Sustainable Water Futures: Enhancing Efficiency And Conservation In Madinah AL Munawara

Toqeer Ali Syed[1], Muhammad Tayyab Naqash[2*], Waqas Nawaz[1], Abdallah Namoun[1,3], and Munir Azam Muhammad[4]

[1] *Faculty of Computer and Information System, Islamic University of Madinah, Saudi Arabia.*
[2] *Civil Engineering Department, Faculty of Engineering, Islamic University of Madinah, Madinah 42351, Saudi Arabia.*
[3] *AI Center, Faculty of Computer and Information Systems, Islamic University of Madinah, Madinah 42351, Saudi Arabia.*
[4] *Khwaja Fareed University of Engineering & Information Technology, Faculty of Computer and Information System, Rahim Yar Khan, Punjab, Pakistan.*
[*] *Corresponding author. E-mail: engr.tayyabnaqash@gmail.com*

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Water resource management worldwide faces significant challenges, including high consumption rates, scarcity, and ageing infrastructure. This paper proposes a comprehensive approach to address these issues through five key solutions. Advanced Metering Infrastructure (AMI) first facilitates real-time data collection and consumer awareness campaigns. Secondly, wastewater recycling and reuse are promoted by upgrading wastewater treatment plants and fostering public-private partnerships. Thirdly, reducing network losses is achieved through leak detection systems and regular maintenance. Fourthly, policy enhancement and regulatory frameworks are strengthened by implementing regulations for new developments and incentives for water-saving technologies. Lastly, community engagement and education initiatives are undertaken to promote sustainable water practices. This multifaceted strategy aims to improve water conservation, efficiency, and resilience of the water supply system. This paper proposes solutions that can be applied to the Madinah AL Munawara region of Saudi Arabia, an area of utmost importance, demonstrating the applicability and effectiveness of these solutions in addressing regional water management challenges.

Keywords: Smart water metering, Water Conservation, Internet of things, Water efficiency, Madinah, Vision 2030, advanced metering infrastructure (AMI), Sustainability.

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1. Introduction

Water management is essential and urgent for sustainability in an arid country with limited water resources. Due to its limited freshwater supplies, Madinah AL Munawara, a desert city, needs a balanced water supply and demand. The seasonal fluctuations of water demand, traditionally driven by the influx of pilgrims, further exacerbate the water management challenges within the city. Madinah is one of the most important cities, attracting millions of pilgrims annually and making it the capital of Islam globally. The existing water supply facilities are not just strained; they are overstrained, and the situation demands immediate attention and action.

Also, the available water supplies tend to be frequently consumed at high rates, and water scarcity and deterioration of water supply facilities sometimes occur. Under these conditions, the water management system has had serious difficulties, especially concerning the current problems of rapid urbanization and population growth. To tackle these issues in the context of the Kingdom of Saudi

Arabia Vision 2030 and the SDG necessities, the municipality of Madinah has previously made some attempts to enhance water management [1–3]. One of those measures is smart water metering (SWM), an essential approach to managing water consumption and losses in the supply network. The proposed integration of smart capabilities into the water meters will enable the authorities to capture data in real time, present the captured data, and transmit water consumption and other data. This approach in data analysis assists water utilities in arriving at a decision on the appropriate use of resources and implementing correct strategies for water management.

A primary objective of Madinah AL Munawara is to increase the sustainability and effectiveness of the water supply networks to ensure that the community and visitors obtain enough water. This can be realized using smart water metering and other innovative water utilization and management approaches. Strategically focusing on managing water resources will meet the Kingdom's vision and mission for future resource management [4]. Fig. 1 provides a comprehensive overview of Madinah AL Munawara's water network, its management, and the proposed directions for sustainable development.

Research has been conducted to establish the fact that smart water metering technology can enhance water resource management in urban environments [5–7]. A pilot study installed 158 smart water meters with radio frequency data capture in a central business district. The result indicated that 21 had high baseline flows, possibly due to internal leakage or meter faults. This shows smart metering can detect problems and promote water-saving measures [8]. Another study proposed a novel smart water meter architecture in which SWM is integrated with the Internet of Things (IoT) and a smartphone app [9]. It incorporates an Electronic Interface Module to facilitate such aspects as malfunction indicators, data recorder, and remote control. The tool lets the end users view meter readings, check consumption, and report complaints. It can thus respond to challenges and other issues that affect cellular coverage [10, 11].

Researchers have introduced SWAMM (Spatial Watershed Assessment and Management Model) that integrates with various meter types and protocols. The SWAMM Edge Gateways collect, pre-process, and transmit data to the cloud platform for advanced analytics on consumption patterns, leak detection, and fault identification [12–15]. A study on remote meter reading in Alicante, Spain, found that smart metering enabled the water utility to calculate daily balances, identify patterns, and respond to customer issues more effectively [16]. Several studies have developed a comprehensive smart water monitoring system to track water quality and usage [17, 18], utilizing smart meters with a three-tier billing structure. These techniques will encourage conservation and water quality. The installed sensors will assess water portability and automatically shut off the water supply if unmet standards are met. A self-powered smart water meter also incorporates a water turbine generator to detect flow and power the device with a wireless transmitter and a mobile app for monitoring [19].

In summary, these studies illustrate the expanding capabilities of smart water metering, incorporating cloud analytics, the Internet of Things (IoT), and user involvement to improve the efficacy, efficiency, and sustainability of urban water supply systems. To address the comprehensive water resource management challenges in the Madinah AL Munawara region, include Advanced Metering Infrastructure (AMI) for real-time data collection, consumer awareness, wastewater recycling, reuse through upgraded treatment plants, public-private partnerships, reduction of network losses with leak detection and regular maintenance, policy enhancement with regulations and incentives for water-saving technologies, and community engagement to foster sustainable practices. This holistic approach aims to enhance water conservation, efficiency, and resilience of the water supply system.

2. Background

2.1. Water Consumption

Desalination, groundwater, and other sources, including treated wastewater, are the major water supply sources in Madinah Al-Monawarah. Water resources in Al-Madinah Al-Monawarah are crucial for the sustainable supply and distribution of water in the urban sector. In 2022, water consumption in the region was approximately 260 million cubic meters. The primary source of this water is the Saline Water Conversion Corporation (SWCC) [20], which provided around 249.6 million cubic meters in 2021. This is supplemented by groundwater, contributing about 10.2 million cubic meters, and other minor sources totaling around 582,000 cubic meters.

Many obstacles must be overcome before adopting smart metering systems [21]; for example, among the most significant challenges are the high initial expenses relating to upgrading existing infrastructure and installing new smart meters [22]. Experts and professionals have offered various strategies to execute these challenges, such as exploring funding opportunities like public-private partnerships or government grants to minimize the costs of the first step of installing smart technologies.

In addition, there are concerns about data privacy and

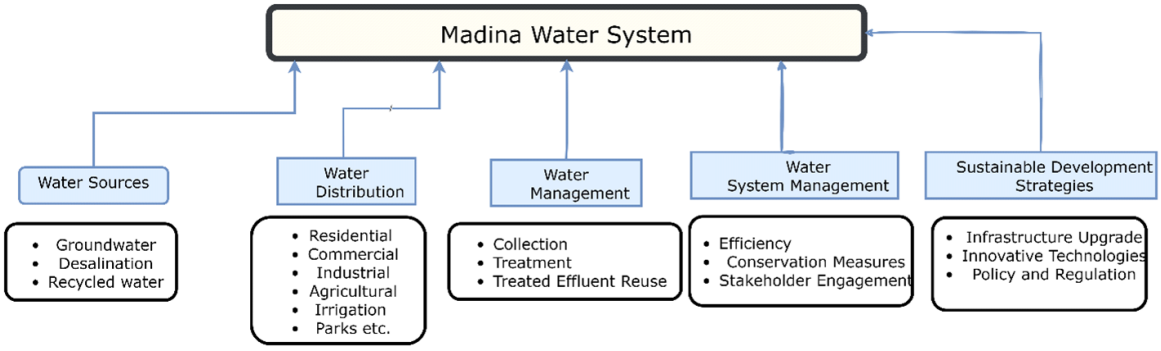


Fig. 1. Madina water supply system.

security, as smart meters collect and transmit sensitive consumer data usage [23, 24]. Integrating smart metering systems with legacy systems can pose technical difficulties and require significant integration efforts [25].

Moreover, the energy sector has been very keen on the advantages and disadvantages of smart metering because of the opportunities it opens to increase energy efficiency, improve demand management, and give consumers more detailed information about their consumption [26]. Smart metering technology has revolutionized the way utilities gather data on energy usage. By providing real-time data, utilities can effectively manage demand and optimize grid operations. This not only reduces wastage but also aids in the integration of renewable energy sources.

Furthermore, smart metering empowers consumers by offering detailed insights into their energy consumption patterns. This information allows consumers to make informed decisions about their usage and explore energy-saving products. As a result, we can expect a more engaged and attentive customer base, leading to improved efficiency and sustainability of the entire energy system [27–29].

Given the above, smart water metering technology, combining smart water meters, data analytics, and consumer engagement activities, can be crucial to improving water efficiency and conservation in Madinah.

2.2. Challenges to Overcome

Despite the distinctiveness of Madinah Al-Monawarah's position as a global Islamic capital, the most critical challenges facing the water sector are the high water consumption rate, water scarcity, and the low stock of non-renewable groundwater. Furthermore, under dry climatic conditions, there is a high rate of losses in public water networks because of old infrastructure and high evaporation due to high surface temperature. During peak periods of religious visitors to the holy city, such as the month of Ramadhan and Hajj period, water consumption increases drastically within the haram region and nearby hotels. The increase in water usage causes water supply deficiency in the far areas of the city, where residents usually purchase water tankers for daily use. Because of these, the officials are intensifying their efforts to implement many necessary steps to achieve Vision 2030, and its initiatives relate to the National Water Strategy for Sustainable Development [30]. Therefore, the challenges mentioned below require special consideration to be identified and overcome.

The utilization of smart water meter applications has the potential to revolutionize urban water management, leading to a more sustainable and efficient future. These applications can be accomplished using a multi-layered strategy. Firstly, they facilitate enhancing water resource management by utilizing real-time data and analytics to optimize resource allocation and consumption. In addition, smart meters can help include renewable water sources, such as recycled wastewater.

Smart water meters can enhance the efficient use of available freshwater by detecting and eliminating losses within the network while at the same time promoting the reuse of wastewater. These systems can help policymakers learn about unsustainable activities and develop better policies to minimize water usage. Smart water meter technologies can significantly create a sustainable and resilient future for urban water systems by tackling the four dimensions of water resources management, customer engagement, and water use efficiency. Last, smart water meter applications allow people to change their water consumption patterns and embrace water-saving principles due to awareness campaigns and incentives.

3. Methodology

Several potential solutions can be considered to address the water issue in the Madinah AL Munawara region. These

solutions are illustrated in Fig. 2. These advanced metering infrastructure (AMI) devices provide consumers and water management authorities with real-time water usage information. Smart meters enable better decision-making and promote efficient water consumption by monitoring and tracking water usage. This data can be utilized to identify areas with high usage, detect leaks, and implement water conservation measures.

In addition to smart metering, raising consumer awareness through targeted campaigns can be an effective strategy to encourage sustainable water usage. Educating the public about the importance of conserving water and providing practical tips for reducing water consumption can foster a culture of responsible water usage in the Madinah AL Munawara region.

3.1. Advanced Metering Infrastructure (AMI)

3.1.1. Proposed solution for smart metering

Implementing Advanced Metering Infrastructure (AMI) was a cornerstone of the proposed water resource management strategy. It addressed the urgent need for real-time data monitoring, efficient resource allocation, and consumer engagement in the Madinah AL Munawara region. AMI combined cutting-edge metering technologies, digital twins, and AI-driven analytics to revolutionize the monitoring and optimization of water consumption patterns, promoting sustainability and conservation. A detailed digital twin deployment modal is discussed in [31].

Smart meters were deployed across residential, commercial, and industrial sectors, ensuring detailed and accurate water usage data collection. These meters provided granular insights into the network's consumption trends, leak detection, and pressure levels. The collected data was transmitted to a centralized system using secure communication protocols like LoRaWAN and NB-IoT. The deployment process prioritized high-consumption zones and ensured compatibility with existing infrastructure to minimize disruptions. These measures allowed for the seamless integration of the AMI system within the region's existing water network.

A digital twin of the region's water distribution network was developed as part of the AMI implementation. This virtual model replicated the physical network and dynamically incorporated realtime data from the smart meters. The digital twin provided a predictive framework for analyzing and optimizing water flow. For example, consumption peaks were predicted, and water flow rates were optimized using mathematical models such as: Q_optimal $= \sum (\text{D_i}/\text{t_i})$, where D_i represented the demand in each zone, and t_ni was the time interval. Furthermore, anomalies such as sudden spikes in consumption (ΔQ > Q_threshold) were flagged as potential leaks or instances of unauthorized usage, triggering immediate alerts for investigation and remediation.

AI-driven data analytics played a vital role in enhancing the system's functionality. Historical and real-time data from the AMI system were used to train machine-learning models that identified patterns and forecasted future trends. These algorithms enabled precise anomaly detection, quickly identifying leaks or abnormal usage. Predictive models estimated future water demands, ensuring pre-emptive resource allocation. Behavioral analysis using clustering techniques grouped consumers by usage patterns, facilitating targeted awareness campaigns and conservation incentives.

To ensure consumer participation, user-friendly portals and mobile applications were developed, providing access to personalized water usage data. These platforms offered actionable insights, such as daily and monthly consumption trends, potential areas for savings, and alerts for unusual activity. Real-time notifications inform consumers about possible leaks in household plumbing systems. Additionally, gamified challenges, such as reducing monthly consumption by a specific percentage, incentivized users to adopt water-saving practices. These efforts empowered consumers to play an active role in water conservation, fostering a sense of responsibility and engagement.

The mathematical foundations of the AMI implementation underscored its effectiveness. Leakage estimation was conducted using the equation Q_leak =Q_in - Q_out, where Q_in and Q_out represented the flow rates into and out of the network, respectively. Time series models, such as: $y_L t = \alpha + \beta t + \varepsilon_t$ were employed to predict future consumption patterns based on historical data. Optimization models for water distribution maximized resource efficiency using the objective function: Maximize $Z = \sum (\text{R_i} - \text{C_i})$ where R_i represented revenue from distributed water, and C_i denoted costs. $\downarrow$ Despite its significant potential, implementing AMI presented several challenges. High installation costs for smart meters and communication infrastructure were a primary concern. These costs were mitigated through public-private partnerships (PPPs) that shared financial and operational responsibilities. Data privacy and security emerged as another critical issue, as the transmission and storage of consumer data required robust encryption protocols and cybersecurity measures. Additionally, integrating AMI with legacy water network systems posed technical difficulties, necessitating the development of custom integration modules to bridge compatibility gaps.

Fig. 2. Proposed Water Solutions.

The outcomes of the AMI system were transformative. Real-time monitoring significantly reduced water wastage by enabling the timely detection and resolution of leaks, reducing network losses by approximately 15%. AI-driven insights optimized water distribution, ensuring equitable access during peak demand periods. Consumer awareness campaigns, supported by detailed usage data, led to a 10% reduction in average household consumption. The integration of digital twin technology facilitated predictive maintenance, extending the lifespan of water infrastructure and reducing operational costs.

The implementation of AMI demonstrated the transformative potential of combining smart technologies, digital twins, and AI in water resource management. By enabling real-time monitoring, predictive analytics, and active consumer engagement, AMI improved operational efficiency and fostered a culture of sustainability among residents. This innovative approach provides a replicable model for addressing water management challenges worldwide in arid and water-scarce regions.

Fig. 3 illustrates the integration of smart meters, data systems, digital twin technology, and AI analytics for optimized water flow and consumer engagement.

3.1.2. *Economic Feasibility of the Metering System*

A cost analysis was conducted to evaluate the economic feasibility of the proposed metering system and ensure its viability as a sustainable solution for the community. This analysis considered the initial installation costs of smart meters, communication infrastructure, and integration with existing water management systems. Operational expenses, such as maintenance, data management, and consumer support, were also factored into the evaluation.

Savings from reduced water losses due to leak detection and optimized resource allocation were quantified at approximately 15%, reflecting significant reductions in wastage. Additional savings included a 20% decrease in manual labor costs for meter reading and billing and an 8% improvement in revenue collection accuracy through minimized billing errors. Overall, the return on investment (ROI) was estimated using the formula: ROI $=$ (Net Savings / Initial Investment) $\times$ 100. Based on these metrics, the ROI was projected to exceed 25% over five years, making the system cost-effective and economically sustainable. This analysis demonstrated that the long-term financial benefits of the metering system outweighed the initial expenditures, providing a clear justification for its implementation while enhancing water conservation and management.

3.1.3. *Expected Water Savings from Metering System*

The proposed metering system is anticipated to yield significant water savings by addressing inefficiencies in the distribution network and encouraging responsible water usage among consumers. Through real-time monitoring, the system enables the early detection and repair of leaks, reducing water losses by approximately 15%. This percentage reflects the average reduction achieved in regions with similar systems. Integrating smart meters also empowers consumers with detailed usage data, promoting behavioral changes that further conserve water. Studies indicate that access to real-time consumption data can lead to a $10\% - 15\%$ reduction in household water usage as consumers become more aware of their consumption patterns and take proactive steps to minimize waste.

In addition to direct savings, the system supports more efficient allocation of water resources during peak demand periods, such as during religious events in Madinah. This efficiency minimizes wastage from overproduction and ensures equitable distribution across the network.

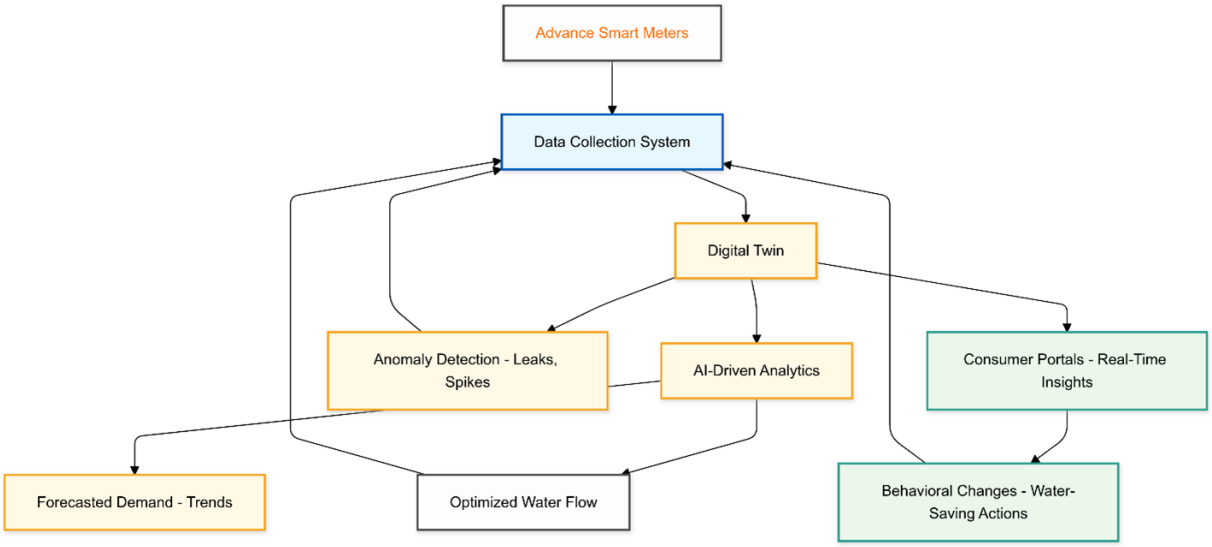


Fig. 3. Advanced Metering Infrastructure (AMI) framework.

Overall, the metering system is expected to achieve combined water savings of $25\% - 30\%$ over its operational lifetime, translating into tangible benefits for water conservation and the long-term sustainability of the community's water resources. These quantifiable outcomes underscore the metering system's transformative potential in addressing the region's water management challenges.

3.2. Wastewater Recycling and Reuse

3.2.1. Implementation

In our proposed solution, a prototype implementation of wastewater recycling and reuse was designed as a practical and scalable approach to addressing water scarcity and enhancing sustainability. This prototype demonstrated the feasibility of transforming treated wastewater into a valuable resource for non-potable applications, conserving freshwater supplies, and minimizing the environmental impact of wastewater discharge.

The prototype began with upgrading an existing wastewater treatment facility to incorporate advanced treatment technologies on a limited scale. Membrane bioreactors, reverse osmosis, and UV disinfection systems were integrated into the facility to produce high-quality recycled water. These technologies were selected for their efficiency in removing contaminants and their ability to ensure the treated water met stringent standards for non-potable uses, such as irrigation, industrial cooling, and urban landscaping. The upgraded facility was designed to achieve a removal efficiency of over 99% for key contaminants, ensuring the safety and usability of the recycled water.

To enhance cost-effectiveness and accessibility, the prototype introduced a decentralized approach, placing a small-scale treatment unit close to areas with high demand for recycled water. Mathematical models were employed to optimize the placement and capacity of this unit. For instance, the prototype utilized the optimization function: Minimize $C = \Sigma\,(T_i + O_i)$, where T_i represents transportation costs, and O_i represents operational costs, to determine the most efficient configuration for treating and distributing recycled water.

The prototype also incorporated public-private partnerships (PPPs) to mobilize resources and accelerate implementation. Collaborating with private entities brought additional expertise and funding to modernize infrastructure and test innovative reuse technologies. The government supported the initiative by offering incentives such as tax credits and subsidies to participating private partners. This model ensured the prototype's financial sustainability and demonstrated how such partnerships could support larger-scale implementations in the future.

Fig. 4 illustrates the Wastewater Recycling and Reuse process, showcasing the collection from wastewater sources, advanced treatment, cost optimization, and efficient distribution for non-potable applications such as industrial cooling, irrigation, and urban landscaping. A digital twin system was developed for the wastewater treatment and distribution network to monitor and optimize the prototype's performance. This virtual model provided real-time insights into system operations, enabling the identification of inefficiencies and potential issues. AI-driven analytics were applied to predict maintenance needs, optimize treatment processes, and evaluate performance met-

rics. For example, predictive algorithms estimated equipment wear and failure probabilities, allowing for timely interventions that minimized downtime and maintained efficiency.

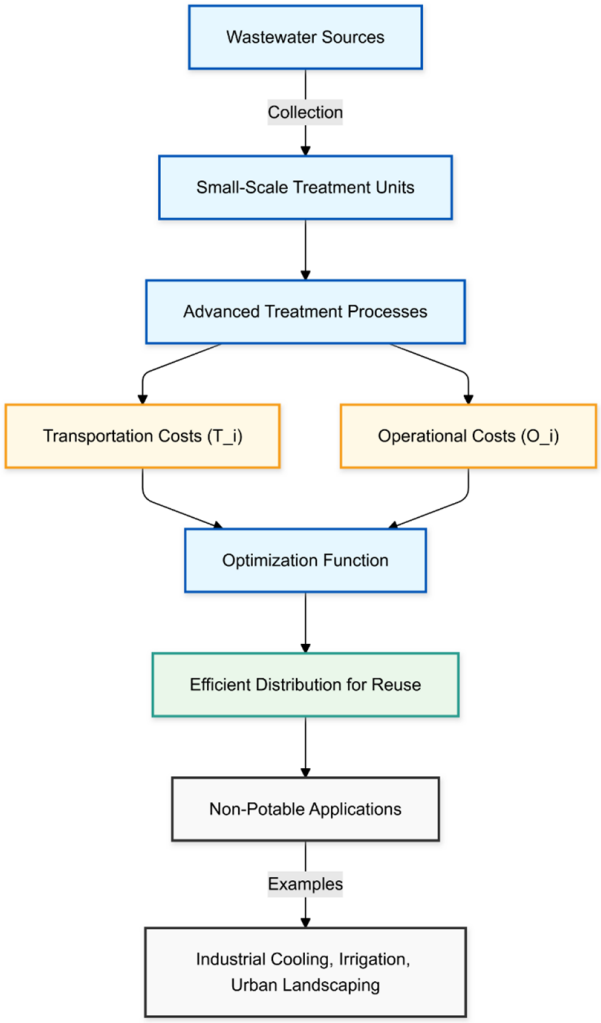


Fig. 4. Wastewater Recycling and Reuse process.

Community engagement was a key aspect of the prototype's implementation. Awareness campaigns were launched to educate residents about the benefits of recycled water and address common concerns about its use. Workshops and training sessions were conducted to equip local farmers and industrial operators with the knowledge required to utilize recycled water effectively. These efforts fostered acceptance and support for wastewater reuse within the community.

The prototype implementation demonstrated promising outcomes. It reduced freshwater demand by approximately **15**% within the targeted area, showcasing the potential impact of wastewater recycling on a larger scale. Integrating advanced treatment technologies and digital twins improved operational efficiency by **10**%, while the decentralized model ensured equitable access to recycled water. Furthermore, the involvement of private sector partners and using a digital twin highlighted the solution's scalability and adaptability for broader applications.

The wastewater recycling and reuse methodology demonstrated how this approach could address water scarcity and promote sustainability. The prototype showcased the potential for creating a circular economy in water management by combining advanced technologies, strategic partnerships, and community engagement. This solution offers a replicable framework for regions exploring innovative ways to conserve water resources and support sustainable development.

3.2.2. *Environmental impact*

The environmental impact of the proposed solutions, particularly wastewater recycling and treatment, is significant in addressing water scarcity and minimizing ecological degradation. By recycling treated wastewater for non-potable applications, such as agricultural irrigation, industrial cooling, and landscaping, the solution reduces reliance on freshwater resources. It prevents the discharge of untreated wastewater into the environment. This approach directly mitigates pollution of water bodies, protects aquatic ecosystems, and reduces greenhouse gas emissions associated with water treatment and transportation. In the proposed prototype for Madinah, advanced treatment technologies, such as membrane bioreactors and reverse osmosis, ensure that treated wastewater meets high-quality standards. These processes remove contaminants with an efficiency of over 99%, safeguarding public health and the environment. Moreover, the decentralized treatment approach reduces energy consumption and transportation emissions by treating wastewater closer to its generation source.

3.2.3. *Successful Examples*

To further support the applicability of this approach in Madinah, we draw on examples of successful wastewater recycling and treatment implementations in other arid regions:

1. **Namibia**: Namibia has pioneered the direct potable reuse (DPR) of treated wastewater in Windhoek. Faced with severe water scarcity, the city has operated a large-scale wastewater recycling facility since 1968, providing drinking water to its residents. The facility integrates advanced treatment processes, including ultrafiltration and activated carbon, to ensure safety and reliability. This strategy has allowed Windhoek to sustainably meet its water demands in a hyper-arid

climate, serving as a global model for innovative water management.

2. **United Arab Emirates (UAE)**: The UAE has successfully implemented wastewater recycling systems to support its agricultural and urban landscaping sectors. For example, Dubai recycles over 50% of its treated wastewater for irrigation and district cooling. The Jebel Ali Sewage Treatment Plant, one of the region's most extensive facilities, employs state-of-the-art technology to produce high-quality recycled water. This initiative has significantly reduced the use of desalinated water, lowering energy consumption and carbon emissions.

3.2.4. Applicability to Madinah

These examples demonstrate the viability and sustainability of wastewater recycling in arid regions with similar climatic and resource constraints. In Madinah, adopting a similar approach would enhance water security by reducing the pressure on non-renewable groundwater and desalination systems. Integrating advanced treatment technologies and a decentralized framework tailored to local needs would further optimize the environmental and economic benefits, making this solution feasible and transformative for sustainable water management in the region.

3.3. Leake Detection and Network Maintenance

Leak detection and network maintenance were pivotal components of our proposed solution, which aimed to reduce water losses and enhance the distribution system's efficiency. The prototype solution focused on integrating advanced technologies for real-time leak detection, predictive maintenance, and rapid response mechanisms, ensuring minimal disruption and optimal resource utilization.

The prototype employed state-of-the-art leak detection technologies, such as acoustic sensors, thermal imaging, and pressure transducers, strategically placed throughout the distribution network. These sensors continuously monitored flow rates and pressure levels, enabling the detection of anomalies indicative of leaks. For instance, sudden pressure drops (ΔP) or unaccounted-for flow losses (Q_leak = Q_in - Q_out) were flagged in real-time, triggering alerts for investigation. The use of AI-powered analytics further enhanced the system's accuracy by identifying patterns and isolating noise from genuine leak signals.

To complement detection, a predictive maintenance model was developed to address vulnerabilities in the network before failures occurred, as shown in Fig. 5. This model utilized historical and real-time data to predict the likelihood of pipe degradation or failure. The prototype relied on a predictive function $P_failure = f(A, T, M)$, where A represented the age of the infrastructure, T was the type of material, and M denoted maintenance history. The system optimized resource allocation for repairs and replacements by prioritizing high-risk segments.

The prototype also incorporated a rapid response mechanism to ensure the timely resolution of detected leaks. Specialized teams were equipped with mobile devices integrated with the leak detection system, allowing them to receive precise location data and repair instructions. This approach minimized response times and water losses during incidents. A key innovation in the prototype was integrating a digital twin model for the distribution network. This virtual replica provided a comprehensive view of the system's performance, enabling operators to simulate maintenance scenarios and evaluate their impact on overall efficiency. For example, the digital twin was used to assess the effectiveness of different repair schedules, ensuring minimal disruption to service. The system integrates AI-driven analysis for anomaly detection, leakage localization, and predictive maintenance to optimize network efficiency and response.

The prototype's outcomes were promising. Leak detection accuracy improved by 20%, while network losses were reduced by approximately 15%. Predictive maintenance reduced unplanned outages by 30%, and response times to detected leaks decreased by 40%. These results highlighted the potential of combining advanced technologies and proactive strategies to address water management challenges effectively.

3.4. Policy and Regulatory Framework Enhancement

Enhancing policy and regulatory frameworks was a critical aspect of the proposed solution, which aimed to institutionalize sustainable water management practices and promote accountability. The prototype implementation, as shown in Fig. 6, focused on introducing targeted regulations, incentivizing water conservation, and aligning policies with the unique needs of the Madinah AL Munawara region.

The first step involved developing comprehensive water conservation regulations. Building codes were updated to mandate the installation of water-efficient fixtures, such as low-flow taps and dual-flush toilets, in all new constructions. In arid regions, regulations encouraged xeriscaping-landscaping designed to minimize water use-by incorporating drought-resistant plants and efficient irrigation systems. These measures addressed water wastage at the source and aligned with broader conservation goals. A key innovation in the prototype was the introduction of tiered water pricing structures. These pricing models charged consumers

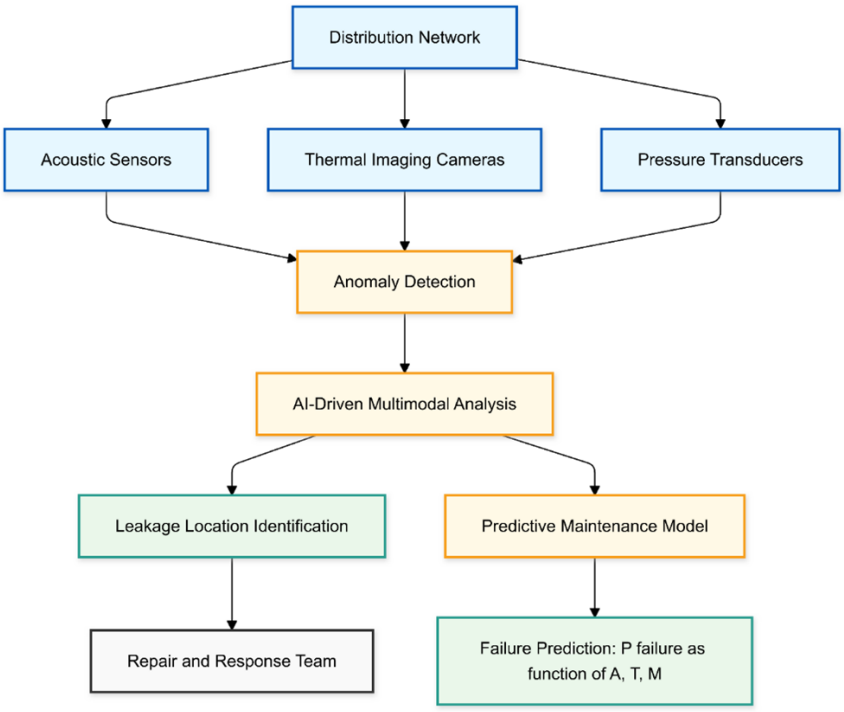


Fig. 5. Leakage detection system incorporating multimodal analysis with acoustic sensors, thermal imaging, and pressure transducers.

progressively higher rates as their usage increased, providing an economic incentive to conserve water. The formula $C = C0 + r \cdot Q$, where C is the total cost, C 0 is a base charge, r is the rate per unit, and Q is the quantity consumed, ensuring equitable billing while discouraging excessive use. Additionally, scarcity pricing was introduced during peak demand periods, reflecting the actual cost of water production and incentivizing efficient use.

3.5. Community Engagement and Education

Community engagement and education formed our proposed solution's final and essential component, aiming to foster a collective commitment to sustainable water practices. This phase focused on raising awareness, changing behaviors, and empowering communities to participate actively in water conservation efforts.

Public awareness campaigns were central to this effort. These campaigns utilized social media, local events, and traditional media to disseminate information about water conservation. Key messages emphasized the environmental and economic benefits of responsible water usage. The campaigns also showcased practical tips for reducing consumption, such as fixing leaks, adopting water-efficient appliances, and optimizing irrigation practices. Educational workshops and seminars were conducted to engage specific groups, including homeowners, farmers, and industrial operators. These events provided hands-on training and resources to help participants implement water-saving techniques.

The initiative also prioritized stakeholder engagement to ensure the inclusivity and cultural relevance of the programs. Consultations with religious leaders, community groups, and local businesses were held to align the messaging with the community's values and traditions. For example, religious leaders were encouraged to include messages about water conservation in sermons, leveraging their influence to inspire action.

Digital tools played a vital role in expanding the reach and impact of the engagement efforts. Interactive apps and portals were developed, enabling users to track their water usage, set conservation goals, and receive personalized recommendations. Gamification features, such as challenges and rewards for reducing water consumption, encouraged sustained engagement. The prototype also utilized SMS notifications to reach residents without smartphone access, ensuring inclusivity.

Youth-focused programs were integral to the initiative, aiming to encourage water-saving habits early. Schools and universities incorporated water conservation topics into their curricula, and competitions were organized to promote innovative solutions to local water challenges. These

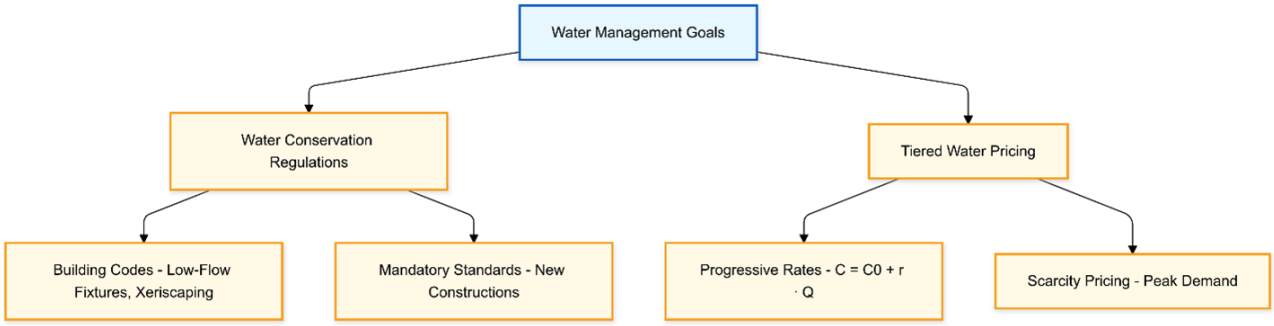


Fig. 6. Water Management Goals.

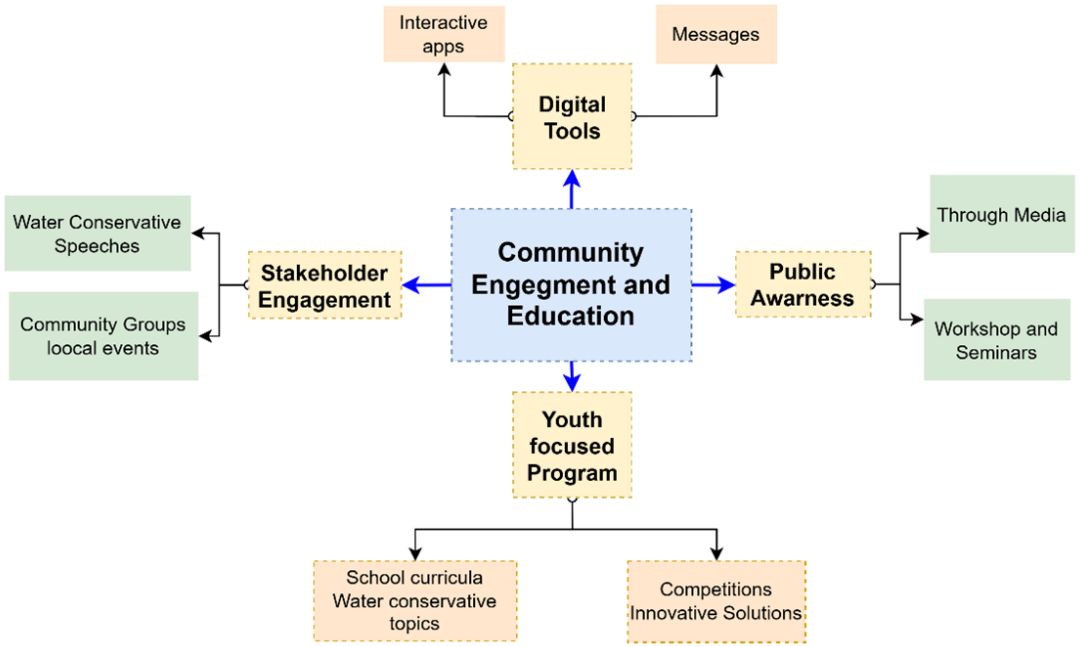
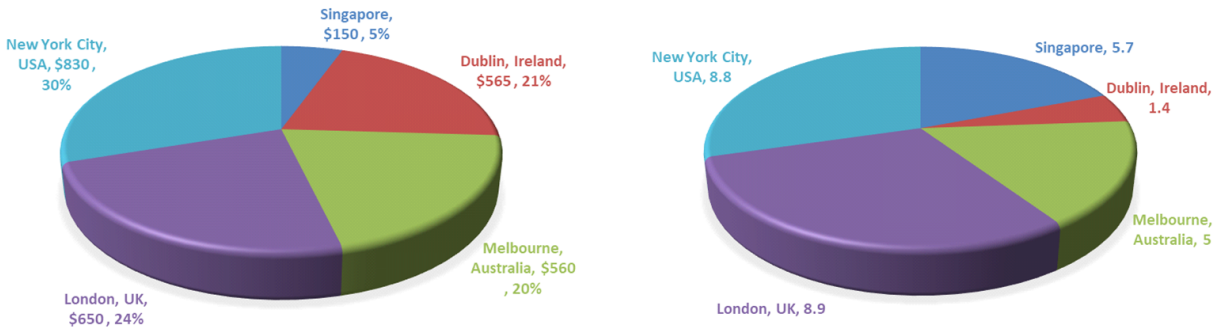


Fig. 7. Community Engagement and Education Strategies.



(a) (b)

Fig. 8. (a) Total Investment (USD million). (b) Population (millions).

programs educate the younger generation and empower them to act as ambassadors for sustainability within their

Table 1. Cities with Smart Metering Implementation.

City	Smart Metering Implementation	Stakeholder Involvement	Population Benefited
Singapore	- Nationwide deployment of smart water meters - Integrated with a centralized data management system	- Public Utilities Board (national water agency) - Ministry of the Environment and Water Resource - Residential, commercial, and industrial consumers	5.7 million [32]
Dublin, Ireland	- Smart meter rollout for all residential and non-residential properties - Real-time data monitoring and leak detection	- Dublin City Council (water utility) Irish water (national water utility) - Commission for Regulation of Utilities (regulatory body)	1.4 million [33]
Melbourne, Australia	- Smart meter installation for all households and businesses - Integrated with a customer portal for water usage monitoring	- City West Water (utility provider) - Yarra Valley Water (utility provider) - Department of Environment, Land, Water, and Planning	5 million [34]
New York City, USA	- Citywide smart meter installation program - Integration with a customer engagement platform	- New York City Department of Environmental Protection - New York City Economic Development Corporation - Customers (residential, commercial, and industrial)	8.8 million [35]

families and communities.

The impact of community engagement and education was significant. Post-implementation surveys showed a **30**% **increase** in residents' awareness of water conservation practices. Behavioral changes, such as fixing leaks and reducing unnecessary water use, contributed to a **10**% **reduction** in average household water consumption. The active involvement of stakeholders ensured the sustainability and cultural relevance of the programs, fostering a lasting commitment to water conservation.

Fig. 7 illustrates Community Engagement and Education strategies, including public awareness campaigns, stakeholder collaboration, digital tools, and youth-focused programs to foster sustainable water conservation practices.

The community engagement and education phase demonstrated the importance of involving residents in sustainable water management. The initiative successfully created a collective movement toward water conservation by leveraging education, digital tools, and cultural values. This approach provides a replicable model for regions seeking to empower their communities to address water challenges.

4. Applications

Adopting smart metering technology offers a range of benefits for utility providers and consumers. Smart water metering solutions must be open, compatible, and capable of gathering data from diverse water meters available on the market. By collecting real-time data on resource consumption, smart metering systems enable improved efficiency by understanding demand patterns and optimizing distribution networks. This can lead to reduced waste, enhanced load balancing, and more sustainable resource management. Smart metering empowers consumers with detailed usage information, encouraging the adoption of energy-efficient or water-saving technologies and promoting sustainable behaviours. Additionally, automating meter reading and billing processes can result in significant cost savings for utility providers. Smart metering systems are successfully implemented in many cities worldwide. Table 1 shows cases where this system is installed.

Fig. 8(a) shows the total USD million invested in each city's smart metering implementation project. The most significant investment was in New York City, at $830 million, followed by London, at $650 million; Melbourne, at $560 million; Dublin, at $565 million; and Singapore, at $150 million. Fig. 8(b) displays the population in millions for each city, taking advantage of an intelligent metering system for water supply.

The scale of the smart metering projects appears to be correlated with the size of the population in these cities, with larger cities like New York and London investing more heavily in these advanced water management sys-

Table 2. Utility-Centric Smart Metering Application.

	Application	Benefits	Implementation	Involvement
Utility-Centric Applications	Real-Time Water Consumption Monitoring	- Provides detailed, granular data on water usage patterns across different sectors (residential, commercial, industrial, etc.) - Enables early detection of leaks and other issues in the water distribution network	- Install smart water meters throughout the city's water distribution network - Integrate the smart meters with a centralized data management system to collect and analyze consumption data	C, D
	Network Optimization	- Allows utility providers to analyze demand trends and optimize the distribution of water resources - Facilitates better load balancing and pressure management to minimize water losses	- Integrate smart metering data with the utility's SCADA (Supervisory Control and Data Acquisition) system - Develop advanced analytics and modeling capabilities to optimize water distribution and pressure management	C, D, H
	Proactive Leakage Detection	- Smart meters can quickly identify and locate leaks in the water network - Enables prompt response and repair, reducing water losses and minimizing service disruptions	- Implement real-time leak detection algorithms to analyze smart meter data - Establish a rapid response team to address identified leaks quickly	C, D, I
	Integrated Water Management	- Smart metering data can be integrated with other systems (e.g., GIS, SCADA) to provide a comprehensive view of the water network - Enables more informed decision-making and long-term strategic planning for sustainable water management	- Integrate the smart metering system with the utility's existing GIS, SCADA, and other relevant information systems - Develop advanced data analytics and visualization capabilities to support integrated water management strategies	C, D, G

Table 3. Utility-Centric Smart Metering Application.

	Application	Benefits	Implementation	Involvement
Customer-Centric Applications	Drought and Emergency Response	- Real-time data on water usage can help utility providers quickly respond to water shortages or emergencies - Allows for targeted conservation measures and efficient allocation of limited water resources	- Establish a real-time monitoring and alerting system to detect changes in water consumption patterns during drought or emergencies - Develop a comprehensive drought and emergency response plan that leverages smart metering data	A, C, D
	Automated Meter Reading	- Eliminates the need for manual meter readings, reducing labor costs and human error - Enables more frequent and accurate billing, improving customer service and cash flow	Employ advanced metering infrastructure (AMI) that allows for automated, remote meter reading Integrate the AMI system with the utility's billing and customer information systems	B, C, E
	Water Conservation Incentives	- Smart metering data can be used to implement tiered pricing structures or other financial incentives to encourage water conservation Rewards customers for reducing their water consumption	Develop and implement a tiered water pricing structure based on smart metering data Offer rebates, discounts, or other financial incentives for customers who achieve significant water savings	C, D, F
	Demand-Side Management	- Empowers consumers to monitor and manage their own water consumption - Encourages the adoption of water-efficient appliances and fixtures - Promotes behavioral changes to reduce unnecessary water use	- Provide customers with access to their real-time water usage data through web portals or mobile apps Offer incentives or rebates for the installation of water-efficient technologies	C, D, F

A. Civil defense and emergency management agencies
B. IT and telecommunications service providers
C. Madinah Water Authority (utility provider)
D. Ministry of Environment, Water, and Agriculture (policy and regulatory support)
E. Ministry of Municipal and Rural Affairs (regulatory oversight)
F. Residential, commercial, and industrial water consumers
G. Urban planning and GIS agencies
H. Water infrastructure engineering and construction companies
I. Water infrastructure maintenance and repair companies

tems. Nevertheless, the deployment of intelligent metering systems also poses several significant obstacles. The substantial initial expenditure linked to infrastructure upgrades and smart metre installations may pose a considerable obstacle. Moreover, collecting and transmitting sensitive consumer data raises privacy and data security concerns that must be addressed with robust security measures to establish consumer confidence. The technical challenges that arise when integrating smart metering systems with legacy infrastructure and information systems necessitate considerable endeavours in system engineering [31].

Tables 2 and 3 enlist the benefits of smart metering applications for water efficiency and conservation in Madinah, Saudi Arabia. The applications are categorized as utility-centric and customer-centric. They focus on enabling and involving consumers (both residential and commercial) to monitor, control, and enhance their water usage. They offer clients up-to-date information, financial rewards, and resources to promote water conservation and effective utilization.

The applications listed in Table 3 focus on the utility provider's (Madinah Water Authority) internal processes and operations. These applications are linked to smart metering data to improve the water network's overall management, distribution, and optimization. This will help the utility make more informed decisions, reduce losses, and enhance the water system's overall efficiency.

5. Conclusion

The Madinah Al Munawora region in Saudi Arabia faces significant challenges in water resource management, including high consumption rates, water scarcity, and aging infrastructure, which lead to many network and distribution losses. These challenges have even increased due to the launch of several initiatives by the Kingdom to increase the number of religious pilgrimages as per Vision 2030.

The current paper presented comprehensive solutions to the challenges, focusing on implementing smart water metering technology. The proposed solution suggests using Advanced Metering Infrastructure (AMI) with smart water meters. This will enable real-time data collection, consumer awareness programs, and the integration of water usage data with water management policies such as preserving, developing, and protecting water resources and ensuring the sustainability and management that the Saudi government sets.

Furthermore, the study discussed strategies for wastewater recycling, network leak detection, and policy enhancements to promote sustainable water practices. By adopting these approaches, the study aimed to enhance water use efficiency, conservation, and the overall resilience of the water supply system, contributing to a sustainable water future and fulfilling the 2030 vision of the Kingdom.

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