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DEVELOPMENT OF ACTIONABLE METRICS FOR WATER LOSS REDUCTION IN WATER DISTRIBUTION SYSTEMS

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by

James R. Markham

B.A., Political Science, Haverford College, 1988

J.D., The University of Chicago Law School, 1992

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

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- the utilities who provided data; and
- my coworkers at the Southwest Environmental Finance Center for listening to my endless chatter about water main breaks.

Dedication

I dedicate this document to:

- my wife Lori for her constant support and encouragement through this long process;
- my parents Heidi and Charles for putting me on the path through life and accepting it when I changed directions;
- my extended family old and new: Markhams, Townsends, Barricks, Lonergans, and Knowles for love and support;
- my furry cheerleaders Frejya, Samson, Rosie, Otis, Fidda and Buster for staying up with me on late nights; and
- all of my friends who now know more about water mains than they probably ever wanted to.

I sincerely thank you all.

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Abstract

Many water utilities lose significant amounts of treated water (and the revenue that does with it) through pipe breaks or undetected leaks in their underground distribution networks. To help utilities understand their water loss, the American Water Works Association (AWWA) developed a water audit software program (Water Audit Software) which calculates lost volumes and system performance indicators based on input supplied by the water utility.

To make the Water Audit Software a more useful tool for a greater number of utilities and the states that mandate auditing, additional fields should be added to the Water Audit Software to collect data about system pipe materials, main line breaks categorized by pipe material, and their average break isolation and repair times. This data should be used to calculate two new PIs: 1) a dimensionless Break Rate Index (BRI) which compares system main line break data to

published national break averages, and 2) a dimensionless Repair Time Index (RTI) that compares system main break repair time averages to best practice repair times.

Including the BRI and RTI in the audit will identify slow repair times and the types of pipe in a system that have the highest failure rates, thereby providing utilities with immediately useful, actionable information upon the completion of the audit that can be used to improve the distribution system and reduce real water loss. It would also result in the creation of a large-scale main break and repair data set that could be used by local, regional and/or national authorities to develop utility standards.

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Abbreviations and Acronyms

AC	Asbestos Cement
AWWA	American Water Works Association
BGL	Background Leakage
CARL	Current Annual Real Loss
CI	Cast Iron
CSC	Cast Spun Concrete
CWS	Community Water System
DI	Ductile Iron
GIS	Geographic Information System
GPS	Global Positioning System
HDPE	High Density Polyethylene
PDF	Portable Document Format
PVC	Poly Vinyl Chloride
DRBC	Delaware River Basin Commission
ILI	Infrastructure Leakage Index
M36	The AWWA M36 Manual
MG/YR	Millions of gallons per year
NRDC	Natural Resources Defense Council
PI	Performance Indicator
PWS	Public Water System
SW EFC	Southwest Environmental Finance Center
UARL	Unavoidable Annual Real Loss

UBL	Unavoidable Background Leakage
US	United States
WADI	AWWA Water Audit Data Initiative
WRF	Water Research Foundation

Chapter 1: Introduction

Water utilities distribute water to their customers through underground pipe networks called water distribution systems. All water distribution systems leak to some extent and billions of gallons of treated water are lost each day in the United States through pipe breaks and undetected leaks. (National Resources Defense Council, 2016) These breaks and leaks result in a significant loss of the product (treated water) and the revenue that goes with it. Growing awareness of these losses, and the realization that it is necessary for water utilities to be good stewards of water resources, has caused utilities to work harder to reduce real water losses from pipes.

While the need for water conservation has been part of public awareness for decades, and conservation efforts have focused on utility customers, the water industry has realized it has to be more responsible for the water leaking from the pipes. As water systems in the US have turned their attention inward, they are focusing on “accountable and efficient management of water supplies.” (AWWA, 2016b) This accountable and efficient management is termed “water loss control” and the specific activities that make up a utility’s program differ from system to system, and region to region, based on a number of factors including system finances, cost of treatment, supply issues, etc. Some systems with abundant supply may want to optimize the water loss reduction versus cost of reduction equation, while others in drought-prone areas may need to reduce real water loss to an absolute minimum due to supply constraints or for other environmental or societal reasons. One of the primary tools available for determining the scope of real loss in a water system is the water audit: a system-wide mass balance exercise.

The American Water Works Association ("AWWA") "promotes water auditing as the best practice for assessing water losses." (Water Research Foundation, 2019) Since 1990, the AWWA has published the M36 Water Audits and Loss Control Manual ("M36 Manual"), which details the generally accepted method for performing water audits in the United States.[1] To further help utilities understand their water loss, and to standardize the water auditing process, the AWWA released an Excel-based water audit software program in 2006 (the "Water Audit Software"). The Water Audit Software is currently on its 5th version and a 6th is under development with an expected release date of 2020.

The Water Audit Software uses the AWWA's M36 water audit methodology and, based on input supplied by the water utility, generates a water balance categorizing system inputs and outputs, and presents several performance indicators (PIs) with which utilities can evaluate their operational performance and frame their water loss control efforts.

Water auditing is mandatory for systems over a certain size in 11 US states and basic water loss reporting is required in at least 22 more. (AWWA, 2016a) Most states that require water audits mandate use of the M36 methodology and Water Audit Software, though a few have slightly modified the methodology and/or software requirement.

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[1] M36 is based on research by and has been developed in coordination with the International Water Association ("IWA").

Integral to the water audit and Water Audit Software are several efficiency PIs including:

1) Current Annual Real Losses ("CARL") - the volume of real losses calculated by subtracting all measured and estimated system outputs from all measured and estimated system inputs;

2) Unavoidable Annual Real Losses ("UARL") - a model of theoretically attainable, system specific, low levels of real losses that is based on system characteristics and is calculated using an empirically derived formula (detailed further below); and

3) the Infrastructure Leakage Index ("ILI") - a dimensionless index comparison metric which is the product of a system's CARL divided by its UARL.

The M36 Manual states that the ILI is the "performance indicator designed for comparisons among water utilities and for benchmarking performance." (AWWA, 2016b)

To paraphrase the British statistician George Box, "all models are wrong, some models are useful." Though both the UARL and ILI are touted as highly accurate in the Water Audit Software and M36 manual, it will be shown that 1) the UARL, when applied to water systems in the US, is likely inaccurate and 2) the ILI (which is based on the UARL) compounds that inaccuracy. Further, neither metric assists utilities with the assessment of the system-specific causes of real water loss. Because the UARL and ILI do not include directly actionable information about the sources of real water loss, the water audit process and

Water Audit Software are not as useful as they could be. Even if the underlying principle behind these PIs is sound, refining them in any meaningful way would likely require a data set that does appear to yet exist and would not overcome their major flaw: they do not present directly actionable information to the system being audited. Therefore, their importance should be de-emphasized, their inaccuracy should be clearly stated, and they should be supplemented with break and repair rate PIs that would provide comparisons of some of the causes of real water loss in systems such as main line leaks and breaks, and the time it takes to repair them. Adding such PIs to the Water Audit Software along with basic component analysis features would provide actionable information to systems using the Water Audit Software and would permit additional meaningful performance comparisons between systems.

1.1 Objective

The objective of this thesis is to investigate methods for water utilities to improve the assessment of real water loss due to breaks in their distribution systems. To achieve this objective,

1. The origins of the UARL and ILI are examined as are the ways the UARL and ILI are used by water utilities. The purported accuracy of the UARL and ILI are evaluated in light of their underlying assumptions, recent studies and real system data.
2. Water distribution system pipe materials, break rates and main break repair times are analyzed to determine whether they are sources of

actionable information for water utilities to identify and combat real water loss problems.

3. It is demonstrated that incorporating break and repair time PIs into a standard water audit will provide water utilities with more actionable information to address some sources of real water loss than the UARL and ILI PIs.

1.2 Data Sources and Methodology

This assessment involved a review of scientific literature, and several thousand water audits from US water systems. Additionally, GIS water main network maps and work order break and repair data from four water utilities in New Mexico were analyzed. This smaller data set was used to develop the proposed break and repair time PIs and demonstrate their effectiveness.

1.2.1 Water Audit Data Sets

An initial review of water audits was conducted using collated water audit data obtained from:

The AWWA Water Audit Data Initiative (covering 2011 to 2017)
The Tennessee Comptroller of the Treasury (covering 2015 to 2016)
The Texas Water Development Board (covering 2010 to 2015)
The Delaware River Basin Commission (covering 2012 to 2017)
The Georgia Department of Natural Resources (2013)
The Wisconsin Public Services Commission (covering 2017)

1.2.2 GIS Data and Work Order Data Sets

GIS databases and/or shapefiles containing water distribution system components were obtained from four New Mexico water utilities. Each of these sets of data was imported into ESRI's ArcMap 10.5 GIS program (ArcMap) and separate water main maps were created for each utility including (among other things) pipe material, diameter and location. All data sets were either delivered in, or were converted to, the appropriate State Plane projection for the area of New Mexico in which the municipality was located. Although the data provided by each of the four New Mexico water utilities was similar, there were some differences which are cataloged below.

1.2.2.1 System 1 Data

System 1 provided a GIS database containing its water distribution network assets. Break data for the periods 1995-2009 was obtained from a study done by the Southwest Environmental Finance Center (SW EFC) on behalf of System 1 in 2009. More recent data came in the form of Excel spreadsheet downloads from System 1's Maximo database. This Excel data was sorted, reduced to a list of main leak- and break-related work orders, and exported as a comma delimited ".csv" file containing all of the available work order attribute data. The exported .csv file was then imported into ArcMap as a table. Each entry in the imported table had a physical address associated with it representing the approximate location of the line break covered by the entry. These addresses were used to assign GPS coordinates to each table entry using the georeferencing tool built into ArcMap. Once the individual addresses were georeferenced, the table was converted to a layer file in ArcMap, and the resulting layer points were associated with distribution system mains by using the ArcMap “Near” tool which moved them to the closest main. After this association was completed annual pipe break statistics by material were calculated.

1.2.2.2 System 2 Data

System 2 provided a series of ArcGIS shapefiles cataloging its water distribution pipe network assets. System 2’s break data, which covers the period 2014 to 2017 came in two forms: 1) a GIS shapefile containing water main work order GPS points that referenced individual PDF forms containing work order details by file name, and 2) the work order PDF forms themselves, which contained all of the work order details. System 2 uses a single form for all water distribution system work. In order to separate breaks and leaks from other work orders, the individual PDF forms were combined into a single PDF file and data including the individual PDF file names was scraped from the combined PDF into an Excel file using an open-source, online software tool called Tabula (available at Tabula.com).

Once this Excel file had been created, it was saved as a comma-delimited .csv file. This .csv file was then imported into ArcMap and joined to the work order GIS layer file using the work order PDF file name reference field common to both. This joined attribute data was then sorted and reduced to break and leak related work orders, after which the points were moved to the nearest main using the ArcMap “Near” function in a manner similar to that used with the System 1 data. As above, pipe break statistics were calculated after the work order and pipe layers were joined by intersection and segregated by calendar year.

1.2.2.3 System 3 Data

System 3 provided a series of ArcGIS shapefiles cataloging its water distribution pipe network assets. System 3’s break data covering the years 2011 to 2016 was provided in the form of a 5-year leak report as well as an Excel spreadsheet containing water main leak data with addresses. The procedures performed on the System 3 break data followed the basic outline listed above for System 1 above.

1.2.2.4 System 4 Data

System 4’s break data came from a copy of their Microsoft Access work order database (System 4 Work Order Database) covering the period 2015 to 2017. All entries in the System 4 Work Order Database were exported into Excel, sorted, reduced to a list of main leak- and break-related work orders, and exported as a comma delimited “.csv” file containing all of the available work order attribute data. This file was then imported into ArcGIS and the same procedures detailed above were followed.

Examples of the pipe break statistic tables created with the data above are contained in Appendix 1 where the “Count_” field represents the number of breaks per pipe segment.

Chapter 2: The Current State of Water Loss Auditing in the US

To frame the discussion of PIs in this thesis, it is necessary to review water auditing practices in the US using the M36 methodology and Water Audit Software.

2.1 The Water Audit is a Mass Balance

Water auditing is an annual, “top-down” analysis used by water utilities to quantify volumes of water and cost values in various categories.[2] The audit is a mass balance: the volume of water entering a distribution system must equal the volume leaving the system when in-system storage is accounted for. Of the water that enters a distribution system, most (hopefully) will be transmitted as intended to customers, some (designated as “apparent loss”) will appear to be lost water but in actuality is the result of metering or accounting errors, or incorrect estimates of unmetered water, and some (designated as “real loss”) will be water that is physically lost through system background leakage, line breaks, and storage tank leaks and overflows.

Mathematically simplified, the water audit mass balance can be presented as follows (where each bracketed term represents a volume of water):

---

[2] Water audits are typically completed for a calendar year though a fiscal year timeframe may be used. The fiscal year option is more convenient when a utility’s fiscal year does not run from Jan 1 to Dec 31 because of the cost accounting elements of the water audit.

$$0 = [\mathit{Accumulation}]$$

$$= [\mathit{Water\ Supplied}] - [\mathit{Authorized\ Consumption}]$$

$$- [\mathit{Apparent\ Losses}] - [\mathit{Real\ Losses}]$$

Where,

$$\mathit{Water\ Supplied} = [\mathit{Water\ Produced}] + [\mathit{Water\ Imported}] - [\mathit{Water\ Exported}]$$

$$\mathit{Authorized\ Consumption}$$

$$= [\mathit{Billed\ Metered}] + [\mathit{Billed\ Unmetered}] + [\mathit{Unbilled\ Metered}]$$

$$+ [\mathit{Unbilled\ Unmetered}]$$

$$\mathit{Apparent\ Losses}$$

$$= [\mathit{Unauthorized\ Consumption}]$$

$$+ [\mathit{Customer\ Metering\ Inaccuracies}]$$

$$+ [\mathit{Systematic\ Data\ Handling\ Errors}]$$

$$\mathit{Real\ Losses} = [\mathit{Main\ and\ Service\ Line\ Background\ Losses}]$$

$$+ [\mathit{Main\ and\ Service\ Line\ Break\ Losses}] + [\mathit{Tank\ overflows}]$$ [3]

It is generally understood that real losses in a water system will never be zero. All water systems leak, and it is technically impossible to locate and repair every leak in a water system. (A. O. Lambert, 2009) This is an area in which perfection is neither necessary, desirable, nor even attainable as the expense of trying to stop every system leak would outweigh the savings resulting from the efforts. Practically, it is a matter of keeping leakage to an economically and environmentally reasonable and sustainable minimum as defined by the utility.

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[3] While the Water Audit Software calculates a sum for real losses (CARL), it does not categorize those losses into its constituent components.

There are many potential sources of error in the water audit mass balance calculation including summation errors made by the auditors developing the various data points, as well as potential errors resulting from the use of Water Audit Software default values for uncertain volumes such as theft, and systematic data collection error. Positive system input error and negative system output error both lead to higher calculated volumes of real loss. Conversely, negative system input error and positive system output error lead to lower calculated real loss volumes which can, in extreme circumstances, show up as negative real loss[4] - and a signal that significant data error is present in the audit.

2.2 The Current US Water Auditing Legislative Landscape

2.2.1 States That Require Some Form of Water Audit

As of the date of publication water auditing is required for systems meeting certain size requirements in California, Georgia, Hawaii, Illinois, Pennsylvania, Tennessee, Texas, Washington and Wisconsin, and in areas of Delaware, New York and New Jersey under the jurisdiction of the Delaware River Basin Commission (DRBC). Auditing is incentivized in New Mexico. (AWWA, 2016b) All of these jurisdictions use the M36 methodology and Water Audit Software with the exception of Washington and Wisconsin which use a modified methodology and reporting scheme, and Texas which uses the M36 methodology, but has its own reporting software. (AWWA, 2016a)

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[4] While it is possible that negative real loss could physically result in a case of infiltration contributing to an extra, unmeasured input, it is highly unlikely that this would occur in a fully pressurized water distribution system.

2.2.2 The Water Audit Software only partially meets the Goals of Water Audit Legislation

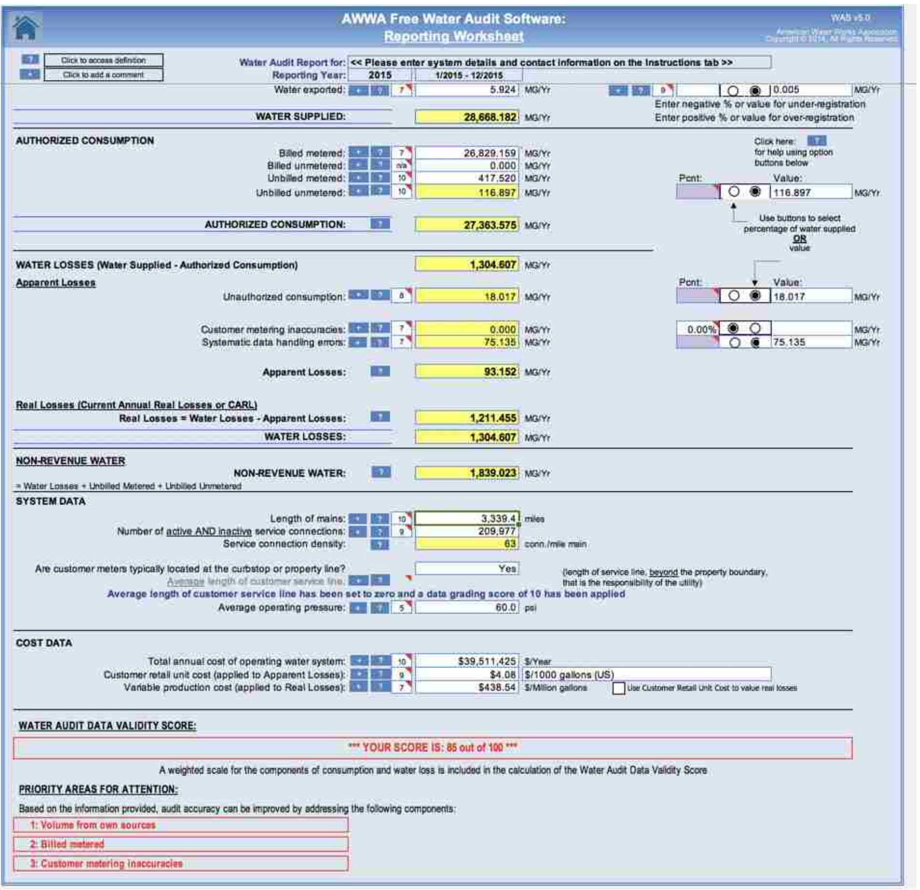
The stated goals of the various jurisdictions that require water auditing vary somewhat but generally “aim to evaluate regional water loss, encourage utilities to proactively pursue water loss control, and defensibly allocate financial and educational resources.” (Water Research Foundation, 2015) For example, the DRBC revised its Comprehensive Plan and Water Code in 2009 “to improve the quality of information available to both utilities and Regulators.” (Water Research Foundation, 2015) The DRBC has also stated that “[t]he purpose of the water audit is to track how effectively water is moved from its sources to customers’ taps and to ensure that public water systems quantify and address water losses.” (K.F. Najjar & J.K. Barr, 2016) Indiana’s enacting legislation refers to disruptions from water main breaks and states that “[r]egular auditing of water volumes is a necessary foundation for the adoption of cost-effective strategies to reduce the level of non-revenue water to economically reasonable levels.” (Indiana General Assembly, 2016) In Hawaii, enacting legislation requiring water auditing references constitutional requirements to “protect, control, and regulate the use of Hawaii’s water resources for the benefit of its people,” and further states that “[a] water audit helps a utility understand how much water is lost from a distribution system through the detailed analysis of data, which the utility can use to make informed decisions to reduce real or apparent losses.” (Legislature of the State of Hawaii, 2016) Colorado’s enacting legislation requires its water resources and power development authority to consider validated water audits before rendering financial assistance to utilities who apply for it. (“HB 16-1283 - Colorado 2016 Regular Session,” 2016) Finally, the NRDC Model State Legislation for Utility Water Loss Audits (which is being considered by several jurisdictions) states that “a water loss audit allows a utility to identify water loss control measures that can rapidly save the utility money.” (“Model-State-Legislation-for-Utility-Water-Loss-Audits.pdf,” n.d.)

As will be shown below, these goals are only partly achieved by completing water audits using the Water Audit Software. While the Water Audit Software does estimate volumes of non-revenue water (NRW), presents the user with an approximate scale of their real loss problem through the ILI, and lists basic actions a utility can take when its ILI is within specific ranges, it only focusses on real water loss symptoms – not their causes, and provides little indication where a utility should look to begin to address real losses.

2.3 The AWWA M36 Water Audit Methodology and Water Audit Software

2.3.1 Water Audit Data Entry

The Water Audit Software uses summary data from a water system to model and graphically display system performance. Water system input and output data is entered into a Reporting Worksheet (see Figure 1), as are various



AWWA Free Water Audit Software:
Reporting Worksheet
WAS v5.0

Click to access definition
Click to add a comment

Water Audit Report for: << Please enter system details and contact information on the Instructions tab >>
Reporting Year: 2015 1/2015 - 12/2015
Water exported: 7 5.924 MG/Yr 9 ○ ● 0.005 MG/Yr
Enter negative % or value for under-registration
Enter positive % or value for over-registration
WATER SUPPLIED: 28,668.182 MG/Yr

AUTHORIZED CONSUMPTION
Click here: for help using option buttons below
Billed metered: 7 26,829.159 MG/Yr
Billed unmetered: n/a 0.000 MG/Yr
Unbilled metered: 10 417.520 MG/Yr
Unbilled unmetered: 10 116.897 MG/Yr Pcnt: ○ ● Value: 116.897 MG/Yr
Use buttons to select percentage of water supplied OR value
AUTHORIZED CONSUMPTION: 27,363.575 MG/Yr

WATER LOSSES (Water Supplied - Authorized Consumption) 1,304.607 MG/Yr
Apparent Losses
Unauthorized consumption: 8 18.017 MG/Yr Pcnt: ○ ● Value: 18.017 MG/Yr
Customer metering inaccuracies: 7 0.000 MG/Yr 0.00% ● ○ MG/Yr
Systematic data handling errors: 7 75.135 MG/Yr ○ ● 75.135 MG/Yr
Apparent Losses: 93.152 MG/Yr

Real Losses (Current Annual Real Losses or CARL)
Real Losses = Water Losses - Apparent Losses: 1,211.455 MG/Yr
WATER LOSSES: 1,304.607 MG/Yr

NON-REVENUE WATER
NON-REVENUE WATER: 1,839.023 MG/Yr
= Water Losses + Unbilled Metered + Unbilled Unmetered

SYSTEM DATA
Length of mains: 10 3,339.4 miles
Number of active AND inactive service connections: 9 209,977
Service connection density: 63 conn./mile main
Are customer meters typically located at the curbstop or property line? Yes
Average length of customer service line: (length of service line, beyond the property boundary, that is the responsibility of the utility)
Average length of customer service line has been set to zero and a data grading score of 10 has been applied
Average operating pressure: 5 60.0 psi

COST DATA
Total annual cost of operating water system: 10 $39,511,425 $/Year
Customer retail unit cost (applied to Apparent Losses): 9 $4.08 $/1000 gallons (US)
Variable production cost (applied to Real Losses): 7 $438.54 $/Million gallons ☐ Use Customer Retail Unit Cost to value real losses

WATER AUDIT DATA VALIDITY SCORE:
*** YOUR SCORE IS: 85 out of 100 ***
A weighted scale for the components of consumption and water loss is included in the calculation of the Water Audit Data Validity Score

PRIORITY AREAS FOR ATTENTION:
Based on the information provided, audit accuracy can be improved by addressing the following components:
1: Volume from own sources
2: Billed metered
3: Customer metering inaccuracies

Figure 1: Sample Water Audit Software Reporting Worksheet

corrections for meter error and other estimated volumes such as theft. CARL (the annual Real Loss component of the mass balance detailed in Section 2.1 above) of course cannot be determined directly and is calculated by subtracting the combined outputs, including apparent losses, from combined inputs.

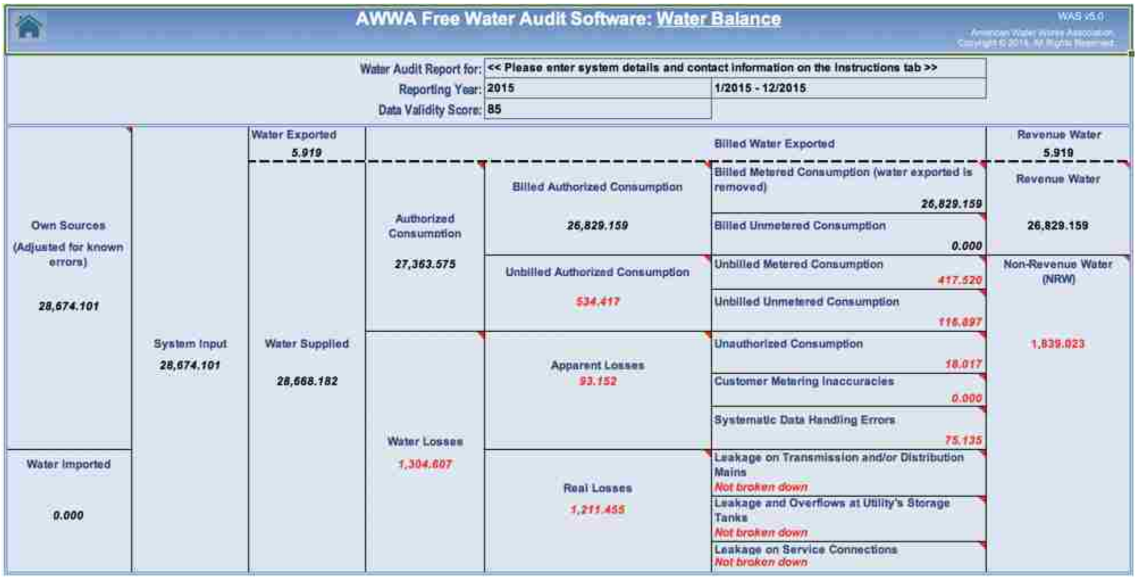
2.3.2 The Impact of Data Entry Errors on Water Audit Results

The accuracy of the real loss volumes calculated by the Water Audit Software depends on the accuracy of the data entered for the calculations (which is, of course, true for any calculation). The Water Audit Software uses summary system data for all inputs and calculations. A single value is input to (or calculated for) each of the 20 data points that the Water Audit Software uses. For example, if a system has several metered wells as water sources, it must aggregate the annual volumes pumped from all of the wells in order to derive a single value for system input volume. Similarly, a single weighted average metering error must be calculated to account for all metering error present in that summarized input volume. Summarization errors are a common factor of real-world auditing, and the author's experience, a source of significant errors in completed water audits.

2.3.3. Water Audit Results

2.3.3.1 The Water Balance

The Water Audit Software uses the system input data to create a diagrammatic Water Balance that tracks input volumes through the system, an example of which is shown below in Figure 2.



AWWA Free Water Audit Software: Water Balance

WAS v5.0

American Water Works Association. Copyright © 2014, All Rights Reserved.

Water Audit Report for: << Please enter system details and contact information on the Instructions tab >>
Reporting Year: 2015 1/2015 - 12/2015
Data Validity Score: 85

Own Sources (Adjusted for known errors) 28,674.101	System Input 28,674.101	Water Exported 5.919			Billed Water Exported	Revenue Water 5.919
		Water Supplied 28,668.182	Authorized Consumption 27,363.575	Billed Authorized Consumption 26,829.159	Billed Metered Consumption (water exported is removed) 26,829.159	Revenue Water 26,829.159
					Billed Unmetered Consumption 0.000	
				Unbilled Authorized Consumption 534.417	Unbilled Metered Consumption 417.520	Non-Revenue Water (NRW) 1,839.023
					Unbilled Unmetered Consumption 116.897	
			Water Losses 1,304.607	Apparent Losses 93.152	Unauthorized Consumption 18.017	
					Customer Metering Inaccuracies 0.000	
					Systematic Data Handling Errors 75.135	
Water Imported 0.000				Real Losses 1,211.455	Leakage on Transmission and/or Distribution Mains Not broken down	
					Leakage and Overflows at Utility's Storage Tanks Not broken down	
					Leakage on Service Connections Not broken down	

Figure 2: Sample Water Balance showing categorized volumes of system water

The Water Balance tracks all water from input through output and categorizes the output volumes broadly as water that produces revenue (“revenue water” or “RW”) and water that does not produce revenue (“non-revenue water” or NRW”). RW includes:

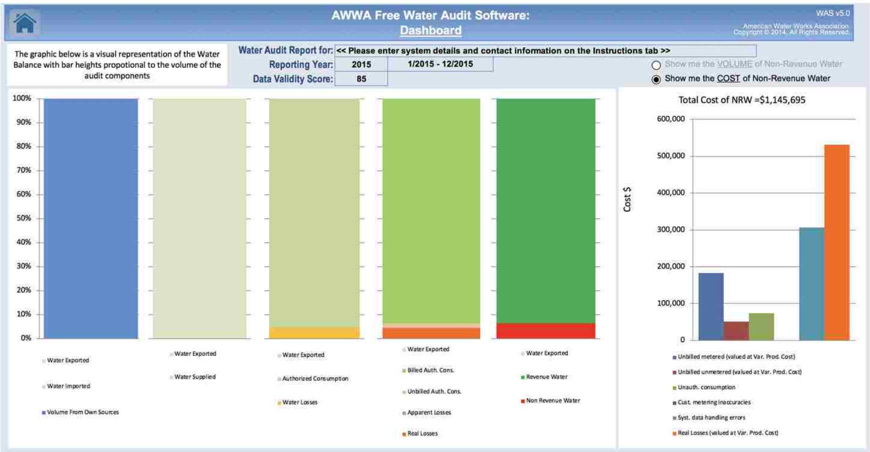
- Billed Water Exported – water sold to other systems through metered connections;
- Billed Metered Consumption – water sold to residential and commercial customers through metered connections; and
- Billed Unmetered Consumption – water sold to residential and commercial customers through unmetered connections (the volumes of which must be estimated).

NRW includes:

- “Unbilled Authorized Consumption” - water the utility knowingly provided at no cost through either metered or unmetered connections, or water the utility used in the course of operations (e.g. flushing);
- “Apparent Losses” – water that reached an end user but did not produce revenue due to meter under-registration, theft, systematic data error or similar accounting failures, and
- “Real Losses” – water physically lost from the system through main and service line background loss, breaks, leaks and storage facility overflows.

2.3.3.2 The Water Audit Software Dashboard

In addition to the water balance shown in Figure 2, the Water Audit Software provides a dashboard that shows both the volumes and costs associated with the different categories of NRW based on the operating costs, variable production costs, and retail pricing information submitted on the Reporting Worksheet. Samples of the dashboard graphs are shown below in Figures 3 (cost), and 4 (volume):



AWWA Free Water Audit Software:
Dashboard

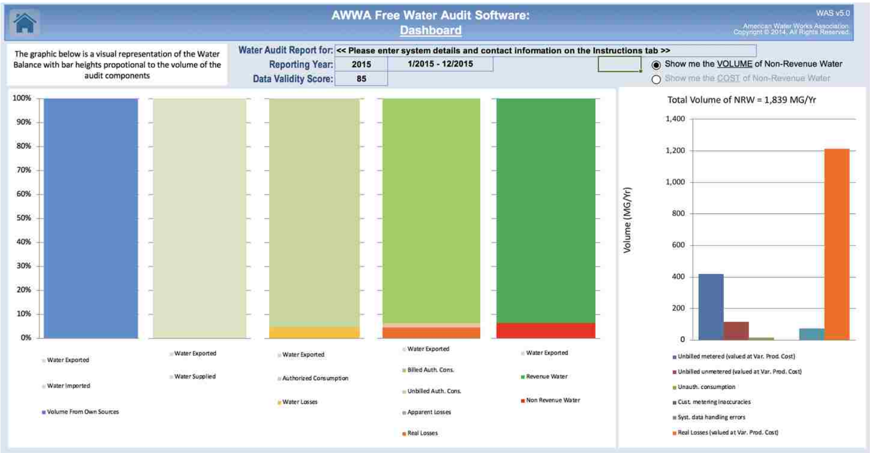
WAS v5.0
American Water Works Association
Copyright © 2014, All Rights Reserved.

The graphic below is a visual representation of the Water Balance with bar heights propotional to the volume of the audit components

Water Audit Report for: << Please enter system details and contact information on the Instructions tab >>
Reporting Year: 2015 1/2015 - 12/2015
Data Validity Score: 85

○ Show me the VOLUME of Non-Revenue Water
● Show me the COST of Non-Revenue Water

Figure 3: Water Audit Software Dashboard - Cost of Non-Revenue Water



AWWA Free Water Audit Software:
Dashboard

WAS v5.0
American Water Works Association
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The graphic below is a visual representation of the Water Balance with bar heights propotional to the volume of the audit components

Water Audit Report for: << Please enter system details and contact information on the Instructions tab >>
Reporting Year: 2015 1/2015 - 12/2015
Data Validity Score: 85

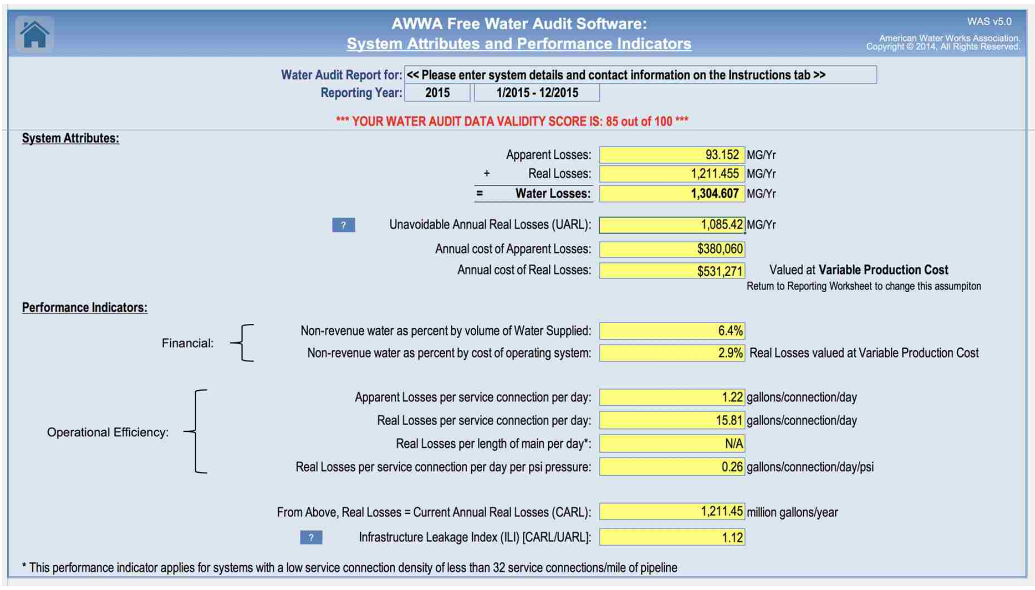
● Show me the VOLUME of Non-Revenue Water
○ Show me the COST of Non-Revenue Water

Figure 4: Water Audit Software - Volumes of Non-Revenue Water

The cost of Real Loss is typically valued at a variable production rate – the rate to treat the next million gallons of water which typically includes only energy and treatment costs, and the cost of treated water if water is purchased from another system - but users can select to use Consumer Unit Retail Cost by checking a box on the reporting worksheet.

2.3.3.3 System Attributes and Performance Indicators Presented in the Water Audit Software

The Water Audit Software also includes a tab of calculated system attributes and PIs (see Figure 5) on which the following values are presented: volumes for real and apparent losses and millions of gallons per year (MG/YR); UARL volume in MG/YR (for systems that meet the definitional requirements), an annual cost of apparent losses and an annual cost of real losses in dollars; NRW as a percent by volume of water supply; NRW as percent by cost of operating the system; several operational efficiency metrics including apparent losses per service connection per day, real losses for per service connection per day, real losses per length of main per day (for systems with densities of fewer than 32 connections per mile), real losses per service connection per day per PSI pressure, CARL in MG/YR, and (when applicable) the ILI.



AWWA Free Water Audit Software:
System Attributes and Performance Indicators

WAS v5.0
American Water Works Association.
Copyright © 2014, All Rights Reserved.

Water Audit Report for: << Please enter system details and contact information on the Instructions tab >>
Reporting Year: 2015 1/2015 - 12/2015

*** YOUR WATER AUDIT DATA VALIDITY SCORE IS: 85 out of 100 ***

System Attributes:

Apparent Losses: 93.152 MG/Yr
\+ Real Losses: 1,211.455 MG/Yr
= **Water Losses:** **1,304.607** MG/Yr

? Unavoidable Annual Real Losses (UARL): 1,085.42 MG/Yr
Annual cost of Apparent Losses: $380,060
Annual cost of Real Losses: $531,271 Valued at **Variable Production Cost**
Return to Reporting Worksheet to change this assumpiton

Performance Indicators:

Financial:
Non-revenue water as percent by volume of Water Supplied: 6.4%
Non-revenue water as percent by cost of operating system: 2.9% Real Losses valued at Variable Production Cost

Operational Efficiency:
Apparent Losses per service connection per day: 1.22 gallons/connection/day
Real Losses per service connection per day: 15.81 gallons/connection/day
Real Losses per length of main per day*: N/A
Real Losses per service connection per day per psi pressure: 0.26 gallons/connection/day/psi

From Above, Real Losses = Current Annual Real Losses (CARL): 1,211.45 million gallons/year
? Infrastructure Leakage Index (ILI) [CARL/UARL]: 1.12

* This performance indicator applies for systems with a low service connection density of less than 32 service connections/mile of pipeline

Figure 5: AWWA System Attributes and Performance Indicators Tab

2.3.3.3.1 CARL – Current Annual Real Loss

Figure 6: CARL Components

As stated above, CARL is simply the calculated annual volume of real loss for the audited system. As is shown in Figure 6, CARL is understood to consist of three components: 1) some level of economically recoverable losses, 2) an additional volume of real losses that are not economic to recover though their recovery is technically possible, and finally 3) some volume of technically unrecoverable losses. (AWWA, 2016b) The economically recoverable loss is the portion of CARL that a system can realistically impact through the implementation of water loss control techniques and practices. The benefits of real loss recovery or reduction do not only include monetary considerations. Viewed through the lens of a “triple bottom line” which includes financial, environmental and societal considerations, instances may arise where loss recovery that is not supported by purely financial considerations will nevertheless be undertaken because it is supported by environmental or societal considerations (or a combination of all of the above). Thus, a system in a drought-stricken area under severe supply constraints might be willing to invest money into real water loss control that exceeds the economic value of the lost water, while a system in an area where water is plentiful may not.

2.3.3.3.2 UARL – Unavoidable Annual Real Loss

The UARL purports to calculate a theoretically achievable low-level threshold of unavoidable losses for any utility that meets specific minimum requirements. Although numerous studies have demonstrated that a multitude of factors such as pipe materials, size and age ((Patricia Gómez-Martinez, Francisco Cubillo, Francisco J. Martín-Carrasco, & Luis Garrote, 2017) water and air temperature covariates (Balvant Rajani, Yehuda Kleiner, & Jean-Eric Sink, 2012) impact water utility line break rates and therefore real loss volumes, the standard UARL formula[5] uses only four system characteristics:

$$UARL = (5.4L_m + 0.15N_c + 7.5L_c) \times P \times 365\frac{days}{yr}$$

Where

$L_m = main\ and\ hydrant\ lead\ length\ in\ miles,$

---

[5] Though originally derived using metric units, this paper uses the Imperial unit version of the UARL formula presented in the M36 manual.

$N_c = the\ number\ of\ active\ and\ inactive\ service\ connections,$

$L_c = \ the\ total\ length\ of\ private\ service\ line\ \ = L_p\ \times \frac{N_c}{5280ft}),$

L_p = the average (the average length of private pipe in feet),

and

$P = system\ pressure\ in\ PSI.$

UARL was developed empirically in the late 1990s "using international statistics for burst frequencies on mains and service connections" (A.O Lambert, M. Takizawa, D. Weimer, & T.G. Brown, 1999),[6] and later tested and validated in other locations. The size of utilities that the UARL formula can be applied to has changed somewhat since its creation and continues to expand to smaller and smaller systems. (A. Lambert, Koelbl, & Fuchs-Hanusch, 2014) The minimum requirements for UARL calculation per the Water Audit Software as of the date of publication are: $L_m + N_c \geq 3000$, and $P \geq 35\ psi$, and a minimum connection density of 16 connections per mile. (AWWA, 2016b)

2.3.3.3.3 ILI – Infrastructure Leakage Index

The ILI is the dimensionless ratio between a system's CARL and UARL:

$$ILI = \frac{CARL}{UARL}$$

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[6] It is worth noting that Lambert's original citation for these statistics includes only 2 references – *UK Water Industry, Managing Leakage, Report E: Interpreting Measured Night Flows, WRc, Swindon 1994,* and *Hirner, W. personal communication.* Report E appears to only include data from the UK.

The ILI is touted as the “best indicator for comparisons among systems… best applied only after sufficient water audit data validity is achieved and all justifiable pressure management is complete.”[7] (AWWA, 2016b) In other words, the ILI is a comparison metric, not a process metric, designed to benchmark performance between water systems with different characteristics. The standard validation method for ILI has been to calculate it for well-documented audits in well-run systems and have the best performing systems fall at or slightly above 1. (A.O Lambert et al., 1999) At least one major study of water audits in the US discarded all audits with ILIs below 1 (17.4% of the total) deeming them “implausible.” (Water Research Foundation, 2015) This was done despite the fact that ILIs below 1 are possible, particularly in small systems. (A. Lambert et al., 2014)

2.3.4 Typical Water Loss Control Activities Undertaken by Utilities

As a practical matter real loss attributable to pipe breaks and leaks can only be reduced with by lowering system pressure, replacing pipe, and/or quickly locating and repairing pipe breaks and leaks as they arise. Thus, systems combating real water loss generally engage in four types of activities:

1) active leakage detection and control
2) optimizing repair activities

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[7] The “after pressure management is complete” caveat is included because of the large weight system pressure has in the UARL formula and the impact that lowering pressure has on calculated ILIs. This topic is discussed further in section 3.7.3 below.

3) pressure management, and

4) system rehabilitation and renewal.

Although activities 2 and 3 can often be undertaken without significant cost and without identifying specific system problems related to real loss, activities 1 and 4 are best attempted when the system has determined that system breaks, leakage, and/or deteriorating infrastructure are problems. Unfortunately, although the Water Audit Software presents the system with a purported summary volume, and an estimate of the scale of reducible real loss in the form of the ILI, it does nothing to categorize those losses or indicate with any specificity what the sources of real losses might be. In other words, when the system looks at its CARL, UARL, ILI and other PIs after an audit, it cannot without further component analysis (using for example the tools developed under WRF Project #4372), determine whether those losses are the result of data error, background leakage, mains leakage, service line linkage, or, more likely, a combination of all of the above. Performing a detailed component analysis is the accepted method of making such determinations and tools exist to do so, but use of these tools is not mandated in any US jurisdiction that requires water auditing.

The Water Audit Software is an extremely useful tool for any system investigating real and apparent water loss. It requires a system to calculate volumes for the various audit inputs, evaluate their policies procedures in data collection and retention practices in a very systematic way, and presents an estimate of the scale of the system’s real and apparent water loss volumes. But, despite its general usefulness, the Water Audit Software has serious deficiencies and de-emphasizes the likely error in two of its PIs – namely the UARL and ILI. These deficiencies are discussed in the following chapter.

Chapter 3: A Critical Evaluation of UARL and ILI PIs

3.1 The UARL Definition has Changed Over Time and is Not Consistent

While the UARL formula has remained basically unchanged in the past 2 decades, the definition of what it calculates has evolved. There are at least 3 different definitions for the UARL. Lambert originally defined UARL as the "real losses to be expected ***in a system with good infrastructure condition, intensive active leakage control, and rapid and effective repairs of all leaks and bursts."*** (A.O Lambert et al., 1999) (emphasis added) Two slightly different definitions are presented in the M36 manual. The first indicates that while UARL is a "reference value" that "does not refer to a specific type of leakage occurring in the water distribution system" (AWWA, 2016b) it

> "represents the minimum level of leakage that is calculated in a system-specific manner for a water utility. It represents the theoretical-low limit of leakage that could be achieved in a **system** ***that is well managed and in good condition at a given average pressure level****.* (AWWA, 2016b) (emphasis added)

A few pages later the M36 manual uses this slightly different definition citing the IWA:

> "A theoretical reference value representing the technical low limit of leakage ***that could be achieved if all of today's best technology could be successfully applied.*** " (Water Audit Software – Definitions) (AWWA, 2016b) (emphasis added)

While the first M36 definition implies that any "well managed" system in "good condition" could achieve the UARL results at a given pressure, the later definition indicates that this is only achievable by successfully implementing "all of today's best technology." "Today's best technology" is certainly vague, and available technologies vary over time. Does this mean that a leakage level equal to the UARL is only achievable if a system uses the latest developed tools such as satellite-based leak detection[8], or in-pipe, multi-channel magnetic flux leakage detection?[9] Probably not, but the definition is imprecise. This second M36 UARL definition, which is presented in the Water Audit Software as well, implies a level of unattainability that arguably discourages attempts to attain water loss reduction to near UARL thresholds, and implies that those standards are extremely low, when (as will be shown below) at least with respect to break related leakage components, the UARL is likely to underestimate what is actually economically achievable.

3.2 UARL and ILI have Very Limited Application

Over time the UARL and ILI have been applied to ever smaller water systems (A. Lambert et al., 2014), but the UARL and ILI PIs as generally accepted are not applicable to the vast majority of US water systems.

2010 US Census data indicates that average household size is 2.53 persons, and, assuming each household equals a connection, a service population of approximately 7590 is an approximation for 3000 connections (a rough shorthand for the UARL/ILI threshold). Per 2009 Census data only 3852

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[8] As has been developed by Hydromax USA and Utilis https://www.waterassetmgmt.com/pdfs/presentations/s3-3-advanced-leak-detection-technology.pdf

[9] See, e.g., Pica Corp's See Snake tool https://www.picacorp.com/Services/Water-Main-Inspection

out of 167,833, or 2.3% of US PWSs served populations over 10,000. (US Census Bureau, 2009) Assuming that all of the 4,684 systems serving between 3,301 and 10,000 persons could meet the UARL threshold that would mean that numerically, only 5.1% of US water systems can use the UARL and ILI PIs, but the actual number is likely lower than that.[10] It is worth noting, however, that this 5.1 % of US water systems serves approximately 90% of the US population.

3.3 Mass Balance Theory of UARL vs its Empirical Calculation

As was shown above, CARL (which cannot be metered or measured directly) is calculated directly using a mass balance approach. The UARL (which includes background losses and loses due to main and service line breaks) is, in concept, a component of CARL, but it is not calculated via the mass balance in the Water Audit framework.[11] Instead, it is an estimate using the empirically derived formula detailed above in section 2.3.4.2.2. Because these two values are calculated independently, instances occur where a calculated UARL is actually greater than a verified CARL leading to an ILI below 1 (which certainly calls the name choice of the UARL into question). The M36 manual indicates that such situations are indicative of world class water loss controls, when it is possible that some systems, due perhaps to their construction, maintenance or

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[10] In New Mexico, a relatively rural state, the UARL and ILI can likely only be calculated for approximately 19 of the 632 CWSs in the state – or 3% of the systems.

[11] Although it should be possible to derive a volume representing unavoidable background loss by tracking all loss volumes due to found breaks leaks and subtracting that volume from CARL, leaving a remainder that represents background losses, the Water Audit Software doesn't have that capability.

age, simply have very low leak rates, and the UARL formula simply doesn't estimate unavoidable losses correctly in those situations.

In such cases, barring any obvious indication that data inputs are wrong (such as a negative water loss result) it is difficult to evaluate the accuracy of the UARL, or to reconcile it with the CARL without performing an intensive, bottom-up component analysis to calculate real loss volumes based on main and other system break run times (in other words – continuing and refining the mass balance exercise beyond the audit itself).

The M36 manual presents the concept of Leakage Component Analysis (LCA) as a follow-on exercise to the CARL determination and promotes WRF Project 4372a, and its companion spreadsheet tool the *Leak Repair Data Collection Guide*. (AWWA, 2016b) But while the LCA tool itself does a very good job of standardizing terminology related to leaks so that data collection is uniform, it too is incomplete, as the only break-related metrics provided look at system-wide values and obscure useful granular information about the condition of water distribution network pipe matrixes. Thus, Project 4372b provides a useful data collection tool, but only provides very basic break-related analytical tools with the package. Further, it is not mandated in the jurisdictions that require water auditing.

3.4 Problems with the UARL Coefficients

3.4.1 There are an overabundance of assumptions underlying the coefficients

The coefficients in the UARL formula are based on break, repair and flow rate allocations from 20-or more-year-old research, primarily conducted outside of the US. The UARL formula coefficients contain a series of assumptions about average break rates, flow rates, and leak discovery and repair time frames which are categorized as 20 different average allowances tied to three main infrastructure components: 1) mains and pipelines, 2) service connections from main to curb stop, and 3) service connections from curb stop to meter.[12] For each infrastructure component, allowances are broken into three categories: 1) background (undetectable) leakage, 2) reported leaks and breaks, and 3) unreported breaks and leaks.

Background (undetectable) leakage is defined as leakage that cannot be discovered through typical leak detection approaches (e.g., acoustic scans) and is described as the “weeps and seeps at joint (sic) and fittings that occur at very low flow rates but may exist pervasively across the water distribution system.” (AWWA, 2016b) Reported leaks include all leaks that are discovered without needing to use additional tools to find the leaks (e.g., the water from the leak was visible on the surface or some other indication of the leak was present) regardless of who reported the leak. Finally, unreported breaks and leaks are those leaks that are found by the utility using active leak detection practices and

---

[12] On its face, the sheer number of allowances would seem to make this formulation suspect when applied to anything but relatively homogenous systems with minimal differences in material make-up and pressure.

technology. A detailed list of the UARL allowances is listed in Table 1 below which is adapted from the M36 Manual.

Table 1: Component values of UARL Allowances at 70 PSI

Infrastructure Component	Background (undetectable) Leakage	Reported Leaks and Breaks	Unreported Leaks and Breaks
Mains or Pipelines	8.5 gal/mi/hr	0.2 breaks/mi/year at 50 gpm for 3 days duration	0.01 breaks/mi/year at 25 gpm for 50 days' duration
Service connections, main to curb stop	0.33 gal/service connection/hr	2.25 leaks/1000 service connections at 7 gpm for 8 days duration	0.75 leaks/1000 service connections at 7 gpm for 100 days duration
Service connections, curb stop to meter or property line (for 50 ft ave. length)	0.13 gal/service connection/hr	1.5 leaks/1000 service connections at 7 gpm for 9 days duration	0.50 leaks/1000 connections at 7 gpm for 101 days duration

Annualized, these allowances equate to the values listed in Table 2 below.

Table 2: Annualized volumes of UARL Allowances at 70 PSI

Infrastructure Component	Background (undetectable) Leakage	Reported Leaks and Breaks	Unreported Leaks and Breaks
Mains or Pipelines	74,460 gal/mi/year	43,200 gal/mi/year	25,200 gal/mi/year
Service connections, main to curb stop	2891 gal/conn/year	181 gal/conn/year	756 gal/conn/year
Service connections, curb stop to meter or property line (for 50 ft ave. length)	1139 gal/service connection/year	136 gal/service connection/year	509 gal/service connection/year

UARL does not categorize those losses, even though it is based on assumptions about them. Nor does the Water Audit Software in any clear way indicate to the user whether those allowances bear any resemblance to typical break and leakage rates, or what's actually going on in the system in question. Further, the

Water Audit Software does not permit users to alter these assumptions in any way.

3.4.2 UARL Main Break Allowances Are Likely Too High

While the allocations (and thus formula coefficients) used in the UARL calculation have remained static, water utility management techniques and leak detection technologies have not. If, as the definition states, the UARL represents "a low limit of leakage that could be achieved in a system that is well managed and in good condition at a given average pressure level," then the allowances it is based on **should** bear some resemblance to the actual break rates and reasonable best practices regarding leak detection and repair times in the jurisdiction in which it is being applied. There is, however, evidence that at least some of these allowances do not correspond well to rates and practices in the US.

The UARL allowance for reported Mains Reported Breaks and Leaks is 20 breaks/100 miles/year, or 0.20 breaks/mile/year. This value does not align with values published in two recent studies from Utah State and other published values. Further, by presenting a single rate, the UARL does not take into account that water distribution systems across the US have very different pipe material matrices, and that these different pipe materials have very different average break rates. Estimating system break rates monolithically as the UARL does is simply the wrong way to do the analysis.

3.4.2.1 How leak categories are defined in various studies

There is no national database of water main breaks or failures. (Blaha & Zhang, 2016) Further, the various North American studies reviewing water main failures do not use a consistent definition of failures, with ”leaks” being used to generally include all failures and “breaks” or “bursts” being used for structural failures. Blaha defines “failure” as ”an event that has occurred that requires a utility to respond to the pipe or pipe appurtenances to address water leaking out of a pressurized potable water system” and does not differentiate between leaks and breaks (Blaha, 2016). This broader definition of failures suffices for this thesis but for simplicity all reported failures that would be classified as “Reported Leaks and Breaks” by the UARL are referred to herein as “breaks.”

3.4.2.2 AWWA Break Rate Values

The AWWA Partnership for Safe Water posits a break rate of 15 breaks per 100 miles of mains (or 0.15 breaks/mile) as a goal for a fully optimized water system which is 25% lower than the UARL reported break rate allowance.

(AWWA Partnership for Safe Water, 2011)

The 2018 AWWA Utility Benchmark document defines a “break” as “physical damage to a pipe, valve, hydrant or other appurtenance that results in an abrupt loss of water,” and a “leak” as “an opening in a distribution pipeline, valve, hydrant, appurtenance or service connection that is continuously losing water.” (AWWA, 2018) While these definitions don’t match the UARL reported break related allowance definitions exactly, they appear to correspond to the

UARL category of reported breaks and leaks. For the reporting period 2017, the combined leaks and breaks/100 miles were as follows[13]:

Table 3: 2017 Aggregate data for combined leaks & breaks/100 miles of pipe

	75th percentile	Median	25th percentile	Sample size	Confidence Level (1-4)	Count
Water Utilities	4.7	12.5	19.2	41	2.8	26
Combined Utilities – Water operations	11.8	18.2	36.4	76	2.7	53

While the median value of 18.2 breaks/100 miles (or 0.18/mile) for combined utilities is close to the allowance used for the UARL, the 75th percentile (arguably a better indicator of "well run" and "good condition") is 11.8/100 miles or 0.12/mile – almost half of the UARL allowance. And when one considers the category of "only water utilities" that number drops to a quarter of the UARL allowance, though there is no indication why there should be such a large discrepancy between them. (Tables breaking out leaks and breaks separately are contained in Appendix 2.)

3.4.2.3 Wisconsin Break Rates

Wisconsin is one of few states that requires utilities to report the number of main and service line repairs per year. It should be noted that there is no leak detection requirement, so these values are assumed herein to represent reported breaks. It should also be noted that the reporting requirement is for *repaired* breaks, thus any unrepaired breaks may not be included. Finally, like the AWWA

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[13] Separate tables breaking out leaks and breaks per 100 miles into separate categories are contained in Appendix 4. There is no breakdown by pipe material or size.

benchmarks, breaks are not categorized by pipe size or material or cause. The data is however worth reviewing. Table 4 summarizes the break data collected by the State of Wisconsin for 2016.

Table 4: 2016 Wisconsin Main Break Data

Total Mean Main Breaks per mile:	0.127
Total Median Main Breaks per mile:	0.071

Small System Mean Main Breaks per mile	0.125
Small System Median Main Breaks per mile	0.061
Large System (over 10000) Mean Main Breaks per mile	0.140
Large System (over 10000) Median Main Breaks per mile	0.104

The 2016 mean was 0.127 breaks per mile (very nearly identical to the AWWA benchmark 75th percentile), with a median of 0.071 breaks per mile. The data also shows some difference in median and mean break rates between small systems (those serving populations of 10,000 or fewer) and large systems (those serving populations greater than 10,000), with small systems mean break equaling 89% of the large system value and the median break rate equaling 59% of the large system value.   While this is only representative of a single years' breaks, the median and mean values are all significantly less than the break rate allowance in the UARL.

3.4.2.4 Utah State Break Rate Survey Values

In 2018 Dr. Folkman at Utah State University published a study that surveyed 170,571 miles of water mains in the US and Canada representing 12.9% of the total. (Folkman, 2018)[14] The failure rate results therefrom are summarized below in Table 5.

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[14] This was a follow on to a similar study published in 2012 which had similar findings, though the rate of CI main failures increased considerably between the two. Many of the other failure rates (including PVCs) decreased slightly in the 2018 results.

Table 5: 2018 Utah State Water Main Failure Rate Study Results

Pipe Type	AC	CI	CSC	DI	HDPE	PVC	PVCO	Steel	Other	Unknown	Total
Miles Surveyed	21589	48471	4940	47595	867	37704	83	4765	1375	3182	170571
% of total	13%	28%	3%	28%	0.5%	22%	0.05%	3%	0.8%	2%	
# Failures	2240	16864	152	2627		878		362	680		23803
Failure Rate/Mile	0.10	0.35	0.03	0.06	0.00	0.02	0.00	0.08	0.49	0.00	
Weighted Average Failure Rate/Mile	0.013	0.099	0.001	0.015	0.000	0.005	0.000	0.002	0.004	0.000	0.140

Folkman's study, which has by far the lowest median failure frequency of recent studies "excludes failures due to joint leakage, construction damage, and service line tapping which the author did not feel were failures of the pipe." (Blaha & Zhang, 2016) It also excluded mains below 3" in diameter. These exclusions do not, however, necessarily require dismissal of the study by this thesis which focuses on the portion of the UARL coefficients related to main failures which Folkman's definition and data appear to fall squarely within. Joint leakage arguably falls into the background leakage category of the UARL. Similarly damage due to service line tapping and construction is not "unavoidable" – it is induced damage that does not necessarily provide information about the structural condition of the pipe (i.e., the pipe has not failed on its own but has been compromised by outside forces).[15] Thus, it does not seem unreasonable to use the Folkman studies when evaluating the UARL's

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[15] While volumes lost from such damage should be accounted for to validate audit results, repeated construction damage tells a utility much about line location and construction practices in its area, but little or nothing about its pipe condition.

reported main break allocations[16] even though the UARL main break allocations may include induced damage.

One would expect a system that is "well maintained and in good condition" (to use the M36 language) to at least be "average" in terms of typical failure rates. Assuming a normal distribution, half of the systems providing data to the Utah State studies would have had failure rates below the average. The weighted average failure rate for the total quantity of pipe covered by 2018 study based on pipe material is 0.14 breaks/mile, which is approximately 70% of the UARL allowance of 0.20 breaks/mile. However, with the exception of CI and Other pipe, the average break rates of pipe materials currently in use in the US are consistently lower than 0.20 breaks/mi/yr. (Folkman, 2012, 2018) This suggests that unless a US system is predominantly CI, the main break rate allowance in the UARL calculation is an overestimate.[17] Further, if a system is primarily PVC, as many systems in the Southwest appear to be, that overstatement could be by an order of magnitude.

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[16] Even if Folkman's study does represent an under-reporting, it nevertheless demonstrates quite clearly that there are different materials used in different US regions, vastly different failure rates by pipe material, and that these rates also differ somewhat by region.

[17] In order to generate a break coefficient equal to that in the standard UARL formula using the average break rates from the Utah State study, a system has to consist of approximately 70% CI pipe.

3.4.2.5 There are Very Different Pipe Matrices in Water Systems Across the US

The Utah State studies demonstrate clearly that: a) there is significant variation in pipe materials used in distribution systems in different regions in the US; b) there are significant differences in the average break rates of different pipe materials; and c) that those differences vary somewhat by region.[18]

Although it is obvious that the length of pipe surveyed by material in each region does not represent the typical pipe material make up of an actual system in those respective regions, it is instructive to use them as proxies for hypothetical systems with differing materials matrixes to demonstrate the futility of trying to develop a fixed standard for main line breaks without taking the materials those mains are made of into account.

The full set of tables is contained in Appendix 3, but by using the length of pipe material surveyed in each region as a proxy for a hypothetical regional system pipe material matrix, and then creating a weighted average break rate based on that makeup the following results:

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[18] It is important to recognize that, like the AWWA Benchmark/UARL comparison, the Utah State/UARL break rates are also not quite "apples to apples" comparisons. The results of the Utah break rate studies are average numbers of failures by pipe type across reporting systems, not a low number representing breaks reported at "well run" utilities om "good condition". There is no information regarding the distribution of these failures by pipe type – only an average is given, with the statement that the data had "considerable scatter." (Folkman, 2018) Further, Folkman did not segregate breaks the way the UARL calculation does: into reported and unreported breaks. As Dr. Folkman put it "Obviously we did not care how the leak was detected." (Folkman, email communication, 2018). Thus, there is no way to differentiate reported from unreported breaks in the Utah break rate study are included in the study. Finally, there is no pressure information associated with the breaks in the Utah studies. To be conservative the author assumes that the break rates reported by Folkman are equivalent only to the Mains Reported Breaks and Leaks component of the UARL.

Table 6: Hypothetical Weighed Average Break Rates if a System had a Pipe Material Mix Similar to that Represented by Miles of Pipe Surveyed in Their Region using 2018 Utah State National Average Break Rates

Region	Year 2018
9 (Canada)	0.133
8 (CT, DC, DE, MA, ME, ND, NH, NJ, NY, PA, RI, VA, VT, WV)	0.171
7 (AL, FL, GA, KY, MS, NC, SC, TN)	0.138
6 (IL, IN, MI, MN, OH, WI)	0.181
5 (AZ, AK, LA, NM, OK, TX)	0.100
4 (IA, KS, MO, NE, ND, SD)	0.170
3 (CO, MT, UT, WY))	0.126
2 (CA, HI, NV)	0.107
1 (AK, ID, OR, WA)	0.170
Mean:	0.144
Median:	0.138
Standard Deviation:	0.030
Coefficient of Variation:	20.9

As is shown in Table 6 and Appendix 3, even in Region 6, the region with the most CI pipe surveyed, a weighted average failure rate for a hypothetical system with a pipe material mix represented by the pipe surveyed in that region would be slightly lower than the allowance the UARL formula posits. But in Region 5 (which includes the state of New Mexico and significantly more PVC pipe) the weighted weighed average failure rate for the hypothetical system is half that considered in the standard UARL. This suggests that, while the UARL's single break rate approach may be useful and accurate where water systems are relatively homogeneous, it may not be as effective in the US where break rates differ drastically from material to material, and the pipe types used differ from region to region.

3.4.3 UARL Main Repair Time Allowances are Likely Too High

The UARL allowance for main break repairs is 3 days for reported breaks. Assuming that the response times indicated in the WRF Project 4695 Report (*Guidance on Implementing an Effective Water Loss Control Plan*), published in March 2019 are valid, the average high-end response and repair speed for reported failures ranges from 3.5 to 46 hours (with an outlier of 2-12 days.) Including the outlier results in a 2.38-day average which is 21% lower than the UARL repair time allocation, which in turn leads to a 21% reduction in the reported breaks and leaks allocation (and the real loss volumes associated with those failures). Without the outlier, the average repair time was 18.72 hours (0.78 days). This average response time – which is less than a third of the allowance the UARL formula uses – appears to represent current best practices.

3.4.4 In its Current Format, the Water Audit Presents Little to No Actionable Information for Real Loss reduction

The Water Audit Software is, in a very real sense, an incomplete tool. States that have required water auditing using the Water Audit Software have thus adopted an incomplete solution to the problems they are attempting to fix: namely the reduction of NRW in general and Real Losses in particular. This is at least partially confirmed by a review of the real water loss per connection values for the 10 systems that participated in multiple years of the WADI study. As is demonstrated in the graph in Figure 7 below, only two systems demonstrate reduced real loss per connection over the time period.

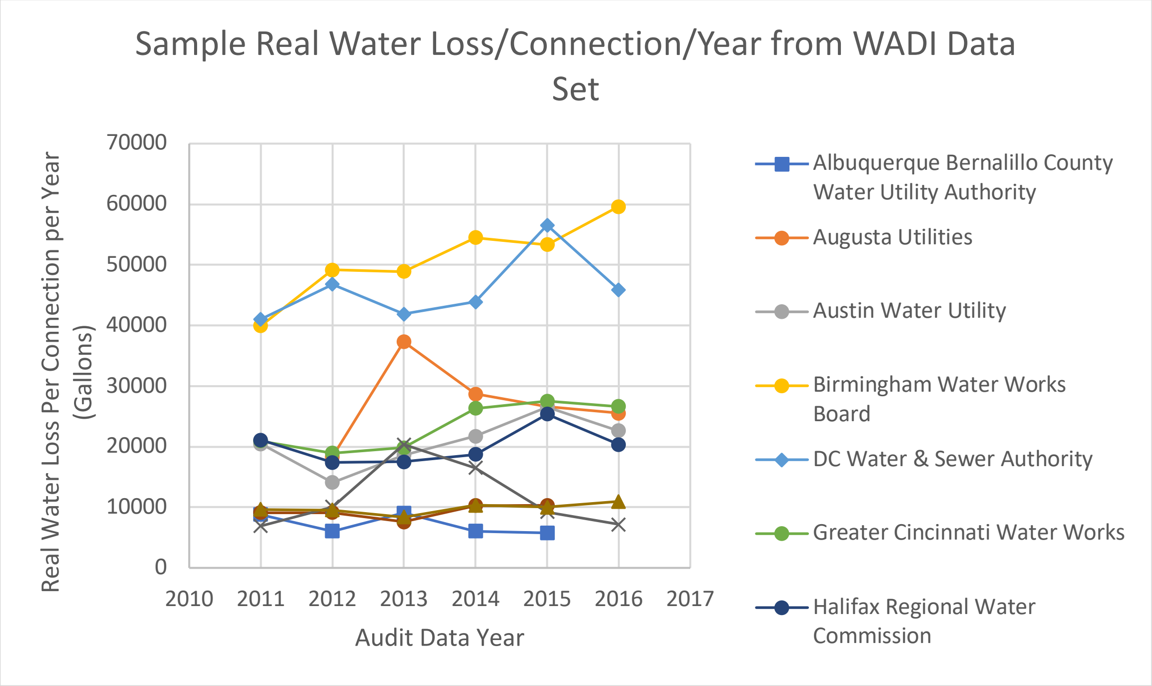

Figure 7: WADI Real Water Loss per Connection per Year

Of course, real water loss reduction does (for the reasons discussed above) take time, and it may be that during the time frame covered by the graph in Figure 7 more focus was paid to bettering data than reducing real loss, or that the initial years results represent a significant underestimation of real loss. Nevertheless, the results imply that auditing alone is not enough.

3.4.5 The UARL Does Not Make Any Meaningful Distinction Between Systems with Varying Break and Repair Rates

Perhaps the biggest flaw in the UARL calculation method is that, by using fixed allowances for break rates and repair times, it (and thus the derivative ILI) treats a low break rate system with slow repair time as an operational equivalent of a high break rate system with a fast repair time. Assuming identical flow rates, a system with a 0.02 break/mile/year rate (the current average failure rate for PVC) could not make repairs for 31.5 days for reported leaks and 505 days for unreported leaks and still fall within the UARL parameters for the main break component of the UARL formula, when the standard formula contemplates 3- and 50-day repair rates respectively for reported and unreported leaks. This does not make sense. Operational efficiency metrics carry implications with them. What the UARL effectively implies is that a break rate of 0.20 breaks/mile/year combined with a repair time of 3 days, is equal to a break rate of .02 breaks/mile/year with a repair time of 31.5 days. While this may be mathematically true in terms of volume of water lost, it is not an operational performance equivalence. One cannot reasonably argue that a water system that takes 31.5 days to repair a reported leak is operating as efficiently as one that takes 3 days, particularly when (in this hypothetical at least) the former system is dealing with an order of magnitude more leaks.

But because the actual system break and repair time rates are not considered in the UARL or ILI metric (nor indeed anywhere else in the Water Audit Software) a system with a low ILI and a break rate/repair combination of 0.02 breaks/mile/year and an average repair time of 31.5 days could, by the PIs presented, be given the impression that they have effectively neared economically achievable perfection despite abysmally slow repair times. This is not a message that should be sent to utilities. If a 3-day repair time is reasonably achievable, systems should be presented with that best practice standard to determine whether they are limiting their losses to “unavoidable” annual losses - or at least be made aware that their practices are sub-par. Otherwise systems that, due to climate, construction or any other variables are inherently less prone to mains breaks are not being held to the same standard and the UARL is decidedly mis-named, as there is nothing “unavoidable” about real losses resulting from sub-standard repair practices.

Of course, simply because a standard exists does not mean it should be followed blindly in all circumstances. Speeding repair time may increase repair costs that may not be offset by the value of the water saved and is thus an economic decision each system has to make for itself. Legitimate economic arguments for not repairing some leaks quickly can be made. But the value of the water lost is not the only factor to be considered here. Presenting best practice standards for comparison can help a system evaluate their operations, and should they decide for whatever reason not to meet the standard, it creates a level of transparency about their actions for them, their customers and for regulators.

3.5 Practical Problems with the Pressure Variable Render the UARL and ILI Calculations Suspect

Examining the UARL formula presented above in section 2.3.3.3.2, it is apparent that system pressure is a linear variable, and that it dominates the calculation. As shown in Figure 8, graphed leakage vs increasing pressure using the UARL formula is a straight line.

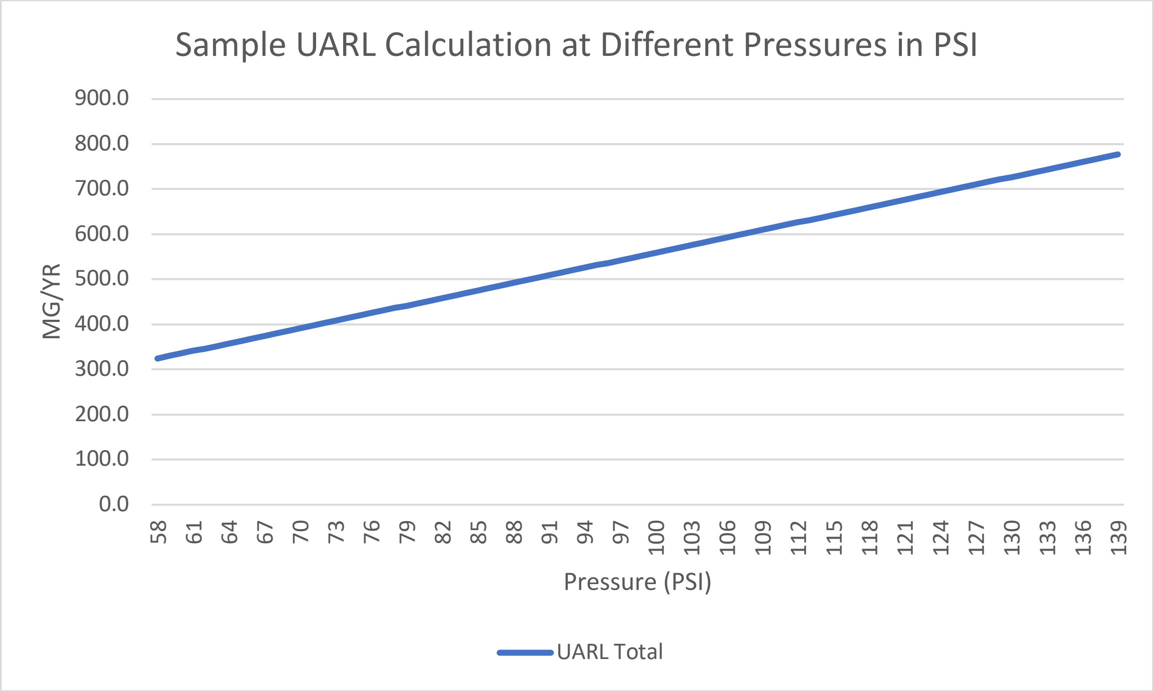

Figure 8: UARL vs Pressure Graph

The fact that pressure is the dominant variable in the UARL formula presents several problems, not the least of which are that average system pressure for a water system over an entire year is difficult to calculate, and that many US systems do not have accurate pressure models. Further, even if accurate pressure models were consistently available, many systems have multiple pressure zones that may experience different break rates.

Small pressure miscalculations can have a significant impact on the resulting UARL value and thus the interpretation of water audit results. Pressure overestimates increase the UARL value which in turn reduces the ILI, minimizing the apparent scale of reducible real loss in the system. For example, a 2 PSI increase in the pressure variable for System 1's 2015 water audit results in a 3.3% increase in UARL (36.2 MG).

Lambert states that the “UARL consists of [unavoidable background leakage] plus losses from detectable Reported and Unreported leaks and bursts.” (Lambert, 2009). In other words, the linear UARL is comprised of two basic components – background leakage and leakage resulting from service line and main breaks.[19] But, despite the fact that both background losses and the losses due to pipe failures have been demonstrated to follow power laws with respect to pressure, the UARL formula is linear and does not present a simple way for systems to accurately compensate for higher or lower pressures based on the break types they most commonly experience.

3.5.1 The UARL’s Background Leakage Component

Lambert’s formula for unavoidable background leakage (UBL) which has been adopted in the M36 Methodology follows a power rule with respect to pressure:

$$UBL\left(thousand\,\frac{gal}{day}\right) = [(0.20 \times L_m) + (0.008 \times N_c) + (0.34\ \times L_c)]\ \times\ (P_{av}/70)^{1.5}$$

or

$$UBL\left(thousand\,\frac{gal}{yr}\right)$$

$$= [(0.20 \times L_m) + (0.008 \times N_c) + (0.34\ \times L_c)]\ \times\ (P_{av}/70)^{1.5} \times\ 365\ d$$

$$/yr$$

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[19] The formula for estimating background leakage that is adopted in the M36 Manual is not included in the Water Audit Software.

A comparison of calculations of background leakage using the UBL formula and the background leakage portion of the UARL formula for systems with meters located at the curb stop (i.e. where there is effectively no private service line between the curb stop and meter as is typical in New Mexico) however, shows that while in a range of 70 to 80 PSI average system pressure the two values are within roughly 5% or less of each other. As pressure exceeds 80 PSI the gap between the values increases substantially.

For example, Figure 9 below shows the variance between UBL and the background component of UARL for a system with L_m = 1258, N_c = 56842 and L_c = 0 at pressures ranging from 58 to 139 PSI. This example is based on the characteristics of Ashville, NC, which runs at a reported average pressure of 138 PSI and was taken from the 2016 WADI Data Set.

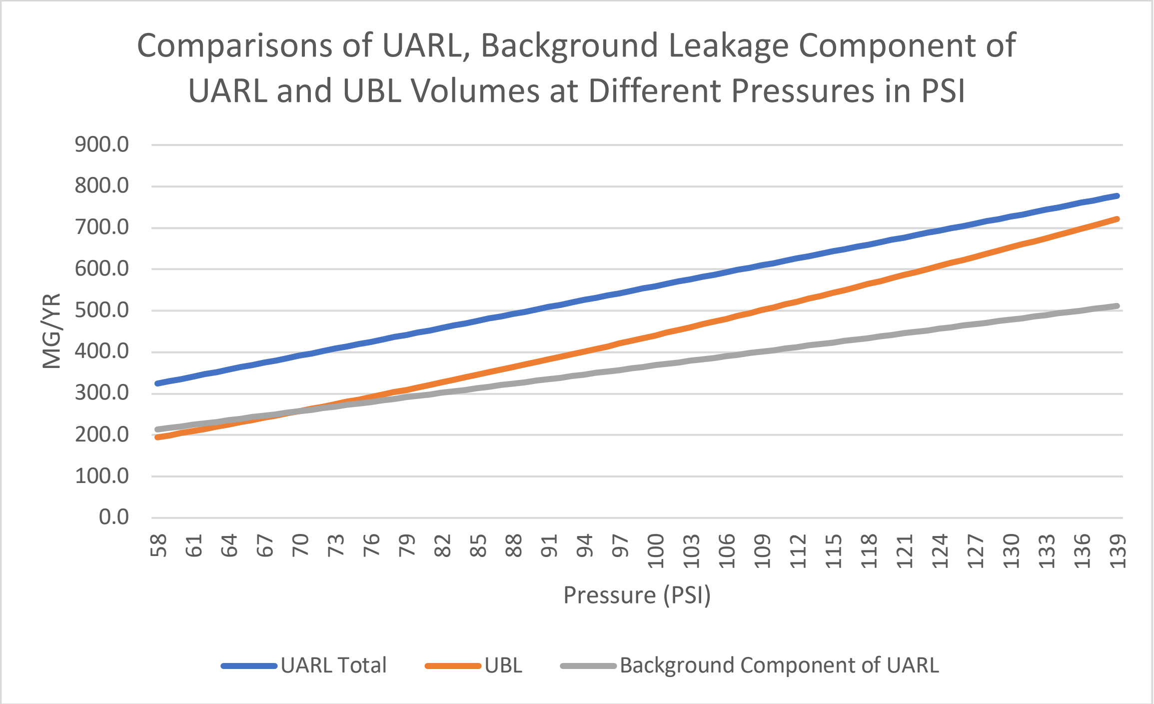

Figure 9: Comparison of UARL, Background Leakage Component of UARL and UBL Volumes at Different Pressures in PSI

Thus, if one assumes the UBL calculation is valid, the UARL systematically underestimates background leakage at pressures over 70 PSI.

Reported average operating pressures vary widely in the audit sets obtained for this study but a review of Tennessee data is informative. In the Tennessee 2016 audit set, the average reported operating pressure of the 255 systems for which a UARL could be calculated was 81.3 PSI, and fully 177 of the systems reported average operating pressures over 70 PSI, with the average pressure in this group being 125 PSI. Thus, there would be significant variations between the two background leakage calculations for almost 70% of the audited systems in Tennessee.

A comparison of calculated UBL values and calculated values of the background component of UARL for all of the systems in the 2016 Tennessee data set for which a UARL can be calculated at their reported average pressures showed an average difference of 8% with a maximum difference of 29%. (See Appendix 4).

3.5.2 The Break-Related Leakage Component

Leakage volumes (L) can vary with pressure (P) according to power laws where L varies with P^{N1}. (Thornton & Lambert, 2005) However, with leakage from reported and unreported breaks N1 typically ranges from 0.5 to 1.5 with circular holes and ring cracks at the low end and variable length splits (such as might occur in flexible plastic pipe) at the higher end, but can be as high as 2.5. (A. O. Lambert, 2009)

But, despite the fact that the UARL is a combination of background loss that can be calculated using a formula that scales with pressure to the power of 1.5, and failure-related volumes that may scale with pressure anywhere from the power of 0.5 to 2.5 or more, the UARL formula assumes that a conglomeration of the background and failure related leakage will be linear with mixed pipe systems. (A. O. Lambert, 2009) While this assumption may be valid in many cases, it may not if the system in question is not running at or near the reference pressure of 70 PSI, if the system pipe isn't as "mixed" as Lambert contemplates, or if the majority of a system's break related real losses are the result of higher power value failures such as variable length splits.[20]

3.6 Possible Error is De-emphasized in Water Audit Software

3.6.1 Data Validity Grading is a Poor Proxy for Confidence Levels or Value Ranges

Despite the fact that statistical methods for reducing error in the PIs exist (B. Babić, M. Stanić, D. Prodanović, B. Džodanović, & A. Dukić, 2014),m the Water Audit Software does not present a <u>quantitative</u> assessment of data accuracy in the form of a confidence level and/or error range. Instead, data accuracy in the Water Audit Software is communicated <u>qualitatively</u> through a Data Validity Score ("DVS") which (in theory at least) "reflects the extent to which the water utility employs best practices in collecting, managing and analyzing water audit data." (Andrews & Water Research Foundation, 2016)

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[20] For example, in 2016 41% of System 3's main breaks involved lateral splits on plastic pipe.

The PI tab of the Water Audit Software (Figure 5 above) lists a composite DVS (some value out of 100) which is a weighted score based on individual data grades of 1 to 10 given to each data input in the system's water audit. (A full list of the criteria is attached in Appendix 4 in a format developed by the SW EFC. While the format is slightly different than that presented in the Water Audit Software, the content is identical).[21]

The accuracy of all of the PIs calculated by the Water Audit Software is of course impacted by any input data error, because the PIs are generated using the volumetric data, costs and infrastructure information entered the Reporting Worksheet. But the existence of this error is only cursorily acknowledged in the Water Audit Software through the qualitative DVS.

While the choice to use DVSs appears to have been made with good intentions, it is problematic for a number of reasons. First, while a high DVS would tend to imply a high degree of PI accuracy and a low DVS would indicate a low degree of PI accuracy, the individual data grades are highly weighted toward

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[21] "When the first version of the AWWA software was developed (around 15 years ago) the AWWA water loss control committee discussed whether 95% confidence intervals should be included or not. Unfortunately it was decided against it." (Liemberger, 2019)

Per the AWWA M36 Publication Subcommittee Chair, "The AWWA Software Subcommittee felt that confidence intervals (a statistical method) were deemed to be [too] mathematically complex and abstract for use in USA water utilities where many thousands of water utilities are small systems with limited staff time and limited funding to hire consultants if that is what they believed was needed to compile the annual water audit.

The data grading capability (grades 1-10) and Data Validity Score (DVS) (scale 1-100) were designed to be simple to employ, particularly since written grading criteria was included in the Software. Also, the criteria is "process based" and provides a direct link for the water utility to see what additional actions they can take for any water audit component to improve the validity and grading. In this way a dual focus on data quality and process quality is emphasized."(Kunkle, 2019) automated systems (with no clear indication why the data so produced is necessarily better) and some of the categories contain confusing or apparently contradictory criteria. Where default values are permitted (for example for loss volumes related to theft and systematic data errors) systems are automatically given a data grade of 5 for choosing the default value.

The Water Audit Software thus incentives the adoption of default values by systems who don't have accurate data for these data points by automatically assigning a data validity grade of 5 out of 10 for any default value used while at the same time obscuring the potential error that may thus be induced into the audit results. Further, a review of the data grading scheme quickly reveals that there is no direct correspondence between qualitative DVS and any quantitative error range or confidence level. Thus, one cannot say that a DVS of 60 equates to a confidence level and/or error range of "x", while a DVS of 80 equates to a confidence level and/or error range of "y." Of the at least 14 commercially available software packages available for water auditing, the Water Audit Software is the only one to take this qualitative approach. (Water Research Foundation, 2014) Thus, possible insight that utilities could gain from displayed (or acknowledged) confidence levels in the Water Audit Software appears to have been traded for ease of use and adoption.

The DVS is a qualitative proxy for confidence level, but an imperfect one. A 2015 WRF study found that "utility self-scoring of data validity does not actually capture true data validity," and that audits with implausible data had a higher average score than audits with plausible data. (Water Research Foundation,

2015) Although the DVS does shed light on the likely accuracy of the PIs presented by the Water Audit Software, it is vague, and the way the PIs are presented (as values without acknowledging that, due to uncertainty in the underlying data, they are actually within some undetermined range of values) the PIs implies an accuracy that is lacking.

3.6.2 Likely error in PIs is Glossed Over by the Water Audit Software

As presented in the Water Audit Software, the ILI appears to give the system being audited specific information about the magnitude of its real water loss problem. The ILI is presented to two decimal places giving the Water Audit Software user an impression of extreme accuracy when, given the vagaries of the underlying calculations, the standard UARL may be off by up to ± 15% when compared to a UARL calculated using system specific break, flow and duration data and the CARL itself may be off by as much as ±20% when ILIs near 1 are calculated. (A. O. Lambert, 2009) The ILI (CARL divided by UARL) compounds these errors. Using a sum of squares approach this results in a possible error margin of ±25%.

The ILI is a comparison metric, but if one is trying to rank systems by ILIs that have an unquantified error the results are bound to be inaccurate. If there are penalties associated with not meeting certain ILI targets, the obscured error may lead to inequity in the application of legal standards. For example, if a state uses hard cut offs for performance, such as Texas with its minimum ILI requirement of 3, a calculated ILI of 3 could in reality be as high as 3.75 or as low as 2.25, potentially allowing some systems that haven't really met state requirements to "pass" and others who have, to "fail."

3.7 Additional Problems Associated with the ILI

3.7.1 The ILI is Frequently Misused in Practice

While the ILI was designed to be used as an international comparison metric, in the author's experience it tends in practice to be used by many utilities and water loss consultants as a shorthand for audit results and system performance. Because (as will be shown below) real loss reduction due to pressure management may not show up in the ILI this misuse of the PI can obscure real progress made in real loss reduction.

3.7.2 Metering Error Problems Can Skew Results

Metering error (particularly on system input master meters) can pose a significant problem in water auditing, because of the manner in which real loss is calculated. A review of US audits, (including those validated water audits in the AWWA's WADI data set), demonstrates that metering error, both on system inputs and outputs, is a significant issue in the United States. Such errors make much of the volumetric data supplied to and calculated by US audits unreliable and will likely continue to do so. If the volumetric data is unreliable, so are the PIs generated using that data, and comparing or ranking systems by their ILI becomes problematic. Even in the WADI data set, which includes only Level 1 validated water audits with data validity grades above 50, the primary suggestion for audit improvement in almost all cases relates to improvements in source metering practices and procedures. For example, the 2017 WADI data (covering the audit year 2016) which includes 16 audits with an average data validity score of 80, offers up “Volume from own sources” or “Water imported” as Priority Area #1 for most of the audits. Priority Area #2 is dominated by “Customer metering inaccuracies,” “Billed metered” values and “Unauthorized consumption.”

In other words, despite high individual data validity grades, and high overall data validity scores, accurate system input and output metering is actually a significant issue with many, if not most US water audits. This lack of reliability suggests that other, non-volume related, PIs may be needed in the Water Audit Software.

3.7.3 Utility Real Loss Prevention Actions Taken Don’t Always Show Up in ILI

Though the ILI is “best applied only after sufficient water audit data validity is achieved and all justifiable pressure management is complete,” (AWWA, 2016b) there is no way to indicate in the Water Audit Software that pressure management is complete, or that it has even been attempted. One could make the argument that an ILI should not even be displayed until a system has affirmatively indicated that pressure management activities are complete, or that there should be a warning that the number should be not be relied upon unless pressure management is complete. Instead of highlighting this issue, the definition section of the Water Audit Software leaves the caveat out, stating only:

“The ratio of the Current Annual Real Losses (Real Losses) to the Unavoidable Annual Real Losses (UARL). The ILI is a highly effective performance indicator for comparing (benchmarking) the performance of utilities in operational management of real losses.” (Water Audit Software, Definitions)

This is problematic because pressure related real water loss control activities may not be reflected in the ILI. If, for example, a system reduces average system pressure in order to reduce real loss, there is the possibility that the actual reduction in real losses that result from the pressure reduction will not be captured by the ILI simply because the UARL and ILI must both be recalculated at the lower pressure. Because pressure reduction typically results in lower real loss, and the UARL is calculated independently of the mass balance and is highly influenced by the pressure variable, reduced system pressure will: a) likely reduce real loss captured in the mass balance CARL, but b) also, reduce the total value of the calculated UARL. Thus, both the numerator and the denominator in the ILI will be reduced. This can in some instances result in no change in the ILI, or even a higher ILI value after pressure reduction despite a reduction real loss, which gives the impression of decreased performance.

3.7.4 Artificially Low Calculated ILIs May Disincentivize Water Loss Control Activities.

The UARL (or denominator in the ILI ratio) purports to calculate a theoretically achievable low limit of loss for the system being audited. Thus, a water system with an ILI value near 1 (in other words when real losses are close to equal to the calculated UARL), appears to have reached the attainable low-level of real water loss. An ILI value of 1 would seem to indicate perfection, and is likely to signal to any system receiving such a score that further attempts at water loss reduction will either be pointless or at least not cost-effective – even if that indication is untrue, and despite that fact that the ILI is not meant to be a performance metric. If the UARL formula does systematically underestimate economically achievable low leakage levels (by for example using break and repair time allowances that are too generous), it is essentially setting the water loss control bar too low.

3.7.5 ILIs Below 1 are Common

While ILIs typically range between 1 and 10, lower ILIs are possible. (A. Lambert et al., 2014) Approximately 18% of the water audits reviewed by the author for which a UARL value can be calculate have ILI values below 1, sometimes significantly so. And while many reviewed results can be attributed to data error (as evidenced by impossible results such as negative water loss) it is possible that many of these results are valid.[22] Recent studies in Austria have shown that valid ILIs below 1 are realistically possible to achieve economically[23] particularly in smaller systems or systems where leaks tend to surface quickly. (A. Lambert et al., 2014) Further, as Table 7 demonstrates, the AWWA's own WADI data set, which covers a 5-year period and includes only Level 1 validated

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[22] It is worth noting that some reviews of water audits (including one done by the EPA) simply discard all ILI values below 1 out of hand deeming the results implausible. This may be due to the methodology used by Lambert et al to validate the ILI which essentially involves choosing "well run" systems engaged in active water loss reduction activities, auditing them and taking an ILI value near (but above) 1 as confirmation that the UARL formula is valid.

audits that have undergone some basic scrutiny, has a significant number of systems with ILI with values near or below one.

Table 7: WADI Data Set ILI Values

Year	Total Systems Participating	Systems with ILI ≤ 1.2	% of Systems with ILI ≤ 1.2	Systems with ILI ≤ 1.00	% of Systems with ILI ≤ 1.00
2016	16	3	18.8	1	6.25
2015	29	5	17.2	3	10.3
2014	33	2	6.1	1	3.0
2013	26	1	3.8	1	3.8
2012	26	4	15.4	1	3.8

Further, the 2018 AWWA benchmarks show a median ILI of 1.48 and a 75th percentile value of 0.90. (AWWA Benchmarks, 2018). All of these point to sub-ILIs being less of an exception, and becoming instead, a more common occurrence, particularly as more states mandate auditing, and more systems engage in water loss control activities. The lower the ILI boundary goes, the more confusing the meaning of that PI gets.

3.8 Impact of Alternate Break and Repair Allowances on the UARL and ILI

One could argue that the UARL should use a weighted average break rate allowance (WABRA) based on low level break rates for the types of pipe in a given system (and only use a monolithic value when that pipe makeup is unknown), and that incorporating best practices for repair times would also help recalibrate the formula. The concept of a system specific UARL calculation is not a new one[24] and modifying the standard UARL formula to reflect WABRAs and

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[24] Allan Lambert developed and distributes an excel worksheet that a system can use to develop system specific coefficients for the UARL calculation – but it has never been included in the Water Audit Software and is only referenced in the M36 manual. A SSUARL calculation may have been omitted for convenience – to make the audit process as simple as possible to encourage

best practice repair time could have a dramatic effect on the UARL, but the ability to make such calculations has been left out of the Water Audit Software.

Incorporating a WABRA approach to the UARL would arguably present a more accurate representation of what a “well run” system “in good condition,” with the pipe matrix it has in place, could achieve, particularly if combined with repair time allowances that reflect current best practices. This in turn could provide a better estimate of the value of lost water falling between the actual CARL and the hypothetical UARL. But all of the other flaws in the UARL calculation as presented in the Water Audit Software remain. There are many other assumptions, there is no real indication of the likely error in the calculated PIs, and the resulting improved PIs still would not be actionable. All one would have is a theoretically slightly better approximation of the scale of real loss with no clear indication where it was coming from, or what to do about it.

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widespread adoption; or because the SSUARL calculation was deemed close enough for its purposes. Mr. Lambert has indicated that a SSUARL is unlikely to differ from the standard UARL calculation by more than 20%, but 20% is significant.

Chapter 4: Proposed Alternatives to the Current Water Audit Approach

4.1 Adding Component Analysis will make the Water Audit Software more useful

The best way to validate water audit results is to perform a bottom-up leakage component analysis (LCA) in which leak and break event data (along with data about flushing and other activities) is analyzed and compared to the water audit results, but there are no LCA fields in the Water Audit Software and it is unclear how many systems actually engage in component analysis because it is not mandated.

Should systems choose to perform an LCA, the tools developed in WRF Project 4372 do calculate estimates of break related and background loses, and compare total main line frequency failures to rates of 15 and 25 breaks/100 miles/year discussed above in order "to make this determination more valuable." (Water Research Foundation, 2014) But these comparisons also fall short in their effectiveness because, despite the fact that the data for more granular analysis can be collected with the WRF *Leak Repair Data Collection Guide*, the LCA tool only provides an analysis looking at leaks and breaks as a monolithic value, when breaks are not typically uniformly distributed throughout a system, particularly a system that has mixed pipe materials of varying sizes. Thus, a useful granular level of analysis, and related PIs are missing.

The WRF Component Analysis Model also collects repair time data and contains a "What if" tab that allows systems to determine the impact of shortening leak location and repair times – but it does not present a standard best practices value against which current repair times can be evaluated, and it is not mandated.

Systems that track operational data, particularly break and repair time data, are the position to make data driven decisions with that data. Facilitating comparisons of break rates and repair times to a regional or national standard by modifying the Water Audit Software would let systems know how their performance compares to that of other systems, and also present evidence of best practices that could be adopted and implemented. Including LCA data entry fields relating to a system's pipe matrix with the Water Audit Software itself would encourage (or in some cases force) data collection and would enable the calculation of additional useful PIs for systems to evaluate their performance and audit results by, thus rendering the Water Audit Software a more practically useful tool for real water loss analysis.

4.2 Incorporating Pipe Failure Rates into the Audit will Provide Actionable Information

4.2.1 Activities that Reduce Water Loss

As was stated above there are 4 basic actions a system can engage in to reduce real water loss: active leakage detection and control, optimizing repair activities, pressure management and system rehabilitation and renewal. But there are no PIs in the current form of the Water Audit Software that address such actions directly. In and of themselves, neither the UARL not the ILI provides any guidance for systems to engage in these activities except (assuming against the evidence) that if the UARL is correct it provides a low level target volume with which a system can evaluate the cost of potential water loss control activities and compare them to the value of the water to be saved by real loss reduction.

4.2.2 Actionable vs Non-Actionable Information

In the near short-term many, if not most, water systems are stuck with what they have in the ground. While simply replacing all leaky pipe in a system might be a laudable goal, it is usually not economically possible (or prudent) and given that the current US pipe replacement cycle is about 125 years (Folkman, 2018), not very likely. Pinpointing and replacing leaky pipe, reacting quickly to breaks, and (where possible) reducing system pressure are, however, the quickest ways that a system can make an immediate impact on its real losses.

The inclusion of a break rate and repair time index PIs in the Water Audit Software would provide additional clarity regarding the sources of the real water loss by introducing a basic element of component analysis into the audit, and would in many cases provide actionable information that points to potential solutions in a way the current PIs do not. Such PIs would also provide systems with feedback that could be immediately acted upon and provide them with a high-level validation of their CARL calculation. If the audit can demonstrate that a system is not completing repairs in a reasonable time frame, it immediately presents an action item (more timely response) that any system can act upon, and that is guaranteed to produce positive results by reducing water loss if acted upon. Similarly, if an audit could demonstrate that a system has high failure rates in one or more classes of pipe, the system would have information with which to begin formulating a plan to address those specific pipes, either through increased leak detection, or strategic pipe replacement.

Further, by including this data as part of an audit, State authorities who collect water audits could build a better picture of failure rates, repair times and real water loss in their jurisdictions and could use that information to develop standards and/or allocate funding resources. Collection of this data by states would also create a database of information that would lead to regularly updating the average break rates by material. Finally, if it can be determined that normalized break rates for large and small systems are comparable, these indexes would be valuable to, and could be calculated for, systems of any size – thus overcoming another of the UARL and ILI PIs limitations. If the rates are determined to be different, the PIs could be calibrated for systems of different sizes.

4.3 Alternative Performance Metrics Based on Component Data: Break Rate Index and Repair Rate Index for Mixed Pipe Systems

It is suggested that dimensionless index PIs based on system main break rates and repair times, instead of real water loss volumes, may be more practically useful (and possibly more universally applicable) to US water systems at this time than the UARL and ILI. Such PIs would not be based on potentially suspect volumetric data and could thus be used to help interpret the audit results that are based on volumetric data. Such PIs would not only allow systems to compare themselves to other systems, but would (if relevant data were systematically collected and analyzed) be helpful for developing local, regional, national and/or international standards related to failure rates and repair times which could in turn be used to calibrate, validate, or invalidate the UARL and ILI. Further, such PIs actually would be useful as comparison metrics AND process metrics. They would let systems compare their actual performance vis-à-vis breaks and repairs with other water systems, while at the same time giving them specific information about aspects of their system that contribute to real water loss – namely how often their mains are breaking, which types of pipe are breaking, how quickly they repair those breaks, and whether their leak detection and pipe replacement strategies are working – something that neither the UARL nor ILI can do. If systems reduce and rapidly repair breaks and leaks, real water loss reduction naturally follows.

4.3.1 BRI - Break Rate Index

A Break Rate Index (BRI) is proposed consisting of the dimensionless ratio of a system's annual main break rate divided by a weighted average break rate factoring in that system's material make up and national or regional break rate averages:

$$System\ BRI = \left(\frac{TB_1}{MM}\right) \div WABR$$

Where:

$TB_1 = total\ number\ of\ main\ breaks\ occurring\ in\ system\ in\ last\ year$

$MM = total\ miles\ of\ mains\ in\ system$

$WABR$ = weighted average break rate for your system $[(ACBR \times AC) + (CIBR \times CI) + (CSCBR \times CSC) + (DIBR \times DI) + (PVCBR \times PVC) + (SBR \times S) + (OBR \times O)] \div MM$

And:

$AC = miles\ of\ asbestos\ cement\ pipe\ in\ system$

$CI = miles\ of\ cast\ iron\ pipe\ in\ system$

$CSC = miles\ of\ concrete\ steel\ cylinder\ pipe\ in\ system$

$DI = miles\ of\ ductile\ iron\ pipe\ in\ system$

$PVC = miles\ of\ polyvinyl\ chloride\ pipe\ in\ system$

$S = miles\ of\ steel\ pipe\ in\ system$

$O = miles\ of\ other\ pipe\ in\ system$

As of the date of publication the values for the various material break rates (taken from Folkman, 2018) are as follows:

$ACBR = 0.104$
$CIBR = 0.348$
$CSCBR = 0.031$
$DIBR = 0.055$
$PVCBR = 0.023$
$SBR = 0.076$
$OBR = 0.124$

The break rates values listed above were used for the system specific calculations in Section 4.4 below.

In addition to the System BRI, individual material BRIs for each of the 7 pipe materials listed above are calculated as follows:

$$\text{Material BRI} = \frac{\dfrac{\text{annual \# of breaks for pipe material}}{\text{miles of pipe of that material in the system}}}{\text{Material national average per mile break rate}}$$

The system BRI and individual material BRIs are displayed using a radar graph giving the system both an overall visual snapshot of their system wide break rate compared to national averages, and individual BRI values by material. (See Figure 10)

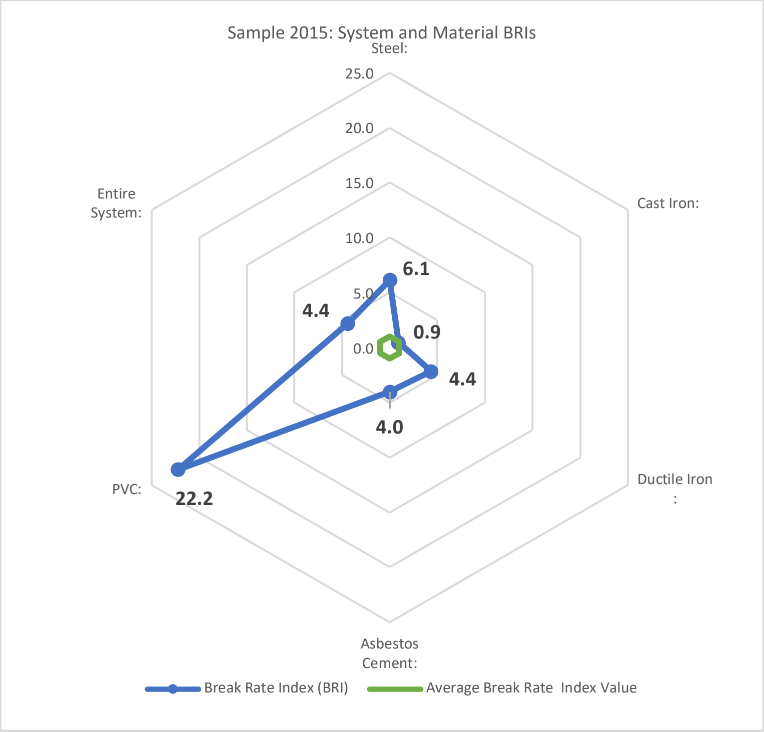


Figure 10: Sample BRI Radar Graph

Companion graphs comparing the percentages of distribution system pipe broken down by type, and the percentage of system breaks for each pipe type along with a theoretical number of breaks calculated using national average break rates will aid systems in the interpretation of their BRI values. Examples of these graphs are included in Section 4.4 below.

From such graphs a system would be able to determine for example, that their system BRI was below the national average, but that they have higher than average break rates on specific types of pipe; or that a high break rate is associated with specific diameters of pipe that is not likely to result in significant water loss. This is actionable information because it points the utility to the types of pipe that are causing the most problems instead of merely verifying that a real loss problem exists.

For smaller systems, or for a longer term of analysis, the basic BRI formula could be modified to use an n-year rolling average of system breaks:

$$BRI_n = \left(\frac{\frac{TB_n}{n\ years}}{MM} \right) \div WABR$$

Where:

$BRI_n = BRI\ value\ for\ the\ time\ period\ covering\ n\ years$

$TB_n = total\ number\ of\ main\ breaks\ occurring\ in\ system\ in\ last\ n\ years$

and all other values are the same as above. Using a 5-year rolling average would allow for smoothing of break rates over time, particularly in very small systems where a few breaks in the course of a year could drive the annual break rate to an extremely high level that is not representative of longer-term trends.

Using a material based weighted average national break rate for the BRI denominator would ensure a) that the break rate standard would not be set unrealistically high, and b) that systems would not be penalized for simply having a distribution system made up of more break prone materials – such as CI or DI. The calculation would only consider what they actually have in the ground. If, over time, significant regional differences in material specific failure rates were demonstrated to exist, national averages could be replaced by regional averages.

Of course, the BRI will not show a utility exactly which piece of pipe to address, but it will give the utility a frame of reference within which to evaluate the different types of pipe in their system and it can be done without a GIS analysis using a simple spreadsheet (though GIS, of course, makes the analysis easier and would help a system pinpoint the specific sections of pipe in any material class that need attention).

4.3.2 RTI - Repair Time Index:

The companion to the BRI is a Repair Time Index (RTI), a dimensionless index consisting of an annual average system repair time in hours, divided by an agreed upon repair time standard, also in hours:

$$RTI = \frac{ART}{RTS}$$

where

$ART = Average\ system\ repair\ time\ in\ hours$, and

$RTS = Repair\ Time\ Standard\ in\ hours.$

An RTI of 1 would indicate that the system is meeting the established best practices repair time standard, and could be presented either as a simple index value or be accompanied by a simple bar graph where the national average index value is 1, and the

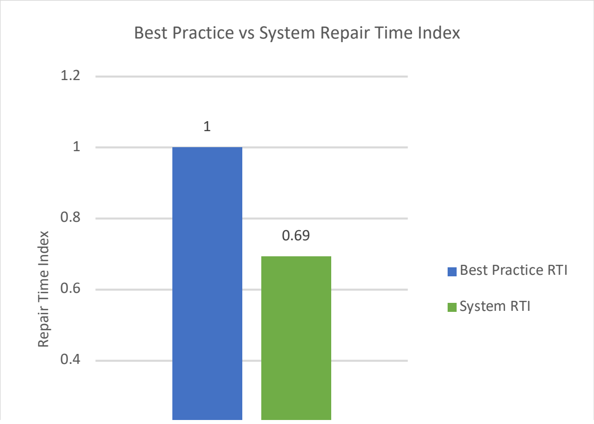


Figure 11: Sample Repair Time Index Graph

system value is presented next to it for greater visual effect as shown in Figure 11.

Two values suggest themselves for the initial RTS value. The first of these is 72 hours (3 days) based upon the 3-day repair time used in the creation of the standard UARL equation. This value, however, does not appear even close to best practices currently observed in the US. It is suggested that the 18.7-hour best practice repair time identified above in Section 3.4.3 above be designated as the initial RTS value.

4.4 Analysis of 4 New Mexico Systems Using Proposed Performance Metrics

To demonstrate the usefulness of the proposed BRI and RTI and their interpretive graphs, data from 4 New Mexico water systems was analyzed and the results of this analysis are presented below. System 1 includes data covering several years. The remaining analysis focuses on a single year per system.

4.4.1 System 1:

System 1 has a long history of water auditing. For the period 1995 to 2003 (well before the implementation of its Asset Management Plan) the weighted average break rate allocation for System 1 based on its actual pipe material makeup, and the average national break rates reported would have been 0.196 breaks/mi/yr, effectively the same value that the UARL contemplates.

System 1’s break rate during the 1995 to 2003 period was driven almost entirely by a small amount of Steel pipe breaking at far greater rates than the nation average. However, nothing in a standard water audit would have provided System 1 with this information. Instead, a relatively sophisticated GIS analysis was used by the Southwest Environmental Finance Center (SW EFC) to demonstrate that Steel Pipe was the major component in System 1’s breaks.

Similar results could have been found using a spreadsheet of basic break data that included information about the system’s pipe matrix breakdown, the pipe material being repaired, the leak report time and data, the leak isolation or repair time and date, and the BRI PI as will be shown below using data from four time periods: 1995-1999, 2000-2003, 2004-2009 and 2017. Note that the miles of distribution system pipe that were analyzed in each successive period increased from 2553 in the period 1995-1999 to approximately 3245 miles of pipe in 2017.

4.4.1.1 BRI:

The graph in Figure 12 clearly demonstrates that over the 1995-1999 time frame while System 1’s total weighted average break rate was significantly lower than the national average for a system with its material matrix (the System BRI is 0.4) including extremely low break rates for CI and PVC, its break rates for Other is slightly higher than the national average and the Steel pipe break rate is more than 7 times the national average. The interpretive graphs in Figures 13 and 14 reinforce the BRI graph indicating that 5% of the System 1 network (the Steel pipe) accounts for 49% of the breaks. They also show that during this period System 1’s CI break rate was very low compared to the national average.

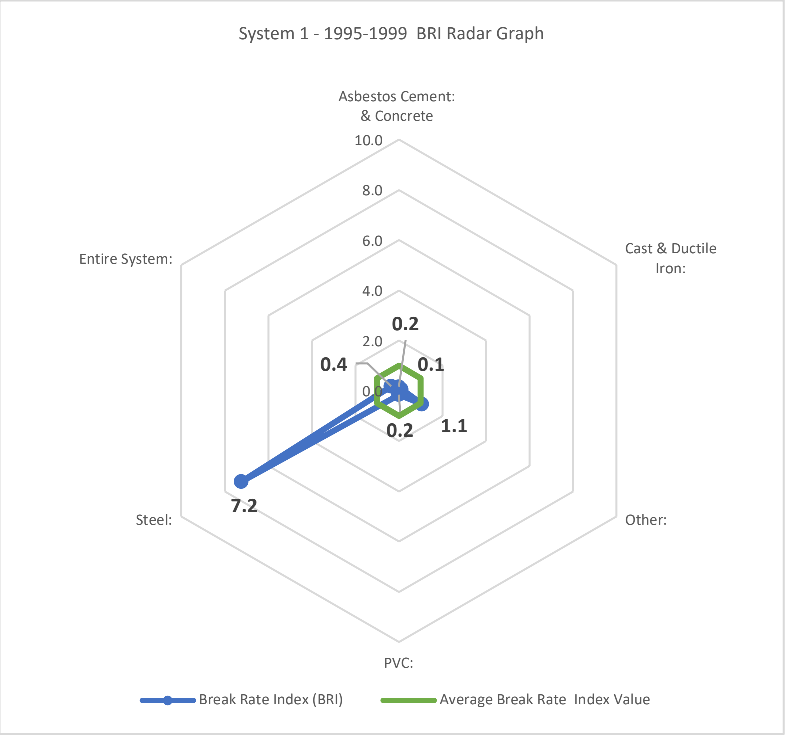


Figure 12: System 1 -1995-1999 BRI Radar Graph

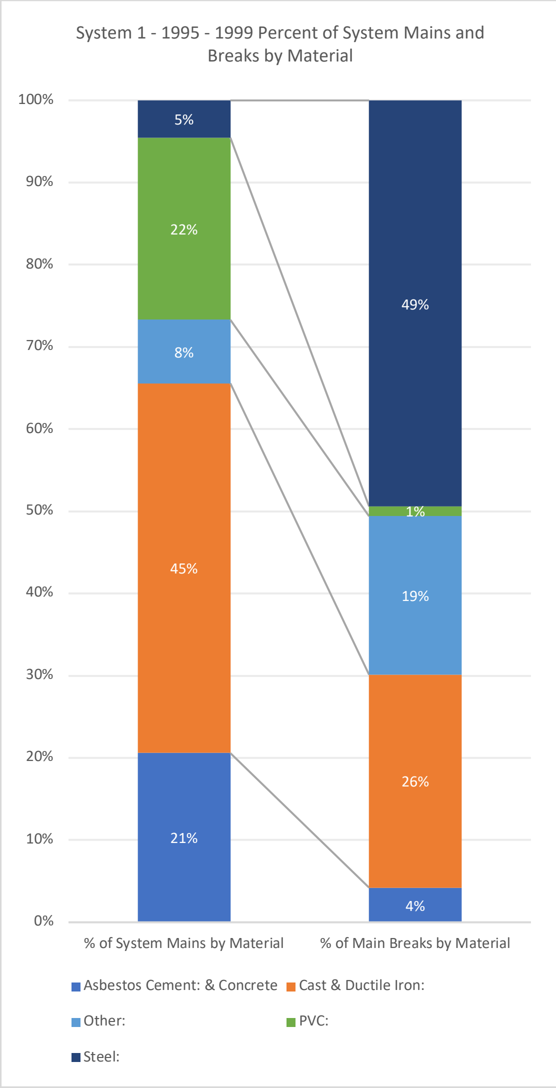


Figure 13: System 1 - 1995-1999 Percent of System Mains vs Breaks by Material

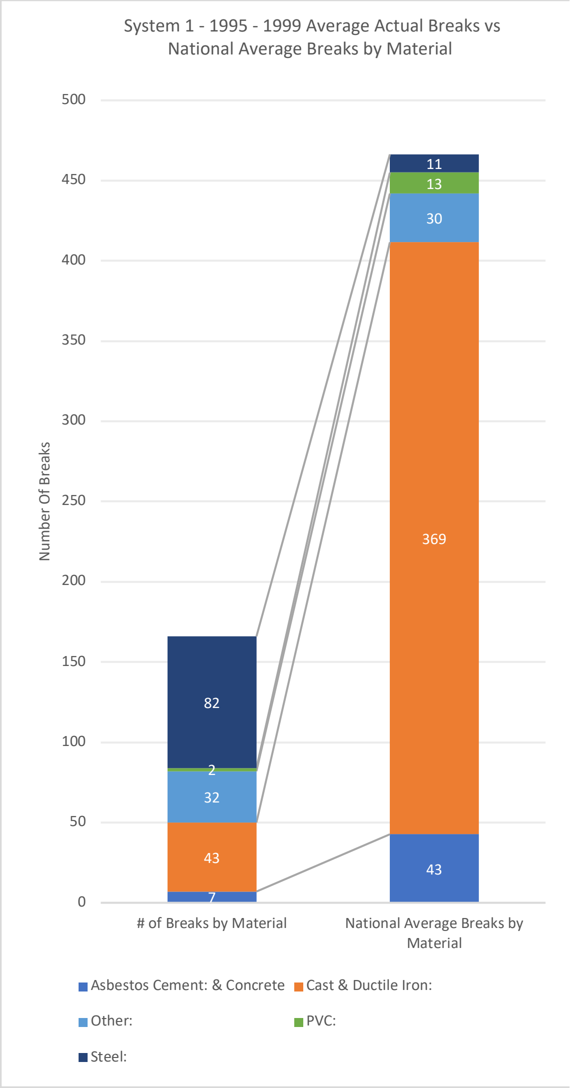


Figure 14: System 1 - Actual Breaks vs National Average Breaks by Material

Using summary data from the period 2000-2003 we get the results shown in Figure 15.

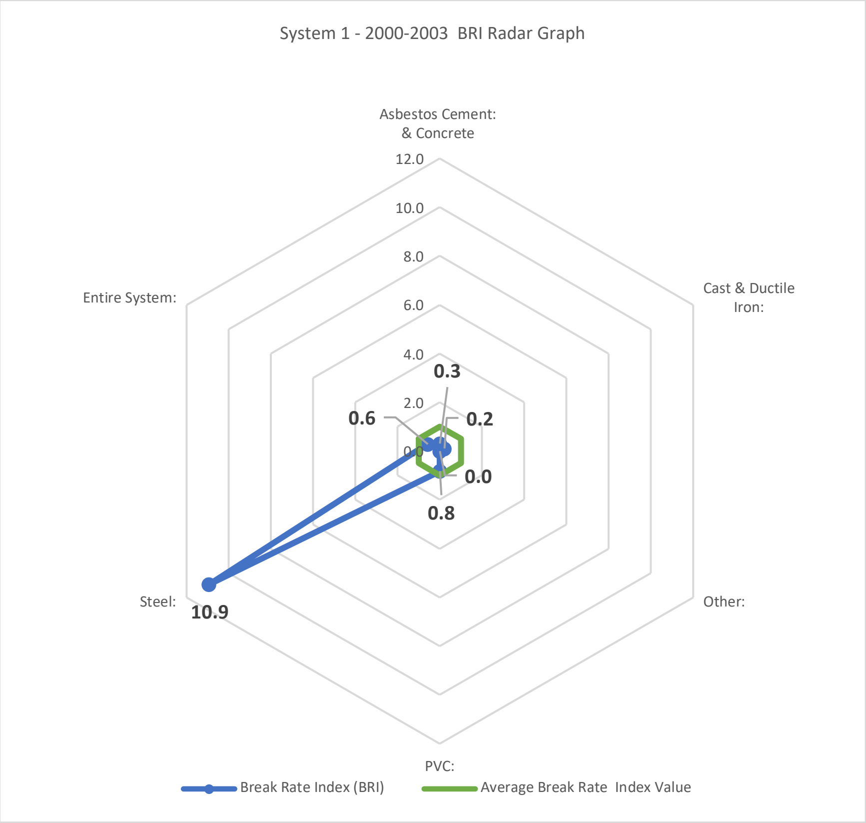


Figure 15: System 1 - 2000-2003 BRI Radar Graph

These results show an overall slight increase in System BRI to 0.6, and a marked increase in the Steel break rate evidenced by the Steel Material BRI of 10.9 – this despite an 11% decrease in the amount of Steel pipe in the system. It is easy to determine from comparisons of the two radar graphs that a) the overall break rates went up slightly, and that the Steel pipe remained the biggest problem despite the removal of some Steel pipe from the system. As is shown by Figures 16 and 17 the Steel pipe only made up 4% of the system, it represented 40% of system breaks during this time frame.

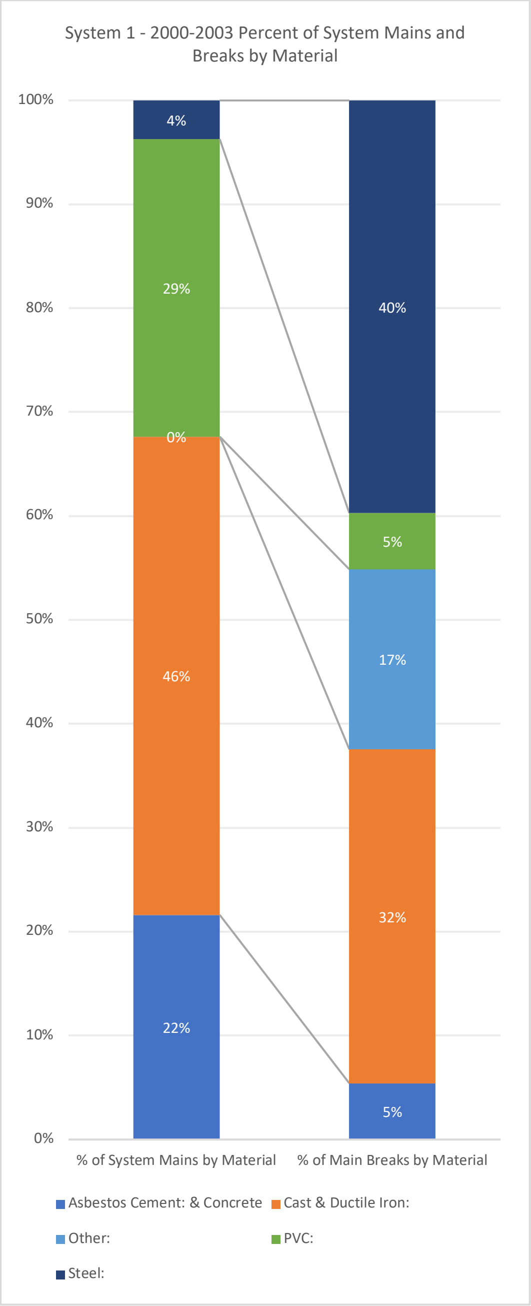


Figure 16: System 1 - 2000-2003 Percent of System Mains vs Percent of System Breaks by Material

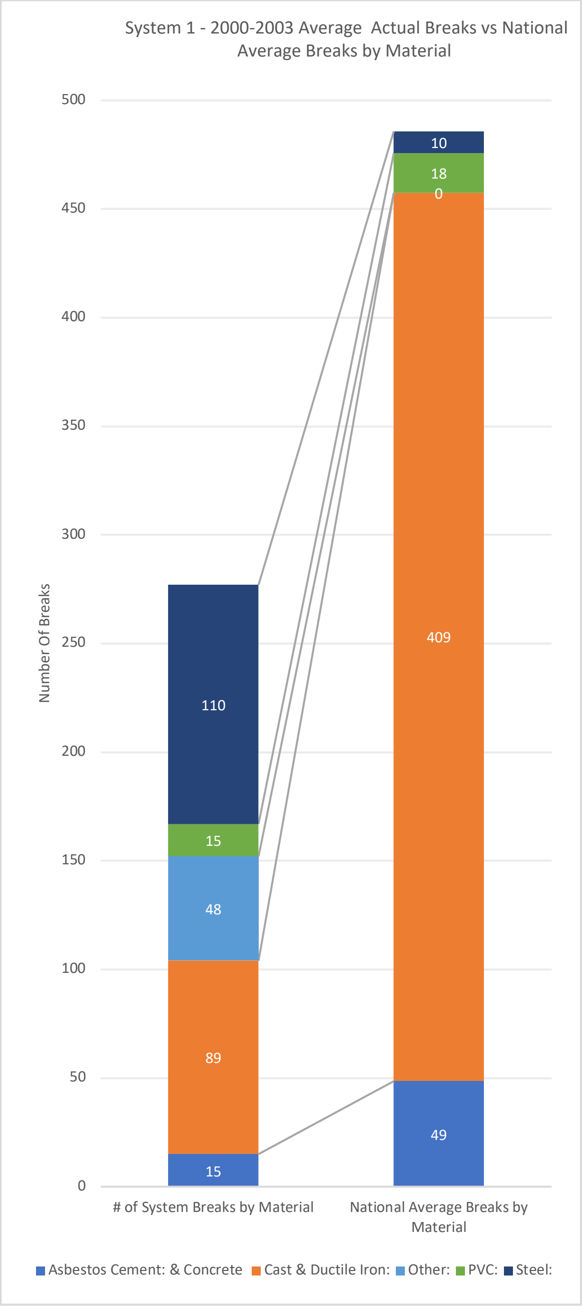


Figure 17: System 1 - 2000-2003 Actual Breaks vs National Average Breaks by Material

For the period 2004-2009, after which System 1 had the results of the initial SW EFC break data study covering the period 1994-2003, System 1 began to make serious headway on removing the leakiest sections of steel pipe. The System BRI had decreased slightly and remained well below the national average, and the Steel Material BRI was more than halved to 4.9. (See Figure 18) PVC breaks on the other hand were on the rise, but as shown by Figures 19 and 20, PVC contributed a very low number of breaks to the total. Figures 19 and 20 also demonstrate that System 1's low system break rate was driven primarily by low CI break rates.

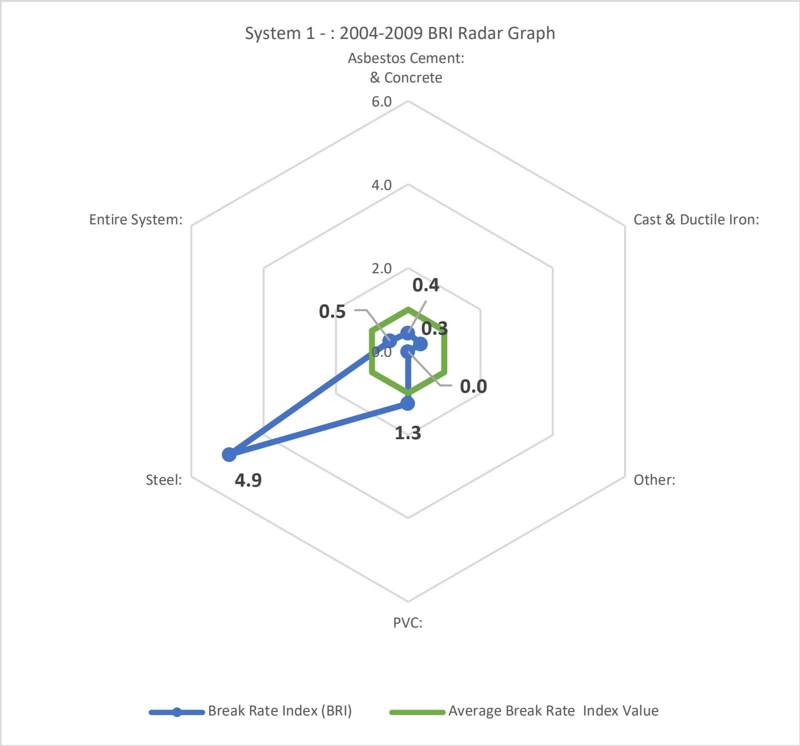
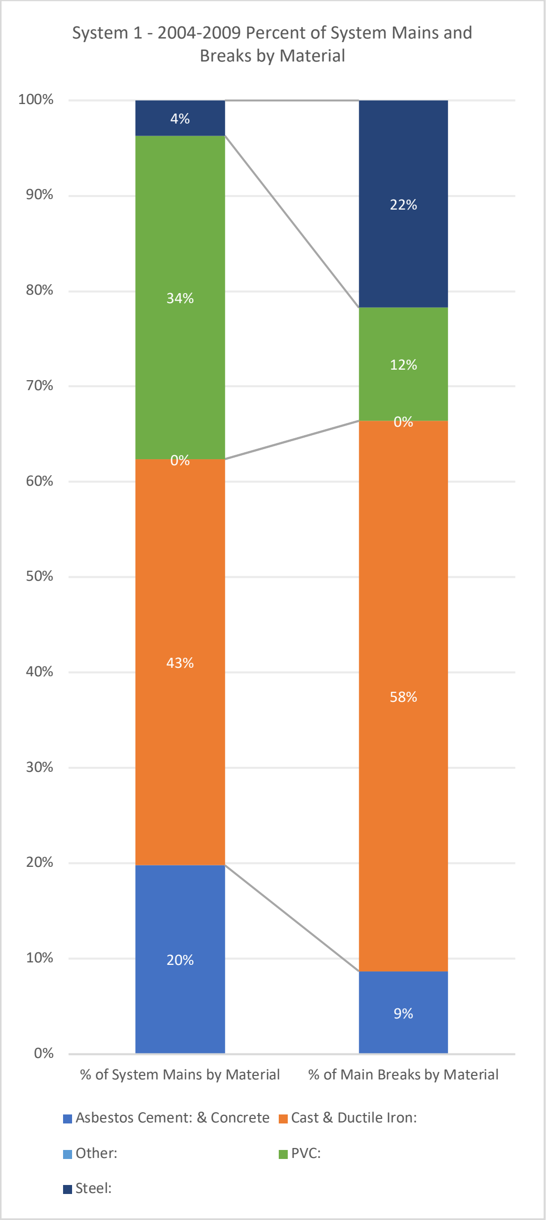


Figure 18: System 1 - 2004-2009 BRI Radar Graph



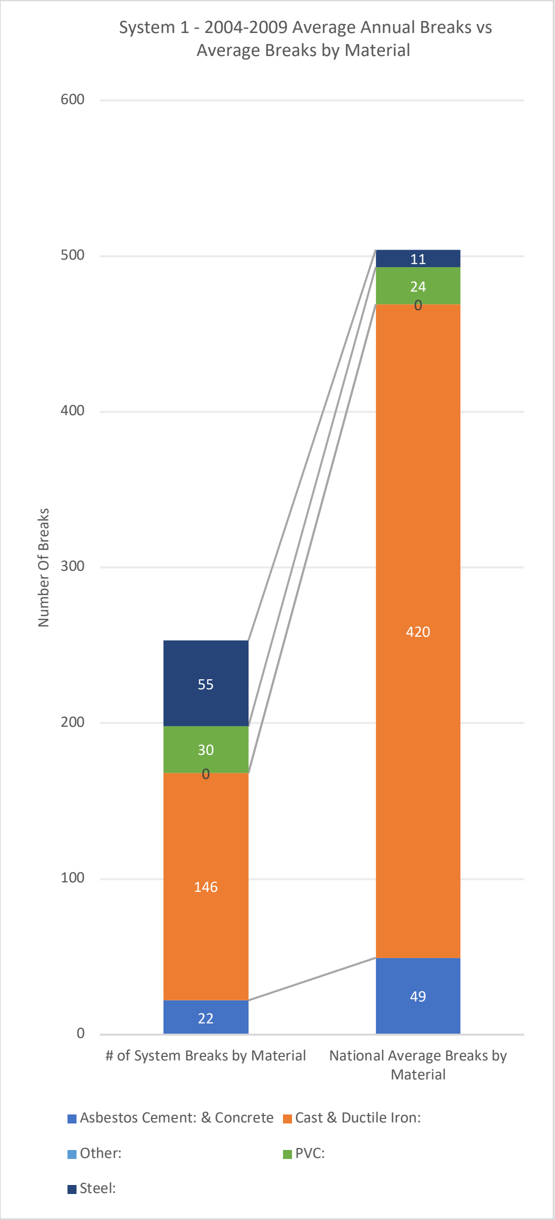


Figure 19: System 1 - 2004-2009 Percent of System Mains and Breaks by Material

Figure 20: System 1 - 2004-2009 Average Annual Breaks vs National Average Breaks by Material

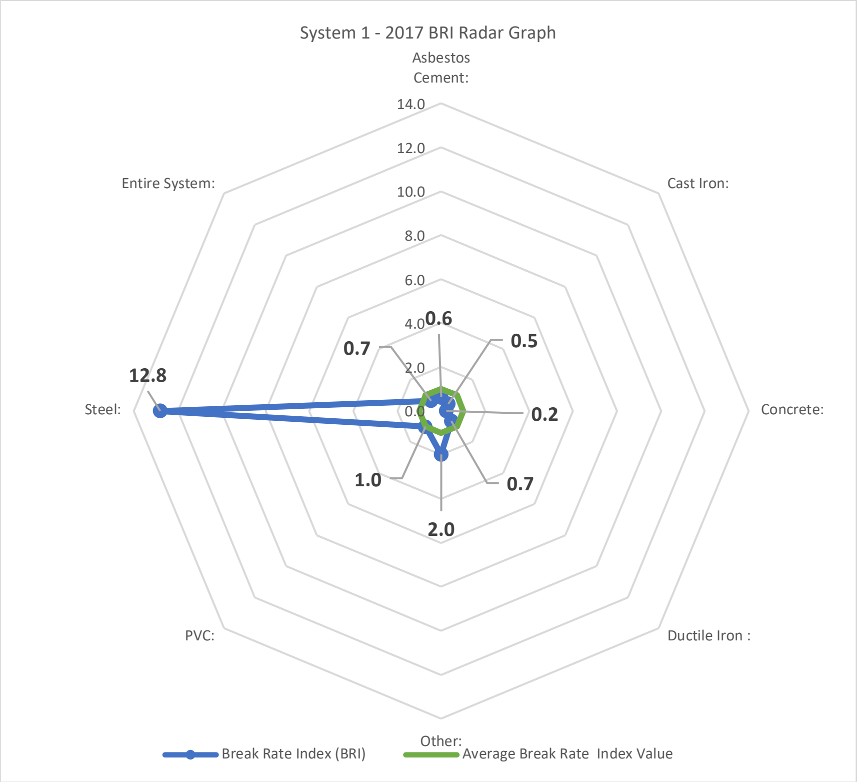


Figure 21: System 1 - 2017 BRI Radar Graph

2017 data is a bit more refined than the earlier data sets in which some categories of pipe (such as CI and DI) were combined. It shows that while System 1 continued to have a lower than national average break rate for the entire system, its System BRI had increased to 0.7. This value was still well below a weighted national average and is a single year value that may not be indicative of longer-term trends.

While System1 continued to make progress removing break prone Steel mains between 2009 and 2017, Figure 21 shows that the Steel BRI increased in that period, having almost tripled since 2009. Figure 22 shows that Steel pipe only made up 1.4% (46.45 miles) of the system in 2017 but was responsible for

21.4% of main breaks. Figure 23 demonstrates that System 1's low break rate is still driven predominantly by low CI break rates.

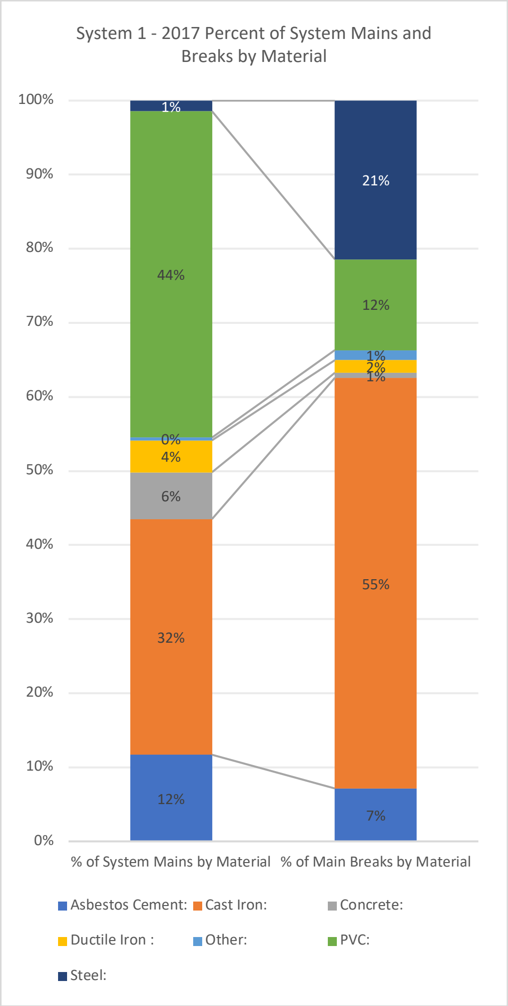


Figure 22: System 1 - 2017 Percent of System and Breaks by Material

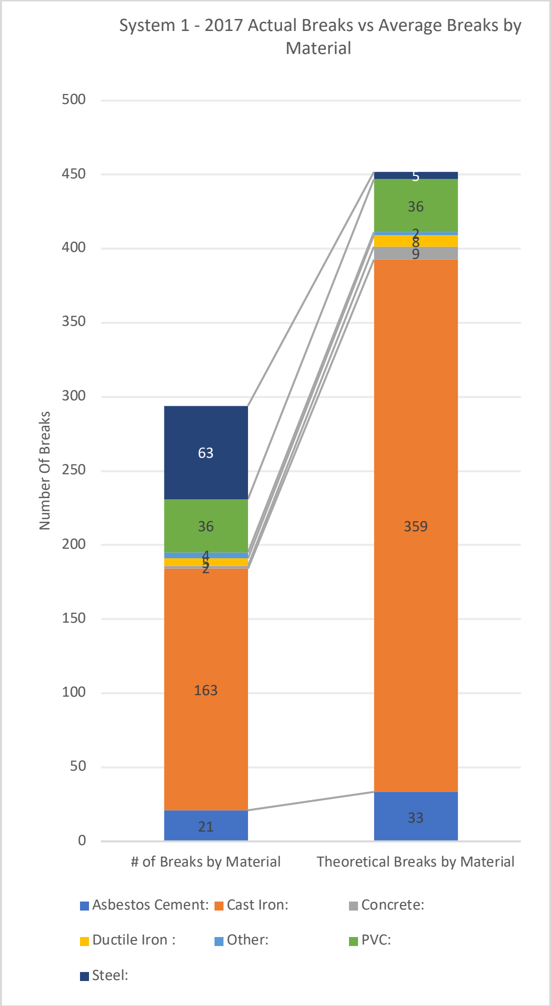


Figure 23: System 1 - 2017 Actual Breaks vs National Average Breaks by Material

However, System 1 is reportedly currently replacing mains at a rate of >2% per year and it is not unreasonable to believe that all 46 miles of Steel pipe (or some other sections of Steel and other leaking pipe that are in worse shape) could be removed in a relatively short period of time. Such changes made over time eliminating that Steel pipe would also be plainly evident in the BRI radar graph as the Steel pipe category would disappear.

Tracking breaks by pipe type and combining that information with system pipe matrix information as shown above in the BRI calculation would have produced similar results to the GIS analysis done by the SWEFC if System 1 had data in a suitable digital format for such analysis, pointing to the high Steel pipe break rate as a major problem.[25] A comparison of the first two graph sets also shows that the methods used by System 1 to address its break rates through pipe replacement in the 1995-2003 time frame were not working: though some Steel pipe had been removed from the distribution network, what remained still counted for almost half of the system breaks. Focusing Steel pipe replacement on the leakiest sections after the 2003 time frame has produced results. It should be noted that the amount of pipe in the System 1 distribution network has increased dramatically in the period since 1994 and that total numbers of annual breaks has also increased, but the BRI normalizes that to a breaks/mile standard.

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[25] It should be noted, however, that System 1 did not have its break in a format that would have allowed it to complete a BRI analysis at the time. SWEFC staff spent a significant amount of time and effort converting paper records into a digital format that could be used for the GIS (or BRI) analysis.

4.4.1.2 RTI:

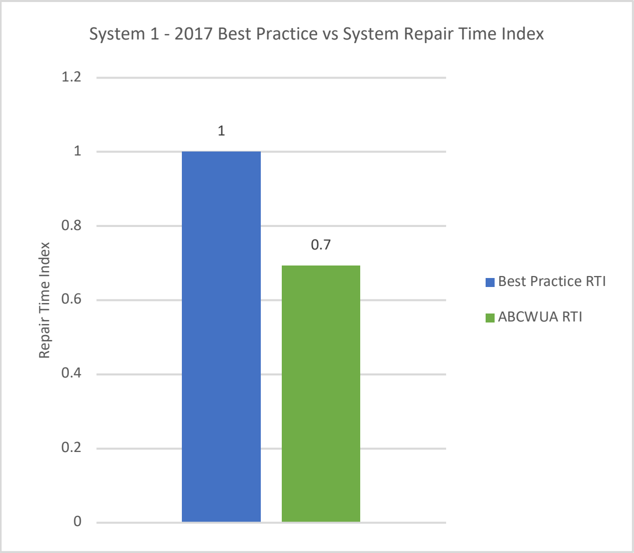

Figure 24: System 1 - 2017 Best Practice vs System Repair time Index

System 1 has an extremely fast average main break repair time of 13 hours. While this is not the fastest repair time reported, it is significantly faster than the author's suggested best practice repair time of 18.75 hours. Figure 24 shows that System 1's 2017 RTI is 0.7 indicating that slow repair time is not a likely not currently a major cause of real water loss in the System 1 distribution network.

4.4.2 System 2:

4.4.2.1 BRI:

System 2 has a higher than average system break rate as is demonstrated by its 2017 System BRI of 3.1. (See Figure 25) Interestingly, the individual Material BRI values are very close to each other, ranging from a low of 2.9 for PVC, to a high of 4 for DI and Other.

However, as is shown in the graphs in Figures 26 and 27 the highest proportion of system breaks are coming from CI and AS pipe~~.~~ CI only accounts for 11% of the System 2 distriution network by length, but is responsible for 43% of the breaks, and thus would present a good starting point for further analysis, but the uniformly high BRIs may point to a more systemic probem (or problems).

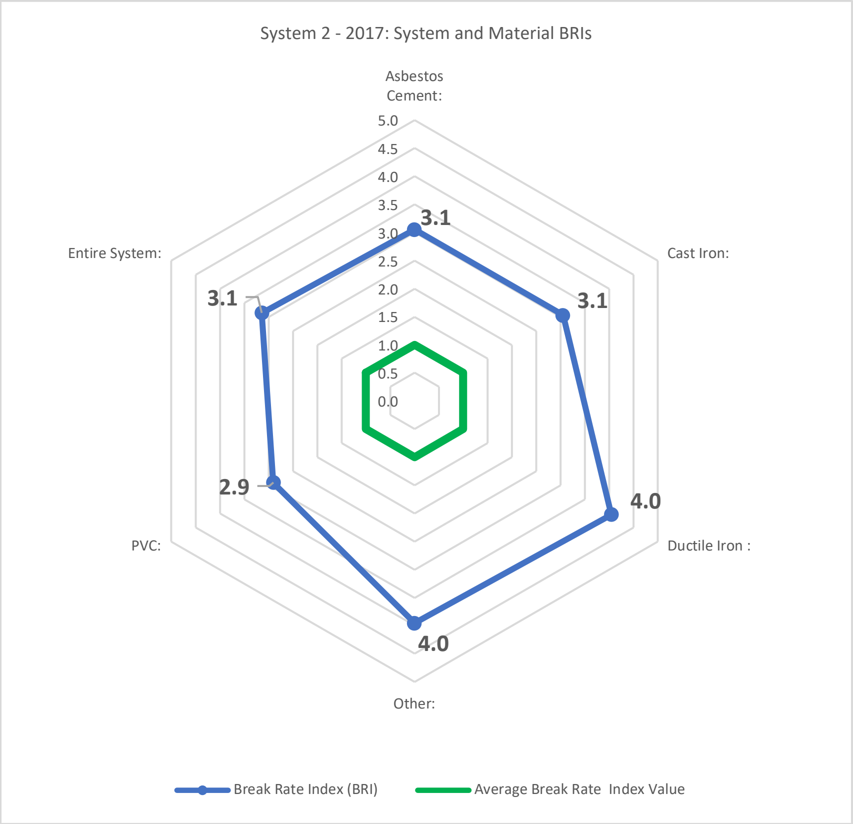

Figure 25: System 2 - 2017 System and Material BRI Radar Graph

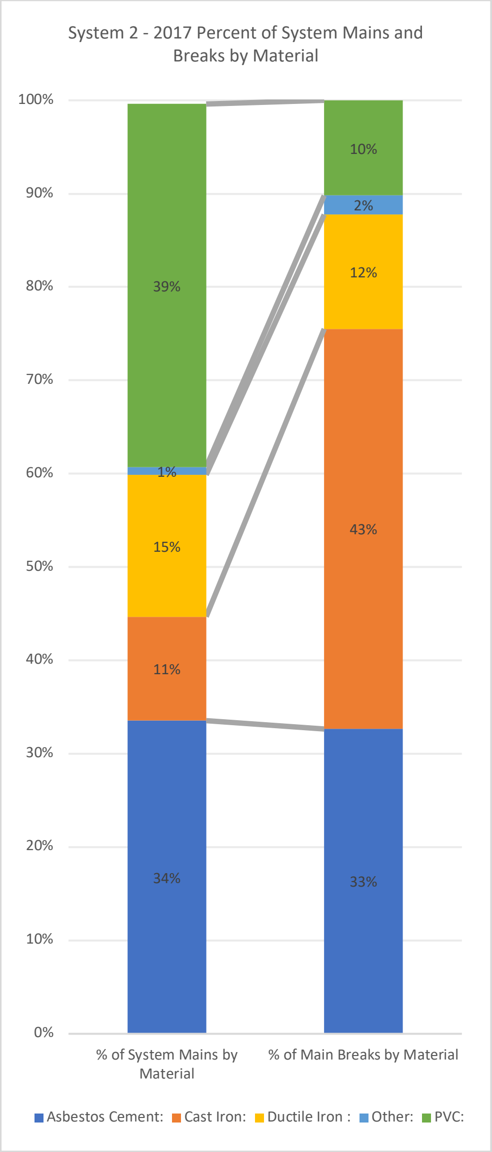

Figure 26: System 2 - 2017 Percent of System and Breaks by Material

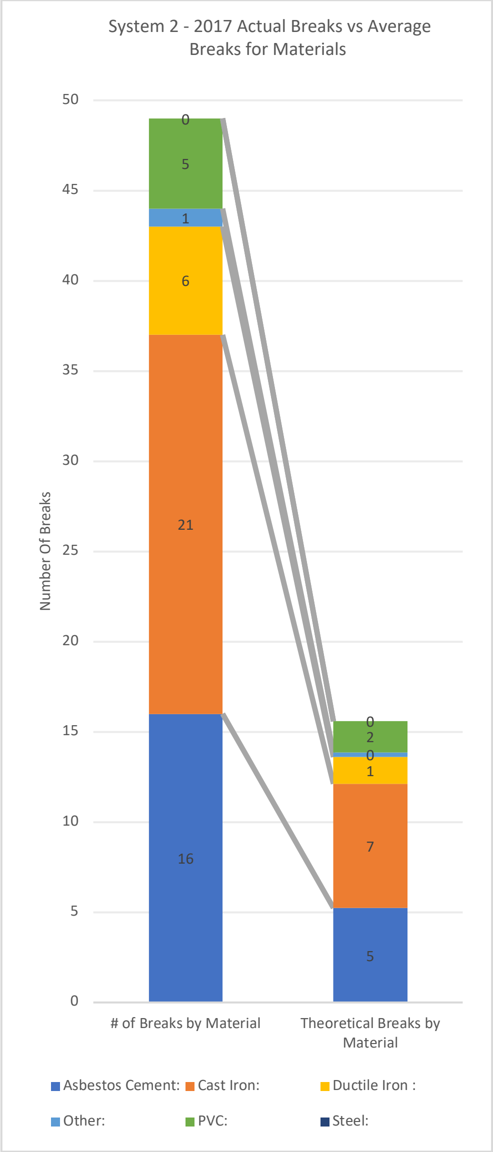

Figure 27: System 2 - 2017 Actual vs National Average Main Breaks by Material

4.4.2.2 RTI:

Estimating System 2’s RTI required making some assumptions as 3 of the 50 main break work order records were missing completion dates and scraping time data from the work order PDFs proved impractical. Work orders that were completed the same day that the main break they covered was reported were assigned a completion time of 0.5 days. Time for work orders not completed on the same day they were reported were calculated by subtracting the completion date from the report date. For the three records where the report date or the completion date was missing a value of 0.5 days was assigned. Using this method, System 2's average main repair time in 2017 was approximately 0.8 days.

When using the suggested RTS of 0.78 days System 2's 2017 average repair time yields an RTI of 1.02 (see Figure 28) suggesting that System 2 is currently meeting the best practice standard for mains repairs, and that slow repairs are not a likely a significant contributor to real losses.

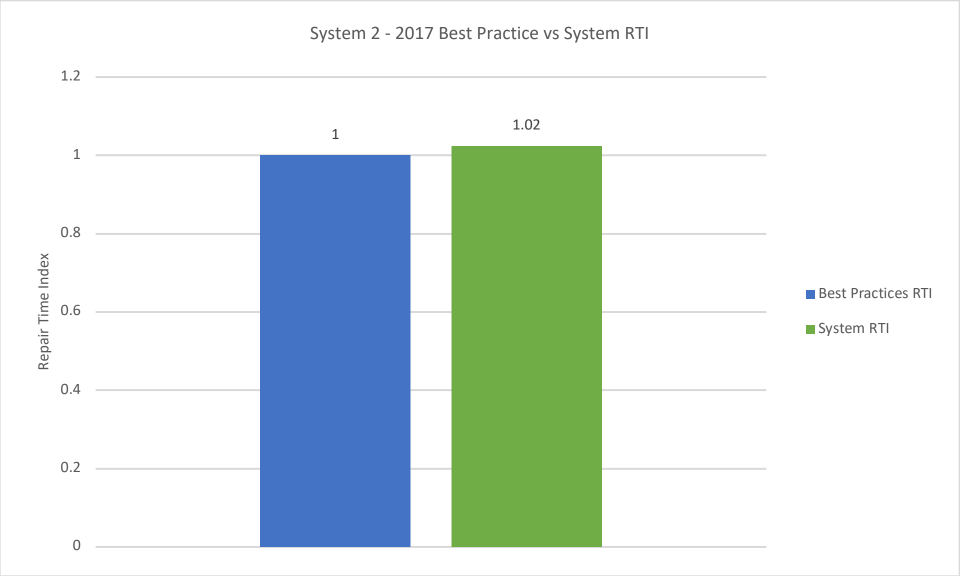

Figure 28: System 2 - 2017 RTI Graph

However, System 2's 2015 RTI was 1.4 and its 2016 RTI was 1.7 thus it is difficult to say whether the 2017 RTI is representative of improved performance, or whether the low value is simply due to the 2017 main breaks not being as severe as in prior years, or to incorrect estimates being made or the RTI calculation.

4.4.3 System 3:

System 3 is actively engaged in with real water loss control, has a long history of water auditing. However, it has been documented that in addition to its high main break rate, the utility has struggled for years with service line breaks - to such a degree that all of the service lines in the entire network are being replaced. In the period Jan 1, 2011 to Dec 31, 2015 System 3 experienced 185 main breaks, and 4040 service line leaks. In that same period 3014 service lines were replaced indicating that main breaks may not be System 3's primary concern, yet.

4.4.3.1 BRI:

System 3's mains are almost 95% PVC, with CI, DI and AS pipe making up 0.3%, 4.1%, and 0.7% of the network respectively. Figure 29 shows that in 2016 all of System 3's main breaks were on PVC pipe. The break rate for PVC, however, was almost 3 times the national average. Figures

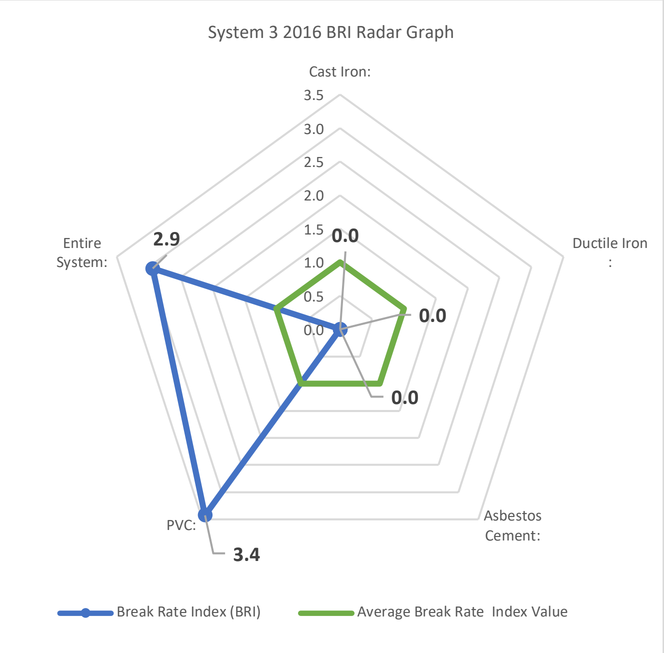

Figure 29: System 3 - 2016 BRI Radar Graph

30 and 31 reinforce this. As System 3 gets its service line break situation under control, it may begin to focus on determining the cause source of its high PVC break rates. Further categorization of pipe types within the PVC category and GIS location analysis may yield clues.

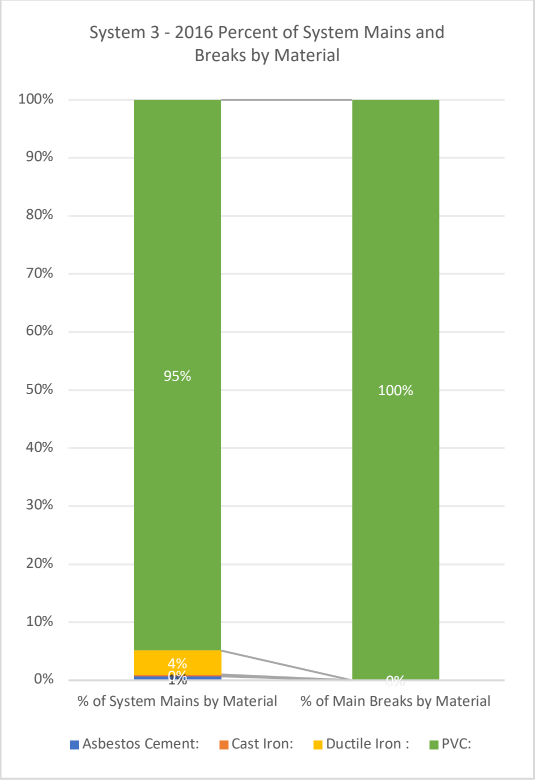

Figure 30: System 3 - 2016 Percent of System vs Percent of Breaks by Material

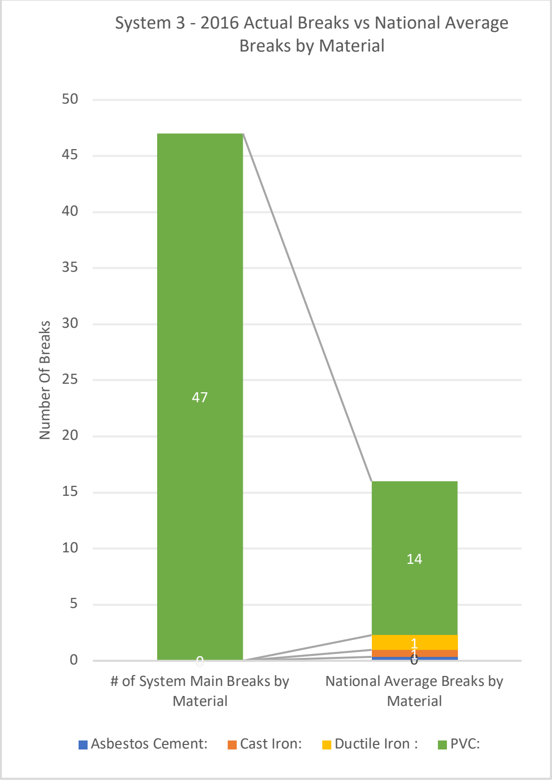

Figure 31: System 3 - 2016 Actual Breaks vs National Average Breaks by Material

4.4.3.2 RTI:

The work order data provided by System 3 yielded an average response time during 2016 was 1.42 days (34.1 hours), which equates to an RTI of 1.8

(see Figure 32) indicating that System 3 main break repair time is not quite twice the best practice repair time standard identified above. This value is, however, suspect and must be taken with a grain of salt. While each main repair had three time stamps: reported, responded, and repaired, all but 4 of the entries had identical time stamps for responded and complete, and six records had time stamps that indicated the work was completed before to the indicated response time. While this may be due to a faulty export of work order data from System 3's database, it suggests that developing better work order record keeping or export protocols may be required to get a better understanding of the utility's main break response time.

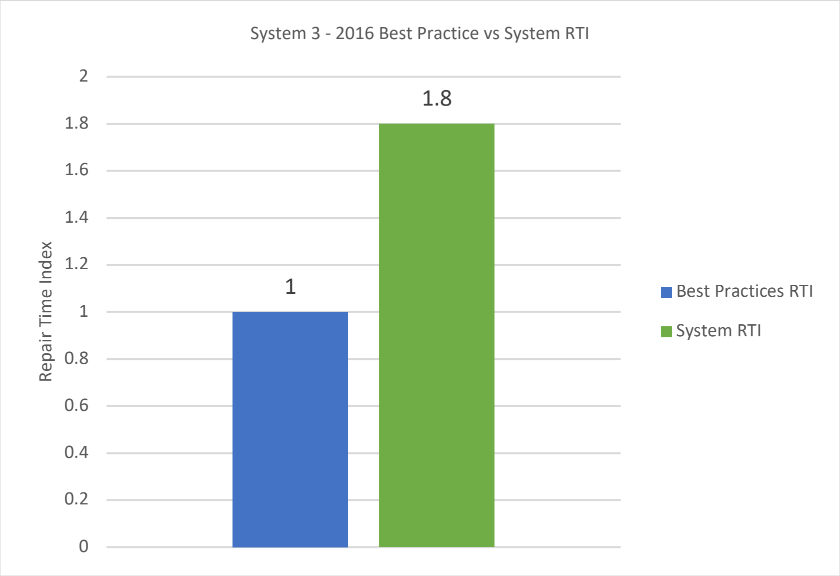

Figure 32: System 3 - 2016 RTI Graph

4.4.4 System 4:

Real losses are a significant issue for System 4. System 4's latest draft water audit covering the period 7/2017-6/2018 showed 266.49 MG/YR or 44.7% of water supplied to the system as CARL. The calculated UARL was 108.06 MG/YR and ILI was 2.47.

The fact that System 4’s main break rates are many times the national average in all material categories (as shown by the BRI graph below) tends to corroborate high calculated real loss volumes on a macro level – higher than average break rates logically equate to higher real loss numbers.

Further, the BRI and accompanying interpretation graphs will provide insight for System 4 to begin prioritizing its leak detection efforts as it will give them information about their system’s condition that the water audit alone will not: namely break rates by material with a comparison to national averages and a graphic display of breaks by pipe size & material which indicates which pipe classes are the most problematic, and which are likely to contribute significantly to real losses. An evaluation of this information will enable System 4 to judge the severity and impact of its various categories of breaks and determine how to begin implementing both leak detection and pipe replacement.

4.4.4.1 BRI:

The 2015 BRI radar graph shows System 4 had a system wide break rate 4.4 times the national average. While its CI break rates were low, all other categories were high, and the PVC rate was an astronomical 22.2 times the national average. (See Figure 33)

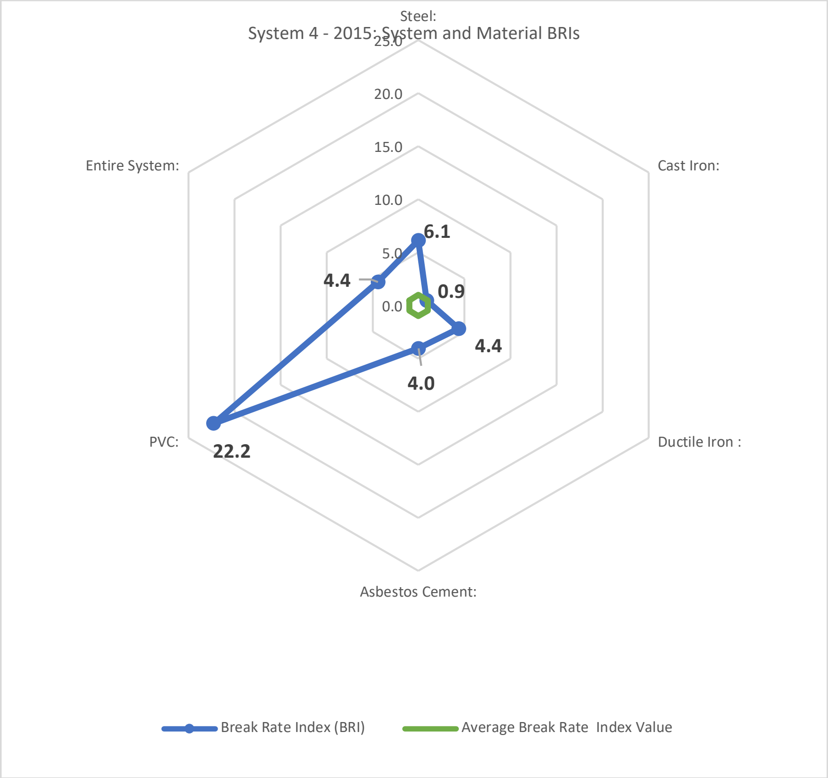

Figure 33: System 4 - 2015 System and Material BRIs

The data graphed in Figures 34 and 35 shows that and that the main drivers for the high system BRI were PVC and Galvanized Steel pipe.

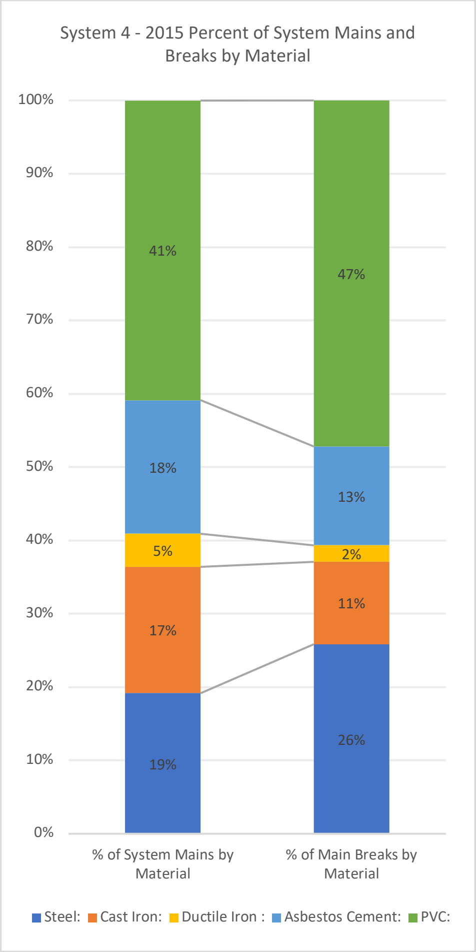

Figure 34: System 4 - 2015 Percent of System Mains and Breaks by Material

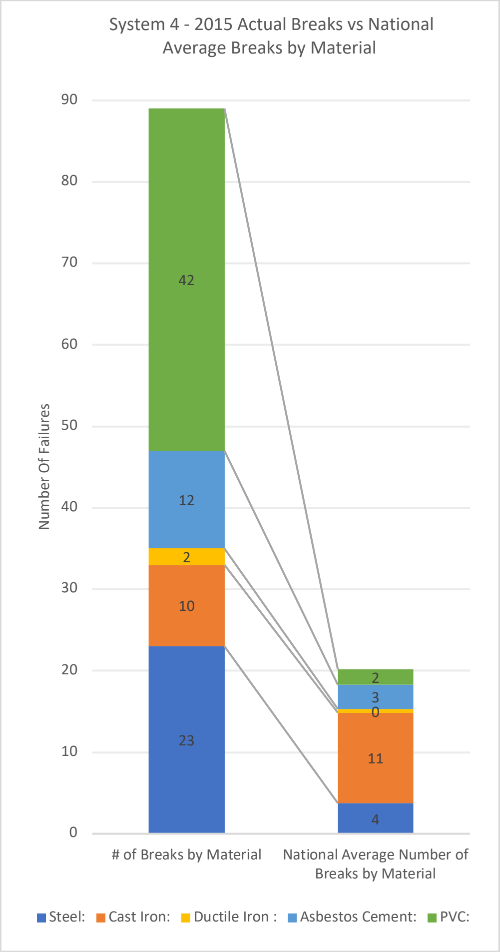

Figure 35: System 4 - Actual Breaks vs National Average Breaks by Material

These pipe types should be monitored for leaks and investigated to determine the failure causes. System 4 runs its water distribution system at a relatively high average system pressure – 100 PSI or more. Pressure (both typical system pressure and pressure transients), deterioration and other causes such as installation, should be investigated to determine the reason for high Galvanized Steel, AC, and PVC failure rates.

System 4 plans to invest in leak detection equipment during FY2019. The BRI and accompanying interpretation graphs provide insight for System 4 to begin prioritizing its leak detection efforts as they give System 4 information about their system's condition that the water audit alone will not. An evaluation of this information will enable System 4 to judge the severity and impact of its various categories of breaks and determine how to begin implementing both leak detection and pipe replacement.

4.4.4.2 RTI:

The break data System 4 provided did not allow the calculation of an RTI value. Work orders from the early 2000s (which were not analyzed in this study) seem to indicate that the vast majority of repairs done on work orders related to main leaks are completed in less than a day, but the work order entries covered in this section were not time stamped and there is no completion date field from which one could calculate the duration of the main leak report to isolation or repair cycle.

4.4.5 Analysis Summary

BRI/RTI analysis can point systems to physical and operational sources of real water loss (such as break-prone Steel pipe in the case of System 1, and slower repair times in the case of System 3) – thus giving systems targets for water loss control activities. BRI/RTI reviews provides an inexpensive, low-tech means of corroborating calculated real loss values from a water audit at a macro level without relying on the volumetric data contained in the audit. High break rates and slow repair times naturally lead to higher real loss that low break rates and fast repair times.

Though a BRI analysis will not show a system exactly which pieces of pipe are the leakiest, in a mixed pipe system it can help identify classes of pipe in a system that are more break-prone – and thus are candidates for leak detection or replacement. Done over time the BRI analysis will show increasing break rates by material and can thus point the way for more in-depth, location-based analysis of break patterns – either on paper or using a more sophisticate method like GIS analysis. A BRI analysis can be done with a minimum amount of data, using basic spreadsheet tools, and does not require the use of GIS programs, though GIS can greatly simplify the analysis, and provides the additional location specific pattern analysis element that a BRI analysis alone cannot do.

While a BRI analysis may clearly show problems in a mixed pipe system, in a single-material system, or a system with only a few types of pipe such as System 3, the predominant sources of main break-related real loss may not be so easily identified. But the analysis is still useful, as it will let a system know how their break rates compares to national averages, and the analysis format could be adapted to evaluate other factors such as age, or pipe diameter as more data is collected.

An RTI analysis provides a simple way for a system to determine whether a system's main break isolation and repair procedures measure up to industry best practices. Improving leak isolation and/or repair speeds is a simple way to reduce real water loss. The shorter a leak's run time, the less water will be lost.

Of course, the decision to speed up repairs is not without cost and determining the optimal repair time is a system specific determination that will include more factors than real water loss.

Chapter 5: Conclusion and Recommendations

5.1 UARL and ILI should be supplemented by BRI and RTI

The UARL and ILI – at least in the US context – may be disincentivizing water loss control actions by US water utilities that are engaged in auditing by presenting a theoretical low loss level standard that is too high. They may also be giving regulators an incorrect impression of economically attainable low loss limits for water systems under their jurisdiction, and just how well those systems are meeting their water loss goals. The number of underlying assumptions in the UARL formula, the underlying uncertainties of the calculations, and the fact that major variations in the combination of flow rate, repair time and break right can yield the same results are all problematic. In its current format, the Water Audit Software PIs such as the UARL and ILI provide a call to do better with regards to real loss, without a clear indication of how to go about that. While such indications can be uncovered by doing additional LCA, it is unclear how many systems actually engage in such activities after (or concurrent with) their water audit process. Adding the BRI and RTI PIs to the Water Audit Software would be a relatively simple way to introduce systems to basic LCA that can point to break prone pipe types and slow repair times in water systems.

5.2 Changing the Audit Format to Include BRI & RTI Will Make Audit Results More Actionable

The Water Audit Software in its current format gives the auditing system very little actionable information that can be used to address sources of real water loss. Though the Water Audit Software calculates the volume and cost of CARL and gives a theoretical scale of the problem through the UARL and ILI calculations, neither the UARL nor the ILI gives either utility any indication about what their real problem is. Of course, UARL and ILI proponents are likely to respond “So what? That’s not the function of the UARL or the ILI, or even the audit itself - its purpose is to estimate volumes,” to which the author’s response is “Why not?” The whole purpose of the water audit process is to help systems identify real and apparent losses with the idea that systems will then do something about those losses. The easier it is for systems to identify and categorize real loss and its sources, the easier it is for them to determine what actions they could take to impact those losses - particularly if the audit itself can point to likely culprits.

Incorporating the BRI and RTI into the Water Audit Software structure can accomplish just that. Systems will be prompted to collect break and repair time data – which in and of itself contributes to operators and managers knowing more about their systems. The data they collect, when input into the Water Audit Software and analyzed via the BRI and RTI will provide them with actionable information – by demonstrating via the RTI when their repair times are slow, and by indicating via the BRI and accompanying radar and interpretive graphs which types of pipe are breaking most in their system, and which are breaking at higher than average rates. The system of course still must undertake an economic analysis to determine if and how to address its results – but the important thing is that the water audit results would give them a target for action.

5.3 Increased Reporting is Not a Significant Burden

If additional data fields related to actual main line failures and repairs were added to the Water Audit Software for the purpose of calculating BRI and RTI, systems would be incentivized to collect data that they, as well-run systems should already be collecting: namely break data, repair time data, and loss estimates.[26] The additional reporting burden in jurisdictions that require auditing would be minimal, but the value of the data collected would be immense. Including pipe break and repair time data in the audit would provide the seed for developing a national main break rate database by collecting significant amounts of data in a uniform format.

Data for BRI and RTI calculations that is submitted to jurisdictions requiring water audits would provide a treasure trove of uniform information that could be used to develop regional or national main break databases for further study. Such information could be leveraged in many ways to benefit a vital component of our national infrastructure: our water distribution systems. It could be mined to monitor regional and national trends relating to water system main

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[26] Indeed, some states, such as Texas and Wisconsin, already require basic reporting of main break data.

breaks by material, size and other variables. From it tools to further evaluate individual distribution system condition could be developed.

States that require auditing using the AWWA software would gain valuable insight into both the actual break rates prevalent in their jurisdictions and the typical repair time frames utilities are working under. This information could over time, both allow minimum standards to be developed, and would also permit state authorities to identify systems that are paragons in the area of water loss control, and also those who are in need of assistance in implementing best practices.

This is not to suggest that minimum standards be developed as a way to punish underperforming systems. Instead the data gleaned through such a data collection scheme could be used to identify statewide training needs, and could also potentially be used to promote healthy competition between systems, and to allocate funding in the form of grants or low interest loans, as state authorities would be able to determine which systems are in the need of most help and which systems are performing well in the arena of water loss control.

5.4 The BRI and RTI Provide a Bridge to Larger-scale LCA

The problem of systems not doing separate LCA would be mitigated by changing the audit format to include some of the LCA data points on which the BRI and RTI calculations are based. While this would make the water audit a slightly more involved process and thus might discourage the completion of water udits in areas where it is not required, this alone is not reason enough to exclude basic LCA from the audit itself. Systems auditing voluntarily are looking to improve their water loss control and will likely make the effort. Systems that are required to audit by legal mandate will have no choice but to comply.

The incorporation of the BRI and RTI, and associated data would add a basic level of LCA into the audit process, and provide insight to the systems into whether failure rates and repair times were a likely and significant cause of real losses, and more importantly point to the types of pipe in their actual systems that is performing well or poorly. As systems collect more data, and see the usefulness thereof, larger scale LCAs will seem less daunting.

5.5 Suggested Further Research

This thesis only addressed the reported mains breaks and leaks component of the UARL and ignores the service line break components of the UARL. In New Mexico meters are typically located at the curb stop and utilities are not responsible for the real losses that occur after the meter on the service lines. But in many areas of the US meters are not located at the curb but are instead located further away (such as in basements as is typical in colder states such as Michigan). In such cases, real losses on the service lines before the meter accrue to the utility. This volume can make up a substantial portion of the real loss volume and can be greater than losses on mains. Thus, regional and national data should be developed for service lines as well, and if possible, metrics similar to the BRI and ILI should be developed from that data to help water utilities evaluate their service line breaks rates and repair times.

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Appendix 1: New Mexico System Main Breaks by Main Material and Diameter

Appendix 1.1 System 1 - 2017 Main Breaks by Main Material and Diameter

OBJECTID_1	PIPE_LENGTH	PIPE MATERIAL	PIPE EXTERNAL DIAMETER	Count_
90116	593.00	AC	4	1
104069	477.10	AC	4	1
109258	285.85	AC	4	1
7629	377.48	AC	6	1
10611	96.80	AC	6	1
11572	503.71	AC	6	1
32392	268.92	AC	6	1
48439	220.95	AC	6	1
49432	679.66	AC	6	1
51101	716.97	AC	6	1
75729	30.75	AC	6	1
77312	46.88	AC	6	1
25	238.08	AC	8	1
93150	959.00	AC	8	1
121310	63.25	AC	8	1
122031	154.99	AC	8	2
81892	306.00	AC	10	1
112377	207.54	AC	10	1
112831	296.14	AC	10	1
115662	453.00	AC	12	1
15302	407.52	AC	16	1
124008	111.62	CCYL	10	1
108908	367.76	CCYL	16	1
121878	347.00	CCYL	16	1
48146	301.50	CCYL	18	1
47741	380.83	CCYL	20	1
74816	913.85	CCYL	20	1
113525	608.38	CCYL	20	1
89883	387.80	CCYL	24	1
16913	250.00	CCYL	24	2
19997	3737.57	CCYL	36	1
22985	1128.25	CCYL	36	1
45954	674.47	CCYL	36	1
107674	2377.97	CCYL	42	1
32856	258.97	CI	2.25	1
103795	166.49	CI	2.25	1
23692	202.88	CI	4	1
31067	232.18	CI	4	1
34574	1259.51	CI	4	1
74475	221.02	CI	4	1

78016	542.75	CI	4	1
80323	192.00	CI	4	1
81615	321.98	CI	4	1
89588	214.67	CI	4	1
112937	300.62	CI	4	1
516	43.00	CI	6	1
1245	247.12	CI	6	1
3160	703.52	CI	6	1
3921	424.30	CI	6	1
4693	430.14	CI	6	1
6335	15.00	CI	6	1
7035	88.00	CI	6	1
7598	256.38	CI	6	1
8585	624.03	CI	6	1
10366	574.36	CI	6	1
10969	645.92	CI	6	1
12194	260.01	CI	6	1
13770	252.87	CI	6	1
14777	264.28	CI	6	1
16854	778.40	CI	6	1
17300	234.77	CI	6	1
17664	409.24	CI	6	1
18076	223.75	CI	6	1
18404	773.75	CI	6	1
23053	205.28	CI	6	1
26735	547.81	CI	6	1
30288	304.40	CI	6	1
30553	488.04	CI	6	1
31520	593.77	CI	6	1
33404	68.12	CI	6	1
33914	401.00	CI	6	1
36130	678.00	CI	6	1
38354	762.13	CI	6	1
43835	646.00	CI	6	1
50246	30.75	CI	6	1
50467	295.32	CI	6	1
52422	780.97	CI	6	1
52869	1190.00	CI	6	1
55358	393.80	CI	6	1
60137	57.00	CI	6	1
71687	788.67	CI	6	1
72053	353.82	CI	6	1
73108	40.31	CI	6	1
73486	174.38	CI	6	1
73514	566.15	CI	6	1
73797	456.52	CI	6	1
74352	307.98	CI	6	1
81333	577.57	CI	6	1

82013	942.95	CI	6	1
82383	286.63	CI	6	1
82510	576.05	CI	6	1
83811	194.05	CI	6	1
84092	419.25	CI	6	1
91830	248.25	CI	6	1
91986	125.00	CI	6	1
92057	452.53	CI	6	1
94123	389.03	CI	6	1
95091	654.50	CI	6	1
95182	506.00	CI	6	1
100925	292.73	CI	6	1
102243	935.00	CI	6	1
102538	443.72	CI	6	1
102767	194.88	CI	6	1
103929	228.03	CI	6	1
105278	612.98	CI	6	1
106646	70.63	CI	6	1
107203	62.00	CI	6	1
107918	31.51	CI	6	1
109450	199.00	CI	6	1
110907	551.20	CI	6	1
111876	41.00	CI	6	1
114015	449.25	CI	6	1
118074	465.14	CI	6	1
120594	300.79	CI	6	1
121032	522.80	CI	6	1
122541	196.68	CI	6	1
122727	412.18	CI	6	1
127373	578.75	CI	6	1
25007	550.78	CI	6	2
92118	472.89	CI	6	2
96405	260.02	CI	6	2
106476	515.44	CI	6	2
2322	537.41	CI	6	3
6818	34.78	CI	6	3
27929	724.22	CI	6	3
105780	541.53	CI	6	3
124880	159.60	CI	6	3
2951	356.69	CI	8	1
13987	1127.65	CI	8	1
46293	258.74	CI	8	1
122236	434.68	CI	8	1
60614	153.99	CI	10	1
92454	454.00	CI	10	1
124121	127.45	CI	10	1
2760	37.67	CI	12	1
4185	541.00	CI	12	1

14988	219.31	CI	12	1
15385	24.21	CI	12	1
26157	61.66	CI	12	1
47325	80.27	CI	12	1
72594	304.07	CI	12	1
73593	2528.23	CI	12	1
102636	511.29	CI	12	2
38151	870.50	CI	16	1
84277	139.51	CI	18	1
90005	3159.59	CI	18	1
36299	816.34	CI	20	2
103948	226.41	CI	24	2
10293	81.00	DIP	6	1
72857	630.38	DIP	6	1
55262	60.10	DIP	12	1
78354	789.00	DIP	14	1
118457	365.28	DIP	14	1
7189	158.28	DIP	16	1
16386	1896.15	DIP	16	1
86363	1618.22	DIP	16	1
9173	511.51	GSP	2	1
49457	715.62	LWS	6	1
38100	86.52	PVC	4	1
97738		PVC	4	1
2462	75.75	PVC	6	1
3320	510.78	PVC	6	1
8061	62.61	PVC	6	1
9850	194.17	PVC	6	1
13294	723.78	PVC	6	1
20045	230.78	PVC	6	1
22402	318.00	PVC	6	1
24161	185.75	PVC	6	1
24545	959.00	PVC	6	1
24967	58.94	PVC	6	1
29431	323.24	PVC	6	1
43366		PVC	6	1
44539	10.00	PVC	6	1
44953	2.00	PVC	6	1
44990	4.00	PVC	6	1
45047	40.00	PVC	6	1
45051	36.00	PVC	6	1
45078	334.00	PVC	6	1
45144	825.00	PVC	6	1
50720	52.50	PVC	6	1
52974	449.00	PVC	6	1
54039	379.06	PVC	6	1
55985	250.91	PVC	6	1
56435	504.00	PVC	6	1

57510	809.13	PVC	6	1
58702	180.83	PVC	6	1
65774	84.00	PVC	6	1
65777	269.00	PVC	6	1
66169	460.00	PVC	6	1
68578	359.00	PVC	6	1
68870	82.00	PVC	6	1
69630	40.47	PVC	6	1
70428	340.00	PVC	6	1
72715	552.52	PVC	6	1
73994	2.00	PVC	6	1
76722	144.47	PVC	6	1
77579	55.28	PVC	6	1
78662	460.84	PVC	6	1
81243	588.00	PVC	6	1
81251	255.00	PVC	6	1
90245	1268.00	PVC	6	1
92026	306.00	PVC	6	1
95534	2.00	PVC	6	1
98782	14.00	PVC	6	1
100414	1380.46	PVC	6	1
101450		PVC	6	1
101987	53.60	PVC	6	1
102988	349.15	PVC	6	1
108136	254.69	PVC	6	1
120531	290.84	PVC	6	1
121002	309.00	PVC	6	1
124634	188.32	PVC	6	1
45021	525.00	PVC	6	2
52009	49.45	PVC	6	2
52821	584.00	PVC	6	2
65843	638.00	PVC	6	2
91179	220.43	PVC	6	2
98830	307.00	PVC	6	2
98779	727.00	PVC	6	4
15706	309.37	PVC	8	1
40553	268.00	PVC	8	1
45062	229.00	PVC	8	1
53102	872.56	PVC	8	1
53690	239.00	PVC	8	1
60687	43.93	PVC	8	1
77124	307.72	PVC	8	1
85059	181.67	PVC	8	1
111312	510.75	PVC	8	1
117312	231.32	PVC	8	1
121877	119.00	PVC	8	1
20358	190.00	PVC	10	1
36862	53.26	PVC	10	1

40622	363.00	PVC	10	1
52469	301.00	PVC	10	1
92331	253.28	PVC	10	1
93244	363.73	PVC	10	1
45491	109.75	PVC	10	2
129522	27.66	PVC	10	
129523	780.56	PVC	10	
13974	347.97	PVC	12	1
15576	235.48	PVC	12	1
17270	194.88	PVC	12	1
21888	254.00	PVC	12	1
54632	113.00	PVC	12	1
61099	799.00	PVC	12	1
63014	587.45	PVC	12	1
66247	294.00	PVC	12	1
74250	551.42	PVC	12	1
117961	123.76	PVC	12	1
52907	1930.16	RCP	30	1
114318	207.37	RCP	36	1
26038	503.80	STL	2	1
3313	344.75	STL	4	1
110400	479.91	STL	4	1
125001	79.91	STL	4	1
34889	224.93	STL	5	1
13249	270.37	STL	6	1
19473	359.55	STL	6	1
22797	873.67	STL	6	1
98940	1200.77	STL	6	1
122259	414.69	STL	6	1
126819	258.26	STL	6	1
732	218.88	STL	8	1
19142	43.56	STL	8	1
80633	646.28	STL	8	1
129358	337.20	STL	10	1
45289	377.51	STL	12	1
92328	1000.83	STL	12	1
75583	511.13	STL	12.75	2
51979	219.91	STL	16	1
126395	2748.77	STL	16	1
12634	4029.16	STL	16	2
127553	1432.49	STL	20	1
127615	119.49	STL	20	1

Appendix 1.2: System 2 - 2017 Main Breaks by Main Material and Diameter

OBJECTID	Diameter	Material	Count_	Sum_EST DAYS_TO_REPAIR	Shape_Length
2069			1	0.5	43.3789306
2140	10"	AC	1	1	2808.8325
1955	4"	AC	1	0.5	598.0692072
1356	6"	AC	1	0.5	1488.213559
1752	6"	AC	1	1	1557.236243
1774	6"	AC	2	1	1444.363848
1776	6"	AC	1	0.5	166.7735592
1892	6"	AC	1	0.5	542.7643678
1948	6"	AC	1	0.5	1466.274249
1956	6"	AC	1	0.5	728.8301273
2027	6"	AC	2	1	993.4052654
2210	6"	AC	1	1	498.8199644
2275	6"	AC	1	0.5	830.5889719
2657	6"	AC	1	0.5	550.0641471
2733	6"	AC	1	1	518.574183
1309	8"	AC	1	2	6243.574505
695	10"	CI	2	1.5	1641.366512
583	2"	CI	1	0.5	378.7356432
1486	4"	CI	1	0.5	720.8960819
1493	4"	CI	1	0.5	688.0110505
519	6"	CI	1	0.5	1132.959227
520	6"	CI	1	1	1908.758769
526	6"	CI	1	0.5	2167.166713
696	6"	CI	2	3.5	3106.996287
3019	6"	CI	2	1	255.3021235
710	8"	CI	1	0.5	353.3302175
689	10"	DI	2	1.5	317.5272281
1236	14"	DI	1	0.5	893.1978884
459	16"	DI	2	1.5	976.7894127
497	16"	DI	1	0.5	776.8892753
1404	16"	DI	1	1	2610.508326
1986	6"	DI	1	1	1116.002262
457	8"	DI	1	0.5	2399.849178
3050	12"	PVC	1	0.5	1796.065025
3056	16"	PVC	1	0.5	3531.155353
513	4"	PVC	1	0.5	1797.021129
1594	6"	PVC	1	0.5	324.6963078
281	8"	PVC	2	1	1308.409686
492	8"	PVC	1	0.5	517.6736352
660	8"	PVC	1	0.5	886.0456772
2039	8"	PVC	1	0.5	9731.666424
704	12"	STL	1	0.5	2528.042432
982	8"	UNK	1	0.5	2738.646664

Appendix 1.3: System 3 - 2016 Main Breaks by Material and Diameter

FID	Material	Diameter	Shape_Leng	Count_
38	PVC	3	24.353213	1
0	PVC	6	607.9197707	2
1	PVC	6	300.0562054	1
2	PVC	6	1197.334787	1
3	PVC	6	884.4077741	1
4	PVC	6	299.4356826	1
5	PVC	6	1962.739924	1
6	PVC	6	877.7315669	1
9	PVC	6	210.8808244	1
10	PVC	6	226.9172218	1
11	PVC	6	309.9445133	1
13	PVC	6	1000.296128	1
14	PVC	6	313.5064749	1
16	PVC	6	1372.673818	1
19	PVC	6	417.2771416	1
20	PVC	6	583.7679302	1
22	PVC	6	1462.991216	1
25	PVC	6	564.5932751	1
26	PVC	6	1167.289462	1
29	PVC	6	582.9547343	1
35	PVC	6	268.610248	1
7	PVC	8	763.5726271	1
8	PVC	8	913.5686998	1
12	PVC	8	291.7654271	1
15	PVC	8	1611.58714	1
17	PVC	8	320.1519427	1
18	PVC	8	127.9300595	1
21	PVC	8	1098.62642	1
23	PVC	8	689.7235607	1
31	PVC	8	571.6023325	1
33	PVC	8	954.4036454	1
36	PVC	8	155.8338955	1
27	PVC	10	574.0031483	1
30	PVC	10	73.18174516	1
37	PVC	10	1313.903796	3
32	PVC	12	584.6707383	1
39	PVC	12	802.3085503	2
40	PVC	12	1285.078339	3
24	PVC	14	393.4787006	1
28	PVC	16	372.6123343	1
34	PVC	24	5650.379312	1

Appendix 1.4: System 4 - 2016 Water Main Breaks by Main Material and Diameter

System 4 - 2015 Main Failures by Material and Pipe Diameter

FID	LABEL	DIAMETER	MATERIAL	LINEAR_FT	Count_
3	P25-146	6	AC	176.13	3
26	P3-010	6	AC	92.6	1
31	P36-151	6	AC	205.89	2
32	P36-180	6	AC	799.36	1
39	P22-285	6	AC	988.04	1
42	P26-075	6	AC	1311.63	1
51	P36-111	6	AC	234.18	1
53		16	AC	16172.76	2
0	P25-036	2	ASSUMED	364.7	1
9	P27-170	2	ASSUMED	371.8	1
15	P28-212	2	ASSUMED	371.04	1
22	P10-146	2	ASSUMED	528.52	1
23	P10-007	2	ASSUMED	245.2	2
29	P36-097	2	ASSUMED	530.34	1
30	P36-008	2	ASSUMED	99.39	1
34	P21-278	2	ASSUMED	618.05	3
35	P21-322	2	ASSUMED	1117.27	2
37	P22-173	2	ASSUMED	763.84	2
40	P22-318	2	ASSUMED	984.59	4
41	P22-320	2	ASSUMED	896.48	1
50	P27-007	2	ASSUMED	472.86	1
54	P20-101	6	ASSUMED	1055.85	2
2	P25-040	6	CI	128.41	1
6	P25-156	6	CI	278.32	1
11	P28-003	6	CI	580.65	4
38	P22-225	6	CI	186.13	1
48	P25-133	6	CI	359.93	2
49	P27-146	6	CI	438.04	1
45	P36-004	8	DI	1468.11	1
12	P28-388	12	DI	1418.48	1
16	P20-040	2	PVC	378.68	1
1	P25-196	6	PVC	63.31	1
7	P27-276	6	PVC	730.2	1
8	P27-287	6	PVC	555.8	3
10	P28-432	6	PVC	690.05	1
13	P28-279	6	PVC	485.34	1
14	P28-229	6	PVC	270.41	1
18	P10-153	6	PVC	255.15	1
19	P10-308	6	PVC	793.44	1
20	P10-016	6	PVC	507.94	2
21	P10-167	6	PVC	489.32	2
24	P10-501	6	PVC	16.03	1
25	P10-015	6	PVC	142.99	2

27	P36-158	6	PVC	1203.74	2
33	P21-082	6	PVC	607.68	1
36	P22-171	6	PVC	483.44	1
43	P25-129	6	PVC	115.45	5
46	P34-003	6	PVC	258.14	1
47	P34-006	6	PVC	354.91	1
52	P36-178	6	PVC	984.75	1
17	P20-098	8	PVC	72.32	1
4	P25-057	6	PVC AC	323.69	2
5	P25-216	2	PVC C900	110	3
28	P36-005	2	PVC C900	527.61	1
44	P36-080	2	PVC C900	36.85	5

Appendix 2: AWWA 2018 Benchmark Break Data

2017 Aggregate data for leaks/100 miles of pipe

	75th percentile	Median	25th percentile	Sample size	Confidence Level (1-4)	Count
Water Utilities	1.2	6.0	9.9	22	2.7	16
Combined Utilities – Water operations	4.3	8.4	21.7	52	2.5	39

2017 Aggregate data for breaks/100 miles:

	75th percentile	Median	25th percentile	Sample size	Confidence Level (1-4)	Count
Water Utilities	1.2	5.6	11.8	23	3.0	15
Combined Utilities – Water operations	3.4	7.9	19.4	59	2.7	41

2017 Combined leaks and breaks/100 miles:

	75th percentile	Median	25th percentile	Sample size	Confidence Level (1-4)	Count
Water Utilities	4.7	12.5	19.2	41	2.8	26
Combined Utilities – Water operations	11.8	18.2	36.4	76	2.7	53

Appendix 3: Hypothetical Weighted Average Break Rate by Region Based on Length of Pipe Surveyed in Region and National Average Break Rates by Material from 2018 Utah State Break Rate Study

Regions list:

Region:	States included in Region:
Region 1	AK, ID, OR, WA
Region 2	CA, HI, NV
Region 3	CO, MT, UT, WY
Region 4	IA, KS, MO, NE, ND, SD
Region 5	AZ, AK, LA, NM, OK, TX
Region 6	IL, IN, MI, MN, OH, WI
Region 7	AL, FL, GA, KY, MS, NC, SC, TN
Region 8	CT, DC, DE, MA, ME, ND, NH, NJ, NY, PA, RI, VA, VT, WV
Region 9	Canada

Region	Material	2018 Percentage	Average Percentage	2018 Break Rate/100 miles/yr	2018 Average Break Rate/ mile/year	Weighted Average Break Rates	Regional Weighted Average Break Rate/mile/yr
9	CI	29	29	34.8	0.348	0.101	
	DI	19	19	5.5	0.055	0.010	
	PVC	36	36	2.3	0.023	0.008	
	CPP	3	3	3.1	0.031	0.001	
	Steel	3	3	7.6	0.076	0.002	
	AC	9	9	10.4	0.104	0.009	
	Other	1	1	12.4	0.124	0.001	0.133

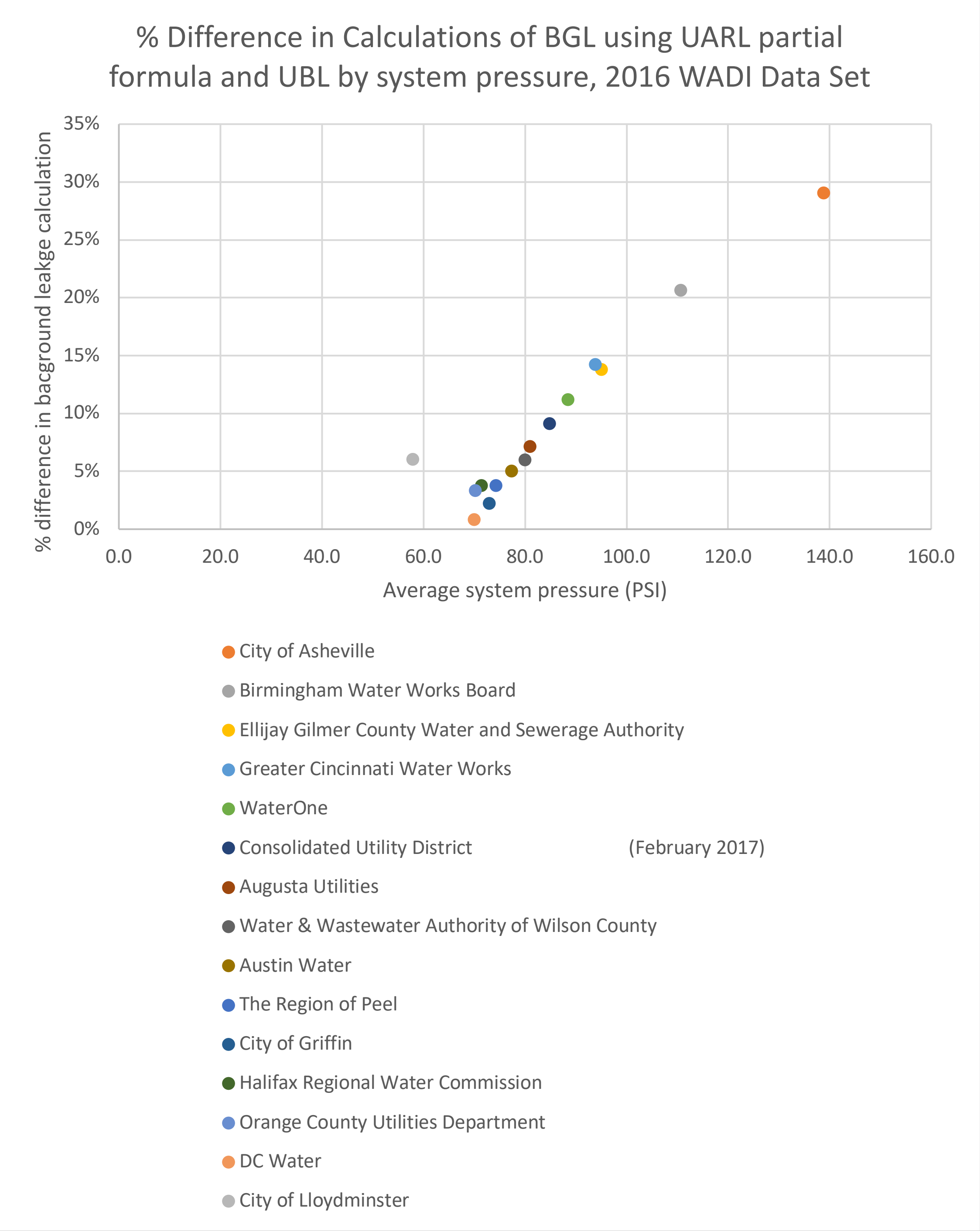
8	CI	39	39	34.8	0.348	0.136	
	DI	36	36	5.5	0.055	0.020	
	PVC	12	12	2.3	0.023	0.003	
	CPP	2	2	3.1	0.031	0.001	
	Steel	1	1	7.6	0.076	0.001	
	AC	7	7	10.4	0.104	0.007	
	Other	3	3	12.4	0.124	0.004	0.171
7	CI	28	28	34.8	0.348	0.097	
	DI	47	47	5.5	0.055	0.026	
	PVC	13	13	2.3	0.023	0.003	
	CPP	2	2	3.1	0.031	0.001	
	Steel	2	2	7.6	0.076	0.002	
	AC	4	4	10.4	0.104	0.004	
	Other	4	4	12.4	0.124	0.005	0.138
6	CI	43	43	34.8	0.348	0.150	
	DI	43	43	5.5	0.055	0.024	
	PVC	7	7	2.3	0.023	0.002	
	CPP	3	3	3.1	0.031	0.001	
	Steel	0	0	7.6	0.076	0.000	
	AC	1	1	10.4	0.104	0.001	
	Other	3	3	12.4	0.124	0.004	0.181
5	CI	15	15	34.8	0.348	0.052	
	DI	17	17	5.5	0.055	0.009	
	PVC	37	37	2.3	0.023	0.009	
	CPP	5	5	3.1	0.031	0.002	
	Steel	0	0	7.6	0.076	0.000	
	AC	20	20	10.4	0.104	0.021	
	Other	6	6	12.4	0.124	0.007	0.100
4	CI	37	37	34.8	0.348	0.129	
	DI	43	43	5.5	0.055	0.024	
	PVC	1	1	2.3	0.023	0.000	
	CPP	1	1	3.1	0.031	0.000	
	Steel	13	13	7.6	0.076	0.010	
	AC	3	3	10.4	0.104	0.003	
	Other	3	3	12.4	0.124	0.004	0.170
3	CI	25	25	34.8	0.348	0.087	
	DI	22	22	5.5	0.055	0.012	

	PVC	33	33	2.3	0.023	0.008	
	CPP	2	2	3.1	0.031	0.001	
	Steel	6	6	7.6	0.076	0.005	
	AC	11	11	10.4	0.104	0.011	
	Other	2	2	12.4	0.124	0.002	0.126
2	CI	14	14	34.8	0.348	0.049	
	DI	7	7	5.5	0.055	0.004	
	PVC	29	29	2.3	0.023	0.007	
	CPP	5	5	3.1	0.031	0.002	
	Steel	9	9	7.6	0.076	0.007	
	AC	35	35	10.4	0.104	0.036	
	Other	2	2	12.4	0.124	0.002	0.107
1	CI	39	39	34.8	0.348	0.136	
	DI	34	34	5.5	0.055	0.019	
	PVC	13	13	2.3	0.023	0.003	
	CPP	2	2	3.1	0.031	0.001	
	Steel	4	4	7.6	0.076	0.003	
	AC	6	6	10.4	0.104	0.006	
	Other	2	2	12.4	0.124	0.002	0.170

Summary Data:

States in Region	Region	Year 2018 Weighed Average Break Rate/mile/year
Canada	**9**	0.133
ME, NH, VT, NY, PA, WV, VA, MA, RI, CT, NJ, DE, MD, DC	**8**	0.171
KY, TN, MS, AL, NC, SC, GA, FL	**7**	0.138
MN, WI, IL, IN, MI, OH	**6**	0.181
AZ, NM, TX, OK, AR, LA	**5**	0.100
ND, SD, NE, IA, KS, MO	**4**	0.170
MT, WY, UT, CO	**3**	0.126
CA, NV	**2**	0.107
AK, WA, OR, ID	**1**	0.170
	Mean:	0.144
	Median:	0.138
	Standard Deviation:	0.030
	Coefficient of Variation:	20.9

Appendix 4: Difference between UBL calculation and Background Portion of UARL formula at different pressures



% Difference in Calculations of BGL using UARL partial formula and UBL by system pressure, 2016 WADI Data Set

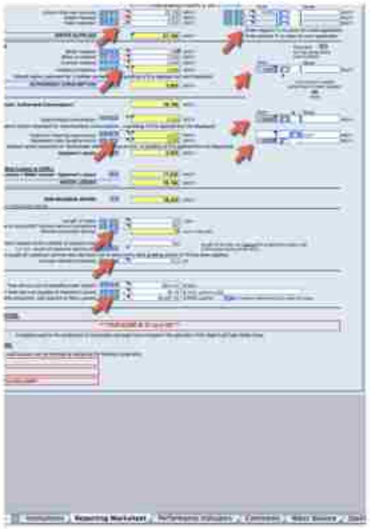
(February 2017)

Appendix 5: Sample Data Validity Criteria Worksheets

AWWA Free Water Audit Software Grading Matrix

The tables listed on the following pages reproduce the data grading criteria for each input in the AWWA Water Audit Software Reporting Worksheet.

The data grades will be entered in columns E and J of the worksheet in cells denoted with a red triangle in their upper right-hand corners as shown in the image at the right:



To select the correct data grading for each input, determine the highest grade where the utility meets or exceeds all criteria for that grade and all grades below it.

Please note that, for some inputs you will have the option to choose a default value, which will automatically be assigned a data grade of 5.

Adapted from the AWWA Water Audit Software ver. 5.0 by the:

SOUTHWEST
ENVIRONMENTAL
FINANCE CENTER

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Department of Civil Engineering MSC01 1070
1 University of New Mexico, Albuquerque, NM 87131
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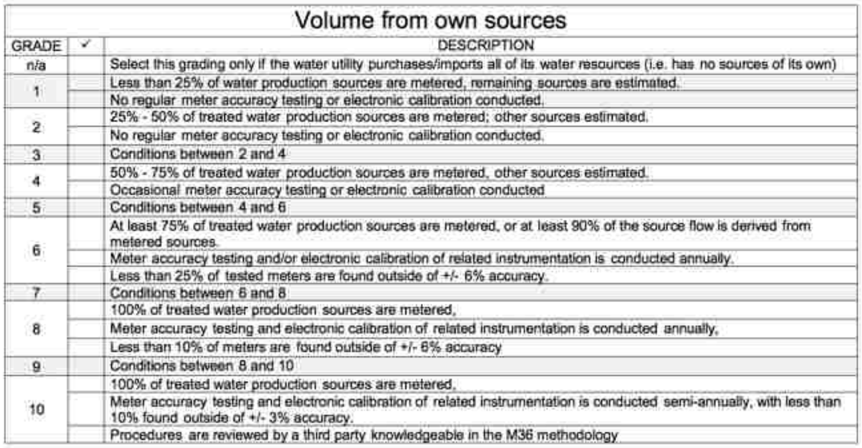
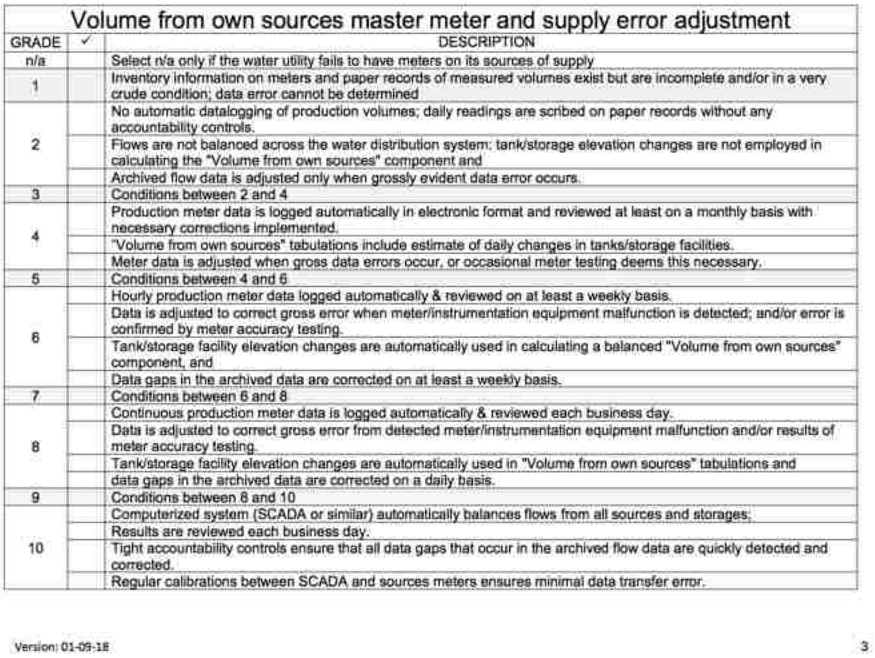


Volume from own sources		
GRADE	✓	DESCRIPTION
n/a		Select this grading only if the water utility purchases/imports all of its water resources (i.e. has no sources of its own)
1		Less than 25% of water production sources are metered, remaining sources are estimated.
		No regular meter accuracy testing or electronic calibration conducted.
2		25% - 50% of treated water production sources are metered; other sources estimated.
		No regular meter accuracy testing or electronic calibration conducted.
3		Conditions between 2 and 4
4		50% - 75% of treated water production sources are metered, other sources estimated.
		Occasional meter accuracy testing or electronic calibration conducted
5		Conditions between 4 and 6
6		At least 75% of treated water production sources are metered, or at least 90% of the source flow is derived from metered sources.
		Meter accuracy testing and/or electronic calibration of related instrumentation is conducted annually.
		Less than 25% of tested meters are found outside of +/- 6% accuracy.
7		Conditions between 6 and 8
8		100% of treated water production sources are metered,
		Meter accuracy testing and electronic calibration of related instrumentation is conducted annually,
		Less than 10% of meters are found outside of +/- 6% accuracy
9		Conditions between 8 and 10
10		100% of treated water production sources are metered,
		Meter accuracy testing and electronic calibration of related instrumentation is conducted semi-annually, with less than 10% found outside of +/- 3% accuracy.
		Procedures are reviewed by a third party knowledgeable in the M36 methodology



Volume from own sources master meter and supply error adjustment

GRADE	✓	DESCRIPTION
n/a		Select n/a only if the water utility fails to have meters on its sources of supply
1		Inventory information on meters and paper records of measured volumes exist but are incomplete and/or in a very crude condition; data error cannot be determined
2		No automatic datalogging of production volumes; daily readings are scribed on paper records without any accountability controls.
		Flows are not balanced across the water distribution system: tank/storage elevation changes are not employed in calculating the "Volume from own sources" component and
		Archived flow data is adjusted only when grossly evident data error occurs.
3		Conditions between 2 and 4
4		Production meter data is logged automatically in electronic format and reviewed at least on a monthly basis with necessary corrections implemented.
		"Volume from own sources" tabulations include estimate of daily changes in tanks/storage facilities.
		Meter data is adjusted when gross data errors occur, or occasional meter testing deems this necessary.
5		Conditions between 4 and 6
6		Hourly production meter data logged automatically & reviewed on at least a weekly basis.
		Data is adjusted to correct gross error when meter/instrumentation equipment malfunction is detected; and/or error is confirmed by meter accuracy testing.
		Tank/storage facility elevation changes are automatically used in calculating a balanced "Volume from own sources" component, and
		Data gaps in the archived data are corrected on at least a weekly basis.
7		Conditions between 6 and 8
8		Continuous production meter data is logged automatically & reviewed each business day.
		Data is adjusted to correct gross error from detected meter/instrumentation equipment malfunction and/or results of meter accuracy testing.
		Tank/storage facility elevation changes are automatically used in "Volume from own sources" tabulations and data gaps in the archived data are corrected on a daily basis.
9		Conditions between 8 and 10
10		Computerized system (SCADA or similar) automatically balances flows from all sources and storages;
		Results are reviewed each business day.
		Tight accountability controls ensure that all data gaps that occur in the archived flow data are quickly detected and corrected.
		Regular calibrations between SCADA and sources meters ensures minimal data transfer error.

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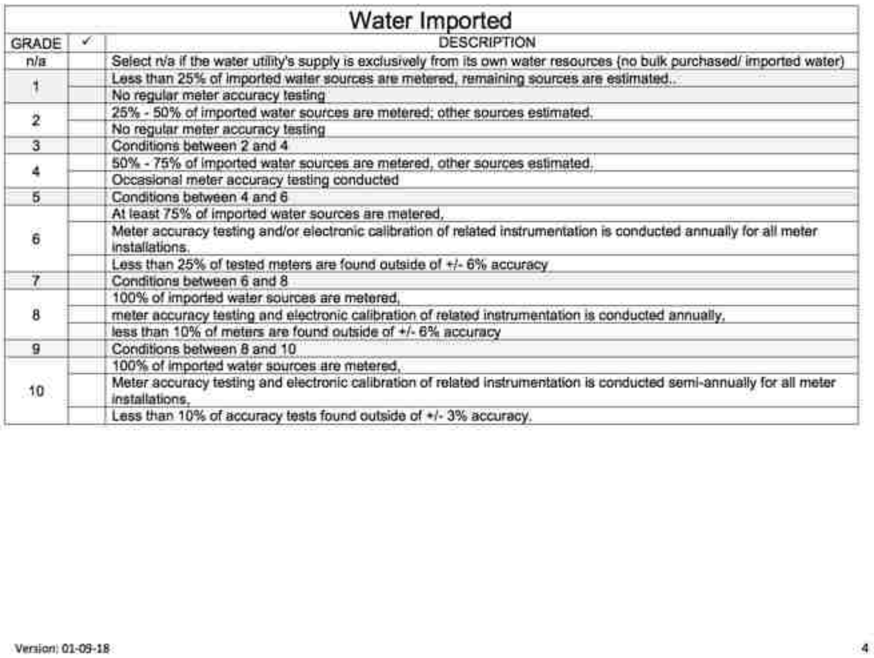

Water Imported

GRADE	✓	DESCRIPTION
n/a		Select n/a if the water utility's supply is exclusively from its own water resources (no bulk purchased/ imported water)
1		Less than 25% of imported water sources are metered, remaining sources are estimated..
		No regular meter accuracy testing
2		25% - 50% of imported water sources are metered; other sources estimated.
		No regular meter accuracy testing
3		Conditions between 2 and 4
4		50% - 75% of imported water sources are metered, other sources estimated.
		Occasional meter accuracy testing conducted
5		Conditions between 4 and 6
6		At least 75% of imported water sources are metered,
		Meter accuracy testing and/or electronic calibration of related instrumentation is conducted annually for all meter installations.
		Less than 25% of tested meters are found outside of +/- 6% accuracy
7		Conditions between 6 and 8
8		100% of imported water sources are metered,
		meter accuracy testing and electronic calibration of related instrumentation is conducted annually,
		less than 10% of meters are found outside of +/- 6% accuracy
9		Conditions between 8 and 10
10		100% of imported water sources are metered,
		Meter accuracy testing and electronic calibration of related instrumentation is conducted semi-annually for all meter installations,
		Less than 10% of accuracy tests found outside of +/- 3% accuracy.

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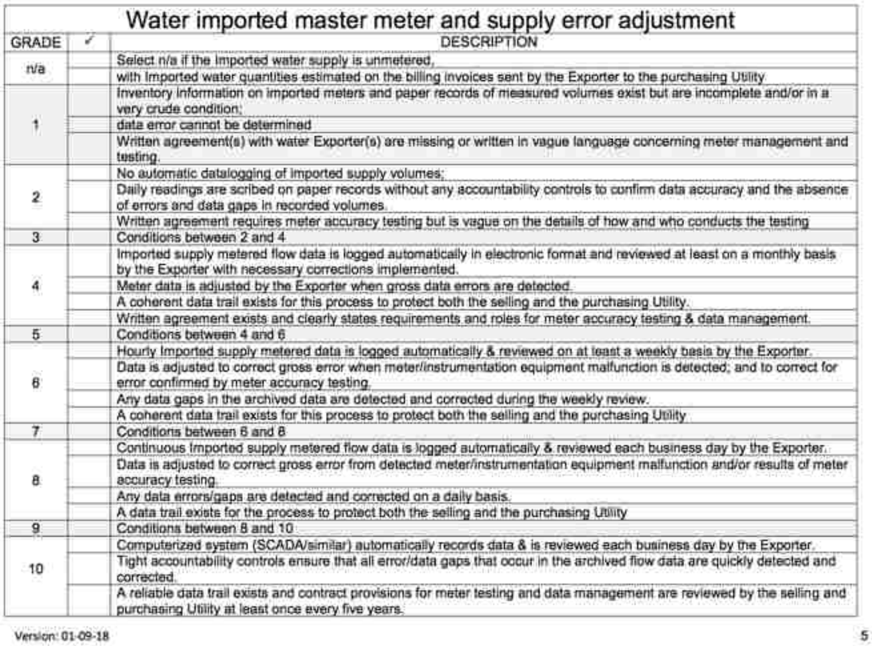
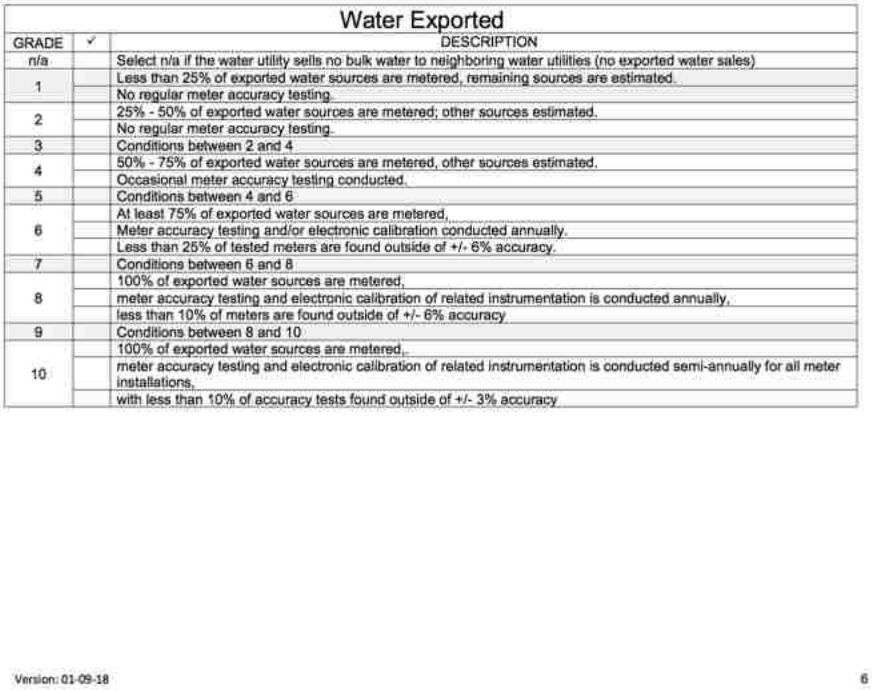


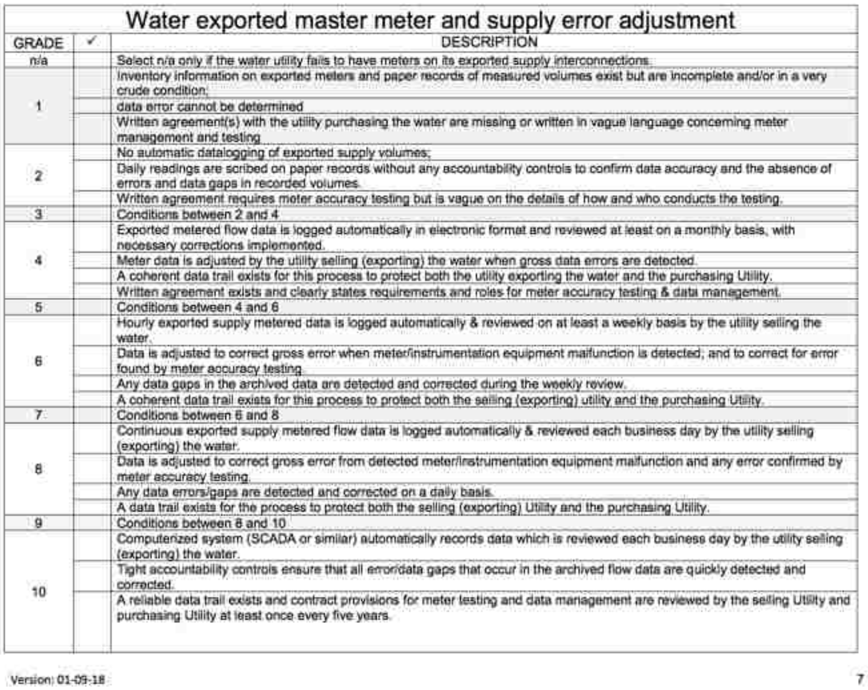
Water imported master meter and supply error adjustment

GRADE	✓	DESCRIPTION
n/a		Select n/a if the Imported water supply is unmetered,
		with Imported water quantities estimated on the billing invoices sent by the Exporter to the purchasing Utility
1		Inventory information on imported meters and paper records of measured volumes exist but are incomplete and/or in a very crude condition;
		data error cannot be determined
		Written agreement(s) with water Exporter(s) are missing or written in vague language concerning meter management and testing.
2		No automatic datalogging of imported supply volumes;
		Daily readings are scribed on paper records without any accountability controls to confirm data accuracy and the absence of errors and data gaps in recorded volumes.
		Written agreement requires meter accuracy testing but is vague on the details of how and who conducts the testing
3		Conditions between 2 and 4
4		Imported supply metered flow data is logged automatically in electronic format and reviewed at least on a monthly basis by the Exporter with necessary corrections implemented.
		Meter data is adjusted by the Exporter when gross data errors are detected.
		A coherent data trail exists for this process to protect both the selling and the purchasing Utility.
		Written agreement exists and clearly states requirements and roles for meter accuracy testing & data management.
5		Conditions between 4 and 6
6		Hourly Imported supply metered data is logged automatically & reviewed on at least a weekly basis by the Exporter.
		Data is adjusted to correct gross error when meter/instrumentation equipment malfunction is detected; and to correct for error confirmed by meter accuracy testing.
		Any data gaps in the archived data are detected and corrected during the weekly review.
		A coherent data trail exists for this process to protect both the selling and the purchasing Utility
7		Conditions between 6 and 8
8		Continuous Imported supply metered flow data is logged automatically & reviewed each business day by the Exporter.
		Data is adjusted to correct gross error from detected meter/instrumentation equipment malfunction and/or results of meter accuracy testing.
		Any data errors/gaps are detected and corrected on a daily basis.
		A data trail exists for the process to protect both the selling and the purchasing Utility
9		Conditions between 8 and 10
10		Computerized system (SCADA/similar) automatically records data & is reviewed each business day by the Exporter.
		Tight accountability controls ensure that all error/data gaps that occur in the archived flow data are quickly detected and corrected.
		A reliable data trail exists and contract provisions for meter testing and data management are reviewed by the selling and purchasing Utility at least once every five years.



Water Exported

GRADE	✓	DESCRIPTION
n/a		Select n/a if the water utility sells no bulk water to neighboring water utilities (no exported water sales)
1		Less than 25% of exported water sources are metered, remaining sources are estimated.
		No regular meter accuracy testing.
2		25% - 50% of exported water sources are metered; other sources estimated.
		No regular meter accuracy testing.
3		Conditions between 2 and 4
4		50% - 75% of exported water sources are metered, other sources estimated.
		Occasional meter accuracy testing conducted.
5		Conditions between 4 and 6
6		At least 75% of exported water sources are metered,
		Meter accuracy testing and/or electronic calibration conducted annually.
		Less than 25% of tested meters are found outside of +/- 6% accuracy.
7		Conditions between 6 and 8
8		100% of exported water sources are metered,
		meter accuracy testing and electronic calibration of related instrumentation is conducted annually,
		less than 10% of meters are found outside of +/- 6% accuracy
9		Conditions between 8 and 10
10		100% of exported water sources are metered,.
		meter accuracy testing and electronic calibration of related instrumentation is conducted semi-annually for all meter installations,
		with less than 10% of accuracy tests found outside of +/- 3% accuracy



Water exported master meter and supply error adjustment

GRADE	✓	DESCRIPTION
n/a		Select n/a only if the water utility fails to have meters on its exported supply interconnections.
1		Inventory information on exported meters and paper records of measured volumes exist but are incomplete and/or in a very crude condition;
		data error cannot be determined
		Written agreement(s) with the utility purchasing the water are missing or written in vague language concerning meter management and testing
2		No automatic datalogging of exported supply volumes;
		Daily readings are scribed on paper records without any accountability controls to confirm data accuracy and the absence of errors and data gaps in recorded volumes.
		Written agreement requires meter accuracy testing but is vague on the details of how and who conducts the testing.
3		Conditions between 2 and 4
4		Exported metered flow data is logged automatically in electronic format and reviewed at least on a monthly basis, with necessary corrections implemented.
		Meter data is adjusted by the utility selling (exporting) the water when gross data errors are detected.
		A coherent data trail exists for this process to protect both the utility exporting the water and the purchasing Utility.
		Written agreement exists and clearly states requirements and roles for meter accuracy testing & data management.
5		Conditions between 4 and 6
6		Hourly exported supply metered data is logged automatically & reviewed on at least a weekly basis by the utility selling the water.
		Data is adjusted to correct gross error when meter/instrumentation equipment malfunction is detected; and to correct for error found by meter accuracy testing.
		Any data gaps in the archived data are detected and corrected during the weekly review.
		A coherent data trail exists for this process to protect both the selling (exporting) utility and the purchasing Utility.
7		Conditions between 6 and 8
8		Continuous exported supply metered flow data is logged automatically & reviewed each business day by the utility selling (exporting) the water.
		Data is adjusted to correct gross error from detected meter/instrumentation equipment malfunction and any error confirmed by meter accuracy testing.
		Any data errors/gaps are detected and corrected on a daily basis.
		A data trail exists for the process to protect both the selling (exporting) Utility and the purchasing Utility.
9		Conditions between 8 and 10
10		Computerized system (SCADA or similar) automatically records data which is reviewed each business day by the utility selling (exporting) the water.
		Tight accountability controls ensure that all error/data gaps that occur in the archived flow data are quickly detected and corrected.
		A reliable data trail exists and contract provisions for meter testing and data management are reviewed by the selling Utility and purchasing Utility at least once every five years.

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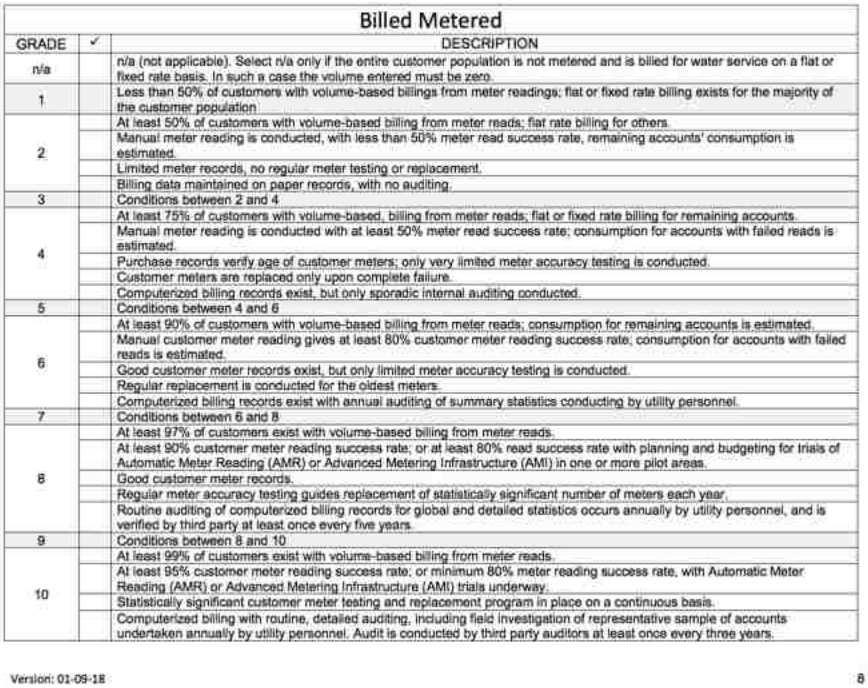

Billed Metered

GRADE	✓	DESCRIPTION
n/a		n/a (not applicable). Select n/a only if the entire customer population is not metered and is billed for water service on a flat or fixed rate basis. In such a case the volume entered must be zero.
1		Less than 50% of customers with volume-based billings from meter readings; flat or fixed rate billing exists for the majority of the customer population
2		At least 50% of customers with volume-based billing from meter reads; flat rate billing for others.
		Manual meter reading is conducted, with less than 50% meter read success rate, remaining accounts' consumption is estimated.
		Limited meter records, no regular meter testing or replacement.
		Billing data maintained on paper records, with no auditing.
3		Conditions between 2 and 4
4		At least 75% of customers with volume-based, billing from meter reads; flat or fixed rate billing for remaining accounts.
		Manual meter reading is conducted with at least 50% meter read success rate; consumption for accounts with failed reads is estimated.
		Purchase records verify age of customer meters; only very limited meter accuracy testing is conducted.
		Customer meters are replaced only upon complete failure.
		Computerized billing records exist, but only sporadic internal auditing conducted.
5		Conditions between 4 and 6
6		At least 90% of customers with volume-based billing from meter reads; consumption for remaining accounts is estimated.
		Manual customer meter reading gives at least 80% customer meter reading success rate; consumption for accounts with failed reads is estimated.
		Good customer meter records exist, but only limited meter accuracy testing is conducted.
		Regular replacement is conducted for the oldest meters.
		Computerized billing records exist with annual auditing of summary statistics conducting by utility personnel.
7		Conditions between 6 and 8
8		At least 97% of customers exist with volume-based billing from meter reads.
		At least 90% customer meter reading success rate; or at least 80% read success rate with planning and budgeting for trials of Automatic Meter Reading (AMR) or Advanced Metering Infrastructure (AMI) in one or more pilot areas.
		Good customer meter records.
		Regular meter accuracy testing guides replacement of statistically significant number of meters each year.
		Routine auditing of computerized billing records for global and detailed statistics occurs annually by utility personnel, and is verified by third party at least once every five years.
9		Conditions between 8 and 10
10		At least 99% of customers exist with volume-based billing from meter reads.
		At least 95% customer meter reading success rate; or minimum 80% meter reading success rate, with Automatic Meter Reading (AMR) or Advanced Metering Infrastructure (AMI) trials underway.
		Statistically significant customer meter testing and replacement program in place on a continuous basis.
		Computerized billing with routine, detailed auditing, including field investigation of representative sample of accounts undertaken annually by utility personnel. Audit is conducted by third party auditors at least once every three years.

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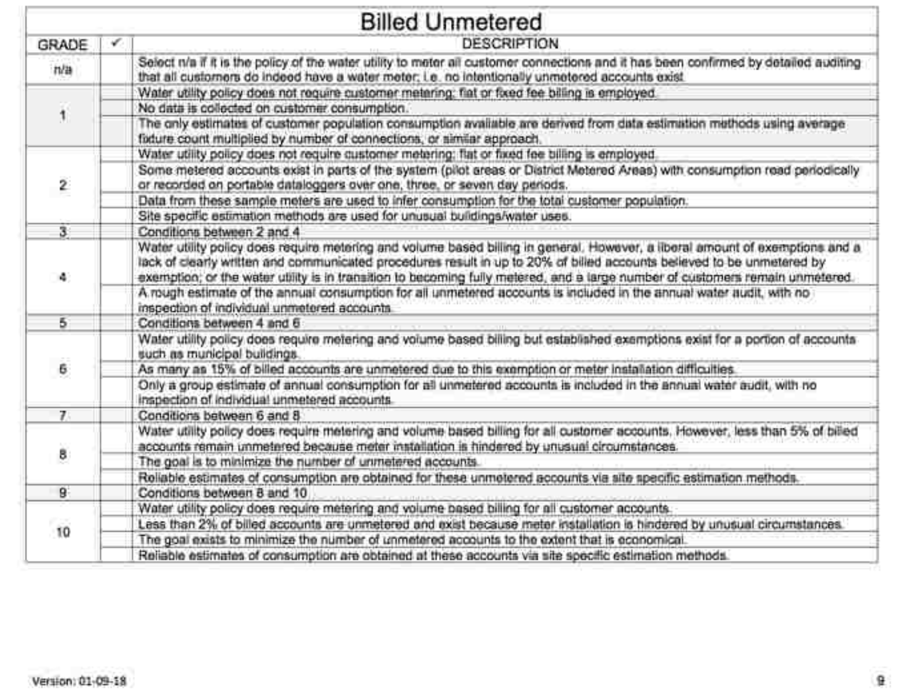
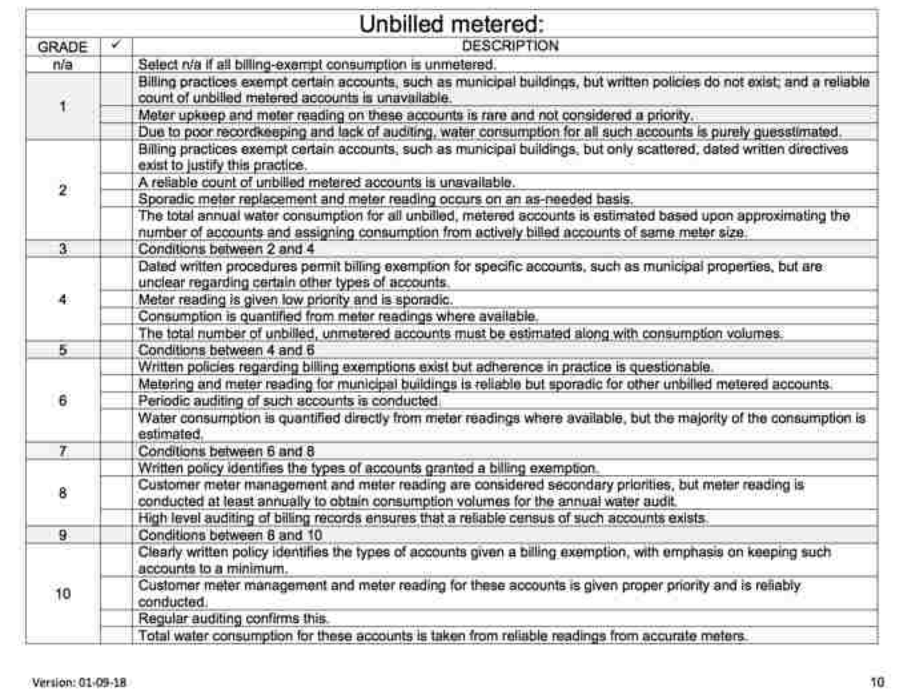
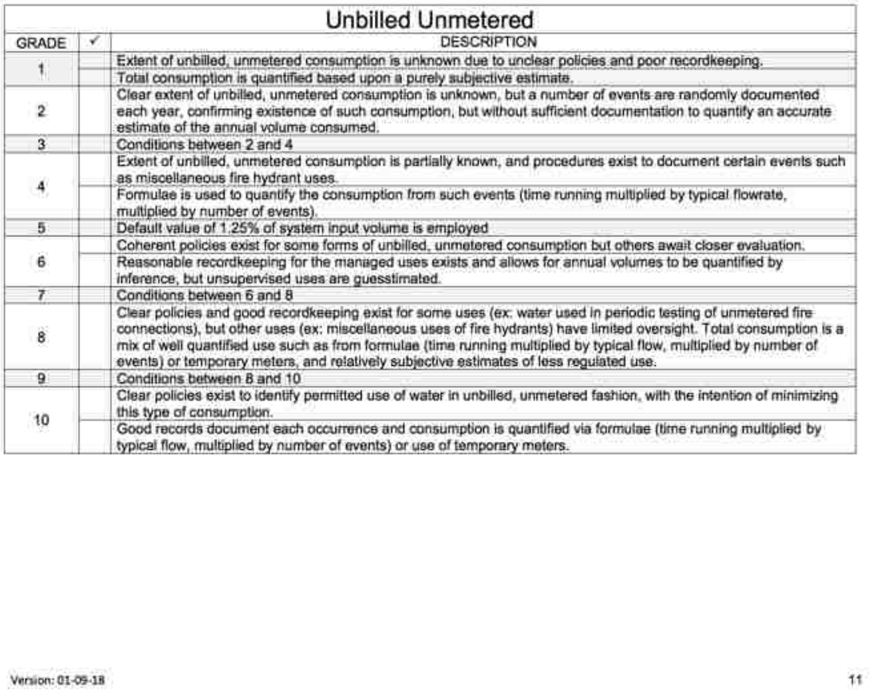


Billed Unmetered		
GRADE	✓	DESCRIPTION
n/a		Select n/a if it is the policy of the water utility to meter all customer connections and it has been confirmed by detailed auditing that all customers do indeed have a water meter; i.e. no intentionally unmetered accounts exist.
1		Water utility policy does not require customer metering; flat or fixed fee billing is employed.
		No data is collected on customer consumption.
		The only estimates of customer population consumption available are derived from data estimation methods using average fixture count multiplied by number of connections, or similar approach.
2		Water utility policy does not require customer metering; flat or fixed fee billing is employed.
		Some metered accounts exist in parts of the system (pilot areas or District Metered Areas) with consumption read periodically or recorded on portable dataloggers over one, three, or seven day periods.
		Data from these sample meters are used to infer consumption for the total customer population.
		Site specific estimation methods are used for unusual buildings/water uses.
3		Conditions between 2 and 4
4		Water utility policy does require metering and volume based billing in general. However, a liberal amount of exemptions and a lack of clearly written and communicated procedures result in up to 20% of billed accounts believed to be unmetered by exemption; or the water utility is in transition to becoming fully metered, and a large number of customers remain unmetered.
		A rough estimate of the annual consumption for all unmetered accounts is included in the annual water audit, with no inspection of individual unmetered accounts.
5		Conditions between 4 and 6
6		Water utility policy does require metering and volume based billing but established exemptions exist for a portion of accounts such as municipal buildings.
		As many as 15% of billed accounts are unmetered due to this exemption or meter installation difficulties.
		Only a group estimate of annual consumption for all unmetered accounts is included in the annual water audit, with no inspection of individual unmetered accounts.
7		Conditions between 6 and 8
8		Water utility policy does require metering and volume based billing for all customer accounts. However, less than 5% of billed accounts remain unmetered because meter installation is hindered by unusual circumstances.
		The goal is to minimize the number of unmetered accounts.
		Reliable estimates of consumption are obtained for these unmetered accounts via site specific estimation methods.
9		Conditions between 8 and 10
10		Water utility policy does require metering and volume based billing for all customer accounts.
		Less than 2% of billed accounts are unmetered and exist because meter installation is hindered by unusual circumstances.
		The goal exists to minimize the number of unmetered accounts to the extent that is economical.
		Reliable estimates of consumption are obtained at these accounts via site specific estimation methods.



Unbilled metered:		
GRADE	✓	DESCRIPTION
n/a		Select n/a if all billing-exempt consumption is unmetered.
1		Billing practices exempt certain accounts, such as municipal buildings, but written policies do not exist; and a reliable count of unbilled metered accounts is unavailable.
		Meter upkeep and meter reading on these accounts is rare and not considered a priority.
		Due to poor recordkeeping and lack of auditing, water consumption for all such accounts is purely guesstimated.
2		Billing practices exempt certain accounts, such as municipal buildings, but only scattered, dated written directives exist to justify this practice.
		A reliable count of unbilled metered accounts is unavailable.
		Sporadic meter replacement and meter reading occurs on an as-needed basis.
		The total annual water consumption for all unbilled, metered accounts is estimated based upon approximating the number of accounts and assigning consumption from actively billed accounts of same meter size.
3		Conditions between 2 and 4
4		Dated written procedures permit billing exemption for specific accounts, such as municipal properties, but are unclear regarding certain other types of accounts.
		Meter reading is given low priority and is sporadic.
		Consumption is quantified from meter readings where available.
		The total number of unbilled, unmetered accounts must be estimated along with consumption volumes.
5		Conditions between 4 and 6
6		Written policies regarding billing exemptions exist but adherence in practice is questionable.
		Metering and meter reading for municipal buildings is reliable but sporadic for other unbilled metered accounts.
		Periodic auditing of such accounts is conducted.
		Water consumption is quantified directly from meter readings where available, but the majority of the consumption is estimated.
7		Conditions between 6 and 8
8		Written policy identifies the types of accounts granted a billing exemption.
		Customer meter management and meter reading are considered secondary priorities, but meter reading is conducted at least annually to obtain consumption volumes for the annual water audit.
		High level auditing of billing records ensures that a reliable census of such accounts exists.
9		Conditions between 8 and 10
10		Clearly written policy identifies the types of accounts given a billing exemption, with emphasis on keeping such accounts to a minimum.
		Customer meter management and meter reading for these accounts is given proper priority and is reliably conducted.
		Regular auditing confirms this.
		Total water consumption for these accounts is taken from reliable readings from accurate meters.



Unbilled Unmetered

GRADE	✓	DESCRIPTION
1		Extent of unbilled, unmetered consumption is unknown due to unclear policies and poor recordkeeping. Total consumption is quantified based upon a purely subjective estimate.
2		Clear extent of unbilled, unmetered consumption is unknown, but a number of events are randomly documented each year, confirming existence of such consumption, but without sufficient documentation to quantify an accurate estimate of the annual volume consumed.
3		Conditions between 2 and 4
4		Extent of unbilled, unmetered consumption is partially known, and procedures exist to document certain events such as miscellaneous fire hydrant uses. Formulae is used to quantify the consumption from such events (time running multiplied by typical flowrate, multiplied by number of events).
5		Default value of 1.25% of system input volume is employed
6		Coherent policies exist for some forms of unbilled, unmetered consumption but others await closer evaluation. Reasonable recordkeeping for the managed uses exists and allows for annual volumes to be quantified by inference, but unsupervised uses are guesstimated.
7		Conditions between 6 and 8
8		Clear policies and good recordkeeping exist for some uses (ex: water used in periodic testing of unmetered fire connections), but other uses (ex: miscellaneous uses of fire hydrants) have limited oversight. Total consumption is a mix of well quantified use such as from formulae (time running multiplied by typical flow, multiplied by number of events) or temporary meters, and relatively subjective estimates of less regulated use.
9		Conditions between 8 and 10
10		Clear policies exist to identify permitted use of water in unbilled, unmetered fashion, with the intention of minimizing this type of consumption. Good records document each occurrence and consumption is quantified via formulae (time running multiplied by typical flow, multiplied by number of events) or use of temporary meters.

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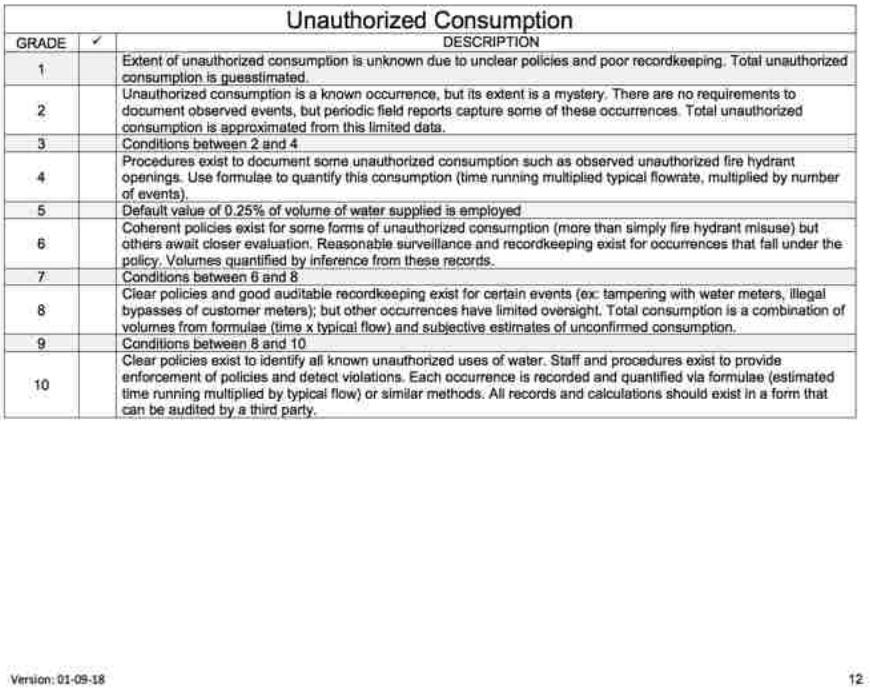

Unauthorized Consumption

GRADE	✓	DESCRIPTION
1		Extent of unauthorized consumption is unknown due to unclear policies and poor recordkeeping. Total unauthorized consumption is guesstimated.
2		Unauthorized consumption is a known occurrence, but its extent is a mystery. There are no requirements to document observed events, but periodic field reports capture some of these occurrences. Total unauthorized consumption is approximated from this limited data.
3		Conditions between 2 and 4
4		Procedures exist to document some unauthorized consumption such as observed unauthorized fire hydrant openings. Use formulae to quantify this consumption (time running multiplied typical flowrate, multiplied by number of events).
5		Default value of 0.25% of volume of water supplied is employed
6		Coherent policies exist for some forms of unauthorized consumption (more than simply fire hydrant misuse) but others await closer evaluation. Reasonable surveillance and recordkeeping exist for occurrences that fall under the policy. Volumes quantified by inference from these records.
7		Conditions between 6 and 8
8		Clear policies and good auditable recordkeeping exist for certain events (ex: tampering with water meters, illegal bypasses of customer meters); but other occurrences have limited oversight. Total consumption is a combination of volumes from formulae (time x typical flow) and subjective estimates of unconfirmed consumption.
9		Conditions between 8 and 10
10		Clear policies exist to identify all known unauthorized uses of water. Staff and procedures exist to provide enforcement of policies and detect violations. Each occurrence is recorded and quantified via formulae (estimated time running multiplied by typical flow) or similar methods. All records and calculations should exist in a form that can be audited by a third party.

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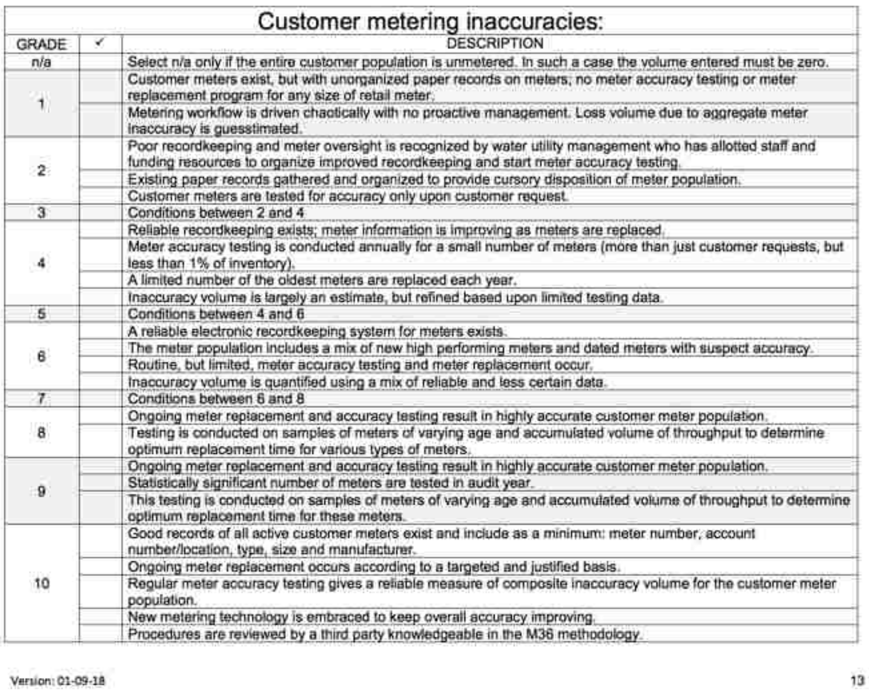

Customer metering inaccuracies:

GRADE	✓	DESCRIPTION
n/a		Select n/a only if the entire customer population is unmetered. In such a case the volume entered must be zero.
1		Customer meters exist, but with unorganized paper records on meters; no meter accuracy testing or meter replacement program for any size of retail meter.
		Metering workflow is driven chaotically with no proactive management. Loss volume due to aggregate meter inaccuracy is guesstimated.
2		Poor recordkeeping and meter oversight is recognized by water utility management who has allotted staff and funding resources to organize improved recordkeeping and start meter accuracy testing.
		Existing paper records gathered and organized to provide cursory disposition of meter population.
		Customer meters are tested for accuracy only upon customer request.
3		Conditions between 2 and 4
4		Reliable recordkeeping exists; meter information is improving as meters are replaced.
		Meter accuracy testing is conducted annually for a small number of meters (more than just customer requests, but less than 1% of inventory).
		A limited number of the oldest meters are replaced each year.
		Inaccuracy volume is largely an estimate, but refined based upon limited testing data.
5		Conditions between 4 and 6
6		A reliable electronic recordkeeping system for meters exists.
		The meter population includes a mix of new high performing meters and dated meters with suspect accuracy.
		Routine, but limited, meter accuracy testing and meter replacement occur.
		Inaccuracy volume is quantified using a mix of reliable and less certain data.
7		Conditions between 6 and 8
8		Ongoing meter replacement and accuracy testing result in highly accurate customer meter population.
		Testing is conducted on samples of meters of varying age and accumulated volume of throughput to determine optimum replacement time for various types of meters.
9		Ongoing meter replacement and accuracy testing result in highly accurate customer meter population.
		Statistically significant number of meters are tested in audit year.
		This testing is conducted on samples of meters of varying age and accumulated volume of throughput to determine optimum replacement time for these meters.
10		Good records of all active customer meters exist and include as a minimum: meter number, account number/location, type, size and manufacturer.
		Ongoing meter replacement occurs according to a targeted and justified basis.
		Regular meter accuracy testing gives a reliable measure of composite inaccuracy volume for the customer meter population.
		New metering technology is embraced to keep overall accuracy improving.
		Procedures are reviewed by a third party knowledgeable in the M36 methodology.

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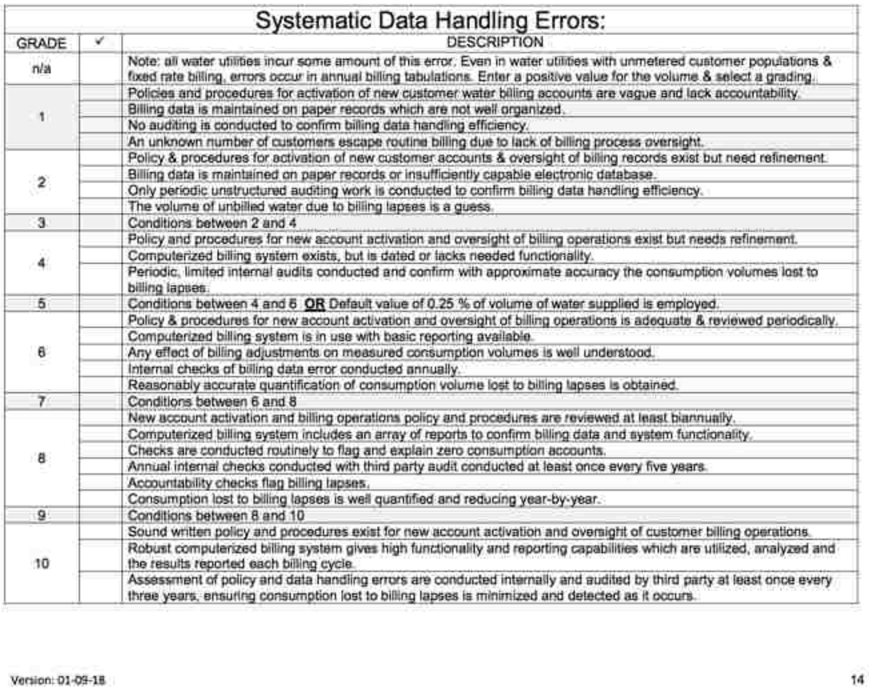

Systematic Data Handling Errors:

GRADE	✓	DESCRIPTION
n/a		Note: all water utilities incur some amount of this error. Even in water utilities with unmetered customer populations & fixed rate billing, errors occur in annual billing tabulations. Enter a positive value for the volume & select a grading.
1		Policies and procedures for activation of new customer water billing accounts are vague and lack accountability.
		Billing data is maintained on paper records which are not well organized.
		No auditing is conducted to confirm billing data handling efficiency.
		An unknown number of customers escape routine billing due to lack of billing process oversight.
2		Policy & procedures for activation of new customer accounts & oversight of billing records exist but need refinement.
		Billing data is maintained on paper records or insufficiently capable electronic database.
		Only periodic unstructured auditing work is conducted to confirm billing data handling efficiency.
		The volume of unbilled water due to billing lapses is a guess.
3		Conditions between 2 and 4
4		Policy and procedures for new account activation and oversight of billing operations exist but needs refinement.
		Computerized billing system exists, but is dated or lacks needed functionality.
		Periodic, limited internal audits conducted and confirm with approximate accuracy the consumption volumes lost to billing lapses.
5		Conditions between 4 and 6 **<u>OR</u>** Default value of 0.25 % of volume of water supplied is employed.
6		Policy & procedures for new account activation and oversight of billing operations is adequate & reviewed periodically.
		Computerized billing system is in use with basic reporting available.
		Any effect of billing adjustments on measured consumption volumes is well understood.
		Internal checks of billing data error conducted annually.
		Reasonably accurate quantification of consumption volume lost to billing lapses is obtained.
7		Conditions between 6 and 8
8		New account activation and billing operations policy and procedures are reviewed at least biannually.
		Computerized billing system includes an array of reports to confirm billing data and system functionality.
		Checks are conducted routinely to flag and explain zero consumption accounts.
		Annual internal checks conducted with third party audit conducted at least once every five years.
		Accountability checks flag billing lapses.
		Consumption lost to billing lapses is well quantified and reducing year-by-year.
9		Conditions between 8 and 10
10		Sound written policy and procedures exist for new account activation and oversight of customer billing operations.
		Robust computerized billing system gives high functionality and reporting capabilities which are utilized, analyzed and the results reported each billing cycle.
		Assessment of policy and data handling errors are conducted internally and audited by third party at least once every three years, ensuring consumption lost to billing lapses is minimized and detected as it occurs.

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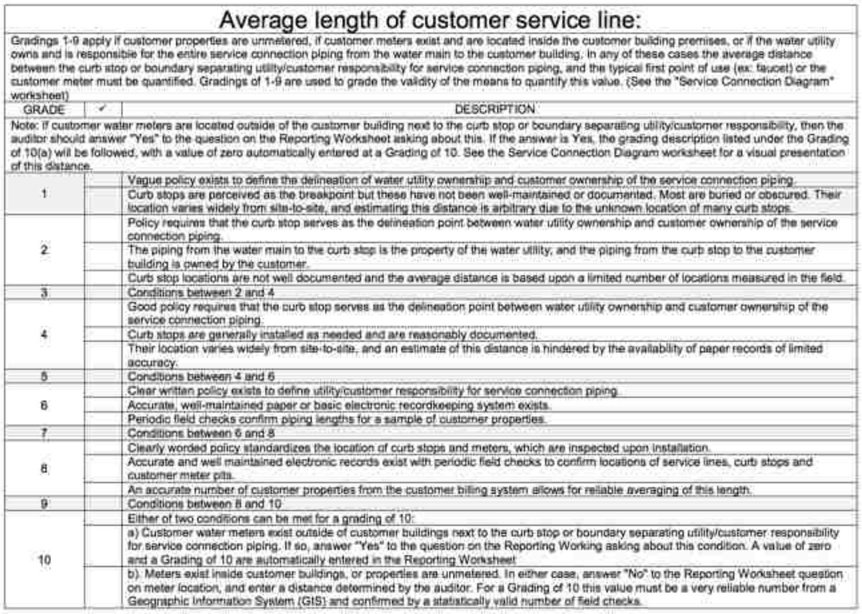
Length of Mains

GRADE	✓	DESCRIPTION
1		Poorly assembled and maintained paper as-built records of existing water main installations makes accurate determination of system pipe length impossible. Length of mains is guesstimated.
2		Paper records in poor or uncertain condition (no annual tracking of installations & abandonments).
		Poor procedures to ensure that new water mains installed by developers are accurately documented.
3		Conditions between 2 and 4
4		Sound written policy and procedures exist for documenting new water main installations, but gaps in management result in an uncertain degree of error in tabulation of mains length.
5		Conditions between 4 and 6
6		Sound written policy and procedures exist for permitting and commissioning new water mains.
		Highly accurate paper records with regular field validation; or electronic records and asset management system in good condition.
		Includes system backup.
7		Conditions between 6 and 8
8		Sound written policy and procedures exist for permitting and commissioning new water mains.
		Electronic recordkeeping such as a Geographical Information System (GIS) and asset management system are used to store and manage data.
9		Conditions between 8 and 10
10		Sound written policy exists for managing water mains extensions and replacements.
		Geographic Information System (GIS) data and asset management database agree and random field validation proves truth of databases.
		Records of annual field validation should be available for review

Number of active AND inactive service connections

Note: The number of Service Connections does not include fire hydrant leads/lines connecting the hydrant to the water main

GRADE	✓	DESCRIPTION
1		Vague permitting (of new service connections) policy and poor paper recordkeeping of customer connections/billings result in suspect determination of the number of service connections, which may be 10-15% in error from actual count
2		General permitting policy exists but paper records, procedural gaps, and weak oversight result in questionable total for number of connections, which may vary 5-10% of actual count.
3		Conditions between 2 and 4
4		Written account activation policy and procedures exist, but with some gaps in performance and oversight.
		Computerized information management system is being brought online to replace dated paper recordkeeping system.
		Reasonably accurate tracking of service connection installations & abandonments; but count can be up to 5% in error from actual total.
5		Conditions between 4 and 6
6		Written new account activation and overall billing policies and procedures are adequate and reviewed periodically.
		Computerized information management system is in use with annual installations & abandonments totaled.
		Very limited field verifications and audits.
		Error in count of number of service connections is believed to be no more than 3%.
7		Conditions between 6 and 8
8		Policies and procedures for new account activation and overall billing operations are written, well-structured and reviewed at least biannually.
		Well-managed computerized information management system exists and routine, periodic field checks and internal system audits are conducted.
		Counts of connections are no more than 2% in error.
9		Conditions between 8 and 10
10		Sound written policy and well managed and audited procedures ensure reliable management of service connection population.
		Computerized information management system, Customer Billing System, and Geographic Information System (GIS) information agree; field validation proves truth of databases.
		Count of connections recorded as being in error is less than 1% of the entire population.



Average length of customer service line:

Gradings 1-9 apply if customer properties are unmetered, if customer meters exist and are located inside the customer building premises, or if the water utility owns and is responsible for the entire service connection piping from the water main to the customer building. In any of these cases the average distance between the curb stop or boundary separating utility/customer responsibility for service connection piping, and the typical first point of use (ex: faucet) or the customer meter must be quantified. Gradings of 1-9 are used to grade the validity of the means to quantify this value. (See the "Service Connection Diagram" worksheet)

GRADE	✓	DESCRIPTION
Note: If customer water meters are located outside of the customer building next to the curb stop or boundary separating utility/customer responsibility, then the auditor should answer "Yes" to the question on the Reporting Worksheet asking about this. If the answer is Yes, the grading description listed under the Grading of 10(a) will be followed, with a value of zero automatically entered at a Grading of 10. See the Service Connection Diagram worksheet for a visual presentation of this distance.		
1		Vague policy exists to define the delineation of water utility ownership and customer ownership of the service connection piping.
		Curb stops are perceived as the breakpoint but these have not been well-maintained or documented. Most are buried or obscured. Their location varies widely from site-to-site, and estimating this distance is arbitrary due to the unknown location of many curb stops.
2		Policy requires that the curb stop serves as the delineation point between water utility ownership and customer ownership of the service connection piping.
		The piping from the water main to the curb stop is the property of the water utility; and the piping from the curb stop to the customer building is owned by the customer.
		Curb stop locations are not well documented and the average distance is based upon a limited number of locations measured in the field.
3		Conditions between 2 and 4
4		Good policy requires that the curb stop serves as the delineation point between water utility ownership and customer ownership of the service connection piping.
		Curb stops are generally installed as needed and are reasonably documented.
		Their location varies widely from site-to-site, and an estimate of this distance is hindered by the availability of paper records of limited accuracy.
5		Conditions between 4 and 6
6		Clear written policy exists to define utility/customer responsibility for service connection piping.
		Accurate, well-maintained paper or basic electronic recordkeeping system exists.
		Periodic field checks confirm piping lengths for a sample of customer properties.
7		Conditions between 6 and 8
8		Clearly worded policy standardizes the location of curb stops and meters, which are inspected upon installation.
		Accurate and well maintained electronic records exist with periodic field checks to confirm locations of service lines, curb stops and customer meter pits.
		An accurate number of customer properties from the customer billing system allows for reliable averaging of this length.
9		Conditions between 8 and 10
10		Either of two conditions can be met for a grading of 10:
		a) Customer water meters exist outside of customer buildings next to the curb stop or boundary separating utility/customer responsibility for service connection piping. If so, answer "Yes" to the question on the Reporting Working asking about this condition. A value of zero and a Grading of 10 are automatically entered in the Reporting Worksheet
		b). Meters exist inside customer buildings, or properties are unmetered. In either case, answer "No" to the Reporting Worksheet question on meter location, and enter a distance determined by the auditor. For a Grading of 10 this value must be a very reliable number from a Geographic Information System (GIS) and confirmed by a statistically valid number of field checks.

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Average operating pressure

GRADE	✓	DESCRIPTION
1		Available records are poorly assembled and maintained paper records of supply pump characteristics and water distribution system operating conditions.
		Average pressure is guesstimated based upon this information and ground elevations from crude topographical maps.
		Widely varying distribution system pressures due to undulating terrain, high system head loss and weak/erratic pressure controls further compromise the validity of the average pressure calculation.
2		Limited telemetry monitoring of scattered pumping station and water storage tank sites provides some static pressure data, which is recorded in handwritten logbooks.
		Pressure data is gathered at individual sites only when low pressure complaints arise.
		Average pressure is determined by averaging relatively crude data, and is affected by significant variation in ground elevations, system head loss and gaps in pressure controls in the distribution system.
3		Conditions between 2 and 4
4		Effective pressure controls separate different pressure zones; moderate pressure variation across the system, occasional open boundary valves are discovered that breech pressure zones.
		Basic telemetry monitoring of the distribution system logs pressure data electronically.
		Pressure data gathered by gauges or dataloggers at fire hydrants or buildings when low pressure complaints arise, and during fire flow tests and system flushing.
		Reliable topographical data exists.
		Average pressure is calculated using this mix of data.
5		Conditions between 4 and 6
6		Reliable pressure controls separate distinct pressure zones; only very occasional open boundary valves are encountered that breech pressure zones.
		Well-covered telemetry monitoring of the distribution system (not just pumping at source treatment plants or wells) logs extensive pressure data electronically.
		Pressure gathered by gauges/dataloggers at fire hydrants and buildings when low pressure complaints arise, and during fire flow tests and system flushing.
		Average pressure is determined by using this mix of reliable data.
7		Conditions between 6 and 8
8		Well-managed, discrete pressure zones exist with generally predictable pressure fluctuations.
		A current full-scale SCADA System or similar realtime monitoring system exists to monitor the water distribution system and collect data, including real time pressure readings at representative sites across the system.
		The average system pressure is determined from reliable monitoring system data.
9		Conditions between 8 and 10
10		Well-managed pressure districts/zones, SCADA System and hydraulic model exist to give very precise pressure data across the water distribution system.
		Average system pressure is reliably calculated from extensive, reliable, and cross-checked data.
		Calculations are reported on an annual basis as a minimum.

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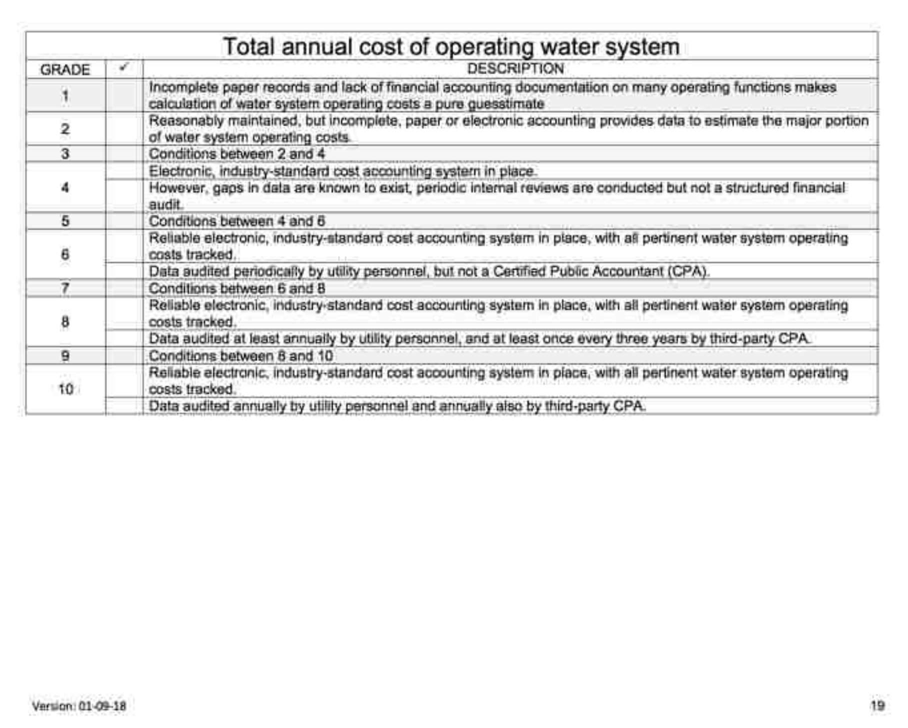
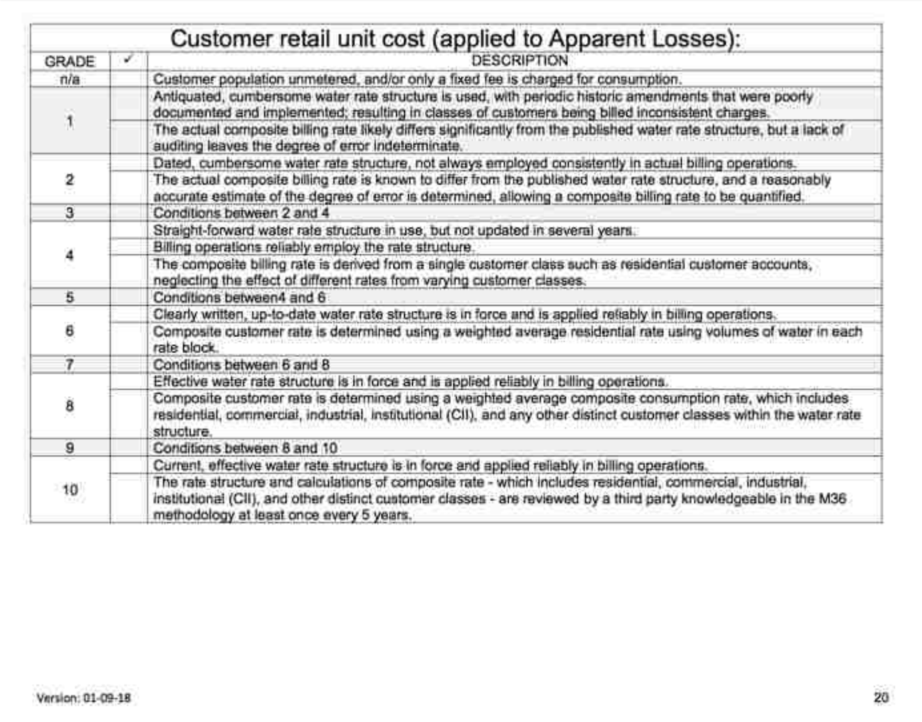


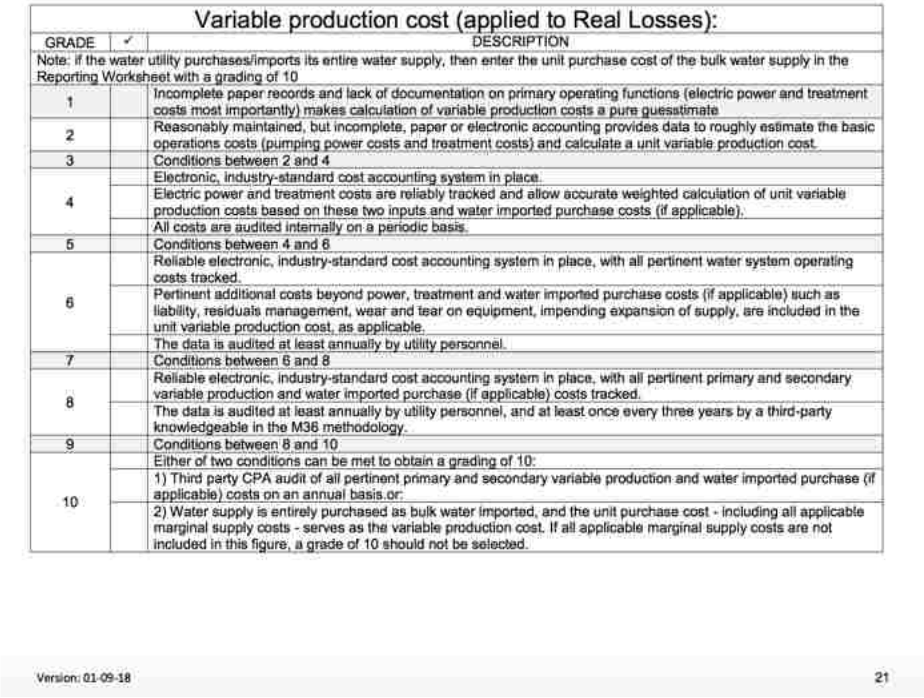
Total annual cost of operating water system

GRADE	✓	DESCRIPTION
1		Incomplete paper records and lack of financial accounting documentation on many operating functions makes calculation of water system operating costs a pure guesstimate
2		Reasonably maintained, but incomplete, paper or electronic accounting provides data to estimate the major portion of water system operating costs.
3		Conditions between 2 and 4
4		Electronic, industry-standard cost accounting system in place.
		However, gaps in data are known to exist, periodic internal reviews are conducted but not a structured financial audit.
5		Conditions between 4 and 6
6		Reliable electronic, industry-standard cost accounting system in place, with all pertinent water system operating costs tracked.
		Data audited periodically by utility personnel, but not a Certified Public Accountant (CPA).
7		Conditions between 6 and 8
8		Reliable electronic, industry-standard cost accounting system in place, with all pertinent water system operating costs tracked.
		Data audited at least annually by utility personnel, and at least once every three years by third-party CPA.
9		Conditions between 8 and 10
10		Reliable electronic, industry-standard cost accounting system in place, with all pertinent water system operating costs tracked.
		Data audited annually by utility personnel and annually also by third-party CPA.



Customer retail unit cost (applied to Apparent Losses):

GRADE	✓	DESCRIPTION
n/a		Customer population unmetered, and/or only a fixed fee is charged for consumption.
1		Antiquated, cumbersome water rate structure is used, with periodic historic amendments that were poorly documented and implemented; resulting in classes of customers being billed inconsistent charges.
		The actual composite billing rate likely differs significantly from the published water rate structure, but a lack of auditing leaves the degree of error indeterminate.
2		Dated, cumbersome water rate structure, not always employed consistently in actual billing operations.
		The actual composite billing rate is known to differ from the published water rate structure, and a reasonably accurate estimate of the degree of error is determined, allowing a composite billing rate to be quantified.
3		Conditions between 2 and 4
4		Straight-forward water rate structure in use, but not updated in several years.
		Billing operations reliably employ the rate structure.
		The composite billing rate is derived from a single customer class such as residential customer accounts, neglecting the effect of different rates from varying customer classes.
5		Conditions between4 and 6
6		Clearly written, up-to-date water rate structure is in force and is applied reliably in billing operations.
		Composite customer rate is determined using a weighted average residential rate using volumes of water in each rate block.
7		Conditions between 6 and 8
8		Effective water rate structure is in force and is applied reliably in billing operations.
		Composite customer rate is determined using a weighted average composite consumption rate, which includes residential, commercial, industrial, institutional (CII), and any other distinct customer classes within the water rate structure.
9		Conditions between 8 and 10
10		Current, effective water rate structure is in force and applied reliably in billing operations.
		The rate structure and calculations of composite rate - which includes residential, commercial, industrial, institutional (CII), and other distinct customer classes - are reviewed by a third party knowledgeable in the M36 methodology at least once every 5 years.



Variable production cost (applied to Real Losses):

GRADE	✓	DESCRIPTION
Note: if the water utility purchases/imports its entire water supply, then enter the unit purchase cost of the bulk water supply in the Reporting Worksheet with a grading of 10		
1		Incomplete paper records and lack of documentation on primary operating functions (electric power and treatment costs most importantly) makes calculation of variable production costs a pure guesstimate
2		Reasonably maintained, but incomplete, paper or electronic accounting provides data to roughly estimate the basic operations costs (pumping power costs and treatment costs) and calculate a unit variable production cost.
3		Conditions between 2 and 4
4		Electronic, industry-standard cost accounting system in place.
		Electric power and treatment costs are reliably tracked and allow accurate weighted calculation of unit variable production costs based on these two inputs and water imported purchase costs (if applicable).
		All costs are audited internally on a periodic basis.
5		Conditions between 4 and 6
6		Reliable electronic, industry-standard cost accounting system in place, with all pertinent water system operating costs tracked.
		Pertinent additional costs beyond power, treatment and water imported purchase costs (if applicable) such as liability, residuals management, wear and tear on equipment, impending expansion of supply, are included in the unit variable production cost, as applicable.
		The data is audited at least annually by utility personnel.
7		Conditions between 6 and 8
8		Reliable electronic, industry-standard cost accounting system in place, with all pertinent primary and secondary variable production and water imported purchase (if applicable) costs tracked.
		The data is audited at least annually by utility personnel, and at least once every three years by a third-party knowledgeable in the M36 methodology.
9		Conditions between 8 and 10
10		Either of two conditions can be met to obtain a grading of 10:
		1) Third party CPA audit of all pertinent primary and secondary variable production and water imported purchase (if applicable) costs on an annual basis.or:
		2) Water supply is entirely purchased as bulk water imported, and the unit purchase cost - including all applicable marginal supply costs - serves as the variable production cost. If all applicable marginal supply costs are not included in this figure, a grade of 10 should not be selected.

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Appendix 6: New Mexico System BRI Calculations

System 1 - 1995-1999

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	National Average Breaks by Material	Break Rate Index (BRI)
Asbestos Cement: & Concrete	2560800	485.00	20.6%	7	4.2%	0.01	0.088	43	0.16
Cast & Ductile Iron:	5596800	1060.00	45.0%	43	25.9%	0.04	0.348	369	0.12
Other:	960960	182.00	7.7%	32	19.3%	0.18	0.167	30	1.05
PVC:	2756160	522.00	22.2%	2	1.2%	0.00	0.025	13	0.15
Steel:	564960	107.00	4.5%	82	49.4%	0.77	0.106	11	7.23
Total:	12439680	2356	100.0%	166	100.0%	0.07	0.20	466	0.36

System 1 - 2000-2003

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of System Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	National Average Breaks by Material	Break Rate Index (BRI)
Asbestos Cement: & Concrete	2914560	552.00	21.6%	15	5.4%	0.03	0.088	49	0.31
Cast & Ductile Iron:	6204000	1175.00	46.0%	89	32.1%	0.08	0.348	409	0.22
Other:	0	0.00	0.0%	48	17.3%		0.167	0	
PVC:	3859680	731.00	28.6%	15	5.4%	0.02	0.025	18	0.82
Steel:	501600	95.00	3.7%	110	39.7%	1.16	0.106	10	10.92
Total:	13479840	2553	100.0%	277	100.0%	0.11	0.19	486	0.57

System 1 - 2004-2009

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of System Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	National Average Breaks by Material	Break Rate Index (BRI)
Asbestos Cement: & Concrete	2962080	561.00	19.8%	22	8.7%	0.04	0.088	49	0.45
Cast & Ductile Iron:	6367680	1206.00	42.6%	146	57.7%	0.12	0.348	420	0.35
Other:	0	0.00	0.0%		0.0%		0.167	0	
PVC:	5068800	960.00	33.9%	30	11.9%	0.03	0.025	24	1.25
Steel:	554400	105.00	3.7%	55	21.7%	0.52	0.106	11	4.94
Total:	14952960	2832	100.0%	253	100.0%	0.09	0.18	504	0.50

System 1 - 2017

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	Theoretical Breaks by Material	Break Rate Index (BRI)
Asbestos Cement:	2003792.14	379.51	11.7%	21	7.1%	0.06	0.088	33	0.63
Cast Iron:	5450974.29	1032.38	31.8%	163	55.4%	0.16	0.348	359	0.45
Concrete:	1083234.67	205.16	6.3%	2	0.7%	0.01	0.043	9	0.23
Ductile Iron :	738235.66	139.82	4.3%	5	1.7%	0.04	0.055	8	0.65
Other:	63945.21	12.11	0.4%	4	1.4%	0.33	0.167	2	1.98
PVC:	7549195.2	1429.77	44.1%	36	12.2%	0.03	0.025	36	1.01
Steel:	245232.26	46.45	1.4%	63	21.4%	1.36	0.106	5	12.80
Total:	17134609.43	3245.19118	100.0%	294	100.0%	0.09	0.14	452	0.65

System 2 - 2017

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of Breaks by Material	% of Main Breaks by Material	Break Rate/ mile	National Average Break Rates	Theoretical Breaks by Material	Theoretical % of Breaks by Material Based on National Average	Break Rate Index (BRI)
Asbestos Cement:	314386.27	59.54	33.5%	16	32.7%	0.27	0.088	5	11%	3.05
Cast Iron:	104375.49	19.77	11.1%	21	42.9%	1.06	0.348	7	14%	3.05
Ductile Iron:	142338.05	26.96	15.2%	6	12.2%	0.22	0.055	1	3%	4.05
Other:	8001.1	1.52	0.9%	1	2.0%	0.66	0.167	0	1%	3.95
PVC:	364316	69.00	38.9%	5	10.2%	0.07	0.025	2	4%	2.90
Total:	937153.42	177.491178	100.0%	49	100.0%	0.28	0.09	16	32%	3.14

System 3 - 2016

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of System Main Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	National Average Breaks by Material	Break Rate Index (BRI)
Asbestos Cement:	21210	4.02	0.7%	0	0.0%	0.00	0.088	0	0.00
Cast Iron:	9402.53	1.78	0.3%	0	0.0%	0.00	0.348	1	0.00
Ductile Iron :	125894.25	23.84	4.1%	0	0.0%	0.00	0.055	1	0.00
PVC:	2897533.47	548.78	94.9%	47	100.0%	0.09	0.025	14	3.43
Total:	3054040.25	578.42	100.0%	47	100.0%	0.08	0.03	16	2.94

System 4 - 2015

System Main Materials	# Feet	# Miles	% of System Mains by Material	# of Breaks by Material	% of Main Breaks by Material	Break Rate/mile	National Average Break Rates	National Average Number of Breaks by Material	Theoretical % of Breaks by Material Based on National Average	Break Rate Index (BRI)
Steel:	187136.45	35.44	19.2%	23	25.8%	0.65	0.106	4	4%	6.1
Cast Iron:	168295.53	31.87	17.2%	10	11.2%	0.31	0.348	11	12%	0.9
Ductile Iron :	44090.45	8.35	4.5%	2	2.2%	0.24	0.055	0	1%	4.4
Asbestos Cement:	177989.93	33.71	18.2%	12	13.5%	0.36	0.088	3	3%	4.0
PVC:	398850.57	75.54	40.8%	42	47.2%	0.56	0.025	2	2%	22.2
Other:	260.16	0.05	0.0%		0.0%	0.00	0.167	0	0%	0.0
Total:	976623.09	184.96649	100.0%	89	100.0%	0.48	0.11	20	23%	4.4