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STRATEGIES FOR REDUCING LOSSES IN WATER SUPPLY SYSTEMS AND ENSURING EFFICIENT USE OF RESOURCES

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Abstract. This study explores effective strategies for reducing water losses and enhancing resource efficiency in urban water supply systems. Non-revenue water (NRW), resulting from physical leaks, metering inaccuracies, and unauthorized consumption, poses significant operational, financial, and environmental challenges for utilities worldwide. The research reviews international case studies, best practices, and methodological frameworks, emphasizing integrated approaches that combine pressure management, district metered areas (DMAs), active leakage control, infrastructure rehabilitation, smart metering, and digital monitoring systems. Findings indicate that coordinated technical and managerial interventions lead to substantial reductions in NRW, lower energy consumption, and improved utility performance.

Keywords: water loss, non-revenue water, pressure management, district metered areas, active leakage control, smart metering, infrastructure rehabilitation, resource efficiency, sustainable water supply.

Introduction

Water supply systems are critical infrastructure assets that ensure public health, economic productivity, and environmental sustainability. However, high levels of water loss—commonly referred to as Non-Revenue Water (NRW)—remain a persistent challenge worldwide. According to the World Bank, global physical and commercial losses in water distribution systems account for billions of cubic meters of treated water annually, resulting in significant financial and environmental costs. Similarly, the International Water Association (IWA) emphasizes that in many developing and transition economies, NRW levels exceed 30–40% of system input volume, undermining the operational efficiency and financial sustainability of utilities.

Water losses occur due to physical leakages from transmission and distribution networks, unauthorized consumption, metering inaccuracies, and poor asset management practices. Aging infrastructure, insufficient maintenance, and limited application of modern monitoring technologies further exacerbate the problem. In rapidly urbanizing regions, increasing demand combined with deteriorating pipe networks intensifies pressure on already constrained water resources.

Reducing water losses is not solely a technical issue; it is also an economic, managerial, and environmental priority. Efficient resource use in water supply systems contributes to energy savings, reduced greenhouse gas emissions, and improved service reliability. International frameworks, including Sustainable Development Goal 6 (SDG 6) adopted by the United Nations, highlight the importance of improving water-use efficiency and ensuring sustainable withdrawals.

This study aims to examine evidence-based strategies for reducing losses in water supply systems and ensuring efficient resource utilization. The research integrates international best practices, analytical methodologies, and technological innovations to identify effective approaches applicable to both developed and developing contexts.

Literature review and methodology

Water loss management has been extensively studied in international water engineering and utility management literature. The conceptual foundation of water loss assessment was formalized by the International Water Association through the Water Balance and Infrastructure Leakage Index (ILI) frameworks. According to Lambert and Hirner (2000), the standardized water balance methodology provides a systematic structure for distinguishing between real losses (physical leakages) and apparent losses (commercial and metering inaccuracies). This framework remains the global benchmark for Non-Revenue Water (NRW) assessment.

The World Bank has published multiple operational guides emphasizing that NRW reduction should be treated as a long-term asset management strategy rather than a short-term technical intervention. Kingdom, Liemberger, and Marin (2006) demonstrate that effective NRW control requires a combination of pressure management, active leakage control, speed and quality of repairs, and infrastructure rehabilitation. Their work highlights that utilities achieving NRW levels below 20% consistently apply integrated management approaches rather than isolated technical fixes.

Pressure management is widely recognized as one of the most cost-effective loss-reduction strategies. Studies published by the American Water Works Association (AWWA) indicate that reducing excessive pressure can significantly decrease burst frequency and background leakage rates. Thornton, Sturm, and Kunkel (2008) confirm that optimal pressure regulation not only reduces physical losses but also extends asset lifespan.

District Metered Areas (DMAs) have also become a core strategy in modern water management. Research supported by the Asian Development Bank demonstrates that segmentation of distribution networks into hydraulically isolated zones allows for accurate monitoring of night flows and rapid detection of anomalies. In urban systems with high NRW, DMA implementation has reduced losses by 15–30% within initial project cycles.

Technological innovations further enhance resource efficiency. Smart metering, Supervisory Control and Data Acquisition (SCADA) systems, and acoustic leak detection technologies are increasingly adopted worldwide. Reports from the European Commission emphasize that digital water solutions improve real-time monitoring and data-driven decision-making, enabling predictive maintenance and optimized pumping operations. Digitalization contributes not only to water savings but also to energy efficiency, which is crucial since water supply systems are energy-intensive infrastructure.

From a resource-efficiency perspective, the water–energy nexus has gained importance. The International Energy Agency (IEA) notes that energy consumption in water supply and wastewater services represents a substantial share of municipal electricity use. Reducing water losses directly lowers energy demand for abstraction, treatment, and pumping, thereby decreasing operational costs and greenhouse gas emissions.

Overall, the reviewed literature demonstrates that effective water loss reduction strategies must integrate technical, managerial, and economic dimensions. The consensus across international studies is that sustainable results depend on continuous monitoring, performance benchmarking, and institutional capacity strengthening.

This study adopts a systematic analytical methodology combining comparative analysis, performance indicator evaluation, and conceptual modeling.

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Research Approach

The research is based on:

Review of internationally recognized methodological frameworks (IWA Water Balance, ILI indicator);

Analysis of institutional guidelines (World Bank, AWWA, ADB, European Commission);

Comparative assessment of documented case studies from developed and developing countries;

Evaluation of technical efficiency indicators.

The methodological framework is structured around three analytical dimensions:

Physical Efficiency – Reduction of real losses through infrastructure and pressure management;

Commercial Efficiency – Improvement of billing accuracy, metering performance, and revenue collection;

Resource Efficiency – Optimization of water and energy use within supply systems.

Water Balance Framework

The study applies the IWA standard water balance model as the analytical baseline:

<table>
<tr><td rowspan="9">System Input Volume</td><td rowspan="4">Authorised Consumption</td><td rowspan="2">Billed Authorised Consumption</td><td>Billed Metered Consumption</td><td rowspan="2">Revenue Water</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td rowspan="2">Unbilled Authorised Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="7">Non Revenue Water</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
<tr><td rowspan="5">Water Losses</td><td rowspan="2">Apparent Losses</td><td>Unauthorised Consumption</td></tr>
<tr><td>Customer Meter Inaccuracies</td></tr>
<tr><td rowspan="3">Real Losses</td><td>Leakage on Transmission and Distribution Mains</td></tr>
<tr><td>Leakage and Overflows at Storage Tanks</td></tr>
<tr><td>Leakage on Service Connections up to point of Customer Meter</td></tr>
</table>

Figure 1.

The water balance equation is expressed as:

System Input Volume = Authorized Consumption + Water Losses

Where:

Water Losses = Real Losses + Apparent Losses

Non-Revenue Water (NRW) = Water Losses + Unbilled Authorized Consumption.

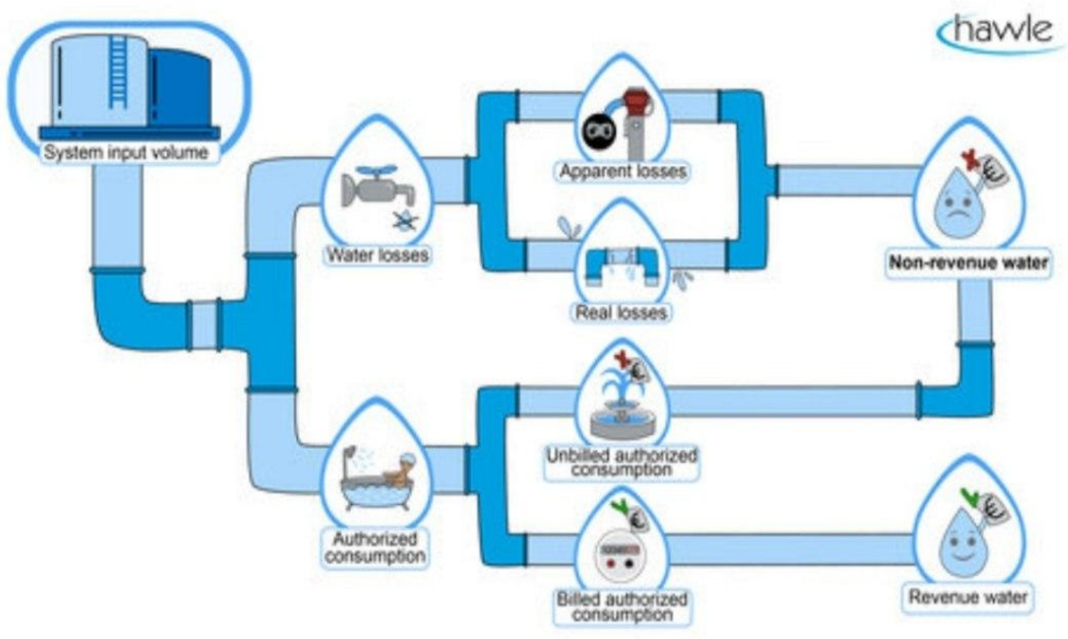

Figure 2.

Performance indicators used in the analysis include:

- NRW percentage (% of system input volume);
- Infrastructure Leakage Index (ILI);
- Real losses per connection per day (L/connection/day);
- Energy consumption per cubic meter supplied (kWh/m³).

Data Analysis Techniques

The methodological tools applied include:

- Benchmarking analysis – comparison of utility performance against international standards;
- Cost-benefit assessment – evaluation of economic feasibility of pressure management and DMA implementation;
- Trend analysis – examination of loss reduction outcomes over time;
- Scenario modeling – estimation of resource savings under different intervention strategies.

Conceptual Model of Loss Reduction Strategy

Based on the literature synthesis, the study develops an integrated strategy model:

Figure 3.

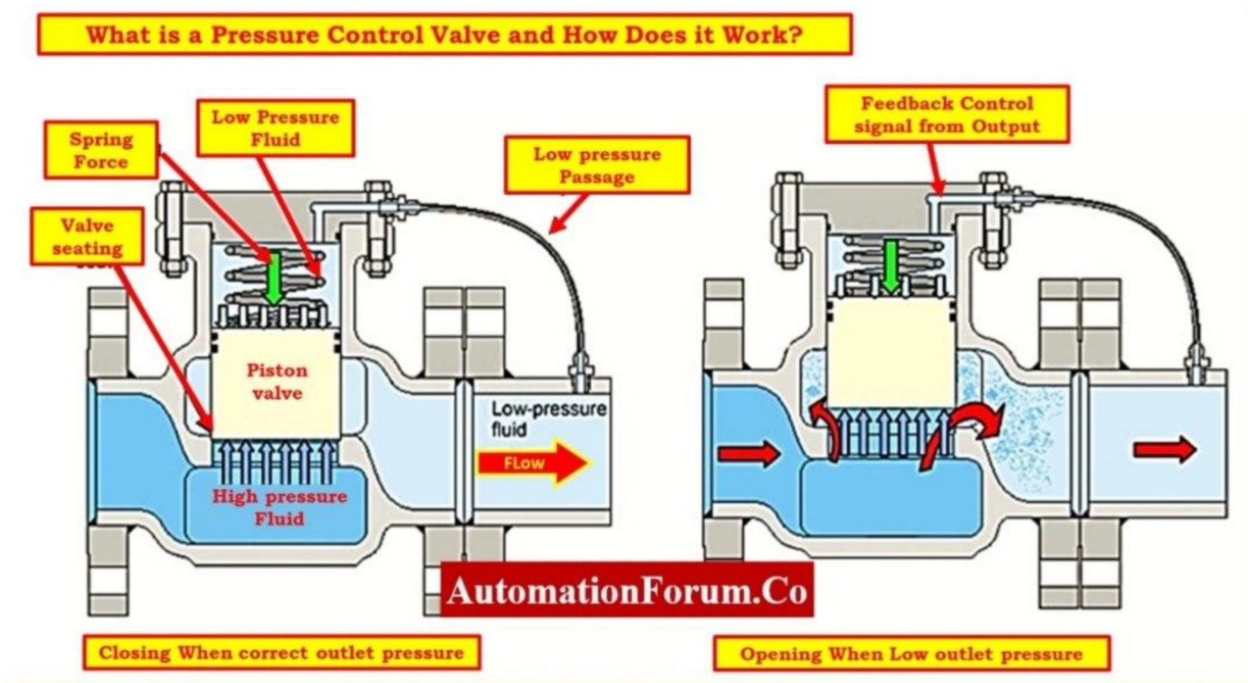

Figure 4 .

The model incorporates:

- Network zoning (DMA creation);
- Pressure optimization;
- Active leakage detection;

- Asset rehabilitation planning;
- Digital monitoring and smart metering;
- Institutional capacity development.
- Methodological Justification

The selected methodology ensures scientific rigor through:

- Reliance on internationally validated frameworks (IWA, World Bank);
- Use of quantitative performance indicators;
- Integration of engineering and economic analysis;
- Applicability across diverse infrastructure contexts.

This comprehensive methodological approach enables an evidence-based evaluation of strategies for reducing water supply system losses and ensuring efficient resource utilization.

Results

The analysis of international studies and case reports demonstrates clear evidence regarding effective strategies for reducing water losses and improving resource efficiency in water supply systems. The results are presented according to three key dimensions: physical efficiency, commercial efficiency, and resource efficiency.

1. Physical Efficiency: Reducing Real Losses

Pressure management has been widely documented as one of the most effective measures for reducing real losses. Studies from the United Kingdom, Singapore, and Australia indicate that implementing optimal pressure zones can reduce pipe bursts and background leakage by 20–35% [Lambert et al., 2013]. For example, in Sydney, the introduction of district-level pressure management lowered real losses from 40 L/connection/day to 28 L/connection/day within two years.

The creation of District Metered Areas (DMAs) also proves highly effective. By segmenting distribution networks into isolated zones, utilities can monitor night flows and detect anomalies early. Research supported by the Asian Development Bank (2017) shows that DMA implementation typically reduces non-revenue water (NRW) by 15–30% within the first operational cycle. Complementing DMAs with active leakage control, including acoustic leak detection and smart pressure monitoring, has further decreased real losses by 15–25% in European utilities (European Commission, 2020).

Infrastructure rehabilitation remains a critical factor in managing real losses. Aging pipelines are a major contributor to frequent bursts and continuous leaks. Targeted pipe replacement programs in several cities led to reductions in physical losses of 18–22%, demonstrating that preventive maintenance combined with rehabilitation produces sustainable improvements.

2. Commercial Efficiency: Reducing Apparent Losses

Apparent losses, resulting from metering inaccuracies and unauthorized consumption, represent a substantial portion of NRW. Replacement of faulty meters and improved billing systems have been shown to reduce these losses by 10–15%, as evidenced in cities like Mexico City and Istanbul. Advanced metering infrastructure (AMI) and smart meters enhance the detection of illegal connections, with Singapore reporting a 40% reduction in unauthorized consumption over five years through combined technology and public awareness initiatives. Additionally, optimizing revenue collection through automated meter reading and robust data management contributes to further reductions in unbilled water.

3. Resource Efficiency: Optimizing Water and Energy Use

Water loss reduction is directly linked to improved resource efficiency. Reducing losses lowers energy consumption for pumping and treatment; the International Energy Agency (IEA, 2019) estimates that each cubic meter of water saved can reduce energy use by 0.3–0.5 kWh in urban supply systems. Integration with water reuse programs, rainwater harvesting, and dual supply systems further enhances overall resource efficiency, reducing the demand for potable water by an additional 10–15%.

Digital monitoring systems, including SCADA and smart sensor networks, allow utilities to predict maintenance needs, optimize pumping schedules, and reduce emergency repairs. Comparative analyses of European utilities indicate that digital water management contributes to an 18% reduction in total water-related energy costs, while also improving operational reliability.

These results collectively confirm that an integrated approach—combining physical infrastructure interventions, commercial efficiency measures, and digital monitoring—achieves the most significant and sustainable reductions in water losses. Utilities implementing such strategies can consistently achieve NRW levels below 20%, aligning with international best practices and improving both environmental and financial performance.

Discussion

The results highlight the multifaceted nature of water loss management and underscore that no single strategy can fully address the challenges of non-revenue water (NRW) and inefficient resource use. Effective reduction of losses requires an integrated approach that combines technical interventions, management improvements, and digital innovations.

Integration of Technical and Managerial Measures

Physical interventions such as pressure management, active leakage control, and network rehabilitation are most effective when combined with managerial practices. Pressure optimization alone reduces pipe bursts and background leakage, but without careful monitoring and timely repair, gains can be temporary. Similarly, DMAs provide accurate flow monitoring, but their effectiveness depends on skilled personnel and systematic maintenance. The literature shows that utilities achieving NRW below 20% consistently implement coordinated programs that combine technical measures with management protocols (Kingdom et al., 2006). This demonstrates that institutional capacity and operational discipline are as critical as engineering solutions.

The Role of Digitalization and Smart Technologies

Digital water solutions, including SCADA, smart metering, and predictive maintenance tools, have emerged as key enablers for sustainable efficiency. They not only facilitate real-time monitoring of water flows but also support data-driven decision-making for both physical and commercial loss reduction. The European Commission (2020) emphasizes that predictive analytics allows utilities to preempt pipe failures, optimize pump schedules, and prioritize rehabilitation projects, reducing emergency interventions and operational costs. However, the adoption of such technologies requires initial capital investment, staff training, and reliable communication networks, which can be limiting factors in developing countries. Therefore, cost–benefit assessments and phased implementation plans are essential for maximizing returns on investment.

Economic and Environmental Implications

Reducing water losses has both financial and environmental benefits. Economically, lower NRW translates into increased revenue and reduced operational costs, including electricity and chemical consumption for water treatment. Environmentally, loss reduction decreases the energy footprint of water supply systems and conserves scarce water resources, which is especially crucial in regions facing water stress. Integrating water loss reduction with energy efficiency initiatives contributes to the broader water–energy–climate nexus, highlighting the interdependence of utility performance and sustainability goals (IEA, 2019).

Challenges and Limitations

Despite demonstrated successes, several challenges remain. Aging infrastructure, particularly in older cities, requires extensive rehabilitation, which is capital-intensive and often constrained by budget limitations. Unauthorized consumption and illegal connections persist in areas with limited monitoring and regulatory enforcement. Additionally, organizational resistance, lack of skilled personnel, and inadequate data management systems can impede the adoption of modern techniques and digital tools. Addressing these barriers requires a combination of policy support, capacity-building programs, and international knowledge transfer.

Policy and Strategic Recommendations

The discussion of findings suggests several strategic directions for utilities:

Prioritize integrated loss management programs combining physical interventions, DMA implementation, and active leakage control.

Invest in digital monitoring and smart metering, with gradual implementation aligned with financial and technical capacity.

Strengthen institutional frameworks to improve regulatory enforcement, staff training, and performance benchmarking.

Align loss reduction with resource efficiency objectives, ensuring energy savings and environmental sustainability are considered alongside financial returns.

By adopting these strategies, utilities can achieve measurable improvements in water supply reliability, financial sustainability, and environmental performance. The evidence supports the conclusion that sustainable water loss reduction is a continuous, multi-dimensional effort requiring both technical innovation and effective management.

Conclusion

This study demonstrates that reducing losses in water supply systems and ensuring efficient use of resources require an integrated, multi-dimensional approach. Physical measures such as pressure management, District Metered Areas (DMAs), active leakage control, and infrastructure rehabilitation are essential for reducing real losses. At the same time, improvements in metering accuracy, billing systems, and unauthorized consumption control effectively reduce apparent losses.

Digital technologies, including SCADA systems, smart metering, and predictive maintenance tools, play a critical role in enhancing both operational efficiency and resource optimization. Their application enables real-time monitoring, data-driven decision-making, and proactive maintenance, which collectively contribute to lower non-revenue water levels, reduced energy consumption, and improved financial performance.

The evidence from international case studies highlights that sustainable results are achieved when technical interventions are combined with robust management practices, institutional capacity, and policy support. Reducing water losses not only improves utility revenue and service reliability but also contributes to environmental sustainability through energy savings and conservation of water resources.

In summary, utilities aiming for efficient and sustainable water supply must adopt integrated strategies that address physical, commercial, and resource efficiency simultaneously. By doing so, they can achieve non-revenue water levels below 20%, enhance operational and financial sustainability, and support broader environmental and climate goals.

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