearity between the four parameters is presented as Figure 40, and suggests that there is a strong relationship between the length of mains and number of connections. However, due to the fundamental understanding of where leaks occur and their inclusion in the UARL equation, both parameters were retained in this analysis. All variables of this model were taken as natural log transformations, aside from L_p as it has the capability of being a zero value. Therefore, the model form used in this study is presented in Table 17.

***Table 17**: Formation of the multivariate regression for Real Losses used in the frontier analysis.*

Dependent variable:	RL	Real water loss	*MG / year*
Independent variables:	N_c	Number of active and inactive service connections	*count*
	L_m	Length of mains	*miles*
	P_{AO}	Average operating pressure	*psi*
	L_p	Average length of customer service line	*feet*
Model Form	<u>General form:</u> $\ln(RL) = c_1 + c_2 * \ln(N_c) + c_3 * \ln(L_m) + c_4 * L_p + c_5 * \ln(P_{AO})$ <u>Simplified form:</u> $\mathrm{RL} = \widehat{c_1} * {N_c}^{c_2} * {L_m}^{c_3} * e^{(c_4 * L_p)} * {P_{AO}}^{c_5}$ where $\widehat{c_1} = e^{c_1}$		

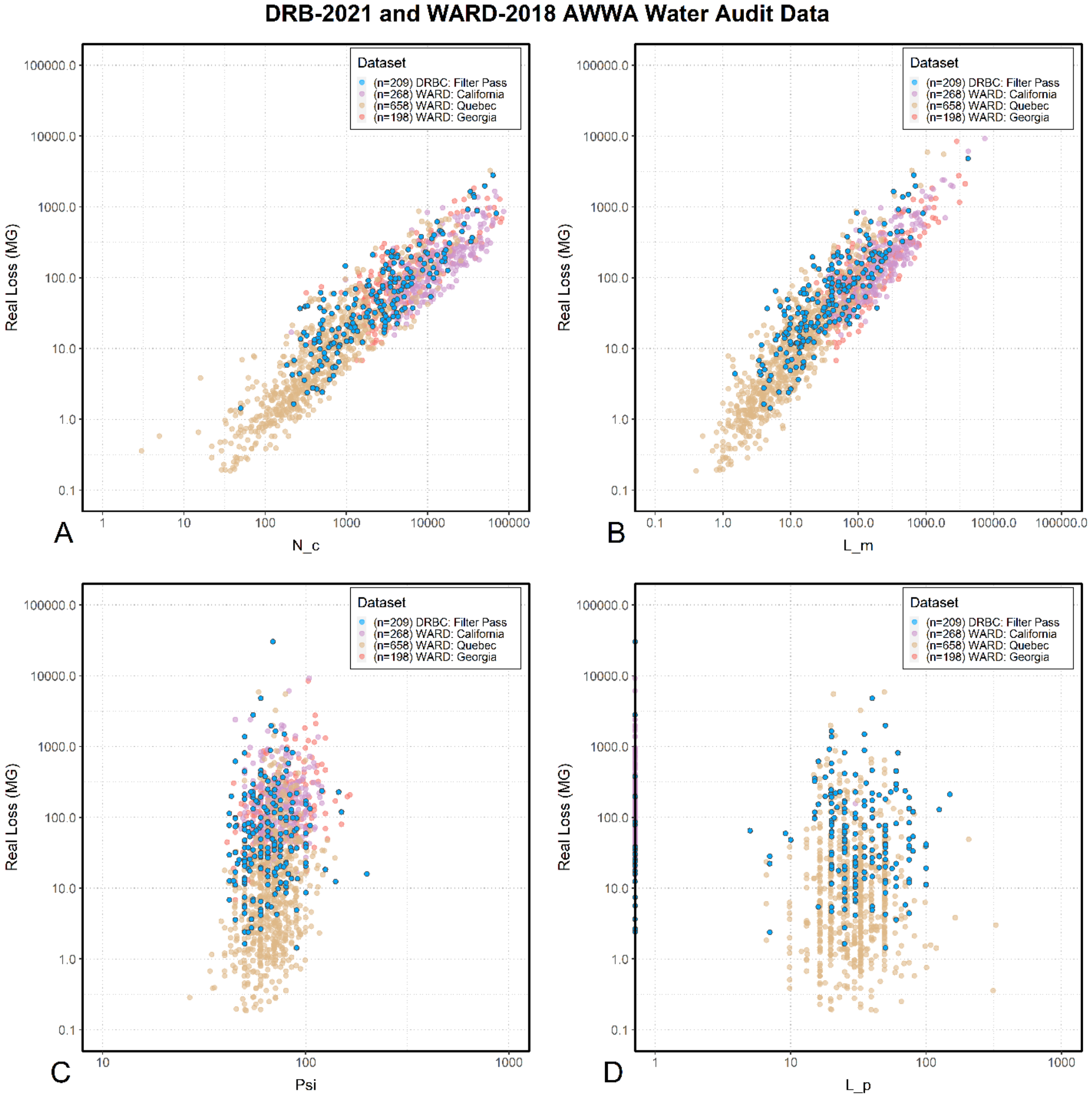


Figure 39: *Data from Water Audit Reference Dataset (WARD) as described in Section 2.8.2 of this report plotted in comparison to data collected by DRBC in 2021. Only the four parameters being included in a multivariate model for real losses are presented. Only DRBC data which met all filter criteria (n=209) are presented (DRB.f-2021).*

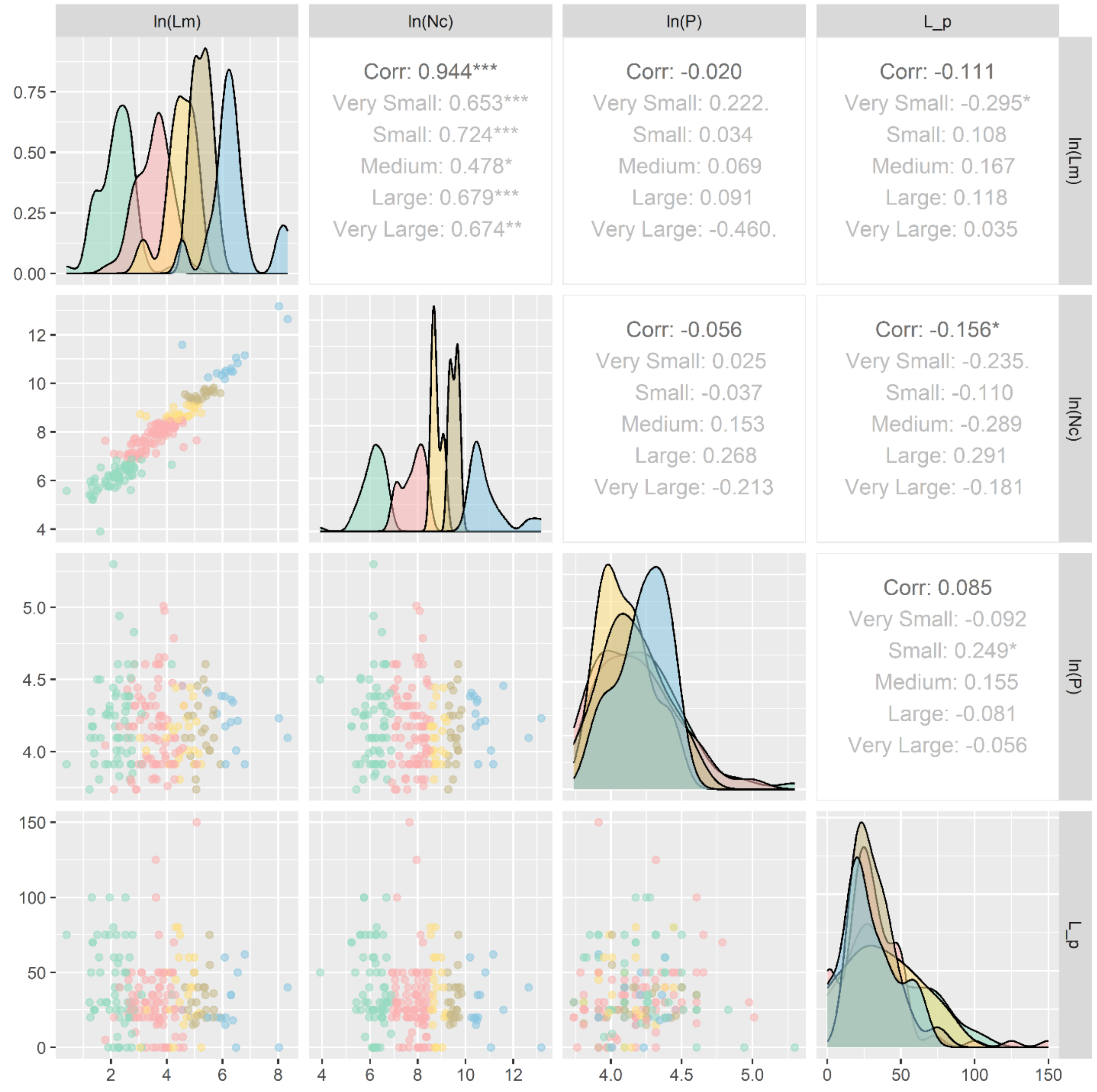


__Figure 40__: A generalized pairs plot (DRB.f-2021) showing the bivariate relatiosnhip between all paris of variables used in the multivariate model for real losses. The plot was developed using the R package {GGally} (Schloerke et al., 2021), as described in (Emerson et al., 2013).

The multivariate regression was calculated in R using the function *lm()* (R Core Team, 2023), using the data from DRB.f-2021 (n=209); the model returned the below statistics. While not all variables are considered to be significant, they were again retained in the model based on the fundamental understanding of real losses provided by the UARL equation. The results of the multivariate regression are plotted on Figure 41, which shows the observed value as compared to the predicted value (O/P ratio, or O/P), and a grey 1:1 line representing an O/P=1, which would represent a perfect model fit.

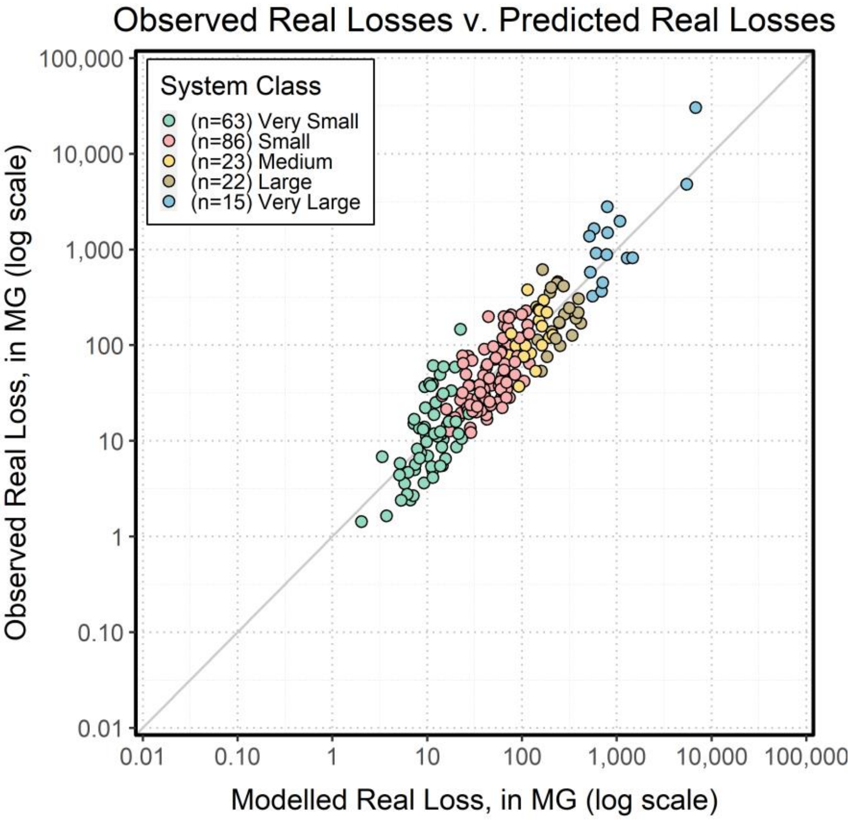


***Figure 41**: The results of the multivariate model predicting system real losses. The 1:1 slope grey line represents the scenario where the model makes a perfect prediction. Points above the line have an O/P > 1, and points below the grey line have O/P < 1.*

Multivariate model statistics:

```
Coef.       Estimate    Std. Error      t value      Pr(>|t|)
c1        -6.317851     0.885019       -7.139      1.62E-11  ***
c2         0.822673     0.096609        8.515      3.62E-15  ***
c3          0.16055     0.103515        1.551      1.22E-01
c4         0.006819     0.001945        3.507      5.58E-04  ***
c5         0.711673     0.175377        4.058      7.05E-05  ***

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 0.1388 on 208 degrees of freedom
Multiple R-squared:  0.8215,    Adjusted R-squared:  0.818
F-statistic: 234.7 on 4 and 204 DF, p-value: < 0.00000000000000022
```

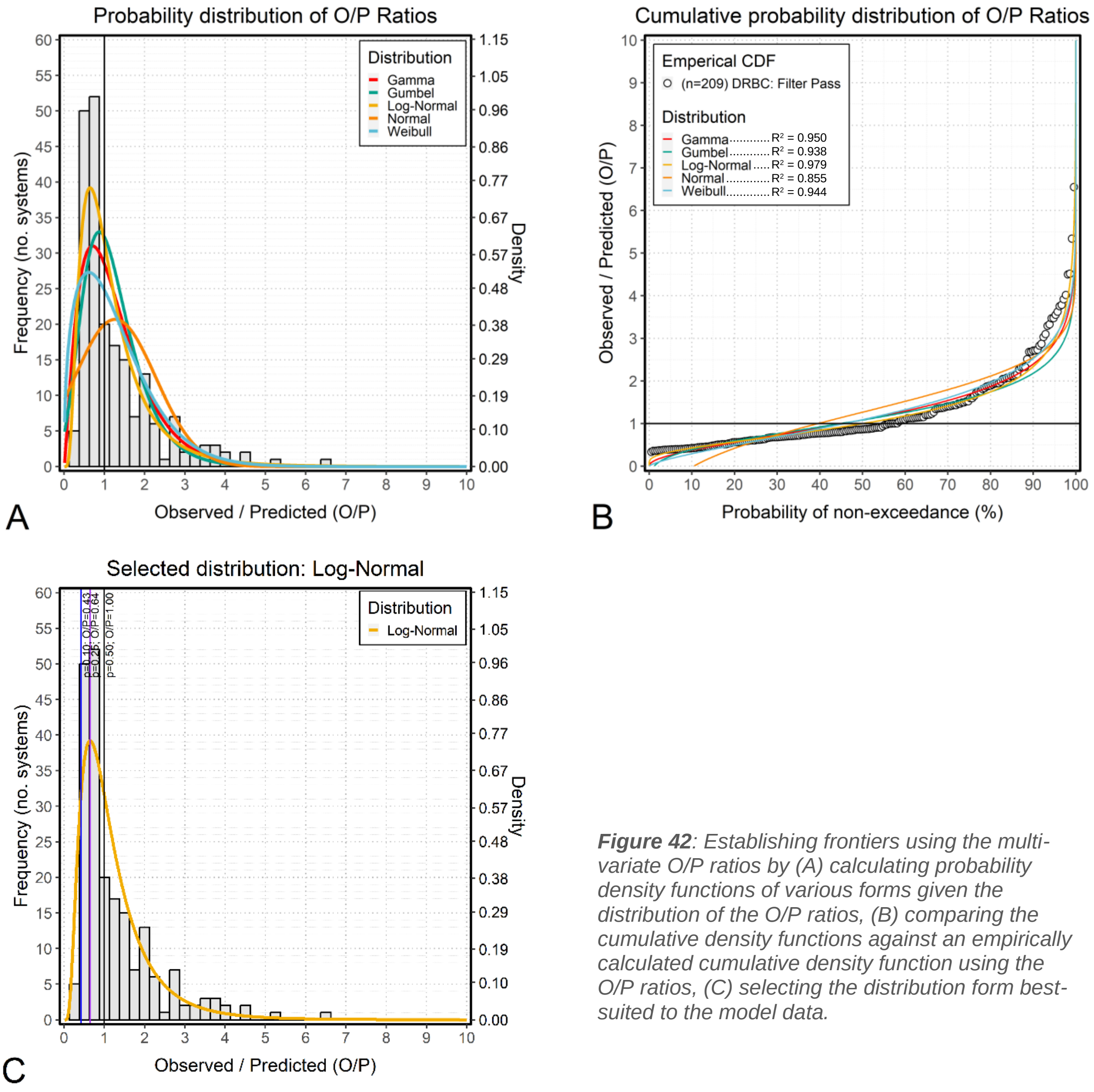


***Figure 42**: Establishing frontiers using the multi-variate O/P ratios by (A) calculating probability density functions of various forms given the distribution of the O/P ratios, (B) comparing the cumulative density functions against an empirically calculated cumulative density function using the O/P ratios, (C) selecting the distribution form best-suited to the model data.*

Considering the O/P ratios of all systems in the model, Figure 42A shows the distribution of O/P ratios as a histogram of grey bars, overlain with various calculated probability density functions (PDFs) using the R package {EnvStats} (Millard, 2013) and {stats} (R Core Team, 2023). Cumulative density functions (CDFs) were then calculated for each PDF in Figure 42A and are presented in Figure 42B; additionally, an empirical CDF using the O/P ratios was calculated using a plotting position formula termed the "Weibull plotting position" (Weibull, 1939), where is P_i is the calculated probability for the i^{th} ranked observation, given n total observations.

$$P_i = \frac{i}{n+1}$$

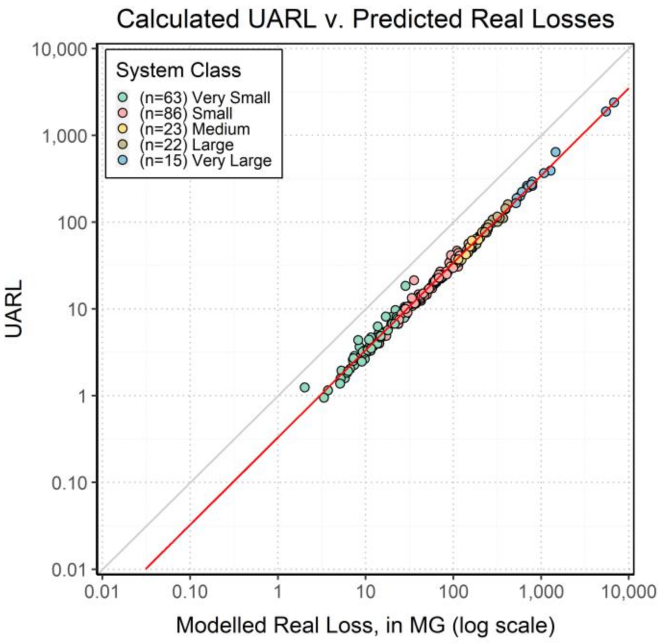
The emperical CDF is compared to the fitted CDFs by calculating a simple coefficient of correlation (R^2), as are presented on Figure 42B, which suggest that most distributions provide a good fit to the data. For the purposes of this study, a Log-Normal distribution was selected to establish the frontiers, which is consistent with the findings of Walker et al., 2022 who stated that "*utility points on the plot of the observed water loss volume versus the predicted water loss volume, do not conform to a normal distribution.*" The Log-Normal distribution is highlighted on Figure 42C along with three low frontiers (probabilities of non-exceedance) represented as colored vertical lines. Following the example of Walker et al., 2022, frontiers are established as:

Average (p50): .... The 50th percentile, suggesting that half of the systems performed better than the model (O/P < 1.00) and half of the systems performed worse (O/P > 1.00)

Good (p25): .... The 25th percentile, suggesting that only 25% of systems reported real losses below this fraction of the modeled value (O/P ≤ 0.64)

Very Good (p10): .... The 10th percentile, suggesting that only 10% of systems reported real losses below this fraction of the modeled value (O/P ≤ 0.43)

However, these frontiers are only established based on an inter-comparison of system performance and do not necessarily reflect theoretical limits of real loss reduction. One possible improvement to the frontier analysis methodology may be realized by attempting to incorporate theoretical limits on the real loss reduction via incorporation of the Unavoidable Annual Real Loss (UARL) calculation. Because the multivariate equation and UARL share the same units (and fundamental variable inputs), a strong relationship can be estimated between the two as shown in Figure 43. While not perfect, this fitted relationship (red line) may serve as a visual guide to suggest that there is a theoretical "lowest" frontier. Figure 44 presents the final analysis with the three frontiers plotted over the O/P ratio data, and the approximate UARL relationship. Example calculations of reduction potential are presented below the figure.



```
Model Form: ln(UARL) = c₁ + c₂*ln(Modeled Real Loss)

Coef.      Estimate     Std. Error      t value     Pr(>|t|)
c₁        -1.105163       0.026124        -42.3        2E-16    ***
c₂         1.006268       0.006306        159.6        2E-16    ***

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 0.1292 on 207 degrees of freedom
Multiple R-squared:  0.9919,    Adjusted R-squared:  0.9919
F-statistic: 2.546e+04 on 1 and 207 DF,  p-value: < 2.2E-16
```

***Figure 43**: A linear model between the natural log of UARL and the natural log of the modeled real losses. Having a slope essentially equal to 1, this trend shows that creating a multi-variate equation using the same variables as UARL helps incorporate UARL as a frontier. However, scatter in the trend shows that the trend line is not exact, and the actual UARL should be referenced for each point when performing reduction potential calculations.*

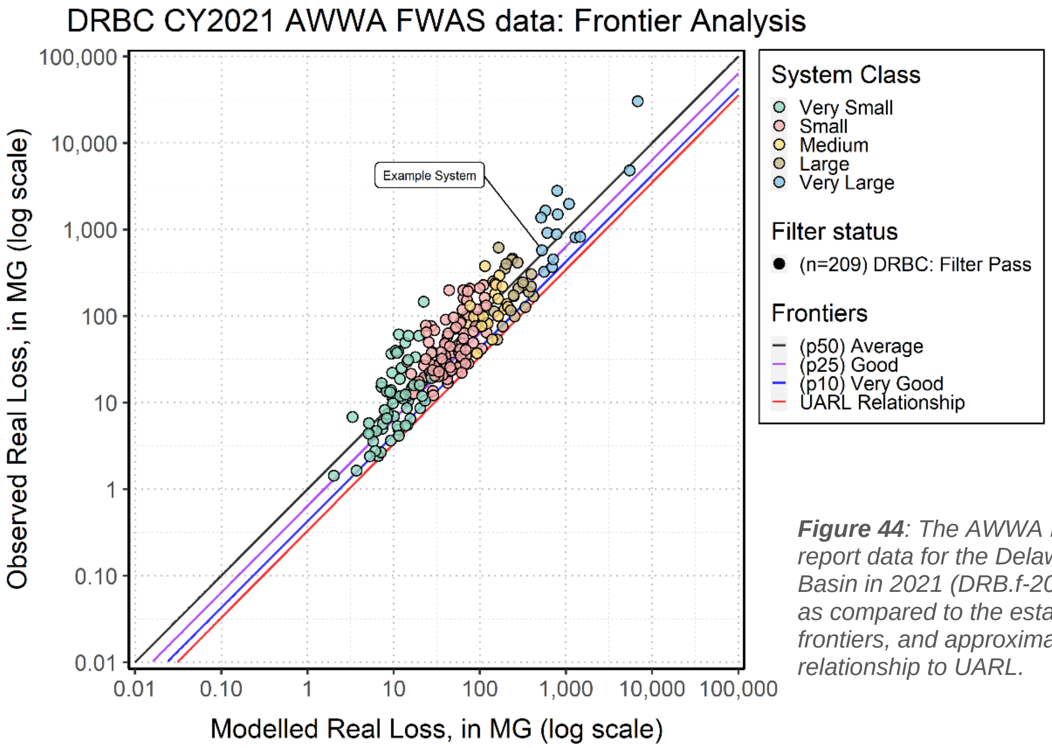


***Figure 44**: The AWWA FWAS report data for the Delaware River Basin in 2021 (DRB.f-2021, n=209) as compared to the established frontiers, and approximate relationship to UARL.*

Calculations for the example system indicated above:

	Parameter	**Value**	**Units**	**Calculation**
Data reported on the AWWA FWAS	Reported real losses	579.041	MG	--
	Nc	28,171	conn.	--
	Lm	241.6	miles	--
	P	82.1	psi	--
	Lp	20	feet	--
	Predicted real losses	526.195	MG	$WL = \hat{c_1} * N_c^{c_2} * L_m^{c_3} * P_{AO}^{c_4} * e^{c_5 * L_p}$
	O/P ratio	1.10	--	579.041 / 531.498
If the system were to improve to **Average (p50)** performance	p50 O/P ratio	1.00	--	--
	p50 predicted real losses	526.195	MG	1.00 * 526.195
	p50 reduction potential	52.846	MG	579.041 – 526.195
If the system were to improve to **Good (p25)** performance	p25 O/P ratio	0.64	--	--
	p25 predicted real losses	336.765	MG	0.64 * 526.195
	p25 reduction potential	242.276	MG	579.041 – 336.765
If the system were to improve to **Very Good (p10)** performance	p10 O/P ratio	0.43	--	--
	p10 predicted real losses	226.264	MG	0.43 * 526.195
	p10 reduction potential	352.777	MG	579.041 – 226.264
Theoretical limit based on UARL	UARL	189.778	MG	$(5.41\ L_m + 0.15\ N_c + 7.5\ N_c L_p) \times P_{AO} \times 365$
	UARL reduction potential	389.263	MG	579.041 – 189.778

A note on the standard UARL equation application:

It is important to note that while this study has attempted to incorporate UARL into the analysis, there are recommended limits on the use of the standard UARL equation (discussed in Section 2.2.3.2.3). Currently, the recommended limits as outlined by Lambert, 2020 are that systems should have $N_c > 5{,}000$ and that the pressure range should be between 45m (64 psi) $< P_{AO} <$ 60m (85 psi). If a system were to fall outside of these bounds, Lambert, 2020 recommends that a dimensionless System Correction Factor (SCF) be applied – in many cases reducing the value of UARL. In this study, the standard UARL equation has been applied to all systems passing the filters, including systems outside of the bounds indicated in Lambert, 2020. An SCF pilot study on five small systems is presented in Section 7. As the SCFs will likely lower the UARL and therefore increase the reduction potential, the authors feel that presenting these estimates are still appropriate, until such a time that SCFs can be incorporated into analyses more comprehensively.

Data for the systems which did not meet the filter criteria are presented in comparison to the frontiers in Figure 45. It is worth noting here that many of the smaller systems are plotting with observed real losses below the calculated UARL, which may simply be related to the fact that the UARL could be corrected using a SCF (refer to Section 7). Many systems in this dataset fall below all frontiers or UARL, and therefore do not return any reduction potentials.

The total real loss reduction potential (RLRP) for each scenario is summarized in Table 18 (total volume in million gallons per year) and Table 19 (the average real loss KPI in gallons per connection per day). From these calculations, there are multiple conclusions which can be stated:

1. Based on the best available data, it is estimated that real losses could be reduced between about 34,000 – 52,000 million gallons per year (or about 95 - 144 MGD on average). Based on the estimated 2021 real loss of 184 MGD (as outlined in Section 4.4), this represents a reduction of about 50% - 75%.
2. Real loss reduction to the UARL level is not a realistic goal for many systems as there are economic impacts associated with leakage control. Concepts such as the Economic Level of Leakage (ELL) described in POST, 1995 and briefly in Lambert et al., 1999 may pose better targets, but require assessment on an individual basis. While incorporation of SCF may still lower UARL values for smaller systems, this estimate based on UARL is more representative of a lower limit than a realistic possibility for Basin-wide improvement.
3. While Very Large systems account for the majority of the RLRP by volume (Table 18), assessing normalized reductions in gallons per connection per day (Table 19) shows that they are comparable to other classes.
4. Should systems improve water conservation measures and reduce real losses, future frontier analyses will yield different frontiers and therefore different reduction potentials. An alternative yet similar analysis can be performed to assess the Infrastructure Leakage Index, discussed in Section 6.2 of this report.

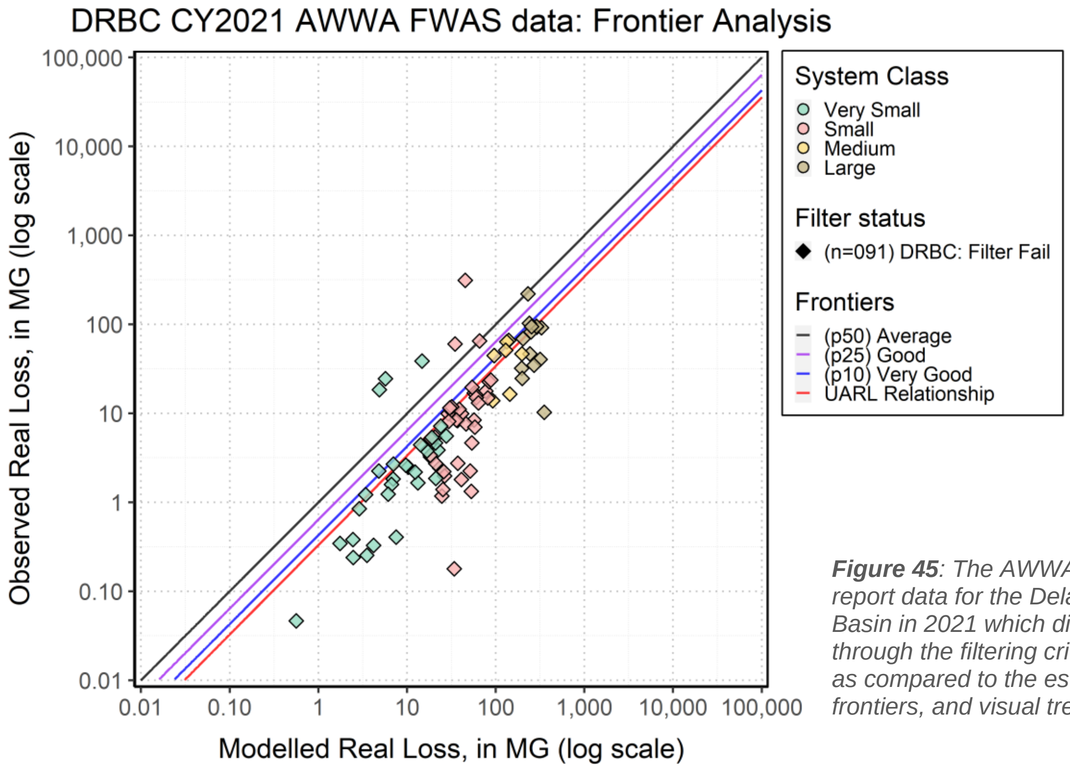


***Figure 45**: The AWWA FWAS report data for the Delaware River Basin in 2021 which did not pass through the filtering criteria (n=91) as compared to the established frontiers, and visual trend for UARL.*

***Table 18:** A summary of aggregate real loss reduction potentials in **million gallons per year (MGY).** These represent volumes of real water loss which could be mitigated should individual systems improve system efficiency to meet frontier predictions of real loss.*

Dataset	Symbol	Count	System Class	Improvement to **Average (p50)** performance	Improvement to **Good (p25)** performance	Improvement to **Very Good (p10)** performance	Improvement to **UARL** performance
Filter Pass (n=210)	●	63	Very Small	521	673	796	844
	●	86	Small	1,730	2,718	3,521	3,903
	●	23	Medium	848	1,415	1,954	2,220
	●	22	Large	1,393	2,076	2,916	3,339
	●	15	Very Large	29,711	35,510	40,070	41,725
Subtotal		*209*	--	34,203	42,392	49,257	52,031
Filter Fail (n=090)	◆	31	Very Small	55	64	70	73
	◆	39	Small	272	301	332	340
	◆	7	Medium	0	0	0	0
	◆	14	Large	0	0	36	55
	◆	0	Very Large	0	0	0	0
Subtotal		*91*	--	327	366	438	468
Grand Total (MG)				34,530	42,758	49,694	52,499
Grand Total (MGD)				95	117	136	144

Table 19: *A summary of average real loss reduction potentials in* ***gallons per connection per day (gcd).*** *These represent volumes of real water loss which could be mitigated should individual systems improve system efficiency to meet frontier predictions of real loss.*

Dataset	Symbol	Count	System Class	Improvement to **Average (p50)** performance	Improvement to **Good (p25)** performance	Improvement to **Very Good (p10)** performance	Improvement to **UARL** performance
Filter Pass (n=210)	○	63	Very Small	44.515	58.774	69.939	74.245
	○	86	Small	19.140	31.033	41.136	45.900
	○	23	Medium	13.463	22.879	32.407	37.305
	○	22	Large	12.960	19.204	26.696	30.456
	○	15	Very Large	35.896	48.290	57.829	61.236
Filter Fail (n=090)	◇	31	Very Small	11.042	12.638	13.577	14.133
	◇	39	Small	8.332	9.379	10.392	10.624
	◇	7	Medium	0.000	0.000	0.000	0.000
	◇	14	Large	0.000	0.000	0.537	0.824
	◇	0	Very Large	0.000	0.000	0.000	0.000

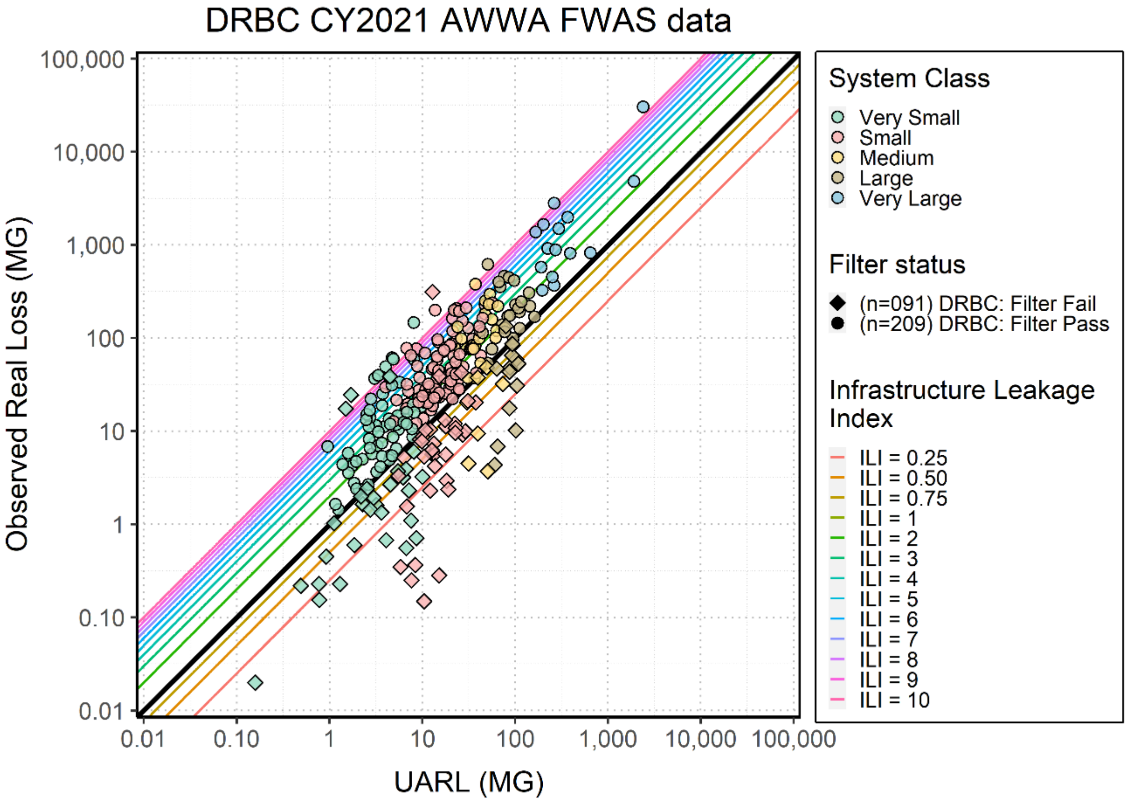


***Figure 46**: A cross-plot showing the current annual real losses (CARL) compared against the calculated unavoidable annual real losses (UARL). Points on this graphic therefore inherently reflect the infrastructure leakage index (ILI).*

6.2. ILI assessment for real loss reduction potential

Unavoidable Annual Real Losses (UARL) is a concept based on decades of research and has proven its utility time and time again. Because this study developed the multivariate model in the frontier analysis using the same components of UARL (to give it a conceptual foundation), it became clear once attempting to incorporate UARL as a frontier that the relationship between the modeled real losses and UARL was very strong (Figure 43). This then begs the question of how much benefit is gained from a frontier analysis versus its complexity. The same paper which established UARL also defined a performance metric termed the Infrastructure Leakage Index (ILI) (Lambert et al., 1999). If the current annual real losses (CARL) for each system are plotted against the UARL, graphically the data represents the ILI, as it is defined as the ratio between the two values. As shown in Figure 46, multiple levels of ILI can be presented graphically behind the plotted data and bears a striking resemblance to the frontier analysis. If each of the ILI lines is thought of as a "frontier", real loss reduction potentials (RLRP) can be calculated should systems increase efficiency to particular levels. It is important to note that UARL was calculated for all systems using the standard UARL equation, regardless of the number of connections or average operating pressure. A Basin-wide RLRP can be calculated assuming that "all systems above ILI=X were to reduce real losses to reach an ILI=X". The RLRP results are summarized in Table 20 for units of million gallons (MG), and in Table 21 for units of gallons per connection per day.

Table 20**: A summary of the real loss reduction potentials, based on an assessment of each system's performance increase to meet specified levels of ILI.* ***Units are in million gallons.

Data	Sy.	No.	System Class	ILI=10	ILI=9	ILI=8	ILI=7	ILI=6	ILI=5	ILI=4	ILI=3	ILI=2	ILI=1
Filter Pass (n=209)	○	63	Very Small	119	150	184	225	280	348	424	508	627	844
	○	86	Small	72	94	169	290	468	705	1,058	1,662	2,560	3,903
	○	23	Medium	7	44	94	154	215	330	536	871	1,389	2,220
	○	22	Large	112	163	213	264	324	550	924	1,369	1,906	3,339
	○	15	Very Large	6,650	9,308	12,065	15,091	18,116	21,313	25,025	29,018	34,450	41,725
Subtotal		*209*	--	6,960	9,760	12,725	16,024	19,403	23,245	27,967	33,428	40,932	52,031
Filter Fail (n=091)	◇	31	Very Small	10	13	19	27	35	42	50	58	65	73
	◇	39	Small	184	197	210	223	236	248	261	274	296	340
	◇	7	Medium	0	0	0	0	0	0	0	0	0	0
	◇	14	Large	0	0	0	0	0	0	0	0	0	55
	◇	0	Very Large	0	0	0	0	0	0	0	0	0	0
Subtotal		*91*	--	194	210	229	249	270	291	311	332	361	468
			Grand Total (MG)	7,154	9,970	12,954	16,273	19,673	23,536	28,278	33,760	41,293	52,499
			Grand Total (MGD)	20	27	35	45	54	64	77	92	113	144

Table 21**: A summary of the real loss reduction potentials, based on an assessment of each system's performance increase to meet specified levels of ILI.* ***Units are in gallons per connection per day (gcd). *Note that the "Total average" fields are not averages of the values above them, but rather calculated given the entire population of data.*

Data	Sy.	No.	System Class	ILI=10	ILI=9	ILI=8	ILI=7	ILI=6	ILI=5	ILI=4	ILI=3	ILI=2	ILI=1
Filter Pass (n=209)	○	63	Very Small	8.176	10.912	13.850	17.451	22.087	28.104	34.939	42.847	54.101	72.841
	○	86	Small	0.694	0.935	1.714	2.936	4.957	7.804	11.886	18.841	29.356	45.900
	○	23	Medium	0.102	0.635	1.405	2.376	3.348	5.282	8.810	14.269	22.788	37.305
	○	22	Large	1.071	1.554	2.037	2.520	3.094	5.247	8.781	12.891	17.793	30.456
	○	15	Very Large	2.783	4.371	6.465	9.963	13.461	17.623	24.064	32.053	42.790	57.904
Filter Fail (n=091)	◇	31	Very Small	2.732	3.587	4.752	6.092	7.432	8.772	10.113	11.453	12.793	14.133
	◇	39	Small	5.599	5.991	6.382	6.774	7.166	7.558	7.950	8.341	9.105	10.624
	◇	7	Medium	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	◇	14	Large	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.824
	◇	0	Very Large	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The results of this ILI RLRP analysis are similar to those from the frontier analysis; the following comparisons, while not exact, can be aligned to show these consistencies:

- RLRP ≈ 34,500 MG (~95 MGD) → FA "Average" Performance, ...or ILI=3
- RLRP ≈ 43,000 MG (~118 MGD) → FA "Good" Performance, ...or ILI=2
- RLRP ≈ 50,000 MG (~137 MGD) → FA "Very Good" Performance
- RLRP ≈ 52,500 MG (~144 MGD) → FA "UARL" Performance, ...or ILI=1

Even the RLRP to the level of ILI=3, which may not be considered unreasonable for many systems, results in an average water loss savings of approximately 95 MGD. Overall, this would represent about half of the current real losses calculated from systems operating within the Delaware River Basin in 2021. This said, it is important to remember that the majority of the volumetric RLRP achieved when reaching an average ILI=3 would be from Very Large systems. Additionally, not all systems will be economically justified to reduce leakage to particular levels of ILI; incorporation of ELL analyses would help to improve the practicality of estimates for Basin-wide improvement.

6.2.1. Consideration for the Economic Level of Leakage (ELL)

As was noted prior in this report, a preferred benchmark for an individual system would be the Economic Level of Leakage (ELL). It was highlighted that AWWA M36 had provided a table of guideline ILI targets "*in lieu of having a determination of the system-specific economic level of leakage"* (Table 4). It was also recognized by USEPA, 2016a that if the reported data met data validity requirements but had ILI > 3, and ELL analysis was recommended to justify the higher rate of water loss. The authors are currently aware of only one ELL analysis performed in 2010 for a Very Large system in the Basin. The specific ELL analysis provided a suggested optimum ILI and unit real loss rate (gcd). Because it is the only study known and due to its age, it has not been quantitatively included in this analysis of ILI. However, the importance and significance of ELL analyses are stated herein. It is noted how the accuracy/practicality of Basin-wide RLRP analyses could be improved with ELL analyses for the fifteen Very Large systems in the Basin, who collectively account for about 80% of the theoretical possible reductions (41,725 / 52,031).

6.2.2. Influence of average operating pressure

When discussing the UARL equation, it is worth highlighting that one of the major components is the term average operating pressure (P_{AO}). Considering a system with consistent infrastructure data (N_c, L_p, L_m), the calculated UARL can decrease if the system is operated at a lower average pressure. However, pressure and leakage share an inherent relationship because flow through an orifice is dependent upon the pressure gradient between the inside and outside of the pipe (van Zyl et al., 2017). If a system were to reduce pressure, it would seem logical that real losses would in turn decrease (in addition to the calculated UARL), and the ILI would adjust accordingly. Ultimately, some of the challenges associated with pressure management, as well as the specific nature of the data parameter P_{AO} have been discussed in Section 2.5 of this report.

6.2.3. Water loss reduction potential compared to projected demand

The most recent projection of water withdrawn from the Delaware River Basin by public water supply systems is presented in Figure 2, which is an updated figure adapted from Thompson & Pindar, 2021. This figure shows that in CY2020 about 775 million gallons per day (MGD) were withdrawn from the Basin by public water suppliers, whereas it was reported to DRBC through water audits that the CY2020 volume from own sources was about 768 MGD. This difference is logical for a few reasons, namely (1) not all systems which withdraw water are required to submit audits, (2) some reports for CY2020 were missing and replaced with backfilled data, (3) some systems reporting audits may be on the Basin divide and the total VOS may include data from sources outside the Basin, and/or (4) the AWWA FWAS VOS is theoretically measured as water leaving the treatment facility, whereas state withdrawal data is measured at the source (and therefore leakage of raw water may be a small factor).

The original study performed by Thompson & Pindar, 2021 provided two notable conclusions regarding projected public water supply withdrawals, and specifically their relationship to growing populations within the Basin boundary:

1. The results from 335 individually assessed systems (and projected "unassociated" data) indicate continued decreases in modeled withdrawals from the Delaware River Basin of approximately 34.610 MGD by 2060, a 4.3% reduction.
2. The pattern of increasing population and decreasing withdrawals is assumed to be related to advances in leak detection and water conservation by utilities, regulatory efforts such as plumbing standards, and general public awareness of water conservation.

Ignoring the possibility of decreasing per-capita consumption rates (e.g., "general public awareness of water conservation") and plumbing standards' effects on water demand, the projected decrease (2017-2060) of 34.610 MGD (~12,600 MGY) still leaves much room for improvement. Assuming that any one of the ILI frontiers in Table 20 has the possibility of being met by the year 2060 (regardless of feasibility, economic or otherwise) the different levels of withdrawal reduction can be superimposed on Figure 2 to create the graphic shown in Figure 47.

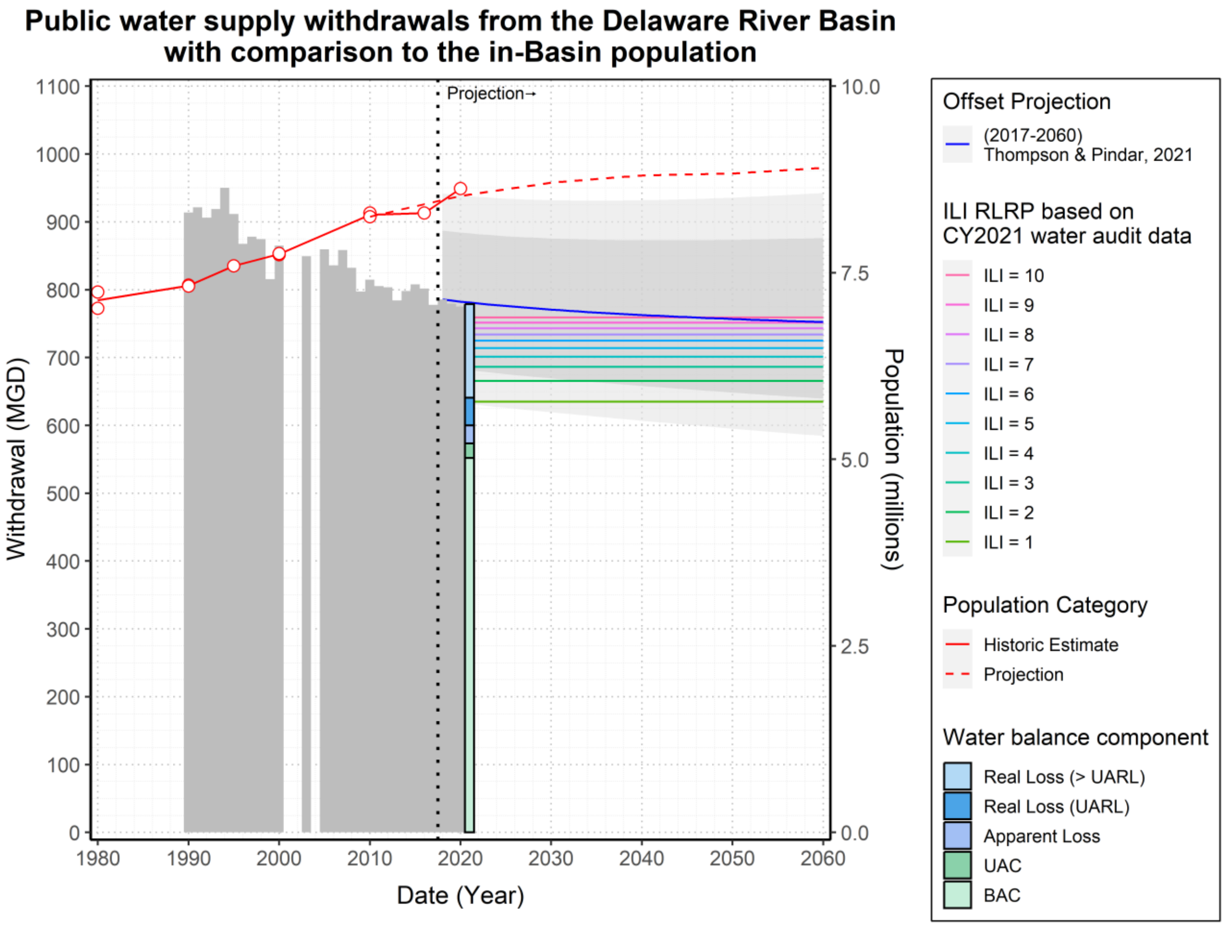


Figure 47: The projections from Thompson & Pindar, 2021 have been offset by about 33 MGD, equal to the error between the model and reported withdrawals in CY2017. Horizontal lines representing the ILI frontiers have been calculated for each ILI based on applying the real loss reduction potential (RLRP) to the CY2021 VOS.

In Figure 47, all previous withdrawal data has been color coded grey whereas the water audit data from CY2021 has been color coded by water balance component. Technically, the water balance components should add up to equal the water supplied (WS) volume (i.e., Figure 11). However, to be most comparable to the grey bars (which represent withdrawals from within the Basin boundary) the CY2021 water audit data should represent the volume from own sources (VOS). As there was a small net import of water, the Basin-wide VOS≠WS; therefore, each water balance component has been scaled proportionally by the ratio VOS/WS.

The horizontal ILI frontiers in Figure 47 are calculated by applying the respective RLRPs to the CY2021 water audit data (VOS=779 MGD, color coded by scaled water balance component). Notably, this figure suggests that if withdrawals continue to follow the projection which represented a best estimate of current operational trends, the projected decrease (2021-2060) of 28.518 MGD (10,500 MGY) is equivalent in volume to the potential reduction in CY2021 real losses for all systems above ILI=9 reducing to ILI=9. Primarily, viewing the data in this fashion highlights how much more reduction could be achieved by advancing beyond the current operational trends – ultimately showing that a plateau for water efficiency has not yet been reached. There are many considerations when looking at this figure which should be noted:

1. It is worth reiterating that a few systems submitting water audits are on the Basin divide and may include withdrawal sources from outside the Basin; therefore, RLRPs for those specific systems are likely not entirely applicable to the Basin-wide analysis but are included as a consequence of the collected data scale.
2. The ILI frontiers do not consider the Economic Level of Leakage, and it is not a realistic expectation for all systems to achieve an ILI=1. However, the frontier for ILI=1 does present a good order of magnitude estimate for the limits on water conservation related to real loss mitigation. It has been noted how the analysis might improve to provide a more realistic picture of RLRP if ELL analyses for the largest fifteen systems were able to be incorporated in the analysis.
3. The ILI frontiers only represent water reduction due to real loss reduction, whereas the offset projection from Thompson & Pindar, 2021 shows a reduction which is likely a combination of real loss reduction, water conservation awareness (i.e., decreased usage by customers) and plumbing standard implementation. Therefore, it is possible that the potential for water conservation could be more when considering the other two factors, especially trends in per-capita rates.
4. The ILI frontiers were determined such that "all systems above ILI=X reduce to ILI=X". If broader real loss mitigation efforts are implemented throughout the Basin, it is not likely that *only* those above a certain ILI would be improving. It is more than likely that improvements would unfold such as a Very Large system improving slightly (e.g. 10 → 9), and many Medium systems improved moderately (e.g. 5 → 3) yielding a reduced real loss volume as though "all systems above ILI=X reduce to ILI=X".

Overall, the assessment of ILI in relation to RLRPs has proven to be a useful assessment, primarily as it is inherently based upon the UARL equation, which is founded upon physical characteristics and limits of each system. The analysis has shown that there is more room for water conservation throughout the Basin, by as much as 144 MGD – although this is likely not attainable due to economic feasibility for individual systems. It was shown that the results of the ILI analysis are comparable to those of the frontier analysis, and that the ILI analysis requires a significantly lower level of computational effort. It is noted that consideration should be given to the Economic Level of Leakage regardless of analytical method used (frontier analysis, ILI) to increase analysis accuracy; referencing RLRP volumes without giving consideration to ELL should be noted as theoretical limits of loss reduction. As leak detection and conservation continue to advance on an individual system basis throughout the Basin, it is thought that the reported water withdrawals by public water suppliers have the potential to decrease below the offset Thompson & Pindar, 2021 projection.

6.3. UARL unit rate and ILI cross-plot

It has been noted throughout this report that a preferred metric by many organizations is the unit real loss rate, expressed in gallons per connection per day (gcd). Consequently, the cross-plot shown in Figure 46 used to demonstrate the calculation of real loss reduction potentials can be converted into “per connection” units. To accurately do this, both the real losses and the annual volume of UARL must also be converted into units of gcd. Consequently, dividing the standard UARL equation (Equation 8, which has units of gallons per year) by $N_c * 365$ yields the following:

Equation 11 .... $$UARL\ (gcd) = \left(5.41\ \frac{L_m}{N_c} + 0.15\ + 7.5\ L_p\right) \times P_{AO}$$

Because of the rational basis on which the standard UARL equation was developed, converting the standard UARL equation to a unit rate per connection conveniently yields a rational and useful equation. In this version of the UARL equation, the first term inside the parentheses represents a normalized “length of mains per connection”, and the last term simply changes from the total length to the average length of customer service connection piping. Notably, the middle term inside the parentheses associated with N_c effectively becomes a constant, which is logical as the equation now yields UARL in units of gallons per connection per day. Based on a typical low average operating pressure of about 40 psi, Equation 11 suggests that there is a typical lower limit in the range of 6 gcd of unavoidable real losses per connection per day, which is logical based on how the standard UARL equation was derived in Lambert et al., 1999. However, in reality the miles of main per connection and the length of customer pipe for each connection affect the final UARL unit rate. Logically the equation suggests that lower density networks have a higher potential unavoidable loss, as there is more length of main attributed to each connection. Likewise with a longer average customer length, would come more associated leakage per connection.

The unit rate data (real loss vs. UARL) is cross plotted in Figure 48 which again inherently represents the Infrastructure Leakage Index. Assessing the data in this fashion collapses the spread of data along the 1:1 line such that systems of all sizes are grouped along the x-axis based on similar expected UARL unit values (previously plotting total volumes in Figure 46, there is clear separation of data between classes based on system size, which is this report is based on N_c). Using unit rates in Figure 48 introduces another component of comparison between systems (beyond ILI bands), showing how systems of different sizes may have similar expected unavoidable loss rates.

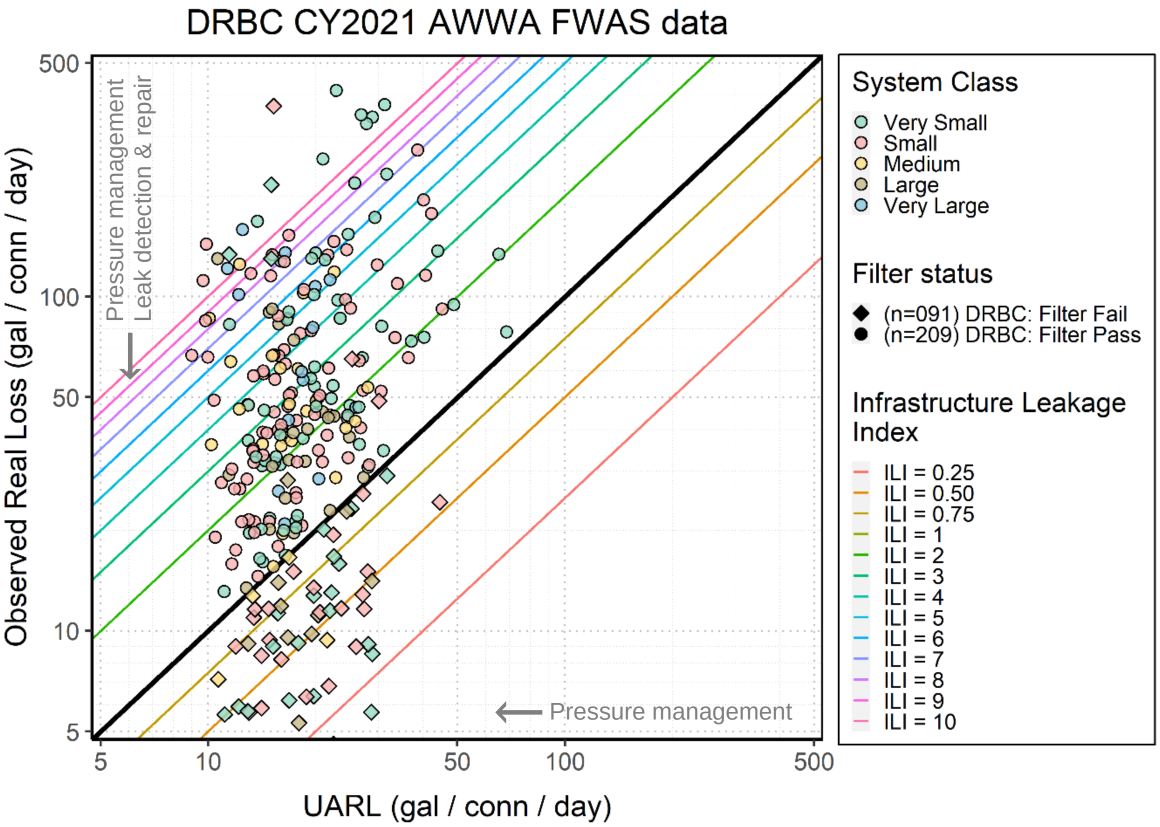


***Figure 48**: A cross-plot showing the current annual real losses (CARL) compared against the calculated unavoidable annual real losses (UARL), both in units of gallons per connection per day. In a similar fashion to Figure 46, the points on this graphic inherently reflect the infrastructure leakage index (ILI). Note that some points with calculated ILI less than one have plotted below the lower y-axis limit and are not visible.*

In Figure 48, there are two directions a point (system) can move while improving the performance of water conservation:

1. **Pressure Management**: Operating the system at a lower pressure will by default calculate a lower UARL unit rate and move a point to the left. However, as has been noted previously, pressure and leakage flow rate share a direct relationship (i.e., orifice equation) and reducing the average operating pressure should also reduce the volume of leakage, assuming the number of bursts and background leaks is constant. Other benefits to pressure management such as reduced break frequency will likely also further drive loss reductions. Therefore, it is assumed that pressure management moves a point toward the origin at a slope which is unknown and likely variable.
2. **Leak detection and repair**: Improving the leak detection and repair procedures is intended to directly reduce the amount of water lost. Given the same system conditions (i.e., constant UARL unit rate), reducing the volume of real losses moves a point vertically downward.

6.4. Pearson/Trow quad analysis

The quadrant analysis shown in Figure 49 compares the Infrastructure Leakage Index (ILI) and a variable referred to as the Pressure Management Index (PMI), initially proposed by (Trow, 2009), which is defined as a system's average operating pressure divided by some reference pressure (in this case 50 psi). This analysis is referred to as the Pearson-Trow Quadrant Analysis, after the authors who proposed the analysis in 2012 (Pearson & Trow, 2012). Primarily, this analysis provides the most benefit for individual utilities to better understand how to improve water efficiency graphically, i.e., whether the problem may be primarily leaks, pressure, or a combination of the two. However, it is possible to scale the size of the point by the unit real loss rate (gallons per connection per day), and color code the points by system class. This offers additional insight at a broader scale, and highlights what has been shown in previous analyses (e.g., Table 21) – that the largest potential reduction in unit real loss rates (gcd) appear to be with Very Small systems. Note that scaling the size of the points according to the total real loss volume will undoubtedly correlate point size with system class directly.

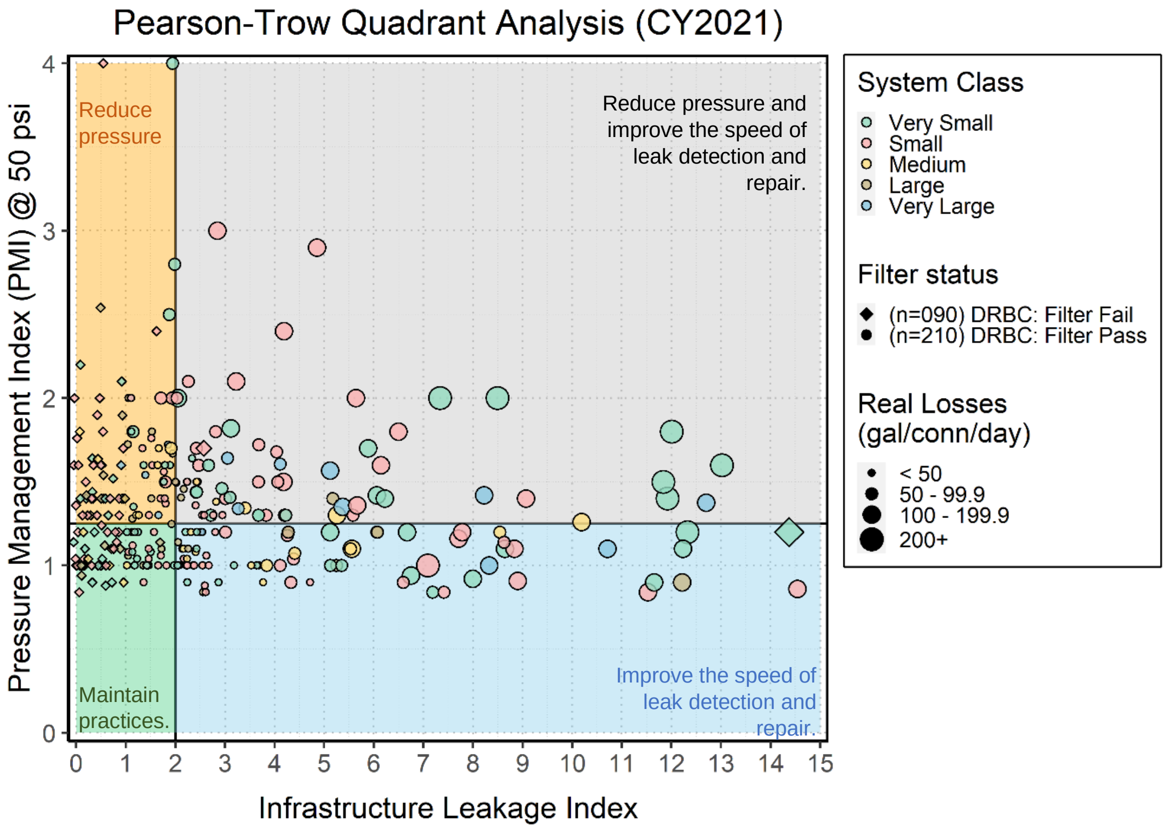


__Figure 49__: The CY2021 data collected through the DRBC Water Audit program as visualized using the Pearson-Trow quadrant analysis (Pearson & Trow, 2012) which provides diagnostic information based on the Infrastructure Leakage Index, and the Pressure Management Index (PMI) calculated at 50 psi (Trow, 2009).

6.5. Combined Real Loss Indicator (CRLI)

It has been noted for some time that using a real loss KPI in the units of gallons per connection per day (gcd) may not be the most effective tool for water supply systems with low connection densities; for example, Report 26 (DOE & NWC, 1980) recommended the use of liters/property/hour in urban areas and liters/kilometer of main/hour in rural areas. In the United States today, the current version of AWWA M36 (4th ed.) recommends a real loss unit rate (gcd), unless there is a low density of customer service connections (less than 32 connections per mile), in which case it recommends units of gallons per mile of main per day (gmd) (AWWA, 2016b). Two separate KPIs for a single parameter (real losses) can pose challenges, which have led to a concept termed the "Combined Real Loss Indicator" (CRLI). By generating a cross-plot of unit real loss (gcd) and unit real loss (gmd), the $CRLI = (x * y)^{½}$. Therefore, the CRLI has the following units:

$$CLRI = \sqrt{\left(\frac{gal}{N_c * day}\right) * \left(\frac{gal}{L_m * day}\right)} = \frac{gal}{\left(\sqrt{N_c L_m}\right) * day}$$

Allan Wyatt notes that this indicator is like a blended infrastructure parameter, the units akin to something like "gallons per network component per day" (Wyatt, 2020a). Data for the filtered DRBC CY2021 dataset (DRB.f-2021) are plotted in this fashion on Figure 50 – which then demonstrates how iso-curves for different CRLI values can be overlain with the data points. As noted by Allan Wyatt, a typical range of CRLI for water systems in the United States is 100 < CRLI < 1,000 (Wyatt, 2020a), which seems consistent with the data as shown in Figure 50. Many of the example plots shown using CRLI also present lines of equal connection density (N_c/L_m) extending from the origin of the plot. However, it was unclear how to incorporate the lines of equal connection density data into Figure 50, so it has been left off. Points which were filtered out based on the criteria discussed in Section 3.3.3 have been presented as light grey points and, interestingly, appear to have plotted at CRLI values generally less than 100. It was demonstrated by Wyatt, 2020a how the distribution of CRLI values could be used to calculate percentiles and therefore generate frontiers to compare performance among systems. However, further analysis using the CRLI is not performed in this study as two other methods have already been assessed in estimating reduction potentials of real losses due to increased performance.

It was noted by Wyatt, 2020a how CRLI has the convenience of not incorporating a pressure term. An example is generally cited where a given system only changes the average operating pressure term thereby decreasing the calculated UARL – the example assumes the system experiences the same leakage, and therefore the resulting ILI value increases just due to a change in P_{AO}. However, as noted previously in this study, pressure and leakage share an inherent relationship because flow through an orifice (i.e., a leak) is dependent upon the pressure gradient between the inside and outside of the pipe (van Zyl et al., 2017). If a system were to reduce pressure, it would seem logical that real losses would in turn decrease (in addition to the calculated UARL); therefore, it is possible that the ILI could decrease, remain the same or possibly increase – any of which might be suggested to be justifiable.

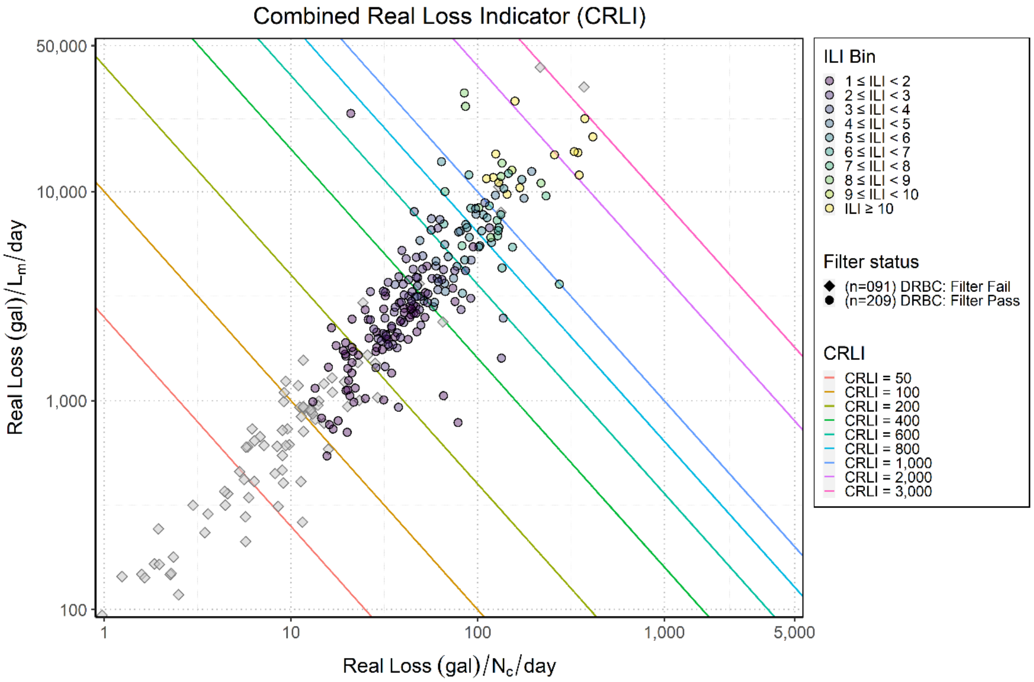


***Figure 50**: A cross-plot showing the unit real losses (gmd) compared against the unit real losses (gcd) for water audits submitted in CY2021. Points on this graphic therefore inherently reflect the (CRLI)[2].*

It is worth noting that cross-plots of technical indicators have been used before, albeit, without much of the interpretation which has accompanied CRLI. In the mid-1990s, cross-plots of the two unit rates proposed in Report 26 were used as a seemingly standard tool by OFWAT in the United Kingdom to compare system leakage, and even to show how points should move toward the origin as they improved to meet leakage targets (OFWAT, 1997). Additionally, Allan Lambert has previously shown how the unit real loss rates can be further normalized by pressure (liters / N_c / day / meter of pressure), allowing the iso-curves to be drawn representative of the Infrastructure Leakage Index (Lambert, 1999). Furthermore, while CRLI has been shown to be technically rigorous (Wyatt, 2020a, 2020b), it is not yet abundantly clear given a CRLI value for a specific system, to what value of CRLI that system could be reasonably expected to reach as a result of reducing real losses within the system (without assessing the performance on peer systems).

7. UARL SYSTEM CORRECTION FACTORS (SCF)

The Unavoidable Annual Real Loss (UARL) equation was initially developed when the IWA Operation and Maintenance Committee set up a Task Force in 1996, specifically addressing the second goal of providing recommended preferred performance indicators for international comparison of losses (Lambert et al., 1999). The UARL equation was developed based on a conceptual understanding of the way leakage occurs, structured around the Burst and Background Estimate (BABE) model (Lambert, 1994). The UARL equation therefore used a component-based approach, looking at the three ways leakage occurs at three main components of a system:

Infrastructure component

[1] L_m , mains
[2] N_c , service connections to edge of street
[3] L_p , service connections after the edge of street

Leakage component

[1] reported bursts
[2] un-reported bursts
[3] background leakage

The 1st IWA Water Loss Task Force used international data to assess parameters to calculate the nine leakage components for well maintained infrastructure in good condition at 50 metres (70 psi) pressure. Each infrastructure component then received a single unit rate (the sum of the three components), before the average leak flow rates were adjusted for average system pressures higher or lower than 70 psi using a simplified linear relationship. UARL was then calculated for each of 27 large diverse water systems from 20 countries, and the ratio of Current Annual Real Losses (CARL) divided by UARL produced a range of ILIs from 0.7 to 10.8. The methodology was accepted by IWA in 1999 and by AWWA in 2003.

Boundary limits for system size and pressure have evolved since 1999 and the latest recommended limits for applying the UARL equation are $N_c > 5{,}000$, and that the pressure range should be between 45m (64 psi) < P < 60m (85 psi) (Lambert, 2020). Often data from smaller systems (i.e., data outside the recommended range) may yield high UARL values such that the reported real losses return an ILI < 1. This was shown in Figure 46, where many Very Small and Small systems plotted below the solid black line of ILI=1. This type of finding was a large driver for research into modifications to the UARL equation which can account for the influences of small system sizes (including DMAs), diversity of pipe material, and for the influences of pressure on burst frequency. The result is a non-dimensional “System Correction Factor” (SCF), which is multiplied by the UARL to provide a more realistic depiction of the unavoidable real losses. There are three interacting concepts supporting the use of SCF calculations:

1. **The relationship between pressure and leakage flow rate (P:Q)**

   In 1994, a study on the relationship between pressure and leakage flow rate (P:Q), later known as Fixed and Variable Area Discharges (FAVAD), suggested that some leak areas may expand with pressure (subsequently increasing leak discharge) to the point where entire systems may exhibit uniform “expansion” behavior with respect to the orifice discharge equation (May, 1994). This concept was understood by Lambert et al., 1999 during development of the original UARL equation, as they cited the 1994 study as well as emperical data which suggested $P \propto Q^{1.15}$ (Ogura, 1979). However, Lambert et al., 1999 concluded that simplifying the relationship to a power law exponent of 1 was sufficient for analysis of large systems (except for extreme high/low pressures). Nevertheless, by 2001 ensuing research showed that applying FAVAD concepts could generalize the pressure:leakage relationship used for UARL as a power law: $P \propto Q^{N1}$ where N1 might vary between 0.50 and 2.50 (Lambert, 2001). In 2003, it was recommended by the UK Water Industry Research (UKWIR) in Report No. 03/WM/08/29 that (1) a linear P:Q relationship should be used for large zones or entire systems, or where high precision results is not a priority, (2) a power-law relationship should be used for smaller zones or where more precision is required (UKWIR, 2003). By 2005, it had been demonstrated that N1 typically lies between 0.50 (fixed area leaks) and 1.50 (variable area leaks and background leakage), that the UARL equation could be corrected by a dimensionless factor to account for FAVAD effects, and that the factor (C_p) could be correlated with the percentage of detectable leaks on rigid pipes (p%) (Thornton & Lambert, 2005). In 2009, Lambert, 2009, presented a figure showing how C_p could change as a function of pressure, as well as the percentage of rigid pipes within a system (e.g. 100% rigid pipes would indicate that all detectable bursts have fixed areas), the standard UARL equation was shown to be within +/-10% of the original UARL equation for pressures between about 15 to 115 psi. Developed between 2008 and 2013 (Lambert et al., 2013), this approach has now been superceded by the SCF approach which permits different power laws for the percentages of rigid and flexible pipe materials on each infrastructure component.

2. **Low burst (leak) frequencies in small systems**

   Burst frequency (i.e. the number of main or service line bursts per year) was a consideration in developing the coefficients for the UARL equation; however, the datasets used were primarily from large water distribution systems. It has been noted by Lambert, 2020 that small systems (i.e. $N_c < 5{,}000$) may exhibit different probabilistic characteristcs regarding breaks as compared to large systems. As the number of connections within a system decreases (below 5,000), it is suggested that the number of bursts per year becomes increasingly skewed and is better represented by a Poisson Distribution (as opposed to a Normal Distribution). Therefore, the burst frequency assumptions made in developing the standard UARL equation can be adjusted to account for these dynamics when assessing small systems. Allan Lambert has noted that a useful feature of the Poisson distribution is that it is skewed for small systems, and the median value rather than the average is used for the small number of UARL bursts. However as number of service connections increases past 5000 service connections, the number of UARL bursts increases and approximates to a normal distribution (in which the median and average values are almost equal) (A. Lambert, personal communication, 2023).

3. **The relationship between pressure and burst frequency (P:BF)**

   Based on limited field data, it had also been noted by Lambert, 2001 that a relationship exists in many water distribution systems between system pressure (P_{AO}) and the frequency of bursts (BF) experienced in a water distribution system. By 2005, it was suggested that a simple power law relationship might exist ($P \propto BF^{N2}$), such that reductions in pressure would result in a reduction of new leaks by an exponent of N2, which could range between 0.5 - 6.5 (Thornton & Lambert, 2005). Additional case study investigations by Pearson et al., 2005 suggested that N2 may vary 0.2 – 8.5 for mains (median 2.47), and 0.2 – 12 for service pipe breaks (median 2.36). Additional research by Thornton & Lambert, 2006 proposed a hypothesis that zones within a system may have low failure rates until a particular pressure is exceeded, and defined a Burst Frequency Index (BFI) as the ratio of the observed burst frequencies (mains and service lines) to the burst frequencies used in developing the UARL equation. However, additional research clarified that there are some number of bursts per year which are not pressure dependent (BF_{npd}), and those which are pressure dependent (BF_{pd}) have a seemingly cubic relationship to pressure (P $\propto BF_{pd}{}^{3}$, i.e. N2≈3) (Thornton & Lambert, 2011).

The corrections to UARL for items (2) and (3) require data on the number of service connections and pressure, for which data are routinely collected through the AWWA FWAS. However, to correct for FAVAD (item 1), additional data is required on the percentage of mains and service connections which have rigid versus flexible piping – data which is not collected by the AWWA FWAS. Therefore DRBC coordinated with New Jersey American Water to compile the necessary pipe material information on five small public water supply systems within the New Jersey portion of the Delaware River Basin. Data collected by the AWWA FWAS for CY2021 are presented for the five systems in Table 22, along with the supplemental data required to calculate SCF. While there were substantial portions of service line pipe materials which were unknown, the ratio of rigid to flexible piping for the known pipes was accepted to represent entire respective systems.

Currently there are three scenarios evaluated by (Lambert, 2020) which result in the calculation of a SCF, all of which are presented in Table 22. Each calculated SCF can be applied to the UARL as determined using the original equation, yielding a "corrected" UARL and subsequent "corrected" ILI. From the results in Table 22, there is not a large effect on the UARL equation based solely on the FAVAD concept, as the majority of all five systems were estimated to be comprised of rigid pipes; therefore, the standard UARL should be within +/-10% assuming the pressures were between about 15 to 115 psi (which they are). In this case it appears that the largest effect on the SCF is due to adjusting the assumption related to the distribution of bursts per year in small systems – acknowledging that smaller systems may skew lower in terms of the number of bursts per year, as compared to the data used from larger systems in developing the standard UARL equation coefficients. As would be expected from the research previously discussed, it appears that the effects of adjusting the probability distribution skewness are a more drastic effect the smaller a system gets. Finally, applying an adjustment which considers that pressure may also affect the number of bursts per year, and which slightly lowered the SCF for all systems which have pressures below 50m (~70 psi), had no effect on the system operating at that range, and slightly raised the SCF for one system operating above that threshold.

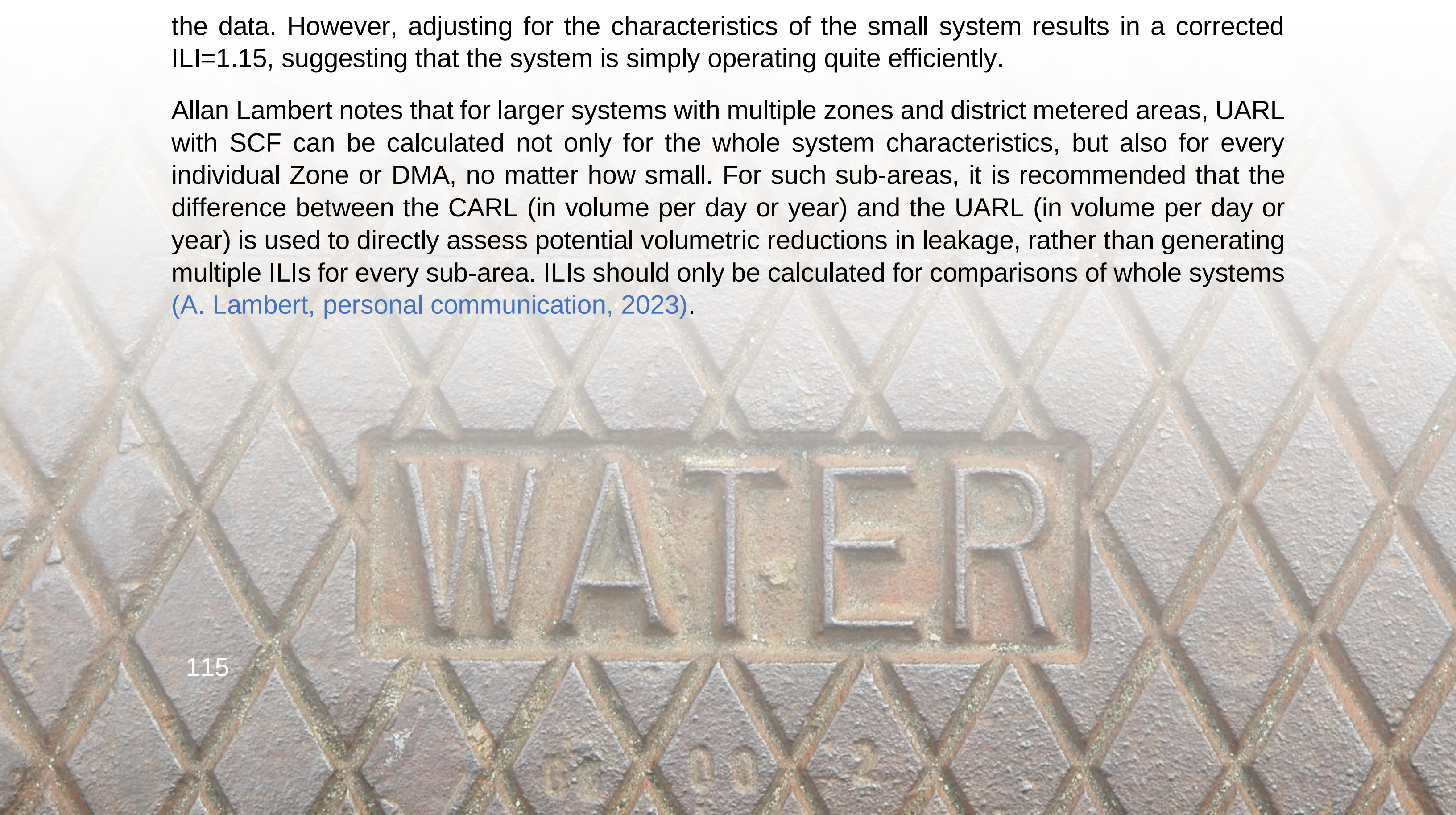
Calculation of a "corrected UARL" based on the combination of all three correction scenarios is presented in Table 22, as well as the corrected ILI. For small systems these adjustments are expected to more accurately reflect the idea of "how low can you go", when it comes to water loss. Interestingly, prior to the adjustment System 2 had a calculated ILI < 1 which would suggest that the system reported real losses lower than the theoretical UARL and possibly has errors in

***Table 22**: System data related to UARL for six small water public water supply systems in New Jersey, with supplemental data and calculations related to the System Correction Factors (SCF) as it applies to the UARL.*

Dataset	Parameter	Units	System 1	System 2	System 3	System 4	System 5
AWWA FWAS Data	N_c	--	473	1,293	2,582	3,902	4,850
	L_p	feet	25	25	25	25	25
	L_m	miles	7	12	52	72	95
	P	psi	73	57	52	50	86.1
	Real Loss	MG	9.821	5.172	63.225	47.827	163.405
	UARL	MG	3.347	6.341	14.431	20.319	44.427
	ILI	--	2.93	0.82	4.38	2.35	3.68
Supplemental data (% rigid pipes)	Service Connections (Main to Prop. Line)	%	65%	72%	98%	97%	96%
	Service Connections (Prop. Line to Meter)	%	80%	96%	77%	62%	77%
	Mains	%	100%	100%	99%	98%	100%
System Correction Factors	FAVAD	--	1.01	0.95	0.96	0.95	1.04
	FAVAD & POISSON	--	0.74	0.74	0.80	0.83	0.96
	FAVAD & POISSON & PRESSURE BURSTS	--	0.74	0.71	0.76	0.77	1.02
Modified based on FAVAD & POISSON & PRESSURE BURSTS	UARL (corrected)	MG	2.477	4.502	10.967	15.646	45.316
	ILI (corrected)	--	3.97	1.15	5.76	3.06	3.61

the data. However, adjusting for the characteristics of the small system results in a corrected ILI=1.15, suggesting that the system is simply operating quite efficiently.

Allan Lambert notes that for larger systems with multiple zones and district metered areas, UARL with SCF can be calculated not only for the whole system characteristics, but also for every individual Zone or DMA, no matter how small. For such sub-areas, it is recommended that the difference between the CARL (in volume per day or year) and the UARL (in volume per day or year) is used to directly assess potential volumetric reductions in leakage, rather than generating multiple ILIs for every sub-area. ILIs should only be calculated for comparisons of whole systems (A. Lambert, personal communication, 2023).



8. PRIVATE AND PUBLIC SYSTEMS

A concept which has not been discussed much in literature, or in prior DRBC studies, is that the ownership type across water supply systems can vary. Data was retrieved from the USEPA SDWIS database on May 25, 2023, using the R package {echor} (Schramm, 2020), which includes information on the “ownership type”. The categories of ownership type are specified as Federal government (F), Local government (L), Public/Private (M), Native American (N), Private (P), and State government (S). Following QAQC of the data within the Delaware River Basin, there are only two categories of ownership: Local government and Private systems[3]. While a similarly sized system of each ownership type (L, P) likely has the same operational goal of providing potable and palatable drinking water, it may be unwise to ignore the fact that a privately owned system *may* have different business initiatives than a system owned by a local government (e.g., municipal system or water authority), or have different constraints on what is possible to do (in terms of maintenance or upgrades).

To better understand the makeup within the Delaware River Basin, the same infrastructure related data presented in Figure 4 have been separated into the two categories of ownership type, presented in Figure 51. The majority of systems in the Basin subject to auditing requirements are owned by local governments (221 systems) and serve an estimated population of 4.694 million people (67.6% of the total population served); consequently, the remaining 79 privately owned systems serve an estimated population of 2.251 million people (32.4%). This ratio of about 2/3 to 1/3 is also present when assessing the length of mains, as well as the number of connections in each category of system ownership.

Metrics on real loss can be assessed using the filtered dataset for CY2021 (n=209) across system classes, considering the type of ownership. The real loss unit rate (gcd) is presented in Figure 53A, and the Infrastructure Leakage Index is presented in Figure 53B. The number of data points in some class/ownership categories is small, but this cannot be avoided in this analysis. For most system classes (Very Small, Small, Medium and Large) the data does not suggest strong differences in the real loss unit rates; it is noticeable that there are more outliers and wider distributions for local government systems. The most noticeable difference in real loss unit rates between local government and private systems occurs in the Very Large system class. The median real loss rate for all 15 Very Large systems is 59.6 gcd, whereas the median real loss unit rates for Very Large local government systems and private systems is 104.3 gcd and 42.7 gcd, respectively. This is similar to the findings in ILI where the overall median for Very Large systems is ILI=3.3, whereas the median ILI for Very Large local government systems and private systems is ILI=5.2 and ILI=2.5, respectively.

However, while ownership status may affect certain aspects of how systems are operated or maintained, it is only one piece to the puzzle and should not be considered by itself. It is again worth noting that there is an extensive history of waterworks in the Delaware River Basin, with many systems established in the early 1800s. Seven of the Very Large systems in the local government category are cities, and based on a brief review of historical records, it is possible to conclude that the average year in which these systems were founded (albeit as considerably smaller systems) is 1801. Three of the five Very Large systems which are privately owned have service areas outside of major city centers, primarily in surrounding developed and suburban areas. More detailed information on the age and material of pipe, subsurface geology and even loading patterns of traffic would be useful to help investigate these differences. Additionally, as mentioned before, other factors such as "red-tape" constraints imposed by ownership type, business priorities or the extent of capital resources also likely have effects, but are much more difficult to quantify compared to other information (e.g., pipe age, pipe material, etc.).

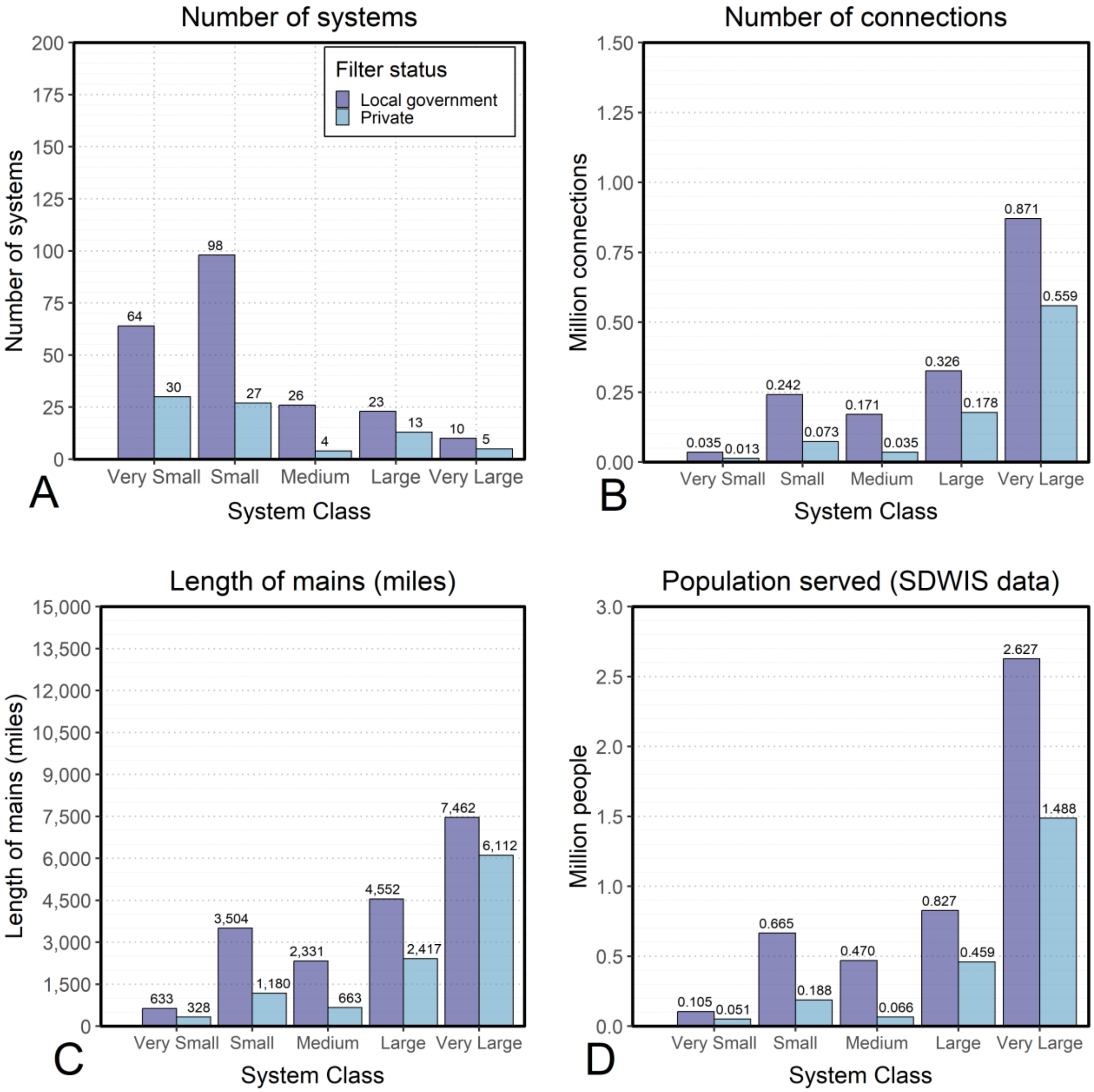


Figure 51: Data for the 300 systems meeting DRBC water audit requirements for the year 2021 – the same data presented in Figure 4 has been separated by the type of ownership (Local government, or Private).

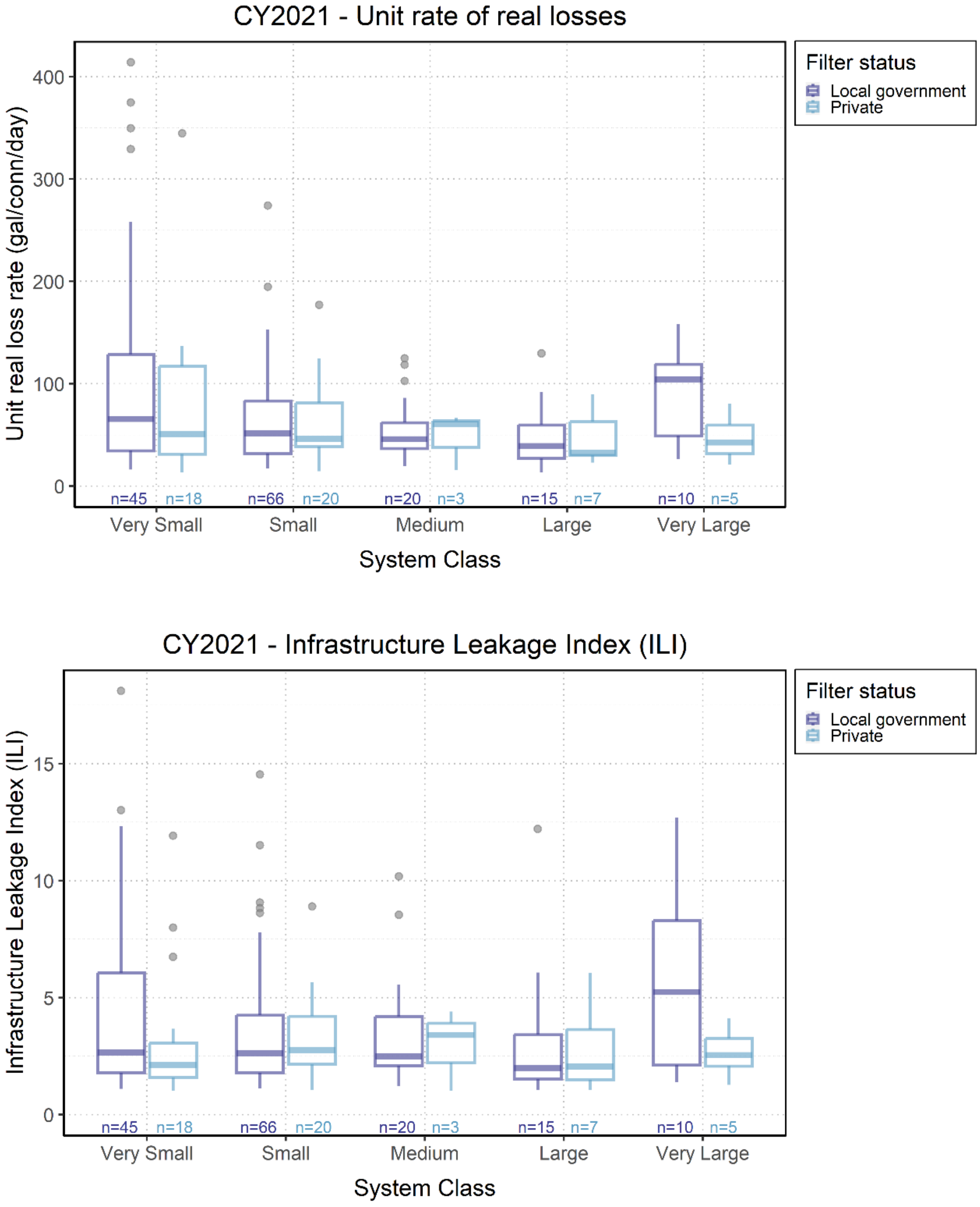


*Figure 52: CY2021 water audit data for systems in the Delaware River Basin which meet filtering criteria (n=209). The figures show the distribution of metrics on real losses, including **(A)** the unit rate of real losses in gallons per connection per day (gcd), and **(B)** the Infrastructure Leakage Index (ILI).*

9. SOURCE WATER DESIGNATION

An analysis which has not previously been conducted by DRBC is one that looks at water supply system performance based on the type of source water the system uses (i.e. groundwater, surface water, or a combination of the two). This form of data is not collected via the AWWA FWAS; therefore, DRBC relied upon a review of regulatory approvals, water use data, and the USEPA SDWIS database. The number of systems within each size class that rely on the various forms of source water is presented in Figure 53A. As the size of a system increases, there is an increased dependance on surface water. In the system classes of Small – Medium, 214 of the 249 systems completely rely on groundwater (about 86%). Whereas, for the Large and Very Large systems, only 26 completely rely on groundwater which is only about 51% of the total.

In terms of system performance, one of the most appropriate metrics to be used when comparing data across class size are unit metrics, such as unit real losses (in gallons/connection/day). The metrics for data in the filtered dataset (DRB.f-2021) are presented in Figure 53B by class size and source water designation. As the data is split into 15 categories with the majority of systems classified as groundwater-only systems, some categories did not have enough data for a statistical presentation. Overall, a general pattern seems to indicate that groundwater-only systems have a lower median unit real loss rate than systems which incorporate surface water. However, this is not to say that source water is an explanatory variable of unit system loss. It is likely that there are variables correlated with a system's dependence on either groundwater or surface water, which would in turn play a role in explaining these observations on unit real losses.

It is hypothesized that one such parameter driving the disparity in unit real losses between groundwater and surface water/combined systems may be the temperature of source water. It is shown in the following sections that groundwater temperature may only vary on the order of 10°F or less throughout the year, whereas surface water temperature can vary on the order of 35°F. Therefore, it does not seem unreasonable to assume that more drastic temperature changes in source water may inversely affect the system infrastructure and consequently rates of water loss.

9.1. Groundwater temperature

Currently, one of the most popularly referenced national maps of groundwater temperature is that produced by Collins, 1925. That map shows the temperature of shallow groundwater in any given place throughout the United States, based on the assumption that groundwater temperature is in general about the same as the mean annual air temperature. Collins, 1925 noted that it is probable (given adopted rates of groundwater temperature increase with depth) that groundwater temperature at a depth of 20-200 feet be relatively uniform (varying only by about 3-6°F). Collins, 1925 then provides a generalized map of probable shallow groundwater temperature (20-60 feet below ground surface) based on a map by the United States Weather Bureau, which showed normal annual air temperature. Given the age and scale (national) of this study and the assumptions used to generate the map, it was determined that more detailed data on groundwater temperature for the Delaware River Basin was required.

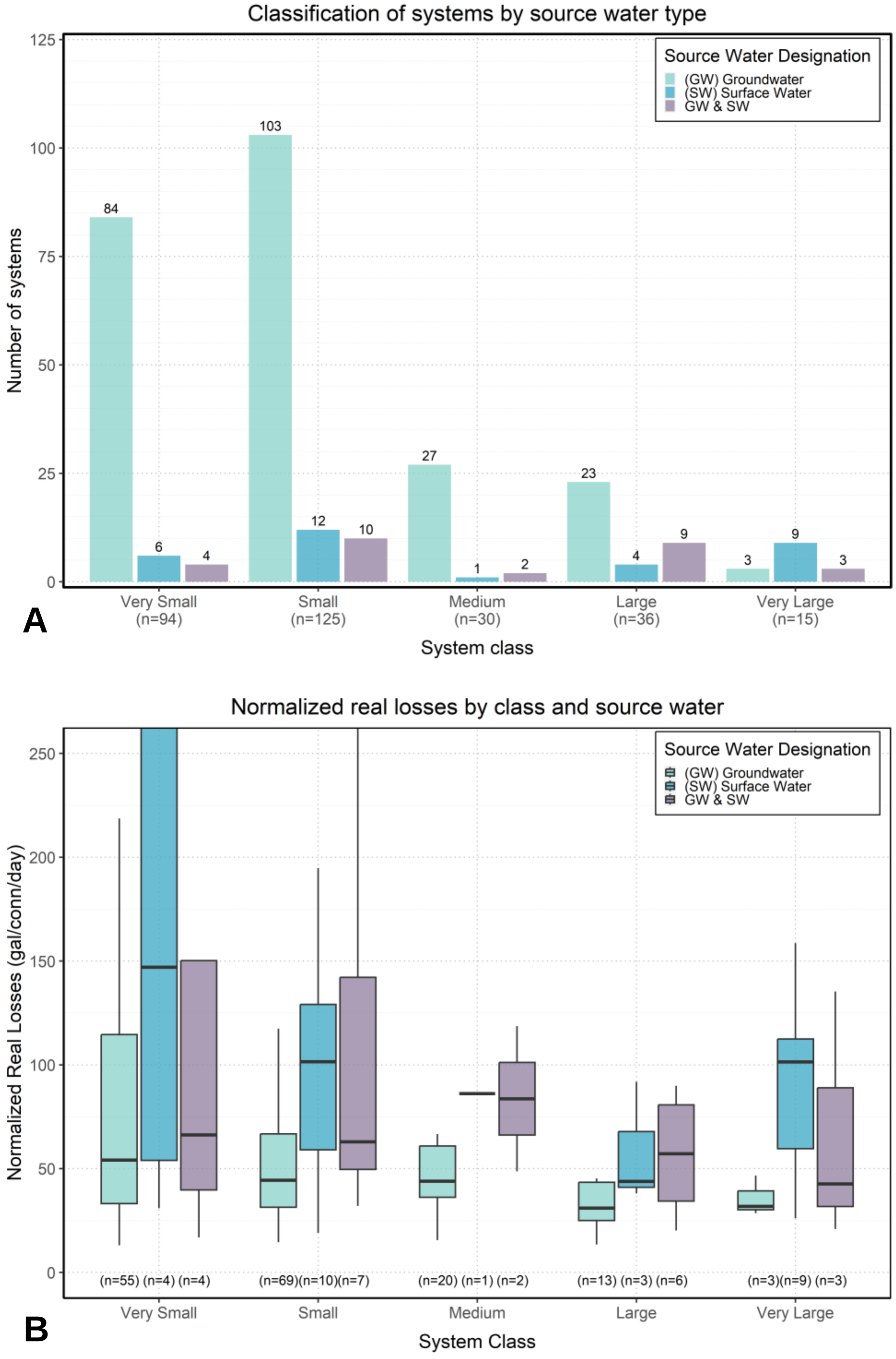


Figure 53: ***(A)*** *Systems within the Delaware River Basin with audits for CY2021, categorized by the type of source water used (n=300, which includes 18 missing records which were backfilled with prior data – refer to Table 8).* ***(B)*** *The filtered dataset (n=209) showing the distribution of unit Real Losses for each system class and source water; note that outliers have not been plotted to increase readability.*

Water quality data was obtained for the area around the Delaware River Basin for the extent bound by the following coordinates (N43°, E-74°, S38°, W-77°) from USGS Water Quality Portal (WQP) using the R package {DataRetrieval} (De Cicco et al., 2022). Data was retrieved specifically for USGS parameter 00010 (Temperature, water, degrees Celsius), for samples collected between the 10-year range (2012-01-01 to 2021-12-31). Only "Accepted" and "Sample-Routine" data points were retained in the dataset (meaning that "Preliminary" and "Quality Control Sample-Field Replicate" data points were excluded). This returned 1,745 sample points from 968 locations. The sample locations presented in Figure 54 and are color coded by whether or not information on sample depth was available (578 samples include information on depth). Not color coded is that almost all samples had information on the respective well's elevation (1,713 of the samples). Groundwater isotherms were generated in ArcGIS Pro (using the "Topo to Raster" function in the 3D Analyst Tools toolbox) without respect to the time of year a sample was collected; where a point has more than one temperature value (i.e., multiple samples from the same well), a mean value was used in contour generation.

Without consideration of sample depth, temperature data for the 1,713 samples with elevation information are presented by sample month and elevation in Figure 55A. From the smaller dataset of 578 samples, which do include information on depth, a plot of temperature by depth is provided in Figure 55B (without consideration of season). From analyses such as these, it can be concluded that groundwater changes only slightly with season and depth. Considering the map of groundwater temperatures across the Delaware River Basin (Figure 54), it appears that groundwater temperature likely changes with elevation, as does annual average ambient temperature; therefore, Figure 55A presents the data in separate elevation classes separated around 1,000 feet above mean sea level (ft. amsl). This elevation was selected based on assessment of physiography across the Basin as a qualitative break point (refer to Section 9 of this report). It appears that groundwater at lower elevations of the Basin (south) returned an overall average temperature of about 59°F (with notably lower winter samples included in the average); the median measured value in each month ranges between 51-61°F. The groundwater at higher elevations of the Basin (north) returned an overall average temperature of about 52°F (with notably lower winter samples included in the average); the median measured value in each month ranges between 47-54°F. Most samples which have associated depth information fall in the elevation class below 1,000 ft. amsl.

9.2. Surface water temperature

Data was retrieved for 52 surface water monitoring locations across the Delaware River Basin where both USGS Parameter Code 00060 (Discharge, cubic feet per second) and 00010 (Temperature, water, degrees Celsius) have daily value data between 2012 and 2021, with a minimum of three years of data. These sites are presented on Figure 56, and the stations are classified by the overall average flow during the period of record within the specified date range (not all stations have a complete data record within the range). The average monthly temperature for each station was calculated and a distribution is presented in Figure 57. It is not surprising that the surface water temperature varies with season, as would the ambient air temperature. The range of median temperature values is between 36°F (January) and 71°F (July).

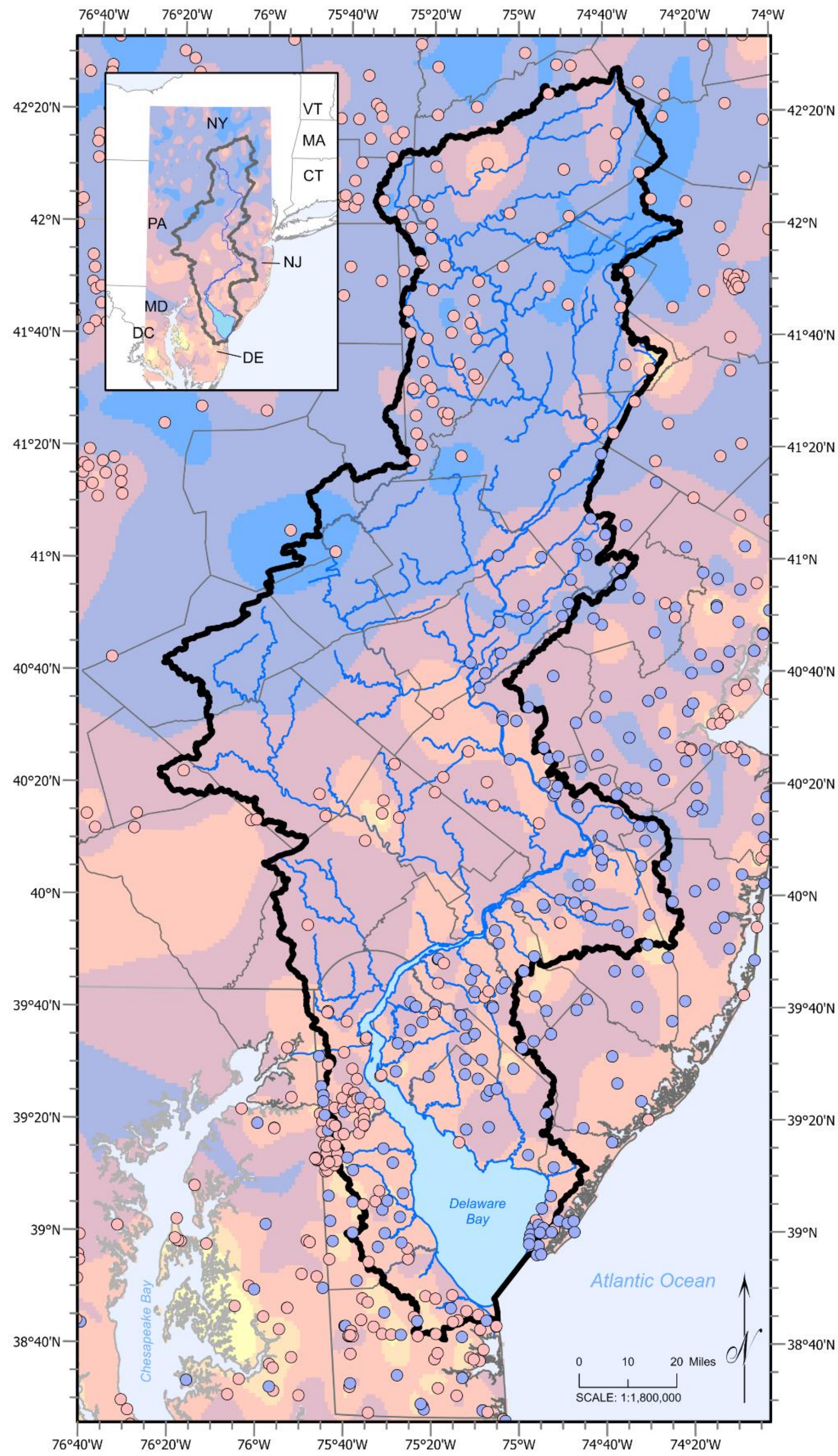


***Figure 54**: A map of interpolated groundwater temperature generated from 1,745 groundwater quality samples collected in and around the Delaware River Basin for which USGS Parameter Code 00010 (Temperature, water, degrees Celsius) was included in the sample analysis (2012-2021). Isotherms were generated without respect to the time of year a sample was collected. Where a point has more than one value, and mean value was used in contour generation. A subset of these samples have associated information on well elevation (1,713 samples), and a different subset of samples have associated information on sample depth (578 samples).*

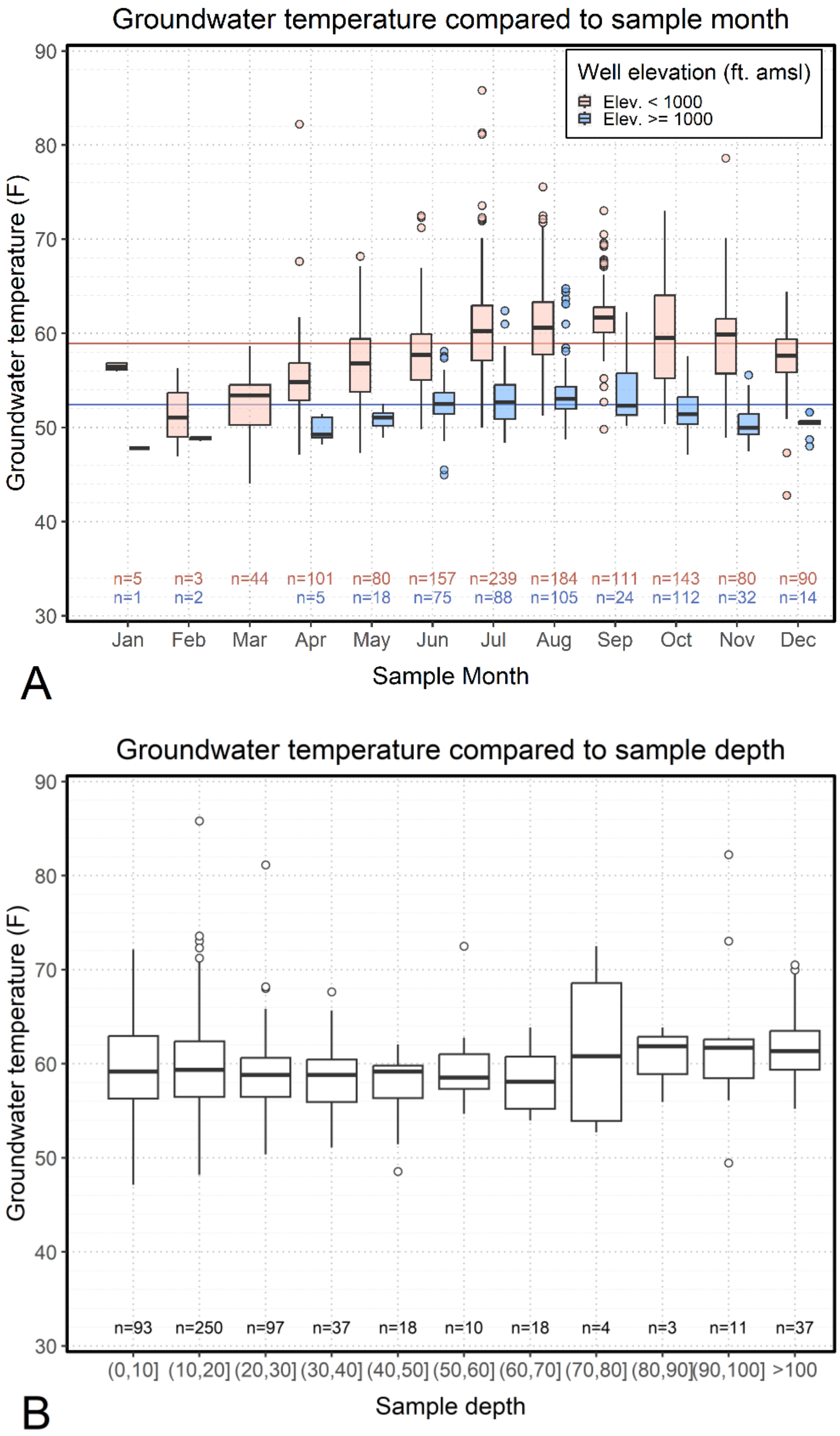


Figure 55: *Groundwater temperature data as collected by the USGS around the Delaware River Basin at the locations shown in Figure 54.* ***(A)*** *The 1,713 data points which have information related to well elevation.* ***(B)*** *The 578 samples which have information on sample depth (e.g. feet below ground surface).*

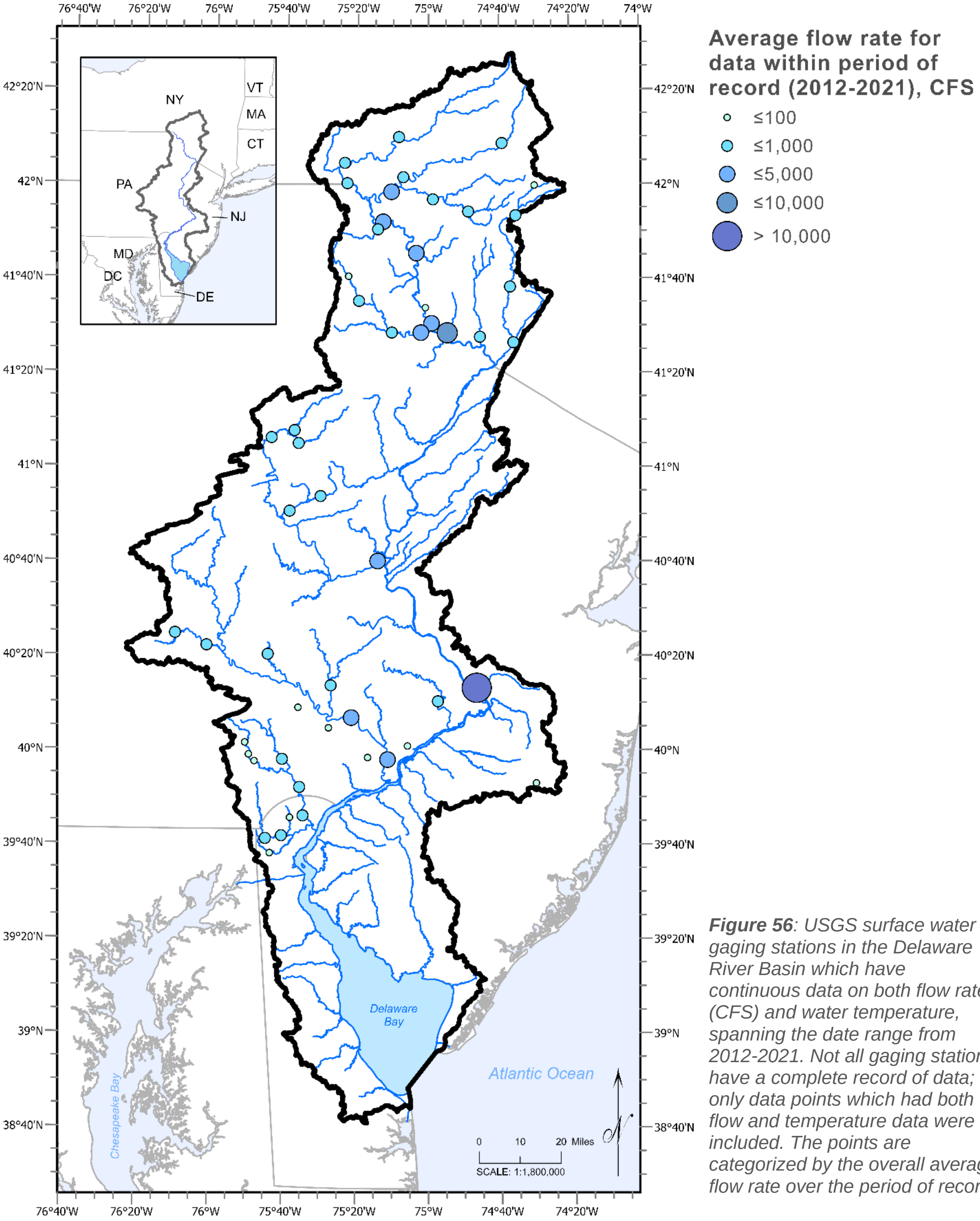


Figure 56*: USGS surface water gaging stations in the Delaware River Basin which have continuous data on both flow rate (CFS) and water temperature, spanning the date range from 2012-2021. Not all gaging stations have a complete record of data; only data points which had both flow and temperature data were included. The points are categorized by the overall average flow rate over the period of record.*

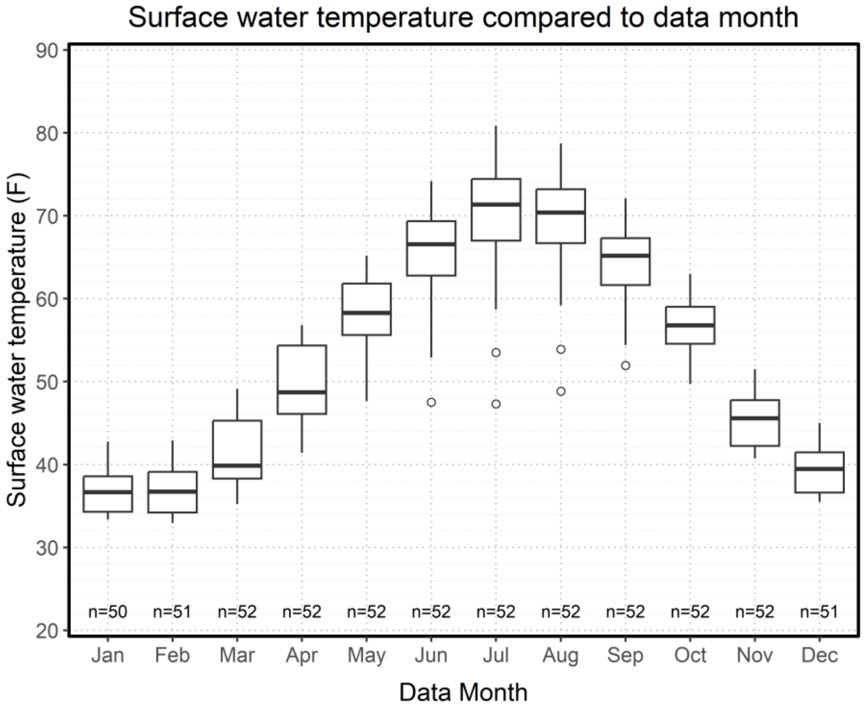
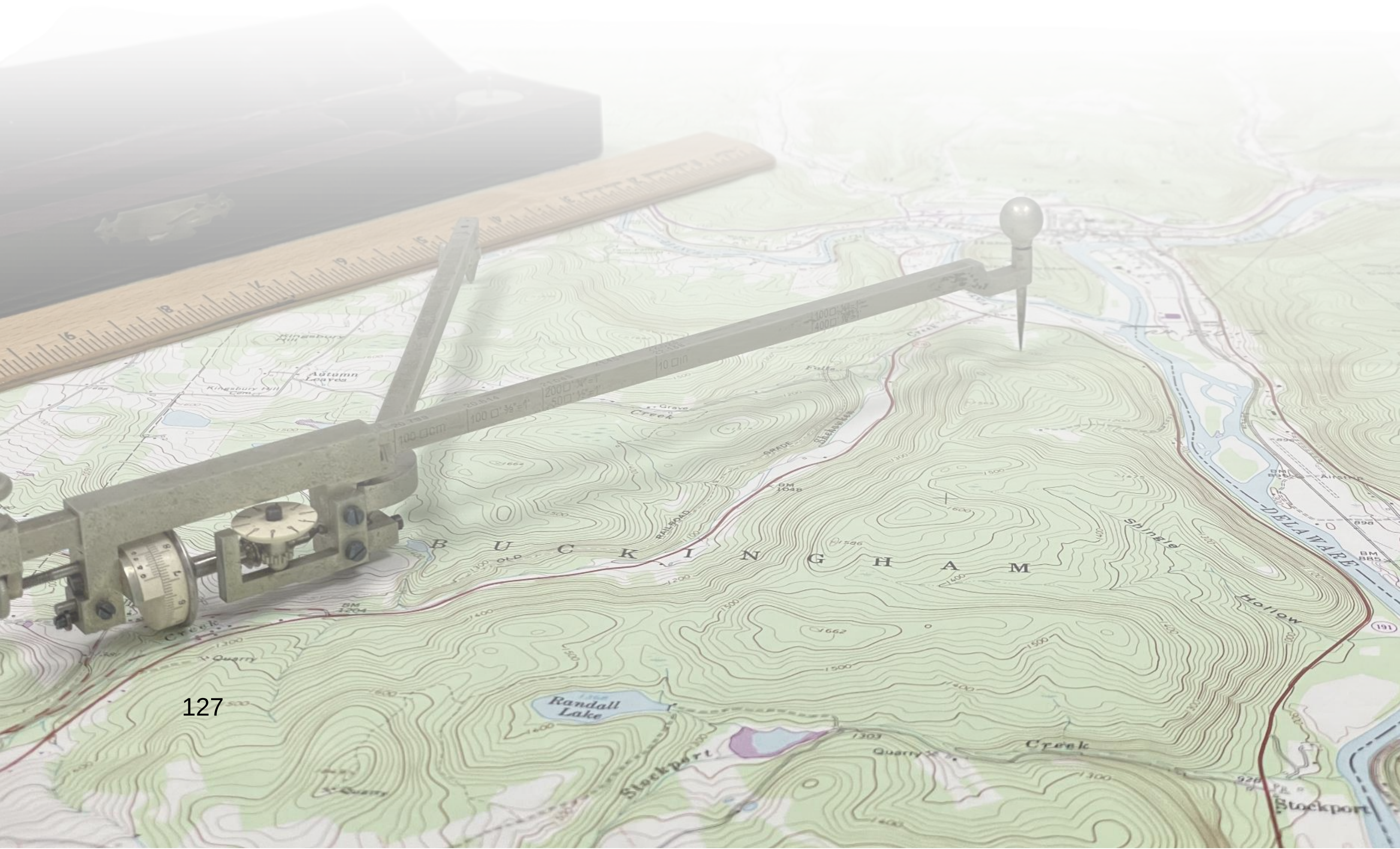


***Figure 57**: Surface water temperature data collected at the 52 USGS gaging stations shown in Figure 56. Each box represents the distribution of 52 monthly averages, each average calculated from a respective stations' period of record between 2012-2021.*

Wing Dam on The Delaware River
Lambertville New Jersey on the left and
New Hope Pennsylvania on the right.
Credit: © James Loesch
Used with permission



10. PHYSIOGRAPHIC ANALYSES

A recent draft publication in support of a revision to the New Jersey State Water Plan concluded that within New Jersey, there was statistically higher real water losses for water supply systems in the northern physiographic provinces (bedrock areas) versus systems in the southernmost physiographic province, the Coastal Plain (Van Abs & Drabik, 2022). While the study did not directly address the causes for these differences, the authors did suggest that higher real losses in the northern physiographic provinces could be related to factors such as higher pressure zones to overcome elevation differences within the service areas, system age, or even the validity of data. Consequently, it has then been realized by the authors of this report that one characteristic of public water supply systems which has not been studied in detail, especially in terms of its relationship to water loss and conservation, is the elevation differential within the footprint of the service area.

10.1. Physiographic description

The Delaware River Basin is comprised of two physiographic divisions: (1) the Appalachian Highlands, which has four physiographic provinces, and (2) the Atlantic Coastal Plain, which has a single physiographic province within the Basin (as shown in Figure 58). These physiographic provinces vary considerably in topography, geology, and hydrology, which create characteristic land development patterns in each section (Fischer et al., 2004) and as one might imagine, in turn also influence the existence and extent of public water supply systems. As briefly summarized in Byun et al., 2019:

1. **The Appalachian Highlands** consist predominantly of consolidated sedimentary rock. This area includes four provinces, each of which has distinctive geology, landforms, and hydrologic characteristics.
    - Appalachian Plateau. This area is largely comprised of the Catskill and Pocono Mountains, where rivers and streams have carved deep and narrow valleys through folded shales and sandstone. The highest point in the Delaware River Basin is also the highest point in the Catskill Mountains, atop of Slide Mountain at an elevation of around 4,180 feet above mean sea level (amsl); the western slope drains to the headwaters of the Neversink River in a valley around 2,380 feet amsl. The highest point in the Pocono Mountains is also within the Delaware River Basin, Kistler Ledge at an elevation of 2,215 feet amsl.
    - Ridge and Valley. The northern portion contains series of long forested mountain ridges, while the southern portion is a broad lowland with rolling hills called the “Great Valley”. A visualization of the aspect ratio between the Ridge and Valley can be seen as Figure 59, noting that the Appalachian trail tracks along the top of a ridge.
    - Highlands. This is characterized by extensive forested hills and ridges drained by a network of steep, rocky streams.
    - Piedmont. Widespread branching streams, rolling hills and good agricultural soils cover low yielding sedimentary and crystalline rock.

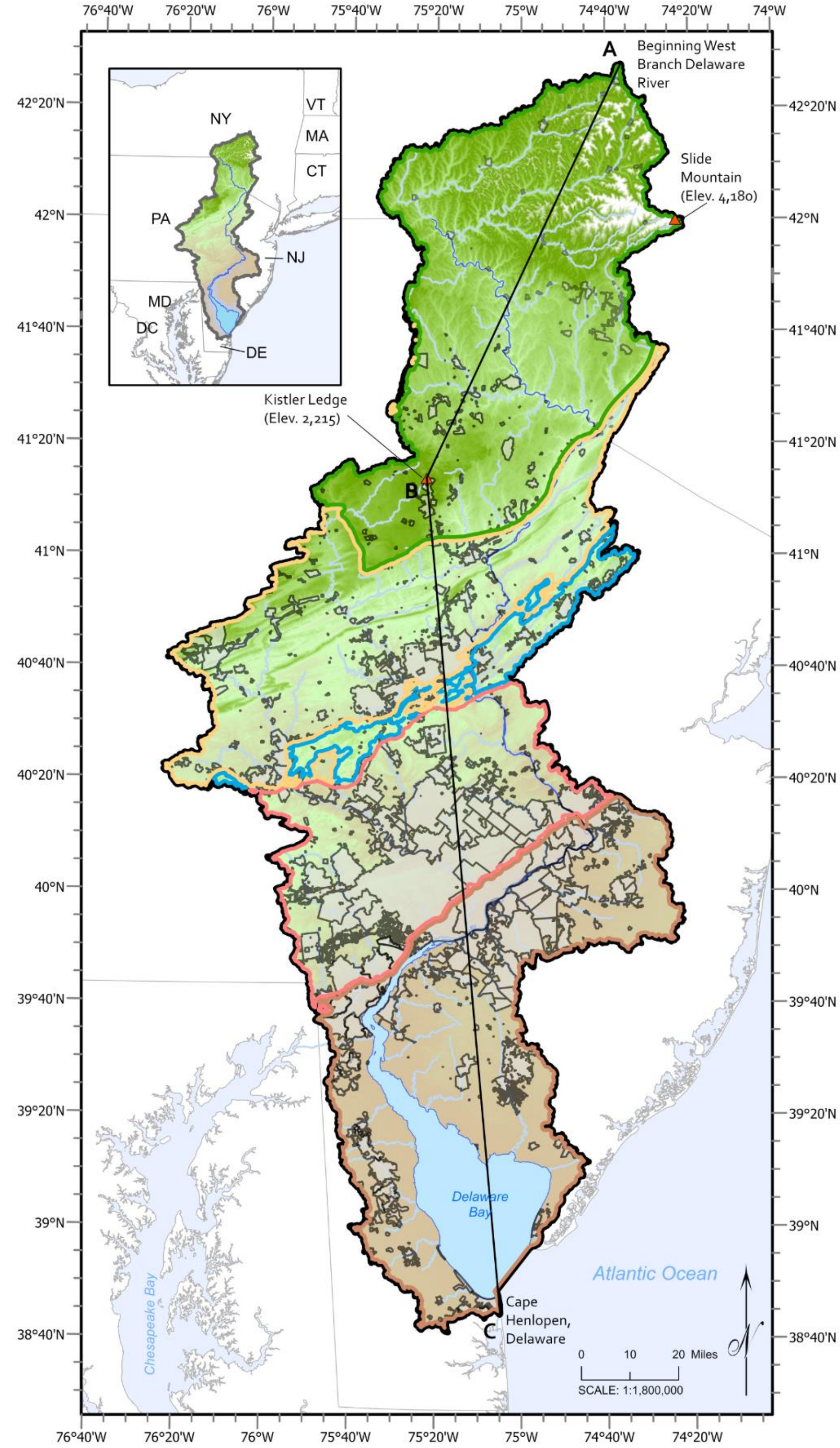


***Figure 58**: The Delaware River Basin showing elevation (USGS 1/3 arc-second digital elevation map), physiographic province outlines, and the outlines of public water supply service areas as semi-transparent grey shapes in NJ (NJDEP, 2019), NY (NYSDOH, 2021), and PA (PADEP, 2020). Note that service areas for Delaware have been previously accepted as CPCN boundaries (DE PSC, 2021); however, DRBC contacted private utilities in Delaware to obtain more accurate boundaries. CPCN boundaries remained for municipal authorities, aside from one which required use of the municipal boundary.*

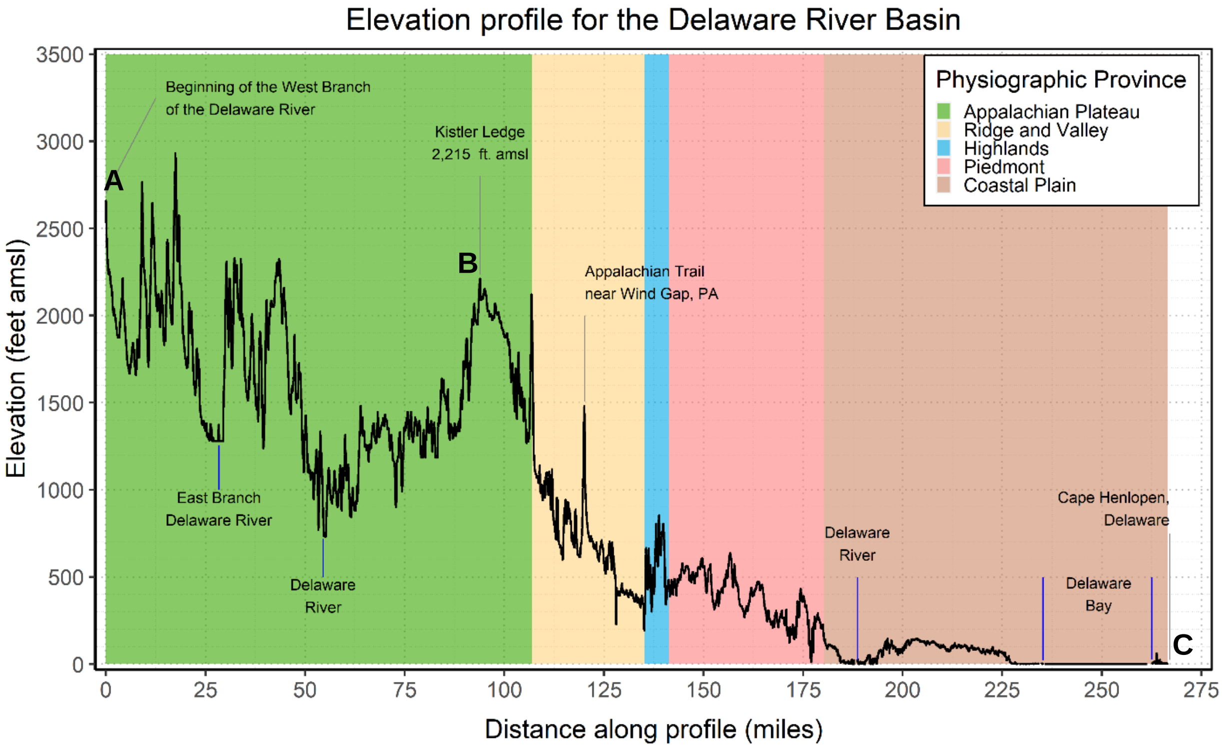


***Figure 59**: The elevation along profile A-B-C shown on Figure 58, transecting the Delaware River Basin across all five physiographic provinces. Useful landmarks are labelled, as well as locations where the transect crosses the Delaware River and Bay.*

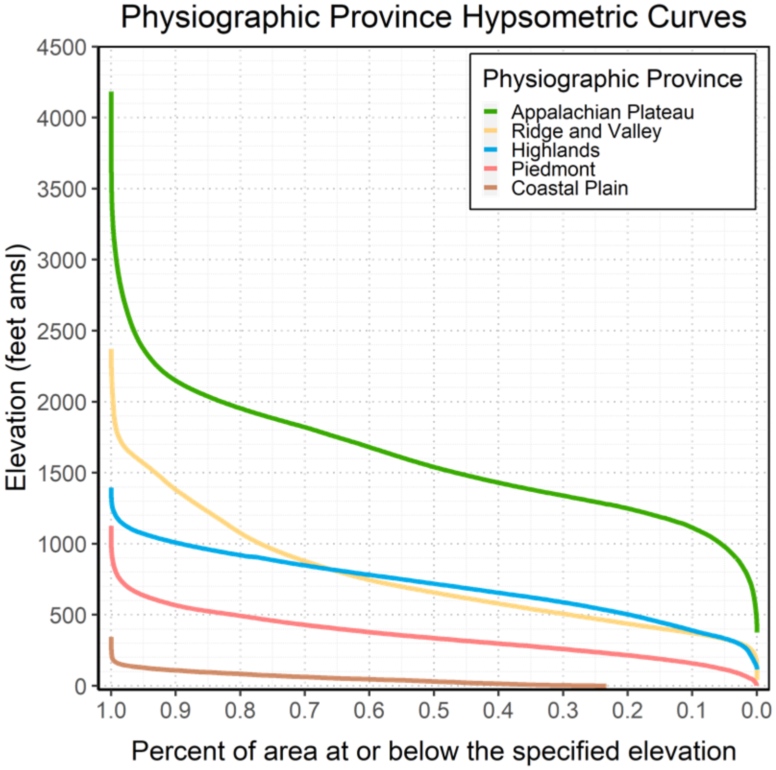


***Figure 60**: The hypsometric curves for each of the physiographic provinces within the Delaware River Basin, calculated using the USGS 1/3 arc-second digital elevation map restricted to each physiographic province.*

***Table 23**: Population summarized by physiographic province; population data obtained from the USEPA 2010 dasymetric population dataset (USEPA, 2016b), as was shown in Figure 3.*

Province	Area (mi^2)	Population	Density (per. / mi^2)
Appalachian Plateau	4,119	295,010	72
Ridge and Valley	2,737	1,269,892	464
Highlands	538	225,443	419
Piedmont	2,323	2,886,727	1,242
Coastal Plain	3,893	3,593,985	923
Total:	13,611	8,271,057	--

2. **<u>The Atlantic Coastal Plain</u>** consists of a southward dipping and thickening wedge of unconsolidated sediments underlain by bedrock and overlain by a veneer of local surficial sediments (dePaul et al., 2009). The deposits consist of alternating aquifers and confining layers, ranging from about 50 feet thick near the Delaware River to over 6,500 feet thick near the Atlantic Ocean, and generally striking northeast-southwest and dipping 10–60 ft/mi to the southeast (Zapecza, 1989). According to the analysis presented in Thompson et al., 2022, generalized surficial geology thickness can be determined by assessing the geologic descriptions provided in NJDEP, 2007; this assessment shows that deposit thicknesses are typically less than 50 feet (about 95% of New Jersey Coastal Plain area).

An elevation profile along transect A-B-C in Figure 58 is presented as Figure 59, and highlights some of the physiographic differences between the regions. However, the profile only shows one transect across the Basin. A broader analysis of the entire area within each province may also help portray how different the regions are and help explain the different challenges faced by public water supply systems within each province. The raster data obtained from the USGS has a resolution of 1/3 arc-second, meaning that each square pixel is about 10 meters dimensionally (or about 30 feet) (USGS, 2019). A count of the pixels at each elevation allows a hypsometric curve to be generated for each province, shown in Figure 60, quantifying the percent of area within a province at or below a particular elevation. Hypsometric curves are a long established analysis for assessing the stage of geologic development of a drainage basin (Strahler, 1952). While the area of each province is not related to specific watershed boundaries, the hypsometric curves help show how the Appalachian Plateau experiences (on average) much higher relief as compared to all other provinces. When considering how physiography can influence the location of human habitation, it is then not surprising that the population density of the Appalachian Plateau is substantially lower than any other province (Table 23).

10.2. System physiographic characteristics

The service areas for public water supply systems within the Delaware River Basin are presented in Figure 58. There is one primary difference between these services areas and those presented in previous DRBC work, which is related to the areas within Delaware. Due to the availability of statewide data, Thompson & Pindar, 2021 presented areas for CPCNs (Certificate of Public Convenience and Necessity) which are similar to water supply service areas, but not necessarily

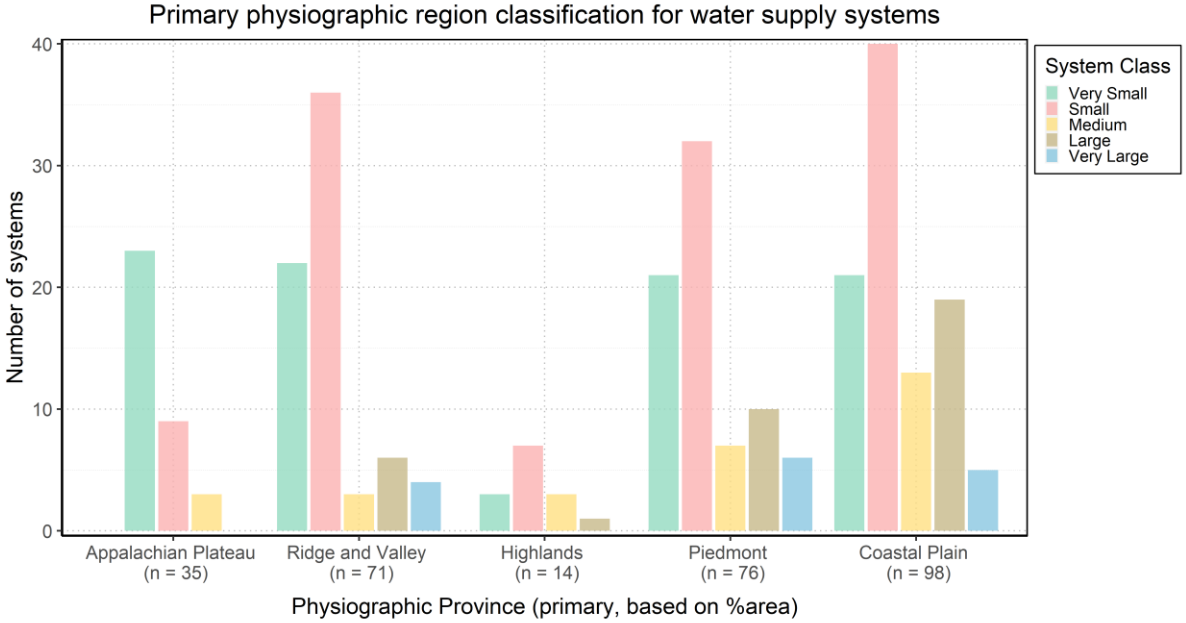


***Figure 61**: The service area for systems in this AWWA FWAS analysis were assigned a "primary" physiographic province based on a percent area method (n=294).*

the same (for example, some may be strictly related to wastewater, or some may have yet to be supplied and are only permitted). This study contacted private utility companies directly to obtain accurate service area boundaries, and only used the CPCN boundaries for known municipal water works; in one circumstance the municipal boundary was used as the service area.

Of the 300 systems considered for CY2021, 294 are able to be linked to service areas within the respective datasets shown in in Figure 58. A "primary" physiographic province has been assigned to each system within this study based on a percent area approach, for which the results are shown in Figure 61. Furthermore, it is possible to assess service connection density by physiographic province, as shown in Figure 62. Looking at the figures together, the Appalachian Plateau generally has smaller and more expansive systems with a median connection density of about 50 connections per mile of main (consistent with the lower population density shown in Table 23). The median connection density values for the remaining four provinces range between 60-75 connections per mile of main.

Analyzing the Digital Elevation Map (DEM) 1/3 arc-second data underlaying each system service area, it is possible to calculate a new useful statistic: the total elevation differential within a service area (Figure 63). The northernmost three provinces have the highest median service area elevation differential of approximately 123 feet (Appalachian Plateau), 115 feet (Ridge and Valley), and 139 feet (Highlands). Systems within the Piedmont returned a median elevation differential of about 78 feet, while systems within the Coastal Plain returned a median elevation differential of about only 25 feet. Considering the large discrepancies in population density (Table 23), elevation differentials within a service area can be normalized by service area size as shown by Figure 63.

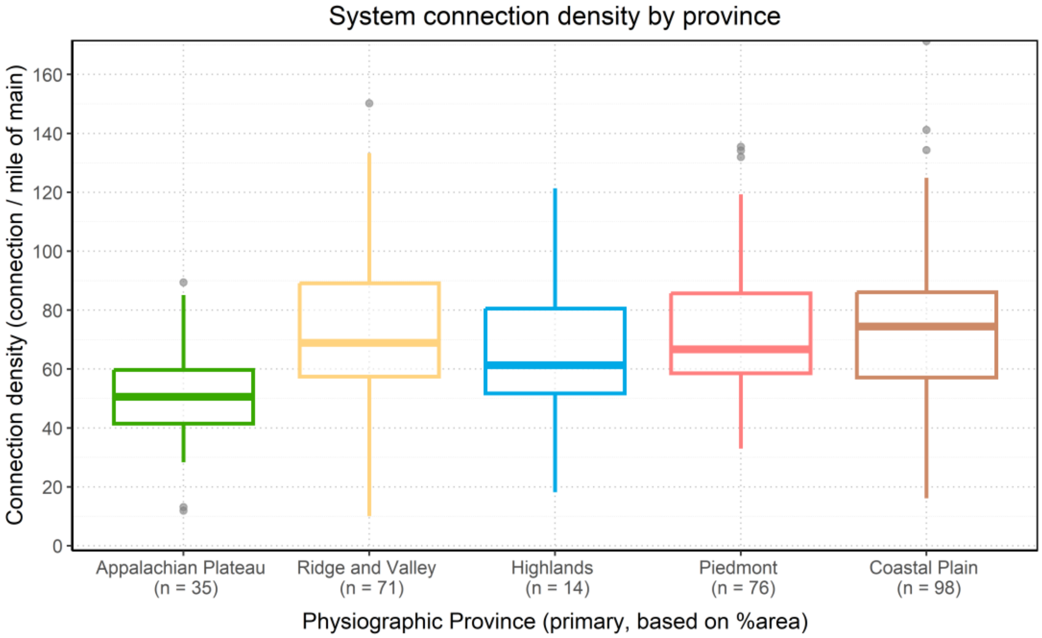


***Figure 62**: System connection density (connections per mile of main) grouped by physiographic province, which was assigned based on a percent area analysis. Note that there are a few points which plot beyond the y-axis limit, which has been restricted for viewing simplicity.*

10.3. Limitations of GIS analysis

The northern three provinces have significantly higher elevation differentials within service areas than do the Piedmont, and the Coastal Plain. However, it should be noted this analysis has its limitations and may overestimate the elevation differential experienced by the system infrastructure as compared to the elevation differential found within the service area footprint. In mountainous areas, population centers which rely on public water supply are more likely located in the valleys, and therefore the distribution infrastructure may have no need to travel up the ridges or mountains (or it may not be feasible). For example, if a service area is not delineated by offsetting a GIS layer of distribution pipes but by bounding a geographic footprint based on customer connections, it may end up including mountains or ridges where pipes are not actually present (thereby overestimating the elevation differential). It is assumed that error in the opposite direction (e.g., valleys) is less common and less extreme in magnitude, and that error is overall skewed towards overestimation. With these limitations in mind, the authors still consider the results presented in by Figure 63 to be meaningful and consistent with expectations based on analyses of population density and elevation within each province.

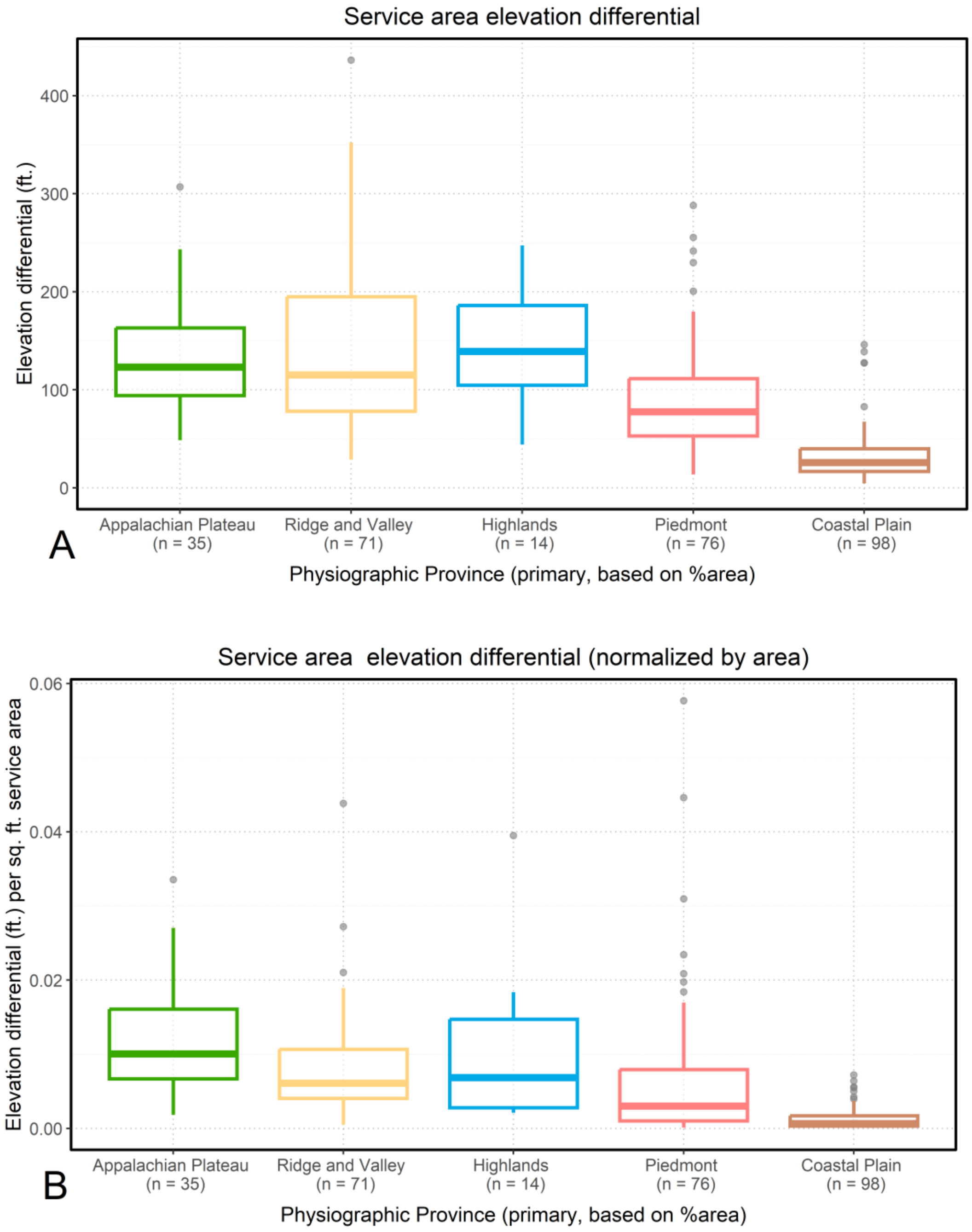


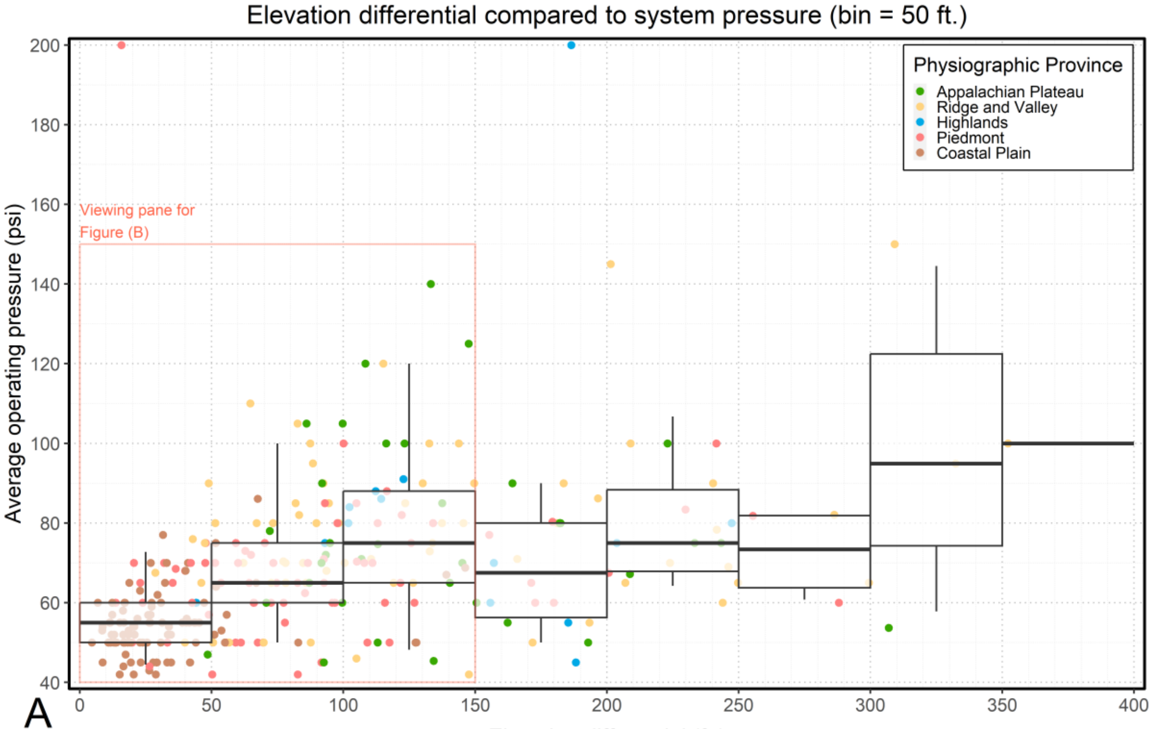
***Figure 63**: Elevation differentials within water supply service areas, grouped by physiographic province, which was assigned based on a percent area analysis. **(A)** Service area elevation differential, and **(B)** elevation differentials normalized by the size of the service area.*

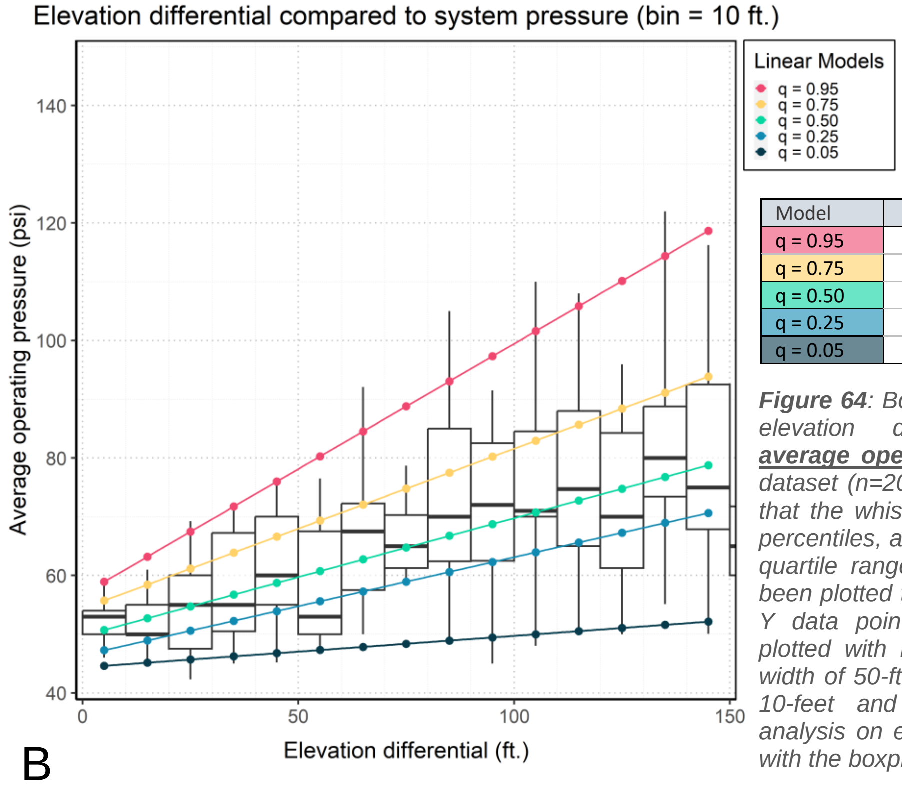
10.4. Relationship to system pressure

Using this new parameter of elevation differential, it is intuitive that some relationship may exist with the average operating pressure for the system (e.g., with higher elevation gain *may* come higher average pressure). An analysis investigating this relationship is shown as Figure 64A, where individual system points are color coded by physiographic province. The dataset used in this model was restricted to the filtered dataset of n=209 for CY2021 (DRB.f-2021). While the individual points may not suggest a strong relationship, binning the points into "groups" of elevation difference and overlaying boxplots help identify general relationships (for example, between the elevation differential "bin" and the median operating pressure for systems in that "bin"). In Figure 64A, the bins of elevation differential were set at 50-feet, and it appears that there is a strong relationship for the first 150 feet of elevation gain, but then the increase in pressure plateaus. This is theorized for two reasons:

1. **Limits of analysis**. As discussed previously, the elevation differential calculated within the service area is used as a proxy for elevation differential experienced within the distribution network. The actual location of distribution mains may or may not reach the extremes of the elevation differential within the service area. In some specific cases where there are high relief areas and population centers may be located in valleys, it is likely that the service area elevation differential is an overestimate. If this is the case, it is possible that points to the far right in Figure 64A would start to move left if corrected, which may end up making the plateau less elongated.
2. **Limits on operating pressure**. There are physical limits on what pipes can carry in terms of pressure, operational goals to reduce excess leakage, and even regulatory limits on the pressure which can be delivered to customers. Therefore, it is understandable and even expected that a plateau should occur in an analysis such as this. For example, Pennsylvania code states that utilities should maintain normal operating pressures in the range of 25-125 psi at the main (52 Pa. Code 65.6). While it does not appear that all states within the Delaware River Basin have upper limits on water pressure within mains, the International Residential Code (IRC) which is widely used throughout the United States indicates that pressure entering residential properties should not be more than 80 psi, or a pressure-reducing valve shall be installed on the domestic water branch main or riser at the connection to the water service pipe (IRC, 2018).

Understanding the limitations of the GIS analysis and findings presented in Figure 64A, a second analysis is presented in Figure 64B examining the relationship between the service area elevation differential (SAED) and the average system operating pressure (P_{AO}). The bin size for this analysis was reduced from 50 feet to 10 feet of elevation differential. Each quantile of the boxplot was treated as a separate linear regression, and all but the 5th-percentile yield very strong statistical relationships. Each equation was calculated using the mid-point of the individual boxes as the independent variable, and the respective quantiles as the dependent variables. It is notable that the 95th-percentile equation remains below 125 psi (logical based on the reference to Pennsylvania code), and that the median value is near the IRC maximum residential pressure of 80 psi. It is suggested that these equations be used where the SAED < 150 feet, and that the actual SAED be rounded to the nearest SAED interval (i.e., from=5, to=145, by=10).





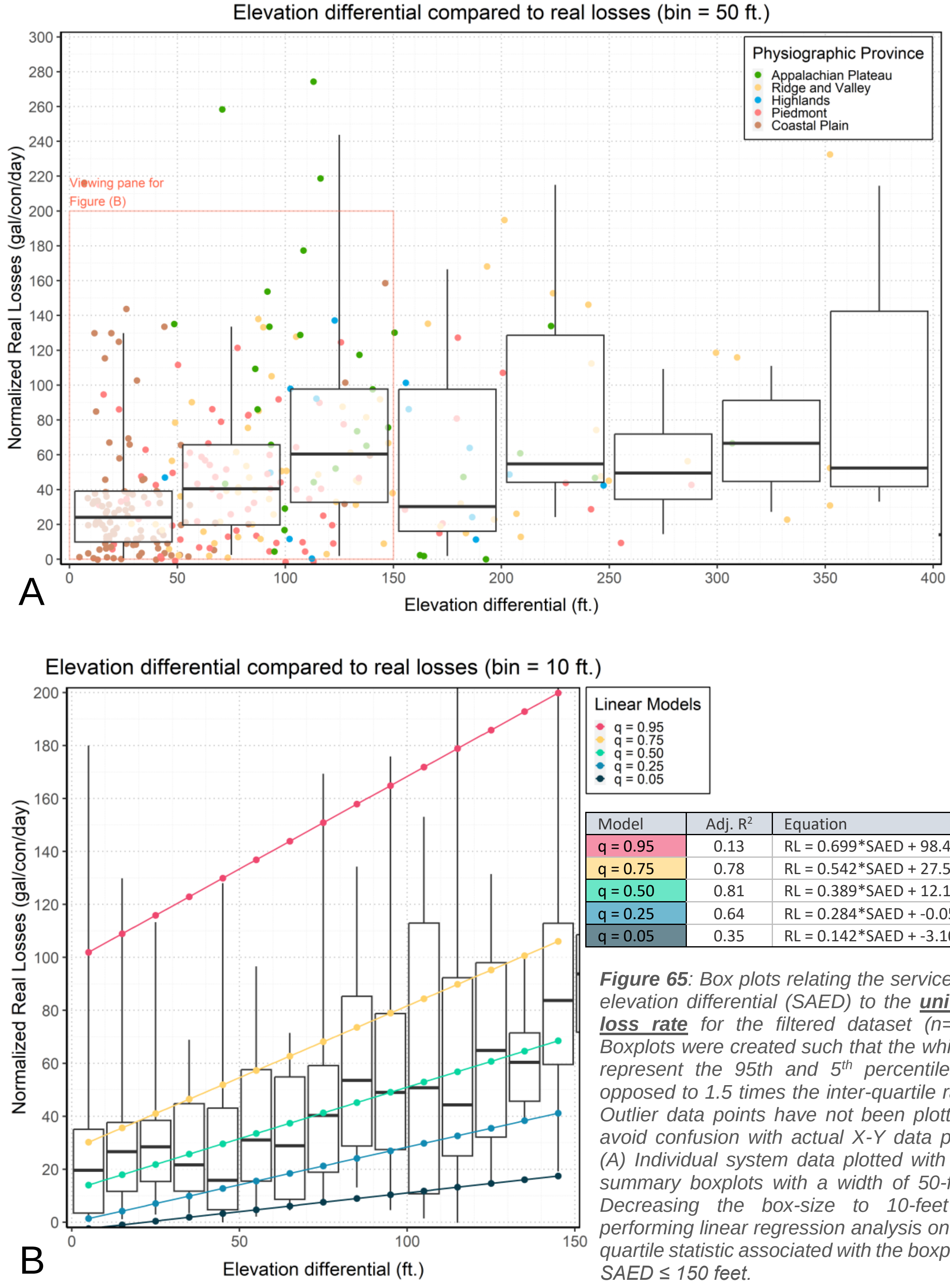
Model	Adj. R^2	Equation
q = 0.95	0.87	P = 0.427*SAED + 56.798
q = 0.75	0.92	P = 0.272*SAED + 54.363
q = 0.50	0.86	P = 0.200*SAED + 49.712
q = 0.25	0.81	P = 0.167*SAED + 46.432
q = 0.05	0.28	P = 0.054*SAED + 44.354

***Figure 64**: Box plots relating the service area elevation differential (SAED) to the **average operating pressure** for the filtered dataset (n=209). Boxplots were created such that the whiskers represent the 95th and 5th percentiles, as opposed to 1.5 times the inter-quartile range. Outlier data points have not been plotted to avoid confusion with actual X-Y data points. (A) Individual system data plotted with large summary boxplots with a width of 50-ft. (B) Decreasing the box-size to 10-feet and performing linear regression analysis on each quartile statistic associated with the boxplot for SAED ≤ 150 feet.*

10.5. Relationship to real losses

The unit real losses for each system (gcd) are plotted in relation to the calculated SAED in Figure 65A. The dataset used in this model was restricted to the filtered dataset of n=209 for CY2021 (DRB.f-2021). Similar to assessing the pressure, it is suggested here that more accurate information on SAED would likely shift many points on the right of the chart, to the left – again this analysis is cut-off at 150 feet of elevation differential. The bin interval is decreased to 10-feet, and linear trends are computed for each of the probability intervals shown in Figure 65B. Again, the boxplots were calculated where the whickers represent the 5th and 95th percentiles, as opposed to 1.5 times the inner-quartile range (IQR). As pressure is such a large driver of system leakage, it is not surprising to see similar trends in the data.

The data presented in Figure 65B suggests that there are decent statistical relationships between SAED and the 25th, median and 75th percentiles (the IQR). At the lower end with 0 - 10 feet of elevation differential, the IQR real loss rate is modeled to be between 1.5 - 30 gcd; at the higher end with 140 - 150 feet of elevation differential, the IQR real loss rate is modeled to be between 41 - 106 gcd. The model for the 5th percentile in the first elevation range is about -2 gcd and is considered a lower bound of zero. Over the range of elevation differentials, the 5th percentile trend therefore only suggests a change of about 0 – 17 gcd, whereas the 95th percentile ranges between 100 – 200 gcd. Overall, the data for a real loss rate at any specific elevation differential has a large range between the percentiles, which is expected because SAED (as a proxy for system infrastructure elevation differential) is not the sole driver affecting system leakage. The expansion of the IQR from low SAED to high SAED is substantially less than the expansion of the range between the 5th - 95th percentiles. It is likely that analyses such as this are regionally specific, and therefore the utility of such plots is currently unknown. Given a lack of data for a hypothetical system (aside from elevation differential), there is a large discrepancy in real loss rate depending upon the percentile curve selected. It is suggested that future research may find additional and more regionally specific methods for relating real loss rates to the elevation differentials within service areas.



Model	Adj. R^2	Equation
q = 0.95	0.13	RL = 0.699*SAED + 98.415
q = 0.75	0.78	RL = 0.542*SAED + 27.501
q = 0.50	0.81	RL = 0.389*SAED + 12.105
q = 0.25	0.64	RL = 0.284*SAED + -0.054
q = 0.05	0.35	RL = 0.142*SAED + -3.104

***Figure 65**: Box plots relating the service area elevation differential (SAED) to the **unit real loss rate** for the filtered dataset (n=209). Boxplots were created such that the whiskers represent the 95th and 5th percentiles, as opposed to 1.5 times the inter-quartile range. Outlier data points have not been plotted to avoid confusion with actual X-Y data points. (A) Individual system data plotted with large summary boxplots with a width of 50-ft. (B) Decreasing the box-size to 10-feet and performing linear regression analysis on each quartile statistic associated with the boxplot for SAED ≤ 150 feet.*

11. CONCLUSIONS

11.1. Summary

Public water supply within the Delaware River Basin is an essential undertaking which provides drinking water to an estimated 7.366 million people residing within the Delaware River Basin (approximately 85% of the total estimated in-Basin population based on 2020 U.S. Census Bureau data). The most recent year of data analyzed in this report is 2021, during which 300 systems were required to submit annual water audits to DRBC, representing 328 Public Water System Identification numbers (PWSID), over 29,000 miles of water main and 2.506 million active and inactive service connections. While not all individual sources and customers may be within the Basin, (although the vast majority are) the systems collectively withdrew 779 million gallons of water per day (MGD) from their own sources (per AWWA water audit reports).

The AWWA Free Water Audit Software implements a “top-down” approach to calculating water losses within a water supply system, meaning it starts with high level data such as the volume from own sources, and downscales to back-out the components such as real losses or authorized consumption. It was highlighted in Section 2 of this report that there has been a long-standing community of research focused on the issue of water loss reduction, starting with the advent of “unaccounted-for water” in the early 1900s made possible by the onset of customer metering. Seminal work almost a century later in the 1990s led to standardized international terms (replacing unaccounted-for water with non-revenue water) and standardized methods for calculation (the top-down water balance). These methods have been adopted in part by the AWWA since the early 2000s, and as such most data in this report is consistent with those standard practices.

Collection of water audit data from CY2021 marked 10 years of data collection through the Delaware River Basin Commission’s water auditing program (2012-2021). Data has been collected in multiple versions of the AWWA software; consequently, it was shown in Section 3 of this report that care must be taken to normalize datasets for consistency (as reasonably as can be done). The major aspects of quality control / quality assurance (QA/QC) undertaken included backfilling missing data for an accurate representation of volumetric trends, and filtering data based on metric thresholds to more accurately represent trends of Key Performance Indicators (KPIs). However, it is important to note that data collected by DRBC have not been “Level 1 Validated” according to the AWWA recommended practice. The subsequent five sections of the report each dealt with different aspects related to the water audit data – the primary findings are summarized in the list below.

§4. WATER AUDIT ANALYSIS (2021)

There were 282 water audits submitted to DRBC, and 18 reports were backfilled from prior years. Systems withdrew an estimated average of 779 million gallons per day (MGD) from their own water supply sources. As many systems are interconnected, cumulative exports (60 MGD) and imports (76 MGD) suggest a net import of about 16 MGD. Therefore, the total volume of water supplied by these systems is estimated to average 795 MGD. The fifteen largest systems in the Basin had a cumulative water supplied volume of 513 MGD, which is approximately 65% of the total 795 MGD. It was shown that 53% of the water supplied is attributed to 77 reports with high data validity (Tiers IV and V), that 37% is attributed to 125 reports with moderate data validity (Tier III), and that 10% is attributed to 98 reports on the low end of data validity (Tiers I and II). The total estimated real loss volume was 182 MGD, and the total estimated apparent loss volume is 27 MGD; additionally, unit real and apparent losses (gallons per connection per day) were analyzed by system class.

The top three priority areas for improving the DVS of water audit reports submitted in CY2021 using AWWA FWAS v6.0 were analyzed. The three data inputs most cited as potential areas for improvement are the volume from own sources (VOS), the billed metered authorized consumption (BMAC), and the customer metering inaccuracies (CMI). Specifics of the data grading for these three inputs were investigated further, highlighting what interactive data grading question may have limited the score of each parameter.

§5. WATER AUDIT DATA TRENDS (2012-2021)

There were 2,755 water audits submitted to DRBC over the ten-year period, resulting in an overall compliance rate of 91%, meaning that 265 reports (in various years) were backfilled with data from adjacent years. Over the last 10 years, the trend in VOS has been largely stable hovering around a mean value of about 772 MGD; this data was shown to have very strong agreement with source-level monthly withdraw data reported to respective state agencies (ratios > 0.95 annually). The volume of real losses has remained relatively constant between 150-175 MGD (CY2012-CY2019) and showed a slight increase in the past two years (CY2020-CY2021). It was hypothesized that these increases could be related to: (1) implementation of AWWA FWAS v6.0, (2) impacts of the COVID-19 pandemic, and (3) climatic variables such as low temperatures which may affect rates of pipe bursts. Of these hypotheses, the impacts of the COVID-19 pandemic seem the most promising – although additional research is needed to confirm any of the hypotheses. Unit real loss rates did not show any significant trends Basin-wide, or in individual system classes. Apparent loss volumes appeared to have a decreasing trend but was shown to be attributed to Systematic Data Handling Errors (SDHE) and whether or not default calculations were available in the specific version of the AWWA FWAS. Comprehensively, non-revenue water (NRW) did not show any specific trends Basin-wide.

§6. REAL LOSS ANALYSES

Two assessments of Basin-wide Real Loss Reduction Potential (RLRP) were performed using CY2021 water audit data:

i. A frontier analysis was used to compare system performance against each other by developing a multivariate model for estimating real loss based on the four parameters of the standard UARL equation (N_c, L_m, Psi, L_p). The ratio of observed/predicted (O/P) real losses was used to establish performance frontiers as Average (50th percentile), Good (25th percentile) or Very Good (10th percentile). A fourth frontier was established based on the observed real loss to the calculated UARL using the standard UARL equation. The RLRP for each frontier was calculated assuming that systems performing worse than the frontier (an observed real loss higher than the specific O/P ratio) would improve to frontier (decrease observed real losses to lower the O/P ratio).

ii. The Infrastructure Leakage Index (ILI) was used in a similar fashion where ten frontiers were established (ILI=10 through ILI=1). A RLRP was calculated for each frontier where all systems above ILI=X would improve performance to that frontier by decreasing the current annual real losses (CARL).

The results between the two analyses were similar and comparable, due to the fact that the frontier analysis used the components of the standard UARL equation. The following bulleted list presents the possible reductions in real losses assuming systems above particular frontiers improved to the frontiers:

- RLRP ≈ 34,500 MG (~95 MGD) → FA "Average" Performance, ...or ILI=3
- RLRP ≈ 43,000 MG (~118 MGD) → FA "Good" Performance, ...or ILI=2
- RLRP ≈ 50,000 MG (~137 MGD) → FA "Very Good" Performance
- RLRP ≈ 52,500 MG (~144 MGD) → FA "UARL" Performance, ...or ILI=1

It was noted that given similar results, the computational effort for performing the ILI analysis is significantly lower. Notably, the FA does not capture the "theoretical limits" on real losses that ILI inherently does due to the UARL equation (although this study used the components of UARL in the FA). The use of ILI creates a relatively static set of frontiers for a system (unless the infrastructure or operating conditions change significantly), whereas creating frontiers based on the percentiles of a groups' performance will change as systems continue to improve (e.g., frontiers move lower). In either analysis, it was noted that the lowest frontiers are likely not realistic pictures as they do not account for the Economic Level of Leakage. Comparing the RLRP volumes for each ILI frontier against historical and projected water withdrawals helped to highlight that while water conservation progress has been made in the Delaware River Basin, there is still room for improvement.

§7. UARL SYSTEM CORRECTION FACTORS (SCF)

As the ILI was shown to be of significant utility in assessing possible real loss reductions and comparing system performance, a pilot study was performed based on current research related to the ILI and small water systems. Currently the UARL equation is not recommended for systems with a small number of connections ($N_c < 5{,}000$) or an average operating pressure outside of a "normal range" (about 65 psi < P < 85 psi) (Lambert, 2020). A pilot study using data for five small systems from a single organization helped show how "System Correction Factors" may be applied to appropriately adjust the UARL equation and yield more accurate estimates of the ILI.

§8. PRIVATE AND PUBLIC SYSTEMS

This study was able to separate water audit data based on "ownership type" which highlighted that of systems subject to water audit requirements in the Delaware River Basin, there are two types: (1) Local government (i.e., "public"), and (2) Private. This is the first time DRBC has been able to provide an assessment of this nature. The majority of systems in the Basin subject to auditing requirements are owned by local governments

(221 systems) and serve an estimated population of 4.694 million people (67.6%); consequently, the remaining 79 privately owned system serve an estimated population of 2.251 million people (32.4%). Based on a limited analysis of system performance, the only notable difference in unit rate of real losses was for Very Large systems. Without the capacity to investigate additional driving factors, some possible causes were mentioned, but additional research is suggested.

§9. SOURCE WATER DESIGNATION

Investigation into the designation of source water (groundwater v. surface water) as it relates to water audit data has not previously been conducted for systems in the Basin, primarily as source water designation is not data collected by the AWWA FWAS. A summary of data showed that for all system classes, real loss rates were the lowest among systems which withdrawal only groundwater. The source water designation itself is not an explanatory variable, as it is likely a function of other variables such as water temperature. The only national map of groundwater temperature located during a literature review was determined to be inadequate; therefore, a map of groundwater temperature was created for the Delaware River Basin. Median monthly groundwater temperatures were shown to range between 51-61°F in the southern portion of the Basin (<1,000 ft. amsl) and range between 47-54°F in the northern portion of the Basin (>1,000 ft. amsl). Surface water temperatures showed a consistent trend across the entire Basin with median temperature values between 36°F (January) and 71°F (July). Additional research was determined to be necessary to draw specific conclusions, although it seems possible that systems with raw water subjecting associated infrastructure to larger temperature fluctuations may correlate with increased leakage.

§10. PHYSIOGRAPHIC ANALYSES

A recent draft publication in support of a revision to the New Jersey State Water Plan concluded that within New Jersey, there was statistically higher real water losses for water supply systems in the northern physiographic provinces (bedrock areas) versus systems in the southernmost physiographic province, the Coastal Plain (Van Abs & Drabik, 2022). While the study did not directly address the causes for these differences, the authors did suggest that higher real losses in the northern physiographic provinces could be related to factors such as higher-pressure zones required to overcome elevation differences within the service areas, system age, or even the validity of data. To address the first hypothesis related to higher pressures as a result of elevation differentials, this study performed an assessment of the approximately 300 systems reporting data in CY2021. Service areas for 294 of the systems were analyzed against digital elevation maps to create a new variable termed Service Area Elevation Differential (SAED). It was noted that these are conservative estimates of elevation differential, because system infrastructure (i.e., pipes) would not necessarily be placed at the extremes of each service area. A relationship was observed between SAED and system pressure for SAED < 150 feet, and empirical linear models were developed to describe the relationship. A very similar relationship was observed between SAED and real water loss.

11.2. Key takeaways

Total water withdrawals by public water suppliers in the Delaware River Basin have decreased by about 100 MGD on average over the last 30 years (1990-2020) while the in-Basin population is estimated to have increased by approximately 1.3 million people in the same timeframe. Overall, these statistics suggest successful water conservation activities are taking place. Below are some key takeaways, while recommendations are provided in the subsequent section.

1. This study is the first of its kind, assessing a decade of water audit data compiled from water supply systems across four states, yielding insight as to how water loss control in the public water supply sector can relate to the water resources of the Delaware River Basin.

2. Drinking water is essential, and data on water loss is a critical component of water resource planning. The Delaware River Basin Compact (PL 87-328, 75 Stat. 688) states a purpose of the Commission is to "*adopt and promote uniform and coordinated policies for water conservation, control, use and management in the basin*". Through the water audit program, DRBC has compiled and now vetted a large dataset to support planning efforts at the Basin-scale.

3. The current state of water loss in the Delaware River Basin is assessed for CY2021 using data from the AWWA Free Water Audit Software reports from 300 water supply systems. The volume of water supplied by these systems is estimated to average 795 MGD, of which approximately 65% is attributed to the fifteen largest systems in the Basin. Real water losses (i.e., leakage) are estimated to be 182 MGD, of which approximately 41 MGD are estimated to be unavoidable. The projected trend in water withdrawals from the Basin by water suppliers suggests a decrease of about 28.5 MGD (2021-2060) but is not solely attributed to reduction in leakage. Ultimately, there is still room for improvement towards reducing the real losses that are above what is considered unavoidable.

4. Data suggests that the calculated real loss volume has remained relatively stable (2012-2019), with possible slight increases over the past two years. This trend should not be interpreted as a measure of "performance" for the water audit program within the Delaware River Basin – if anything, it might be considered a baseline. Since the water audit program became mandatory in 2012, the only output from the FWAS report pushing individual systems to perform better has been the knowledge it provides; those who control and operate the systems may do with that knowledge what they choose. AWWA's initiative to introduce interactive data grading in FWAS v6.0 has highlighted previous overestimates of data confidence. Continued use of this software will provide the best quality data such that those with the power to effectuate change can make informed decisions.

11.3. Recommendations

There are numerous recommendations which are being proposed, brought about either during the process of developing this report, or specifically from the findings presented in this report:

1. **Improve data validity.** It is recommended that the process of increasing the overall data validity of AWWA FWAS reports being submitted to DRBC annually be investigated, as well as the logistics for water audit report validation (e.g., Level 1 validation). Currently more than half of the reports are being submitted with a Data Validity Tier III or less (223/300), accounting for 371 MGD of water supplied, on average.
2. **Improve quality of financial data**. It was recognized during this study that financial data collected though the AWWA FWAS was less consistent and more difficult to interpret than volumetric water data (and was therefore absent from most of the report). If increasing data validity alone does not address this issue, it is recommended that alternate means of addressing the financial data component of water audits be investigated.
3. **Improve the water audit review process.** The current review practices for water audit reports submitted to DRBC is limited largely to administrative completeness and correct units. This could be expanded to include more quantitative assessments during the initial review and help improve overall data validity.
4. **Perform analyses on the Economic Level of Leakage.** It is recommended that the feasibility of performing Economic Level of Leakage analyses for the Very Large systems within the Basin be investigated. These fifteen systems collectively account for about 80% of the possible real loss reductions according to the analysis using ILI frontiers. Understanding the economic restrictions would provide a more realistic estimate for the Delaware River Basin, as currently it is understood that the frontier ILI=1 represents a theoretical minimum, and not a realistic scenario for which to plan.
5. **Incorporate System Correction Factors for UARL calculations**. Based on the results of the pilot study presented in this report, it is recommended to evaluate the inclusion of System Correction Factors (SCF) in the calculation of Unavoidable Annual Real Loss (UARL), specifically in smaller systems, but Basin-wide as appropriate. This will improve the accuracy of Infrastructure Leakage Index (ILI) calculations and thus enhance estimates for Basin-wide real loss reduction potentials.
6. **Use of UARL unit rate**. It was demonstrated that converting the UARL to a unit rate (gallons per connection per day) may be a useful KPI, especially when used in combination with the real loss unit rate to graphically show the ILI via cross-plot. It is recommended that the UARL unit rate be considered in future analyses.
7. **Analysis of data on asset condition**. This report discussed the limited data available regarding the condition of system assets. Of specific interest, data on the age and material of pipes for each system (or similar data) may be helpful in future planning analyses. It is recommended that the means of compiling such data be investigated.
8. **Analysis of operational pressure variation data**. It is known that pressure can vary spatially and temporally within a system, and that while useful, the average operating

pressure of a system has inherent assumptions and limitations. It is recommended that additional data variables related to system pressure be investigated as a means of improving upon P_{AO}. Some possible variables for consideration are listed in this report.

9. **Possible modifications to AWWA software:**
    a. It is recommended that the AWWA FWAS collect information related to the personnel compiling the data and filling out the report, including data such as *name*, *occupation* (e.g., Engineer, Licensed Operator, Town Clerk, Administrative Assistant) and *certification* (e.g., state licenses, if applicable). Currently the software has an input field on the Start Page for "Name of Contact Person", for which it has been observed may or may not be the person completing the report.
    b. It is recommended that a method for reporting multiple systems at once be investigated to help reduce data entry error. Organizations responsible for multiple systems may have spreadsheets of data required for input, each data point which is then copied and pasted into a workbook. It may be helpful to have a "reverse compiler" which would populate multiple reports given columns of data for the input variables, or a an AWWA FWAS version tailored for entering tabular data related to multiple systems.
    c. It is recommended that the compiler extract whether or not the default value was used, and if not, what percentage was entered. The current compiler does not consistently do this for all parameters (e.g., VOS MMEA, Import MMEA, Export MMEA, UUAC, UC, CMI and SDHE). Calculating non-default percentages with data extracted in the compiler often resulted in rounding issues. Additionally, it is also difficult to distinguish where data has not been entered, versus where a zero value has been entered, as the compiler reports both as a zero value.

10. **Investigate impacts on leakage due to COVID-19.** It is recommended that research investigating whether or not the COVID-19 pandemic impacted a redistribution of water consumption within the Delaware River Basin would be insightful, focusing on the relationship to real water loss (leakage), assessing whether or not the impacts will remain, and if so to what degree. It is assumed that such research would require more localized assessment and require system specific data not available through the AWWA FWAS (e.g., end-use statistics such as residential vs. non-residential properties, main and service line breaks).

11. **Investigate financial and equity impacts of water loss.** In many cases, ratepayers are directly impacted by the level of real losses within a system; however, the details of who are impacted and by how much are likely system-specific and not always widely available. Investigating how reductions in real losses would affect ratepayers financially and equitably is recommended as a worthwhile endeavor.

12. **Investigate the relationship between source water temperature and leakage.** It is recommended that additional research on sourcewater temperature and the possible impacts on system infrastructure and leakage may be beneficial, including the possibility of temperature impacts from water storage on a more localized timescale.

13. **Update the national groundwater temperature map.** The commonly referenced national map of groundwater temperature appears to be outdated (both age and method) and would benefit from being updated; consequently, more consistent data on groundwater temperature would be beneficial for such an analysis.

12. REFERENCES

16 Del. Admin. C §4462. *Public Drinking Water Systems*. https://regulations.delaware.gov/AdminCode/title16/Department%20of%20Health%20and%20Social%20Services/Division%20of%20Public%20Health/Health%20Systems%20Protection%20(HSP)/4462.shtml

25 Pa. Code §109. (1971, September 2). *Chapter 109. Safe Drinking Water*. https://www.pacodeandbulletin.gov/Display/pacode?file=/secure/pacode/data/025/chapter109/chap109toc.html

25 Pa. Code §65.20. *Water conservation measures—statement of policy.* https://www.pacodeandbulletin.gov/Display/pacode?file=/secure/pacode/data/052/chapter65/s65.20.html

347 U.S. 995. (1954). *New Jersey v. New York.* U.S. Supreme Court.

52 Pa. Code 65.6. *Chapter 65: Water Service, Section 6: Pressures*. https://www.pacodeandbulletin.gov/Display/pacode?file=/secure/pacode/data/052/chapter65/chap65toc.html&d=reduce

7 Del. Admin. C §7303-4.3. *Regulations Governing the Allocation of Water: Section 4.3 Water Conservation Requirements*. https://regulations.delaware.gov/AdminCode/title7/7000/7300/7303.shtml

Alegre, H., Baptista, K., Cabrera Jr, E., Cubillo, F., Duarte, P., Hirner, W [Wolfram], Merkel, W., & Parena, R. (2000). *Performance indicators for water supply services* (1st ed.). *Manual of best practice*. IWA Publishing.

Alegre, H., Baptista, J. F. d. M., Cabrera Jr, E., Cubillo, F., Duarte, P., Hirner, W [Wolfram], Wolf, M., & Parena, R. (2017). *Performance indicators for water supply services* (3rd ed.). *Manual of best practice*. IWA Publishing.

Al-Washali, T. M., Elkhider, M. E., Sharma, S. K., & Kennedy, M. D. (2020). A review of nonrevenue water assessment software tools. *WIREs Water*, *7*(2), e1413. https://doi.org/10.1002/wat2.1413

Andrews, L., Gasner, K., Sturm, R., Kunkel, G., Jernigan, W., & Cavanaugh, S. (2016). *Level 1 Water Audit Validation: Guidance Manual*. WRF Project No. 4639A. Denver, Colorado. Water Research Foundation.

AWWA. (1926). *Water Works Practice. A Manual*. The Williams & Wilkins Company.

AWWA (1948). A Survey of Operating Data for Water Works in 1945. *Journal - American Water Works Association*, *40*(2), 165–260. https://doi.org/10.1002/j.1551-8833.1948.tb16280.x

AWWA (1953). A Survey of Operating Data for Water Works in 1950. *Journal - American Water Works Association*, *45*(6), 585–678. https://doi.org/10.1002/j.1551-8833.1953.tb20157.x

AWWA (1957). A Survey of Operating Data for Water Works in 1955. *Journal - American Water Works Association*, *49*(5), 553–696. https://doi.org/10.1002/j.1551-8833.1957.tb16832.x

AWWA. (1964). *A Survey of Operating Data for Water Works in 1960: Staff Report.* American Water Works Association.

AWWA. (1974). *Operating Data for Water Utilities 1970 & 1964*. AWWA Statistical Report No. 20112. American Water Works Association.

AWWA. (1987). *Leaks in Water Distribution Systems*. A Technical/Economic Overview. American Water Works Association.

AWWA. (1990). *Water Audits and Leak Detection* (1st Edition). *AWWA manual: M36*. AWWA.

AWWA. (2009). *Water audits and loss control programs* (3rd ed.). *AWWA manual: M36*. American Water Works Association.

AWWA. (2011). *VALIDATED WATER AUDIT DATA FOR RELIABLE UTILITY BENCHMARKING*. THE AWWA WATER LOSS CONTROL COMMITTEE’S WATER AUDIT DATA COLLECTION

INITIATIVE - 2011. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/VALIDATED-WATER-AUDIT-DATA-FOR-RELIABLE-UTILITY-BENCHMARKING.pdf?ver=2018-12-09-155229-227

AWWA. (2015). *2015 Establishing the Level of Progress in Utility Asset Management: Survey Results*. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Technical%20Reports/Level%20of%20Progress%20in%20Utility%20Asset%20Management%20v4.0.pdf?ver=2021-05-21-124023-250

AWWA. (2016a). *The State of Water Loss Control in Drinking Water Utilities*. A White Paper From the American Water Works Association. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/WLCWhitePaper.pdf?ver=2017-09-11-153507-487

AWWA. (2016b). *Water audits and loss control programs* (4th ed.). *AWWA manual: M36*. American Water Works Association.

AWWA. (2018). *Addendum to: AWWA Manual M6, Water Meters—Selection, Installation, Testing, and Maintenance, Fifth Edition*. Denver, Colorado. American Water Works Association.

AWWA. (2020). *AWWA Free Water Audit Software Version 6 – Evolutions.* American Water Works Association. https://www.awwa.org/Portals/0/AWWA/Nosearch/Release_Memo_v6.0.pdf?ver=2020-12-02-161533-623

AWWA. (2021a). *AWWA Free Water Audit Software v6.0*. Software. American Water Works Association. https://www.awwa.org/Resources-Tools/Resource-Topics/Water-Loss-Control

AWWA. (2021b). *AWWA Water Audit Reference Dataset (WARD)*. (Microsoft Excel spreadsheet and reference document). Denver, Colorado. American Water Works Association.

AWWA. (2023). *Level of Progress in Utility Asset Management: Survey Results*. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Technical%20Reports/Level%20of%20Progress%20in%20UAM%20Survey%20Results.pdf?ver=2023-07-27-153358-613

Bakchan, A., Roy, A., & Faust, K. M. (2022). Impacts of COVID-19 social distancing policies on water demand: A population dynamics perspective. *Journal of Environmental Management*, *302*(Pt A), 113949. https://doi.org/10.1016/j.jenvman.2021.113949

Barfuss, S. L., Johnson, M. C., & Neilsen, M. A. (2011). *Accuracy of in-service water meters at low and high flow rates*. WRF Project #4028. Water Research Foundation.

Bennevelli, L. M. (1978). Accounting for Unaccounted-for Water. *Journal of the New England Water Works Association*, *93*(2), 258–266.

Blackwell, D., Jernigan, W., Kunkel, G., & Trachtman, G. (2022). *Governmental Policies for Drinking Water Utility Water Loss Control*. Survey Results of Water Loss Control Policies. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Technical%20Reports/35392%20Governmental%20Policies_FINAL_REV.pdf?ver=2023-01-03-160429-817

Boulos, P. F., Karney, B. W., Wood, D. J., & Lingireddy, S. (2005). Hydraulic Transient Guidelines for Protecting Water Distribution Systems. *Journal - American Water Works Association*, *97*(5), 111–124. https://doi.org/10.1002/j.1551-8833.2005.tb10892.x

Brackett, D. (1904). Report on the Measurement, Consumption and Waste of Water Supplied to the Metropolitan Water District. *Journal of the New England Water Works Association*, *18*(2), 107–160.

Burke, R., Hans, L., Palmer, K. C., Spilka, B., & Schempp, A. (2022). *2022 State Policy Scorecard for Water Efficiency and Sustainability*. Chicago, Illinois. Alliance for Water Efficiency. https://www.allianceforwaterefficiency.org/2022Scorecard#:~:text=The%20Alliance%20for%20Water%20Efficiency's,was%20the%20top%20ranked%20state

Byun, S. A., Kwityn, E., Pindar, C., & Thompson, M. (2019). *State of the Basin 2019*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/about/public/SOTB2019.html

Cabrera Jr., E., Dane, P., Haskins, S., & Theuretzbacher-Fritz, H. (2011). *Benchmarking Water Services*. Guiding water utilities to excellence. *Manual of best practice*. IWA Publishing.

Carpenter, T., Lambert, A., & McKenzie, R [R.] (2003). Applying the IWA approach to water loss performance indicators in Australia. *Water Science and Technology: Water Supply*, *13*(1), 153–161.

Carr, C., & Pike, C. (1986). *Water Audit and Leak Detection Guidebook*. water conservation guidebook no. 5. Sacramento, CA. California Department of Water Resources; AWWA.

Case, E. D. (1950). Water Waste Surveys and Unaccounted-for Water. *Journal - American Water Works Association*, *42*(3), 245–248. https://doi.org/10.1002/j.1551-8833.1950.tb18840.x

Cheong, L. C. (1991). Unaccounted for Water and the Economics of Leak Detection. *Water Supply: The Review Journal of the International Water Supply Association*, *9*(3/4).

Chester, J. N., & Bankson, E. E. (1924). Leakage and Unaccounted for Water. *Journal - American Water Works Association*, *11*(2), 381–388. https://doi.org/10.1002/j.1551-8833.1924.tb14263.x

Cole, E. S., Aldrich, E. H., Allen, E. J., Auld, D., Case, A. D., Gierlich, O. A., Johnson, D. W., Kuranz, A. P., Niemeyer, H. W., Van Zandt, W. K., & Wright, H. R. (1957). Revenue-producing Versus Unaccounted-for Water. *Journal of the American Water Works Association*, *49*(12), 1587–1592 (A report of Committee 4450 D).

Cole, E. S. (1970). SURVEY FORM FOR EVALUATING WATER UTILITY OPERATIONS. *Journal - American Water Works Association*, *62*(6), 354–355. https://doi.org/10.1002/j.1551-8833.1970.tb03918.x

Collins, W. (1925). *Temperature of water available for industrial use in the United States: Chapter F in Contributions to the hydrology of the United States, 1923-1924*. Washington, D.C. U.S. Geological Survey. https://doi.org/10.3133/wsp520F

52 Pa. Code 65.20a.

Cook, A. T. (1939). Increasing the Efficiency of Water Systems. *Journal of the American Water Works Association*, *31*(7), 1110–1123. https://doi.org/10.1002/j.1551-8833.1939.tb12848.x

CUWCC. (2016). *Memorandum of Understanding Regarding Urban Water Conservation in California.* California Urban Water Conservation Council. https://www.mwdh2o.com/media/16987/california-urban-water-conservation-council-mou-re-urban-water-conservation-in-ca.pdf

De Cicco, L. A., Lorenz, D., Hirsch, R. M., Watkins, W., & Johnson, M. (2022). *dataRetrieval: R packages for discovering and retrieving water data available from U.S. federal hydrologic web services*. Version 2.7.12. Reston, Virginia. U.S. Geological Survey. https://code.usgs.gov/water/dataRetrieval https://doi.org/10.5066/P9X4L3GE

dePaul, V. T., Rosman, R., & Lacombe, P. J. (2009). *Water-Level Conditions in Selected Confined Aquifers of the New Jersey and Delaware Coastal Plain, 2003*. Scientific Investigations Report 2008-5145. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/sir20085145

DOE. (1992). *Using Water Wisely*. London, UK. Department of the Environment, Welsh Office.

DOE, & NWC. (1980). *Leakage Control Policy and Practice*. London. Department of Environment; National Water Council. https://dwi-content.s3.eu-west-2.amazonaws.com/wp-content/uploads/2020/10/27105844/dwi0190.pdf

DRBC. (1981). *The Delaware River Basin: The Final Report and Environmental Impact Statement of the Level B Study*. West Trenton, New Jersey. Delaware River Basin Commission.

DRBC. (1982). *Annual Report*. Ewing, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/1982AR.pdf

DRBC. (1994). *Delaware River Basin Commission Water Resources Program 1994-1995*. West Trenton, New Jersey. Delaware River Basin Commission.

DRBC. (2008). *State of the Basin, 2008*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.state.nj.us/drbc/programs/basinwide/sotb2008.html

DRBC. (2013). *State of the Basin, 2013*. West Trenton, New Jersey. Delaware River Basin Commission. https://nj.gov/drbc/programs/basinwide/sotb2013/

DRBC. (2021). *Delaware River Basin Commission Water Resources Program FY 2022-2024*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/WRPFY22-24.pdf

DRBC. (2023). *Delaware River Basin Commission Water Resources Program FY 2024-2026*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/WRPFY24-26.pdf

DRBC in prep. (2024). *Climate Change Impacts in the DRB (working title).*

Emerson, J. W., Green, W. A., Schloerke, B., Crowley, J., Cook, D [Dianne], Hofmann, H., & Wickham, H. (2013). The Generalized Pairs Plot. *Journal of Computational and Graphical Statistics*, *22*(1), 79–91. https://doi.org/10.1080/10618600.2012.694762

EPA. (2022). *Drought Resilience and Water Conservation*.

Farley, M., & Trow, S. (2003). *Losses in Water Distribution Networks: A Practitioners' Guide to Assessment, Monitoring and Control* (1st ed.). International Water Association. https://doi.org/10.2166/9781780402642

Fischer, J. M., Riva-Murray, K., Hickman,, R. E., Chichester,, D. C., Brightbill,, R. A., Romanok, K. M., & Bilger, M. D. (2004). *Water Quality in the Delaware River Basin, Pennsylvania, New Jersey, New York, and Delaware, 1998–2001*. Circular 1227. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/cir1227

Franklin, B. (1746). *Poor Richard, 1746. An Almanack For the Year of Christ 1746*. Printed and sold by B. Franklin.

Friedman, M., Kirmeyer, G., Lemieux, J., LeChevallier, M., Seidl, S., & Routt, J. (2010). *Criteria for Optimized Distribution Systems*. Denver, Colorado. Water Research Foundation.

Fuller, T. (1732). *Gnomologia: Adages and Proverbs, Wise Sentences, and Witty Sayings, Ancient and Modern, Foreign and British*. Dean's Yard, Westminster and the Red-Lion in Paternoster Row.

Hansen, S., Lambert, P. J., Bloom, N., Davis, S., Sadun, R., & Taska, B. (2023). *Remote Work across Jobs, Companies, and Space*. Working Paper 31007. Cambridge, MA. National Bureau of Economic Research. https://doi.org/10.3386/w31007

Haydock, C. (1947). Reducing Unaccounted-for Water. *Journal of the American Water Works Association*, *39*(12), 1204–1210. https://doi.org/10.1002/j.1551-8833.1947.tb18635.x

Hazen, A., Cuddeback, A. W., Blackmer, A. E., Tighe, J. L., Bettes, C. R., & Betts, P. (1916). Committee on Meter Rates. Report on Waste: To which is added suggestions for service charges for large meters. *Journal of New England Water Works Association*, *30*(4), 458–473.

Hill, N. S., Jr. (1915). Pipe Distribution Systems. *Journal of the American Water Works Association*, *2*(1), 107–159 (Part I: A Study of Considerations Regarding the Design of Pipe Distribution Systems).

Howson, L. R. (1928). Unaccounted for Water. *Journal - American Water Works Association*, *20*(3), 349–369. https://doi.org/10.1002/j.1551-8833.1928.tb13640.x

Hudson, W. D. (1978). Increasing Water System Efficiency Through Control of Unaccounted-For Water. *Journal - American Water Works Association*, *70*(7), 362–365. https://doi.org/10.1002/j.1551-8833.1978.tb04194.x

ILMSS Ltd. (2013). *CheckCalcsNZ version 4a (software)*. https://www.waternz.org.nz/Article?Action=View&Article_id=42

IRC. (2018). *2018 International Residential Code (IRD), Chapter 29, P2903.3.1 Maximum Pressure.* International Code Council. https://codes.iccsafe.org/content/IRC2018P7/chapter-29-water-supply-and-distribution

ITA. (2000). *SIGMA Lite*. (software). Grupo Mecánica de Fluidos, Instituto de Technología del Agua, Universidad Politécnica de Valencia.

ITA. (2006). *SIGMA Lite 2.0*. (software). Instituto de Technología del Agua, Universidad Politécnica de Valencia.

Jernigan, W., Kunkel, G., Trachtman, G., & Wyatt, A [Alan]. (2019). *Key Performance Indicators for Non-Revenue Water*. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/WLCCKPIReport%202019.pdf?ver=2019-11-20-094638-933

Johnson, W. S. (1907). Some New Facts Relating to the Effect of Meters on the Consumption of Water. *Journal of the New England Water Works Association*, *21*(2), 109–180.

Karl, M., Culbertson, E., Abrera, J., & Janke, R. (2022). *Utilizing Smart Water Networks to Manage Pressure and Flow for Reductions of Water Loss and Pipe Breaks*. WRF Project No. 4917.

Karney, B. W., & McInnis, D. (1990). Transient Analysis of Water Distribution Systems. *Journal - American Water Works Association*, *82*(7), 62–70. https://doi.org/10.1002/j.1551-8833.1990.tb06992.x

Kazak, J. K., Szewrański, S., Pilawka, T., Tokarczyk-Dorociak, K., Janiak, K., & Świąder, M. (2021). Changes in water demand patterns in a European city due to restrictions caused by the COVID-19 pandemic. *DESALINATION and WATER TREATMENT*, *222*, 1–15. https://doi.org/10.5004/dwt.2021.27242

Kingdom, B., Knapp, J., LaChance, P., & Olstein, M. (1996). *Performance Benchmarking for Water Utilities*. Water Research Foundation Report #164. Denver, Colorado. AWWA Research Foundation and American Water Works Association.

Kuichling, E. (1897). The Financial Management of Water-Works. *Transactions of the American Society of Civil Engineers*, *38*(2), 1–20. https://doi.org/10.1061/TACEAT.0001298

Kunkel, G. (2003). Committee Report: Applying worldwide BMPs in water loss control. *Journal - American Water Works Association*, *95*(8), 65–79. https://doi.org/10.1002/j.1551-8833.2003.tb10430.x

Lambert, A. (1994). Accounting for losses - the bursts and background estimates concepts. *J. Institution Water Environ. Mngnt.*, *8*(2), 205–214.

Lambert, A. (1999). *Rational International Comparisons of Real Losses*. Leakage Management & Measurement Seminar, IWEX, Birmingham, United Kingdom.

Lambert, A. (2001). *What Do We Know About Pressure:Leakage Relationships in Distribution Systems?* Brno, Czech Republic. International Water Association. http://www.studiomarcofantozzi.it/BRNOP4.1.pdf

Lambert, A. (2009). *Ten Years Experience in using the UARL Formula to calculate Infrastructure Leakage Index*. Cape Town, South Africa. IWA Waterloss 2009 Conference (28-30 April 2009). https://www.leakssuitelibrary.com/wp-content/uploads/2020/12/2009_LambertWaterlossCapetown-Update-8Dec.pdf

Lambert, A. (2020). *System Correction Factor SCF can customise the standard UARL equation for pipe materials, small systems and pressure: bursts relationships.* Water Loss Research & Analysis Ltd. https://www.leakssuitelibrary.com/low-ilis-and-small-systems/

Lambert, A., Brown, T. G., Takizawa, M., & Weimer, D. (1999). A review of performance indicators for real losses from water supply systems. *Journal of Water Supply: Research and Technology—AQUA*, *48*(6), 227–237. https://doi.org/10.2166/aqua.1999.0025

Lambert, A., Fantozzi, M., & Thornton, J. (2013). *Practical approaches to modeling leakage and pressure management in distribution systems – progress since 2005*. Perugia, Italy. 12th International Conference on Computing and Control for the Water Industry.

Lambert, A., & Hirner, W [W.]. (2000). *Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures*. IWA Blue Pages. International Water Association.

https://waterfund.go.ke/watersource/Downloads/001.%20Losses%20from%20water%20supply%20systems.pdf

Lambert, A., Koebl, J., & Fuchs-Hanusch, D. (2014). *Interpreting ILIs in Small Systems*. Vienna, Austria. Water Loss 2014 Conference Proceedings.

LeChevallier, M. W., Yang, J., Xu, M., Hughes, D., & Kunkel, G. (2014). *Pressure Management: Industry Practices and Monitoring Procedures*. WRF Project No. 4321. Denver, Colorado. Water Research Foundation.

Li, D., Engel, R. A., Ma, X., Porse, E., Kaplan, J. D., Margulis, S. A., & Lettenmaier, D. P. (2021). Stay-at-Home Orders during the COVID-19 Pandemic Reduced Urban Water Use. *Environmental Science & Technology Letters*, *8*(5), 431–436. https://doi.org/10.1021/acs.estlett.0c00979

Liemberger, R., & McKenzie, R [Ronnie]. (2003). *Aqualibre™ - A New Innovative Water Balance Software.* Aqualibre. http://www.geocities.ws/kikory2004/6_Liemberger.pdf

Mabee, W. C. (1928). Unaccounted-for Water. *Journal of the American Water Works Association*, *19*(6), 639–652.

May, J. H. (1994). Pressure Dependent Leakage. *World Water and Environmental Engineering*, *17*(8), 10.

McKenzie, R [R.]. (2007). *AquaLite Water Balance Software (Version 2.0.2 User Guide)*. WRC Report Number TT 315/07. https://www.wrc.org.za/wp-content/uploads/mdocs/TT315.pdf

McKenzie, R [R.], Bhagwan, J. N., & Lambert, A. (2002). *LEAKAGE REDUCTION SOFTWARE DEVELOPED THROUGH THE WATER RESEARCH COMMISSION*. Cyprus. IWA Conference 'Leakage Management – A Practical Approach'. https://www.miya-water.com/fotos/artigos/04_leakage_reduction_software_developed_through_the_water_research_commission_20375794735a327150a9fdf.pdf

McKenzie, R [R.], & Lambert, A. (2008). *Benchmarking of Water Losses in New Sealand Manual*. (Incorporating the User Manual for the 2008 update of the BenchlossNZ Software: Version 2a). https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=3676

McKenzie, R [R.], Lambert, A., Kock, J. E., & Mtshweni, W. (2002). *BENCHMARKING OF LEAKAGE FOR WATER SUPPLIERS IN SOUTH AFRICA*. User Guide For the BENCHLEAK Model (TT 159/01). Pretoria, South Africa. South African Water Research Commission.

McKenzie, R [R.], & Seago, C. (2005). Assessment of real losses in potable water distribution systems: some recent developments. *Water Supply*, *5*(1), 33–40. https://doi.org/10.2166/ws.2005.0005

Metcalf, L., Gifford, F. J., & Sullivan, W. F. (1912). Report of the Committee on Water Consumption Statistics and Records. *Journal of New England Water Works Association*, *27*(1), 29–143.

Millard, S. P. (2013). *_EnvStats: An R Package for Environmental Statistics_ // EnvStats: An R Package for Environmental Statistiscs*. Springer.

Moyer, E. E. (1985). *Economics of Leak Detection and Repair - A Case Study Approach*. American Water Works Association.

Myers, J. M., Jr. (1946). Increasing the Sale of Revenue Water. *Journal of the American Water Works Association*, *38*(2), 215–222. https://doi.org/10.1002/j.1551-8833.1946.tb17562.x

N.J.A.C. 7:10. (1979, July 13 (last amended 2020, June 1)). *Safe Drinking Water Act Rules*. https://www.nj.gov/dep/rules/rules/njac7_10.pdf

N.J.A.C. 7:19-6.4. *Water Supply Allocation Permits rules: Unaccounted-for water.* New Jersey Department of Environmental Protection. https://www.nj.gov/dep/rules/rules/njac7_19.pdf

N.Y.C.R.R. tit. 10, §.-1. *SubPart 5-1 - Public Water Supplies*. https://www.health.ny.gov/environmental/water/drinking/regulations/

Najjar, K. F., & Barr, J. K. (2016). *Analysis of Calendar Year 2014 Water Audit Data from Public Water Supply Systems in the Delaware River Basin*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/wateraudits/CY2014audit-report.pdf

Najjar, K. F., Pindar, C. E., & Rowland, R. D. (2018). *Analysis of Calendar Year 2016 Water Audit Data from Public Water Supply Systems in the Delaware River Basin*. West Trenton, New Jersey.

Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/wateraudits/CY2016audit-report.pdf

Nemati, M., & Tran, D. (2022). The Impact of COVID-19 on Urban Water Consumption in the United States. *Water*, *14*(19), 3096. https://doi.org/10.3390/w14193096

NJDEP. (2007). *Surficial Geology of New Jersey, 1:100,000, DGS07-2, Edition 200708*. Digital Geologic Series DGS07-2 (GIS Shapefile). New Jersey Department of Environmental Protection (NJDEP), New Jersey Geological Survey (NJGS). https://gisdata-njdep.opendata.arcgis.com/datasets/njdep::surficial-geology-of-new-jersey/about

NJDEP. (2016). *New Jersey Water System Asset Management Assessment: Baseline Survey Report*. Trenton, New Jersey. New Jersey Department of Environmental Protection. https://www.nj.gov/dep/assetmanagement/pdf/am-baseline-survey-report.pdf

NRA. (1995). *Saving Water: The NRA's Approach to Water Conservation & Demand Management*. NRA Water Resources 31. Worthing, UK. National Rivers Authority. http://www.environmentdata.org/archive/ealit:3180

NRDC. (2020). *Cutting Our Losses: State Policies to Track and Reduce Leakage from Public Water Systems*. https://www.nrdc.org/resources/cutting-our-losses

NWC. (2006). *Drinking Water Distribution Systems: Assessing and Reducing Risks*. The National Academies Press. https://doi.org/10.17226/11728

NYC DEP. (2022). *One Water NYC: 2022 Demand Management Annual Update*. New York, New York. NYC Department of Environmental Protection. https://www.nyc.gov/assets/dep/downloads/pdf/water/drinking-water/water-conservation-report2022.pdf

NYC DEP. (2023a). *Delaware Aqueduct Repair Project: Final Connection and Water Supply Management Plan*. New York, New York. NYC Department of Environmental Protection. https://www.nyc.gov/assets/dep/downloads/pdf/whats-new/programs-initiatives/delaware-aqueduct-repair-project-presentation.pdf

NYC DEP. (2023b). *One Water NYC: 2023 Water Demand Management Plan*. New York, New York. NYC Department of Environmental Protection. https://www.nyc.gov/assets/dep/downloads/pdf/water/drinking-water/water-conservation-report2023.pdf

NYSDEC. (2021). *Water Withdrawal Permits*. https://www.dec.ny.gov/lands/86935.html

OFWAT. (1997). *1997-98 Report on leakage and water efficiency.* Office of Water Services (OFWAT). https://data.parliament.uk/DepositedPapers/Files/DEP2009-2769/DEP2009-2769.pdf

OFWAT. (2006). *The Development of the Water Industry in England and Wales.* Office of Water Services (OFWAT). https://www.ofwat.gov.uk/wp-content/uploads/2015/11/rpt_com_devwatindust270106.pdf

Ogura (1979). Experimentation on the relationship between water leakage and water pressure. *Japan Waterworks Journal*, *June*, 38–45.

Pearson, D., Fantozzi, M., Soares, D., & Waldron, T. (2005). *Searching for N2: How does Pressure Reduction Reduce Burst Frequency?* Halifax, Nova Scotia. IWA Conference ‘Leakage 2005’.

Pearson, D., & Trow, S. (2005). *Calculating Economic Levels of Leakage*. Halifax, Nova Scotia. IWA Conference ‘Leakage 2005’. http://rash.apanela.com/tf/leakage/Calculating%20Economic%20Levels%20of%20Leakage.pdf

Pearson, D., & Trow, S. (2012). *Comparing Leakage Performance Using the Frontier Approach.* Manila, Philippines. Proc. of the IWA Water Loss Conference.

PHRC. (2021). *2021 Pennsylvania Alternative Residential Energy Provisions*. https://www.phrc.psu.edu/assets/docs/Publications/2021-PA-Alternative-Residential-Energy-Provisions.pdf

Pierce, M. (2022). *Documentary History of American Water-works.* University of Rochester. http://www.waterworkshistory.us/index.htm

PL 87-328, 75 Stat. 688. (1961, September 27). *Delaware River Basin Compact*. https://www.state.nj.us/drbc/library/documents/compact.pdf

POST. (1995). *The 1995 Drought*. London. Parliamentary Office of Science and Technology.

Pub. L. No. 93-523, 88 Stat. 1660. (1974, December 16). *Safe Drinking Water Act*. https://www.govinfo.gov/content/pkg/STATUTE-88/pdf/STATUTE-88-Pg1660-2.pdf

PWD. (2015). *Water Infrastructure Management*. Philly Watersheds (website). Philadelphia Water Department.

R Core Team. (2023). *A language and environment for statistical computing*. Vienna, Austria. R Foundation for Statistical Computing. https://www.R-project.org/

Resolution No. 2009 – 1. (2009). *A RESOLUTION to amend the Commission's Water Code and Comprehensive Plan to implement an updated water audit approach to identify and control water loss in the Basin.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 76-17. (1976). *A RESOLUTION to amend the Comprehensive Plan by the addition of policy on the conservation of water.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 77-3. (1977). *A RESOLUTION directing an investigation of groundwater conditions in the Delaware River Basin.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 82-25. (1982). *A RESOLUTION accepting the report of the Ground Water Study.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 83-5. (1983). *A RESOLUTION to establish a Water Conservation Advisory Committee.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 86-12. (1986). *A RESOLUTION to amend the Comprehensive Plan and Water Code of the Delaware River Basin in relation to source metering of large surface and ground water withdrawals.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 86-13. (1986). *A RESOLUTION to amend the Commission's Ground Water Protected Area Regulations for Southeastern Pennsylvania in relation to ground water withdrawal metering, recording and reporting.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 87-6 Revised. (1988). *A RESOLUTION to amend the Comprehensive Plan and Water Code of the Delaware River Basin in relation to leak detection and repair.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 87-7 Revised. (1988). *A RESOLUTION to amend the Comprehensive Plan and Water Code of the Delaware River Basin in relation to service metering.* Ewing, New Jersey. Delaware River Basin Commission.

Resolution No. 98-21. (1998). *A RESOLUTION to dissolve the Ground Water Advisory Committee and the Water Conservation Advisory Committee and to establish a Water Management Advisory Committee.* Ewing, New Jersey. Delaware River Basin Commission.

Rezaei, H., Ryan, B., & Stoianov, I. (2015). Pipe Failure Analysis and Impact of Dynamic Hydraulic Conditions in Water Supply Networks. *Procedia Engineering*, *119*, 253–262. https://doi.org/10.1016/j.proeng.2015.08.883

Rochera, E. C., Gallego, A. C., Llorens, R. G., Rodríguez, B. M., & Vergara, F. J. V. (2009). *SIGMA Lite 3, version 3.4.0.0*. (software). Instituto de Technología del Agua, Universidad Politécnica de Valencia.

Sayers, D., Jernigan, W., Kunkel, G., & Chastain-Howley, A. (2016). The Water Audit Data Initiative: Five Years and Accounting. *Journal - American Water Works Association*, *108*, E598-E605. https://doi.org/10.5942/jawwa.2016.108.0169

Sayers, D., Najjar, K. F., & Barr, J. K. (2015). *Analysis of Calendar Year 2012 Water Audit Data from Public Water Supply Systems in the Delaware River Basin*. West Trenton, New Jersey. Delaware

River Basin Commission. https://www.state.nj.us/drbc/library/documents/wateraudits/CY2012audit-report.pdf

Schloerke, B., Cook, D [Di], Larmarange, J., Francois, B., Moritz, M., Edwin, T., Amos, E., & Jason, C. (2021). *GGally: Extension to 'ggplot2'*. R package version 2.1.2. https://CRAN.R-project.org/package=GGally

Schramm, M. (2020). *echor: Access EPA 'ECHO' Data.* Texas Water Resources Institute. https://doi.org/10.5281/zenodo.3635017

Schroepfer, G. J., Johnson, A. S [A. S.], Seidel, H. F [H. F.], & Al-Hakim, M. B. (1948). A Statistical Analysis of Water Works Data for 1945. *Journal - American Water Works Association*, *40*(10), 1067–1098. https://doi.org/10.1002/j.1551-8833.1948.tb15057.x

Seidel, H. F [Harris F.] (1978). A Statistical Analysis off Water Utility Operating Data for 1965 and 1970. *Journal - American Water Works Association*, *70*(6), 315–323. https://doi.org/10.1002/j.1551-8833.1978.tb04180.x

Seidel, H. F [Harris F.] (1985). Water Utility Operating Data: An Analysis. *Journal - American Water Works Association*, *77*(5), 34–41. https://doi.org/10.1002/j.1551-8833.1985.tb05536.x

Seidel, H. F [Harris F.], & Baumann, E. R. (1957). A Statistical Analysis of Water Works Data for 1955. *Journal - American Water Works Association*, *49*(12), 1531–1566. https://doi.org/10.1002/j.1551-8833.1957.tb15522.x

Seidel, H. F [Harris F.], & Cleasby, J. L. (1966). A Statistical Analysis of Water Works Data for 1960. *Journal - American Water Works Association*, *58*(12), 1507–1527. https://doi.org/10.1002/j.1551-8833.1966.tb01724.x

Seidel, H. F [Harris F.], Johnson, A. S [A. Stanford], & Dencker, D. O. (1953). A Statistical Analysis of Water Works Data for 1950. *Journal - American Water Works Association*, *45*(12), 1309–1333. https://doi.org/10.1002/j.1551-8833.1953.tb19105.x

Sjøvold, F., SINTEF, Mobbs, P., WRc, & SGI. (2005). *TILDE - D20 Benchmarking tools: EC Contract No. IPS-2001-42077*. Trondheim, Norway. SINTEF Technology and Society.

Smith, J. C. (1987). *Estimating unavoidable leakage in water distribution systems*. Thesis (M.S.). Provo, Utah. Brigham Young University.

Smith, L., Dickinson, M. A., & Christiansen, W. (2019). *State-Level Water Loss Laws in the United States*. A Supplement to the Alliance of Water Efficiency 2017 Report, The Water Efficiency and Conservation State Scorecard: An Assessment of Laws. Chicago, Illinois. Alliance for Water Efficiency. https://www.allianceforwaterefficiency.org/sites/default/files/highlight_documents/AWE_Water_Loss_Scorecard_Final_2019.pdf

4 Del. Admin. C §4455-2.0. https://regulations.delaware.gov/AdminCode/title16/Department%20of%20Health%20and%20Social%20Services/Division%20of%20Public%20Health/Health%20Systems%20Protection%20(HSP)/4455.shtml#:~:text=4455%20Delaware%20Regulations%20Governing%20a%20Detailed%20Plumbing%20Code

NJ. Stat. §464, 2022. https://pub.njleg.state.nj.us/Bills/2020/PL21/464_.PDF

N.Y. ENG § 11-104. https://www.nyserda.ny.gov/All-Programs/New-York-State-Appliance-and-Equipment-Efficiency-Standards#:~:text=The%20first%20batch%20of%20standards,are%20detailed%20in%20Current%20Standards.

Strahler, A. N. (1952). HYPSOMETRIC (AREA-ALTITUDE) ANALYSIS OF EROSIONAL TOPOGRAPHY. *Geological Society of America Bulletin*, *63*(11), 1117. https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2

Sturm, R., Gasner, K., & Andrews, L. (2015). *Water Audits in the United States: A Review of Water Losses and Data Validity*. WRF Project No. 4372b. Denver, Colorado. Water Research Foundation; U.S. Environmental Protection Agency.

Sturm, R., Gasner, K., Wilson, T., Preston, S., & Dickinson, M. A. (2014). *Real Loss Component Analysis: A Tool for Economic Water Loss Control*. WRF Report #4372a. Denver, Colorado. Water Research Foundation.

Sturm, R., Stief, C., Jernigan, W., & Blackwell, D. (2021a). *Level 1 Water Audit Validation Guidance Manual*. Project 5057. Denver, Colorado. American Water Works Association.

Sturm, R., Stief, C., Jernigan, W., & Blackwell, D. (2021b). *Level 1 Water Audit Validation Guidance Manual: Second Edition (5057): Task 3 Memo*. Denver, Colorado. Water Research Foundation. https://www.waterrf.org/resource/level-1-water-audit-validation-guidance-manual-second-edition-task-3-memo-level-1

Thompson, M. Y., & Pindar, C. E. (2021). *Water Withdrawal and Consumptive Use Estimates for the Delaware River Basin (1990-2017) With Projections Through 2060*. DRBC Report No: 2021-4. West Trenton, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/water-use/DRBC_2021-4_Water2060_Final_101421.pdf

Thompson, M. Y., Sayed, S. C., Beganskas, S., & Pindar, C. E. (2022). *Estimated Groundwater Availability in the Delaware River Basin 2020–2060*. DRBC Report No. 2022-5. Ewing, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/DRB_Rpt_GW_Availability_dec2022.pdf

Thornton, J., Kunkel, G., Reinhard, S., Pearson, D., Stuart, T., & Gauley, B. (2002). *Water loss control manual* (1st ed.). *McGraw-Hill's AccessEngineering*. McGraw-Hill. https://www.accessengineeringlibrary.com/content/book/9780071499187

Thornton, J., & Lambert, A. (2005). *Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships*. Halifax, Nova Scotia. IWA Conference 'Leakage 2005'. https://www.miya-water.com/fotos/artigos/10_progress_in_practical_prediction_of_pressure_leakage_pressure_burst_frequency_and_pressure_consumption_relationships_16541036425a328d4c63c6c.pdf

Thornton, J., & Lambert, A. (2006). Managing pressures to reduce new break frequencies, and improve infrastructure management. *Water21*(December).

Thornton, J., & Lambert, A. (2011). The relationships between pressure and bursts - a 'state of the art' update. *Water21*, *April*.

TNCT. (2020). *Memorandum: Water Loss Filing per Section 7-82-401(i) and 68-221-1010 (d)(3), Tennessee Code Annotated*. Nashville, Tennessee. Tennessee Comptroller of the Treasury. https://comptroller.tn.gov/content/dam/cot/wwfb/advanced-search/WaterLossAnnualReport2020.pdf

Trachtman, G., & Wyatt, A [Allen]. (2019). *Assessment of Performance Indicators for Non-Revenue Water Target Setting and Progress Tracking*. Denver, Colorado. American Water Works Association. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/WLCCAssessmentReport2019.pdf?ver=2019-11-20-094731-123

Trachtman, G., Wyatt, A [Alan], Davis, S. E., & Kunkel, G. (2019). *Guidance on Implementing an Effective Water Loss Control Plan*. WRF Project No. 4695. Alexandria, Virginia. Water Research Foundation.

Trow, S. (2009). *Development of a Pressure Management Index (PMI)*. Cape Town, South Africa. Proc. of International Water Association Conference.

Tsitsifli, S., & Kanakoudis, V. (2010). *Presenting a new user friendly tool to assess the performance level & calculate the water balance of water networks*.

https://www.researchgate.net/publication/324822947_Presenting_a_new_user_friendly_tool_to_assess_the_performance_level_calculate_the_water_balance_of_water_networks

UKWIR. (2003). *Leakage Index Curve and the Longer-Term Effects of Pressure Management*. Report Ref. No. 03/WM/08/29. London, UK. UK Water Industry Research. https://ukwir.org/eng/reports/03-WM-08-29/67026/Leakage-Index-Curve-and-the-LongerTerm-Effects-of-Pressure-Management

USACE & DRBC. (2008). *Enhancing Multi-jurisdictional Use and Management of Water Resources for the Delaware River Basin, NY, NJ, PA, and DE*. West Trenton, New Jersey. USACE Philadelphia District and the Delaware River Basin Commission. https://www.nj.gov/drbc/about/public/multi-juris-study.html

USEPA. (2016a). *Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion*. EPA-810-B-16-005. Washington, D.C. US Environmental Protection Agency, Office of Water. https://www.epa.gov/sustainable-water-infrastructure/best-practices-water-conservation-and-efficiency-alternative-water

USEPA. (2016b). *EnviroAtlas - Dasymetric Population for the Conterminous United States*. GIS Shapefile. U.S. Environmental Protection Agency. https://www.epa.gov/enviroatlas

USGS. (2019). *3D Elevation Program 10-Meter Resolution Digital Elevation Model*. Files: USGS_13_n39w075_20210624, USGS_13_n39w076_20220713, USGS_13_n40w075_20210624, USGS_13_n40w076_20220524, USGS_13_n41w075_20221115, USGS_13_n41w076_20221115, USGS_13_n41w077_20220429, USGS_13_n42w075_20221115, USGS_13_n42w076_20221115, USGS_13_n43w075_20190416, USGS_13_n43w076_20220429. U.S. Geological Survey.

Van Abs, D. J., & Drabik, J. (2022). *New Jersey Assessment of Water Losses for Public Community Water Systems*. DRAFT FOR PUBLIC REVIEW. Trenton, New Jersey. New Jersey Department of Environmental Protection.

van Zyl, J. E., Lambert, A. O., & Collins, R. (2017). Realistic Modeling of Leakage and Intrusion Flows through Leak Openings in Pipes. *Journal of Hydraulic Engineering*, *143*(9), Article 04017030. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001346

Virginia Tech. (2017). *PIPEiD: PIPELINE infrastructure DATABASE.* Virginia Polytechnic Institute and State University (Virginia Tech). http://www.pipeid.org/

Walker, J., Wyatt, A [Alan], Seefeldt, J., Goshen, D., Bock, M., Johnston, I., & Black, M. (2022). *Hidden Reservoirs: Addressing Water Loss in Texas*. Austin, Texas. National Wildlife Federation. https://texaslivingwaters.org/deeper-dive/water-loss/

Wallace, L. P. (1987). *Water and Revenue Losses: Unaccounted-for Water*. WRF Report #90531.

WEF. (2017). *Found in Philadelphia: 200-Year-Old Wooden Water Mains.* Water Environment Federation. https://news.wef.org/found-in-philadelphia-200-year-old-wooden-water-mains/

Weibull, W. (1939). A Statistical Theory of the Strength of Materials. *The Swedish Academy of Sciences' Documents (Vetenskapsakademiens Handlingar)*, *151*.

Whitman, E. B. (1932). Per Capita Water Consumption. *Journal of the American Water Works Association*, *24*(4), 515-528. https://doi.org/10.1002/j.1551-8833.1932.tb18069.x

Wickham, H., Vaughan, D., & Girlich, M. (2023). *tidyr: Tidy Messy Data*. R package version 1.3.0. https://CRAN.R-project.org/package=tidyr

Wyatt, A [Alan] (2020a). *Introducing the Combined Real Loss Indicator - CRLI: Water Loss Specialist Group Webinar Series*. presentation. International Water Association.

Wyatt, A [Alan] (2020b). The use of Frontier Analysis to assess the technical rigor of water loss performance indicators. *H2Open Journal*, *3*(1), 102–117. https://doi.org/10.2166/h2oj.2020.006

Zapecza, O. S. (1989). *Hydrologic Framework ok the New Jersey Coastal Plain; Regional Aquifer-System Analysis*. U.S. Geological Survey Professional Paper 1404-B. Washington, D.C. U.S. Geological Survey. https://doi.org/10.3133/pp1404B

12.1. Picture References

i...............“*Access to water supply*”, ID 40789732 © Subhadeepmanna | Dreamstime.com
vi.............*“Fairmount Water Works”,* Partnership for the Delaware Estuary, Used with permission
1 ....*No title.* © Merchantville-Pennsauken Water Company. Used with permission.
13 ....“*Road spurt water beside traffic cones and a technician*”, ID 47823348 © Giorgio Rossi | Dreamstime.com
21 ....“*The main leader of water*”, ID 8356827 © Yanko16 | Dreamstime.com
26 ....“*Data analysis isometric vector illustration. Abstract 3d datacenter or data center room background*”, ID 133783639 © Polegaevmark | Dreamstime.com
40 ....“*Isometric Data Analysis Graph*”, ID 142774582 © Emojoezthai | Dreamstime.com
43 ....“*IBM PC 5150 Color*”, Reprint Courtesy of IBM Corporation © Used with permission.
51/52 ......“*Large water supply valve with a white background of the cement wall*”, ID 192419331 © Narong Pobout | Dreamstime.com
53 ....“*Water pressure gage*”, ID 77141620 © Patamaporn Jansuebsri | Dreamstime.com
73 ....“*metal pipe with valve is leaking in water treatment plant*”, ID 1674855835 © Ody_Stocker | Shutterstock.com
79 ....“*Metal pipe for water city supply*”, ID 24391030 © Toa555 | Dreamstime.com
87 ....“Blue modern radio water counter meter”, ID 117758174 © Piotr Adamowicz | Dreamstime.com
89 ....“*An orange street cone between two small fountains of water*”, ID 199875101 © Madscica | Dreamstime.com
100 ....“*Water meter and Plumbing*”, ID 59933035 © Tothekop79 | Dreamstime.com
111 ....“*Water pipe 400 mm diameter PN10 broken by external force*”, ID 487755196 © designbydx | Shutterstock.com
115 ....“*Water Utilities*”, ID 936460 © Steve Mann | Dreamstime.com
119 ....“*Industrial water temperature meter with pipes*”, ID 291051713 © Khotenko Vladymyr | Shutterstock.com
126 ....“*Wing Dam on The Delaware River*”, © James Loesch, Used with permission.
127 ....“*Topographic map*”, © Michael Thompson, DRBC
139 ....“*Water being released during repair*”, ID 24996691 © Chrisp543 | Dreamstime.com
147 ....“*Water valve at the drip fence from a long-used plumbing pipe. Selective focus.*”, ID 2209966041 © Oasishifi| Shutterstock.com

APPENDICES

A. List of systems included in analysis (CY2021)

Row	Name	Reference Number	State	N_c (2021)	Class
1	Alburtis Borough Authority	D-1991-042 CP-4	PA	998	Very Small
2	Aqua New Jersey- Riegel Ridge Fox Hill Warren Glen	AA-1977-049 CP-2	NJ	399	Very Small
3	Aqua New Jersey-Blackwood	D-1993-013 CP-4	NJ	15,867	Large
4	Aqua New Jersey-Hamilton	AA-2000-036	NJ	16,378	Large
5	Aqua New Jersey-Lawrenceville	OP-1983-026 CP REN-2	NJ	2,680	Small
6	Aqua New Jersey-Phillipsburg	AA-1977-061 CP	NJ	11,315	Large
7	Aqua New Jersey-Woolwich	AA-2000-037 CP	NJ	2,919	Small
8	Aqua PA - Bristol System	D-1989-097 CP	PA	11,790	Large
9	Aqua PA - Chalfont System	D-1993-083 CP-3	PA	2,599	Small
10	Aqua PA - Fawn Lake (Lackawaxen) System	D-1981-061 CP-4	PA	778	Very Small
11	Aqua PA - Flying Hills System	D-1977-094 CP-3	PA	1,482	Small
12	Aqua PA - Hamilton System	D-1985-055 CP-4	PA	477	Very Small
13	Aqua PA - Hatboro System	D-1974-073 CP	PA	4,982	Small
14	Aqua PA - Hawley System	D-2014-007 CP-1	PA	605	Very Small
15	Aqua PA - Honesdale System	D-1995-057 CP-2	PA	1,793	Small
16	Aqua PA - Honeybrook System	D-2000-048 CP	PA	744	Very Small
17	Aqua PA - Perkiomen Twp	D-2001-050 CP-3	PA	1,461	Small
18	Aqua PA - Perkiomen Woods	D-1976-104 CP	PA	439	Very Small
19	Aqua PA - Superior System	D-2001-015 CP-6	PA	4,372	Small
20	Aqua PA - Tanglewood Lakes Golf	D-2010-042 CP-2	PA	662	Very Small
21	Aqua PA - UGS North	D-2003-033 CP-2	PA	3,758	Small
22	Aqua PA - UGS South System (Spring Run)	D-2003-033 CP-2	PA	3,512	Small
23	Aqua PA - Uwchlan System	D-1990-050 CP-4	PA	16,156	Large
24	Aqua PA - Waymart	D-1975-078 CP-5	PA	383	Very Small
25	Aqua PA - West Chester System	D-1990-079 CP-2	PA	14,093	Large
26	Aqua PA Main System	D-1991-086 CP-3	PA	309,482	Very Large
27	Artesian Water (Augustine Creek)	D-2003-022 CP-4	DE	207	Very Small
28	Artesian Water (Bayview Beach)	D-2003-022 CP-4	DE	44	Very Small
29	Artesian Water (Beaver Creek)	AA-2010-512	DE	2,707	Small
30	Artesian Water (Burtonwood)	D-2004-001 CP-1	DE	505	Very Small
31	Artesian Water (Church Creek)	D-2001-034 CP-2	DE	2,942	Small
32	Artesian Water (Fox Hunter Crossing)	D-2003-022 CP-4	DE	6,562	Medium
33	Artesian Water (Windsong)	D-2001-025 CP	DE	494	Very Small
34	Artesian Water Company	D-2002-034 CP-4	DE	69,984	Very Large
35	Artesian Water Company (Delaware City)	D-1998-046 CP	DE	786	Very Small
36	Auburn Municipal Authority	D-1990-052 CP	PA	326	Very Small
37	Audubon Water Company	D-2004-004 CP-3	PA	2,837	Small
38	Bath Borough Authority	D-2007-016 CP-2	PA	1,224	Small
39	Bedminster Municipal Authority (Pennland)	D-2004-002 CP-2	PA	216	Very Small
40	Bedminster Municipal Authority (Stonebridge)	D-2004-002 CP-2	PA	989	Very Small
41	Bellmawr Water Department	D-1990-082 CP REN	NJ	2,815	Small

Row	Name	Reference Number	State	N_c (2021)	Class
42	Berryman's Branch MHP	OP-2019-507	NJ	310	Very Small
43	Birdsboro Municipal Authority	D-0000-001 ENT 277	PA	2,030	Small
44	Blue Mountain Water Cooperative	D-1993-027 -3	PA	50	Very Small
45	Blythe Township Municipal Authority - Crystal Run	D-1991-051 CP	PA	1,067	Small
46	Blythe Township Municipal Authority - Moss Glen	D-1991-051 CP	PA	767	Very Small
47	Blythe Township Municipal Authority - Silver Creek	D-1991-051 CP	PA	700	Very Small
48	Borough of Allentown Water Department	D-1989-032 CP REN	NJ	712	Very Small
49	Borough of Alpha Water Department	OP-1987-062 CP REN-2	NJ	1,147	Small
50	Borough of Ambler	D-1985-026 CP-6	PA	5,796	Medium
51	Borough of Bally	D-1978-019 CP-3	PA	648	Very Small
52	Borough of Boyertown	D-1973-199 CP-5	PA	3,300	Small
53	Borough of Clayton Water Department	AA-1995-045 CP	NJ	2,943	Small
54	Borough of Coopersburg	D-1967-125 CP	PA	1,004	Small
55	Borough of Elmer	D-1985-024 CP-4	NJ	577	Very Small
56	Borough of Emmaus	D-1976-058 CP	PA	4,377	Small
57	Borough of Fleetwood	D-1995-058 CP-3	PA	1,850	Small
58	Borough of Hopatcong	OP-1992-085 CP-3	NJ	1,906	Small
59	Borough of Jim Thorpe	D-1981-071 CP-5	PA	1,982	Small
60	Borough of Kutztown Water System	D-1983-023 CP-4	PA	1,868	Small
61	Borough of Leesport Water Authority	D-2001-012 CP-2	PA	950	Very Small
62	Borough of Orwigsburg	D-1992-005 CP-3	PA	1,138	Small
63	Borough of Roosevelt Water Department	D-1985-008 CP REN 2	NJ	303	Very Small
64	Borough of Schuylkill Haven / Tumbling Run Water Treatment Plant	D-1989-096 CP REV	PA	3,214	Small
65	Borough of Slatington (Slatington Municipal Works)	D-1990-097 CP	PA	1,430	Small
66	Borough of Wenonah Water System	OP-2013-003 CP-1	NJ	825	Very Small
67	Borough of Woodbury Heights Public Works	OP-1973-120 CP-1	NJ	1,210	Small
68	Borough of Woodstown Water Department	OP-1999-004 CP	NJ	1,518	Small
69	Branchville Water Department	OP-2000-027 CP-1	NJ	388	Very Small
70	Brodhead Creek Regional Authority	D-1991-001 CP-4	PA	5,785	Medium
71	Brooklawn Borough Water Department	OP-1985-018 CP REN-2	NJ	814	Very Small
72	Buck Hill Falls Water Company	D-2009-002 CP-1	PA	313	Very Small
73	Buckingham Township - Buckingham Village System	D-2003-013 CP-7	PA	121	Very Small
74	Buckingham Township - Cold Spring System	D-2003-013 CP-7	PA	1,773	Small
75	Buckingham Township - Fenton's Corner	D-2003-013 CP-7	PA	74	Very Small
76	Buckingham Township - Fieldstone System	D-2003-013 CP-7	PA	104	Very Small
77	Buckingham Township - Furlong System	D-2003-013 CP-7	PA	1,233	Small
78	Buckingham Township - Mill Creek	D-2003-013 CP-7	PA	73	Very Small
79	Bucks County Water & Sewer Authority - Lower Bucks	D-1969-190 CP	PA	14,778	Large
80	Bucks County Water & Sewer Authority - New Hope	D-2004-039 CP-2	PA	667	Very Small
81	Bucks County Water & Sewer Authority - Solebury Township	D-1999-066 CP-2	PA	679	Very Small
82	Buena Borough Municipal Utility Authority	AA-2002-037	NJ	1,576	Small
83	Burlington Township Water Department	OP-1999-050 CP-2	NJ	7,976	Medium
84	Camden-Wyoming Sewer and Water Authority	AA-1997-030 CP	DE	2,975	Small

Row	Name	Reference Number	State	N_c (2021)	Class
85	Catasauqua Municipal Waterworks	D-1987-060 CP-4	PA	2,342	Small
86	Chester Water Authority	D-1984-055 CP	PA	50,556	Very Large
87	City of Bethlehem	D-1995-019 CP-2	PA	36,594	Very Large
88	City of Bordentown Water Department	OP-2004-011 CP-2	NJ	5,860	Medium
89	City of Bridgeton Water Department	AA-1998-050 CP	NJ	5,086	Medium
90	City of Burlington	OP-1973-046 CP-2	NJ	3,852	Small
91	City of Camden Water	OP-1979-083 CP-1	NJ	13,050	Large
92	City of Dover	D-2001-043 CP	DE	13,026	Large
93	City of Harrington	AA-1988-027 CP	DE	1,372	Small
94	City of Millville Water Utility	AA-1996-005 CP	NJ	7,891	Medium
95	City of Newark Delaware	D-2002-002 CP	DE	10,328	Large
96	City of Port Jervis Department of Public Works	D-2013-019 CP-1	NY	3,000	Small
97	City of Vineland Municipal Water Utility	AA-1995-047 CP	NJ	16,286	Large
98	City of Wildwood Water Utility	D-2008-042 CP-1	NJ	17,481	Large
99	City of Woodbury	OP-1980-062 CP	NJ	3,873	Small
100	Clementon Water Department	OP-1987-092 CP REN	NJ	1,610	Small
101	Collegeville Trappe Joint Public Works Department	D-2000-057 CP-2	PA	3,031	Small
102	Collingswood Water Department	D-1989-003 CP REN	NJ	5,988	Medium
103	Community Utilities of Pennsylvania Inc. - Tamiment	D-1989-033 CP-4	PA	511	Very Small
104	Community Utilities of Pennsylvania/Penn Estates Utilities	D-2003-036 CP-3	PA	1,732	Small
105	Delaware Water Gap Borough	D-1997-032 CP-3	PA	448	Very Small
106	Deptford Township Municipal Water Authority	D-1994-068 CP-2	NJ	10,839	Large
107	Downingtown Municipal Water Authority	D-1989-063 CP-3	PA	3,965	Small
108	Doylestown Borough	D-1979-018 CP-6	PA	3,443	Small
109	Doylestown Township Municipal Authority	D-1995-009 CP-3	PA	2,785	Small
110	Dublin Borough	D-2000-011 CP-3	PA	1,419	Small
111	East Greenville Borough Water Department	D-2004-003 CP-2	PA	1,172	Small
112	East Greenwich Township Water & Sewer Department	OP-1974-132 CP	NJ	3,945	Small
113	East Stroudsburg Water Department	D-1992-072 CP-2	PA	3,034	Small
114	Easton Area Water System	D-1999-062 CP-2	PA	34,069	Very Large
115	Evesham Municipal Utilities Authority	OP-1998-015 CP-1	NJ	16,849	Large
116	Fleischmanns Water Department	D-2009-008 CP-2	NY	315	Very Small
117	Florence Township Water & Sewer	AA-1994-082 CP	NJ	5,493	Medium
118	Freeland Municipal Authority	D-1994-063 CP-3	PA	2,431	Small
119	Glassboro Water & Sewer Department	OP-1996-054 CP-2	NJ	6,312	Medium
120	Gloucester City	D-1968-114 CP	NJ	4,130	Small
121	Hackettstown Municipal Utilities Authority	AA-2004-023 CP	NJ	5,576	Medium
122	Haddon Township Water Department	OP-1966-065 CP-2	NJ	4,017	Small
123	Hamburg Municipal Authority	D-2012-022 CP-1	PA	2,385	Small
124	Hampton Borough Water Company	D-1974-008 CP REN	NJ	510	Very Small
125	Hazleton City Authority	D-1991-065 CP-4	PA	15,362	Large
126	Hellertown Borough Authority	D-2000-053 CP-2	PA	2,630	Small
127	Hemlock Farms Community Association	D-2000-060 CP-2	PA	3,674	Small
128	Hilltown Township Water & Sewer Authority	D-1992-020 CP-4	PA	2,260	Small
129	Honey Brook Borough Authority	D-1991-099 CP-3	PA	806	Very Small

Row	Name	Reference Number	State	N_c (2021)	Class
130	Horsham Water & Sewer Authority	D-1997-016 CP-4	PA	8,135	Medium
131	Kennett Square Municipal Water Works	D-2012-003 CP-1	PA	1,905	Small
132	Kiamesha Artesian Spring Water Company	D-1990-068 CP-4	NY	435	Very Small
133	Lake Valley Water	AA-1992-056 CP	NJ	543	Very Small
134	Lansford-Coaldale Joint Water Authority	D-1995-013 CP-2	PA	3,872	Small
135	LCA Allentown Division	D-1984-016 CP	PA	33,491	Very Large
136	Lehigh County Authority (Central)	D-2001-020 CP-6	PA	18,535	Large
137	Lehigh County Authority (North Whitehall)	D-1992-040 CP	PA	969	Very Small
138	Lehigh County Authority (Washington Township)	D-1992-040 CP	PA	367	Very Small
139	Lehighton Water Authority	D-1989-093 CP	PA	3,706	Small
140	Lewes Board of Public Works	D-1985-054 CP RENEWAL	DE	3,792	Small
141	Lower Bucks County Joint Municipal Authority	D-1969-190 CP	PA	19,479	Large
142	Lower Saucon Authority	D-1111-001	PA	2,188	Small
143	Lower Township Municipal Authority	D-1994-021 CP-3	NJ	10,916	Large
144	Lyons Borough Municipal Authority	D-1965-008 CP	PA	224	Very Small
145	Macungie Borough Authority	D-1968-057 CP	PA	1,205	Small
146	Maidencreek Township Authority	D-1991-058 CP-4	PA	2,790	Small
147	Mantua Township Municipal Utility Authority	AA-2000-004	NJ	5,473	Medium
148	Manwalamink Water Company	D-1989-050 CP-6	PA	1,270	Small
149	Matamoras Municipal Authority	D-1981-078 CP-9	PA	1,270	Small
150	Medford Township	AA-1995-055 CP	NJ	5,661	Medium
151	Merchantville Pennsauken Water Commission	OP-1997-005 CP-2	NJ	15,972	Large
152	Meter Services Company - Village of Buckingham Springs	D-1994-049 CP-3	PA	185	Very Small
153	Midlakes Water System Northeast Land Company	D-1989-010 CP-4	PA	266	Very Small
154	Milford Borough (NJ)	OP-1968-095 CP	NJ	535	Very Small
155	Milford Borough (PA)	D-1965-168 CP-2	PA	801	Very Small
156	Milford City	D-1995-044 CP	DE	7,772	Medium
157	Milford Township Water Authority	D-2003-037 CP-2	PA	1,308	Small
158	Minersville Municipal Water Authority	D-2014-001 CP-1	PA	2,816	Small
159	Monroe Municipal Utilities Authority	OP-1993-009 CP-2	NJ	10,632	Large
160	Montague Water Company	OP-1991-075 CP REN	NJ	801	Very Small
161	Moorestown Township	AA-1995-059 CP	NJ	8,090	Medium
162	Morrisville Municipal Authority	D-1974-072 CP	PA	4,261	Small
163	Mount Laurel Township Municipal Utilities Authority	OP-1985-009 CP-3	NJ	17,691	Large
164	Mount Olive Township Water & Sewer	D-1971-059 CP	NJ	5,666	Medium
165	Mount Penn Borough Municipal Authority	D-1969-161 CP	PA	3,681	Small
166	Muhlenberg Township Authority	D-2001-030 CP-3	PA	9,094	Medium
167	Myerstown Water Authority	D-1981-067 CP-4	PA	3,016	Small
168	Narrowsburg Water	D-1992-081 CP-3	NY	324	Very Small
169	National Park Water Department	D-1977-018 CP-2	NJ	1,143	Small
170	Nesquehoning Borough Authority	D-1994-047 CP-2	PA	1,297	Small
171	Netcong Borough Water System	AA-2000-041 CP	NJ	1,051	Small
172	New Castle City - Municipal Services Commission	D-1978-071 CP-3	DE	2,337	Small

Row	Name	Reference Number	State	N_c (2021)	Class
173	New Jersey American Water - Western	D-1990-108 CP-3	NJ	107,843	Very Large
174	New Jersey American Water System (Belvidere)	AA-1990-089 CP	NJ	1,300	Small
175	New Jersey American Water System (Bridgeport)	OP-1993-028 CP-3	NJ	342	Very Small
176	New Jersey American Water System (Frenchtown)	D-1968-115 CP	NJ	473	Very Small
177	New Jersey American Water System (Harrison)	OP-1999-057 CP-1	NJ	3,202	Small
178	New Jersey American Water System (Homestead)	OP-1981-073 CP-4	NJ	1,293	Small
179	New Jersey American Water System (ITC)	D-1994-083	NJ	272	Very Small
180	New Jersey American Water System (Logan)	OP-1999-073 CP	NJ	2,582	Small
181	New Jersey American Water System (Mt Holly-Mansfield)	D-1995-046 CP-2	NJ	15,062	Large
182	New Jersey American Water System (New Egypt)	OP-2009-050 CP-1	NJ	468	Very Small
183	New Jersey American Water System (Penns Grove)	OP-1993-077 CP-3	NJ	3,902	Small
184	New Jersey American Water System (Sunbury)	AA-2001-003 CP	NJ	386	Very Small
185	New Jersey American Water System (Washington)	OP-1985-002 CP-3	NJ	4,850	Small
186	Newfield Borough Water Department	D-1977-028 CP	NJ	814	Very Small
187	Newmanstown Water Authority	D-1997-040 CP-3	PA	1,034	Small
188	Newtown Artesian Water Company	D-1978-029 CP-4	PA	10,563	Large
189	North Coventry Water Authority	D-2002-047 CP-3	PA	974	Very Small
190	North Penn Water Authority	D-1992-044 CP-4	PA	35,297	Very Large
191	North Wales Water Authority	D-1990-006 CP-4	PA	26,525	Very Large
192	Northampton Borough Municipal Authority	D-2004-006 CP-2	PA	15,855	Large
193	Northampton Bucks County Municipal Authority	D-2001-013 CP-3	PA	12,138	Large
194	Oley Township Municipal Authority	D-2001-036 CP-2	PA	810	Very Small
195	Palmerton Municipal Authority	D-1981-024 CP-8	PA	2,239	Small
196	Paulsboro Water/Sewer	OP-1972-067 CP-2	NJ	2,109	Small
197	Pemberton Borough	OP-1996-007 CP	NJ	591	Very Small
198	Pemberton Township Water	AA-1992-056 CP	NJ	4,011	Small
199	Pennington Water Department	D-1984-033 CP-4	NJ	1,006	Small
200	Pennsylvania American Norristown	D-1966-100 CP-2	PA	31,180	Very Large
201	Pennsylvania American Water / Blue Mnt /Nazareth Dist # 560	D-1977-047 CP	PA	10,452	Large
202	Pennsylvania American Water / Coatesville District # 650	D-1996-016 CP-3	PA	13,124	Large
203	Pennsylvania American Water / Glen Alsace Dist # 633	D-1999-030 CP-5	PA	9,355	Medium
204	Pennsylvania American Water / Lehman Pike District # 680	D-2003-019 CP-2	PA	9,468	Medium
205	Pennsylvania American Water / Pocono Dist # 570	D-1998-016 CP-4	PA	9,964	Medium
206	Pennsylvania American Water / Royersford District # 640	D-1986-059 CP-3	PA	16,790	Large
207	Pennsylvania American Water / Wyomissing Penn Dist # 630	D-1998-043 CP-3	PA	11,826	Large
208	Pennsylvania American Water / Yardley Dist # 520	D-1995-053 CP-2	PA	11,737	Large
209	Pennsville Township Water Department	OP-2002-016 CP	NJ	4,862	Small
210	Pennsylvania American Water Company - Valley Springs	D-1988-031 CP-4	PA	823	Very Small
211	Perkasie Regional Authority	D-1997-012 CP-4	PA	5,226	Medium

Row	Name	Reference Number	State	N_c (2021)	Class
212	Philadelphia Water Department	D-0000-002 ENT PHL	PA	525,457	Very Large
213	Phoenixville Borough	D-1967-123 CP-3	PA	6,251	Medium
214	Pine Hill Borough	OP-2018-501 -1	NJ	3,330	Small
215	Pinelands Water Company	AA-1992-042 CP	NJ	2,459	Small
216	Pitman Water Department	AA-1971-155 CP	NJ	3,292	Small
217	Plum Creek Municipal Authority	D-1991-020 CP-4	PA	1,244	Small
218	Plumstead Township	D-1997-033 CP-4	PA	2,615	Small
219	Portland Borough Authority	D-1997-029 CP-4	PA	401	Very Small
220	Pottstown Water Treatment Plant	D-1964-036 CP-2	PA	12,008	Large
221	Quakertown Water Department	D-2000-064 CP-4	PA	4,232	Small
222	Reading Area Water Authority	D-2000-059 CP-3	PA	28,171	Very Large
223	Richland Borough	D-1992-001 CP-3	PA	641	Very Small
224	Richland Township Water Authority	D-1996-044 CP-4	PA	2,350	Small
225	Richlandtown Borough	D-1969-148 CP	PA	461	Very Small
226	Riegelsville Borough Waterworks	D-1967-085 CP	PA	413	Very Small
227	Roamingwood Sewer and Water Association; Agent of South Wayne County Water and Sewer Authority	D-1988-045 CP-4	PA	3,324	Small
228	Roxbury Water District	D-2002-014 CP-3	NY	269	Very Small
229	Salem City Water Department	D-2002-046 CP	NJ	2,309	Small
230	Schuylkill County Municipal Authority	D-1990-049 CP-4	PA	10,310	Large
231	Schwenksville Borough Authority	D-2003-029 CP-2	PA	2,239	Small
232	Shoemakersville Borough	D-1990-007 CP-4	PA	735	Very Small
233	South Coventry Township Ridglea Water System	D-2000-026 CP-2	PA	198	Very Small
234	South Whitehall Township Consecutive Sys	D-1991-082 CP-3	PA	531	Very Small
235	South Whitehall Township Main System	D-1991-082 CP-3	PA	6,164	Medium
236	Sparta Township Water Utility	D-1998-001 CP	NJ	6,493	Medium
237	Stanhope Water Department	AA-1980-084 CP	NJ	1,464	Small
238	Stillwater Water District #1	D-1979-056 CP	NJ	403	Very Small
239	Stockton Borough	OP-1995-051 CP-1	NJ	227	Very Small
240	SUEZ Lambertville	D-0000-003 ENT 305	NJ	1,790	Small
241	Summit Hill Municipal Water Authority	D-1984-003 CP-4	PA	1,217	Small
242	Summit Management and Utilities	D-2001-056 CP-2	PA	358	Very Small
243	Swedesboro	OP-1970-112 CP-1	NJ	1,077	Small
244	Tamaqua Area Water Authority	D-2010-028 CP-1	PA	3,579	Small
245	Telford Borough Authority	D-2004-010 CP-2	PA	2,733	Small
246	The Upper Hanover Authority/Red Hill Water Authority	D-2002-010 CP-4	PA	4,183	Small
247	Tidewater Utilities Inc. - Camden	D-2004-024 CP-3	DE	4,332	Small
248	Tidewater Utilities Inc. - East District	AA-2006-012	DE	1,780	Small
249	Tidewater Utilities Inc. - Garrison Lake - North Dover District	D-2005-026 CP-2	DE	4,189	Small
250	Tidewater Utilities Inc. - Rehoboth - Lewes	D-2002-004 CP-3	DE	15,642	Large
251	Tidewater Utilities Inc. - Wild Quail	D-2005-027 CP-2	DE	328	Very Small
252	Topton Borough	D-1973-121 CP	PA	931	Very Small
253	Town of Clayton	D-1984-034 CP RENEWAL 3	DE	2,100	Small

Row	Name	Reference Number	State	N_c (2021)	Class
254	Town of Fallsburg Consolidated Water District	D-1990-105 CP-5	NY	5,472	Medium
255	Town of Felton	D-1999-026 CP-2	DE	621	Very Small
256	Town of Frederica	D-1989-073 CP RENEWAL	DE	472	Very Small
257	Town of Georgetown	D-1994-037 CP-3	DE	2,048	Small
258	Town of Liberty Stevensville Water Dist.	D-1967-121 CP-2	NY	465	Very Small
259	Town of Liberty White Sulphur Springs Water dist.	D-1967-121 CP-2	NY	188	Very Small
260	Town of Middletown Water Department	D-1978-064 CP-2	DE	8,336	Medium
261	Town of Milton	D-1983-022 CP REN 2	DE	1,914	Small
262	Town of Rockland Livingston Manor Water District	D-1963-004 CP-2	NY	524	Very Small
263	Town of Rockland Roscoe Rockland Water District	D-1963-004 CP-2	NY	331	Very Small
264	Town of Smyrna	AA-1993-072 CP	DE	3,500	Small
265	Township of Allamuchy	AA-1977-060 CP	NJ	2,305	Small
266	Township of Maple Shade	OP-1978-018 CP-2	NJ	4,709	Small
267	Township of Roxbury	OP-1996-017 CP-2	NJ	1,731	Small
268	Trenton Water Works	OP-1998-009 CP-2	NJ	63,500	Very Large
269	Trumbauersville Municipal Waterworks	D-1977-005 CP	PA	389	Very Small
270	Upper Deerfield Township/Water Department	OP-1993-016 CP-3	NJ	843	Very Small
271	Upper Makefield Township	D-2007-024 CP-2	PA	691	Very Small
272	Upper Saucon Township	D-2000-051 CP-3	PA	3,061	Small
273	Upper Southampton Municipal Authority	D-1965-023 CP-3	PA	5,119	Medium
274	Utilities Inc - Westgate	D-1968-111 CP	PA	985	Very Small
275	Veolia Water Delaware	D-1996-050 CP-3	DE	40,687	Very Large
276	Village of Delhi	D-1975-070 CP-2	NY	701	Very Small
277	Village of Deposit	D-1999-064 CP-2	NY	660	Very Small
278	Village of Hancock	D-1969-058 CP	NY	481	Very Small
279	Village of Hobart	D-1976-094 CP	NY	185	Very Small
280	Village of Liberty	D-2013-002 CP-1	NY	1,644	Small
281	Village of Margaretville	D-1974-157 CP-3	NY	300	Very Small
282	Village of Monticello	D-2001-005 CP-2	NY	2,108	Small
283	Village of Walton	D-1972-061 CP	NY	1,201	Small
284	Village of Wurtsboro	D-1994-025 CP-2	NY	473	Very Small
285	Wallenpaupack Lake Estates	D-1971-150 CP-2	PA	1,419	Small
286	Walnutport Authority	D-1990-087 CP-3	PA	1,092	Small
287	Warminster Municipal Authority	D-2000-019 CP-2	PA	10,979	Large
288	Warrington Township Water and Sewer	D-1990-019 CP-4	PA	8,688	Medium
289	Warwick Township Water & Sewer Authority	D-1998-019 CP-3	PA	4,282	Small
290	Washington Township Municipal Utilities Authority	AA-1999-043 CP	NJ	17,666	Large
291	Weatherly Borough Water System	D-1980-080 CP-4	PA	970	Very Small
292	Wernersville Municipal Authority	D-2001-017 CP-2	PA	2,303	Small
293	West Deptford Township Water Department	OP-1979-082 CP-4	NJ	7,205	Medium
294	West Grove Borough Authority	D-1996-026 CP-3	PA	923	Very Small
295	Westville Water Department	OP-1979-086 CP RENEWAL	NJ	1,827	Small
296	Whitehall Township Authority	D-2000-009 CP-2	PA	2,908	Small
297	Willingboro Municipal Utilities Authority	OP-1987-042 CP-3	NJ	12,870	Large
298	Wilmington Water Department	D-0000-004 ENT 140	DE	37,309	Very Large

Row	Name	Reference Number	State	N_c (2021)	Class
299	Womelsdorf-Robesonia Joint Authority	D-1998-023 CP-3	PA	2,258	Small
300	Wrightstown Borough MUA	AA-1974-113 CP	NJ	264	Very Small

B. AWWA Free Water Audit Software Definitions

Item Name	Abv.	Description
Apparent Losses	AL	= systematic data handling errors + customer metering inaccuracies + unauthorized consumption Apparent Losses include all types of inaccuracies associated with customer metering (worn meters as well as improperly sized meters or wrong type of meter for the water usage profile) as well as systematic data handling errors (meter reading, billing, archiving and reporting), plus unauthorized consumption (theft or illegal use). NOTE: Over-estimation of Apparent Losses results in under-estimation of Real Losses. Under-estimation of Apparent Losses results in over-estimation of Real Losses.
AUTHORIZED CONSUMPTION	AC	= billed metered + billed unmetered + unbilled metered + unbilled unmetered consumption The volume of metered and/or unmetered water taken by registered customers, the water utility's own uses, and uses of others who are implicitly or explicitly authorized to do so by the water utility; for residential, commercial, industrial and public-minded purposes. Typical retail customers' consumption is tabulated usually from established customer accounts as billed metered consumption, or - for unmetered customers - billed unmetered consumption. These types of consumption, along with billed water exported, provide revenue potential for the water utility. Typically a lag will exist between timing for reading of supply meters and reading of customer meters. A lag-time correction should typically be calculated to account for this. **Be certain to tabulate the water exported volume as a separate component and do not "double-count" it by including in the billed metered consumption component as well as the water exported component.** Unbilled authorized consumption occurs typically in non-account uses, including water for fire fighting and training, flushing of water mains and sewers, street cleaning, watering of municipal gardens, public fountains, or similar public-minded uses. Occasionally these uses may be metered and billed (or charged a flat fee), but usually they are unmetered and unbilled. In the latter case, the water auditor may use a default value to estimate this quantity, or implement procedures for the reliable quantification of these uses. This starts with documenting usage events as they occur and estimating the amount of water used in each event. (See Unbilled Unmetered Authorized Consumption)

Item Name	Abv.	Description
Average Length of (private) Customer Service Line	L_p	This is the average length of underground customer service line, Lp, that is owned and maintained by the customer; from the point of ownership transfer to the customer water meter, or building line (if unmetered). The quantity is one of the data inputs for the calculation of Unavoidable Annual Real Losses (UARL), which serves as the denominator of the performance indicator: Infrastructure Leakage Index (ILI). The value of Lp is multiplied by the number of customer service connections to obtain a total length of customer owned piping in the system. The purpose of this parameter is to account for the unmetered service line infrastructure that is the responsibility of the customer for arranging repairs of leaks that occur on their lines. In many cases leak repairs arranged by customers take longer to be executed than leak repairs arranged by the water utility on utility-maintained piping. Leaks run longer - and lose more water - on customer-owned service piping, than utility owned piping. If the customer water meter exists near the ownership transfer point (usually the curb stop located between the water main and the customer premises) this distance is zero because the meter and transfer point are the same. This is the often encountered configuration of customer water meters located in an underground meter box or "pit" outside of the customer's building. The Free Water Audit Software asks a "Yes/No" question about the meter at this location. If the auditor selects "Yes" then this distance is set to zero and the data grading score for this component is set to 10. If water meters are typically located inside the customer premise/building, or properties are unmetered, it is up to the water auditor to estimate a system-wide average Lp length based upon the various customer land parcel sizes and building locations in the service area. Lp will be a shorter length in areas of high density housing, and a longer length in areas of low density housing and varied commercial and industrial buildings. General parcel demographics should be employed to obtain a total Lp length (Lc) and subsequently a weighted average Lp length for the entire system. Refer to the "Service Connection Diagram" worksheet for a depiction of the service line/metering configurations that typically exist in water utilities. This worksheet gives guidance on the determination of the Average Length, Lp, for each configuration.
Average Operating Pressure	P_{AO}	This is the average pressure in the distribution system that is the subject of the water audit. If the water utility is compiling the water audit for the first time, the average pressure can be approximated, but with a low data grading. In subsequent years of auditing, effort should be made to improve the accuracy of the average pressure quantity. This will then qualify the value for a higher data grading. In the absence of a hydraulic model, the average pressure may be approximated by obtaining readings of static water pressure from a representative sample of fire hydrants or other system access points evenly located across the system. A weighted average of the pressure can be assembled; but be sure to take into account the elevation of the fire hydrants, which typically exist several feet higher than the level of buried water pipelines. If your water utility has an up-to-date and calibrated hydraulic model of the water distribution system, it can be utilized to obtain a very accurate quantity of average pressure. However using the average pressure of all "nodes" in the system model is not necessarily the most accurate way to calculate the average operating pressure. This is especially true if there are significant pressure differences throughout the system, and the "nodes" are not evenly distributed throughout the distribution system. The most accurate calculation is to obtain the average pressure that each pipe segment experiences. The way to do this is to calculate the pressure at each end of the pipe. Then calculate the average of those two values and multiply this average value by the length of that pipe. This must be calculated for all pipe segments in the model. Finally calculate the sum of all of these values and divide by the total pipe length. This effectively calculates a weighted average of pressure over the total pipe length. For low density systems (<32 connections/mile), average mains pressures at the service connection or curb stop may have greater influence and should be considered.
Billed Authorized Consumption	BAC	All consumption that is billed and authorized by the utility. This may include both metered and unmetered consumption. See "Authorized Consumption" for more information.

Item Name	Abv.	Description
Billed Metered Authorized Consumption	BMAC	All metered consumption which is billed to retail customers, including all groups of customers such as domestic, commercial, industrial or institutional. **It does NOT include water supplied to neighboring utilities (water exported) which is metered and billed. Be sure to subtract any consumption for exported water sales that may be included in these billing roles. Water supplied as exports to neighboring water utilities should be included only in the Water Exported component.** The metered consumption data can be taken directly from billing records for the water audit period. The accuracy of yearly metered consumption data can be refined by including an adjustment to account for customer meter reading lag time since not all customer meters are read on the same day of the meter reading period. However additional analysis is necessary to determine the lag time adjustment value, which may or may not be significant.
Billed Unmetered Authorized Consumption	BUAC	All billed consumption which is calculated based on estimates or norms from water usage sites that have been determined by utility policy to be left unmetered. This is typically a very small component in systems that maintain a policy to meter their customer population. However, this quantity can be the key consumption component in utilities that have not adopted a universal metering policy. **This component should NOT include any water that is supplied to neighboring utilities (water exported) which is unmetered but billed. Water supplied as exports to neighboring water utilities should be included only in the Water Exported component.**
Customer Metering Inaccuracies	CMI	Apparent water losses caused by the collective under-registration of customer water meters. Many customer water meters gradually wear as large cumulative volumes of water are passed through them over time. This causes the meters to under-register the flow of water. This occurrence is common with smaller residential meters of sizes 5/8-inch and 3/4 inch after they have registered very large cumulative volumes of water, which generally occurs only after periods of years. For meters sized 1-inch and larger - typical of multi-unit residential, commercial, institutional and industrial accounts - meter under-registration can occur from wear or from the improper application of the meter; i.e. installing the wrong type of meter or the wrong size of meter, for the flow pattern (profile) of the consumer. For instance, many larger meters have reduced accuracy at low flows. If an oversized meter is installed, most of the time the routine flow will occur in the low flow range of the meter, and a significant portion of it may not be registered. It is important to properly select and install all meters, but particularly large customer meters, size 1-inch and larger. The auditor has two options for entering data for this component of the audit. The auditor can enter a percentage under-registration (typically an estimated value), this will apply the selected percentage to the two categories of metered consumption to determine the volume of water not recorded due to customer meter inaccuracy. Note that this percentage is a composite average inaccuracy for all customer meters in the entire meter population. The percentage will be multiplied by the sum of the volumes in the Billed Metered and Unbilled Metered components. Alternatively, if the auditor has substantial data from meter testing activities, he or she can calculate their own loss volumes, and this volume may be entered directly. Note that a value of zero will be accepted but is not recommended, as all metered systems tend to have some degree of inaccuracy. A positive value should be entered. A value of zero in this component is generally valid only if the water utility does not meter its customer population. The formula for calculating a volume of CMI from a percentage input is as follows: CMI volume = (BMAC+UMAC)/(1-CMI%)-(BMAC+UMAC)

Item Name	Abv.	Description
Customer Retail Unit Charge	CRUC	The Customer Retail Unit Charge represents the volumetric portion of the total charges that customers pay for water service. The CRUC does not include fixed charges. This unit charge cost is applied routinely to the components of Apparent Loss, since these losses represent water reaching customers but not (fully) paid for. Since most water utilities have a rate structure that includes a variety of different charges costs based upon class of customer, a volume-weighted average of water sold at each unique rate should be calculated to determine a single composite charge that should be entered into this cell. Finally, the weighted average charge should also include additional charges for sewer, storm water or biosolids processing, but only if these charges are based upon the volume of potable water consumed. For water utilities in regions with limited water resources and a questionable ability to meet the drinking water demands in the future, the Customer Retail Unit Charge Cost might also be applied to value the Real Losses; instead of applying the Variable Production Cost to Real Losses. In this way, it is assumed that every unit volume of leakage reduced by leakage management activities will be sold to a customer. Note: the Free Water Audit Software allows the user to select the units that are charged to customers (either \$/1,000 gallons, \$/hundred cubic feet, or \$/1,000 litres) and automatically converts these units for purpose of calculating Apparent Loss valuations. The monetary units are United States dollars, \$.
Infrastructure Leakage Index	ILI	The ratio of the Current Annual Real Losses (Real Losses) to the Unavoidable Annual Real Losses (UARL). This performance indicator is dimensionless. **NOTES ON THE UARL AND ILI:** 1. This Free Water Audit Software version 6 presents the calculated UARL and ILI for systems of all sizes and all pressures. Some published research is now available on predicting how UARL is likely to be modified when modeling low leakage limits in systems that are very small (< 3000 conn), or have very low average pressures, or have very high pressures (aka boundary cases). Inherent over- or under- estimation of UARL volume may exist in these boundary cases, as they operate at or near the limits of the UARL model assumptions. More widespread application and understanding of system specific corrections to the UARL model in these boundary cases is now likely to occur, but are not included in the FWAS at the time of this publication. Caution is advised when using the standard UARL modeled value (and subsequently the ILI) for boundary cases. In boundary cases, the ILI may still be considered a general Performance Indicator, but not used as an absolute performance measurement or for benchmark comparisons. 2. The UARL term is based on average operating pressure in a given audit year, and a utility's current pressure conditions may not be optimized. Thus, ILI should always be interpreted with some measure of pressure, and only used for tracking progress if all justifiable pressure management has already been completed.
Length of Mains	L_m	Length of all pipelines (except service connections) in the system starting from the point of system input metering (for example at the outlet of the treatment plant). It is also recommended to include in this measure the total length of fire hydrant lead pipe. Hydrant lead pipe is the pipe branching from the water main to the fire hydrant. Fire hydrant leads are typically of a sufficiently large size that is more representative of a pipeline than a service connection. The average length of hydrant leads across the entire system can be assumed if not known, and multiplied by the number of fire hydrants in the system, which can also be assumed if not known. This value can then be added to the total pipeline length. Total length of mains can therefore be calculated as: Length of Mains, miles = (total pipeline length, miles) + [{(average fire hydrant lead length, ft) x (number of fire hydrants)} / 5,280 ft/mile] or Length of Mains, kilometres = (total pipeline length, kilometres) + [{(average fire hydrant lead length, metres) x (number of fire hydrants)} / 1,000 metres/kilometre]

Item Name	Abv.	Description
NON-REVENUE WATER	NRW	= Apparent Losses + Real Losses + Unbilled Metered Consumption + Unbilled Unmetered Consumption. This is water which does not provide revenue potential to the utility.
Number of Service Connections	N_c	Number of customer service connections, extending from the water main to supply water to a customer. This includes the actual number of pressurized piping connections, including fire connections, **whether active or inactive**. This may differ substantially from the number of customers (or number of accounts). **Note: this number does not include the pipeline leads to fire hydrants. The total length of piping supplying fire hydrants should be included in the "Length of mains" input, and excluded from the Number of service connections input.**
Real Losses	RL	Physical water losses from the pressurized system (water mains and customer service connections) and the utility's storage tanks, up to the point of customer consumption. In metered systems this is the customer meter, in unmetered situations this is the first point of consumption (stop tap/tap) within the property. The annual volume lost through all types of leaks, breaks and overflows depends on frequencies, flow rates, and average duration of individual leaks, breaks and overflows.
Revenue Water	RW	Those components of System Input Volume that are billed and have the potential to produce revenue.
Service Connection Density	SCD	=number of customer service connections / length of mains

Item Name	Abv.	Description
Systematic Data Handling Errors	SDHE	Apparent losses caused by accounting omissions, errant computer programming, gaps in policy, procedure, and permitting/activation of new accounts; and any type of data lapse that results in under-stated customer water consumption in summary billing reports. Systematic Data Handling Errors occur as a customer consumption volume and can result in a direct loss of revenue potential. Water utilities can find "lost" revenue by keying on this component. Utilities typically measure water consumption volumes registered by water meters at customer premises. The meter should be read routinely (ex: monthly) and the data transferred to the Customer Billing System, which generates and sends a bill to the customer. Data Transfer Errors result in the registered consumption volume value being less than the actual consumption volume, creating an apparent loss. Such error might occur from illegible and mis-recorded hand-written readings compiled by meter readers, inputting an incorrect meter register unit conversion factor in the automatic meter reading equipment, or a variety of similar errors. Apparent losses also occur from Data Analysis Errors in the archival and data reporting processes of the Customer Billing System. Inaccurate estimates used for accounts that fail to produce a meter reading are a common source of error. Billing adjustments may award customers a rightful monetary credit, but do so by creating a negative value of consumption volume, thus under-stating the actual consumption. Account activation lapses may allow new buildings to begin using water for months without meter readings and billing. Poor permitting and construction inspection practices can result in a new building water service commencing without a billing account, a water meter and meter reading; i.e., the customer is unknown to the utility's billing system. Close auditing of the permitting, metering, meter reading, billing and reporting processes of the water consumption data trail can uncover data management gaps that create volumes of systematic data handling error. Utilities should routinely analyze customer billing records to detect data anomalies and quantify these losses. For example, a billing account that registers zero consumption for two or more billing cycles should be checked to explain why usage has seemingly halted. Given the revenue loss impacts of these losses, water utilities are well-justified in providing continuous oversight and timely correction of data transfer errors & data handling errors. If the water auditor has not yet gathered detailed data or assessment of systematic data handling error, it is recommended that the auditor apply the default value of 0.25% of the Billed Authorized Consumption volume. However, if the auditor has investigated the billing system and its controls, and has well validated data that indicates the volume from systematic data handling error is substantially higher or lower than that generated by the default value, then the auditor should enter a quantity that was derived from the utility investigations and select an appropriate grading. Negative or zero values are not allowed for this audit component. Note: occasionally billed consumption volumes for a customer account may be over-stated due to issues of double-counting an account or applying an over-stated meter multiplier. The possibility of such occurrences should be explored in the data validation process, particularly if billed authorized consumption volumes for the year, or for any sub-group of customers (by classification or meter size), appears to be inordinately high. It is recommended to correct any such errors in the billed consumption total for the year, rather than consider these volumes part of Systematic Data Handling Error.
Total annual operating cost (optional input)	TAOC	*This input has been made optional, as it is no longer used in calculating a Performance Indicator. Auditors are welcome to continue to track this input as desired.* These costs include those for operations, maintenance and any annually incurred costs for long-term upkeep of the drinking water supply and distribution system. It should include the costs of day-to-day upkeep and long-term financing such as repayment of capital bonds for infrastructure expansion or improvement. Typical costs include employee salaries and benefits, materials, equipment, insurance, fees, administrative costs and all other costs that exist to sustain the drinking water supply. Depending upon water utility accounting procedures or regulatory agency requirements, it may be appropriate to include depreciation in the total of this cost. This cost should not include any costs to operate wastewater, biosolids or other systems outside of drinking water.

Item Name	Abv.	Description
Unauthorized Consumption	UC	Includes water illegally withdrawn from fire hydrants, illegal connections, bypasses to customer consumption meters, or tampering with metering or meter reading equipment; as well as any other ways to receive water while thwarting the water utility's ability to collect revenue for the water. Unauthorized consumption results in uncaptured revenue and creates an error that understates customer consumption. In most water utilities this volume is low and, if the water auditor has not yet gathered detailed data for these loss occurrences, it is recommended to use the default value of 0.25% of the Billed Authorized Consumption volume. However, if the auditor has investigated unauthorized occurrences, and has well validated data that indicates the volume from unauthorized consumption is substantially higher or lower than that generated by the default value, then the auditor should enter a quantity that was derived from the utility investigations. Note that a value of zero will not be accepted since all water utilities tend to have some volume of unauthorized consumption occurring in their system.
Unavoidable Annual Real Losses	UARL	The UARL is a theoretical reference value representing the technical low limit of leakage for well managed systems in good condition, with aggressive active leakage control. It is a key variable in the calculation of the Infrastructure Leakage Index (ILI). UARL (gallons) = (5.41Lm + 0.15Nc + 7.5Lc) x P x 365 d/year, or UARL (liters) = (18.0Lm + 0.8Nc + 25.0Lc) x P x 365 d/year Where: Lm = length of mains (miles or kilometers) Nc = number of customer service connections Lp = the average length of customer service connection piping (feet or meters) (see the Worksheet "Service Connection Diagram" for guidance on deterring the value of Lp) Lc = total length of customer service connection piping (miles or km) Lc = Nc X Lp (miles or kilometers) P = Average operating pressure (psi or meters) (see Average Operating Pressure definition) **NOTES ON THE UARL AND ILI:** 1. This Free Water Audit Software version 6 presents the calculated UARL and ILI for systems of all sizes and all pressures. Some published research is now available on predicting how UARL is likely to be modified when modeling low leakage limits in systems that are very small (< 3000 conn), or have very low average pressures, or have very high pressures (aka boundary cases). Inherent over- or under- estimation of UARL volume may exist in these boundary cases, as they operate at or near the limits of the UARL model assumptions. More widespread application and understanding of system specific corrections to the UARL model in these boundary cases is now likely to occur, but are not included in the FWAS at the time of this publication. Caution is advised when using the standard UARL modeled value (and subsequently the ILI) for boundary cases. In boundary cases, the ILI may still be considered a general Performance Indicator, but not used as an absolute performance measurement or for benchmark comparisons. 2. The UARL term is based on average operating pressure in a given audit year, and a utility's current pressure conditions may not be optimized. Thus, ILI should always be interpreted with some measure of pressure, and only used for tracking progress if all justifiable pressure management has already been completed.
Unbilled Authorized Consumption	UAC	All consumption that is unbilled, but still authorized by the utility. This includes Unbilled Metered Authorized Consumption (UMAC) + Unbilled Unmetered Authorized Consumption (UUAC). See "Authorized Consumption" for more information.
Unbilled Metered Authorized Consumption	UMAC	Metered consumption which is authorized by the water utility, but, for any reason, is deemed by utility policy to be unbilled. This might for example include metered water consumed by the utility itself in treatment or distribution operations, or metered water provided to civic institutions free of charge. **It does not include water supplied to neighboring utilities (water exported) which may be metered but not billed.**

Item Name	Abv.	Description
Unbilled Unmetered Authorized Consumption	UUAC	Any kind of Authorized Consumption which is neither billed nor metered. This component typically includes water used in activities such as fire fighting, flushing of water mains and sewers, street cleaning, fire flow tests conducted by the water utility, etc. In most water utilities it is a small component. This component does NOT include water supplied to neighboring utilities (water exported) which is unmetered and unbilled – an unlikely case. Also, if any potable water used at a water treatment plant is tapped from a location upstream of the meter(s) used to determine the Volume from Own Sources in the audit, this is outside of the boundary of the audit and should therefore not be included as part of Unbilled, Unmetered Authorized Consumption. This component has many sub-components of water use which may not yet be quantified. The default is 0.25% of the Billed Authorized Consumption volume (BMAC + BUAC), and is recommended for temporary use if customized estimates are not yet available, with recommendation to begin tracking and estimating these volumes for the next audit. Note that a value of zero is not permitted, since all water utilities likely have some volume of water in this component occurring in their system.
Variable Production Cost (applied to Real Losses)	VPC	The cost to produce and supply the next unit of water (e.g., $/million gallons). This cost can include both short-run and long-run marginal costs. See the VPC data grading questions on IDG tab for examples of short-run and long-run marginal costs that may be included. It is common to apply the VPC unit cost to the volume of Real Losses. However, if water resources are strained and the ability to meet future drinking water demands is in question, then the water auditor may be justified in applying the Customer Retail Unit Charge to the Real Loss volume, rather than applying the Variable Production Cost.
Volume from Own Sources(VOS)	VOS	The volume of water withdrawn (abstracted) from water resources (rivers, lakes, streams, wells, etc) controlled by the water utility, and then treated for potable water distribution. Most water audits are compiled for utility retail water distribution systems, so this volume should reflect the amount of treated drinking water that entered the distribution system. Often the volume of water measured as treated effluent of the treatment works is slightly less than the volume measured at the raw water source, since some of the water is used in the treatment process. Thus, it is useful if flows are metered at the effluent of the treatment works. Water treatment plants are also often supplied potable drinking water and therefore are a "customer" of the water utility. If the service connection line serving the water treatment plant is downstream of treated water effluent flowmeters, this water should be metered and billed as billed authorized consumption. In this case, this volume of water does not enter into any calculations for Volume from Own Sources. If the service connection line suppling potable water to the treatment plant is upstream of treated water effluent flowmeters, then this water is considered "process" water and included with calculations accounting for process water use. If metering exists only at the raw water source, an adjustment for water used in the treatment process should be included to account for water consumed in treatment operations such as filter backwashing, basin flushing and cleaning, plant potable water consumption (if the supply is drawn upstream of effluent flow metering.) and similar uses. If the audit is conducted for a wholesale water agency that sells untreated water, then this quantity reflects the measure of the raw water, typically metered at the source.

Item Name	Abv.	Description
Volume from own sources: error adjustment	VOSEA	An estimate or measure of the degree of inaccuracy that exists in the master (production) meters measuring the annual Volume from own Sources, and any error in the data trail that exists to collect, store and report the summary production data. This adjustment is a weighted average number that represents the collective error for all master meters for all days of the audit year and any errors identified in the data trail. Meter error can occur in different ways. A meter or meters may be inaccurate by under-registering flow (did not capture all the flow), or by over-registering flow (overstated the actual flow). Data error can occur due to data gaps caused by temporary outages of the meter or related instrumentation. All water utilities encounter some degree of inaccuracy in master meters and data errors in archival systems are common. Enter a positive percentage or volume, then select 'under-registration' or 'over-registration' from the drop-down immediately adjacent. **See Water Supplied Error Adjustments definition for guidance on how to calculate this input.**
Water Exported	WE	The Water Exported volume is the bulk water conveyed or sold by the water utility to neighboring water systems that exists outside of their service area. Typically this water is metered at the custody transfer point of interconnection between the two water utilities. Usually the meter(s) are owned by the water utility that is selling or transferring the water: i.e. the exporter. If the water utility who is compiling the annual water audit sells or transfers bulk water in this manner, they are an exporter of water. Note: The Water Exported volume is typically sold to wholesale customers who are charged a wholesale rate that is different than retail rates charged to the retail customers existing within the service area. Many state regulatory agencies require that the Water Exported volume be reported to them as a quantity separate and distinct from the retail customer billed consumption. For these reasons - and others - the Water Exported volume is always quantified separately from Billed Authorized Consumption in the standard water audit. **Be certain not to "double-count" this quantity by including it in both the Water Exported box and the Billed Metered Consumption box of the water audit Worksheet. This volume should be included only in the Water Exported box.**
Water Exported: Error Adjustment	WEEA	An estimate or measure of the volume by which the Water Exported volume is incorrect. This adjustment is a weighted average that represents the collective error for all of the metered and archived exported flow for all days of the audit year. Meter error can occur in different ways. A meter may be inaccurate by under-registering flow (did not capture all the flow), or by over-registering flow (overstated the actual flow). Error in the metered, archived data can also occur due to data gaps caused by temporary outages of the meter or related instrumentation. All water utilities encounter some degree of error in their metered data, particularly if meters are aged and infrequently tested. Occasional errors also occur in the archived data. Enter a positive percentage or volume, then select 'under-registration' or 'over-registration' from the drop-down immediately adjacent. If regular meter accuracy testing is conducted on the meter(s) - which is usually conducted by the water utility selling the water - then the results of this testing can be used to help quantify the meter error adjustment. Corrections to data gaps or other errors found in the archived data should also be included as a portion of this meter error adjustment. S**ee Water Supplied Error Adjustments definition for guidance on how to calculate this input.**
Water Imported	WI	The Water Imported volume is the bulk water purchased to become part of the Water Supplied volume. Typically this is water purchased from a neighboring water utility or regional water wholesale supplier, and is metered at the custody transfer point of interconnection between the two water utilities. Usually the meter(s) are owned by the water supplier selling the water to the utility conducting the water audit. The water supplier selling the bulk water usually charges the receiving utility based upon a wholesale water rate.

Item Name	Abv.	Description
Water Imported: Error Adjustment	WIEA	An estimate or measure of the volume by which the Water Imported volume is incorrect. This adjustment is a weighted average that represents the collective error for all of the metered and archived imported flow for all days of the audit year. Meter error can occur in different ways. A meter may be inaccurate by under-registering flow (did not capture all the flow), or by over-registering flow (overstated the actual flow). Error in the metered, archived data can also occur due to data gaps caused by temporary outages of the meter or related instrumentation. All water utilities encounter some level of meter inaccuracy, particularly if meters are aged and infrequently tested. Occasional errors also occur in the archived metered data. Enter a positive percentage or volume, then select 'under-registration' or 'over-registration' from the drop-down immediately adjacent. If regular meter accuracy testing is conducted on the meter(s) - which is usually conducted by the water utility selling the water - then the results of this testing can be used to help quantify the meter error adjustment. See Water Supplied Error Adjustments definition for guidance on how to calculate this input.
WATER LOSSES	WL	= apparent losses + real losses = water supplied - authorized consumption Water Losses are the difference between Water Supplied and Authorized Consumption. Water losses can be considered as a total volume for the whole system, or for partial systems such as transmission systems, pressure zones or district metered areas (DMA), if one of these configurations are the basis of the water audit.

Item Name	Abv.	Description
Water Supplied Error Adjustments	WSEA	**Disclaimer**: The guidance provided below should be considered general, representing a typical approach to determining Error Adjustment. Supply metering setups, metering technologies, instrumentation, data recording/archival, and data management systems can vary significantly from one water utility to the next. Inherent margins of error will also vary among different testing and calibration methods and the measurement systems being tested. Other factors that may be important include, but are not limited to, frequency of testing and calibration practices, data communication outages in the audit period, tested flowrates versus typical operating flowrates, and test durations. All of these factors must be considered when assessing Error Adjustment for the Water Supplied inputs. Each specific situation should be carefully analyzed to determine the most appropriate approach for determining the Error Adjustment to input, if any. **General**: For the Water Supplied inputs, there are three typical sources of error that may warrant an Error Adjustment on the Worksheet. 3. **Meter error**: measurement inaccuracy in the meter(s) used to derive the input volume, typically identified through in-situ flow accuracy testing. Applicable for VOS, WI and WE. If no such testing has been performed, adjustment for meter error is not typically recommended. 4. **Data transfer error**: inaccuracy in archived volumes, typically due to gaps in data, programming errors impacting unit conversions, and/or programming errors impacting totalization of measured volumes over the audit period. Applicable for VOS, WI and WE. These errors are typically identified through electronic calibration to verify data transfer at the secondary device (i.e. conversion to mA, meter transmitter or similar instrumentation) and/or the tertiary device (i.e. SCADA, historian or other computerized archival system). 5. **Net distribution storage change**: The difference between end of audit period and beginning of audit period for total finished water stored, downstream of the system input meter(s). Typically applicable for VOS or WI. This volume is typically derived by comparing distribution storage tank water levels at end and beginning of the water audit period and using approximate tank geometry to convert levels to volumes. **Derivation Guidance**: If an Error Adjustment input is being calculated as a volume, each source of error (described above) may be separately calculated, with careful consideration of under- vs over-registration, then added together to determine the composite volume to input. The composite input should be entered on the Worksheet as a positive number, then under- or over-registration selected on the adjacent dropdown. If an Error Adjustment input is being calculated as a percent, some very general guidance for calculating each error source (described above) is provided below. The auditor is again cautioned that each specific water supply setup needs to be evaluated closely as noted in the Disclaimer. Refer to the latest AWWA M36 Manual for additional discussion and guidance on this matter. 1. Meter error: If in-situ flow accuracy testing has been performed, and inherent testing method error is understood, first the meter accuracy % may be determined as follows: meter accuracy % = System input meter(s) volume / Reference volume Then, the meter error % may be determined as follows: meter error % = meter accuracy % - 100% 2. Data transfer error: If electronic calibration at the secondary (i.e. conversion to mA, meter transmitter or similar instrumentation) and/or tertiary (i.e. SCADA, historian or other computerized archival system) devices has been performed, first the data transfer accuracy % may be determined as follows: data transfer accuracy % = Tertiary device volume / Reference volume (typically at Secondary device) Then, the data transfer error % may be determined as follows: data transfer error % = data transfer accuracy % - 100% If no error is identified, or if electronic calibration has not been performed, or if no secondary or tertiary devices exist, a data transfer error % adjustment is not typically recommended. 3. Net distribution storage change. If meter error and/or data transfer error are being calculated as a %, it is recommended to make the adjustment for net distribution storage change as a volume adjustment, directly in the VOS or WI input, as applicable. The final step is to add meter error % and data transfer error %: Error Adjustment % = meter accuracy % + data transfer error % If the total Error Adjustment % calculates out as a negative number, it represents an under-registration. Vice versa, if positive. The composite input should be entered on the Worksheet as a positive number, then under- or over-registration selected on the adjacent dropdown.