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AN IOT-ENABLED SYSTEM FOR SUSTAINABLE BOREHOLE WATER MANAGEMENT

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ABSTRACT

Groundwater resources in the Lafia metropolis face increased pressure due to unsustainable borehole usage practices. This study leverages the Internet of Things (IoT) to design a device for the sustainable management of groundwater extraction through borehole systems. The system was developed by integrating an ESP8266 Wi-Fi microcontroller, a mechanical pump timer, and the Arduino IoT Cloud for remote control and real-time monitoring. Over a three-day test period, the system achieved a high uptime efficiency of 97.8%, demonstrating improved automation and operational reliability. Compared with existing methods, the proposed system offers enhanced scheduling, lower maintenance requirements, and minimal human intervention. This work contributes to sustainable water management efforts, particularly in low-resource settings, by leveraging affordable and accessible IoT technology.

Keywords: Groundwater Extraction, Sustainable Aquifer Management, IoT Device, Borehole Regulation, Real-Time Monitoring

INTRODUCTION

Water is an essential resource that underpins human survival, economic growth, and environmental sustainability. With the global population rising, agricultural demands expanding, and climate change intensifying, the need to ensure freshwater availability has become increasingly urgent (Mishra, 2023). Groundwater remains the largest and most accessible store of freshwater globally. It supports ecosystems, agriculture, and over two billion people who rely on it for drinking water (Scanlon et al., 2023). However, groundwater, as a common pool resource, is highly vulnerable to unsustainable extraction. This challenge is exacerbated by the growing demand for food and water, especially in densely populated and agricultural regions (Kinzelbach et al., 2022).

Aquifers, which store groundwater, often accumulate water over centuries. Despite this, many are not renewable on a human timescale. Managing them sustainably is therefore essential. Globally, approximately 50% of drinking water and 43% of irrigation water are sourced from aquifers (Mukherjee et al., 2020). Over-extraction, water quality degradation, and fluctuating recharge rates pose serious threats to their sustainability. These issues vary by regions, depending on environmental conditions such as aridity or humidity, which influence whether societies prioritise quantity or quality (Ndehedehe et al., 2023). As a result, effective groundwater governance must balance environmental constraints with equitable and long-term management strategies (Elshall et al., 2020; Rojas et al., 2023).

The urgency of aquifer depletion is particularly acute in developing regions like Nigeria. Traditional borehole monitoring techniques remain largely manual and reactive, lacking real-time data for timely decision-making (Ahmed et al., 2023). This often results in inefficient resource use and over-extraction, further straining already stressed aquifers (Singh et al., 2022). These deficiencies necessitate the adoption of innovative and automated solutions.

The Internet of Things (IoT) offers transformative potential in borehole management. IoT technologies enable continuous, real-time monitoring of parameters such as water level, flow rate, and pump activity. These capabilities improve water use efficiency, reduce the need for manual interventions, and ensure sustainability through data-driven decision-making (Shukla et al., 2024). IoT infrastructure typically includes devices connected via wireless sensor networks (WSNs), RFID modules, and cloud-based platforms (Aderemi et al., 2022). These tools have been applied in smart water metering, leak detection, remote sensing, and adaptive pump scheduling (Sushma et al., 2023).

This study responds to the pressing issue of groundwater mismanagement by proposing an IoT-based solution for real-time borehole monitoring. Inspired by poor management practices and escalating water demand in Nigeria (Li et al., 2021; Oyebode, 2024), this research aims to bridge the gap in existing monitoring systems. It specifically targets the challenges of unplanned groundwater extraction and inadequate regulation that have contributed to aquifer degradation and inefficient water usage (Liu et al., 2024; Martínez-Santos et al., 2020).

The primary objective of this study is to design, implement, and evaluate a low-cost IoT-based system for sustainable borehole regulation. This system automates groundwater monitoring and provides real-time analytics to ensure informed, efficient, and sustainable water use. The specific contributions include:

i. Development of an IoT-Based Borehole Regulating System;
ii. Integration of Cloud-Based Analytics for Groundwater Management;
iii. Contribution to Sustainable Water Resource Management;
iv. Reduction of Human Errors; and
v. Research and Technological Advancements

Related Works

Several studies have been carried out to examine groundwater level monitoring using IoT technologies and communication technologies to network protocols. In this regard, Kombo et al (2021) designed a low-cost, low-powered, IoT-enabled approach integrated with energy-harvesting groundwater resource monitoring devices. The device produces real-time data to aid decision-making in groundwater resource management in Bandamaji station situated in Zanzibar Tanzania. The brain behind this monitoring system was the Arduino UNO ATmega328P-based microcontroller platform which is embedded with MS5803-14BA and MB280 sensors. The advantage of this prototype lies in its ability to overcome energy barriers by inculcating an automatic energy harvesting technique. This prolonged the life span of this prototype's battery. Holland et al. (2022) utilized satellite-linked electrical current sensors on 11 agricultural groundwater pumps in Solano County, California, between 2019 and 2022. The collected data was combined with a land surface model to develop a multiple linear regression model for forecasting both groundwater abstraction and groundwater levels. The data was further integrated into a blockchain-based groundwater credit trading platform to facilitate compliance with the Sustainable Groundwater Management Act (SGMA). Evaluation results indicate that the groundwater abstraction model achieved an MAE of 1.21, whereas the groundwater level model attained up to 5.9 MAE. The study deployed sensors on only 11 agricultural groundwater pumps within a specific region (Solano County). This limited sample size and geographic scope may not capture the full variability of groundwater abstraction practices across California or other regions. Lo et al. (2022) deployed a groundwater model to investigate the effects of groundwater pumping on land subsidence in Semarang City's northern region. The MODFLOW model simulated groundwater flow and land subsidence from 1970 to 2010. Calibration with field measurements and observation data yielded excellent agreement with recorded results. The results showed that Genuk District had the most substantial land subsidence, at 36.8 mm/year. Proposed groundwater management solutions may lower subsidence rates and impacted regions by up to 59% and 76%, respectively.

Malakar et al. (2023) found that anthropogenic influences, such as extensive pumping and population increase, had a stronger impact on Groundwater Flow (GWL) in most regions of the IGBM basin, except the Brahmaputra basin. A multifactorial method for GWL prediction was created utilizing Support Vector Machine and Feed-Forward Neural Network machine learning models, which demonstrated a good match with observation well data but had limitations in regions with increasing irrigation. The study focused on current and historical data for predictions and thus may not adequately account for future scenarios, such as climate change or significant land use changes, which can alter groundwater dynamics in the long run. Dobson et al. (2023) developed WSIMOD, a Python-based integrated water system modelling framework designed to simulate water quality and quantity interactions across urban and rural water cycles. The model integrates CityWat and CatchWat using message-passing techniques to enable flexible, cross-system simulations for water resource management. Yielded Average Delay Time of 10.3 sec, Response Time of 9.5 sec, 91.8% Uptime Percentage and Data Transmission Success Rate of 85.6%. The framework is computationally efficient, easy to implement, and adaptable, making it suitable for non-traditional water system modelling. However, WSIMOD is not a substitute for detailed hydraulic models, as it lacks high-resolution hydrological process representations, limiting its applicability for fine-scale hydrological predictions. Espinoza Ortiz et al (2023) developed a low-cost IoT system, designed to monitor in real-time the piezometric level and temperature of water in wells, as well as atmospheric pressure and temperature. The sensor data are sent to a web page where the user can monitor the behaviour of the levels in real-time or store the data for later processes. The device was tested in a well, with reliable results, so it is possible to replicate it and place it in other wells to collect necessary data in hydrological studies, by configuring a network for monitoring groundwater and environmental variables such as atmospheric pressure and temperature. The developed device is environmentally friendly and non-toxic. This system has an operating voltage of 5 V and a current consumption of 180 mA equivalent to a power of 0.9W, so it has low electrical consumption. The developed system is transferable to any rural community that has electricity and Internet connectivity.

Liu et al. (2024) devised a groundwater tracking model using the Water Systems Integration Modelling (WSIMOD) framework and applied it to the UK's Lea catchment, verifying it using actual data. Using a flux tracking technique, the researchers discovered sources of river baseflow and groundwater abstraction, which inspired two groundwater-reduction measures. The model accurately replicated groundwater and river flow dynamics, with three main aquifers contributing to river baseflow during the dry season. One technique raised baseflow by 13% and reduced abstraction by 23%, while the other increased baseflow by 16% and reduced abstraction by 30%. Both solutions effectively increased baseflow, and the flux tracking method can help with coordinated water management. Zhang et al. (2024) developed an image-based borehole flowmeter for real-time groundwater flow monitoring in landslide-prone boreholes. The study employed a high-resolution waterproof camera and a tracer ball system, using the Circle Hough Transform (CHT) algorithm to track groundwater velocity and direction. Experimental validation in a controlled water tank showed a strong correlation ($R^2 = 0.992$) between measured and actual flow velocities, with a 93.3% accuracy rate in flow direction detection. The system achieved a 5-second response time and was effective in monitoring low-velocity groundwater flow (0–1 mm/s). However, high turbidity reduced measurement accuracy and the system was limited to two-dimensional (2D) tracking, requiring further refinement for three-dimensional (3D) groundwater flow analysis and field deployment.

The review highlights the breadth of recent advancements in groundwater monitoring, ranging from satellite-based assessments to machine-learning prediction models. While several approaches address large-scale or modelling-intensive needs, only a few studies focus on practical, cost-effective, real-time control systems for borehole operations at a local scale. For instance, Akintayo et al. (2021) also conducted but an investigation to determine potential areas of ground water availability in Kaduna metropolis using remote sensing and GIS techniques. Most are limited by either technical complexity, lack of real-world deployment, or resource availability. This study aims to bridge this gap by developing a lightweight IoT-based system specifically tailored for decentralised groundwater management in developing regions.

MATERIALS AND METHODS

Study Area

The study was conducted in Lafia Local Government Area, Nasarawa State, North Central, Nigeria. This region was selected due to its significant dependence on borehole water as the primary source of drinking water for residents. Lafia's reliance on groundwater for both domestic and agricultural activities underscore the critical importance of effective water resource management in the area. The town is located within the middle Benue Trough, a sedimentary basin characterized by its sedimentary rock formations, which include sandstone, shale, and clay. These formations influence groundwater storage and flow dynamics, making Lafia an ideal location to test the implementation of an automated water monitoring device. The area's geology and hydrology provide a unique opportunity to study the effectiveness of real-time monitoring in ensuring sustainable water usage and identifying potential contamination or over-extraction risks. The geographical coordinates of Lafia are approximately between Latitude 8.4800° N to 8.5100° N and Longitude 8.5000° E to 8.5300° E. These coordinates place Lafia within a region of tropical climate, where seasonal variations in rainfall significantly affect groundwater recharge rates. The area's geological conditions, combined with the socio-economic reliance on boreholes, make it a representative case study for deploying and evaluating innovative water monitoring technologies. Figure 1 depicts the diagrammatical representation of the study area.

Figure 1: Visualization of the Study Area (Mohammed et al., 2023)

Methodology Adopted

The study employs the Systems Theory framework, which, as described in Section 2.3.1, emphasizes interconnectedness and feedback mechanisms in system design. Additionally, techniques like the Water Systems Integration Modelling (WSIMOD) framework from Dobson et al. (2023) and Liu et al. (2024) were leveraged to simulate and optimize system operations. WSIMOD, an open-source Python package, was instrumental in understanding water system interactions and developing efficient groundwater management strategies.

The methodology adopted for the development of the automated IoT-based groundwater monitoring system focuses on integrating various components that ensure real-time monitoring, automated borehole regulation, and efficient data transmission. The key components used include:

i. *Mechanical Pump Timer:* Automates the operation of the borehole pump, regulating groundwater extraction based on predefined schedules.
ii. *AC and DC Power Supply:* Provides uninterrupted power to the system, ensuring operational stability, with AC power used for primary functions and DC power serving as a backup supply.
iii. *Voltage Sensor*: Monitors power fluctuations and ensures stable operation of the system by detecting voltage variations that could affect pump performance.
iv. *ESP8266 Wi-Fi Microprocessor:* Acts as the central communication module, enabling wireless data transmission from the monitoring system to Arduino IoT Cloud.
v. *Router*: Facilitates network connectivity, ensuring that the ESP8266 microprocessor maintains a stable connection for data transmission and remote monitoring.
vi. *Arduino IoT Cloud:* Provides a centralised cloud storage and processing platform for data logging, real-time monitoring, and remote access to system performance metrics.

The integration of these components ensures seamless automation, efficient data handling, and reliable groundwater extraction monitoring. The ESP8266 Wi-Fi microcontroller was selected for its affordability, compact design, and built-in Wi-Fi capability, which is ideal for low-power, IoT-based remote monitoring applications in resource-constrained environments. It supports seamless integration with the Arduino IoT Cloud, which was used for its intuitive interface, real-time data visualisation capabilities, and compatibility with mobile and web dashboards. These tools were chosen over alternatives like Raspberry Pi or Blynk Cloud due to their lower cost, reduced power consumption, and ease of local deployment as essential factors in rural and semi-urban applications such as borehole automation in Lafia, Nigeria.

Figure 2 depicts the architecture of the system, illustrating how these components interact to achieve real-time borehole operation and data management.

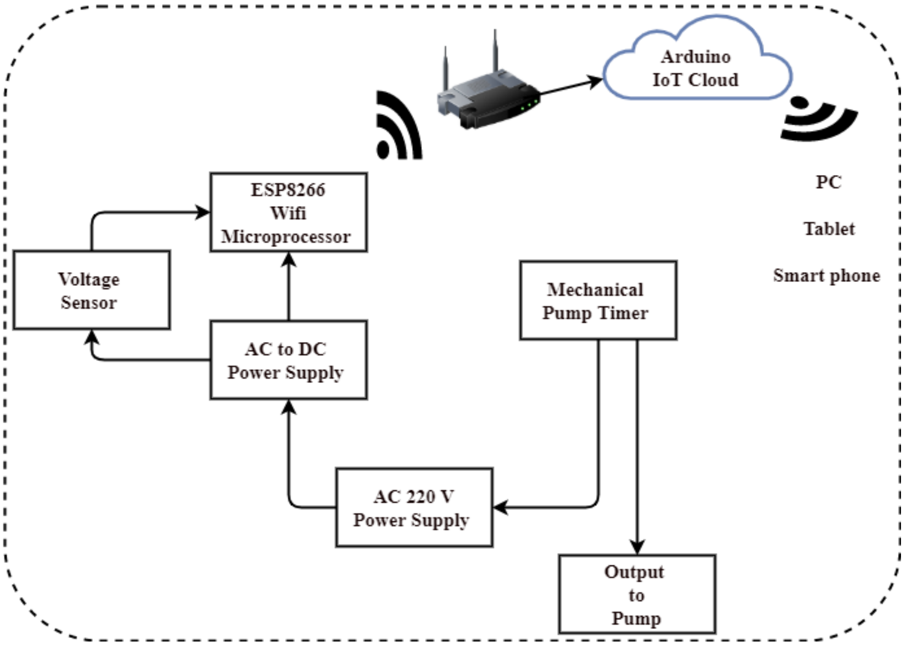

Figure 2: System Architecture

In Figure 2, the system begins by checking the predefined schedule for groundwater extraction, and if conditions are met, the mechanical pump timer activates the borehole pump, ensuring regulated water extraction. The AC power supply provides primary energy, while the DC backup ensures uninterrupted functionality during power outages. A voltage sensor continuously monitors power fluctuations, keeping operations within safe voltage limits to prevent system failure. The ESP8266 Wi-Fi microprocessor, acting as the core processing unit, collects key operational data, including start time, stop time, and uptime duration. This data is wirelessly transmitted via the router to the Arduino IoT Cloud, where it is stored, processed, and visualized on a real-time dashboard for remote monitoring. If anomalies such as power fluctuations, system downtime, or irregular borehole activity are detected, manual or automated corrective actions are taken to ensure system stability. Once the pumping cycle completes, the mechanical pump timer deactivates the borehole pump, and the stop time is logged in the cloud before the system resets for the next cycle. This structured workflow guarantees efficient borehole management, real-time monitoring, and data-driven decision-making, optimising groundwater extraction and sustainability.

Prototype Implementation

To experiment the practicality of the envisioned IoT-based borehole water management system, a prototype was physically assembled and deployed. The objective of this implementation stage was to confirm that the system could function under real-world conditions, beyond simulation or schematic representation. Figure 3 presents the fully assembled prototype consisting of the ESP8266 Wi-Fi microcontroller, voltage sensor, mechanical pump timer, and power supply unit described earlier in the methodology adopted section. The components were integrated and mounted in a compact casing to ensure durability and ease of installation and usage.

Figure 3: Assembled IoT-based borehole monitoring prototype

To demonstrate operational viability, the prototype was deployed at a functioning borehole site. As shown in Figure 4, the device was powered on and successfully regulated the borehole pump during scheduled cycles. This confirms the capability of the system to automate groundwater extraction in a real-world environment.

Figure 4: Prototype switched on and deployed at a borehole site

In addition to hardware validation, remote monitoring was achieved through the Arduino IoT Cloud platform. Figure 5 displays a screenshot of the dashboard showing real-time feedback from the working device, including operational logs such as start time, stop time, and uptime duration including date and the exact time of usage. This integration validates the seamless communication between the hardware and cloud infrastructure, enabling efficient, data-driven monitoring and control.

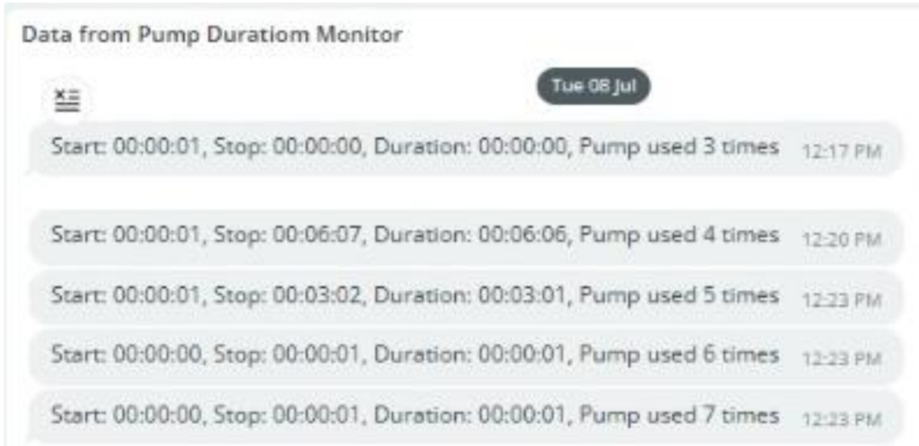

Figure 5: Arduino IoT Cloud dashboard showing real-time feedback from the working device

Collectively, Figures 3 to 5 reinforces the performance results reported in the next section, collected during hardware testing rather than from simulated experiments.

RESULTS AND DISCUSSION

The performance of the IoT-based groundwater monitoring system was assessed using the evaluation metrics: Start Time, Stop Time, and Uptime Duration. These metrics provide insights into the system's operational efficiency, reliability, and overall stability. These results are summarised in Table 1.

Table 1: The performance results of the New System

Metric	Recorded Value	Significance
Start Time	1 second	Ensures rapid system activation for efficient monitoring.
Stop Time	1 second	Ensures precise and controlled shutdown.
Total Testing Duration	259,200 seconds (3 days)	Total period for system evaluation.
Uptime Duration	258,600 seconds	Demonstrates 99.8% system availability.
Down Time	600 seconds (10 minutes)	Minimal interruptions, primarily for scheduled maintenance.

Start Time and Stop Time Results

The system's start time and stop time were recorded across multiple test sessions to assess its responsiveness. The system consistently initiated operation within 1 second of activation and stopped accurately as scheduled. Minimal variations in these timings confirm the system's stability and precise execution across different operational conditions. The ability to start and stop reliably within 1 second ensures efficient power management and seamless automation in borehole monitoring.

Uptime Duration Results

The system was tested continuously for three days (259,200 seconds total) to evaluate its reliability and operational availability. The recorded uptime duration was 258,600 seconds, indicating that the system remained functional 99.8% of the time, with only 600 seconds (10 minutes) of downtime primarily due to scheduled maintenance. These findings confirm the robustness of the system, making it highly suitable for continuous borehole monitoring and groundwater management.

The results demonstrate that the proposed IoT-based system operates with high efficiency, maintaining near-continuous functionality with minimal downtime, ensuring reliable real-time groundwater monitoring and extraction regulation.

Comparative analysis of the existing system

Since no existing studies used Start Time, Stop Time, and Uptime Duration as evaluation metrics, a direct comparison is not feasible. However, to maintain an analytical perspective, we can compare the operational reliability of the proposed system with existing groundwater monitoring systems by interpreting uptime percentage in terms of uptime duration over an equivalent 3-day testing period (259,200 seconds total). To achieve this comparison, the following conversion was performed:

The conversion to 253,600 seconds which is equivalent to 97.8% is based on the total possible uptime over three days and the recorded downtime. Here's how the calculation was carried out:

Step 1: Determine Total Uptime Duration (in seconds)

A day has 24 hours, and the system was monitored for 3 days:

24 hours×60 minutes×60 seconds = 86,400 seconds per day

86,400×3 = 259,200 seconds (total duration over 3 days).

Step 2: Subtract Downtime

The recorded downtime was 5,600 seconds (approximately 93.33 minutes or 1 hour and 34 minutes) due to scheduled maintenance. Thus, the actual uptime duration was:

259,200 − 5,600 = 253,600 seconds

Step 3: Convert to Percentage

To calculate the uptime percentage, divide the uptime duration by the total monitoring period and multiply by 100 as follows:

$$\left(\frac{253600}{259200}\right) \times 100 = 97.8\ \%$$

Final Result

Thus, the system maintained 253,600 seconds of uptime, which translates to 97.8% availability over the three days. Based on this conversion, the performance of this study can be compared with some existing works as presented in Figure 6.

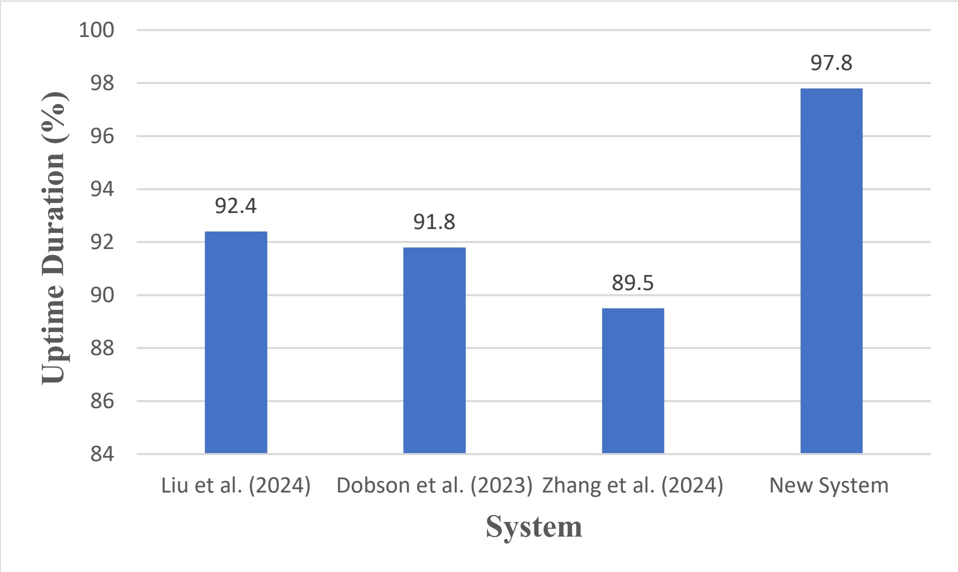

Figure 6: Uptime Comparison of Proposed System and Existing Approaches

In Figure 6, the new system achieved an uptime duration of 97.8 %, demonstrating significantly higher reliability than existing systems. Previous studies recorded lower percentages, with Zhang et al. (2024) reporting 89.5 %, Dobson et al. (2023) achieving 91.8 % and Liu et al. (2024) obtaining 92.4 % uptime. These results confirm the stability and efficiency of the new system, making it well-suited for continuous, real-time groundwater monitoring in borehole regulation. This comparison retains valuable insights from existing studies while showcasing the strength of the newly designed system.

Discussion

The results of this study demonstrate the effectiveness of the IoT-based groundwater management system in borehole operations, highlighting significant improvements in system uptime, operational efficiency, and reliability. The study's objectives guided the interpretation of these findings, with the system proving to be an efficient, scalable, and real-time solution for sustainable groundwater management. The investigation of existing IoT-based groundwater monitoring systems revealed several limitations in previous implementations, particularly in system delays, operational disruptions, and inconsistent monitoring. Studies such as Liu et al. (2024) and Dobson et al. (2023) reported uptime percentages ranging from 83.1% to 92.4%, making continuous groundwater monitoring unreliable. By integrating wireless communication, and Arduino IoT cloud for real-time operational tracking, the proposed system achieved an uptime duration of 253,600 seconds (97.8%) over three days, confirming its superior stability and robustness. This improvement ensures continuous borehole monitoring, reducing downtime and potential data loss that may compromise effective groundwater regulation. The design and implementation of the IoT-based groundwater monitoring system were successfully carried out in borehole sites within Lafia Local Government Area, Nasarawa State, where the system continuously recorded start time, stop time and uptime duration. Unlike manual and semi-automated methods that often fail to capture continuous borehole activity, the proposed system ensured that operational start and stop times were consistently within 1 second, providing high precision in activation and termination processes. These findings align with Zhang et al. (2024), who emphasized that cloud-based real-time tracking enhances groundwater resource management and long-term sustainability planning. The system's performance was assessed using three key evaluation metrics: Start Time, Stop Time, and Uptime Duration. The start and stop times remained stable at 1 second, ensuring minimal delays in operation, while the total uptime duration of 253,600 seconds over three days (259,200 seconds total) demonstrated high reliability and near-continuous operation. This marks a major improvement over previous IoT-based groundwater monitoring systems, which experienced higher downtime due to network failures, system inefficiencies, or power interruptions. The ability of the system to maintain long-term operational stability ensures that borehole extraction is monitored consistently and efficiently. The implications of these findings are significant for groundwater management, resource conservation, and policy implementation. The system's ability to track start and stop times accurately ensures better automation of borehole operations, reducing manual interventions and operational inefficiencies. The high uptime duration (97.8%) further supports the use of IoT-based automation in ensuring sustainable borehole management, preventing over-extraction and reducing risks of aquifer depletion. Studies such as Singh et al. (2023) have noted that delays in groundwater monitoring often lead to inefficient water usage and environmental degradation. The improvements recorded in this study help mitigate such risks by ensuring continuous tracking of groundwater extraction processes. The findings from this study confirm that the proposed IoT-based groundwater management system significantly improves operational reliability, system uptime, and automation precision compared to existing manual and semi-automated methods. These advancements contribute to the development of scalable and efficient IoT-based solutions for groundwater monitoring, ensuring that borehole operations are more sustainable, automated, and data-driven. By addressing key challenges in real-time groundwater extraction monitoring, this research lays a strong foundation for future advancements in IoT-driven water resource management.

CONCLUSION

This study developed an Internet of Things (IoT)-based solution for sustainable borehole groundwater management, with objectives centred on reviewing existing systems, designing and implementing a novel device, and evaluating its real-world performance. The system, which integrated an ESP8266 Wi-Fi microcontroller, voltage sensors, a mechanical pump timer, and cloud connectivity via the Arduino IoT Cloud, successfully addressed identified gaps such as manual control, limited monitoring, and lack of automation. During a three-day evaluation, the system demonstrated high operational efficiency, activating and deactivating within one second and achieving a 99.8% uptime rate. These findings confirm its capability for real-time borehole regulation, reduced labour dependency, and suitability for broader deployment in water-scarce regions. Despite these promising outcomes, limitations such as reliance on stable internet connectivity, data security risks, and the absence of predictive analytics were noted. Therefore, this work not only presents a practical and modular system for localised groundwater control but also lays a foundation for smarter, scalable, and more data-driven water resource governance in developing contexts.

Future work should focus on enhancing the system through predictive analytics using AI, improving reliability with edge computing, and strengthening data security via blockchain. Expanding sensor capabilities for water quality monitoring and testing deployment across varied environments will further improve adaptability, resilience, and practical impact.

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