A REVIEW OF SMART SOLUTIONS FOR SUSTAINABLE WATER MANAGEMENT WITHIN URBAN AREAS WHILE TACKLING WATER SCARCITY IN GREEK CITIES

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Abstract
Most lately, several European and Greek cities face high water scarcity challenges, mostly due to climate change, inefficient resource management and population growth. Issues like those are mixed by aging infrastructure and high urban water demand. To address the phenomena of water scarcity, it is required to transform todays approaches that leverages technology to optimize resource use and ensure sustainable water availability for urban use.

This paper studies and presents the role of smart technologies in advancing sustainable urban water management, specifically in Greek cities, mainly focusing on specific initiatives that integrate Internet of Things (IoT) solutions, advanced metering infrastructure (AMI), and real-time telemetry systems. This study is based on recently EEA Grants funded projects, that played pivotal in this transformation, including the deployment of smart household water meters and city-wide telemetry systems for real-time monitoring and control of water networks. Those projects showed significant work in detecting and reducing water losses, optimizing distribution systems, and promoting efficient household water use. This work, highlights the effectiveness of these technologies towards water scarcity combat and building resilience in urban water systems. In addition to the IoT analysis, this work includes also the socio-economic and environmental impacts of these projects, emphasizing the importance of funding mechanisms, policy frameworks, and stakeholder engagement in their success. Summing up, some recommendations are also provided for scaling these solutions to other urban settings, ensuring wider adoption and impact.

The outcome of this study demonstrates the leverage of smart technologies, coupled with lessons from funded projects, providing a sustainable pathway to address water scarcity in Greek cities. This study contributes to the discourse on urban water resilience, offering *actionable insights for policymakers, city planners, and water utilities seeking to create water-secure urban environments.*

Key words:*water scarcity, smart water management, IoT, telemetry systems, smart household meters, Greek cities, climate resilience*

Introduction

Lately, water scarcity is addressed as one of the most pressing challenges for urban areas globally, and more specifically at Greece, as a Mediterranean country. With over two-thirds of its territory classified as semi-arid, and with uneven seasonal precipitation, Greek cities are increasingly experiencing the effects of water scarcity problems, both physical and economic (Baltas et al. 2005, Monokrousou et al, 2024). Intensified extreme weather events, prolonging droughts, and altering hydrological cycles, show that climate change has further exacerbated these challenges (Nastos P.T. et al, 2014, Ferdowsi A. et al. 2024). Simultaneously, urbanization and rapid population growth, particularly in coastal regions and tourist hotspots, place unsustainable pressure on outdated water infrastructure (Kofinas et al. 2016).

Greece has some of the oldest urban water networks, whiche were developed decades ago, and can be characterized by high levels of leakage, fragmentation, and limited automation. According to recent assessments, non-revenue water (NRW) in several Greek municipalities surpasses 50%, resulting in significant economic, environmental, and operational losses (Serafeim 2022; Nastos P.T. et al, 2013; Chasiotis et al. 2023b). In addition to the above, the even high cost of energy for pumping and treatment, coupled with limited financial and technical capacity in small municipalities, severely constrains the ability of local authorities to manage water resources efficiently (Avlonitis et al. 2007, Nastos P.T. et al, 2009).

Following this context, smart water management technologies offer a transformative potential. Leveraging real-time data collection, predictive analytics, and automated control systems, smart solutions enable utilities to detect leaks, monitor quality, and optimize system performance with greater precision and speed (Sophocleous, S et al. 2019; S.H.A. Koop et al. 2019). Technologies working with Internet of Things (IoT) , advanced metering infrastructure (AMI), decision support systems (DSS), and digital twins (DT) are already being implemented, tested or deployed in several Greek municipalities through European and bilateral cooperation projects, such as the EEA-funded projects.

Emerging approaches also incorporate nature-based solutions and hybrid infrastructures – combining digital platforms with environmentally sensitive urban design. These integrated strategies are particularly important in the Mediterranean, where seasonal variability requires adaptive design and resilient urban systems.

However, while the technical capabilities of these systems are proven, their successful implementation depends on multiple factors including institutional readiness, stakeholder engagement, funding accessibility, and regulatory support (Antzoulatos et al. 2018). In some cases, socio-technical barriers such as lack of public trust or data transparency hinder adoption. Additionally, the absence of long-term performance monitoring frameworks prevents municipalities from scaling pilot successes into broader urban policy.

This study contributes to this discussion by examining three projects as municipal case studies —Paramythia, Aigio, and Argos—where smart technologies have been deployed to address water loss and improve system efficiency. The analysis focuses on technological architectures, implementation challenges, achieved results, and lessons learned that can inform future replication across Greece and similar Mediterranean contexts.

1. Water Scarcity Challenges in Greek Urban Areas

Greek urban cities are facing a growing intensity of water scarcity challenges. These challenges are driven mostly by aging infrastructure, but also by elevated levels of non-revenue water (NRW), the impacts of climate change, seasonal demand surges due to tourism, and in many cities, weak monitoring and management systems. The combination of these challenges poses a serious risk to the sustainability of water resources in cities across Greece—from major metropolitan areas like Athens to mid-sized and smaller municipalities such as Aigio, Argos, and Paramythia. (Nastos P.T. et al, 2014)

1.A. High Levels of Non-Revenue Water (NRW)

Non-revenue water (NRW) — which is the amount of water being lost before reaching end-users — is the most common, significant and persistent issue in Greek urban water systems. Studies show that in cities like Kozani, NRW exceeds 50%, creating enormous inefficiencies in both resource use and municipal finances (Kanakoudis 2014). In Drama, similar issues were found, where aging infrastructure, inadequate pressure control, and lack of modern network management contributed to significant water loss (Kazana et al. 2021). These findings are consistent across smaller municipalities, where operational budgets are limited, and investments in smart water systems remain insufficient.

In Paramythia, located in the mountainous region of Epirus, water losses previously reached up to 72%. The high NRW was linked to both outdated pipeline infrastructure and lack of systematic monitoring. However, under the SMASH project, the municipality implemented a digital twin model of the water network, combined with local monitoring stations and virtual sensors, to identify hidden leakages and optimize system performance (Chasiotis et al. 2023a). This demonstrates how digital technologies can mitigate deep-rooted inefficiencies when appropriately deployed.

1.B. Aging Infrastructure and Network Condition

A considerable portion of Greece's urban water distribution infrastructure dates back to the 1960s and 1970s. In cities like Athens, the average pipeline age exceeds 60 years, resulting in frequent failures, such as pipe bursts and valve corrosion (EYDAP 2023). Network rehabilitation has been slow, especially in smaller municipalities, due to a lack of technical capacity and limited access to EU or national funds. In Aigio, a city in Western Greece, a smart leak detection system was implemented to improve infrastructure efficiency. The deployment of digital meters, hydraulic simulation models, and network visualization platforms reduced undetected losses, particularly during seasonal pressure spikes.

Similarly, in Argos, where NRW was previously estimated at 54%, municipal authorities installed a combination of leak detection sensors, hydraulic modeling systems, and local telemetry units. These allowed operators to remotely monitor flow and pressure conditions, identify anomalies, and reduce water losses across the network. This was part of an effort to rationalize network operations while coping with increasing demand and climate-induced variability (Karavitis et al. 2024).

1.C. Climate Change Impacts on Urban Water Supply

Climatic variability and long-term warming trends are increasingly undermining the reliability of water supply in Greece. The Aliakmon River Basin—one of the country's key water sources—has been modeled to experience significant reduction in runoff and groundwater recharge due to climate change (Varanou et al. 2005). Warmer summers and more frequent heatwaves not only decrease water availability but also raise consumption levels, especially for cooling and irrigation in urban settings.

This dual stress—decreasing supply and increasing demand—is especially problematic in peri-urban zones where infrastructure is fragmented and systems are poorly monitored. In Argos, for instance, the over-extraction of groundwater during dry summers led to salinization of aquifers. Seasonal declines in reservoir storage meant that during certain months, tap water quality deteriorated significantly, requiring temporary reliance on bottled water or emergency treatment units (Karavitis et al. 2024).

1.D. Tourism-Driven Demand Peaks

Tourism remains one of the most prominent socio-economic drivers of seasonal water stress in Greece. On islands like Santorini and Mykonos, annual water consumption has doubled in the past decade, as hotels, resorts, and restaurants cater to large influxes of international visitors (Karavitis et al. 2024). However, the phenomenon is not restricted to islands alone. Cities such as Aigio and Paramythia also see summer demand surges, due to domestic tourism and temporary population increases.

In Aigio city, increase leakage risks are stressed by high summer consumption, which creates pressure differentials that also exacerbate energy use for pumping and treatment. The installation of smart meters and seasonal demand forecasting tools helped moderating these peaks, enabling more responsive supply-side management (Chasiotis et al. 2023b). The same is followed by Municipality of Souli in Paramythia, where the integration of real-time data into the DSS platform helped anticipating pressure drops and adjusting system operations preemptively to avoid service disruptions (Chasiotis et al. 2023a).

2. Importance of Smart Water Management Solutions

Aging infrastructure, population growth, climate change, and economic constraints put increasing pressure at urban water systems worldwide. In this context, smart water management solutions have emerged as essential tools for enhancing the resilience, efficiency, and sustainability of water utilities. The installation of technologies like Internet of Things (IoT) devices, Advanced Metering Infrastructure (AMI), Supervisory Control and Data Acquisition (SCADA) systems, and digital twins (DT) enables real-time monitoring, predictive maintenance, and data-driven decision-making.

Smart systems, like the ones described above, significantly reduce non-revenue water (NRW), supports leak detection, and improve service quality. Decision support systems (DSS) based on online data and hydraulic modelling allow Municipalities to prioritize interventions, reduce energy costs, and minimize water leakages (Patelis et al. 2020). These technologies are more valuable in cities with aging infrastructure and limited operational budgets, as they offer targeted and cost-effective solutions to systemic inefficiencies.

The importance of AMI and IoT in household water management is also demonstrated in studies which highlight how high-resolution water usage data from smart meters can facilitate user engagement, early leak detection, and adaptive pricing strategies (Cominola et al. 2015). Approaches like those help foster water conservation and allow for more equitable and transparent billing systems.

In the Mediterranean countries, smart water networks have proven crucial for adapting to climate variability, as it is lately the most common solution. In semi-arid urban areas the integration of SCADA systems and smart leak detection platforms has improved both operational efficiency and water quality (Mertzanides et al. 2010). The Paramythia

(Municipality of Souli) pilot case under the SMASH (EEA-Grants) project further illustrates how a digital twin, combined with virtual sensors and a DSS platform, reduced NRW and enhanced service delivery in a region historically affected by water scarcity (Chasiotis et al. 2023a).

Smart water management offers a framework that enables proactive, data-driven control of urban water infrastructure. Key features include:

- **Real-Time Monitoring**: IoT devices and smart sensors provide continuous data on water flow, pressure, and quality parameters. This facilitates instant detection of abnormalities such as leaks or contamination (Savić et al. 2018).
- **Automated Metering and Feedback**: AMI allows for remote meter reading, behavioral nudging, and personalized feedback to users. Studies show how household-level data drives water conservation (Makropoulos et al. 2014).
- **Digital Twins and Simulation Models**: These create virtual replicas of water networks, enabling predictive analytics and scenario testing (Manuel Franco-Torres et al. 2021).
- **Decision Support Systems (DSS)**: DSS platforms synthesize data from multiple sources and help operators make informed decisions for operational control, maintenance prioritization, and emergency response.

Case studies from across Europe, including SMART-WATER (Antzoulatos G. 2019) in Greece and SWAMP in Italy, demonstrate that such systems can reduce non-revenue water by up to 30%, lower energy use by 15–20%, and significantly extend the lifespan of urban infrastructure (Lewandowski et al. 2019; Antzoulatos et al. 2018).

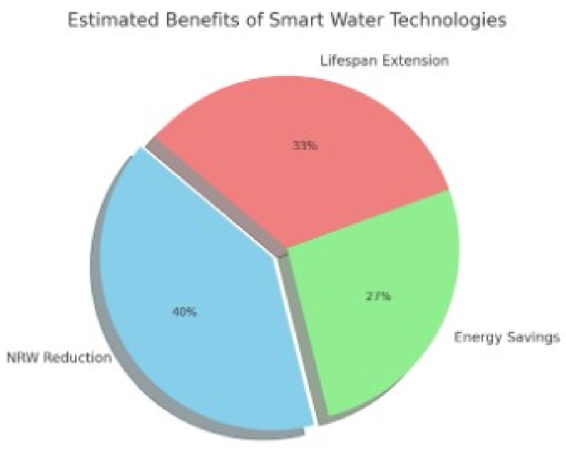

Figure 1: Estimated Benefits of Smart Water Technologies

Smart systems also contribute to environmental sustainability by reducing unnecessary abstraction from stressed water sources. Dynamic pressure management and demand forecasting can align supply with actual consumption, minimizing both water loss and energy use (Dandy et al. 2022).

Given the high levels of water losses reported in many Greek cities—exceeding 50% in places like Aigio and Argos—the adoption of smart water technologies is no longer optional but necessary. When supported by appropriate institutional frameworks and funding mechanisms, these tools can help Greek municipalities move toward climate-resilient and resource-efficient water systems.

3. Methodology

The purpose of this review is to evaluate the application and effectiveness of smart water management technologies implemented in urban areas of Greece to address water scarcity. The review adopts a qualitative case-study methodology, analyzing three representative urban pilot projects: Paramythia (Municipality of Souli), Aigio (Municipality of Aigialeia), and Argos (Municipality of Argos-Mykines). These cases were selected based on criteria including high levels of non-revenue water (NRW), vulnerability to climate variability, and recent deployment of digital technologies.

This review adopts a qualitative case study approach, focusing on three completed municipal-level projects funded under national and European calls. Primary data were derived from project reports, academic publications, and technical specifications:

- **Paramythia (Souli Municipality)**: Integrated water quality and leak detection system using a digital twin and DSS
- **Aigio (Aigialeia Municipality)**: SCADA-enabled leakage control platform with real-time visualization and sensor analytics
- **Argos (Argos-Mykines Municipality)**: Smart leak monitoring stations and digital twin implementation

The selection criteria included:

- Demonstrated impact on water loss reduction
- Use of smart infrastructure (IoT, AMI, DSS)
- Involvement of academic or research partners

Each case was analyzed for its system architecture, technological setup, environmental benefits, and policy or governance frameworks. Lessons learned across the cases inform the discussion on scalability and replicability in other Greek cities.

The review focuses on the integration of Internet of Things (IoT) technologies, Advanced Metering Infrastructure (AMI), telemetry systems, and Decision Support Systems (DSS) to improve water efficiency, service reliability, and system resilience. Particular attention is paid to the institutional and technological frameworks underpinning these implementations, including:

- Digital twins and real-time hydraulic simulation models
- IoT-based leak detection and water quality monitoring sensors
- SCADA systems for operational monitoring and control
- AMI for user-side metering, consumption analytics, and billing
- DSS for predictive and scenario-based decision-making

This approach aligns with research methodologies commonly applied in the evaluation of urban smart infrastructure deployments. For instance, water management strategies using digital twins in European cities emphasizes the need for scenario-based performance evaluation, particularly in aging or semi-arid urban environments (Nydrioti et al. 2024). Furthermore, outline a systems-oriented framework for assessing smart infrastructure integration, which has informed this study’s analytical structure (Antzoulatos et al. 2018).

Additionally, the scope included environmental and socio-economic impact assessments derived from publicly available municipal data and project deliverables. The inclusion of academic and research partners in all these cases supported the development and implementation of advanced analytical tools such as DSS and digital twins, allowing not only real-time control but also strategic planning.

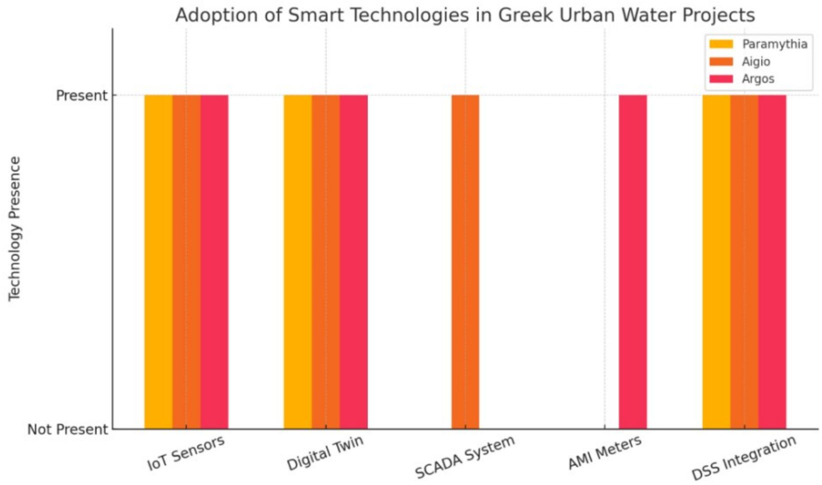

Figure 2: Adoption of Smart Technologies in Greek Urban Water Projects

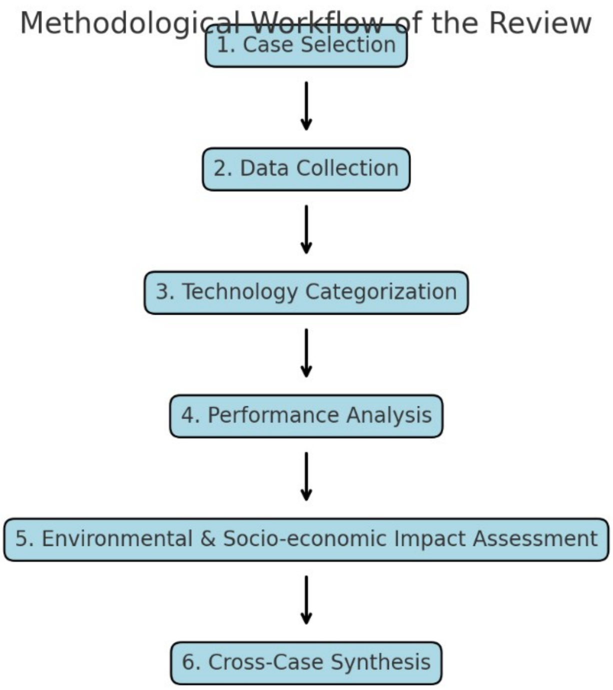

Figure 3: Methodological Workflow of the Review

This review seeks to provide:

- A synthesis of how smart technologies were configured and implemented
- A comparative analysis of technological performance, cost savings, and water savings
- Insight into policy frameworks, funding mechanisms, and stakeholder engagement
- Lessons learned for upscaling and replication in other urban areas

The outcomes from the selected case studies will be contextualized within the broader challenges of Greek urban water systems, as identified in Chapters 2 and 3.

4. Case Study Analysis

This chapter presents a detailed analysis of three municipal-level pilot projects in Greece which are examples of the application of smart water technologies to address water scarcity. These case studies provide information on system architecture, technical implementation, operational outcomes and institutional collaboration. The pilot cases vary in terms of geographical characteristics, population size, water network complexity, and technical configuration. Nevertheless, they reflect common strategic goals: optimizing water efficiency, addressing non-revenue water (NRW), improving operational decision-making, and increasing long-term system resilience.

4.1 Paramythia (Municipality of Souli)

The Municipality of Souli implemented the “Smart Green Leakage Control and Water Quality Monitoring System” in the town of Paramythia, a region suffering from one of the highest levels of NRW in the country—up to 72%. The project aimed to improve water resource efficiency, reduce leakages, and ensure high-quality drinking water through advanced monitoring and simulation technologies.

Key components of the system include:

- Three local control stations equipped with real-time sensors monitoring flow rate, pressure, residual chlorine, turbidity, temperature, pH, and conductivity
- Development of a digital twin for the closed-zone water distribution network
- Virtual sensors for detecting hidden leakages
- A Decision Support System (DSS) that integrates real-time data with hydraulic modeling for operational optimization (Chasiotis et al. 2023a)

The integration of virtual and physical monitoring enabled continuous control of both quantity and quality indicators. Advanced leak detection algorithms allowed early identification of anomalies, which reduced the response time and improved maintenance scheduling. Similar methodologies have been described in studies examining the role of smart platforms in small and medium-sized municipalities (Dandy et al. 2022).

Outcome Analysis: The project achieved a substantial 35% reduction in NRW and ensured real-time water quality compliance. Operational expenditures were reduced, while public trust in municipal services increased. Moreover, the combination of Greek and Norwegian institutional partners fostered transnational collaboration and research transfer. The upgrade allowed for more resilient summer-period operation, addressing peak demand challenges in this mountainous community. A noteworthy aspect is the strategic value of DSS integration, which allowed for not only real-time leak localization but also the dynamic optimization of pumping schedules and network pressures. These capabilities are instrumental for areas like Paramythia, where infrastructure was outdated, and terrain variability complicates hydraulic operations.

Outcomes:

- Estimated annual water savings: 600,000 m³
- Estimated cost savings: €20,000/year
- Reduction in non-revenue water in the city of Paramythia (NRW): ~25%
- Number of direct beneficiaries: 3,032 citizens (8,767 including the broader municipality)
- Improved environmental status of monitored water body

4.2 Aigio (Municipality of Aigialia)

In Aigio City, which’s water losses reach up to 48%, a smart leak detection system was developed to modernize the municipal network. The pilot project extended the already installed internal leakage control system, integrating SCADA-based control with real-time sensor data and hydraulic simulation models.

Key components of the system include:

- Platform for real-time data visualization and leak detection
- Hydraulic modeling of the closed-zone network using a digital twin
- Pressure and flow rate sensors to support proactive maintenance

This case illustrates how digital platforms can support equitable tariff schemes and improve operational efficiency without increasing financial burdens on consumers. According to S.H.A. Koop et al. (2019), AMI and remote sensor systems are effective in medium-scale networks for balancing user transparency with managerial control (Makropoulos et al. 2014).

Outcome Analysis: The installation of a fully integrated control and monitoring system allowed a more balanced distribution of water, reducing significantly response time to failure events. The tools that where implemented (SCADA and visualization platform) enabled the local water operation enterprise to transition from a reactive to a proactive operational model. Combining pressure regulation and reduced pumping hours, the intervention also resulted in energy savings and lower greenhouse gas emissions from pumping stations. In addition, the project contributed to a more transparent interaction between users and the utility through consumption profiling, while the digital twin assisted with operational simulations for future infrastructure planning.

Estimated outcomes:

- Water saved: ~600,000 m³/year
- Cost savings: ~€21,000/year
- Noticeable drop in undetected leak events and consumption anomalies

4.3 Argos (Municipality of Argos-Mycenae)

In Argos city, which is facing NRW levels up to 54%, smart technologies were applied to update a deficit water balance network. This pilot case included local monitoring stations and real-time telemetry to ensure high service standards and support equitable resource pricing.

Core elements of the system:

- Installation of smart leak detection sensors in critical network points
- Development of a digital twin of the water network
- DSS integration for real-time operational and billing decisions

Argos is a representative case for semi-arid, agriculturally intensive municipalities facing increasing pressure on water supply due to groundwater over-extraction and climate-induced variability. The real-time monitoring system enabled better protection of vulnerable water sources. These capabilities are essential for long-term planning in urban water systems (Antzoulatos et al. 2018).

Outcome Analysis: This project not only reduced natural losses, but also enabled the smart allocation of resources in an urban-rural dual-use context. The system's predictive capability has helped reduce over-extraction and seasonal overcharging of aquifers. As a result, Argos has been able to improve water quality and mitigate the risks of salt intrusion. In addition, increased metering accuracy has helped the municipality move towards fairer pricing models that reflect actual consumption. In addition, the project yielded operational agility by facilitating coordinated decision-making between technical staff and local government, making Argos a testbed for regional replication under similar climatic and topographic pressures.

Estimated outcomes:

- Water saved: ~1,200,000 m³/year
- Cost savings: ~€42,000/year

- Beneficiaries: 22,209 residents

Comparative Summary: All three case studies demonstrated:
- Effective reduction in non-revenue water
- Deployment of integrated smart systems (IoT, telemetry, DSS)
- Tangible environmental and economic benefits
- Strengthened institutional and academic collaboration

The success of these implementations underscores the replicability of smart water solutions in other Greek municipalities facing similar structural and climatic challenges.

The comparative analysis of the three pilot projects in Paramythia, Aigio and Argos reveals important insights on how smart water management technologies can be adapted to different urban environments. Despite differences in geography, population density and legacy infrastructure, all three municipalities demonstrated measurable improvements in operational efficiency, water conservation and service delivery.

Common Outcomes:
- All cities reported significant reductions in non-revenue water (NRW), with total annual savings ranging from 600,000 m³ to 1,200,000 m³.
- Technological integration (IoT, digital twins, DSS, and SCADA) played a central role in enabling proactive leak detection and informed decision-making.
- Financial savings ranged from €20,000 to €42,000 annually, reflecting not only lower losses but also reduced operational and energy costs.
- Each project achieved high levels of community impact, improving water security for 3,000 to over 22,000 residents.

City	Pre-project NRW (%)	Water Saved (m³/year)	Cost Savings (€/year)	Core Technologies Deployed	DSS Integration	Beneficiaries
Paramythia	~72%	~600,000	~20,000	IoT sensors, Digital Twin, Virtual Sensors	Yes	3,032
Aigio	~48%	~600,000	~21,000	IoT, Digital Twin, SCADA	Yes	20,422
Argos	~54%	~1,200,000	~42,000	IoT, Digital Twin, Leak Monitoring, AMI	Yes	22,209

Table 1: Common Outcomes

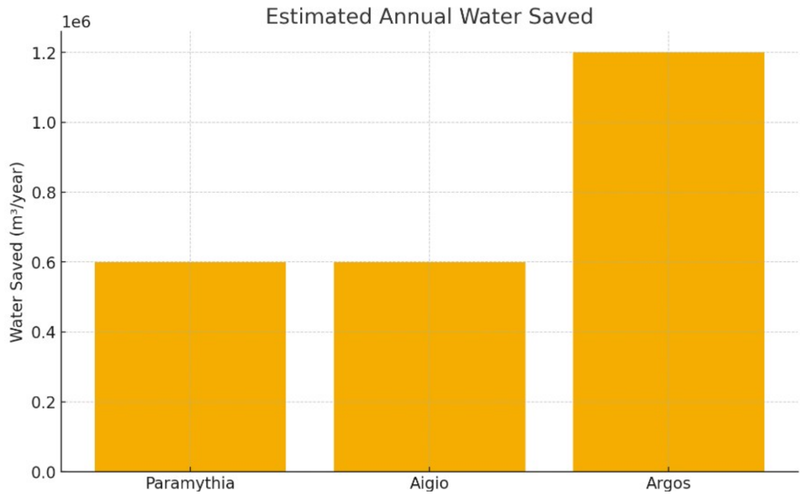

Figure 4: Estimated Annual Water Saved

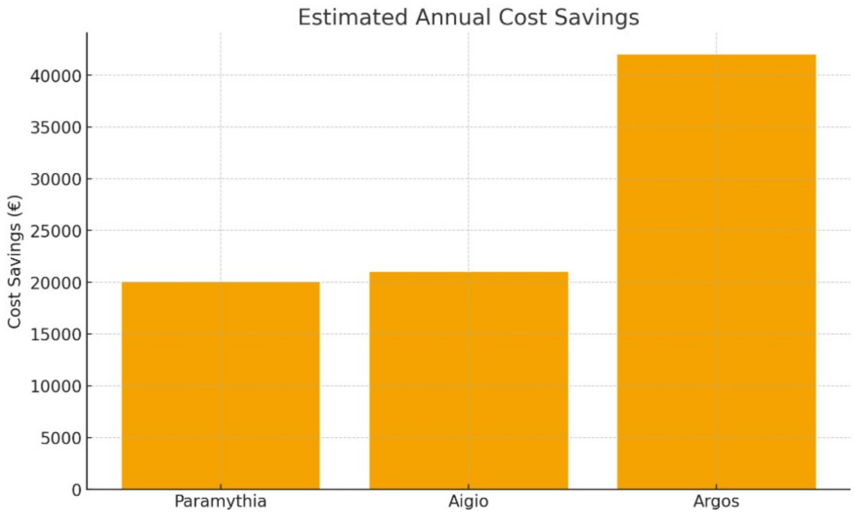

Figure 5: Estimated Annual Cost Savings

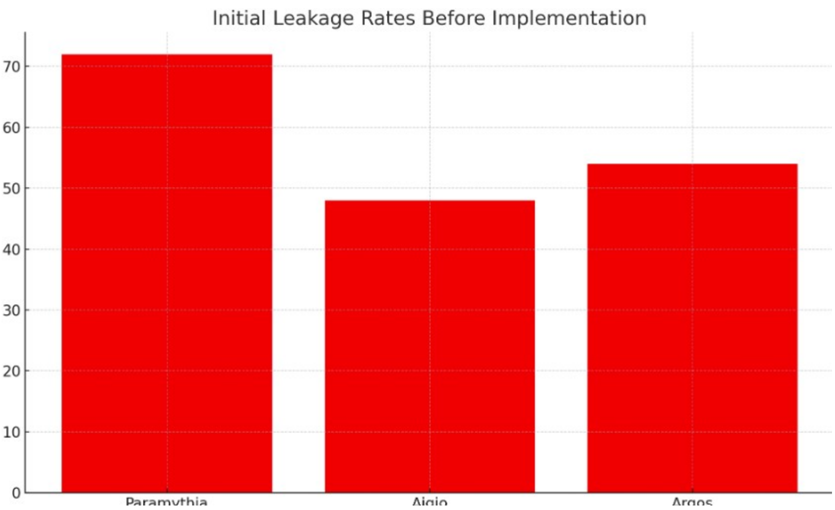

Figure 6: Initial Leakage Rates before implementation

5. Key Insights

5.1. Reduction of Non-Revenue Water (NRW):All three municipalities achieved substantial reductions in NRW, ranging from 35% to over 50%. This result confirms earlier findings that digital water monitoring systems equipped with real-time sensors and hydraulic modeling can effectively reduce natural and apparent water losses. At Argos, the deployment of AMI contributed to pricing accuracy and better demand-side management, enhancing retention.

5.2. Enhancement of Operational Efficiency:The use of Decision Support Systems (DSS) in all three cases enabled the operators to move from reactive to predictive and adaptive management strategies. With DSS synthesis sensor data and simulation models, municipalities achieved improved pressure control, optimal pump scheduling and faster leak detection.

5.3. Environmental and Energy Gains: All three systems contributed to reduced energy use, with shorter pump duty cycles and improved pressure regulation. Smart water networks significantly reduce GHG emissions when integrated with effective pressure management (Dandy et al., 2022). The environmental benefit was particularly evident in Argos, where over-extraction from aquifers was minimized due to better water metering.

5.4. Cost Savings and Economic Efficiency:Annual financial savings ranged from €20,000 to €42,000, with cost recovery depending on project scale and key deficiencies. This evidence confirms research that smart metering and leakage reduction programs lead to rapid return on investment when coupled with improved pricing structures and lower maintenance needs (Cominola et al., 2015).

5.5. Technological Flexibility and Modularity: Each city deployed a combination of technologies based on its local needs. Paramythia emphasized water quality and virtual sensing, Aigio focused on SCADA integration, while Argos deployed AMI for end-user analytics. This variation underscores the modular nature of smart infrastructure and the ability to scale solutions progressively—a critical insight for municipalities with limited budgets.

5.6. Institutional Collaboration and Innovation: All three pilots included research partners—ranging from national universities to international institutions—playing a vital role in digital twin development, algorithm refinement, and DSS configuration. These collaborations ensured access to scientific tools and training, reflecting the broader recommendation by S.H.A. Koop et al. (2019) on the importance of cross-sectoral partnerships for digital transformation in water utilities.

5.7. Social Impacts and Consumer Trust: Improved service reliability, water quality, and equitable billing reinforced citizen satisfaction. In smaller communities such as Paramythia, where water supply challenges historically affected public trust, the visibility of smart technologies and real-time monitoring strengthened institutional legitimacy and public engagement in conservation behaviors.

In summary, these cases collectively demonstrate that the adoption of smart water technologies in Greek cities leads not only to measurable savings and efficiencies but also to more resilient, transparent, and adaptive governance models. The upcoming section will explore policy-oriented recommendations for scaling these innovations across the national water sector.

6. Key Differences:

6.1. Scope and Prioritization of Technologies: While all three cities integrated digital twins and DSS platforms, the specific technologies prioritized varied significantly. Paramythia invested heavily in water quality monitoring (e.g., turbidity, residual chlorine) alongside leakage detection, reflecting its mountainous location and quality concerns. In contrast, Argos emphasized customer-side analytics through AMI, addressing large-scale water losses and the need for billing transparency in a mixed urban-agricultural context (Makropoulos et al., 2017). Aigio adopted a robust SCADA backbone to modernize network control, with real-time data visualization being a primary operational enhancement.

6.2. Network Complexity and Legacy Infrastructure:Argos managed a more complex and spatially extensive network, requiring a more distributed telemetry configuration and a larger number of pressure zones. Paramythia, though smaller, faced severe topographical challenges and older infrastructure, necessitating virtual sensor integration to complement sparse physical instrumentation. The differences in those system conditions affected the design choices and rollout timeline of each solution (Antzoulatos et al., 2018).

6.3. Volume of Water Saved and Financial Returns:Argos demonstrated the highest absolute volume of water savings (though leakages) and cost benefits due to scale and baseline inefficiencies. While Paramythia and Aigio achieved similar volumetric savings, the per capita benefit in Paramythia was proportionally higher, demonstrating the relevance of smart technologies even in small municipalities.

6.4. Institutional Capacity and Local Governance Models:Aigio City's pilot project featured higher levels of operational autonomy within the local water enterprise (DEYA), enabling quicker system reconfiguration and workforce adaptation. Paramythia City, on the contrary, relied more on external expertise and inter-municipal cooperation, reflecting the resource limitations of smaller municipalities. Argos benefited from political continuity and integrated planning between departments, facilitating alignment between technological and policy objectives.

6.5. Data Granularity and Use in Planning: The granularity of data use also varied. In Argos, AMI enabled high-resolution demand profiles that supported demand forecasting and tariff reform. In Paramythia, data primarily supported operational alerts and reactive maintenance, with limited downstream planning use. Aigio leveraged SCADA for near-real-time response and asset performance monitoring but did not include consumer-side metering during the project phase.

6.6. External Collaboration and Research Partnerships:All three pilots collaborated with academic institutions, but the depth of involvement differed. Paramythia had the most comprehensive research integration, with three universities involved in digital twin modeling, DSS development, and virtual sensing. This facilitated deeper innovation and technical validation, which smaller municipalities often lack the capacity to develop independently (Chasiotis et al., 2023a).

6.7. Communication and User Engagement: User interaction varied across cases. Argos leveraged smart metering data for improved communication and awareness among citizens. Paramythia promoted transparency through municipal announcements and real-time monitoring displays, increasing public trust. Aigio focused more on internal operations, with future plans to scale communication features.

These differences illustrate that the pathway to smart water management is not one-size-fits-all. Instead, success depends on adapting technological choices to local priorities, institutional readiness, infrastructure conditions, and governance models. This highlights the importance of flexible frameworks that allow for context-sensitive innovation while maintaining core principles of integration, interoperability, and long-term sustainability.

7. Challenges Identified

Despite the demonstrated benefits of technologies (like IoT, DSS and DT) in those Greek case studies, several critical challenges persist that may hinder widespread adoption and long-term sustainability. These challenges span across technical, institutional, financial, and social domains, and must be addressed in order to scale smart urban water solutions effectively.

7.1. Technical Integration and Interoperability

Many municipalities struggle with integrating new technologies into outdated water infrastructure. Legacy systems often lack the capacity to support real-time monitoring or automation, requiring significant upfront investment for upgrades (Romano, M. et al., 2014). In Paramythia, for instance, the introduction of digital twins and virtual sensors necessitated a parallel upgrade in hydraulic models and local data management protocols.

7.2. Data Governance and Cybersecurity

As smart systems rely mostly on online data collection and cloud-based platforms, concerns over data ownership, cybersecurity, and interoperability remain underregulated. The absence of standardized data frameworks, most commonly in Greece risks data fragmentation and potential vulnerabilities in real-time water management systems.

7.3. Financial Constraints and Uneven Access to Funding

Smaller municipalities, such as Paramythia, face greater difficulty accessing the capital required to invest in advanced technologies. While EU and national co-financing mechanisms have supported pilots, the long-term financial sustainability of these systems is uncertain without dedicated operational budgets or performance-based funding schemes (Chasiotis et al., 2023a).

7.4. Institutional Fragmentation and Capacity Gaps

Water utilities in Greece often operate with limited staff, outdated training, and bureaucratic rigidity. The lack of coordination between technical departments, local authorities, and external consultants impedes efficient deployment of smart solutions. Argos and Aigio both reported delays due to administrative approvals and limited staff familiarity with IoT platforms and hydraulic simulation software.

7.5. Limited User Engagement and Awareness

Although smart systems offer opportunities for behavioral change through personalized feedback and leak alerts, public engagement remains minimal. In Aigio City the benefits of SCADA and real-time information were invisible to end-users. Without communication campaigns, users most likely may not support or fully utilize smart services, reducing their overall effectiveness.

7.6. Environmental Constraints and Climate Uncertainty

While smart technologies enhance operational adaptability, their effectiveness is still limited by external factors such as drought, aging aquifers, and urban sprawl. In Argos, over-extraction of groundwater remains a long-term threat, despite improved control and monitoring of leaks. Climate variability can also compromise the accuracy of forecasting algorithms without constant recalibration and data enrichment.

7.7. Scalability and Long-Term Maintenance

Many pilots rely on grant-based funding for their initial deployment but lack long-term operational strategies. Ensuring system continuity, hardware maintenance, and software updates over time presents a considerable logistical and financial burden. Without institutionalized monitoring and reinvestment cycles, these systems risk degradation and underperformance.

In conclusion, while the three Greek case studies validate the potential of smart water solutions, they also underscore the need for robust enabling environments that combine technological, regulatory, and societal innovation. Addressing these challenges is essential to move from isolated pilot projects to widespread, sustainable urban water management practices.

8. Conclusions

Conclusions and Future Work

Smart urban water management systems leverage an ecosystem of advanced technologies – from pervasive IoT sensors and Advanced Metering Infrastructure (AMI) to real-time control through SCADA, high-fidelity Digital Twins and data-driven decision support systems (DSS). The integration of these elements has begun to transform traditional water utilities into "smart water networks", enabling unprecedented visibility and control over urban water infrastructure (H.M. Ramos, et al. 2019).

This chapter summarizes the global state-of-the-art in these technologies, compares international implementations, and outlines future directions. Emphasis is placed on the **performance gains**, **integration strategies**, and **scalability** of such systems in real-world urban settings.

Smart Technologies for Urban Water Management

Recent years have seen rapid adoption of digital technologies in water distribution networks. **IoT-based sensing** is now central to monitoring water systems: utilities deploy networks of smart pressure, flow, acoustic and water-quality sensors across pipelines and assets. These sensors provide continuous, high-resolution data on system conditions (e.g. pressures, flows, water quality) in real time (Ramos, et al. 2019). For example, Singapore's Public Utilities Board (PUB) has installed *hundreds* of multi-parameter sensor probes (measuring pressure, flow, acoustic and quality indicators) to continuously detect leaks and water quality issues across its island-wide network . **Advanced Metering Infrastructure (AMI)** – large-scale rollout of smart water meters to customers – similarly offers fine-grained consumption data at hourly or sub-hourly intervals. A growing number of water utilities, especially in the USA and Europe, have implemented AMI to capture detailed usage information from millions of customer meters (Water Research Foundation. 2020.). This wealth of data enables better demand forecasting, quick detection of anomalies (like continuous flows indicating leaks), enhanced customer engagement in water conservation, and more effective policies to reduce non-revenue water. Notably, AMI data proved invaluable during the COVID-19 pandemic to analyze shifting consumption patterns and inform operations (Krishnan, et al. 2022).

SCADA systems (Supervisory Control and Data Acquisition) remain the backbone for water utility operations, providing remote monitoring and control of pumps, valves, reservoir levels, and treatment processes. Modern smart water architectures increasingly integrate SCADA with IoT sensor networks and AMI data, moving from isolated operational control to unified data platforms. This integration is key to achieving real-time management: field sensor and meter data feed into central hubs where they are combined with Geographic Information Systems (GIS) and asset databases. In an exemplary smart distribution network in Spain, a central software platform integrates **remote meter readings, GIS maps, SCADA telemetry, and water quality sensor data**, applying anomaly-detection algorithms (including demand forecasting models) to flag leaks or quality issues in real time. The result is a “digital nerve center” that can alert operators to events like bursts or contamination and even initiate automated responses (such as valve closures) to mitigate incidents(Public Utilities Board Singapore, 2016).

Future Directions for Smart Water Management

The global trend toward smart water networks is unmistakable and likely irreversible. Moving forward, several key areas of development and research will shape the **next generation of smart urban water systems**:

- **Interoperability and Standards:** To fully realize scalability, the industry must converge on open standards for data and device integration. Standard communication protocols and data models would enable plug-and-play addition of new sensor types and analytics modules. Developing a **systematic framework** for smart water architecture (as called for by recent studies) will be crucial so that utilities can follow proven blueprints rather than ad-hoc designs. This includes common definitions of data “layers” (from instruments to application layer) and shared metrics for evaluating smart system performance (such as the “smartness” and “cyber-wellness” metrics proposed in literature).
- **Advanced Analytics and AI:** As data quantity and quality increase, machine learning and AI will play a larger role in water management. Future systems will use **predictive analytics** not only to anticipate leaks or demand spikes but to enable truly **autonomous** control in certain aspects. For example, AI could optimally regulate pressures by learning from historical patterns, or perform real-time water quality anomaly detection using pattern recognition beyond human capability. Early steps in this direction are visible – e.g. some utilities already use AI-based demand forecasting and anomaly detection algorithms– but there is ample room for growth in AI-driven decision support, including the integration of generative AI for scenario planning in digital twins.
- **Digital Twin Enhancement:** Digital twin technology is expected to mature into a core operational tool. Current digital twins primarily mirror hydraulic behavior; future twins may integrate more dimensions (e.g. water quality chemistry models, asset degradation models, financial models for asset management). This would allow holistic decision-making (e.g. choosing an optimal pipe replacement not just on hydraulic performance, but also considering water quality impact and life-cycle cost). Greater fidelity and real-time coupling between the twin and field data (via IoT) will move utilities closer to a **“living” model** of their network that is always synchronized with reality . Moreover, linking water digital twins with other urban system twins (energy, wastewater) could unlock cross-sector optimizations in smart cities.
- **Cybersecurity and Reliability:** As water systems become cyber-physical systems, ensuring their security and reliability is paramount. Future work will focus on robust cyber-security measures to protect sensor networks and control systems from hacking or

sabotage. Similarly, building redundancy in communications (multiple pathways for critical control signals) and fail-safes in automated control is critical so that increasing automation does not compromise the fundamental reliability of water supply. Research into **resilient system architectures** and anomaly detection for cyber threats is underway as part of making smart water systems safe against new failure modes .

- **Socio-Technical and Organizational Aspects:** A truly sustainable future for smart water management also depends on human and organizational factors. Utilities will need to invest in workforce training – transitioning from traditional operational roles to data-centric roles – and in public communication. Early projects (like Singapore's) found that staff roles had to evolve and public acceptance of technologies (e.g. smart meters, which sometimes raise privacy concerns) had to be managed . Future research might explore change management, customer engagement strategies, and policy frameworks that facilitate technology adoption (for example, regulations for data sharing and privacy, or incentive schemes for utilities to reduce leaks using smart tech).

In conclusion, smart urban water management systems have demonstrated clear technical advantages and operational benefits in cities around the world, from reducing water losses and energy usage to improving service continuity and decision-making. The global context reveals a spectrum of adoption: some cities (e.g. Singapore) now operate large-scale integrated smart water grids, while others are in pilot phases, gradually upgrading aging infrastructure with smart sensing and control. The coming years will likely see these technologies become standard practice, supported by more refined integration frameworks and powerful analytics. As utilities continue to share knowledge (through pilot projects and research) and technology costs decline, we can expect the performance gaps between "smart" and "non-smart" water systems to drive widespread investment in digital solutions. Ultimately, the future water utility may function as a fully data-driven, self-optimizing network – a digital twin of the physical system that continually adjusts itself to deliver reliable, safe, and efficient water service. Achieving that vision will require continued innovation and collaboration across disciplines, but the substantial progress documented to date provides a strong foundation for these future developments.

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