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Water Infrastructure System Leakage Analysis: Evaluation of Factors Impacting System Performance and Opportunity Cost

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Abstract: Concerns over both water quality and quantity continue to increase globally. As the need for useable and potable water becomes more of a widespread issue, there is an opportunity to review and consider alternatives to how water is used, consumed, and sustained for future use by the world's population. A review of data across cities within North America shows improvement opportunities in water infrastructure systems. Using water audit and loss control data from the American Water Works Association (AWWA) and the Water Research Foundation (WRF), an analysis is provided to define opportunities for mitigating water losses among select North American Water Infrastructure systems in the U.S. states of Georgia and California. The research methodology used includes statistical analysis data while grouping utility sizes to identify utility cost opportunities. Variables on water loss and customer cost that have a positive impact on overall and long-term water system sustainability are identified. The analysis shows California, while having firm water guidance and higher rates compared to Georgia, also demonstrates less overall water loss. The results of the analysis are presented, showing comparison characteristics and opportunities for additional change to improve utility funding.

Keywords: water system management; infrastructure management; technical management; sustainment; opportunity cost; social-ecological systems

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1. Introduction

As concerns for the quality and availability of existing water supplies are mounting, water resource managers are challenged to improve infrastructure systems and internal processes and propose alternatives to the use, consumption, and sustainment of existing water supplies. An analysis of water research data provided by the United States (U.S.) Environmental Protection Agency (EPA), the American Water Works Association (AWWA), and the Water Research Foundation (WRF) presents causal relationships among variables contributing to reductions in water quantity and quality, further suggesting the need for improvements to aged and outdated water system infrastructure [1]. The implementation of improvements via integration of present-day technology would help increase potable, readily available water supplies and result in a more sustainable resource for future generations. This paper provides a discussion of Water Resource Management (WRM) systems, including challenges and opportunities for system improvement. Specifically, the paper presents a case to track volumes of water managed, including measurements of water supplied and unaccounted for, to help develop improved, innovative cost structures in managing the whole system.

Data trend analysis suggests population growth is highly correlated with concerns about water resource quantity and quality, illuminating the urgency with which water resource managers must apply a holistic approach to the management, improvement, and sustainment of water systems. Although significant advances in technology have helped identify and reduce water system losses, further opportunities exist to address water system resiliency and sustainability. Today, many well-developed countries lack proper water system governance and technical management, likely as a result of the high cost of these methodologies [2–4]. While global water problems are well known, this paper focuses on water losses in established distribution systems, an issue critical for resource and technical managers.

The current infrastructure includes systems that are outdated, inefficient, and subject to failure upon the introduction of unplanned system stressors. Action to implement improvement to these water systems, primarily through the introduction of newer technology, would allow for an increase in the amount of useable water supply while also serving as an impetus for sustainability for future generations [3].

The principles of scarcity appear to align with population growth data, illustrating some of the challenges to be encountered as the global population grows [5]. The U.S. risks critical water shortages due to a lack of responsiveness to the demand for dynamic water resource management and sustainability, which speaks to the broader supply shortages occurring on a worldwide scale. In many regions, the quantity of water available for the irrigation of crops is becoming increasingly scarce, and therefore, alternative sources are needed to provide water needed for irrigation [6]. The same is true about supplied water, which is managed and processed from the source, through the utility and to the end-user. Globally, a mindset that shifts away from the idea that water is easily accessible and readily available for use and moves toward the idea that water must be protected as a precious resource is critical [4].

The issues facing the U.S. are seen in the many communities across the nation that struggle with the ability to maintain their water infrastructure [7] and where opportunities exist to implement improvements in water infrastructure. Aging U.S. water and wastewater infrastructure is the top concern among U.S. water utility workers and requires prompt improvement [7]. Reports from the American Society of Civil Engineers (ASCE) include themes suggesting water infrastructure is sub-standard (compared to today's available technology) and well past its service life [8,9].

In 2020, the AWWA Water Loss Control Committee (WLCC) collected a dataset of validated annual water loss audit data from select North American water utilities captured from the calendar year 2018 (data released in 2021). The compilation of this dataset is contained in the AWWA Water Audit Reference Dataset (WARD) and contains data from U.S. states (California and Georgia data are complete) and data from the Canadian province of Quebec. The three selected regions were chosen to be part of this dataset because they all previously met the requirements and followed the guidelines per the WRF's Level 1 Water Audit Validation Guidance Manual, which provides specific guidance for improving water audit accuracy and directions on how to document any discrepancy or uncertainty associated with the water audit data [10]. The water audit validation process properly identifies and appropriately corrects inaccuracies in the water audit data [10], further improving data reliability to the utility. In addition, few U.S. states, including California, have formally developed a written methodology for performing Level 1 validation in great detail, which supports stricter state guidance for water loss controls when compared to other states.

For the 1379 utilities from the most recent AWWA WARD dataset, a detailed filtering process occurred to ensure the reliability of the data captured so as not to skew the dataset. The filtering process removed data from 255 utility locations due to duplications, errors, and other unreliable data, bringing the final number of utilities in the dataset to 1124. Further details on the data filtering process and associated breakdown can be found in [11].

2. Challenges and Complexities with Infrastructure System Management

Maintaining sustainable water services is dependent upon the use of effective processes through regulation and management; furthermore, complexity applies when addressing technical issues when attempting to optimize the system and associated infrastructure [4]. Items such as improper resource support and the lack of a realistic system model contribute to complexities in properly managing and optimizing a system. Financial, governing, supply, and technical challenges all introduce problems warranting exploration. While having reliable water loss data is an invaluable asset to water resource managers, there is no simple fix to resolve all water leakage issues, given the governance and maintenance variables coupled within the system. That said, the aim of this paper is to share an innovative approach to evaluating opportunity costs within the WARD dataset to demonstrate how water loss impacts operational efficiency. A comparison of the AWWA data received across differing regions allows for a comparative analysis to identify where planned improvements based on audit data have resulted in positive improvements for the utility.

2.1. Financial and Economic Challenges

Financial sustainability, including the ability to secure continual contributions from funding sources, is an ongoing problem due to readily available or insufficiently provided funding [12] to support proper and effective technical maintenance needs and water distribution projects. An analysis performed by ASCE estimated the gap in providing sufficient funding to maintain and improve the U.S. water and wastewater system infrastructure to nearly $82 billion U.S. dollars (USD) annually [7]. One facet of maintaining water supplies effectively includes the cost of managing both the infrastructure and system, plus continually optimizing the system to distribute water efficiently to the end user [5]. Increased costs and water rates result in unsatisfied users [13], and utility managers need to have rate structures in place to address economic process efficiencies and resource conservation [14].

The inefficiencies within the water utility system and associated system infrastructure result in water mismanagement issues and revenue opportunity losses to the utility, known as non-revenue water [2]. This is one challenge utilities face due to the inability to accurately quantify water losses. A lack of quantified water losses, coupled with cost impacts, positions technical managers to be unable to justify the need for appropriate funds for new projects to address water system losses. A breakdown of types of water consumed and lost from the overall system includes the following (derived from [15]):

1. Authorized Consumption:
    a. Billed to Customer (Revenue Water)
        i. Metered Consumption
        ii. Unmetered Consumption
    b. Not Billed to Customer (Non-Revenue Water)
        i. Metered Consumption
        ii. Unmetered Consumption
2. Water Loss:
    a. Apparent Loss (Non-Revenue Water)
        i. Unauthorized Water Consumption
        ii. Customer Meter Errors and Inaccuracies
        iii. System Data Errors
    b. Real Loss (Non-Revenue Water)
        i. Water Leakage on Distribution
        ii. Water Leakage Storage Overflow
        iii. Water Leakage on Customer Service Connections

From the description above, one can relate water loss to impacting the overall system's performance measures [16]. For example, the water system input (efficiency) will impact the system output (effectiveness and revenue water), thus impacting the overall system's measure of productivity (output/input, or for this water resource system, revenue water/water system input). Furthermore, non-revenue water can be identified as waste, which considers the system's quality of output. Most water system utilities are budget centers, so the measure of system productivity is important from a total system cost perspective.

Using the AWWA WARD data allows for the measurement of the output from the water utility to the consumer and compares it with what was consumed. Comparing the two, multiplied by the utility cost/rate, shows the cost difference (or opportunity gain).

2.2. Water Utility Governance

The governance structures necessary for effective water delivery are not in place [4]. The support of the government, including the creation of a standard sustainment practice and the establishment of reliable funding streams, is necessary for effective system and infrastructure management. Many municipalities and organizations govern water resource systems without a dedicated, overarching technical organization to support a robust systems management approach. While technicians and maintenance personnel exist to address technical challenges as they occur, proactive management, including preventative maintenance and Reliability-Centered Maintenance (RCM), is not always present in some water utilities to actively identify and address issues before they become major. Historically, priorities have been placed on inspection and not prevention, with the later costs of inspection being greater than developing a model for prevention [17].

A handful of state and regional agencies have implemented requirements for water utilities to submit annual water audit data; this practice has resulted in water utilities making some improvements on annual water losses that come from leakage and improper metering [2]. The AWWA developed rules and specific software for detailing water data to assist the utility in better capturing system-wide losses. Given this guidance, more U.S. state agencies are beginning to implement requirements, knowing that reliable water loss auditing assessments exist [2]. The value of these efforts could also be enhanced if a rating system was used to capture utility performance, further assisting the water utility and end-users, including customers, government officials, financial decision-makers, and public relations/media personnel.

2.3. Water Leakage Tools

At the time of the 2016 AWWA 'State of Water Loss Control in Drinking Water Utilities' study, close to 75% of U.S. states had only rudimentary water loss reporting or no water loss reporting [2]. Worldwide awareness has increased since this study, including water audit guidance, but major cities still face water shortages as climate change continues and the human population increases [18].

New, innovative methods and technologies for auditing water supply and measuring and controlling water leakage and loss continue to be developed, and when adopted by the utility, they assist in controlling losses [2]. Many support organizations have developed a variety of low-cost and, in some cases, no-cost software tools and publications to assist and guide utilities in employing best practices for effective water loss control [2]. The AWWA's Free Water Audit Software (FWAS) Version 6 (v6.0) and active participation in the Water Audit Data Initiative (WADI) have been found to be helpful for assessing existing water utility performance [19] and highlighting opportunities for improvement. The Level 1 WARD data are collected from utilities using this software. The EPA also offers a variety of tools to help water utilities better manage for optimal water and energy efficiency.

2.4. Water Loss Improvements

Some U.S. cities have taken advantage of the available tools offered and thus have seen significant improvements in the overall water loss impact on their utility. The City of Albuquerque (New Mexico) developed an improved process and documentation of water loss procedures, including cost accounting processes to capture the losses. Since implementing water loss control programs, the city has observed water loss decreasing from 102.2 L per connection per day in 2011 to 60.6 L per connection per day in 2016, with examples of corrective actions implemented to mitigate real water losses shown in Table 1 [19]. In addition, Albuquerque is required to submit an annual water loss audit to the New Mexico Office of the State Engineer for data tracking and trend analysis [19].

Table 1. Albuquerque Water Loss Improvements.

Improvement	Detail
Capture Leak/Break Occurrence and Frequency	Document break-in lines and note leaks upon occurrence; inform and prioritize leak detection crews to address them.
Measure Response Time	Document time for maintaining or fixing a leak repair.
Real-Time Field Data	Capture field data of water-using activities outside the utility, including fire hydrant flushing, service line installation, seasonal reservoir drainage, etc.
Municipal Use Measurements	Track water consumed as part of firefighting, street cleaning, and other uses from municipal departments.

The city of Warner Robbins (Georgia) was awarded $11 million USD in February 2022 for water and sewer upgrades through a grant to focus on infrastructure [20]; this came after the city reported it struggled to keep up with the increase in water leaks reported in prior years 876 water leaks reported between January 2021 and August 2021, with an estimated loss of 151 million L of water [21].

Among other U.S. locations, the California Water Loss Control Collaborative (CWLCC) is an initiative helping to transform water loss assessments in California [2]. Some water districts, like the Las Virgenes Municipal Water District (serving about 75,000 residents in western Los Angeles County, California), are implementing water flow restrictors to reduce heavy water usage for customers who have exceeded 150% of their monthly water budgets at least four times and have not reduced their total water usage [22]. In Pennsylvania, the Philadelphia Water Department became the first water utility in the U.S. to implement the AWWA's annual water audit methodology [2].

3. Systems Approach to Water Management

In the U.S., drinking water is supplied via a large network of pipes that stretch over one million miles across the country; many were installed in the early 1900s and have now degraded to the point where they have reached the end of their useful life (roughly 240,000 breaks in U.S. waterlines annually [23]). A systems approach is essential for effective systems management when dealing with an integrated set of sub-components [24], which include the inputs, outputs, and internal and external stresses on the water system. External stressors can be beyond the control of WRM decision-makers and should be treated as parameters in corresponding models [25], with attempts to control, mitigate, and manage. Internal stresses include stakeholder drawdown as well as a leaky, inefficient infrastructure [4]. Not all internal stressors and constraints are necessarily within the control of water resource managers; for example, if groundwater supplies are part of the WRM system, the recharge rate (which is impacted by both natural hydrology and anthropogenic pressures) of an aquifer can be considered as being beyond the direct control of water decision makers specifically [26]. There is no direct symmetry in the relation between periodic/external system stressors and continuous/internal stressors [25].

The integration of System Dynamic Modeling can assist managers in better understanding the system as "The traditional municipal model does not meet important criteria necessary for effective and efficient water service operations" [4]. An accurately modeled system will help predict and identify potential system improvements, weak points, and associated potential problems before they become larger issues [3,27]. In addition to a system model, implementing a unified back-end architecture that includes a simplified planned management approach will help lead to system optimization. Figure 1 has been adapted from the WRF (2019) and shows a high-level diagram that models outside influencers impacting water losses within the water utility system.

Figure 1. Outside Influences on Water Loss Control.

As Figure 1 (derived and expanded from [19] (p. 61)) shows, a synergetic relationship among influencers and impacts achieves the goal of sustainability within the water utility. In addition to the legal, technical, and operational impacts the utility faces in aiming to distribute a high-quality product, conflicting priorities among the three different external influencers pose a challenge to the utility's own objectives. Given the differing priorities of these influencers, the utility's ability to sustain and maintain itself and help mitigate a water loss reduction plan will be impacted. Table 2 (derived from [19] (p. 61)) provides further detail of items falling into the three differing areas of influence.

Table 2. Areas of Influence with Definitions.

Area of Influence	Definition
Economic	Water Utility System, including the Quality of Product, Cost Control and Revenues, and Environmental Stewardship
Social Political	Various Customers and Stakeholders, including perceived Affordability of Service, Quality and Quantity Service, Economic Viability, and Environmental Protection
Environmental	Regulatory Requirements, including Water Resource Management, Public Health, Affordability, and Rate of Return to Utility

3.1. System Process Improvements

In addition to the methods shared by the AWWA and the WRF, further opportunities for system process improvement (including internal process improvements, 6-Sigma (6S), Value-Stream Mapping, or Kaizen-type improvement activities) would help improve systems processes and, after implementation, would save internal costs over time [3]. Moreover, modeling and process mapping for efficiencies and improvements do not end with one project and should be continuously reviewed for improvement. The overall goal should be a better enterprise design with an expectation for major improvement.

Similar to many industries, operations and maintenance (O&M) procedures and standards (including scheduled/planned maintenance-related upgrades) should be a part of a water loss control program [19]. As part of this program, an evaluation of proper design (through modeling and simulation) and installation of new, efficient distribution components would help optimize the utility system. O&M measures such as system flushing, valve exercising, meter assessment testing, meter replacement programs, and water pressure testing all help contribute to improved overall efficiency and reduction in water losses, typically resulting in overall cost savings [19].

3.2. System Sub-Optimization to Aid Improvements

One approach in trying to optimize a system as a whole is to break the system down into components that can be optimized individually [28]. In many complex technical systems, it is necessary to sub-optimize components within the overall system, leading to a more desired and efficient end-state [3]. When sub-optimized, one must note the influence on downstream components. Thus, sub-optimization cannot take place without considering the effect changes may have on the individual components of the system [28]. This system of components works together to reach optimization and, in turn, accomplishes the aim of the overall system [29]. In addition to optimization, resilience is also a critical feature of WRM systems, given the societal urgency for many infrastructure systems to become more resilient and adaptable than they currently are [18]. "Resilience [within water systems] is the ability to cope with, and recover from disruption, and anticipate trends and variability in order to maintain service for people and protect the natural environment [now] and in the future" [30]. Moreover, and conversely, Deming has persuasively argued that focusing on optimizing each individual component at the expense of the overall system may lead to a poorer outcome for the system as a whole [29]. When performing sub-optimization at the component level, one needs to understand the overall system impact, in addition to the impacts downstream. Supplemental to having a system model, a sensitivity analysis of all parameters would also need to be performed to understand overall impacts when changes are made.

3.3. Management of Water Resources

It can be challenging for water and technical managers to collect water quality and use data from a variety of sources; analyzing water quality issues within the infrastructure system and utility can be time-consuming, especially when there are inconsistencies in the measurements and interoperability data processing issues [31,32]. The examples provided reemphasize the need for a common governing body to help assist technical managers in making the best decisions for their water utility. This is one area where engineering technical management and economic modeling tools would be of good use; they would help identify the optimal areas to perform repair and enhancements, aid in optimizing the system, and add fiscal benefits within the system as a result of improvement.

A common theme appears to be the lack of accurate data supporting the amount of water in the system and the amount of water being lost in the system. Water quality monitoring is necessary to better understand the impact of environmental change activities on surface and groundwater quality and help identify strategies to protect source waters. Without obtaining state and government support, municipalities will continue to face significant challenges in trying to implement key Source Water Protection (SWP) plans and strategies; these strategies are a key component of Integrated Water Resource Management (IWRM) in managing drinking water by reducing sediment and nutrient pollution of source water from agriculture and deforestation, which would help municipalities reduce water treatment costs [31]. The cost and resource savings at the source level will help with savings at the utility infrastructure system level, supporting the introduction of regulatory procedures for governance at the source, which would benefit the management of the greater water system. By integrating information from various stakeholders, water managers can improve the interpretation of data to comply with and support new and existing regulations [33].

4. Methodological Approach

The methodologies applied as part of this research include the use of data provided in the AWWA WARD dataset and the AWWA Water Audits and Loss Control Programs Manual of Water Supply Practices—M36 [34]. The research scope includes the study of utility performance data and archival information from water utilities within the U.S. states of Georgia and California, measuring key performance indicators after the implementation of significant infrastructure changes, improved governance, and policy. This comparative analysis aims to address the research problem within the literature of water utility losses when compared among states using the AWWA Level 1 Audit data. Using the aforementioned data, the methodologies applied compared water supplied and consumed, as well as the cost to the utility and cost to the consumer. From the data provided, the general hypothesis is that water utilities are under-charging for water to the end user. Specifically, water opportunity losses (and associated costs) comprise a strategic cost to organizations and could be offset by raising customer rates.

A simplified methodological approach for this research includes (and illustrated in Figure 2) where the AWWA data collection is presented (see Section 1); data groupings by state (Small and Large) are classified (see Section 4.1); the data analysis and calculations of cost reductions, infrastructure, and water losses were determined (see Section 5); hypothesis test for strategic opportunity cost evaluation and analysis was conducted (see Section 5); and finally, conclusions and recommendations are presented (see Section 6).

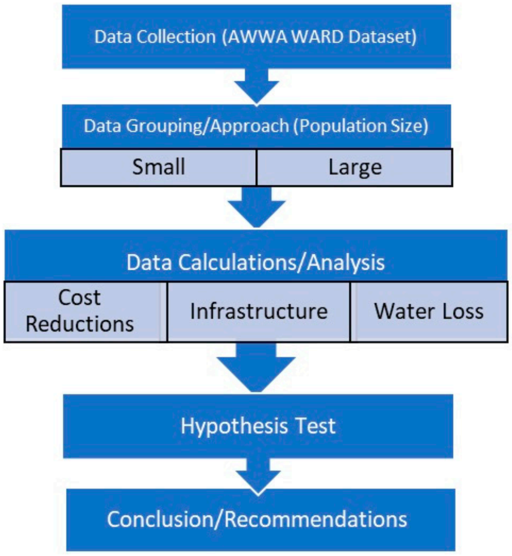

Figure 2. High-Level Research Methodology Flow-Diagram.

For efficient operating organizations, less than 15% opportunity cost is ideal and strategic in nature, according to the literature [17]. Alternatively, opportunity costs of 15% or greater are considered to be strategic and impactful to organizational performance and must be addressed as such. Banasik and Beruvides [13] used this methodology and applied the Prevention, Appraisal, and Failure (PAF) model and compared the Cost of Quality (CoQ) within the water utility sector. In addition, the work of Sandoval-Chavez and Beruvides [17] demonstrates the critical nature of strategic opportunity costs in non-utility operations. As part of this research, the AWWA data from the states of Georgia and California are used to evaluate the significance of water losses and answer if these water loss costs are strategic in nature and impactful to cost operations in a water utility. Thus, the hypotheses guiding this research are as follows:

Hypothesis 1: *The state of California's Water Utility opportunity losses are not strategic in nature and comprise less than 15%, showing minimal cost impact to the utility.*

Hypothesis 2: *The state of Georgia's Water Utility opportunity losses are not strategic in nature and comprise less than 15%, showing minimal cost impact to the utility.*

It is believed that increased funds from the customer would aid in appropriately addressing water loss. Further analysis and discussion will evaluate costs among states compared to water loss groupings based on population sizes and provide results and recommendations for additional research.

4.1. Area Served Quantification Data Structures and Treatment

Georgia and California were selected to be part of this study due to their adherence to the AWWA's guidance on Level 1 Water Validation. In summary, the AWWA guidance on a water loss validation approach aims to achieve the following:

1. Identify and appropriately correct errors in data and the application of the methodology to ensure the reliability of the dataset for analysis.
2. Evaluate and communicate uncertainty in water audit data inputs to eliminate possible data inconsistencies and ensure a reliable dataset.

Note that water loss data from the Canadian province of Quebec were included in the initial 2018 AWWA WARD dataset. However, the population served data were not provided to the AWWA for Quebec, so for the purposes of categorization as part of this research analysis, the Quebec data and information have been removed.

In Georgia, Level 1 validation was required beginning in 2012, where the first three years of data were validated by a state-funded third party. This phased roll-out occurred with the implementation of the State of Georgia Water Stewardship Act Requirements as part of Georgia Senate Bill 370 [35]. The Water Stewardship Act of 2010 applies to Georgia's public water systems, serving over 3300 people. After adoption, the Georgia Environmental Protection Division (GA EPD) has required annual reporting for all water systems falling into this category since March 2013 [35]. Per the Georgia Water System Audits and Water Loss Control Manual, Georgia water systems serving at least 3300 people must conduct an annual water system audit. Additionally, water systems serving a population of at least 3300 people must also implement a water loss control program. Approximately 250 water providers in the state of Georgia are subject to these water loss control requirements. Requirements include the following:

- Completion of an Annual Water Loss Audit (due by March 1 annually to the GA EPD)
- Development and implementation of a Water Loss Control Program (effective July 2016)
- Development of individual goals to set measures of water supply efficiency
- Demonstration of progress toward improving water supply efficiency

As of September 2014, California required all urban water systems to quantify and report the distribution of water losses using the AWWA system methodologies [36]. Level 1 validation of water audit data were mandated in California beginning in 2017, where the first year of data were validated by a state-funded third party [36,37].

Thirty-four water utility distribution system organizations from the State of California did not include Population- Served data as part of the AWWA WARD dataset. In reviewing California water loss data from 2016 and 2017, an attempt was made to extrapolate population-served data for the 2018 analysis. However, this information was not included in the 2016 or 2017 data reports. To further support this research and to achieve a more comprehensive set of data for analysis, population served information for the thirty-four water utility organizations was obtained through information from each water supply organization and has been included in the analysis. An evaluation of the categorization approaches to grouping the water systems is provided in the following subsections.

4.1.1. Population Served Approach Using U.S. Census Data Guidelines

The U.S. Census Bureau groups population areas into three major categories [38]:

1. Urbanized Areas (UAs)—built-up areas with a population of 50,000 or more; for classification purposes, we would call this the Large grouping.
2. Urban Places Outside of UAs or Urban Clusters (UC)—a census-designated place (CDP) with at least 2500 inhabitants; for classification purposes, we would call this the Medium grouping.
3. Rural Places and Territory—any incorporated place or CDP with fewer than 2500 inhabitants that is located outside of an Urbanized Area (UA); for classification purposes, we would call this the Small grouping.

In addition, the U.S. Census Bureau defines a Principal City (PC) within the aforementioned groupings as the largest city in each metropolitan statistical area [39].

This approach was determined not to be the best method for this analysis as the sample size from the Small category (under 2500 people served) for Georgia and California would not provide a large enough sample size for statistical significance. In addition, the State of Georgia Water Stewardship Act of 2010 applies to public water systems in Georgia serving over 3300 in population only, below the Small category size of 2500 people.

4.1.2. Population Served Approach Using NCES Criteria

The National Center for Education Statistics (NCES) Locale Classifications and Criteria approach to population grouping is composed of four basic types (City, Suburban, Town, and Rural), each of which contains three subtypes [40]. This approach takes the definitions developed by the U.S. Census Bureau and breaks them down into lower categories based on location and population size. The following table (Table 3) defines the twelve categories used as part of the NCES approach [40]:

Table 3. NCES Classifications with Definitions [40].

Grouping	Definition
City—Large	Territory inside a UA, inside a PC, and a population of 250,000 or more
City—Midsize	Territory inside a UA and PC with a population less than 250,000 and greater than or equal to 100,000.
City—Small	Territory inside a UA, inside a PC with a population less than 100,000.
Suburban—Large	Territory outside a PC, inside a UA, with a population of 250,000 or more.
Suburban—Midsize	Territory outside a PC, inside a UA with a population less than 250,000 and greater than or equal to 100,000.
Suburban—Small	Territory outside a PC, inside a UA, with a population less than 100,000.
Town—Fringe	Territory inside a UC less than or equal to 10 miles from a UA.
Town—Distant	Territory inside a UC more than 10 miles and less than or equal to 35 miles from a UA.
Town—Remote	Territory inside a UC more than 35 miles from a UA.
Rural—Fringe	Census-defined rural territory less than or equal to 5 miles from a UA and rural territory less than or equal to 2.5 miles from a UC.
Rural—Distant	Census-defined rural territory more than 5 miles but less than or equal to 25 miles from a UA, as well as rural territory more than 2.5 miles but less than or equal to 10 miles from a UC.
Rural—Remote	Census-defined rural territory more than 25 miles from a UA and also more than 10 miles from a UC.

This approach was evaluated and determined not the best method for this analysis as the sample sizes from Georgia and California would be too small for statistical significance in each of the twelve categories. In addition, for the Town and Rural categories, distances from the UA were not provided in the dataset, and obtaining this additional information to support this initial analysis was determined to be non-value added.

4.1.3. Population Served Approach Using U.S. EPA Guidelines

The EPA defines small water drinking systems as serving populations less than 10,000 people; the majority of drinking water systems in the United States fall into this category (greater than 92% of U.S. drinking water systems) [1,41]. Large water drinking systems are classified as serving a population of greater than 10,000 people.

EPA-defined small water systems face unique financial and operational challenges in consistently providing drinking water that meets EPA standards and requirements and works closely with states and federal partners, assisting small systems with financial and technical resources [41]. Given this information and noticing that the EPA has more direct support of smaller water systems, it was determined that the water systems evaluated in this study will be grouped using EPA guidance (reference Figure 2, Item 2, data grouping by state (Small and Large)). However, one caveat in the 2018 AWWA WARD data was that organizations serving less than 3300 people were removed from the analysis based upon the requirements of the Georgia Water Stewardship Act of 2010. For the purposes of this data analysis, Small water systems serve a population between 3300 and 10,000 people, and large water systems serve a population of greater than 10,000 people.

4.1.4. Population Groupings for Georgia and California

Using the methodology described in Section 4.1.3, the following identifies the breakdown of each water system and which category they were grouped in to support the analysis:

1. State of Georgia, 198 total water utilities from the 2018 AWWA WARD dataset:
    a. Five under the three thousand three hundred in population were served (these water utilities have been removed from this analysis)
    b. There were 99 categorized as Small, but one was removed from analysis due to incomplete information, bringing the total Small utilities to 98.
    c. There were 94 categorized as Large
2. State of California, 268 total water utilities from the 2018 AWWA WARD dataset:
    a. Two under the three thousand three hundred population were served (these water utilities have been removed from this analysis and do include 1 in which the population served data were not included in the original dataset but obtained directly through state data)
    b. There were 12 categorized as Small (includes 3 in which population served data were not included in the original dataset but obtained directly through state data)
    c. There were 254 categorized as Large (includes 30 in which population served data were not included in the original dataset but obtained directly through state data)

Given the previously mentioned population-served approach from Section 4.1.3, Table 4 displays the average population served per category used in this analysis. Noted, the averages for both Small and Large categories in the State of Georgia are smaller when compared to the State of California.

Table 4. Average population served (California and Georgia) within each EPA defined category.

	Small	Large
California	7981	104,912
Georgia	5758	72,939

4.2. Evaluation of Key Water Loss Performance Indicators

With all the data collected using the AWWA Free Water Audit Software (FWAS), eight Key Performance Indicators (KPI) are calculated and numbers below to determine the overall health of the water utility system [11]. These KPIs are also key metrics included in the WARD dataset. (Note: AWWA data are provided in U.S. gallons and miles; the equivalent SI values are in brackets):

1. TLCR: Total Loss Cost Rate (measured in USD per connection, per year); equates to the rate of total water loss, including Real and Apparent losses
2. ALCR: Apparent Loss Cost Rate (measured in USD per connection, per year); apparent loss is water that is not physically lost but under-recorded [42]; examples include metering errors and inaccuracies

3. RLCR: Real Loss Cost Rate (measured in USD per connection, per year); real losses include water that is physically lost [42]; examples include pipe leakage and water main failures
4. ULR: Unit Total Losses (measured in gallons [1 gallon = 3.785 L] per connection, per day); equates to the total sum of Unit Real and Unit Apparent losses
5. UAL: Unit Apparent Losses (measured in gallons [1 gallon = 3.785 L] per connection, per day); compromised of adding loss components of systematic data handling errors, customer metering inaccuracies (incorrect meter reading, difficulty of access to meters), and unauthorized consumption [34].
6. URLA: Unit Real Losses A (measured in gallons [1 gallon = 3.785 L] per connection, per day); the difference between total water supplied to consumer and Authorized Consumption to customer, in gallons per connection [34]. For this analysis, the metric is best used when evaluating water leakage per connection.
7. URLB: Unit Real Losses B (measured in gallons [1 gallon = 3.785 L] per mile , per day); the difference between total water supplied to consumer and Authorized Consumption to customer, in gallons per mile [34]. For this analysis, the metric is used when measuring leakage over system distance.
8. ILI: Infrastructure Leakage Index (system performance indicator for comparisons of water leakage management used for benchmarking performance; this KPI is dimensionless); the difference between Current Annual Real Losses (CARL) and Unavoidable Real Loss (UARL) [34].

Additional definitions used as part of this study are included as part of the complete AWWA WARD dataset (AWWA, 2021) and in Key Performance Indicators for Non-Revenue Water—AWWA Water Loss Control Committee Report [42].

The core KPIs identified are based on a loss measurement, and the ILI KPI is a performance calculation for each system to allow for an equal comparison across water systems. The ILI determines the overall infrastructure management performance to be assessed independent of operating pressure influences [43,44] and developed to establish an objective benchmarking indicator for comparison purposes across water systems.

An ILI index score of 1.0 indicates that current annual real losses are equal to unavoidable annual real losses. Based on the score, it is determined if the water utility is operating at a technically low level of leakage, which is very unlikely and uncommon [43]. The AWWA WARD Audit dataset established typical benchmarking percentiles (per the AWWA) for the KPIs after a water audit [11]. This benchmarking information is included as part of the dataset and is used to provide a comparative analysis to evaluate how the water distribution system compares across other systems. The data from state comparison groupings will use this benchmark grouping as part of the ILI results.

The specific methodologies used as part of this research include statistical analysis, which will include the evaluation of the data from the AWWA WARD dataset to identify opportunities and differences in the data for potential gaps and improvement opportunities (note, from the date of this publication, the 2018 data are the latest data made available from the AWWA). The use of the Small and Large data groupings (Table 4) shows a common comparison of similar-sized utilities using the same guidance as the AWWA Level 1 Audit established methodologies.

4.3. Evaluation of Water Supplied and Consumed

Using water-supplied data (versus water-consumed data) and factoring in the customer charge rate, calculations revealed the average amount of water provided to each customer, per utility, the associated costs, and the amount consumed by the customer. This approach compared all individual utilities across Georgia and California as well as the Small and Large groupings to support the comparison study. In doing so, one can evaluate the cost of the water supplied to the customer versus what the customer consumed and what the utility charges the customer. This comparison aims to show the differences between small and large utilities across the two states. Additionally, the data present opportunities to adjust customer rates, as customer rate is determined by the individual utility.

5. Data Analysis and Results

In support of this analysis, the AWWA WARD dataset was broken into Small and Large data groupings to provide a comparative understanding of results across each state (reference Figure 2, Items 2 and 3). The data analyzed reflect the KPI data referenced in Section 4.2. Evaluation of Key Water Loss Performance Indicators.

5.1. Water Loss Data

The Average Water Loss Cost was collected and plotted in Figure 3, showing the differences among the locations and categories. The first observation of an analysis of the data shows that the state of Georgia, in both Small and Large categories, has a Water Loss control problem when compared to California (Real Loss Cost Rate/RLCR, shown in blue). While Georgia has state guidance and controls in place, California maintains stricter guidance on Level 1 water audits and water loss controls (reference Section 4.1).

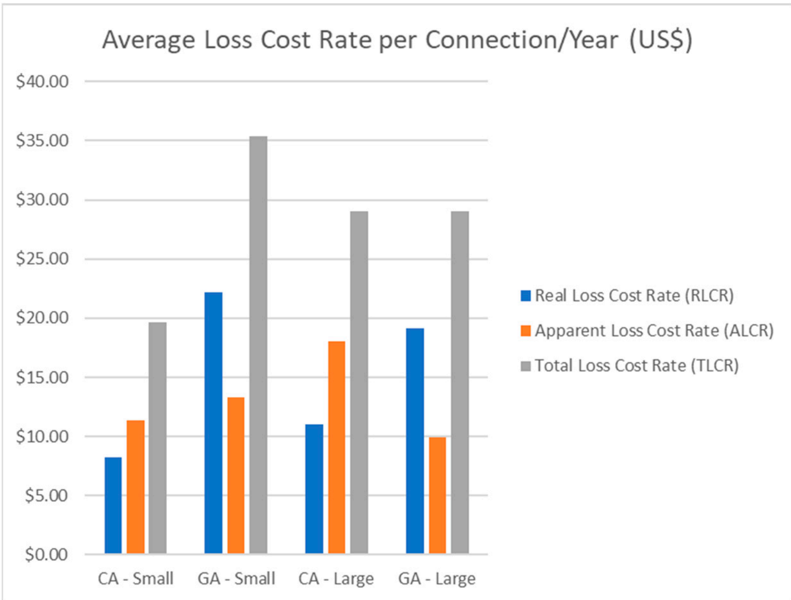

Figure 3. Average Water Loss Cost per Connection per Year.

Comparing the Large state groupings, while California displays better control on the RLCR, the Apparent Loss Cost Rate (ALCR) appears to be problematic for larger cities. This is due to a number of loss contributors, including the wrong type of or aged meter for the water usage profile, data handling errors, and unauthorized consumption, all of which drive up costs from water losses. Driving improvement in these areas allows for more accurate metering (billing), less water loss, and improved utility funding.

One of the fields in the dataset included utility priorities as identified as Priorities 1 through 3. California Small and Large state groupings were relatively consistent in populating infrastructure management priorities for the utility (note: the State of Georgia did not identify priority areas as part of the dataset). California Priority Area #1 resulted in 65.4% of all municipalities reporting maintaining and having water; "Volume from own sources" was the most important to maintain. Per the California Department of Water Resources, California receives 75% percent of its rain and snow from the watersheds north of Sacramento; however, 80% percent of the state's demand for water comes from the southern two-thirds of the state [45]. From a cost perspective, it is more cost-efficient to use the available water in-state as opposed to looking for external resources. Keeping this a utility priority will aid in driving down total costs for the utility and consumer.

California Priority Area #2 included 50.6% of utilities reporting "Customer metering inaccuracies". This aligns with the data and analysis provided earlier, where the state is seeing a high trend of Apparent Water Losses. With older meters and meters that are not a proper fit for the consumer or input pipe size, this will result in inaccurate readings. The cost of the replacement and installation of a meter ranges from $1700 to $3000 USD based on 2022 Fiscal Year Market Data [46] (note: price ranges are based on meter type, location, and associated installation fees). For older developments and towns, this can prove costly given the age of the meters needed to be replaced. While costly upfront, this is preventing the utility from appropriately charging for water consumed by the end-user. Coincidently, California Priority Area #3 was "Billed metered" (38.3% of CA state utilities), showing that meter billing is also a concern that is directly related to meter inaccuracies.

Using the measured water loss for the utility, the Infrastructure Leakage Index (ILI) was calculated. This value is a system performance indicator for comparisons of water leakage management across utilities. An ILI score of 1.0 designates current annual real losses as equal to unavoidable annual real losses (more optimal state). Figure 4 shows the ILI data for California and Georgia, as well as Large and Small utility groupings.

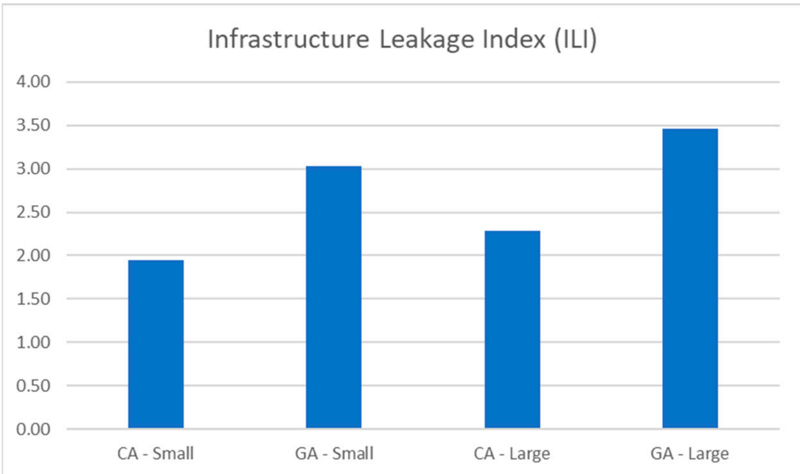

Figure 4. Infrastructure Leakage Index for Georgia and California.

Using the AWWA's established KPIs from the WARD dataset [11] (identified in Section 4.1.4), the state groupings are as follows:

- CA—Small: between the 50 and 75th percentile
- GA—Small: above the 75th percentile
- CA—Large: between the 50 and 75th percentile
- GA—Large: above the 75th percentile

The data provided show that both California groupings are in a better percentile for water loss when compared to Georgia. From the data, it appears California has better overall leakage control across its state utilities. As previously noted, California also has stricter water guidance for its utilities, so this improvement in water system performance is understood. This is especially true in reference to Figure 3, where "GA—Small" utilities show the greatest overall loss rate, driving up the total cost to the utility. Data provided further in this analysis will show loss trends and cost/funding differences that contribute to this difference among states. Additionally, California maintains policies through the California Department of Water Resources to help educate and enforce water conservation practices.

While the ILI is one method of displaying how well the utility is managing water loss, the dataset includes a measure of losses per mile (measured in gallons [1 gallon = 3.785 L] per mile length [1 mile = 1.609 km] of water main, per day), shown in Figure 5.

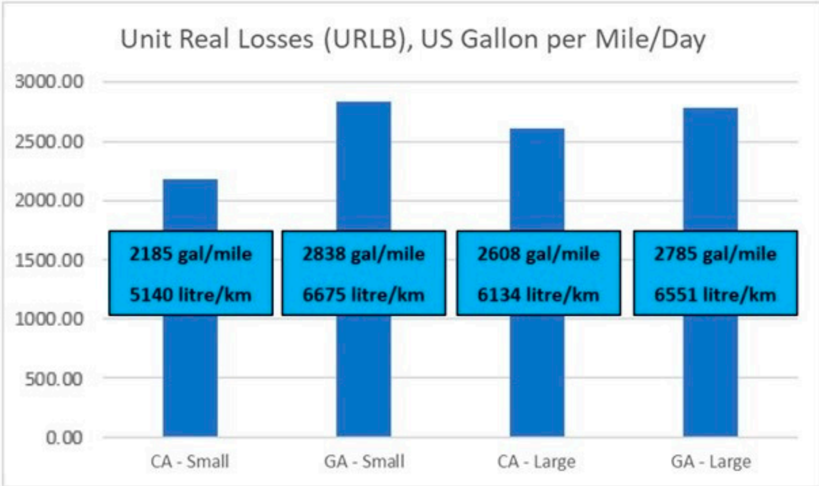

Figure 5. Unit Loses Measured in Water Main Mile per Day.

This metric also demonstrates that while losses are occurring in both states, California is seeing less comparable loss across its water distribution system, supporting the initial hypothesis. Using the leakage evaluation data, one would want to understand how this compares to utility costs to understand if the utility is reviewing appropriate funding from customers to not only provide water service but also pay for the water provided.

5.2. Data Analysis: Cost and Opportunity Evaluation

To further understand customer usage and cost breakdown, the water data were broken out into two sections: Water Supplied (by the utility) and Water Consumed (Authorized Consumption (AC)), or water consumed by the end-user. Table 5 displays a difference in water supplied by the utility compared to water consumed by the end-user. The percentage difference indicates a percentage of overall water loss for each utility grouping.

Table 5. Percentage of Water Loss when compared to supply.

	Water Loss Compared to Water Supplied
CA—Small	14.58%
CA—Large	8.92%
GA—Small	38.58%
GA—Large	20.62%

Using these data, coupled with past and future AWWA Level 1 Audit data, one could project future water loss for the mentioned groupings based on no change in current water management processes. The total water loss displayed here shows a utility opportunity loss and is one measure of quality performance across the utilities. Taking an average unit cost per 1000 gallons (3785 L), one could also convert this to annual financial loss to the utility. This shows that water is being lost from the supplied location by the time it gets to the end-user. However, California appears to have less total water loss from start to end, further supporting the ILI metric. This shows that California water utilities are operating more efficiently when compared to Georgia, and California's large utilities are the most efficient, comparatively speaking. These data can also be used to measure the system's productivity by measuring the efficiency of the water system and how effective it is in supplying water to the end user with minimal water loss.

Table 5 also shows that both Small and Large groupings within California fall below the 15% strategic value for loss estimates. However, in the state of Georgia, both groupings are well above 15%, thus showing a negative cost impact on operations in the water utility.

The ILI percentile metric also aligns where California is within the 50–75th percentile, and Georgia is well above the 75th percentile.

A cost amount (pre-defined per utility) was then applied to the amount of water being supplied compared to water consumed. However, this was broken into three groupings: Charge per Customer Billed, Charge per Customer Authorized, and Charge per Customer Supplied (note, the customer is billed using the Charge per Customer Billed metric, which is advertised as Customer Rate only and does not include state/local taxes, or any other service fees provided by the individual utility). Across the dataset, it was observed that what was billed to the customer was typically less (in some cases, much less) than what was authorized for use and less than what was initially supplied. One could argue that the customer should be billed for what is truly consumed, whether authorized or not. Another may suggest that what is supplied to the customer is what the customer should be billed for. In some unique utility cases, the Charge per Supplied amount nearly doubled what was being billed to the customer. Table 6 displays the average percentage of Billed/Supplied differences across the groupings.

Table 6. Average Customer Charge Differences—Water Billed versus Water Supplied.

	Average Charge Difference—Water Billed vs. Water Supplied
CA—Small	15.70%
CA—Large	9.84%
GA—Small	43.97%
GA—Large	23.99%

The results of these data suggest that California is more in line with billing the customer for water supplied. However, both states should re-evaluate their billing to the customer to bill for what is authorized for use and supplied (helping to decrease opportunity cost). In addition, given the varying rates across each utility, an argument could be made for rate consistency across the states and internal regions, as well as rate fairness, especially as it pertains to low- or fixed-income households. Fairness occurs when each user pays proportionally to the benefit (in this case, potable water) they receive [14]. Overall, mitigating future costs to end users would only be allowed when the utility had a better grasp on water leaks and consumption measurement, where both the utility and consumer would share the costs of the burden of lost water.

6. Conclusions

This comparative research study evaluated selected municipal water infrastructure systems using research data from the AWWA. With the constant evolution of approaches to manage governance, funding, and technology, one can evaluate best practices with regard to the fluid environment of municipal water resource management sectors and the overarching need to improve operations, processes, and infrastructure. The information shared serves as an innovative, data-driven resource to assist the technical manager in developing best practices for long-term efficiency while aiding in cost and performance management.

A discussion of WRM systems, including near-term challenges and opportunities for future improvement within these systems, has been presented. Water utility losses create problems for both the utility and the overall system, including the obvious wasted water and energy resources, fiscal challenges to improve and repair, and many additional negative impacts to all users [2]. In the U.S., a percentage of the cost of municipal water processing and distribution is tied to the electricity needs of the consumer; in addition to driving efficiency in the water utility, the reduction of water leaks will assist in lowering total energy demand, aiding in cutting water production costs.

Water utilities should continue to, or in some cases, begin to track the annual volumes of water they manage, measuring both the amount of water supplied to their customers and the water unaccounted for or lost [2]. Using that information and the data presented herein, this should be applied to develop cost structures to help manage the whole system, including costs for improvement projects, thus minimizing leakage and system inefficiencies.

The results presented summarize three concluding points as part of this research:

1. The utilities analyzed provide rates to customers that do not sufficiently meet the financial needs for growth and improvement to the utility.
2. The state of California has stricter water guidance in place, coupled with rates closer to what is being supplied to the customer and less water loss when compared to utilities in the state of Georgia; states are relying on outside funding for these projects or are unable to complete key projects due to lack of reasonable funding for the utility.
3. An opportunity is presented to evaluate customer rate fairness based on the amount of water that is consumed by the customer when compared to other utilities.

This research shows that current water losses comprise a strategic opportunity cost, and evaluating opportunity costs will initiate a deeper analysis of infrastructure needs; identifying the strategic opportunity cost is a novel contribution of this paper and not currently found in the open literature. The resource conservation issues and economic impact are at this time hidden from water resource managers, and the approaches mentioned will allow for addressing future capital budgeting issues. These data and the analytical technique presented in this study can help the knowledge worker, in this case, the water resource manager, make better decisions on where to focus funding to positively impact the water utility. Making data-driven efforts to initiate system improvements is complicated due to funding challenges, governance, and technical management. About half of the U.S. water utilities that provide drinking water to roughly 12% of the U.S. population are privately owned [23]. The implementation of a common strategy, including regulation for improvement, is more difficult in private sectors than in public sectors. However, this is not impossible, and it needs to be a focused, collaborated effort across the industry, as other industries, including private and public sectors, have been working for commonality in regulation and standards to help drive improvement and drive down costs. Cost structures also need to be evaluated for commonality and fairness, where applicable. The data provided show that California is more in line with appropriately charging customers compared to Georgia, but charging in both states should be closer to how much water is supplied to the customer.

Given current research and guidance provided by the EPA, AWWA, and WRF, additional opportunities exist that would aid in the effort to improve water system infrastructure within WRM. If a complete, audited dataset was available for more water utility systems, the overall management of water resources would allow for the performance of additional studies to help drive infrastructure improvement and less total water losses. The identification of system performance indicators and their impacting relationship to water loss control practices will aid in the predictive management and control of potential system losses. Other areas for consideration include the evaluation of production and operational costs for the total utility and how these costs are funded. The unique approach presented in this research provides a new methodology and metric to assist water utilities technical managers to better manage and address hidden opportunity costs and better understand their organization's cost of quality issues.

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