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Computational Intelligent Techniques for Enhancing the Capabilities and Efficiency of Smart Water Meters

Sapandeep Kaur Dhillon[1,*], Ikvinderpal Singh[2]

Abstract

In recent years, the realm of smart water meters has undergone a transformative evolution driven by the integration of computational intelligent techniques. This research work embarks on an exploration of the multifaceted applications of these techniques, delving into their profound impact on enhancing the functionality and efficiency of smart water meters. The convergence of artificial intelligence (AI) and machine learning (ML) algorithms with smart water meters presents a paradigm-shifting opportunity to revolutionize the conventional landscape of water management, conservation, and distribution. The synergy of these advanced technologies endows water meters with a newfound capability to transcend their traditional roles, becoming instrumental in addressing the pressing challenges of modern water resource management. Through the analysis of real-time data, these techniques enable efficient leak detection, anomaly detection, predictive maintenance, demand forecasting, usage analytics, and more. This study reviews the state-of-the-art computational intelligent techniques used in smart water meters, their advantages, challenges, and potential future developments in the field.

Keywords: Smart water meters, computational intelligent techniques, artificial intelligence, machine learning, water management, water conservation

INTRODUCTION

Water scarcity and the increasing demand for water resources pose critical challenges to sustainable water management globally. Conventional water meters have not been able to adequately handle these problems. However, with the advent of computational intelligent techniques, such as artificial intelligence (AI) and machine learning (ML), smart water meters have emerged as powerful tools to revolutionize the water industry. Smart water meters equipped with AI and ML algorithms go beyond simply measuring water consumption; they can analyze real-time data, make intelligent decisions, and provide valuable insights for efficient water management and conservation [1]. These computational intelligent techniques enable smart water meters to detect leaks, identify anomalies, predict maintenance needs, forecast demand patterns, monitor water quality, and offer personalized usage analytics to consumers. The purpose of this study is to investigate how computational intelligence techniques can be applied to improve the functionality and effectiveness of smart water meters. It delves into the state-of-the-art technologies and methodologies employed in the integration of AI and ML with smart water meters, highlighting the advantages they offer over traditional metering systems.

***Author for Correspondence**
Sapandeep Kaur Dhillon
E-mail: sapandhillon@gmail.com

[1]Assistant Professor, Department of Computer Science, Guru Nanak Dev University, Amritsar, Punjab, India
[2]Assistant Professor, PG Department of Computer Science and Applications, Trai Shatabdi Guru Gobind Singh Khalsa College, Amritsar, Punjab, India

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The following sections of the study provide a comprehensive review of existing literature on the topic, discussing the various computational intelligent techniques applied to smart water meters. Additionally, the study presents case studies of successful implementations, showcasing the real-world impact of these technologies in achieving water conservation goals and improving water management practices. Moreover, the study addresses both the advantages and challenges associated with employing computational intelligent techniques in smart water meters [2]. While AI and ML bring unprecedented potential, concerns about data security, privacy, and the need for skilled personnel require careful consideration. The future of smart water meters and computational intelligent techniques holds great promise. It is anticipated that AI algorithms will grow increasingly complex as technology develops, allowing for more intelligent and effective water management. Recommendations for policymakers and utility providers will be offered, emphasizing the importance of embracing these innovations and incorporating them into future water management strategies. Computational intelligent techniques have opened up new horizons for smart water meters, transforming them into proactive, data-driven, and highly efficient tools for water conservation and management. By harnessing the power of AI and ML, smart water meters can play a vital role in addressing the water challenges of the present and the future, ultimately paving the way for a more sustainable and water-resilient world.

RELATED WORK

1. *Demand Forecasting in Smart Water Meters using Long Short-Term Memory (LSTM) Networks* [3]: In this research, LSTM networks are employed to forecast water demand in smart water meters. Historical consumption data, weather conditions, and demographic information are used as input to the LSTM model. The study demonstrates accurate short-term and long-term demand forecasting, enabling utilities to optimize water distribution, ensure sufficient supply, and minimize wastage.
2. *Behavioral Analysis and Consumer Feedback in Smart Water Meters* [4, 5]: This research investigates the use of AI-driven behavioral analysis in smart water meters to provide personalized feedback to consumers. By analyzing individual water consumption patterns, the system generates tailored recommendations for water conservation. The study demonstrates that consumers who receive personalized feedback exhibit a higher level of water conservation awareness and reduce their water usage significantly.
3. *Predictive Maintenance of Smart Water Meters using Machine Learning Techniques* [6]: This study explores the application of machine learning techniques for predictive maintenance of smart water meters. By analyzing historical data from smart meters, the researchers develop ML models to predict meter failures before they occur. By using the suggested predictive maintenance technique, utilities can plan maintenance tasks in advance, cutting down on downtime and maintenance expenses. The results indicate a notable increase in the lifespan of smart water meters, contributing to improved water management practices.
4. *AI-Driven Smart Water Management System for Leakage Detection and Prevention* [7]: This research proposes a smart water management system that employs AI algorithms for leakage detection and prevention in water distribution networks. Data from smart water meters with pressure gauges and flow sensors is used by the system. AI-based anomaly detection algorithms analyze the real-time data to identify potential leaks and abnormalities in the network. The study demonstrates significant improvement in leak detection accuracy and efficiency, resulting in reduced water losses and enhanced water network reliability.
5. *Real-time Water Quality Monitoring using AI-Powered Smart Water Meters* [8–10]: This study presents an AI-powered smart water meter system capable of real-time water quality monitoring. The system continuously analyses water quality factors like pH, turbidity, and chemical pollutants using sophisticated sensors. AI algorithms process the sensor data, providing immediate alerts in the event of water quality deviations. The implementation of this system in a water distribution network has proven effective in early detection of contamination events, safeguarding public health.

6. *Data Security and Privacy in AI-Enabled Smart Water Meters* [11]: This work addresses the critical issue of data security and privacy in AI-enabled smart water meters. The study offers a thorough framework for guaranteeing the availability, confidentiality, and integrity of data. The study highlights the significance of user permission procedures, secure communication protocols, and encryption in defending sensitive data from cyberattacks and illegal access.
7. *Challenges and Future Directions in AI Applications for Smart Water Meters* [12]: This review paper provides an in-depth analysis of the challenges faced in the adoption of AI in smart water meters. It talks about the possible biases in AI algorithms, the initial implementation costs, and the requirement for qualified staff. Additionally, the paper highlights potential future directions, such as integrating AI with Internet of Things (IoT) platforms and advanced analytics, to further enhance smart water meter capabilities.

The related works in the field of computational intelligent techniques for smart water meters demonstrate the broad applicability and potential benefits of AI and ML algorithms. These studies offer valuable insights into leakage detection, predictive maintenance, demand forecasting, water quality monitoring, usage analytics, and privacy concerns. Smart water meters are positioned to be crucial to attaining effective water management and conservation as long as academics keep looking in new directions and tackling current issues.

COMPUTATIONAL INTELLIGENT TECHNIQUES IN SMART WATER METERS

Smart water meters, integrated with computational intelligent techniques, utilize artificial intelligence (AI) and machine learning (ML) algorithms to transform traditional water metering systems into proactive, data-driven, and highly efficient tools for water management and conservation. These computational intelligent techniques offer numerous applications that enhance the capabilities and efficiency of smart water meters. Below are some key techniques and their contributions [13–16]:

Leak Detection and Anomaly Detection

Real-time data from smart water meters is analyzed by AI algorithms to find leaks and other irregularities in the water distribution system. By monitoring consumption patterns and flow rates, these algorithms can identify sudden changes that might indicate leaks or irregularities in the system. Early detection of leaks enables utilities to take prompt action, reducing water losses and minimizing the potential for infrastructure damage.

Predictive Maintenance

Machine learning models are used for predictive maintenance of smart water meters. To forecast probable failures, historical data on meter performance and maintenance records are examined. Utilities can schedule maintenance activities proactively; ensuring meters are replaced or serviced before they break down completely. This approach reduces downtime, improves meter longevity, and optimizes maintenance costs.

Demand Forecasting

Using historical data, meteorological conditions, and other pertinent variables, AI-driven demand forecasting is used to predict patterns of water consumption. By accurately forecasting water demand, utilities can efficiently allocate water resources and optimize distribution strategies. This results in reduced wastage, energy consumption, and operational costs while maintaining a consistent and reliable water supply.

Water Quality Monitoring

Real-time water quality monitoring is made possible by AI-powered sensors built into smart water meters. Numerous characteristics, including pH, turbidity, and chemical pollutants, can be analyzed by these sensors. Data is processed by AI algorithms to find variations from acceptable water quality criteria. Timely detection of water quality issues ensures swift response measures to safeguard public health.

Usage Analytics and Consumer Feedback

Computational intelligent techniques are employed to analyze individual water usage patterns and provide personalized feedback to consumers. By offering insights into their water consumption behavior, consumers become more aware of their usage habits and are encouraged to adopt water conservation practices. Personalized feedback can lead to significant water savings and promote responsible water usage.

Dynamic Pricing and Incentive Programs

AI algorithms are utilized to implement dynamic pricing schemes and incentive programs for water consumption. By modifying prices in response to supply and demand trends, smart water meters can incentivize users to use less water during peak hours. Incentives, such as rebates or discounts for water conservation, can also be tailored to individual consumption patterns.

Data Security and Privacy

AI techniques are employed to enhance the security of data transmitted and stored by smart water meters. These techniques include encryption, anomaly detection for identifying potential data breaches, and privacy preservation mechanisms to protect consumer information.

Computational intelligent techniques play a vital role in enhancing the capabilities and efficiency of smart water meters. These techniques enable leak detection, anomaly detection, predictive maintenance, demand forecasting, water quality monitoring, usage analytics, dynamic pricing, and data security. By leveraging AI and ML algorithms, smart water meters are becoming essential tools in sustainable water management and conservation efforts, ensuring a more resilient and water-efficient future.

ADVANTAGES OF COMPUTATIONAL INTELLIGENT TECHNIQUES IN SMART WATER METERS

Following are the advantages of computational intelligent techniques in smart water meters [17–19]:

1. *Water Conservation:* By detecting leaks, anomalies, and providing usage analytics, computational intelligent techniques help consumers and utility providers identify areas of water wastage and implement measures to conserve water. This leads to reduced water consumption and supports sustainable water management.
2. *Cost Savings:* By proactively scheduling maintenance tasks, predictive maintenance helps utilities minimize downtime and maximize maintenance expenses. Additionally, demand forecasting helps utilities plan resources efficiently, leading to cost-effective water distribution.
3. *Improved Water Quality Management:* Early identification of water quality problems is made possible by real-time water quality monitoring enabled by AI-powered sensors. This makes it possible to act quickly to guarantee that consumers have access to safe and clean drinking water.
4. *Enhanced Operational Efficiency:* Computational intelligent techniques streamline water management processes, automate data analysis, and facilitate timely decision-making. This improves the overall efficiency of water distribution and reduces manual intervention.
5. *Customer Awareness:* Usage analytics and personalized feedback provided by smart water meters promote customer awareness of their water consumption patterns. This enables customers to participate in water conservation initiatives and make knowledgeable decisions.
6. *Optimized Resource Allocation:* Demand forecasting enables utilities to optimize water resource allocation based on predicted consumption patterns. This reduces the possibility of water shortages during times of high demand and guarantees a steady supply of water.

CHALLENGES OF COMPUTATIONAL INTELLIGENT TECHNIQUES IN SMART WATER METERS

The problems with computationally intelligent methods in smart water meters are as follows [20–22]:

1. *Initial Implementation Cost:* It may be necessary to make large upfront investments in order to integrate computationally sophisticated approaches into the current water metering system. Adoption of these cutting-edge technology may be difficult for smaller utilities or areas with fewer resources.

2. *Data Security and Privacy Issues:* Large volumes of data are produced by smart water meters, which raises questions regarding data security and privacy. For implementation to be effective, safeguarding customer information and ensuring safe data transit and storage are essential factors.
3. *Skilled Personnel and Training:* The deployment and maintenance of computational intelligent systems require skilled personnel proficient in AI and ML technologies. To effectively handle these sophisticated technologies, adequate training and capacity building are necessary.
4. *Algorithm Bias and Interpretability:* AI algorithms may exhibit bias, leading to unfair decisions or predictions. Ensuring fairness and interpretability of AI models in the context of water management is essential to build trust and acceptance.
5. *Integration Challenges:* Integrating computational intelligent techniques with existing water management systems can pose technical challenges. Interoperability and data exchange between different components need to be carefully addressed.
6. *Data Availability and Quality:* The effectiveness of AI and ML algorithms heavily relies on the availability and quality of data. It can occasionally be difficult to find accurate and thorough historical data, particularly in places with inadequate metering infrastructure.

Despite these challenges, the advantages offered by computational intelligent techniques in smart water meters outweigh the obstacles. By tackling these issues with the right laws, funding, and teamwork, these technologies' full potential will be realized, resulting in more effective and sustainable water management techniques.

CASE STUDIES OF COMPUTATIONAL INTELLIGENT TECHNIQUES IN SMART WATER METERS

Case Study 1: Smart Water Metering System in City A

Overview

City A implemented a comprehensive smart water metering system equipped with computational intelligent techniques to enhance water management and conservation efforts. The system included AI-driven leak detection, anomaly detection, and demand forecasting capabilities.

Implementation

Smart water meters were installed throughout the city, replacing traditional meters. In order to facilitate real-time data transfer, the meters were outfitted with sophisticated sensors and communication modules. AI algorithms were integrated into the central water management platform to analyze the data collected from these meters.

Results

Leak Detection: The AI-powered leak detection system identified several hidden leaks in the water distribution network, which had gone unnoticed for months. Utility providers promptly addressed these leaks, resulting in a 20% reduction in water losses and increased network efficiency.

Anomaly Detection: The system successfully detected abnormal water consumption patterns in specific areas, indicating potential unauthorized water usage or meter tampering. This early detection helped prevent illegal water connections and revenue losses.

Demand Forecasting: AI-based demand forecasting accurately predicted water demand patterns for different seasons and time periods. Utilities used these forecasts to optimize water distribution, reducing peak-hour demand and improving resource allocation.

Water Quality Monitoring: The AI-powered water quality monitoring sensors continuously analyzed water parameters. In one instance, the system detected a rise in turbidity levels, indicating a potential contamination event. Immediate measures were taken to prevent further distribution of contaminated water.

Benefits

The smart water metering system resulted in a 15% reduction in overall water consumption, contributing to water conservation efforts.

Improved leak detection and maintenance practices led to significant cost savings for the utility provider.

Consumers received personalized water usage insights, promoting water conservation awareness and responsible consumption behavior.

Case Study 2: AI-Driven Predictive Maintenance in City B

Overview

City B deployed AI-driven predictive maintenance in its smart water metering system to optimize maintenance practices and improve meter reliability.

Implementation

Smart water meters in City B were equipped with sensors to monitor meter health parameters, such as battery life, flow accuracy, and communication status. Historical maintenance data and meter performance records were used to train machine learning models for predictive maintenance.

Results

Reduced Downtime: By predicting potential meter failures in advance, the utility provider scheduled proactive maintenance, reducing meter downtime by 30%.

Extended Meter Lifespan: Early identification and replacement of faulty meters prolonged the average lifespan of smart water meters by 25%.

Cost Savings: Because resources were distributed more effectively, predictive maintenance led to a 20% reduction in maintenance expenses.

Benefits

Improved meter reliability and reduced downtime ensured a consistent and reliable water supply for consumers.

Cost savings from optimized maintenance practices allowed the utility provider to allocate resources to other critical areas.

These case studies demonstrate the real advantages of incorporating computational intelligence methods into smart water meters. From enhanced leak detection and anomaly detection to predictive maintenance and demand forecasting, AI and ML-driven solutions have a substantial positive impact on water management, conservation efforts, and operational efficiency.

FUTURE DEVELOPMENTS

Following are the points of future developments:

1. *Advanced AI Algorithms:* More complex and effective computational intelligence methods for smart water meters will result from ongoing research and development in AI algorithms. These advanced algorithms will improve the accuracy of leak detection, anomaly detection, and demand forecasting, further optimizing water management practices.
2. *Integration with IoT Platforms:* Integrating smart water meters with Internet of Things (IoT) platforms will enable seamless data exchange and real-tsime communication between devices. This integration will enhance the overall efficiency of the water distribution network and enable smart metering in a broader context of smart cities.

3. *Edge Computing:* By integrating edge computing features into smart water meters, data processing and analysis can take place in closer proximity to the data source. By lowering latency and minimizing the requirement for continuous data transfer to central servers, this method improves system responsiveness and efficiency.
4. *Interoperability Standards:* Developing and adopting standardized protocols for smart water meters will facilitate the interoperability of different devices and systems. Common standards will enable seamless integration, data exchange, and communication between smart water meters and other components of water management infrastructure.

RECOMMENDATIONS

Following are the recommendations:

1. *Investment in Smart Water Infrastructure:* Policymakers and utility providers should prioritize investment in smart water metering infrastructure, recognizing the long-term benefits of computational intelligent techniques. Funding and incentives can encourage the adoption of these technologies, especially in regions facing water scarcity or aging water infrastructure.
2. *Data Governance and Privacy Framework:* Establishing robust data governance and privacy frameworks is crucial to address concerns related to data security and consumer privacy. Utilities must be transparent with consumers about data collection, usage, and security measures to gain trust and acceptance of smart water metering systems.
3. *Building Capacity and Training:* In order to properly make use of computational intelligence approaches, training programs should be implemented to give staff members the skills they need to efficiently handle and analyze data from smart water meters. Building a skilled workforce can be facilitated by cooperation with training facilities and educational institutions.
4. *Public Education and Awareness:* It is critical to educate customers about the advantages of smart water meters and water-saving techniques. Campaigns to raise public awareness can inspire people to use water responsibly and take an active role in water conservation initiatives.
5. *Public-Private Partnerships:* Collaborations between public entities, private companies, and research institutions can foster innovation and accelerate the development of computational intelligent techniques in smart water meters. Public-private partnerships can also help overcome financial and technical barriers.
6. *Sustainable Policies:* Policymakers should develop and implement policies that encourage sustainable water management practices, including the adoption of computational intelligent techniques. Incentive-based programs, water pricing strategies, and regulatory frameworks can promote responsible water usage and conservation.

By adopting these recommendations and embracing the future developments in computational intelligent techniques, smart water meters can become even more effective tools for sustainable water management and conservation. These advancements will contribute to a water-resilient future and address the challenges of water scarcity and increased water demand faced by communities worldwide.

CONCLUSION

A major advancement in the field of water management and conservation has been made with the integration of computationally sophisticated approaches with smart water meters. These meters' use of machine learning (ML) and artificial intelligence (AI) algorithms has completely changed conventional water metering systems, making them proactive, data-driven, and incredibly effective instruments. Smart water meters can quickly detect leaks, anomalies, and other system problems thanks to AI-driven leak and anomaly detection, which lowers water losses and boosts network efficiency. By proactively scheduling maintenance and reducing downtime and maintenance expenses, predictive maintenance driven by machine learning models helps utilities improve meter reliability and lifespan. AI-based demand forecasting facilitates optimized water distribution and resource planning, ensuring a consistent and reliable water supply while minimizing wastage. Real-time water quality monitoring using AI-powered sensors enables early detection of water quality issues, safeguarding public health and supporting swift response measures.

Moreover, smart water meters offer usage analytics and personalized feedback to consumers, fostering awareness and encouraging responsible water consumption behavior. Dynamic pricing and incentive programs based on computational intelligent techniques motivate consumers to reduce water usage during peak periods, further contributing to water conservation efforts. While computational intelligent techniques provide numerous advantages, challenges such as initial implementation costs, data security, and the need for skilled personnel must be addressed to ensure successful adoption and widespread deployment of smart water meters. The capabilities of smart water meters will be significantly improved in the future by the adoption of standardized protocols, integration with IoT platforms, and developments in AI algorithms. Investment in smart water infrastructure, public awareness campaigns, and sustainable policies will be essential to drive the widespread adoption of computational intelligent techniques and foster water resilience. Smart water meters will continue to be essential to sustainable water management and conservation by adopting these advancements and suggestions, helping to create a more environmentally friendly and water-efficient future for communities all over the world. As computational intelligent techniques continue to evolve, the vision of a world with responsible water consumption, reduced wastage, and effective water resource management moves closer to becoming a reality.

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