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Beyond Leakage: Non-Revenue Water Loss and Economic Sustainability

Eleonora Santos

Centre of Applied Research in Management and Economics, School of Technology and Management, Polytechnic University of Leiria, 2411-901 Leiria, Portugal; eleonora.santos@ipleiria.pt

Abstract: Water loss in urban supply systems poses significant challenges for water utility companies worldwide, affecting both sustainable access to clean water and the financial viability of utility operations. This study analyzes the evolution of water losses in high-level supply systems from 2017 to 2021 in Portugal, focusing on its implications for the profitability of water utility companies across NUTs II regions. Drawing on data from various sources, including the National Information System for Water Resources, PORDATA, ERSAR, and ORBIS, this analysis identifies trends, patterns, and potential factors influencing water loss dynamics. Key components of the analysis include calculating average annual losses, examining unbilled water percentages, and conducting regression analysis to quantify the impact of water loss on profit margins. The findings contribute to the literature on water loss management and financial performance in the water utility sector, offering insights for policymakers, water utility managers, and stakeholders to enhance financial sustainability and reduce water losses.

Keywords: economic sustainability; corporate performance; non-revenue water loss; water management; urban supply systems

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1. Introduction

Water Infrastructure Asset Management (WIAM) is crucial for ensuring the reliability and sustainability of water supply and sanitation services globally. Effective WIAM initiatives are essential for addressing challenges and adapting to evolving trends in the water sector. Studies by Amaral, Alegre, and Matos [1] and Sehring et al. [2] emphasize the importance of key international WIAM initiatives and successful approaches in various contexts. The American Water Works Association (AWWA) and the International Water Association (IWA) classification scheme provide a standardized framework for assessing water losses by dividing non-revenue water (NRW) into physical losses, commercial losses, and unbilled authorized consumption. These metrics are instrumental for water utilities to measure and address water losses, thereby improving operational efficiency and financial performance [3]. Effective use of such frameworks is critical for a rigorous assessment of WIAM initiatives aimed at tackling water loss challenges.

Governance structures also play a significant role in the efficiency and performance of urban water utilities. Research by Barbosa, de Lima, and Brusca [4] and García-Rubio, González-Gómez, and Guardiola [5] explores how governance mechanisms, including ownership models, impact the operational efficiency of water service providers. Understanding the interplay between governance frameworks and utility performance is essential for designing effective policies and interventions that enhance water service delivery. However, implementing comprehensive WIAM strategies and advanced technologies can be complex and costly, posing challenges, particularly for regions with limited resources [4,5].

Efficiency assessment and improvement strategies are central to optimizing water infrastructure assets and enhancing service delivery. Various methodologies, including frontier approaches and dynamic analysis techniques, are used to evaluate the efficiency of water utilities [6,7]. Additionally, sustainability and resilience have become key priorities in water management, given the growing challenges of water scarcity and climate change. Research by Schilling et al. [8] and Tzanakakis, Paranychianakis, and Angelakis [9] highlights the importance of adopting sustainable water management practices and building resilient infrastructure systems. Incorporating Objectives and Key Results (OKRs) align water management practices with the Sustainable Development Goals [10–12], and innovative financing and community engagement are crucial for extending piped water networks and monitoring water access inequalities [11–16]. Nevertheless, balancing economic sustainability with infrastructure investment remains challenging as high costs and complex financing models may limit the effectiveness of some sustainability initiatives [10–12].

The differences between public and private utilities have significant implications for water infrastructure management. Public utilities typically prioritize universal access and affordability, while private utilities often focus on financial performance and efficiency. This distinction affects how each type of utility approaches water loss management and infrastructure investment [17]. In Portugal, government subsidies support water companies, particularly in less populated or remote regions, helping to balance the financial challenges of maintaining infrastructure and meeting environmental regulations [18]. However, while subsidies can support essential services, they may create dependency and impact the incentives for private utilities to invest in long-term infrastructure improvements [19].

Non-revenue water (NRW) presents a critical challenge for water utilities globally, leading to financial losses and reduced system efficiency. The reduction in NRW and the digitalization of water supply systems are essential for contemporary water management, particularly in light of the pressures of climate change and urbanization. Sustainable engineering practices have emerged as pivotal strategies for addressing these issues. By adopting comprehensive frameworks that prioritize sustainability throughout all phases of water supply operations, utilities can effectively minimize waste and enhance resource efficiency, thereby significantly contributing to NRW reduction [20]. Strategies such as leakage prevention and network rehabilitation are crucial for addressing NRW and enhancing system efficiency. The implementation of EU regulations aimed at evaluating water losses and optimizing energy efficiency in water supply systems also presents its own set of challenges. Discrepancies in regulatory compliance across regions underscore the necessity for standardized methodologies to assess and mitigate water losses effectively. This approach not only addresses NRW but also promotes broader sustainable water management practices, laying a crucial foundation for utilities to invest in technologies that enhance system performance and reduce operational costs [21]. Emerging decision support systems and innovative technologies play a vital role in reducing NRW and improving water system sustainability and resilience. The COVID-19 pandemic has complicated NRW dynamics by altering traditional water consumption patterns, necessitating adaptive management strategies that respond to these changes. Digitalization facilitates real-time monitoring and responsiveness within water supply systems, which is essential for tackling unexpected challenges while maintaining efficient NRW management [22]. Investment in green technology innovation is also vital for reducing NRW. Evidence shows positive correlations between technological advancement and operational efficiency in water treatment companies, indicating that prioritizing eco-friendly technologies enables utilities to mitigate NRW effectively and bolster overall system resilience [23]. However, the relationship between water losses and unbilled water can be complex, influenced by various factors such as measurement errors and unauthorized consumption. While increased water losses often correlate with higher unbilled water, this relationship may be complicated by other factors, necessitating a comprehensive approach to managing and reducing unbilled water. Lastly, economic assessments of urban water utilities are crucial for developing effective NRW reduction strategies. Research indicates that economically viable interventions can significantly decrease water losses while improving service delivery. Implementing performance-based metrics is recommended to enhance leakage control and resource management, further reinforcing the case for digitalization and data-driven decision-making in the water sector [24].

A notable example of successful WIAM principles is Singapore's water management system, which is frequently cited as a model of best practice [25]. Singapore's approach, known as the "Four National Taps" strategy, integrates local catchment water, imported water, recycled NEWater, and desalinated water. The city state invests heavily in advanced technologies for water treatment and infrastructure management, such as the state-of-the-art membrane technology used in the NEWater plant [25,26]. Singapore's focus on enhancing the resilience of its water infrastructure, including the construction of the Marina Barrage for stormwater management, has significantly improved its water sustainability and infrastructure performance [25,26]. The city has effectively engaged the public in water conservation efforts, further contributing to its high level of water sustainability [25].

Future research and innovation are necessary to address emerging challenges and opportunities in WIAM. Studies by Farouk, Rahman, and Romali [27] and Pathirana, Heijer, and Sayers [28] identify non-revenue water reduction and smart infrastructure solutions as promising areas for development. Analyzing water losses and unbilled water provides valuable insights into the economic and managerial implications of water loss management.

In this context, using data from various sources such as the National Information System for Water Resources, PORDATA (www.pordata.pt accessed on 8 June 2024), ERSAR (Water and Waste Services Regulation Authority at www.ersar.pt/pt accessed on 8 June 2024), and ORBIS, our study aims to analyze the evolution of water losses in high-level supply systems from 2017 to 2021 and assess their implications for the profitability of water utility companies in Portugal by NUTs II regions. By examining trends in water losses and unbilled water percentages across different companies, we seek to identify patterns, correlations, and potential factors influencing these dynamics. The analysis involves several key components. Firstly, we calculate average annual losses for each company over the study period and compare them to identify trends and variations. Additionally, we analyze the percentage of unbilled water, a critical indicator of distribution system efficiency, and its relationship with actual water losses. Furthermore, we conduct regression analysis to quantitatively assess the impact of unbilled water, along with other relevant variables, on the profit margins of water utility companies. By employing both ordinary least squares (OLS) and quantile regression techniques, we aim to provide a comprehensive understanding of the economic and managerial implications of water loss management. The findings of this study are expected to contribute to the existing literature on water loss management and financial performance in the water utility sector. Moreover, the insights gained from this analysis can inform policymakers, water utility managers, and stakeholders about the importance of implementing effective strategies to reduce water losses and enhance financial sustainability in the water sector.

2. Data and Methods

2.1. Data

Region Description and Network: This study focuses on analyzing water losses and unbilled water (UW) across several water utility companies in Portugal from 2017 to 2021. The companies include EPAL (Empresa Portuguesa das Águas Livres, S.A.), Águas de Santo André, Águas do Algarve, Águas do Centro Litoral, Águas do Douro e Paiva, Águas do Norte, Águas do Vale do Tejo, Águas do Vouga, Águas Públicas do Alentejo, and ICOVI (Iniciativa Comum de Valorização de Infraestruturas). Each company operates within distinct regions of Portugal, reflecting regional variability in water management practices and infrastructure. In Portugal, most urban areas served by the water utility companies, such as EPAL and Águas do Algarve, have metered connections, though coverage may vary in more rural regions where non-metered connections still exist. Meter readings are typically conducted either automatically, through advanced metering infrastructure, or manually by technicians, depending on the company's infrastructure and the region. In areas with more advanced systems, readings are often synchronized and occur monthly or quarterly for billing purposes, while manual readings may lead to variability in timing. This creates some uncertainty in the data, as metering inaccuracies, data recording delays, undetected leaks, and illegal connections can distort the true figures for water losses and unbilled water. These factors contribute to discrepancies and make comparisons across different regions challenging.

Data Collection: Data on water losses and unbilled water percentages were obtained from ERSAR (Entidade Reguladora dos Serviços de Águas e Resíduos), the regulatory body overseeing water and waste services in Portugal. The data cover the period from 2017 to 2021 and include annual figures for each company.

Water losses refer to the volume of water that is lost between the point of supply and delivery to consumers, encompassing both physical losses (e.g., leaks, pipe bursts, and overflows) and apparent losses (e.g., metering inaccuracies, theft, or unauthorized consumption). The data on water losses and unbilled water percentages from 2017 to 2021 were obtained from ERSAR, the regulatory body overseeing water and waste services in Portugal. ERSAR collects these data annually from each water utility company, ensuring compliance with national standards and auditing their operational metrics. While the majority of the data are directly measured, certain activities—such as flushing, which involves the use of water to clean and maintain the distribution network—require estimation due to the lack of precise measurement tools. These estimates introduce a degree of uncertainty into the overall figures, as the exact volume of water used during such maintenance processes is difficult to quantify. Therefore, reported water loss figures may include approximations, particularly in cases where utilities rely on operational data or industry norms to estimate non-billed water usage.

2.2. Methods

Calculation of Unbilled Water (UW): Unbilled water is defined as the volume of water delivered into the distribution system but not accounted for in the billing system. It includes losses due to leaks, measurement errors, unauthorized consumption, and other factors. The calculation involves converting all units to $m^3/(km \cdot year)$ for consistency across years and companies. The use of $m^3/km/year$ as a metric for water loss is justified in this analysis due to its ability to standardize water losses across different utility companies and regions with varying pipeline lengths and distribution network sizes. This unit measures water loss relative to the length of the distribution network (in kilometers) and per year, allowing for consistent comparisons over time and between utilities with different scales of operation. It provides a straightforward way to track losses in terms of volume lost per unit length of pipeline, which is particularly useful when dealing with diverse infrastructure, as seen with the various Portuguese utility companies.

On the other hand, metrics like the Infrastructure Leakage Index (ILI), though widely used, are more complex and require detailed knowledge of each system's theoretical minimum losses, making it harder to compare systems with differing age, quality, and operational conditions. ILI focuses on the efficiency of a system relative to its potential, while $m^3/km/year$ is a more direct and operationally relevant measure of actual losses over time, which is more applicable in contexts where annual water loss trends are the focus. Using $m^3/km/year$ also simplifies cross-company comparisons, given the variability in network conditions across Portugal, and allows a clearer representation of annual performance across the utilities studied. For each year, the total volume of unbilled water is expressed as a percentage of the total water supplied by the utility or provider, calculated using the formula:

$$\text{Percentage of unbilled water} = \frac{\text{volume of unbilled water}}{\text{Total volume of water supplied}} \times 100 \quad (1)$$

Statistical Analysis: Statistical analyses were conducted to explore correlations between water losses and unbilled water percentages across the studied companies. Pearson correlation coefficients were calculated to examine the strength and direction of relationships. Significant correlations were identified based on a significance level of 5%.

Data: The analyzed data are presented in Tables 1 and 2 below, providing insights into water losses (Table 1) and unbilled water percentages (Table 2) for each company from 2017 to 2021.

Table 1. Water Losses ($m^3/(km \cdot year)$).

Company	Region	2017	2018	2019	2020	2021
EPAL	Lisbon	10,402	9974	10,460	11,461	12,622
Águas de Santo André	Alentejo	803	803	253	693	2372
Águas do Algarve	Algarve	2007	135	529	985	949
Águas do Centro Litoral	Centro	3983	3321	1174	1898	1793
Águas do Douro e Paiva	North	3879	4416	4866	4343	4307
Águas do Norte	North	693	657	451	474	511
Águas do Vale do Tejo	Lisbon	912	1095	949	876	949
Águas do Vouga	Centro	292	182	130	36	292
Águas Públicas do Alentejo	Alentejo	1788	1387	1277	1168	1022
ICOVI	Centro	1095	876	805	876	1058

Source: own calculations from data collected from ERSAR.

Table 2. Unbilled water (%).

Company	2017	2018	2019	2020	2021
EPAL	5.9%	5.9%	5.9%	6.55%	7.2%
Águas de Santo André	1.0%	1.1%	0.0016%	2.4%	3.8%
Águas do Algarve	3.5%	2.8%	0.16%	0.48%	0.8%
Águas do Centro Litoral	3.9%	3.4%	0.25%	1.375%	2.5%
Águas do Douro e Paiva	2.3%	2.5%	0.27%	1.485%	2.7%
Águas do Norte	4.7%	3.7%	0.3%	1.65%	3.0%
Águas do Vale do Tejo	6.1%	7.4%	0.74%	3.07%	7.4%
Águas do Vouga	1.9%	1.7%	0.19%	1.045%	1.9%
Águas Públicas do Alentejo	11.5%	9.5%	0.83%	4.565%	8.3%
ICOVI	6.4%	69.5%	63.4%	63.4%	63.4%

Source: ERSAR.

Table 1 provides an overview of water losses (measured in $m^3/(km \cdot year)$) for several water utility companies across different regions from 2017 to 2021. EPAL in Lisbon shows a general upward trend in water losses over the years, reaching its peak in 2021. Águas de Santo André in Alentejo experienced a significant increase in 2019, indicating potential operational changes or anomalies. This significant increase in unbilled water could be justified by the inherent uncertainties associated with estimating water used for operational activities, such as flushing. As the majority of these activities are not directly measured, utilities often rely on estimates to account for the water used, leading to possible variations in reported figures. In 2019, operational changes, such as intensified flushing or system maintenance, could have contributed to the rise in unbilled water. Additionally, the lack of precise measurement tools for such activities means that approximations may have played a role in this observed anomaly, reflecting either an actual increase in operational water use or variations in reporting methodologies.

Águas do Algarve exhibited a spike in 2019 followed by a decrease in subsequent years, suggesting fluctuating conditions or management strategies. Águas do Douro e Paiva and Águas do Norte in the North both saw peaks in 2019, possibly reflecting regional challenges or infrastructure issues. Águas do Centro Litoral in Centro showed variability with a noticeable decrease in 2019. Overall, the data underscore regional disparities and varying trends in water loss management among these utilities, highlighting the need for targeted strategies to improve efficiency and reduce losses across different operational contexts.

Non-revenue water loss involves quantifying and addressing both components: Unbilled Water: This includes water used for firefighting, flushing, or other operational uses that are necessary but not metered for billing purposes. Efficient management involves accurately estimating or metering such uses to reduce unnecessary consumption. Leakage: it occurs due to physical losses from the distribution network, leading to wasted water and potential damage to infrastructure. Managing leakage requires a comprehensive approach that combines proactive maintenance, timely repairs, and modernizing aging infrastructure to reduce water losses. Proactive maintenance involves regular inspection and upkeep of the water distribution network to identify potential problem areas before significant leaks occur. Timely repairs ensure that once a leak is detected, it is addressed swiftly to prevent further water loss. Modernizing infrastructure—such as replacing old pipes and installing more efficient materials—can greatly reduce the frequency of leaks, particularly in older systems. A leak detection strategy is a critical component of managing leakage, utilizing advanced technologies like acoustic sensors, pressure monitoring, and smart meters to locate leaks early, often before they become visible on the surface. These technologies enable continuous monitoring of the network, allowing for real-time identification of leaks and anomalies, thus reducing both water loss and repair costs. By combining these elements, water utilities can effectively reduce unbilled water, improve system efficiency, and extend the lifespan of their infrastructure. Addressing non-revenue water comprehensively is crucial for water utilities to improve efficiency, reduce operational costs, and ensure sustainable water management practices.

To determine the proportion of water that is being delivered into the distribution system but not captured in the billing system, expressed as a percentage of the total water supplied, is crucial for water utilities and providers to assess the efficiency of their distribution system, identify areas of non-revenue water, and implement strategies to reduce losses and improve revenue collection.

We analyse the levels of unbilled water (UW) for each company each year. The calculation of unbilled water refers to the estimation or measurement of water that is produced or treated but not recorded as revenue due to various reasons, such as metering inaccuracies, administrative errors, or deliberate non-metered uses. Unbilled water is typically expressed as a percentage of total water produced or treated.

Examples of unbilled unmetered consumption include the following: Firefighting: Water used by fire departments for extinguishing fires, which is often unmetered due to emergency response needs. Flushing: Water used for flushing public toilets, which may not be individually metered in some systems. Street Cleaning: Water used for cleaning streets, which may be necessary for maintaining cleanliness but not directly billed or metered separately.

These examples illustrate instances where water consumption is necessary for public safety, sanitation, or operational needs but is not directly measured for billing purposes. Addressing unbilled unmetered consumption involves strategies such as estimating or metering these uses more accurately, implementing conservation measures, and improving overall efficiency in water distribution systems.

The analysis of unbilled water (UW) from 2017 to 2021 reveals variations across different companies. In general, Águas de Santo André consistently demonstrates lower UW values, while ICOVI consistently exhibits higher UW values. One likely reason is the state of ICOVI's infrastructure, which may be older or less maintained compared to other companies like Águas de Santo André. Aging pipes, more frequent leaks, and delays in maintenance could contribute to higher physical water losses. Additionally, operational inefficiencies within ICOVI, such as slower response times for repairs or less efficient water management practices, could exacerbate these losses. Another contributing factor could be metering inaccuracies or the presence of non-metered connections, particularly in rural or less developed areas served by ICOVI. If a significant portion of connections are either not metered or inaccurately metered, the volume of water supplied may be underreported, inflating UW figures. EPAL and Águas do Vale do Tejo also show relatively high UW values over the years. However, there are fluctuations in the rankings of other companies, indicating variations in their performance regarding unbilled water over the years.

Table 3 shows the significant correlations between unbilled water and water losses present in companies located in the North, Centro and Alentejo regions.

Table 3. Significant negative correlations between unbilled water and water losses.

Company	Coeficient	t-Statistic	*p*-Value
1	−0.5881 *	0.2970	0.045
2	−0.5165 *	0.3729	0.032
3	−0.7626 *	0.1338	0.020
4	−0.8864 *	0.0452	0.015
5	−0.7665 *	0.1306	0.040
6	−0.8703 *	0.0550	0.022
7	−0.8038 *	0.1012	0.035

Notes. * Significance at 5% level.

A strong and negative correlation between actual water losses in the network and the amount of unbilled water underscores the importance of adopting a comprehensive approach in managing and reducing UW, considering not only physical losses in the network but also other factors contributing to unaccounted water.

We collect financial data for the 7 companies that show a strong negative correlation between unbilled water and water losses, from ORBIS and analyse the financial performance from 2017 to 2021. The objective is to analyse, ceteris paribus, the impact of UW on profit margin and to quantify it. Table 4 shows the basic statistics.

Table 4. Summary statistics.

Variable	Obs	Mean	Std.Dev.	Min	Max
Id	35	4	2.0	1	7
Year	35	2019	1.43	2017	2021
Region	35	2.71	1.50	1	5
Profit Margin	35	13.14	14.37	0	46
Return on Equity	35	13.62	15.01	0	50
Current Ratio	35	1.74	1.26	0	5
Unbilled Water	35	2.61	2.61	0	11.5
Water Losses	35	175,157	467,333.70	36	1,900,000
Turnover	35	56,700.46	52,010.16	7290	189,733
Gross Income	35	4290.82	3924.06	−717	14,062
Net Income	35	3083.02	2794.52	266	10,112
Toal Assets	35	492,158.30	581,132.30	9720	1,884,519
Solvency Ratio	35	16.97	15.36	1	72
Employees	35	180.91	165.62	14	596

The distribution of variables within the dataset provides several insights:

Profit Margins (profmg) and Return on Equity (roe). These metrics demonstrate considerable variability, with standard deviations exceeding their respective means. This variability suggests significant disparities in profitability and returns among the observed companies, ranging from minimal to substantial.

Current Liquidity Ratio (curr). Variability in liquidity ratios indicates differences in short-term financial stability among companies, impacting their ability to meet immediate financial obligations.

Unbilled Water (unbil). The variability in the percentage of unbilled water indicates differences in billing accuracy and efficiency across water utility companies. High levels of unbilled water may signify revenue loss and operational inefficiencies.

Losses (loss). The wide range of loss values underscores the financial impact of water leakage and inefficiencies within distribution systems. The high standard deviation relative to the mean suggests considerable variability in loss magnitudes among the observed companies, or the water loss numbers in the sample are inadequate, e.g., because of uncertainties.

Turnover. Variations in turnover reflect differences in revenue generation, indicating varying levels of sales activity and financial performance.

Gross Income (rb). Variability in gross income highlights differences among companies, influencing their financial resilience and ability to reinvest in operations.

Net Income (netinc). Differences in net income signify variations in profitability, affecting overall financial performance and sustainability.

Total Assets (tass). The significant spread in total asset values highlights varying scales of operation and asset bases among water utility companies, indicating differences in infrastructure and resources.

Solvency Ratio (solv). Variability in solvency ratios indicates differences in financial stability and risk among companies, impacting their ability to meet long-term obligations.

Employment (empl). The standard deviation exceeding the mean implies substantial variability in employment levels across the observed companies, reflecting differences in workforce size and organizational structure.

A stepwise regression is performed to choose the variables to include in the regression model to estimate the impact of unbilled water on profit margin, where:

$$\text{Profit margin} = \frac{\text{Profit before tax}}{\text{Operating Revenue}} \times 100 \tag{2}$$

2.3. Model Summary

The regression analyses employed two distinct variable selection methods: stepwise regression with a *p*-value threshold of 0.2 for both inclusion and exclusion (pr(.2)) and stepwise regression with a *p*-value threshold of 0.2 for entry and stay (pe(.2)). These approaches yielded findings that shed light on their economic implications. The pr(.2) method emphasized identifying variables that significantly contribute to explaining variations in the dependent variable throughout the regression process. In contrast, pe(.2) prioritized retaining variables that consistently demonstrated statistical significance, underscoring their persistent impact on economic outcomes. Both methods provided valuable insights into the factors influencing economic phenomena within the analyzed framework, offering a nuanced understanding of variable selection in regression analysis and its implications for economic interpretation.

In the stepwise regression analyses, the following key findings emerge regarding their economic implications:

- **Overall Model Significance:** Both models exhibit high overall F-statistics, indicating strong statistical significance in explaining profitability margins.
- **R-squared Values:** The models show robust explanatory power, with approximately 97.81% and 97.30% of the variance in profitability margins explained by the variables included in each respective model.
- **Current Ratio (curr):** An increase in the current ratio is found to be associated with higher profitability margins, holding other variables constant. This suggests that liquidity and the ability to cover short-term obligations positively influence profitability.
- **Net Income (netinc):** Higher levels of net income correspond to slightly higher profitability margins, indicating that companies with stronger financial performance tend to achieve better profitability.

- **Turnover (turn):** There is a slight negative relationship observed between turnover and profitability margins. As turnover increases, profitability margins decrease slightly, reflecting potential challenges in managing operational costs as business activity scales up.
- **Unbilled Water (unbil):** Increased levels of unbilled water are consistently linked to lower profitability margins. This underscores the financial impact of water losses and inefficiencies in revenue collection.
- **Solvency (solv):** Higher solvency ratios generally correlate with increased profitability margins, although the significance of this relationship varies across the different regression analyses.
- **Return on Equity (ROE):** A higher return on equity is associated with higher profitability margins. This metric highlights the efficiency of equity utilization and management's ability to generate returns for shareholders.
- **Loss:** The impact of water loss is not found to be statistically significant in either regression model. This suggests that while water loss is an operational concern, its direct influence on profitability margins may be mitigated or overshadowed by other financial and operational factors.

These insights provide a nuanced understanding of how financial metrics and operational efficiencies interact to influence financial performance in publicly owned water utilities, even though they are not profit-oriented. Financial ratios like the current ratio and solvency remain crucial for assessing their financial stability and operational viability. The inclusion of solvency and the insignificance of water loss further underscore the complexity of factors affecting financial performance. Additionally, the size of water utilities and the amount of investment significantly impact their competitiveness, with larger companies benefiting from economies of scale and better access to capital [18,29]. This combination allows for enhanced operational efficiency and competitiveness, highlighting the need for further investigation into strategies that can improve financial health within the sector

We chose to perform regression using ordinary least squares (OLS) with robust standard errors and quantile regression to examine the impact of unbilled water on profit margins. OLS with robust standard errors is a variation of OLS that accounts for potential heteroscedasticity in the data, providing more reliable estimates when the assumption of constant error variance is violated. This method is particularly useful for small sample sizes, like ours with 35 observations.

OLS Regression with Robust Standard Errors. This approach provides estimates of the average impact of unbilled water on profit margins across the sample while also addressing potential issues of heteroscedasticity. It assumes a constant relationship between variables across all quantiles.

Quantile Regression. By using this method, we were able to analyze how the impact of unbilled water on profit margins varies across different quantiles. This gives us a more comprehensive understanding of the relationship, especially if there are variations in the impact at different levels of profit margins.

Given that our sample size is 35 observations, it is essential to consider the limitations of our analysis. With a relatively small sample size, we need to be cautious about drawing generalizable conclusions, as it may affect the reliability and precision of our estimates.

The model is:

$$\text{PROFMGIt} = \beta 0 + \beta 1\ \text{ROEit} + \beta 2\ \text{CURRit} + \beta 3\ \text{UNBILit} + \beta 4\ \text{lOSSit} + \beta 5\ \text{sOLVit} + \mu\text{it} \quad (3)$$

Expected sign of variables:

1. ROE (Return on Equity): Expected Sign Positive

A positive ROE indicates efficient utilization of equity capital to generate profits. Higher ROE suggests better profitability and financial health, which can lead to increased profit margins. Therefore, an increase in ROE is expected to have a positive impact on profit margin.

2. CURR (Current Liquidity Ratio): Expected Sign Positive

A higher current liquidity ratio indicates better short-term financial stability and liquidity. Companies with higher liquidity ratios are better positioned to meet immediate financial obligations, which can lead to improved operational efficiency and financial performance. Therefore, an increase in the current liquidity ratio is expected to have a positive impact on profit margin.

3. UNBIL (Unbilled Water): Expected Sign Negative

Unbilled water represents inefficiencies in revenue collection and potential revenue loss for water utility companies. Higher levels of unbilled water typically indicate challenges in billing accuracy and distribution system integrity, which can reduce revenue streams and negatively impact profit margins. This is because unbilled water represents a portion of water produced and supplied that is not generating income, whether due to leaks, unauthorized use, or metering issues. However, an increase in unbilled water may not always signal inefficiencies; it could also reflect more proactive flushing of the network, where water is deliberately used to clean and maintain the distribution system, contributing to unbilled water but enhancing long-term system integrity. Additionally, an increase in fire incidents could lead to higher unbilled water as large volumes are used in firefighting, which are not billed to customers. Similarly, issues with metering accuracy, such as malfunctioning meters or non-metered connections, can contribute to higher unbilled water if the actual water usage is underestimated. Each of these factors could influence the reported levels of unbilled water, complicating the direct relationship between unbilled water and profit margins, depending on the operational and external conditions at play.

4. LOSS (Water Losses): Expected Sign Negative

Losses in the water distribution system represent inefficiencies and operational challenges for water utility companies. Higher levels of losses lead to increased costs associated with water production, distribution, and infrastructure maintenance, which can result in decreased revenue streams and reduced profit margins. Therefore, an increase in losses is expected to have a negative impact on profit margin.

5. SOLV (Solvency Ratio): Expected Sign Positive

Solvency ratio measures the financial stability and risk management capabilities of water utility companies. Companies with higher solvency ratios have stronger balance sheets and lower financial risk exposure, which can lead to increased investor confidence and operational stability. Therefore, an increase in the solvency ratio is expected to have a positive impact on profit margin.

3. Results

Table 5 summarizes the results from both estimators.

Table 5. Summary results of models (1) and (2).

Variable	(1) OLS Estimator	(2) Quantile Estimator
ROE	0.654 *** (11.18)	0.675 *** (9.95)
CURR	3.256 *** (9.31)	3.430 *** (6.04)
UNBIL	−0.565 ** (−4.09)	−0.676 * (−2.73)
LOSS	−0.00000155 * (−2.38)	−0.00000113 (−0.83)
SOLV	0.0941 (1.99)	0.0608 (0.85)
_cons	−1.295 (−1.35)	−1.032 (−0.75)
Adj. R-squared	0.968	-
N	35	35

Notes. _cons is constant; t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The coefficients from the OLS estimator generally exhibit higher magnitudes compared to those from the quantile estimator, indicating greater sensitivity to changes in the independent variables. In terms of efficiency, the OLS estimator shows higher t-values for most variables compared to the quantile estimator, suggesting superior efficiency in estimating the coefficients.

Comparing the impact of variables across both estimators:

- ROE (Return on Equity): Both estimators demonstrate a positive impact on profit margin (profmg). An increase in ROE is associated with higher profit margins.
- CURR (Current Ratio): Similarly, both estimators indicate a positive relationship with profit margin, suggesting that higher current ratios correlate with higher profit margins.
- UNBIL (Unbilled Revenue): Both estimators reveal a negative impact, though with slight differences in magnitude. This implies that higher levels of unbilled revenue are linked to lower profit margins.
- LOSS (Net Loss): Both estimators suggest a negative impact, but the quantile estimator does not find it statistically significant. This indicates that higher net losses tend to decrease profit margins, with varying effects across different quantiles.
- SOLV (Solvency): The OLS estimator suggests a positive impact, whereas the quantile estimator shows a smaller, statistically insignificant impact. This suggests that higher solvency may lead to higher profit margins, though this relationship may not hold uniformly across different quantiles.

Previous research has emphasized the economic implications of water management practices and financial performance in utility sectors [18–20,28]. Specifically, efficient water management strategies, including minimizing unbilled revenue and reducing operational losses, have been shown to enhance profitability and sustainability [6,10,30]. These studies underscore the importance of effective asset management and conservation initiatives in optimizing financial outcomes within the water utility sector [7,10,28].

The regression results highlight that unbilled water (unbil) significantly impacts profit margins (profmg) across both OLS and quantile estimators. Specifically, the OLS estimator coefficient of −0.565 (t = −4.09) indicates that, holding other variables constant, a one-unit increase in unbilled water is associated with a decrease in profit margin by approximately 0.565 units. Similarly, the quantile estimator coefficient of −0.676 (t = −2.73) reinforces this negative association, albeit with a slightly higher impact.

These findings underscore the criticality of managing unbilled water effectively to enhance financial performance. Strategies aimed at reducing unbilled water through infrastructure upgrades and improved operational efficiencies are essential for mitigating revenue losses and sustaining profitability [5,10,31,32].

The analysis provides insights into the economic relationships between water management practices and financial performance in the utility sector. Effective management of variables such as ROE, CURR, and UNBIL can significantly influence profitability and sustainability, highlighting the importance of strategic decision-making and resource allocation in water utility management [14–16].

Unbilled water represents water that is lost or unaccounted for in the distribution system, leading to revenue losses for water utility companies. As the regression results suggest, a higher level of unbilled water is associated with a decrease in profit margin.

The analysis of the negative impact of unbilled water on profit margins is relevant for publicly owned water utilities, albeit with some distinctions in focus. While these utilities may not operate primarily to generate profit, they still face significant financial pressures related to operational efficiency, sustainability, and service delivery. A coefficient of −0.717 indicates that unbilled water represents a substantial financial burden, leading to revenue losses that can hinder the utility's ability to fund necessary infrastructure upgrades and maintain service quality. Publicly owned water utilities must also consider other financial metrics, such as the current ratio and solvency, which reflect their ability to meet short-term obligations and maintain overall financial health. High levels of unbilled water can strain cash flow, impacting these ratios and potentially limiting access to funding or investment opportunities. Moreover, effective management of unbilled water is crucial for maintaining public trust and fulfilling regulatory requirements. Public utilities often operate under a mandate to provide reliable service to their communities, and high unbilled water levels can undermine their ability to meet this obligation.

In conclusion, while the direct link between unbilled water and profit margins may be less pronounced for publicly owned utilities, the implications of unbilled water on financial health, operational efficiency, and service quality remain critical. The need for effective management strategies to mitigate unbilled water is equally important for ensuring the long-term sustainability and performance of these utilities.

Managerial Implications. Water utility companies should implement strategies to minimize unbilled water, such as improving infrastructure, detecting, and repairing leaks, and combating unauthorized water use. By reducing losses, companies can enhance revenue streams and improve profitability. Investing in advanced metering and monitoring technologies can help companies identify and address unbilled water more effectively. These technologies enable real-time monitoring of water flow, detection of leaks, and precise measurement of consumption, thereby supporting loss reduction efforts. Enhancing operational efficiency in water distribution and management processes can contribute to reducing unbilled water. This may involve optimizing water network design, implementing efficient billing, and metering systems, and enhancing workforce training and supervision. Given the significant impact of unbilled water on profit margin, companies should incorporate measures to mitigate revenue losses into their financial management strategies. This may include budgeting for infrastructure upgrades, allocating resources for leak detection and repair programs, and establishing performance metrics to track progress in reducing unbilled water.

The regression results underscore the importance of addressing unbilled water as a critical factor in improving the financial performance and sustainability of water utility companies. Implementing effective loss reduction strategies and investing in technology and operational improvements are key steps towards mitigating the negative impact of unbilled water on profit margin and ensuring long-term profitability and viability.

4. Discussion

The management of water resources is significantly influenced by the operational structures of water utilities [33], which can be broadly categorized into public and private entities. Public water utilities are typically owned and operated by government entities, with a primary focus on providing affordable water services to all residents rather than maximizing profits. This can lead to a commitment to equity in service delivery but may also result in underinvestment in infrastructure due to budget constraints and political factors. Conversely, private water utilities operate as profit-driven entities, which can foster greater efficiency and innovation due to competitive pressures. They may have more access to capital and technological advancements [29], allowing for quicker adoption of modern practices, such as digitalization and leakage management technologies. The implications of these differences are significant for the findings of this paper, particularly regarding NRW reduction and the adoption of sustainable practices. Public utilities may struggle with slower decision-making processes and bureaucratic constraints, hindering their ability to swiftly implement innovative solutions for NRW management. On the other hand, private utilities, driven by the need to maintain profitability and efficiency, might more readily adopt practices that reduce water losses, such as advanced metering infrastructure and proactive maintenance strategies [34]. Thus, while private utilities may have more immediate access to capital and are often more flexible in adopting innovative practices, public utilities—when supported by effective governance and investment—can achieve comparable, if not superior, outcomes in terms of service equity, infrastructure investment, and non-revenue water (NRW) reduction.

In addition, legislative contexts, such as the EU Directive 2020/2184, also play a critical role in shaping how public and private utilities manage their resources. This directive mandates the publication of leakage rates for all but the smallest utilities, creating an environment of accountability and transparency [35]. For public utilities, this requirement can enhance pressure from stakeholders, including citizens and local governments, to improve efficiency and reduce NRW. However, these utilities might face challenges in meeting the standards set forth by the directive if they lack the necessary resources or political will [34]. For private utilities, the EU Directive may serve as both a challenge and an opportunity. While they must ensure compliance with stringent regulations, the requirement to publish leakage rates can enhance their reputation and foster trust among consumers [36]. Moreover, the transparency imposed by the directive can stimulate competitive practices that lead to better performance and innovation in NRW management [37].

Furthermore, flow meters, including large gauge models, are crucial for accurately measuring water flow in utility systems. However, significant inaccuracies can occur due to various factors, leading to errors in water balance calculations, particularly for non-revenue water (NRW) and unbilled water (UW) assessments. These inaccuracies can arise from several sources, including installation errors, maintenance issues, and the inherent limitations of the technology used [38].

One common issue is the calibration of flow meters, which can drift over time. If not regularly calibrated, flow meters may provide inaccurate readings, resulting in either overestimations or underestimations of actual water usage. Furthermore, factors such as pressure fluctuations, temperature variations, and the presence of air bubbles or sediments can also affect the accuracy of flow measurements [39]. Research indicates that inaccuracies in flow meter readings can vary widely depending on the type and condition of the meter. For instance, older mechanical meters may have an accuracy range of ±5% to ±10%, while modern electromagnetic or ultrasonic meters can achieve accuracies of ±1% to ±2% under optimal conditions [40]. However, if a meter is poorly maintained or installed, these accuracy levels can worsen significantly.

To estimate the impact of these inaccuracies on reported NRW and UW figures, one might consider a hypothetical scenario where a flow meter inaccurately reports a water flow rate that is 10% lower than the actual flow. If a utility reports an NRW of 20% based on these readings, the true NRW could be significantly higher. For example, if the actual water supplied is 1,000,000 L but the flow meter reports only 900,000 L due to inaccuracies, the NRW calculation could reflect a misleadingly low figure, ultimately affecting resource management strategies and policy decisions [41].

Thus, to improve the reliability of NRW and UW calculations, utilities should invest in regular calibration and maintenance of flow meters, utilize advanced measurement technologies, and implement quality assurance protocols [42]. By acknowledging and addressing the potential inaccuracies in flow measurement, utilities can enhance the accuracy of their water balance calculations, leading to more effective management of water resources [43]. Based on this analysis, Águas de Santo André consistently exhibits lower water losses and unbilled water (UW) compared to other companies, suggesting superior distribution system efficiency and management practices. In contrast, EPAL and Águas do Douro e Paiva consistently show higher levels of water losses and UW, indicating potential inefficiencies in their distribution systems. Regionally, companies in the North region generally experience lower water losses and UW than those in the Centro and Alentejo regions, reflecting varying regional water management practices and infrastructure efficiencies [44,45].

The economic impact of water losses on companies' profitability margins involves several theoretical considerations:

Cost Considerations: Water losses incur direct costs including the water's value, infrastructure repairs, and operational expenses related to detection and mitigation.

Revenue Implications: High water losses can diminish revenue by reducing billed water volumes, directly impacting profitability margins.

Operational Efficiency: Companies with high losses may operate less efficiently, incurring additional costs like increased energy usage and labour expenses, further squeezing profit margins.

Investment and Sustainability: Investments in leak detection technology and infrastructure upgrades, while initially costly, can lead to long-term cost savings and improved efficiency, ultimately boosting profitability.

Regulatory and Stakeholder Pressures: Compliance with water conservation regulations and meeting stakeholder expectations for sustainability can influence management strategies, affecting profitability.

Market Competition and Pricing: High water losses can escalate service delivery costs, challenging companies to balance competitive pricing with operational efficiency to maintain profitability.

However, this analysis has limitations. It may not fully encompass all contextual factors like regulatory frameworks, socio-economic conditions, and environmental influences that impact water management practices and financial performance. This study's timeframe limitations may also restrict insights into long-term trends. Addressing these limitations through comprehensive, longitudinal studies would enhance understanding of the complex interplay between water management practices, financial performance, and regional dynamics in the water utility sector.

5. Conclusions

This study investigates the impact of unbilled water on profit margins in the Portuguese water utility sector from 2017 to 2021 using ordinary least squares (OLS) regression with robust standard errors and quantile regression. The analysis reveals a consistent and significant negative relationship between higher levels of unbilled water and lower profit margins across both OLS and quantile estimators. Specifically, the OLS coefficient of -0.565 ($t = -4.09$) and the quantile estimator coefficient of -0.676 ($t = -2.73$) underscore the financial implications of inefficiencies in revenue collection and distribution system integrity. Effective management strategies, including the implementation of advanced metering technologies, infrastructure improvements, and operational optimization, emerge as critical steps to mitigate revenue losses and enhance operational efficiency in the water utility industry. These measures not only support financial sustainability but also contribute to long-term profitability.

Regional analyses highlight significant disparities in water losses and unbilled water among Portuguese water utility companies, with Águas de Santo André demonstrating consistently lower losses, indicative of efficient management practices. In contrast, EPAL and Águas do Douro e Paiva exhibit higher losses, reflecting operational challenges. Regional comparisons further underscore better performance in the North region relative to the Centro and Alentejo regions. Addressing these disparities requires targeted investments in infrastructure, advanced metering technologies, and robust regulatory frameworks to incentivize efficiency improvements and mitigate losses.

This study contributes novel insights into water management by quantitatively analyzing variations in water losses and unbilled water across Portuguese regions and companies. The findings provide replicable metrics for assessing and benchmarking water utility performance, informing policy decisions aimed at reducing losses and enhancing operational efficiency.

Policymakers are urged to prioritize infrastructure investments in regions with higher losses, incentivize efficiency through regulatory frameworks, and empower water utility personnel with training and resources. Stakeholder engagement and public awareness campaigns are crucial for promoting water conservation and accountability, essential for sustainable water management practices.

Future research should emphasize longitudinal studies to track water loss trends, comparative analyses to identify best practices across regions, and assessments of emerging technologies for effective water management. Understanding the scalability and effectiveness of these technologies will guide investment decisions and policy formulation, ensuring robust and efficient water supply systems.

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