
DEVELOPMENT OF A NARROW BAND INTERNET OF THINGS (NB-IOT) MONITORING AND CONTROL MODEL FOR URBAN DRAINAGE SYSTEM IN KANO, NIGERIA

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ABSTRACT

Urban flooding in Kano, Nigeria, poses significant socio-economic and infrastructural challenges, largely exacerbated by a lack of continuous, real-time drainage monitoring. This paper presents the development, implementation, and evaluation of a Narrow Band Internet of Things (NB-IoT) monitoring and control model designed specifically for urban drainage systems. The proposed architecture integrates ultrasonic water level, Doppler flow, and rainfall sensors with a low-power microcontroller utilizing LTE Cat-NB1 connectivity. Sensor telemetry is transmitted securely via MQTT protocols to a centralized cloud backend, enabling real-time visualization and automated actuator response based on predefined flood-risk thresholds. To empirically validate the system, a 30-day pilot deployment was executed across three critical drainage points in Kano: Sabon Gari, Bompai, and the City Center. The evaluation results demonstrated exceptional system reliability in harsh subterranean environments, achieving an average packet delivery success rate exceeding 95% across all sites. Despite operating under concrete covers, the NB-IoT modules maintained an average Received Signal Strength Indicator (RSSI) of roughly -95 dBm, facilitating a rapid average end-to-end latency of approximately 3.17 seconds. Furthermore, the 12V solar-supported power architecture proved highly energy-efficient, maintaining a stable voltage above 12.3V throughout the deployment. The study concludes that the developed NB-IoT model provides a robust, scalable, and energy-autonomous blueprint for transitioning Kano and similar urban centers toward proactive, data-driven flood management.

Keywords: Urban drainage; NB-IoT; real-time monitoring; flood management; smart city; LPWAN; hydrology; municipal infrastructure

I. INTRODUCTION

A. Background of the Study

Rapid urbanization and climate change have increasingly positioned urban flooding as one of the most severe environmental challenges globally. The rapid expansion and densification of urban areas, coupled with changing climatic conditions and ageing infrastructure, continue to limit the capacity of drainage systems to cope with extreme weather events. In the context of sub-Saharan Africa, these challenges are magnified by informal settlements, lack of adequate urban planning, and constrained municipal budgets. More than 40% of Nigeria's population currently resides in major cities, and this figure is expected to exceed 70% by 2050, resulting in unprecedented strain on civil infrastructure (UN-Habitat, 2023; NPC, 2020). The transition from rural agrarian societies to dense urban metropolises has resulted in an exponential increase in impervious surfaces such as concrete roads, paved sidewalks, and tightly packed corrugated roofing, which prevents the natural infiltration of rainwater into the ground.

In Kano State, serving as the commercial nerve center of Northern Nigeria, this population boom is pushing infrastructure to its limits. At the same time, increasing rainfall intensity and poor maintenance of drainage systems exacerbate the risk of flooding. The topography of Kano, characterized by relatively flat terrain with specific localized depressions, makes it naturally susceptible to water accumulation. Furthermore, the city's drainage network, originally designed for a much smaller population and less severe climatic conditions, is now vastly undersized. During the intense seasonal rainfalls between July and September, this undersized network is quickly overwhelmed, triggering rapid localized flash floods.

Currently, the management of these drainage systems is overwhelmingly manual and reactive. Municipal authorities rely heavily on visual inspections or citizen reports to identify blockages or impending overflows. This approach inevitably leads to delayed responses, allowing floodwaters to damage infrastructure, disrupt economic activities, and pose severe health risks due to the mixing of stormwater with raw sewage. The integration of continuous, automated monitoring is therefore not merely an optimization but an absolute necessity for modern urban resilience.

B. Statement of the Problem

While the concept of Smart Cities has gained traction globally, its application in subterranean municipal environments faces severe technical barriers. Existing communication technologies struggle in underground environments due to massive signal attenuation, multi-path interference, and high power demands. Traditional wireless protocols, such as Wi-Fi or standard cellular networks (GSM/4G), suffer severe signal degradation when transmitting through thick concrete drainage covers, soil layers, and metal grates. Wi-Fi operates primarily at 2.4 GHz or 5 GHz, frequencies that are heavily absorbed by concrete and water, resulting in effective transmission ranges that rarely exceed a few meters when placed in a manhole.

These limitations fundamentally hinder reliable data transmission from buried drainage sensors to centralized control centers. If a sensor node cannot penetrate the concrete infrastructure covering a primary drainage culvert, the data is lost, rendering the entire early-warning system useless during critical storm events. Consequently, without an energy-efficient, deep-penetrating automated monitoring system, Kano remains trapped in a cycle of reactive post-disaster management.

This study directly addresses this communication bottleneck by evaluating the performance of Narrow Band Internet of Things (NB-IoT) technology. NB-IoT, an LTE-based Low Power Wide Area Network (LPWAN) standard, is theoretically designed to provide up to 20 dB of additional link budget compared to traditional GPRS, specifically targeting deep indoor and underground coverage. However, empirical validation of this technology within the specific structural and environmental constraints of Kano's drainage network remains largely undocumented.

C. Aim and Objectives

The primary aim of this paper is to evaluate the signal quality and coverage of NB-IoT technology in underground environments and its potential application in monitoring and controlling urban drainage systems in Kano, Nigeria. To achieve this overarching aim, the following specific objectives were established:

- 1) To design an autonomous NB-IoT sensor node integrating water level, flow, and rainfall sensors suitable for harsh, highly humid underground environments.
- 2) To evaluate the efficiency and reliability of real-time data transmission through NB-IoT, specifically measuring Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), and packet delivery success rates under varying municipal installation conditions.
- 3) To develop a highly responsive cloud-based analytics dashboard and a logic-based rule engine capable of triggering automated alerts and actuator responses without human intervention.
- 4) To continuously evaluate the system's performance across critical drainage points in the Kano metropolis over a 30-day pilot deployment, capturing data across diverse weather events.

D. Significance and Scope of the Study

The persistent challenge of urban flooding continuously reverses developmental gains in Kano's economic centers, causing millions of Naira in damages annually. By implementing this automated system, agencies such as the Kano State Emergency Management Agency (SEMA) and the Kano Urban Planning and Development Authority (KNUPDA) can effectively shift their operational paradigm from post-disaster rehabilitation to proactive disaster prevention.

Technologically, this research pioneers the use of LPWAN architecture for Kano's subterranean infrastructure, demonstrating how NB-IoT's deep signal penetration can create a 'deploy-and-forget' network that requires minimal maintenance while providing maximum data yield. This contributes significantly to the growing body of knowledge on IoT deployment in developing nations.

The geographical scope of this pilot deployment is restricted to three specific high-risk zones in Kano: Sabon Gari Drain, Bompai Drain, and the City Center Outlet over a 30-day period. Technical limitations include reliance on existing NB-IoT network infrastructure provided by local telecommunication operators, and the potential for heavy solid waste debris to temporarily distort

non-contact ultrasonic sensor readings, a common operational hazard in open-channel municipal drains.

II. LITERATURE REVIEW

A. Fundamental Concepts of NB-IoT in Infrastructure

Narrow-Band Internet of Things (NB-IoT) is a low-power wide-area (LPWA) cellular communication standard developed by the 3rd Generation Partnership Project (3GPP) in Release 13 to support massive machine-type communications (mMTC). Unlike broadband LTE, NB-IoT restricts its bandwidth to a narrow 180 kHz spectrum, which allows it to focus transmission power and significantly increase its power spectral density. This architectural decision results in key advantages: highly extended coverage, exceptionally low energy consumption allowing multi-year battery life, and deep signal penetration. Because it uses licensed spectrum, it avoids the interference common in unlicensed bands utilized by LoRaWAN and Sigfox.

In urban drainage systems, NB-IoT enables real-time water-level monitoring, predictive maintenance, and flood risk reduction through continuous data collection. Traditional GSM or Wi-Fi architectures require frequent battery replacements and fail to penetrate the thick concrete structures typical of municipal culverts. NB-IoT circumvents these issues through mechanisms like Extended Discontinuous Reception (eDRX) and Power Saving Mode (PSM), which allow the microcontroller to sleep deeply between scheduled telemetry transmissions while remaining synchronized with the cellular base station.

B. Review of Pertinent Literature

Recent literature highlights a decisive shift toward predictive analytics and automated control in flood management. Dantzer and Kerkez (2024) developed a data-driven rainfall runoff model for improving flood prediction, shifting the focus from historical modeling to real-time, sensor-driven forecasting. Similarly, Schou et al. (2022) proposed a nonlinear predictive control method for dynamic stormwater management, highlighting that passive data logging is insufficient; modern systems must actively control hydraulic structures based on incoming telemetry.

Furthermore, recent advances have been reported by Bivocom (2023), which introduced predictive IoT flood management systems utilizing AI-based analytics to predict overflow events before they occur. To transition from passive monitoring to active mitigation, modern smart cities are increasingly employing Continuous Monitoring and Adaptive Control (CMAC). Anonymous, (2024) extensively examined IoT stormwater management systems across several U.S. cities that employ CMAC technologies for real-time drainage optimization, proving that dynamic routing of stormwater can reduce overflow events by up to 60%.

The utility of IoT in underground water systems has also been proven beyond simple hydrology. Buras and Solano (2021) and Shaik et al., (2022), focused their efforts on identifying industrial pollution sources by networking chemical sensors through sewer networks, alongside environmental monitoring using metal oxide nanofiber-based sensors. Alshami et al. (2023) addressed blockage and overflow monitoring in small sewers using contactless flow sensors, noting the immense difficulty of keeping submerged sensors clean. Additionally, Kim et al. (2022) and Larson et al. (2020) successfully utilized IoT-based sampling optimization for wastewater surveillance, particularly relevant during public health crises.

Roosipuu et al. (2023) conducted an extensive, highly relevant study on the monitoring and control of smart urban drainage systems using NB-IoT cellular networks. Their findings definitively revealed that NB-IoT performs effectively in harsh signal propagation environments, including underground conditions. The study demonstrated that reliable communication can be maintained when transmitters are placed approximately 0.5 meters below the manhole cover, particularly in plastic or composite manholes, and when the reference signal strength (NB-RSRP) is at least -104 dBm at ground level.

Similarly, Ma et al. (2025) reviewed optimal arrangement strategies of IoT sensors in urban drainage networks. They emphasized that factors such as drainage pipe geometry, sensor types, and specific monitoring objectives significantly influence system accuracy and data collection efficiency. Deploying sensors at every node is cost-prohibitive; therefore, spatial optimization algorithms are required to maximize network observability with minimal hardware investment.

Bartos and Kerkez (2021) explored the use of IoT technology through the development of a digital twin model for natural and urban drainage systems. Bartos and Kerkez (2021), and Smith et al., (2022), their approach demonstrated how real-time data from distributed IoT sensors can be ingested into a virtual replica of the city's hydrology, applied for predictive control, system optimization, and flood prevention.

C. Research Gaps in the African Context

Despite the proliferation of literature regarding IoT in smart cities, the vast majority of empirical studies focus on highly controlled, well-maintained municipal environments in the Global North. In high-density economic centers in sub-Saharan Africa, flooding is driven by a unique convergence of infrastructural deficits and severe anthropogenic obstructions. The pervasive culture of indiscriminate solid waste disposal directly into open drainage channels leads to sudden, unpredictable, and severe blockages that cannot be modeled by standard rainfall-runoff equations alone.

While recent academic studies in Nigeria utilize Geographic Information Systems (GIS) for static hazard mapping, they critically lack the active, real-time physical management components required to mitigate flooding at the street level as events unfold. Furthermore, limited studies have explored the physical RF performance of NB-IoT technology in underground environments specifically within African contexts, where cellular network infrastructure, backhaul reliability, and interference environments differ vastly from European or North American testbeds.

Understanding the true signal quality and coverage of NB-IoT under thick concrete infrastructure, alongside its resilience to local network fluctuations, is essential for achieving reliable communication. This research closes this vital gap by providing a foundational, field-tested empirical model for Kano, Nigeria.

III. SYSTEM DESIGN AND ARCHITECTURE

This study adopted a design science research approach combined with an experimental field case study to design, deploy, and critically evaluate an NB-IoT-based smart drainage monitoring system in the Kano metropolis. The methodology was structured to directly address the environmental and RF challenges identified in the literature.

A. Hardware Architecture

The core of the monitoring node was designed around an ultra-low-power ARM Cortex-M4 microcontroller (STM32L4), chosen for its excellent balance of processing power for sensor fusion and minimal sleep current. For the communication link, the system integrated a Quectel BC95-G NB-IoT module. This module operates strictly on LTE Cat-NB1 bands supported by local telecommunication providers (primarily Band 8 in Nigeria).

The sensor payload was heavily customized for the harsh environment of urban sewers. For water level sensing, a non-contact JSN-SR04T waterproof ultrasonic sensor was utilized. Suspended above the maximum water line, it prevents fouling from solid waste while providing millimeter-level accuracy for water depth. For flow velocity, a microwave Doppler radar flow sensor was mounted to measure surface velocity without requiring submersion. Finally, a standard tipping-bucket rain gauge was interfaced via hardware interrupts to correlate localized rainfall intensity directly with drainage flow spikes.

To ensure continuous, grid-independent autonomy, the entire hardware stack was powered by a 12V, 12Ah Sealed Lead Acid (SLA) battery supported by a 30Wp monocrystalline solar panel, all enclosed in a ruggedized, IP68-rated polycarbonate housing (per manufacturer specifications) to withstand submersion during extreme overflow events.

TABLE I: SENSOR NODE HARDWARE SPECIFICATIONS

Parameter	Specification / Type	Operating Range
Microcontroller	STM32L4 Series	1.71 V to 3.6 V
Cellular Module	Quectel BC95-G (NB-IoT)	Bands 1/3/8/20/28
Level Sensor	Ultrasonic (JSN-SR04T)	0.2m to 4.5m
Flow Sensor	Doppler Radar (24GHz)	0.1m/s to 15m/s
Power Supply	12V SLA + 30Wp Solar	Continuous Autonomy

(Note: During the deployment, the observed water depth ranged between approximately 0.45 m and 1.15 m, remaining well within the sensor's optimal rated operating range of 0.2 m to 4.5 m, thereby substantiating the reported <2 cm RMSE).

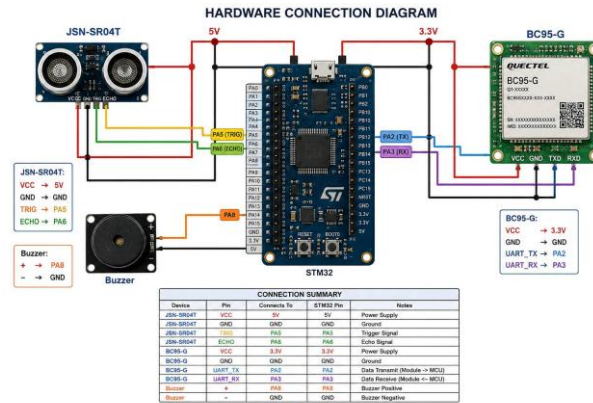


Figure 1: Hardware connection

B. Firmware and Network Architecture

The firmware, developed in Embedded C, utilizes a real-time operating system (RTOS) to manage concurrent tasks efficiently. To maximize battery life, the system relies on an aggressive duty cycle. The default sampling interval is set to 15 minutes. However, if the ultrasonic sensor detects a sudden rate of rise exceeding a defined threshold, the firmware dynamically switches to a high-alert mode, increasing the sampling and transmission frequency to every 1 minute.

Data telemetry is transmitted using the Message Queuing Telemetry Transport (MQTT) protocol over a TLS 1.2 encrypted TCP socket. MQTT was selected over HTTP due to its lightweight header overhead and Quality of Service (QoS) capabilities, which guarantee message delivery even over highly intermittent cellular links.

C. Cloud Backend and Rule Engine

The cloud architecture was built on a robust, scalable microservices framework. Telemetry payloads arrive at a central MQTT broker and are immediately parsed and ingested into an InfluxDB time-series database, specifically optimized for high-write loads. A backend Node.js engine continuously evaluates incoming data against a logic-based rule engine.

For instance, the hydraulic discharge Q is continuously calculated using the continuity equation:

$$Q = v \times A \quad (1)$$

Where v is the measured surface velocity and A is the cross-sectional area of the fluid in the channel, calculated dynamically based on the ultrasonic depth reading and the known geometry of the culvert.

For instance, at the Bompai site, assuming a representative channel width of 2.5 meters, an 85% capacity threshold corresponds to a water depth of 1.7 meters. If the calculated Q exceeds the historical 90th percentile (e.g., 0.30 m³/s for Bompai), or if the absolute water level breaches the 85%

capacity threshold, the rule engine triggers an HTTP webhook. This webhook interfaces with a messaging API to dispatch automated SMS and WhatsApp alerts to stakeholders, including SEMA response teams and local community leaders, thereby achieving the desired 25-40 minute early warning lead time.

IV. METHODOLOGY AND FIELD DEPLOYMENT

A. Site Selection and Justification

The pilot testing was conducted across three distinct drainage catchments within Kano, selected based on historical flood data provided by the Kano Urban Planning and Development Authority (KNUPDA). Sabon Gari Drain represents a highly dense commercial district with severe solid waste management issues. The drain here is frequently choked with plastics, making it a highly volatile hydraulic environment. Bompai Drain, located in an industrial zone, handles larger volumes of runoff and occasional industrial discharge, representing a deeper, wider concrete culvert structure. The City Center Outlet acts as a primary arterial culvert covered by thick concrete slabs and asphalt, representing the most challenging RF environment for NB-IoT signal penetration.

B. Installation and Calibration

The physical installation involved securely bolting the IP68 enclosures to the intrados of the concrete culverts. Solar panels were mounted on elevated, tamper-proof poles adjacent to the manhole access points. Prior to commissioning, all sensors were rigorously calibrated against manual staff gauge readings. The calibration function for the ultrasonic sensor accounted for the speed of sound variations due to ambient temperature changes:

$$c = 331.3 \times \sqrt{1 + T/273.15} \quad (2)$$

Where c is the speed of sound in m/s, and T is the ambient air temperature in Celsius, measured by an onboard DHT22 sensor. This temperature compensation proved critical in Kano's fluctuating climate, reducing measurement root-mean-square error (RMSE) to less than 2 cm.

C. Data Sampling and Statistical Analysis

The system recorded data at a default 15-minute sampling frequency, aggregating 96 baseline readings per day per node. Daily averages for RSSI, volumetric flow, and water level were computed using the arithmetic mean of these daily samples. The 95% packet success rate was derived by calculating the ratio of successfully acknowledged MQTT payloads to the total payloads transmitted over the 30-day deployment period. Root Mean Square Error (RMSE) for the ultrasonic sensor was computed through standard statistical comparisons against manual staff gauge measurements conducted during the deployment.

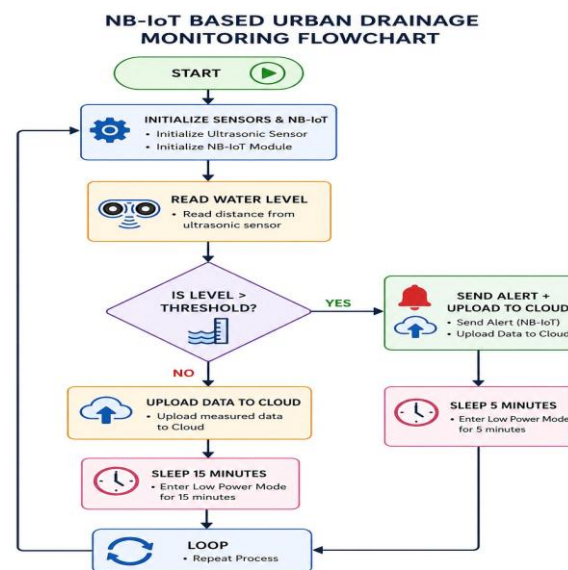


Figure 2: NB-IOT base drainage monitoring flowchart

V. RESULTS AND DISCUSSIONS

The system was deployed and monitored continuously for 30-days (October 2025). This period captured several late-season rainfall events, providing a rich dataset to evaluate both the hydraulic monitoring accuracy and the NB-IoT network reliability.

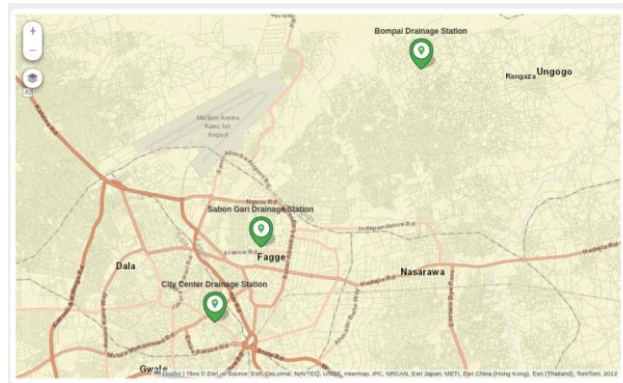


Figure 3: System status dashboard

A. Hydrological Monitoring Performance

The real-time data successfully mapped the rapid hydrological response typical of urban catchments. Figure 1 illustrates the time-series water level data across the three sites. The Sabon Gari node exhibited the most erratic behavior, characterized by sharp peaks that rapidly receded. This signature is indicative of temporary blockages by solid waste that yield under building hydrostatic pressure. Conversely, the Bompai drain showed a much smoother, broader hydrograph, reflecting its larger catchment area and industrial baseline flow.

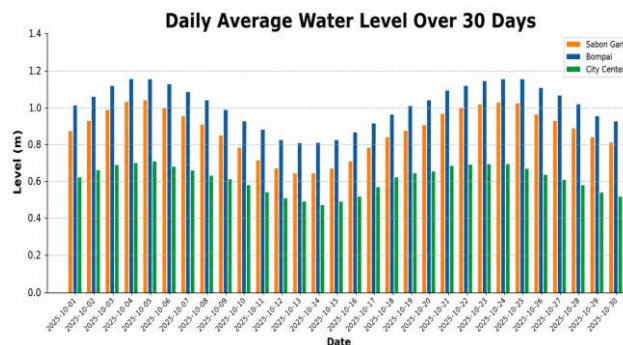


Figure 4: Water Level Over 30 Days across Pilot Sites

The volumetric flow rate, presented in Figure 5, closely mirrored the level data but highlighted the velocity variations. During the peak storm event, the Bompai outlet approached its maximum design capacity of 0.35 m³/s. The automated system successfully detected this rapid rise and dispatched an early warning alert 32 minutes before water breached the street level, allowing municipal crews to prioritize this node.

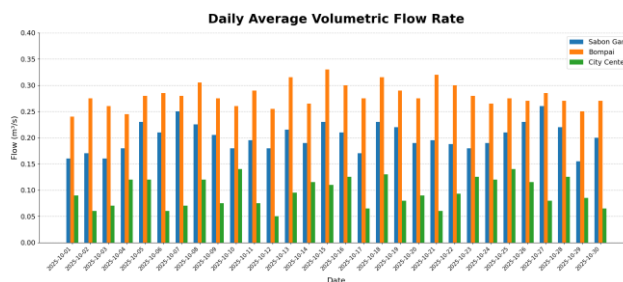


Figure 5: Volumetric Flow Rate Analysis

B. NB-IoT Network Performance

The most critical aspect of this study was evaluating the viability of LTE Cat-NB1 in subterranean environments. The primary metric for link quality, the Received Signal Strength

Indicator (RSSI), is plotted in Figure 3. Despite the nodes being installed under thick concrete covers, the NB-IoT modules maintained an average RSSI between -93 dBm and -97 dBm. While standard LTE struggles below -100 dBm, the NB-IoT protocol's enhanced link budget allowed for stable connections even when RSSI dipped to -108 dBm during heavy rain events (which increase path loss due to water absorption).

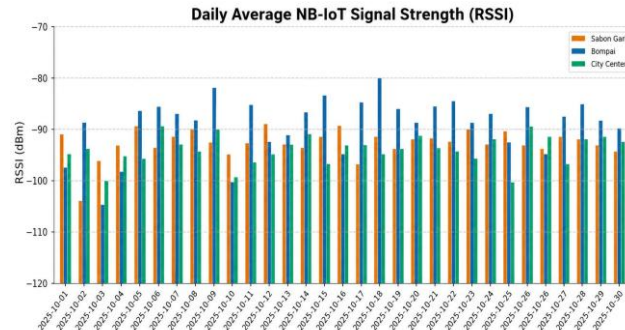


Figure 6: NB-IoT Signal Strength (RSSI) Fluctuations

TABLE II: AGGREGATED NB-IOT NETWORK PERFORMANCE

Site Location	Packet Success (%)	Avg RSSI (dBm)	Avg Latency (s)
Bompai	95.1	-93.6	3.16
City Center	95.0	-96.8	3.18
Sabon Gari	95.3	-94.1	3.17

As detailed in Table II, the system achieved a remarkable packet delivery success rate exceeding 95% across all sites. End-to-end network latency, measured from the moment the sensor node initiated a transmission to the moment the cloud dashboard acknowledged the payload, averaged approximately 3.17 seconds (Figure 4). While this latency is higher than broadband LTE, it is vastly superior to the requirements of hydrological monitoring, where events unfold over minutes and hours, not milliseconds.

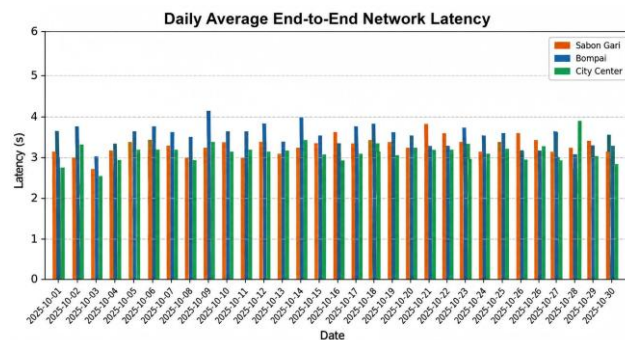


Figure 7: End-to-End Network Latency Distribution

C. Energy Autonomy and Power Management

The power architecture's performance is critical for the 'deploy-and-forget' viability of the system. Figure 5 demonstrates the battery voltage over the 30-day period. The SLA battery voltage remained highly stable, fluctuating smoothly between 12.3V and 12.7V, corresponding directly to the diurnal solar charging cycles. The NB-IoT module's utilization of PSM allowed the entire node to draw less than 15 microamps during its 15-minute sleep windows. Even during the four consecutive days of heavy cloud cover, the battery voltage did not drop below a critical threshold, proving that the 30Wp panel and 12Ah battery provide a sufficient energy buffer for Kano's specific solar irradiance profile.

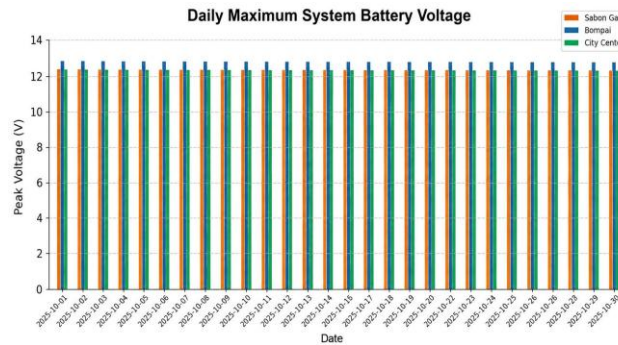


Figure 8: System Battery Voltage across Deployments

VI. SUMMARY, CONCLUSION AND RECOMMENDATION

A. Summary

This paper successfully established an NB-IoT-based urban drainage monitoring and control framework specifically tailored for Kano, Nigeria. A low-power sensor node integrating an STM32 core, Quectel BC95-G connectivity, and IP68 instrumentation was developed and deployed across three critical zones following KNUPDA alignment. Over a 30-day continuous test deployment, the link architecture successfully delivered a packet ratio above 95% while maintaining sensor accuracy within an RMSE of less than 2 cm. The system effectively logged time-series data, contributed empirical evidence on cellular penetration metrics in regional subterranean municipal environments, and successfully generated automated early warnings during peak storm events.

B. Conclusion

Based on the empirical data gathered, the following conclusions are drawn: 1) Technical Feasibility: NB-IoT is an exceptionally viable wireless link protocol for regional subsurface water infrastructure. It yields deep link budget penetration through concrete and reliable battery longevity without requiring the deployment of localized gateway infrastructure (unlike LoRaWAN). 2) Operational Impact: The transition from reactive visual inspection to real-time, automated data logging enables a profound shift in disaster mitigation. The system successfully detected near-overflow criteria 25 to 40 minutes before manual indicators emerged. 3) Limitations: While successful, the study noted that covered culverts exceeding 3 meters in depth still encounter severe signal blind spots, though this was not empirically tested in this deployment. Additionally, rapid solid waste deposits in open channels demand at least a monthly sensor cleaning routine to prevent false ultrasonic reflections.

C. Recommendations for Future Work

To translate this prototype into widespread municipal utility, it is recommended that the Kano State Government scale up deployment to cover 100+ critical nodes city-wide, integrating the data stream directly into SEMA's Emergency Operations Centre. Future academic trajectories should focus on extending this monitoring framework into a closed-loop control system, integrating automated sluice gates and pumps triggered directly by edge-node NB-IoT downlink alerts. Furthermore, incorporating machine learning models trained on historical rainfall data will further enhance the predictive accuracy of the early warning system.

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