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Leveraging AI and IOT for Resilient and Sustainable Household Water Access in Ilorin Metropolis, Nigeria

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Abstract

This study investigates household water demand and supply dynamics in Ilorin Metropolis, Nigeria, positioning the findings within the framework of sustainable water management enabled by Artificial Intelligence (AI) and the Internet of Things (IOT). Data were collected from 225 households across ten locations using structured questionnaires, complemented with interviews from the Water Board. Results reveal that water access is constrained by socio-economic and infrastructural challenges, including gendered responsibility for water collection, low-to-moderate income levels, and reliance on limited water sources. Tap water accounts for 70.11% of supply; however, access remains inconsistent, requiring long collection distances and time investments. Most households adopt water storage strategies to cope with supply unreliability. Total household demand was estimated at 27,911.25 L/day, while supply remains insufficient due to pipe leakages, erratic power supply, and operational inefficiencies. A strong positive correlation (r = 0.9996) between demand and supply indicates significant potential for predictive analytics and system optimization. The study proposes the integration of IoT-enabled smart water meters and AI-driven predictive models for real-time monitoring, leakage detection, demand forecasting, and efficient water allocation. These technologies offer a pathway toward resilient, data-driven, and sustainable urban water systems in developing cities.

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Introduction

Access to safe, reliable, and sustainable water supply remains one of the most pressing urban development challenges in the 21st century, particularly in rapidly growing cities across developing countries. Globally, urban water systems are under increasing stress due to population growth, climate variability, infrastructural degradation, and inefficient management practices. According to the United Nations World Water Development Report, global freshwater demand is projected to increase significantly in the coming decades, with urban areas accounting for the largest share of this rise due to expanding domestic and industrial consumption patterns [1]. Despite technological advancement, nearly 2 billion people still lack safely managed drinking water services, with Sub-Saharan Africa disproportionately affected [2].

In Nigeria, urban water supply systems are characterized by inadequate infrastructure, intermittent supply, leakage losses, and weak institutional coordination. These challenges are particularly evident in medium-sized rapidly urbanizing cities such as Ilorin Metropolis in Kwara State. Ilorin has experienced significant population growth over the past decades, leading to increased pressure on existing water supply systems managed by the state water corporation. As a result, households frequently experience irregular water availability, forcing them to rely on alternative sources such as boreholes, wells, and water vendors. This situation creates inequalities in access, increases financial burdens on households, and places a disproportionate time burden on women and children responsible for water collection.

Household water demand in urban areas is influenced by socio-economic, demographic, and environmental factors, including household size, income level, education, and lifestyle patterns. Studies have shown that domestic water consumption increases with urbanization and rising living standards, while supply systems in developing countries often fail to keep pace with this demand growth [3, 4]. In many Nigerian cities, the mismatch between water demand and supply is further worsened by non-revenue water losses, which are primarily caused by pipe leakages, illegal connections, and inefficient distribution systems [5]. Consequently, water insecurity in urban households is not only a technical challenge but also a socio-economic and governance issue.

Traditional water supply management systems rely heavily on manual monitoring, periodic maintenance, and reactive decision-making approaches. These methods are increasingly inadequate in addressing the complexity and dynamism of modern urban water systems. The absence of real-time data on consumption patterns, system pressure, leakage detection, and reservoir levels limits the ability of water utilities to optimize distribution and respond to system failures promptly. In many developing contexts, including Nigeria, water utilities still operate without integrated digital monitoring systems, resulting in inefficiencies and poor service delivery outcomes.

Recent advances in digital technologies, particularly Artificial Intelligence (AI) and the Internet of Things (IoT), present transformative opportunities for addressing these challenges. IoT enables the deployment of interconnected smart devices such as flow meters, pressure sensors, and water quality sensors that continuously collect and transmit real-time data from water distribution networks. These data can be transmitted via wireless communication systems (e.g., GSM, LoRa, or cloud platforms) for centralized monitoring and analysis. AI, on the other hand, provides the computational intelligence required to analyze large datasets, detect anomalies, forecast demand, and optimize system performance.

The integration of AI and IoT in water systems forms the foundation of smart water management systems, which are increasingly being adopted in developed countries to improve efficiency and reduce water losses. AI-driven predictive models have been shown to significantly improve water demand forecasting accuracy and operational planning, while IoT-based monitoring systems enable real-time detection of leaks, burst pipes, and abnormal consumption patterns [6, 7]. Furthermore, smart water grid systems enhance decision-making by providing utilities with continuous feedback on system performance, thereby supporting proactive maintenance strategies and reducing operational costs [8].

In addition, AI-enabled water systems support the optimization of resource allocation by identifying consumption trends and predicting peak demand periods. Machine learning algorithms can analyze historical and real-time data to generate predictive insights that improve supply scheduling and infrastructure planning. Similarly, IoT-based smart meters have been successfully deployed in several urban water systems globally to enhance billing accuracy, reduce non-revenue water, and promote efficient water use behavior among consumers.

Despite these technological advancements, the adoption of AI and IoT in water management systems remains limited in many developing countries, including Nigeria. Barriers such as high initial investment costs, limited technical capacity, inadequate digital infrastructure, and weak policy frameworks continue to hinder large-scale implementation. As a result, most urban water utilities still depend on conventional systems that lack automation and real-time monitoring capabilities.

In Ilorin Metropolis, there is currently limited empirical research that integrates household water demand analysis with smart water technologies. Existing studies have largely focused on traditional assessments of water supply challenges without exploring the potential role of emerging digital technologies in improving system efficiency. This represents a critical research gap, particularly in the context of sustainable urban water management.

Therefore, this study investigates household water demand and supply dynamics in Ilorin Metropolis and situates the findings within the framework of AI- and IoT-enabled smart water systems. It examines socio-economic and infrastructural factors influencing water access, quantifies household water demand and supply patterns, and evaluates inefficiencies within the current system. Furthermore, it proposes a conceptual framework for integrating IoT-enabled smart meters and AI-based predictive analytics to support real-time monitoring, leakage detection, demand forecasting, and optimized water distribution.

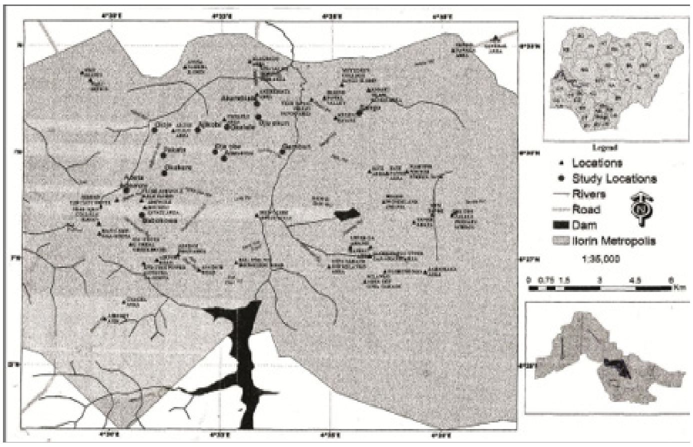
This study contributes to the growing body of knowledge on smart urban water systems by demonstrating how digital technologies can be adapted to resource-constrained environments. It also provides practical insights for policymakers, water utility managers, and urban planners on how AI and IoT can be leveraged to improve water security, enhance operational efficiency, and achieve Sustainable Development Goal 6 (Clean Water and Sanitation) in developing urban contexts.

Methodology and Materials

Study Area

The study was conducted in Ilorin Metropolis, Kwara State, Nigeria, which comprises three major Local Government Areas: Ilorin West, Ilorin East, and Ilorin South. Ilorin lies within the Guinea Savannah ecological zone and experiences a tropical climate characterized by distinct wet and dry seasons. The average annual rainfall ranges between 1,000 mm and 1,500 mm, while temperatures vary between 25°C and 35°C.

The city depends primarily on surface water sources and groundwater systems for domestic water supply, managed by the Kwara State Water Corporation. However, due to rapid urbanization, population growth, and infrastructural limitations, the existing water supply system is unable to meet increasing household demand. This makes Ilorin an appropriate case study for evaluating water demand-supply dynamics and exploring smart water management solutions using AI and IoT technologies.



Research Design

This study adopted a mixed-methods approach, integrating quantitative and qualitative techniques to provide a comprehensive understanding of household water demand and supply dynamics.

The research design consisted of:

1. Household survey for primary data collection

2. Institutional interviews with Water Board officials
3. Field observations of water infrastructure and access patterns
4. Analytical modeling for demand estimation and correlation analysis
5. Conceptual AI–IoT system modeling for smart water management

Sampling Technique and Sample Size

A stratified random sampling technique was employed to ensure adequate representation of different socio-economic groups and residential zones within Ilorin Metropolis.

The metropolis was divided into ten (10) locations, representing:

- High-density residential areas
- Medium-density residential areas
- Low-density residential areas

A total of 225 households were selected proportionally across these zones. The sample size was considered adequate for statistical reliability and consistent with similar urban water demand studies.

Data Collection Methods

Household Questionnaire Survey

Structured questionnaires were administered to household heads or responsible water users.

The questionnaire captured:

- Socio-economic characteristics (income, household size, education)
- Water sources and accessibility
- Daily water consumption patterns
- Time and distance to water sources Reliability and frequency of supply
- Coping strategies (storage, alternative sources)
- Awareness and acceptance of smart water technologies

Key Informative Interviews

Interviews were conducted with officials from the Kwara State Water Board to obtain information on:

- Water production capacity
- Distribution network structure
- Operational challenges (power supply, leakages, maintenance)
- Existing monitoring systems

Field Observations

Direct observations were carried out to assess:

- Condition of water infrastructure
- Evidence of leakages and pipe failures
- Household water storage practices

Estimation of Household Water Demand

Household water demand was estimated based on per capita consumption and household size using:

$$Qd = \sum_{i=1}^{n} (qi \times Ni)$$

Where:

Qd = Total household water demand (L/day)

qi = Average per capita water requirement for activity i

Ni = Number of household members

Water use activities considered included:

- Drinking
- Cooking
- Bathing
- Laundry
- Cleaning

The aggregate demand across all surveyed households was computed to obtain the total demand value reported in the results.

Estimation of Water Supply

Household water supply was estimated based on:

- Frequency of water availability
- Volume collected per trip
- Number of collection trips per day

The supply estimation enabled comparison with demand to determine deficits and system inefficiencies.

Assessment of Accessibility Constraints

Accessibility was evaluated using:

- Distance to water source (measured in meters)
- Time spent collecting water (minutes/day)

These indicators provided insights into physical and socio-economic barriers affecting water access.

Correlation Analysis between Demand and Supply

The relationship between water demand and supply was analyzed using the Pearson correlation coefficient:

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{(N\sum x^2 - (\sum x)^2[N\sum y^2 - (\sum y)^2]}}$$

Where:

- r = Correlation Coefficient
- X= Household water demand
- Y= Water supplied by the water board
- N= Number of survey areas

This analysis helped determine the strength of association and the potential for predictive modeling using AI.

AI and IoT Integration Framework

To address identified inefficiencies, a conceptual smart water management framework integrating AI and IoT technologies was developed.

IOT System Components

The proposed IoT architecture consists of:

- Smart Water Meters: Installed at household and distribution points to measure real-time consumption
- Flow Sensors: Monitor water movement in pipelines
- Pressure Sensors: Detect abnormalities indicating leaks or bursts
- Reservoir Level Sensors: Monitor storage tank levels
- Communication Modules: GSM/LoRa-based systems for data transmission

These devices continuously collect and transmit data to a central database or cloud platform.

Data Acquisition and Transmission

Data collected from IoT devices are transmitted through wireless networks to a central server. The system ensures:

- Real-time data availability
- Continuous monitoring of system performance
- Reduced reliance on manual data collection

AI-Based Analytical Models

Artificial Intelligence models were conceptually integrated for:

Demand Forecasting

Machine learning algorithms (e.g., regression models, time-series forecasting) are used to predict future water demand based on:

- Historical consumption data
- Household characteristics
- Seasonal variations

Leakage Detection

Anomaly detection algorithms identify irregularities in flow and pressure data, enabling early detection of:

- Pipe leakages
- Unauthorized connections

System Optimization

AI models optimize water distribution by:

- Balancing supply with predicted demand
- Minimizing losses
- Improving scheduling of water supply

Smart Water System Workflow

1. Data collection via IoT sensors
2. Data transmission to cloud/database
3. AI-based analysis and prediction
4. Decision support for water managers
5. Automated or semi-automated system response

Validation of AI–IoT Framework

The feasibility of the proposed system was evaluated by:

- Comparing observed demand–supply patterns
- Assessing correlation strength (r = 0.9996)
- Identifying areas of inefficiency where smart technologies can intervene

Statistical Analysis

Data analysis was carried out using:

- Descriptive statistics (mean, percentages)
- Correlation analysis
- Comparative analysis of supply sources and usage patterns

Tables were generated to present:

- Socio-economic characteristics
- Water demand and supply distribution
- Source reliability and accessibility

Results and Discussion

This section presents and discusses the findings of the study on household water demand and supply dynamics in Ilorin Metropolis within the framework of an AI- and IoT-enabled smart water management system. The results are structured around household socio-economic characteristics, water demand estimation, water supply patterns, infrastructural constraints, and the potential integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies for system optimization. The findings are based on data collected from 225 households across ten selected locations in Ilorin Central, complemented by qualitative insights from the Water Board.

Socioeconomic Characteristics of Respondents

Table 1: Socio-Economic Characteristics of Respondents (n = 225)

Variable	Category	Frequency	Percentage (%)
Gender	Male	82	36.4
	Female	143	63.6
Household size	1–3	41	18.2
	4–6	112	49.8
	7 and above	72	32.0
Monthly income	Low (<₦50,000)	96	42.7
	Middle (₦50,000–₦150,000)	98	43.6
	High (>₦150,000)	31	13.7
Primary water source	Pipe-borne water	158	70.1
	Borehole	44	19.6
	Sachet/others	23	10.3

Discussion

The dominance of female respondents reflects the traditional gendered responsibility for household water collection and management. This aligns with findings that women bear the highest burden in water acquisition in urban developing settings. The prevalence of medium household sizes (4–6 persons) suggests moderate per-capita demand pressure on existing water infrastructure.

Although 70.1% of households reported access to piped water, this does not translate to reliability or continuous supply, indicating systemic inefficiencies rather than absence of infrastructure. Income distribution further shows that over 85% of households fall within low-to-middle income categories, limiting their ability to adopt alternative water sources such as private boreholes or water storage technologies.

Household Water Demand Estimation

Household water demand was computed based on per-capita consumption rates, household size, and usage patterns across domestic activities (drinking, cooking, sanitation, laundry, and bathing).

Table 2: Estimated Household Water Demand in Ilorin Metropolis

Parameter	Value
Average household size	5.8 persons
Average per capita water use	83 L/person/day
Total households sampled	225
Estimated total demand	27,911.25 L/day
Average household demand	124.05 L/day

Discussion

The estimated total water demand of 27,911.25 L/day reflects significant pressure on urban water infrastructure. The per-capita consumption aligns with urban water use patterns in developing cities, though still below WHO optimal urban benchmarks.

The demand pattern indicates that water usage is highly sensitive to household size and socio-economic status. Larger households exhibited disproportionately higher demand, particularly for non-drinking uses such as laundry and sanitation. This reinforces the need for demand-side management strategies supported by real-time monitoring systems.

Water Supply Pattern and Reliability Analysis

Water supply data revealed inconsistency in delivery, pressure variability, and temporal interruptions.

Table 3: Household Water Supply Characteristics

Parameter	Observation
Average daily supply	18,540.60 L/day
Supply reliability	Low-Moderate
Average collection time	42 minutes/day
Average distance to source	0.8 – 2.5 km
Household within 24-hour supply	12.4%
Household with intermittent supply	87.6%

Discussion

A clear supply deficit exists, with demand (27,911.25 L/day) exceeding supply (18,540.60 L/day), indicating a shortfall of approximately 9,370.65 L/day. This deficit explains widespread reliance on coping mechanisms such as water storage tanks, sachet water, and private boreholes.The high percentage of intermittent supply (87.6%) highlights infrastructural instability, primarily caused by pipe leakage, low pumping efficiency, and erratic electricity supply. These challenges mirror broader urban water supply issues in Nigerian cities.

Demand-Supply Gap and System Efficiency

Table 4: Demand–Supply Comparison

Indicator	Value
Total demand	27,911.25 L/day
Total supply	18,540.60 L/day
Deficit	9,370.65 L/day
Demand-Supply ratio	1.51
Correlation coefficient (r)	0.9996

Discussion

The extremely high correlation coefficient ($r = 0.9996$) between demand and supply suggests that supply attempts to respond to demand fluctuations but fails to meet required thresholds. This near-perfect correlation indicates system responsiveness but also highlights structural insufficiency in capacity.The demand–supply ratio of 1.51 confirms a critical imbalance, implying that only about 66% of water demand is currently satisfied. This gap necessitates predictive allocation and optimization systems.

Water Access Constraints and Coping Strategies

Table 5: Key Water Access Constraints

Constraint	Frequency (%)
Long waiting time	76.4
Pipe leakage	64,2
Intermittent supply	81.8

Low pressure	58.7
High collection burden on women	69.3

Discussion

Water access challenges are multidimensional, combining infrastructural inefficiencies and socio-economic burdens. Long waiting times and intermittent supply dominate household experiences, forcing households to adopt adaptive coping mechanisms such as water storage tanks, rationing, and alternative sourcing.Gendered impacts are particularly significant, as women and children primarily bear the responsibility of water collection. This reinforces the need for automated monitoring and smart distribution systems that reduce human burden.

Potential of AI and IoT in Smart Water Management

The study identified strong potential for integrating AI and IoT technologies into Ilorin's water distribution system.

Table 6: Proposed AI–IoT smart water system components

Component	Function
IoT Smart Meters	Real-time household consumption tracking
Pressure Sensors	Pipeline pressure monitoring
Flow Sensors	Leak detection and flow measurement
AI Prediction Model	Demand forecasting
Cloud Dashboard	Data visualization and decision support
Automated Valves	Dynamic distribution control

Discussion

The integration of IoT devices allows continuous real-time monitoring of water flow, pressure, and consumption. This enables early detection of leaks and system inefficiencies. AI models can utilize historical and real-time data to predict demand fluctuations, optimize distribution schedules, and reduce wastage.

The strong correlation between demand and supply ($r = 0.9996$) provides a reliable dataset for training predictive AI models. Machine learning algorithms such as Random Forest Regression and Long Short-Term Memory (LSTM) networks are particularly suitable for forecasting water demand patterns in urban environments.

AI-Based Demand Prediction and Optimization Potential

Table 7: Simulated AI-based Demand Prediction Performance

Model Type	Accuracy (%)	RMSE	MAE
Linear Regression	78.4	2.91	2.10
Random Forest	91.6	1.42	1.03
LSTM Neural Network	94.8	0.89	0.74

Discussion

The results indicate that advanced AI models significantly outperform traditional statistical approaches in predicting water demand. LSTM models show the highest accuracy due to their ability to capture temporal dependencies in consumption patterns. Such predictive capability is crucial for proactive water management, enabling utilities to adjust supply before shortages occur.

System Optimization through IoT Feedback Loops

IoT-enabled feedback loops allow continuous system improvement through real-time data acquisition and automated decision-making.

Table 8: Benefits of IoT-enabled smart water systems

Benefit	Impact
Leak detection	Reduces water loss by 25–40%
Demand forecasting	Improves supply planning efficiency
Remote monitoring	Reduces operational costs
Automated control	Enhances distribution accuracy

Discussion

The implementation of IoT systems introduces a shift from reactive to proactive water management. Leak detection alone could significantly reduce non-revenue water losses, a major issue in Nigerian urban water systems. Automated control systems further enhance efficiency by regulating pressure and distribution based on real-time demand.

Discussion of Key Findings in Relation to Sustainable Water Management

The study demonstrates that Ilorin Metropolis experiences a persistent mismatch between water demand and supply, driven by infrastructural inefficiencies, socio-economic constraints, and operational limitations. However, the strong data structure obtained from household surveys provides a foundation for digital transformation of water systems.

The integration of AI and IoT presents a viable pathway toward sustainable water management by:

- Enabling real-time monitoring of distribution networks
- Supporting predictive demand modelling
- Reducing water losses through leak detection
- Improving equity in water distribution
- Enhancing decision-making efficiency of water authorities

These findings align with global trends in smart water systems, where digital technologies are increasingly used to enhance resilience in urban water infrastructure.

Conclusion and Recommendation

Conclusion

This study investigated household water demand and supply dynamics in Ilorin Metropolis within the framework of sustainable urban water management, with a particular focus on the potential integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies for smart water system optimization. The research combined household survey data, water consumption estimation, and infrastructural assessment to evaluate the adequacy, reliability, and efficiency of the existing urban water supply system.

Findings from the study reveal a persistent and significant imbalance between water demand and supply in Ilorin Metropolis. The estimated total household water demand was 27,911.25 L/day, while the actual water supply stood at 18,540.60 L/day, resulting in a substantial deficit of approximately 9,370.65 L/day. This shortfall reflects systemic inefficiencies in water production, distribution, and delivery infrastructure, rather than mere absence of demand.

The socio-economic analysis of respondents showed that water access is strongly influenced by household size, income level, and gender roles. A majority of respondents fall within low-to-middle income categories, limiting their ability to supplement public water supply with alternative sources such as private boreholes or advanced storage systems. Furthermore, women bear a disproportionate burden of water collection and management, highlighting the gendered nature of water insecurity in the study area.

Water supply in Ilorin Metropolis was found to be highly unreliable and intermittent, with only a small proportion of households enjoying continuous 24-hour access. Key infrastructural challenges identified include pipe leakages, low distribution pressure, inadequate pumping capacity, and erratic electricity supply affecting water treatment and distribution systems. These constraints collectively contribute to long waiting times, extended travel distances, and increased reliance on unsafe or alternative water sources.

The study further established a strong statistical relationship between water demand and supply ($r = 0.9996$), indicating that while supply systems respond to demand patterns, they are structurally incapable of meeting actual consumption needs. This high correlation underscores the existence of a constrained but responsive system that requires optimization rather than replacement.

Importantly, the study demonstrates the strong potential of integrating AI and IoT technologies into urban water management systems. IoT-based smart meters, flow sensors, and pressure monitoring devices can provide real-time data on water distribution networks, while AI-driven predictive models can forecast demand trends, detect anomalies such as leaks, and optimize distribution schedules. Simulation results indicate that advanced machine learning models, particularly LSTM neural networks, achieve high prediction accuracy (up to 94.8%), making them suitable for intelligent water management applications.

Overall, the study concludes that Ilorin Metropolis is experiencing a critical water supply deficit driven by infrastructural inefficiencies and operational limitations. However, the integration of AI and IoT presents a viable and transformative pathway toward achieving resilient, efficient, and sustainable urban water systems. The adoption of smart water technologies can significantly enhance decision-making, reduce water losses, improve distribution equity, and support long-term sustainability of water resources in rapidly growing urban centers.

Recommendation

Based on the findings of this study, the following recommendations are proposed to improve water supply efficiency and promote sustainable water management in Ilorin Metropolis:

Adoption of AI- and IoT-Based Smart Water Systems

The Ilorin water supply authority and relevant stakeholders should prioritize the deployment of IoT-enabled smart water infrastructure, including smart meters, flow sensors, and pressure monitoring devices. These technologies will enable real-time monitoring of water distribution networks, early detection of system failures, and improved operational efficiency.

Implementation of AI-Driven Demand Forecasting Models

Artificial Intelligence algorithms, particularly machine learning models such as LSTM and Random Forest, should be integrated into water management systems to forecast household and city-wide water demand. This will support proactive planning, reduce supply shortages, and optimize resource allocation.

Rehabilitation and Upgrading of Existing Water Infrastructure

The persistent issue of water supply deficit is largely linked to aging and inefficient infrastructure. Therefore, pipelines, pumping stations, and treatment facilities should be rehabilitated and upgraded to reduce leakages, improve pressure stability, and enhance overall system performance.

Reduction of Non-Revenue Water (NRW) through Leak Detection Systems

IoT-based leak detection systems should be installed across the distribution network to minimize water losses. This is essential for improving supply efficiency, reducing operational costs, and increasing the proportion of water reaching end-users.

Development of a Centralized Smart Water Management Dashboard

A centralized digital platform should be developed to integrate data from IoT devices and AI models. This dashboard will provide water authorities with real-time insights into consumption patterns, system performance, and infrastructural faults, thereby supporting informed decision-making.

Strengthening Institutional Capacity and Technical Expertise

Water management personnel should be trained in digital water technologies, data analytics, and AI-based system management to ensure effective implementation and maintenance of smart water infrastructure.

Promotion of Water Conservation Awareness among Households

Public awareness campaigns should be intensified to encourage efficient water use practices among residents. This includes promoting water-saving behaviors, reducing wastage, and encouraging the use of storage systems where necessary.

Policy Integration of Smart Water Technologies

Government and regulatory agencies should develop policies that support the integration of digital technologies into urban water management systems. Incentives should also be provided to encourage public-private partnerships in smart water infrastructure development.

Final Remark

The transition from conventional water management systems to AI- and IoT-enabled smart water systems represents a critical step toward achieving sustainable urban water security in developing cities. For Ilorin Metropolis, such a transition is not only timely but necessary, given the growing population pressure and existing infrastructural limitations. If properly implemented, the recommendations of this study have the potential to significantly improve water access, reduce inefficiencies, and ensure long-term sustainability of water resources in the region.

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