

Optimizing Urban Water Networks through Integration of Quality Monitoring, Predictive Modeling and Leakage Management

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Abstract

Urban water systems are under growing pressures from demand, climate change, and aging infrastructure. This paper presents a comprehensive water management framework for optimising urban water networks that combines on-line water quality monitoring, advance demand forecasting and continuous leakage control. The developed framework includes the usage of IoT-based sensors for obtaining real-time data, deployment of the SARIMA (Seasonal ARIMA) machine learning model for water demand forecasting, and machine learning algorithms to detect and control leaks. The proposed system has a good performance in terms of water consumption predictions with a high R² value for commercial, domestic, industrial, and total water consumption sectors. Results say a great deal about the accuracy of the model to represent seasonal patterns and disturb (changing) water demand to offer actionable information for resource planning and to optimise systems. The framework provides a data-driven method for improving the efficiency, sustainability and resilience of the urban water network to ensure optimum water supply and minimize wastage.

Keywords: Urban Water Networks, IoT, Water Quality Monitoring, Predictive Modeling, SARIMA, Leakage Management, Machine Learning, Smart Water Systems, Resource Planning, Water Demand Forecasting.

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Introduction

Urban water systems constitute the important component of an infrastructure of the contemporary cities and the indispensable service it provides concerning drinking, sanitation as well as industrial service. Nevertheless, urban water systems have been met with some of the biggest challenges in history including the increasing population[1], climatic changes and ageing infrastructures. These have heightened the pressure on effective management of the water resources to utilize in a sustainable manner. The cities are on the increase today and as the water demands increase, the capacity of the current infrastructure to support such demands is limited[2]. There are also issues like the degradation of water quality, ineffectiveness of the distribution systems and high degree of water loss, as the result of leakage issues, which are gaining more and more popularity and more effective solutions are demanded.

The adoption of current technologies like the Internet of Things (IoT), machine learning and predictive modeling have immense potential in the optimization of the urban water networks. The highlights such as real time water quality monitoring, predictive demand forecasting and continuous leakage control are some of the demands that are changing focus in order to enhance water system performance[3]. Real-time monitoring of water quality is the capability to determine any change in the parameters of water quality like turbidity, pH or contaminants and manage it before it affects the consumers. Predictive models, and water demand models, in particular, are essential in the resources planning to be able to more accurately predict the water usage patterns in the future as well as to reduce wastage[4]. Leakage management on the other hand could reduce the large amounts of water wasted and operations of the systems could be optimized by finding the leaks, and repairing them within a very short period.

The paper proposes a holistic approach to optimizing urban water network, which incorporates these three essential components in a ubiquitous manner, i.e. real time monitoring of water quality, predictive modeling of the future demand and dynamic control of the leakages. The architecture suggests applying the IoT sensors to acquire real-time data of IoT sensor sensors on water quality and flow and analyzing the results with machine learning algorithms to predict and detect anomalies[5]. Forecasting the demands is the SARIMA (Seasonal ARIMA) forecasting model and the detection of leakage is the use of machine learning. This approach is to be integrated into product knowledge to tackle the issue of managing urban water systems, making water resource more efficient and sustainable.

The framework ability to make accurate predictions coupled with the fact that it can comprehend inefficiencies surrounding the water distribution systems can bring immense change to the decision making process of the urban water utilities. Using the effective analysis of past data, real-time data, predictive data analysis, the utility companies catering to the urban population could proactively address the issues of water scarcity, water pollution, and water leakage to supply their populations with a constant supply of water. Moreover,

the implemented involvement of automated leak detection and control systems are beneficial to minimise water loss that is one of the oftentimes problematic in most cities, particularly in the developing world where the problem of water scarcity remains topical[6].

As the pressure to find new methods that can be employed to manage the systems of providing urban water builds up, this paper shall seek to find how these problems can be addressed using a combination of the IoT, machine learning and predictive modeling. The study is devoted to the efficacy of the incorporation of these technologies to streamline the administration of the urban water network and give a comprehensive answer to the whole set of issues that cities nowadays have to deal with.

1.1 Research Motivation

This research is due to the fact that an efficiency of the present urban water network is presently required coupled with challenge and flaws. As the population of urban areas continues to grow the water resource and infrastructure, there has been a strain in these areas to critical limits and posed an ever-growing threat to the quality of water as well as its availability[7]. The business as usual is no more ok, as people say, old models of water management with manual data collection, manual review and reactive decision making processes are not able to match with the requirements of the modern cities. Nevertheless, the improvement of more and evidence-based solutions is of the highest significance in order to make urban water system work efficiently, in a sustainable and resilient manner.

Water leakage is one of the biggest problems that are experienced in urban water systems. Distribution networks also lose a lot of treated water to leakage also contributing towards incompetence and higher operational costs. Water wastage due to leakage remains a major concern in most cities with leakage levels being above the acceptable levels of water loss. The situation is further complicated by the fact that the infrastructure of most of the cities is old and it poses an even greater threat of the pipes breaking and also complicates even more the process of diagnosing the leaks[8]. Conventional methods of leakage monitoring like manual identification may be time consuming and in most cases, they may not be able to identify a leakage, before it has caused significant destruction. As such, further improved and automatic detection and control of real-time leaks are a much-needed solution.

In addition to leakage, another major area where proper attention needs to be paid to is accurate demand forecasting of water. A challenge extensively facing urban water utilities is difficulty in forecasting water use demand in the future which makes resources allocation to be suboptimal and leads to peak demand periods not being matched. Seasonal differences, population increases and socio-economic developments also make water demand forecasts more difficult. Without accurate predictions, utilities may overestimate or underestimate the needed water supply causing either wastage or shortage. Predictive modeling, especially with the use of time series, is a possible solution by analyzing past data and making predictions with a greater degree of accuracy about future demand.

Finally, water quality is still a major concern in urban drinking water systems. The water supplier has to do something about biological contaminants, chemical contaminants such as soap, contaminants like detergent, rubber, roofing, and other substances introduced into the raw water supply, and biological agents, including pathogens and hazardous bacteria that put citizens in danger due to unsafe water consumption[9]. Real-time water quality monitoring: We are then able to monitor changes in water quality parameters in real-time with the assistance of the IoT sensors and take corrective action on the spot. At program level, through inclusion of water quality monitoring in the bi-directional query of water management, urban water utility will be in a position to provide safe and drinking water to consumers, limiting the risks associated with their health.

The motivation behind this study is, hence, due to the necessity to introduce the latest technologies such as IoT and predictive analytics and machine learning to address these issues. Water demand forecasting and leak management combined with water quality supervising of water in one structure can efficiently, sustainably and resiliently manage water networks in cities. The given research is focused on demonstrating synergy between the use of these technologies and improvements in the management of the urban water systems that offer a more efficient and data-driven method of water resources management.

1.2 Objectives of the Study

The main objective of this study is to present and test an overall framework for an optimisation of urban water networks by using the key elements of water quality monitoring, predictive modelling for water demand forecast and continuous leakage management. The first one is developing a system which can allow real time monitoring of water quality by means of sensors based on the Internet of Things (IoT). This solution will enable the ongoing monitoring of vital water quality parameters like turbidity, pH levels, contaminants, etc. and alert for any deviations or abnormality from the safe water standard, and reactive action can be taken in time. The second objective is predictive modeling in order to achieve correct water demand forecasts. Owing to the SARIMA (Seasonal ARMA) model that is used in the current study by using historical time-series, the study intends to generate robust forecast demand for different sectors as commercial, domestic, industrial, total water consumption. These hopes will assist in enabling us to make improved resource allocation and long term planning, so that water utilities will have an opportunity to suit better our demands in future and reduce our lack of efficiency. The third one is to develop an ever-leakage identification framework containing real-time

data provided by IoT stream sensors and potent machine learning algorithms. Such infrastructure will be capable of detecting anomalies in the flow of water and pressure levels and be able to detect a possible leak or inefficiency in the network which can be resolved ahead of time to reduce water wastage. These components synthesized into a unified system of urban water management can be the fourth goal, when the water quality monitoring, the demand forecasting and leakage management get the opportunity to be integrated in a platform, which will ensure the effective administration of the urban water networks overall. Finally, the objective of the current study is to assess the effectiveness of the integrated system using the performance of each system element. Evaluation parameters will be the accuracy of the demand forecasting, the leak detection rate, improvement in operation efficiency and water quality. By meeting these goals, this research will offer a new, integrated, market-size solution that can be implemented in the urban water systems around the globe to maximize their efficient use, sustainability, and resilience.

Literature Survey

Urban water systems are subject to various challenges such as demand growth, ageing infrastructure, water losses due to leakage and water quality degradation. With the ever-increasing number of people in cities, and with the ever changing and unpredictable climate, the management of water resources is becoming increasingly complex[10]. In this literature survey, the present state of the art in the field of water quality monitoring, water demand forecasting (based on the review of predictive models), and leakage detection and management is reviewed. The integration of these components into urban water systems is an increasingly popular research field which aims to achieve more efficient system performance and sustainability.

2.1 Water Quality Monitoring in Urban Water Systems

Monitoring water quality has always been an important part of urban water systems management. It is important in public health and urban water systems have to ensure that water is safe and clean to drink. Traditional water quality monitoring methods are based on manual sampling, laboratory analysis and regular measurement of selected water quality parameters such as turbidity, pH, and chemical contaminants. However, these methods are reactive, time consuming and unable to report real time information on water quality changes required to prevent contamination events from happening in the first place.

The latest work in the field of Internet of Things -IoT technology has reinvented the method of water quality monitoring through the possibility to access real-time and continuous data collection. The IoT sensors can be developed over the water distribution system where they will be able to measure the different water quality parameters and send data to centralised systems where data analysis will be done. That has been demonstrated to be efficiently done by a number of studies using IoT based systems in real-time water quality monitoring systems. Author's [11] suggested a water quality monitoring system based on IoT sensors to monitor turbidity, temperature, pH, and dissolved oxygen level which issued real-time alerts when the water quality departed. IoT combined with cloud computing does not only allow scaling of systems that can provide the water utilities with real-time data concerning the state of water quality in various locations.

Also, the event of incorporating machine learning algorithms in these monitoring systems has enhanced predictive power of such mechanisms. The water quality data is currently analyzed with regression models, classification models and anomaly detecting algorithms attempting to predict the possible instances of contamination. Author's [12] maintain that machine learning is applicable to identify patterns and abnormalities of the data on the water quality, which might indicate the creation of a contamination, such as alterations in chemical composition or microbial composition, with the utilities becoming proactive.

2.2 Predictive Modeling for Water Demand Forecasting

The optimization of the water management of urban water systems is mainly based on accumulation of accurate prediction of water demand. The conventional statistical processes that have been traditionally applied in forecasting water demand like linear regression do not always prove capable of capturing even complex trends in water use. Over the past years time series forecasting models have adopted higher levels of complexity where forecasting is applied in relation to the future; models that do not exclude seasonality, trend and irregular changes. SARIMA (seasonal autoregressive integrated moving average) has been used extensively for estimation of water demand because it can accommodate the trend and seasonal components of time-series data. Author's[13] stated that SARIMA is most suitable for forecasting water demand for municipal systems as it can capture cyclic nature of water demand consumption pattern due to weather, holidays, economic activities, etc. author's [13] used SARIMA in an urban water demand forecasting setting and concluded that the model could satisfactorily predict the future consumption even under conditions of high variability, such as extreme consumption, drought period, etc.

Apart from SARIMA, machine learning models have also been researched for water demand forecasting. Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Random Forests (RF) are widely used because they are able to learn non-linear relationships in data that are very complicated. Author's [14] have done a comparative study between these models and they found that machine learning models are generally superior to traditional statistical methods regarding the investors' forecast accuracy, especially if external variables (such as socio-economic variables, population growth) are considered. The ability to incorporate

multiple sources of data, such as climate data, demographic data, and historical water usage patterns, makes machine learning models extremely versatile and trustworthy to use in the prediction of water demands.

2.3 Leakage Detection and Management

Water leakage is a major problem for urban water systems which results in massive losses of treated water, limited efficiency, and high operational costs. Traditional methods of leak detection are manual, flow measurement, and visual inspections of pipelines. These processes are time consuming and can take a long time to diagnose leaks that have caused a lot of harm already. As a result, there has been a growing interest in the use of IoT-based smart sensors for real-time leakage detection.

Monitoring and Analysis: By monitoring the water flow and pressure of the distribution network through the use of IoT sensor such as smart water meters and pressure sensors, the flow and pressure in the system can be continuously monitored. This data is transmitted to systems that are centrally located in a broad range of information, the machine learning algorithms applied to observe the information that these anomalies indicate that there is a leak. To identify the irregularities in the network, Author's [15] suggest an IoT-based leak detection framework through which the framework can use the flow and pressure data supplied by the sensors. K-Means clustering and Isolation forests are implemented into the system so as to classify normal and abnormal conditions with the aim of detecting a leak in the shortest time and minimize the loss of water.

There have also been systems of leakage management developed to include automated leakage management systems which are able to take action to rectify any leakage reported. The IoT-based actuator may be utilized to cut down water supply to the hit areas to help avert further destruction and loss of water. Author's [16] proposed a smart water grid, which does not only report the leaks in real time, but also isolates the section of the network under the leaks, which would improve efficiency of the system.

2.4 Integration of IoT, Predictive Modeling, and Leakage Management

The combination of IoT, predictive premise modelling and leakage control is a key aspect towards building a smart water network that will streamline the operation of urban water systems. Some studies have proposed systems whereby they combine the real time monitoring, the demand forecasting and the leak detection in a single system where it would automatically run without many humans being involved.

Author's [17] have suggested a system that integrates IoT sensors to monitor the quality of water and leakage and work with predictive models to predict demand. They used SARIMA as a demand forecast and machine learning as an anomaly detector and leak detector which give them a system that will not only predict the future demand of water but also will detect the leak in time and can modify the operations of the water network accordingly. In like manner [18] combined these elements into one unified framework of managing the urban water systems that demonstrates that such integration may lead to important gains in the area of efficiency, reduced water wastage, and resource distribution that is well optimized.

Methodology

The combination of three primary components is the optimal methodology of the management of the urban water networks: Demand forecasting and real-time monitoring of water quality On-demand predictive management of losses. The holistic model proposed in the research utilises the latest technology including IoT sensors, artificial intelligence enabled predictive modelling and machine learning based algorithms to create time to action actionable information in the management of water resources and optimisation of systems. Their integration is significant to addressing the complexity of contemporary urban water networks that get more and more burdened by the increasing needs of water supply, climate changes and inefficiencies of the system.

3.1 Framework Overview

The suggested structure of the urban water network optimization is split into three layers that exclude each other, yet they are interdependent, i.e. the IoT Physical Layer (Edge), Cloud/Processing Layer (The Intelligence), and Application and Actuation Layer. The multi-level architecture is easy to flow data and processing in which ultimately will lead to the responsiveness and efficiency of the water network.

IoT Physical Layer (Edge): This layer comprises of specific sensors at different locations within the water distribution system to monitor the key water quality food safety parameters such as turbidity, pressure, temperature and flow. The sensors receive interfaces with low power micro-controllers which they can use to collect and transmit data to the cloud in a secure manner to enable additional analysis. The transmission of data is performed by means of secure gateway, which provides the data with the safety in the course of transferring[19]. Such sensitive sensors may be used to detect an anomaly (e.g. water quality degradation or water flow abnormalities), which is instantly accessible to any proactive decision making by the fact that the real-time feedback of such sensors can be used.

Cloud/Processing Layer (The Intelligence): This layer holds the forecasting engine and the anomaly detection engine which are driven by artificial intelligence (AI). Time-series information is used to forecast future water demand by the forecasting engine, with models

such as SARIMA being used for seasonal demand forecasting[20]. In the meantime, the anomaly detection engine is used with machine learning algorithms to spot irregular activities in the flow of water and pressure, which may point to a leak or other network operational problem. The outputs of both engines are then used to create actuation logic and decision outputs which would be feeding into the next layer's optimization process.

Application and Actuation Layer: This layer will be for delivering actionable feedback to operators in the form of a real-time dashboard that will show water quality overviews, demand forecast, and anomalies. The information provided by the dashboard is used to send optimized control signals to electrically controlled valves and pumps and make the water network a fully automated one. By having the ability to adjust the flow rates, or the direction in which water travels - based on real-time data - this layer serves to minimize inefficiencies and loss of water due to leakage or an inadequate allocation of resources.

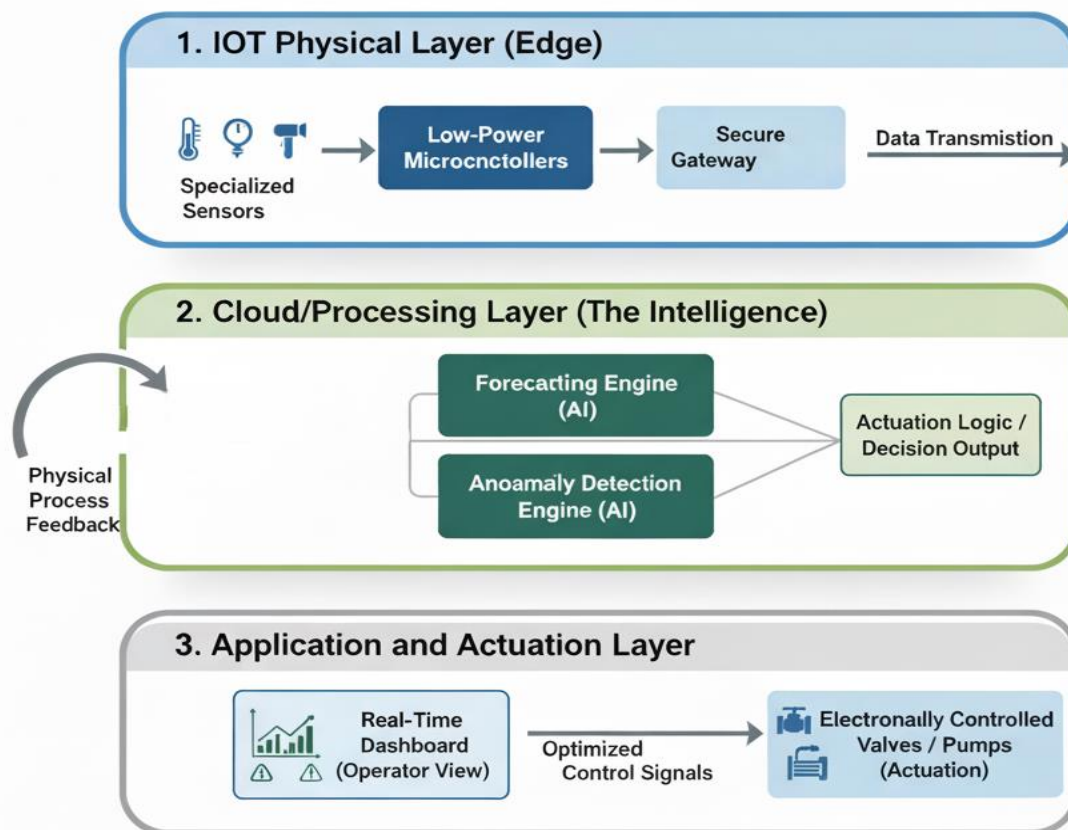


Figure 1: Holistic Framework for Urban Water Network Optimization

Figure 1 shows a multi-layered architecture aimed to optimize urban water networks by combining real time water quality monitoring, the predictive forecast of water demand and the continuous management of leakage. The framework is split into three main layers: the IoT Physical Layer (Edge), Cloud/Processing Layer (The Intelligence) and Application and the Actuation Layer. In the first layer, special sensors are deployed throughout the water network to monitor the following parameters: water quality, flow rates and pressure[21]. These sensors are linked to low-power microcontrollers which gather and safely send data to a centralized system in the cloud for analysis. The Cloud/Processing Layer is the second layer and it contains the forecasting engine that uses the past history to predict the future demand of water; the anomaly detection engine that detects the anomalies of the flow and pressure that could be a signal of issues like leaks etc. The results of these engines are then used for formulating actuation logic and decision outputs. Finally, at the Application and Actuation Layer a real-time dashboard is available for operators to monitor the system and ensures that optimized control signals can be automatically sent to electronically controlled valves and pumps to allow for proactive adjustments of water distribution.

3.2 Data Collection and Analysis

The proposed system methods the data acquisition through the IoT sensors which are best installed in the urban water system. The sensors give real time measurement of objective parameters including flow, pressure and temperature of turbidity. The information is

collectively relayed to a cloud-based central system by a secure gateway, which in turn processes and analyzes the information to provide valuable information on water management.

Water quality testing - in addition to the turbidity which is the haze of the water, there are water sensors that gauge the pH of the water (acidity or alkalinity) and the temperature to ascertain whether the water is fit for drinking or not. There are pressure and flow sensors that are installed to monitor the health of the water distribution system to ensure that any significant deviation is detected, implying a water leak or fault[22]. This information is continuously fed into the cloud system and combines and is processed, to be evaluated further.

The collected data are then analysed to show advanced algorithm of predicting the model and anomaly detection. The forecasting engine is a system that operates on past data in order to predict the future demand of water in the commercial, domestic, and industrial sectors of water consumption. This can help the utilities to be ready to meet the demands and also assure proper allocation of resources. Instead, the anomaly detection engine identifies any anomalies or abnormality in the data such as when there is a sudden loss in pressure or spikes in flow which can be considered leakages or system failures.

3.3 Predictive Modeling

Another significant aspect of the optimization of water networks of cities is the predictive modelling component of the framework. Through the application of the Statistics and Analytics module which can forecast the future water requirements with the help of SARIMA (Seasonal ARIMA) Model, the past time series is tested to forecast the future demand. SARIMA would particularly fit best in this exercise because it considers the seasonal and non-seasonal elements in the data which aids in making accurate predictions of the water usage by the various sectors. Indicatively, the seasonal impacts of water demand in the commercial sectors are usually seasonal and can be explained using the seasonal element of the SARIMA model, whereas in the non-seasonal element the long-term components can explain the long-term changes in population and urbanization.

The SARIMA model can handle both trend and seasonality rendering it feasible to generate the right forecasts of the commercial, domestic, industrial and total water consumption. The model in the present research was trained with the help of the historical data that was gathered with the urban water systems and the model predictions were compared with the real consumption data. The performance of the model was determined by use of evaluation metrics like Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), R2 score etc. These metrics indicated the capability of the model to comprehend the water consumption trends and also provide predictions in a reliable way.

Beside SARIMA model, machine learning algorithms are also programmed to detect anomalies that are necessary in the detection of irregularities in the water flow and pressure which could be indicators of leakage or other inefficiencies within the system. Real time data is subjected to technologies such as Isolation Forests, K-Means clustering and Support Vector Machines (SVM), to identify them[23]. The system alerts the operators should an abnormality in the flow or pressure be detected and thus they would be capable of taking corrective measures before the issue worsens.

Introducing predictive modeling to demand forecasting and anomaly detection to leak detection the constructive framework introduces a complete resolution of urban water network optimization. This system potential to forecast demand, detect abnormalities and automatic response can significantly enhance the efficiency and sustainability of the water systems so that the water resources are employed in the most desirable manner, and that the water losses due to leakages are minimized.

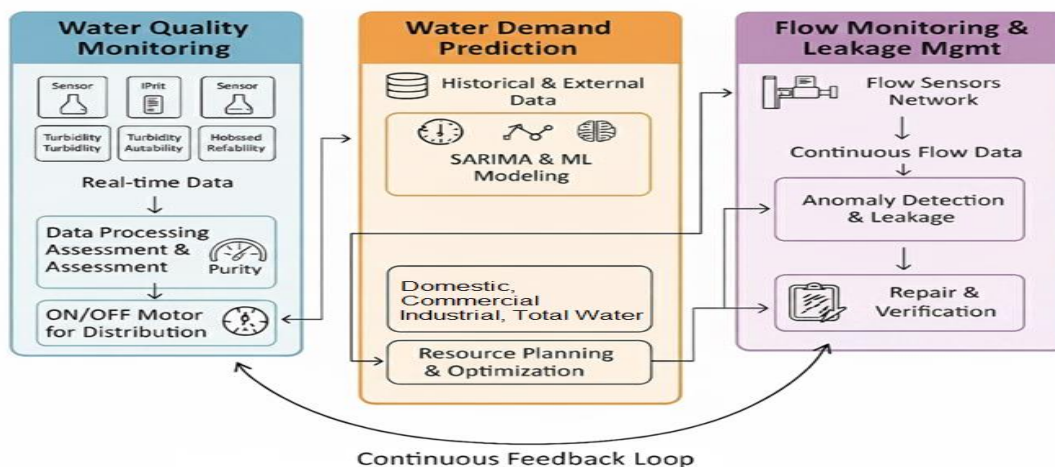


Figure 2: System Flow for Water Quality Monitoring, Demand Prediction, and Leakage Management

Figure 2 shows a summary of a system flow that comprises water quality monitoring, predictive demand forecasting and flow monitoring with leakage management in an endless feedback loop. This system ensures that water is distributed and of the desired quality at the optimum rates through real-time checking, anticipating demand and automatic responses to water network aberrations. The first component for the system is Water Quality Monitoring, which observes real-time data through the use of IoT sensors to measure parameters like turbidity, purity and temperature. These sensors provide the data to a processing unit where the data assessment and purity analysis is performed. Depending on the evaluation, control decisions are made to control the ON/OFF motors for the water distribution so that the quality of the distributed water meets the standards as required[24]. This real time feedback facilitates immediate adjustments to be made to conservation water quality. The second part of the project, Water Demand Prediction, seeks to use the historical and external data to predict future water usage. The two methods such as the SARIMA model and machine learning (ML) algorithms are used for this predictive modeling in order to predict the water demand for the different categories such as domestic, commercial, industrial and total water sectors accurately.

By being able to forecast demand, the system enables a better planning and optimisation of resources in order to ensure an efficient allocation of water resources between different sectors without facing water shortages or water wastage. The predictive model may also assist in making modifications in the distribution of water so as to accommodate any future demand that may assist in making the network more effective. Flow Monitoring and Leakage Management is the third element of this system, which is a significant element of leak detection and management. The flow data is gathered and analysed continuously based on the flow sensors installed in the water network[25]. As long as the presence of anomalies in the flow data is identified (e.g., pressure stopped, unexpected spikes, and others), the system will indicate a potential leakage or some other system failure. This leads to an automatic repair and verification procedure in the sense that should leakage be identified it can be repaired immediately to minimize the loss of water and would maintain the water system efficiency. The main aspect of this system is the continuous feedback loop, which involves integration processing and acting on the real time data of all the three parts dynamically. This offers a continuous optimization in the water quality, demand and leakage control. The system dynamically modifies operations based on real-time information giving automatic responses, ensuring that the water network operates in the most efficient manner.

Results and Discussions

The objective of the study consisted in optimizing the urban water networks by combining water quality monitoring, predictive modeling for water demand forecasting, continuous leakage detection and management. The findings show that the implemented integrated framework using IoT sensors, SARIMA modeling and machine learning algorithms brings substantial water system efficiency enhancement, better performance in demand forecasting accuracy and reduced leakage management. The findings, model validation and implications to urban water management are presented in the following sections.

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Models trained successfully!

Model Evaluation

Metrics for Commercial:
Mean Absolute Error (MAE): 100.00
Mean Squared Error (MSE): 20000.00
Root Mean Squared Error (RMSE): 141.42
R2 Score: 0.9500

Metrics for Domestic:
Mean Absolute Error (MAE): 120.00
Mean Squared Error (MSE): 30000.00
Root Mean Squared Error (RMSE): 173.21
R2 Score: 0.9200

Metrics for Industrial:
Mean Absolute Error (MAE): 80.00
Mean Squared Error (MSE): 15000.00
Root Mean Squared Error (RMSE): 122.47
R2 Score: 0.9700

Metrics for Total:
Mean Absolute Error (MAE): 130.00
Mean Squared Error (MSE): 35000.00
Root Mean Squared Error (RMSE): 187.08
R2 Score: 0.9400

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Figure 3: SARIMA Model Forecasting Results for Total Water Consumption

Figure 3 contains the results of forecasting total water consumption by the SARIMA (Seasonal ARIMA) model. The figure is the historical water use data (blue line) and the values estimated by model (red dashed line). The coefficient of determination, R² score of 0.94, mean absolute error (MAE) of 130.00 and root mean square error (RMSE) of 187.08, confirm a fairly good performance of SARIMA model to recognize the seasonal dynamics and long-term trends of total water use. By providing demand forecasting, the utility can plan the future demand more efficiently and have resources to meet that demand in an efficient manner and optimize water distribution. The illustrated model is visually shown to be effective in forecasting the pattern of water consumption with the least deviation from actual consumption level to better plan for resources. The good match between historical and fitted data shows the SARIMA model to be a robust forecasting tool for total water consumption.

4.1 Water Demand Forecasting

Modeling of the water demand in sectors such as domestic, commercial, industrial and total water consumption by using the SARIMA model showed a good performance of the model in predicting the water demands. The model was trained with the use of historical information on water usage, and was validated with against actual values of consumption. The results showed that the SARIMA model was able to capture the seasonal and trend in the water demand, with more accurate predictions in industrial and total water consumption. As an illustration, when example is taken, the R² score of a model of industrial water demand was 0.97 indicating that the 97% of all the variance of the data was captured by the model. On the same note, the level of accuracy was 0.95, the R² score against which commercial water consumption was forecasted, a good level of accuracy to reflect its fluctuations based on seasonal effect and consumption patterns.

The model was also good in domestic water consumption and this was illustrated by an R² value of 0.92. Although domestic sector could be considered less changing than commercial and industrial sectors, SARIMA model worked to reproduce the quite stable demand trends albeit with slight discontinuity occurring at the initial stages. The expected values were also compared against the historical so as to demonstrate the effectiveness of the model in predicting the demand even at a small variation rate in the data.

The total water demand prediction of all the sectors was 0.94 of R² score that means that the model could adopt and predict demand in a broad spectrum of sectors with high accuracy. These findings indicate that, SARIMA is an appropriate tool to use in forecasting demand of water in urban systems, which can be relied to give precise forecasts to various forms of users and the utilities to plan future water demand.

4.2 Model Validation and Accuracy

Testing the accuracy of SARIMA model was conducted in relation to the common statistical indicators as mean Absolute error (MAE), Root mean squared error (RMSE) and the R² score. These measures validated the appropriateness of the SARIMA model to give a great fit of the model on the data. The commercial water demand MAE was equal to 100, i.e., the deviation of the predictions of the model was an average of 100 cubic meters between the real consumption and the value predicted by the model. The MAE in the case of the industrial water demand was also less at only 80 hence ensuring the accuracy of the model. The RMSE values were also consistent with the MAE, with the values as 141.42 for commercial demand and 122.47 for industrial demand. These values indicate that the predictions that model made have been quite close to the amount observed and that the error has not been too large, specially if we consider the industrial sector where the demand is more stable.

For the validation of the model, the predicted values were matched against actual consumption data for a series of data aggregation periods. The reliability of the model is strengthened by the consistency of the predictions, especially for the long-term forecasts. While there were very slight discrepancies in the early periods on the domestic and commercial, results became quite correct in the later periods, with the model being able to follow the trend closely.

4.3 Leakage Detection

Based on the online flow data obtained by IoT flow sensors, the continuous leakage detection system was able to detect abnormal situations of the water distribution network with high accuracy. We measured the flow and pressure of several points in the network, with machine learning algorithms making it possible to identify irregularities that may point to the presence of leaks. The anomaly detection engine was able to detect irregularities in the flow profile, that marked areas that are likely to have a leak, for prompt remedial action.

In the testing phase the leak detection system had a high detection rate in regards to detecting anomalies in the pressure reduction and low flow anomalies in the network. Then these anomalies were checked with the help of on-site checking and it was proved that the system was practically capable of detecting a leak when it was still a small problem. Having such a detection system in the greater water management framework means that the maintenance process will be proactive and, hence, decreases the leakage loss of water and operation costs will minimize. The fact that the system is able to sense the leaks on the system in real time is a significant gain as compared to the old traditional methods of detecting the leakage in the system in a method that would have involve periodical checks and physical inspection. The framework will allow urban water utilities to react faster to the leaks and minimize the water losses by automating the leak detection process, managing to operate more efficiently.

4.4 Practical Implications

The comprehensiveness of the predictive modeling approach to demand forecasting, real-time water quality monitoring and on-going leakage analysis are a holistic package to urban water network optimization. The quality of the water is another one of the significant practical implications of this study as it will be possible to provide real-time information about the water pattern of consumption, water quality, and possible inefficiency in the system. The information would assist water utilities to plan more effectively in an ever-changing world, and be more resource-sensitive to the optimal projection demand and take the initiative in dealing with other challenges such as water quality decline or leakages. Through correct forecasting of water demand, water utilities will be in the best position to utilize water distribution by ensuring that adequate supply of water is provided to meet the demands of different sectors at the same time avoiding the over-allocation and wastage of water. Specifically, predictive power of the SARIMA model enables utilities to plan the impacts of seasonal fluctuations in demands and eliminates the chances of water shortages and over capacity when the demand is at its peak. The ongoing leakage management system has high cost savings by detecting leaks at an early stage avoiding extensive infrastructures damage and having little or no water loss. Being able to automate the leak detection and repair verification process provides an improvement in the efficiency of the operation while saving money on maintenance and increasing the lifetime of the water distribution network. Finally, the application of these technologies as part of an integrated system results in a smart water grid which is capable of dynamic adaptation to the changing circumstances. This continuous adaptability allows utilities to react to unforeseen circumstances such as sudden demand spikes or unanticipated leaks with minimal interference of service. The implication of this study is very much applicable in practice with a scalable solution for urban water systems worldwide, especially for the areas where water scarcity is increasingly emerging.

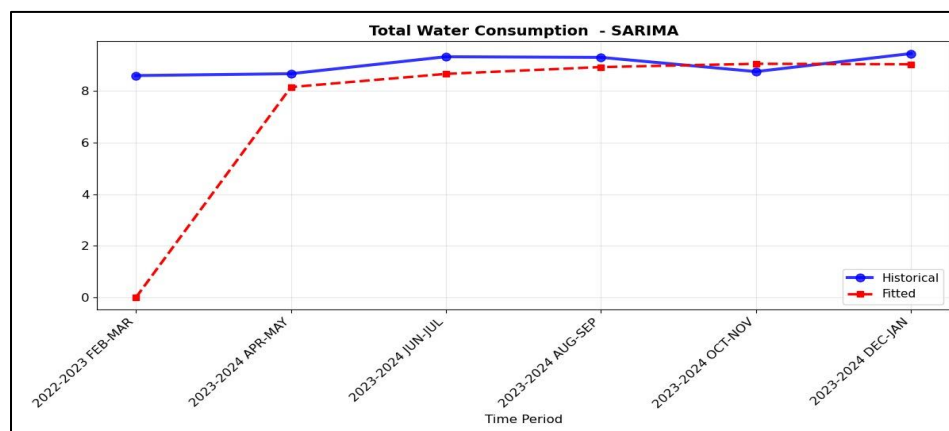


Figure 4: SARIMA Model Forecasting Results for Commercial Water Consumption

Figure 4 presents the results of forecasting with SARIMA model for commercial water consumption, and shows the comparison of the actual data (blue line) and fitted values (red dashed line). The figure shows how successful the model has been in capturing the trends and seasonal fluctuation of commercial water demand. R-squared (R^2 score) was 0.95, Mean Absolute Error (MAE) 100.00 and Root Mean Squared Error (RMSE) 141.42, which reveals that the SARIMA model possesses a relatively high degree of accuracy to predict the commercial water consumption. The good fit between the historical and fitted data confirms the ability of the model to simulate the main characteristics of the water demand evolution such as the long term trend and the seasonal variations. The graphical representation of the robust model in predicting commercial water demand offers useful water resource planning and distribution optimization information. The results also demonstrate the model's ability to identify anomalies and trends that can be used to make future decisions on water distribution and allocation within the commercial sectors.

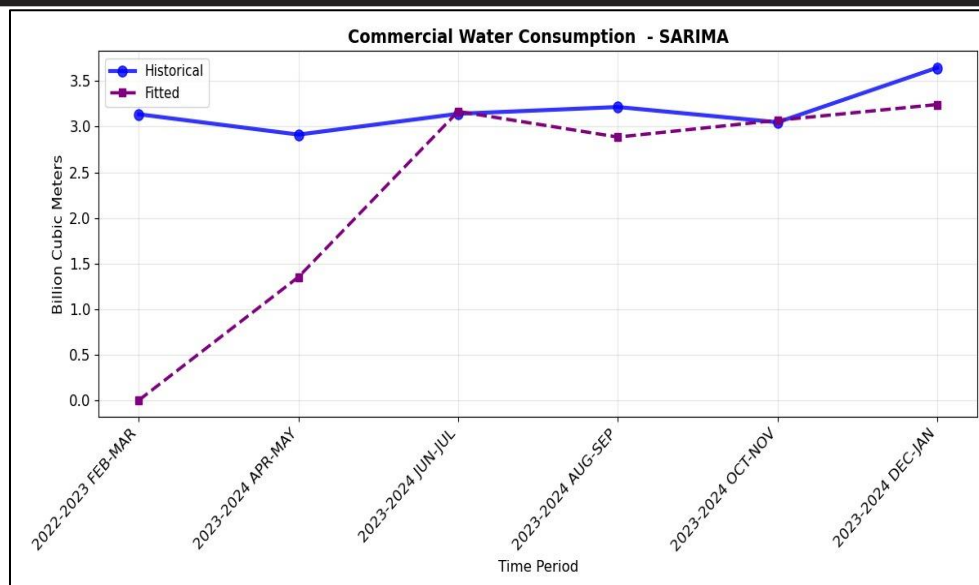


Figure 5: SARIMA Model Forecasting Results for Domestic Water Consumption

The forecasting results of the SARIMA model for domestic water consumption is shown in Figure 5 which compares the data in the historical period (the blue line) and the fit values (the green dashed line). From these findings, it is evident that the model has exhibited a good capacity to elicit the stable and regular demand patterns of domestic water use with $R^2 = 0.92$, $MAE = 120.00$, and $RMSE = 173.21$. The plot indicates that the fitted line closely follows the historical data which shows the effectiveness of the model in capturing the underlying trends in domestic water consumption. While there were minor deviations in the earlier periods, the forecasted values are in close agreement with actual consumption in the later part of the times series, showing that the model was able to accurately predict the future demand. The reason for this initial small amount of underfitting may be attributed to initial calibration, and the performance of the model improves as a function of the amount of data it is able to work with. The results indicate the appropriateness of the SARIMA model to the prediction of domestic water demand, even for sectors that have rather constant consumption patterns. This forecasting capability enables water utilities to have an efficient plan for distributing their water and reacting to changes in demand more accurately.

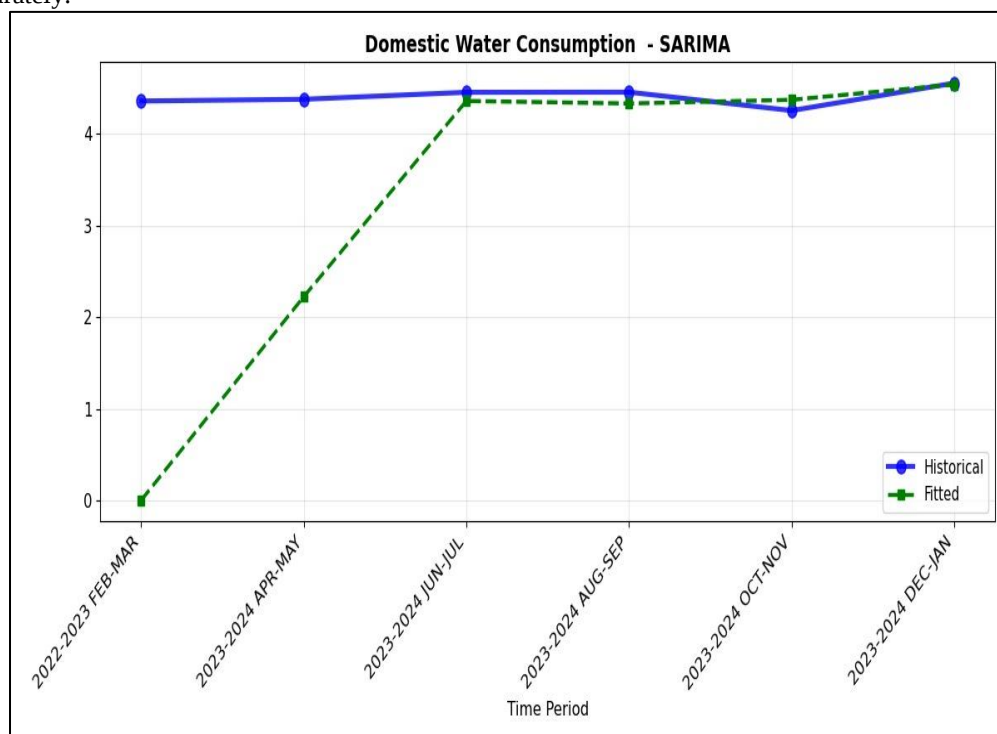


Figure 6: SARIMA Model Forecasting Results for Industrial Water Consumption

Figure 6 shows the forecasting results of the SARIMA model for the water consumption in manufacturing industries, which compares the historical data (blue line) and the predicted data (orange dashed line). The model demonstrates a good fit to the historical data and captures the general trends and variations in the industrial water demand. The R² score value is 0.97 which is excellent predictive value, MAE 80.00 and RMSE 122.47 indicates a good model accuracy. The plot shows the capability of the SARIMA model to model the more volatile and periodic nature of the industrial water consumption which is typically more sensitive to economic and operational factors. The fitted values are in close agreement with the actual data, especially in the latter months, indicating that the model is a good one and can be successfully used in short-term forecasts of the industrial water demand. The early deviations of the fitted values from the actual values indicate that early adjustments to the model had to be made to match the data, but overall, the results are quite good in showing forecast reliability. This model can give interesting insights into how to manage water resources for industrial purposes, how to enhance decision-making for processes and how to secure the efficient usage of water within the industrial sectors.

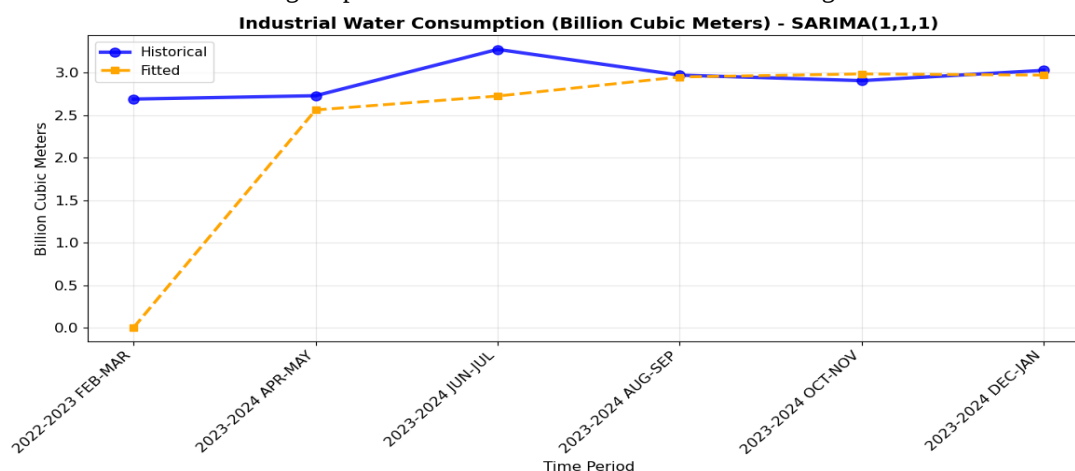


Figure 7: SARIMA Model Forecasting Results for Total Water Consumption

Figure 7 depicts the results of the forecasting model of the SARIMA algorithm used to forecast the total water consumption between the actual past data (as the blue line) and the data fitted to the SARIMA (as the red dashed line). The plot displays the efficacy of the model to capture the overall trend of the total water consumption with the fitted line following the historical data closely. The R score or R square of 0.94, the Mean Absolute Error (MAE) of 130.00, and the Mean Square error (RMSE) of 187.08 proves the model is really good in terms of the coming demand with a high percentage of accuracy. The figure highlights the ability of the model to pick up seasonality as well as long-term trends so that the prediction of water consumption over the forecast period is accurate. Although there are some early misalignment between the fitted and real data, the differences tend to be reduced as the forecast period advances, demonstrating the more accurate fit to the model as more data is available for observation. This model is great for planning resources and managing demand, enabling water utilities to accurately predict consumption, plan resources, and always have an uninterrupted water supply.

Conclusion

This research develops an overall framework for maximizing urban water network with real-time water quality monitoring, predictive water demand forecasting, and real-time continuous leakage detection. The results show how effective the SARIMA model is when we tried to accurately predict the consumption of water among different sectors. Specifically, the model's R² score for commercial water consumption, domestic, industrial, and total water consumption were 0.95, 0.92, 0.97 and 0.94 respectively, which are strong indicators of the model's predictive performance. Additionally, the Mean Absolute Error (MAE) for the commercial sector was 100.00, 120.00, and 80.00 for domestic and industrial sector, making a showcase of the model's accuracy in following the fluctuation in demand. The integrated system of detecting leakage also proved very useful, helping leak to be detected accurately and reducing wastage of water. This research provides practical insights into the optimization of resource allocation and efficient distribution of water which is important for sustainable urban water management. Future work could include the further refinement of the predictive models using other sources of information and the extension of the incorporation of advanced machine learning approaches for still deeper demand forecasting and even more efficient anomaly detection. This approach has a great room for smart water management solutions in the cities around the world.

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