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NIGERIAN ONLINE JOURNAL OF EDUCATIONAL SCIENCES AND TECHNOLOGY

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APPLICATION OF IOT AND AI FOR REAL-TIME FLOOD EARLY-WARNING AND RESILIENCE MANAGEMENT IN IBADAN METROPOLITAN AREA

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Abstract

Urban flooding poses a persistent threat to lives, infrastructure, and economic activities in rapidly growing African cities, yet early-warning systems in many contexts remain reactive and data-poor. This study develops and empirically evaluates an integrated Internet of Things (IoT) and Artificial Intelligence (AI)–based flood early-warning prototype for the Ibadan metropolitan area, Southwest Nigeria. Real-time hydrological data were collected through strategically deployed rainfall and water-level sensors across flood-prone communities and integrated with historical datasets to train an artificial neural network model for flood prediction. Geospatial analysis was used to map flood-risk hotspots, while system performance was assessed using accuracy, precision, recall, and warning lead-time metrics. Results show that the integrated IoT–AI system achieved prediction accuracy exceeding 90% and increased average warning lead time by nearly threefold compared to conventional monitoring approaches. Stakeholder validation further confirmed high usability and operational relevance for disaster response agencies and local communities. The findings demonstrate that locally developed, low-cost smart technologies can substantially enhance urban flood preparedness and resilience. The study provides a scalable model for climate adaptation planning and supports evidence-based integration of smart early-warning systems into urban disaster risk management frameworks in Nigeria and similar developing-country contexts.

Keywords: Flood early warning; Internet of Things; artificial intelligence; urban resilience; Ibadan; Nigeria

Introduction

Urban flooding has emerged as one of the most recurrent and destructive climate-related hazards affecting cities in sub-Saharan Africa, with profound implications for human safety, infrastructure, economic productivity, and long-term urban resilience. Rapid urbanisation, land-use change, climate variability, and inadequate drainage infrastructure have combined to increase both the frequency and severity of flood events in many African cities (UNDRR, 2022; Adelekan, 2022). Unlike slow-onset climate risks, floods often occur with little warning, overwhelming emergency response systems and disproportionately affecting low-income and high-density urban communities. In Nigeria, flooding has become a persistent urban challenge, particularly in the Southwest geopolitical zone. Ibadan, the capital of Oyo State and one of the largest metropolitan areas in West Africa, has a long history of devastating flood events. Major incidents such as the 1980 Ogunpa flood and the 2011 Bodija–Apete disaster resulted in extensive loss of lives, displacement of residents, and destruction of critical infrastructure. Despite decades of awareness and multiple structural interventions, Ibadan remains highly vulnerable due to its undulating topography, extensive impervious surfaces, encroachment on floodplains, and poorly maintained drainage networks (Adelekan, 2022; Adeniran et al., 2023).

Traditional flood management approaches in Nigerian cities are largely reactive, relying on historical rainfall records, manual river observations, and post-event emergency response. These approaches are increasingly inadequate in the face of climate change–induced rainfall variability, where extreme precipitation events occur with greater intensity and unpredictability. Studies have shown that the absence of real-time hydrological monitoring and early-warning intelligence significantly reduces response lead time and limits effective evacuation and preparedness measures (UNDRR, 2022). Consequently, there is growing consensus that flood risk reduction in urban Africa must transition from reactive disaster response to proactive, data-driven resilience planning. Emerging digital technologies—particularly the Internet of Things (IoT) and Artificial Intelligence (AI) have transformed flood risk management globally. IoT enables the deployment of distributed, low-cost sensors that collect real-time environmental data such as rainfall intensity, river stage, and drainage flow conditions. AI, on the other hand, allows these large and heterogeneous datasets to be analysed using machine learning algorithms capable of identifying patterns, learning from historical events, and predicting flood likelihood with high accuracy (Zhou et al., 2021). When integrated, IoT and AI systems support real-time flood detection, early warning dissemination, and adaptive decision-making.

Globally, several cities have demonstrated the effectiveness of AI- and IoT-based flood early-warning systems. In Jakarta and Mumbai, hybrid systems combining sensor networks, neural network models, and geospatial data have significantly improved flood forecasting accuracy and increased warning lead times, enabling authorities to reduce casualties and economic losses (Kundu & Sinha, 2022; Sharma & Rao, 2022). Similarly, studies in Southeast Asia have shown that artificial neural networks and deep learning models outperform conventional hydrological models when trained on high-resolution rainfall and river-level data (Tan et al., 2021). Despite these advances, Nigerian cities have been slow to adopt smart flood management technologies. Existing flood mitigation efforts in Ibadan—such as dredging, channelisation, and public sensitisation—are not supported by real-time monitoring or predictive intelligence, limiting their effectiveness (Olayemi & Ogunleye, 2023). Furthermore, imported flood modelling solutions are often expensive, data-intensive, and poorly adapted to local infrastructural and socio-economic conditions. This has created a critical gap for affordable, locally tailored, and scalable flood early-warning systems that integrate real-time data with predictive analytics.

Ibadan presents a particularly compelling case for IoT- and AI-driven flood resilience planning. The city's recurrent flood history, combined with its diverse hydrological features and growing population, provides a suitable testbed for deploying smart early-warning technologies. Developing a locally trained AI model that leverages real-time sensor data offers the potential to improve flood prediction accuracy, extend warning lead times, and enhance community preparedness. Such a system would not only support disaster response agencies but also empower communities with timely, actionable information. Against this backdrop, this study develops and deploys an IoT- and AI-based real-time flood early-warning prototype for high-risk areas in the Ibadan metropolitan area. By integrating hydrological sensors, geospatial mapping, and artificial neural network models, the research evaluates the technical performance, predictive accuracy, and practical usability of smart flood warning technologies in a Nigerian urban context. The study contributes empirical evidence to the growing literature on digital disaster risk reduction and provides policy-relevant insights for scaling smart flood resilience systems in Ibadan and other flood-prone cities in Southwest Nigeria, in alignment with Sustainable Development Goal 11 on sustainable and resilient cities.

Literature Review

Urban flooding has intensified globally due to the combined effects of climate change, rapid urbanisation, and inadequate stormwater infrastructure. Increased impervious surfaces, encroachment on floodplains, and aging drainage systems reduce infiltration capacity and accelerate runoff, thereby amplifying flood risk in cities (UNDRR, 2022). In developing-country cities, these challenges are compounded by weak land-use enforcement and limited investment in hydrological monitoring. Empirical studies across Africa consistently show that flood impacts are most severe where early-warning capacity is weak and response systems are reactive rather than anticipatory (Adelekan, 2022; Adeniran et al., 2023). Ibadan exemplifies this pattern, with recurrent flood events driven by intense rainfall, topographic constraints, and limited real-time situational awareness.

Flood early-warning systems (FEWS) are widely recognised as cost-effective tools for reducing disaster losses by increasing lead time for preparedness and evacuation. Traditional FEWS rely on hydrological and hydraulic models calibrated with historical data, which can be effective but often struggle to capture non-linear dynamics under changing climate conditions. Recent literature emphasises the need for real-time intelligence that integrates continuous monitoring with adaptive prediction models to enhance warning accuracy and timeliness (UNDRR, 2022). Cities that have adopted real-time FEWS report significant reductions in flood-related casualties and damage, highlighting the value of proactive risk management. The Internet of Things has enabled a new generation of flood monitoring systems by facilitating the deployment of distributed, low-cost sensors capable of capturing hydrological variables such as rainfall intensity, river stage, and drainage flow in real time. IoT-based sensor networks provide high-frequency data streams that improve situational awareness and enable rapid detection of threshold exceedance events (Zhou et al., 2021). Studies from Asia and Europe demonstrate that IoT sensors, when strategically deployed, can significantly improve the spatial and temporal resolution of flood monitoring compared to conventional gauge stations. However, challenges remain regarding data reliability, power supply, network connectivity, and system maintenance, particularly in resource-constrained urban environments.

Artificial intelligence, especially machine learning techniques such as artificial neural networks (ANN), convolutional neural networks (CNN), and recurrent neural networks (RNN), has gained prominence in flood prediction due to its ability to model complex, non-linear relationships between hydrometeorological variables. Empirical evidence shows that AI-based models often outperform traditional statistical and physics-based models in short-term flood forecasting, particularly when trained on high-resolution datasets (Tan et al., 2021; Sharma & Rao, 2022). AI models can continuously learn from new data, making them well suited for dynamic urban flood environments where rainfall patterns and land-use characteristics evolve rapidly. Recent research highlights the synergistic value of integrating IoT and AI in flood risk management. IoT provides real-time data streams, while AI transforms these data into actionable predictions and alerts. Hybrid IoT–AI systems deployed in cities such as Jakarta and Mumbai have improved flood prediction accuracy and increased warning lead times, enabling authorities to coordinate emergency response more effectively (Kundu & Sinha, 2022). Beyond early warning, such systems support broader urban resilience by informing infrastructure planning, community awareness, and climate adaptation strategies. Despite these demonstrated benefits, adoption in African cities remains limited, largely due to cost, technical capacity gaps, and lack of locally adapted models (Olayemi & Ogunleye, 2023).

While global evidence supports the effectiveness of IoT–AI flood early-warning systems, there is a notable gap in locally developed and empirically validated systems in Nigeria. Existing studies on flooding in Ibadan focus primarily on historical analysis, vulnerability assessment, and post-disaster impacts, with little emphasis on real-time monitoring or predictive modelling (Adelekan, 2022; Adeniran et al., 2023). Moreover, few studies have assessed system performance using objective metrics such as prediction accuracy, precision, recall, and warning lead time, or incorporated stakeholder feedback on system usability. This study addresses these gaps by developing and validating a locally trained IoT–AI flood early-warning prototype tailored to Ibadan's hydrological and infrastructural context.

Methodology

This study adopted a multidisciplinary, prototype-based empirical design integrating real-time sensing, artificial intelligence modelling, geospatial analysis, and stakeholder validation to develop and evaluate an IoT–AI flood early-warning system for the Ibadan metropolitan area. Flood-prone communities including Apete, Bodija, Oke-Ado, and adjoining catchments were purposively selected based on historical flood records, topography, drainage density, and population exposure. In the first phase, flood-risk mapping was conducted using satellite imagery, digital elevation models, drainage networks, and historical rainfall and flood data to identify high-risk zones and optimal sensor locations. In the second phase, low-cost IoT sensors (rainfall gauges, ultrasonic water-level sensors, and drainage flow indicators) were deployed at strategic river channels, culverts, and drainage outlets, with data transmitted in real time to a central server via GSM/LoRaWAN communication modules. Historical hydrometeorological data obtained from the Nigerian Meteorological Agency (NiMet) and local authorities were combined with live sensor feeds to train an artificial neural network (ANN) flood prediction model developed using Python-based libraries (TensorFlow and Keras). Model optimisation involved tuning network architecture, learning rate, and activation functions, while performance was evaluated using accuracy, precision, recall, F1-score, and warning lead time. A web-based dashboard and SMS alert system were implemented to simulate real-time warning dissemination. System effectiveness and usability were further assessed through simulation exercises, stakeholder validation workshops, and semi-structured interviews with disaster management officials and community representatives. All procedures complied with ethical requirements, and approval was obtained prior to sensor deployment and data use.

Results

Performance of IoT Sensor Network

The deployed IoT sensor network functioned reliably throughout the monitoring period, capturing real-time hydrological indicators across flood-prone locations. Data completeness exceeded 90%, indicating stable communication and power performance.

Table 1: Performance Summary of Deployed IoT Sensors

Sensor Type	Measured Variable	Deployment Points (n)	Data Accuracy (%)	Uptime (%)
Rainfall gauge	Rainfall intensity (mm/hr)	6	96.4	93.8
Ultrasonic sensor	River/drainage water level (cm)	8	94.9	91.5
Flow indicator	Drainage flow velocity	5	92.1	90.3

The high data accuracy and uptime recorded by the deployed IoT sensors demonstrate the technical feasibility of real-time hydrological monitoring in a resource-constrained urban African context. Rainfall and water-level sensors achieved reliability levels comparable to those reported in smart flood monitoring systems implemented in Asian megacities, where sensor uptime above 90% is considered operationally acceptable (Zhou et al., 2021; Sharma & Rao, 2022). The minor data gaps observed during peak rainfall events mirror challenges reported in similar deployments, often linked to network congestion and power instability rather than sensor failure. This finding reinforces the argument that low-cost IoT architectures, when carefully sited and maintained, can provide dependable real-time data for flood risk management in Nigerian cities.

Flood-Risk Mapping and Hotspot Identification

Geospatial analysis integrating sensor data, topography, and historical flood records identified clear spatial variation in flood risk across Ibadan. Apete and Bodija emerged as the most flood-prone zones.

Table 2: Flood-Risk Classification of Selected Communities

Community	Mean Elevation (m)	Drainage Density	Flood Frequency (2000–2023)	Risk Category
Apete	173	High	7	Very High
Bodija	169	High	6	Very High
Oke-Ado	182	Moderate	5	High
Orogun	188	Moderate	3	Medium
Eleyele axis	195	Low	2	Low

The flood-risk mapping results highlight clear spatial heterogeneity in flood exposure across Ibadan, with Apete and Bodija consistently classified as very high-risk zones. This aligns strongly with historical flood records and prior vulnerability studies that identify these areas as recurrent flood hotspots due to low elevation, dense drainage networks, and extensive impervious surfaces (Adelekan, 2022; Adeniran et al., 2023). The convergence between model-derived risk categories and documented flood history validates the robustness of the geospatial component of the system and supports the use of integrated GIS–sensor frameworks for urban flood risk assessment. Importantly, the results demonstrate how real-time data can move flood mapping beyond static hazard maps toward dynamic, continuously updated risk intelligence.

AI Flood Prediction Model Performance

The artificial neural network (ANN) model demonstrated strong predictive capability when trained on combined historical and real-time data. Model outputs significantly outperformed baseline threshold-based detection methods.

Table 3: Performance Metrics of Flood Prediction Models

Model Type	Accuracy (%)	Precision (%)	Recall (%)	F1-Score
Threshold-based model	71.6	68.2	65.4	0.67
ANN (historical data only)	84.3	82.1	80.6	0.81
ANN (historical + real-time IoT data)	91.8	90.4	89.7	0.90

The artificial neural network model significantly outperformed threshold-based and historical-data-only approaches, achieving prediction accuracy above 90% when real-time IoT data were incorporated. This finding is consistent with global evidence showing that AI models, particularly neural networks, are better suited to capturing the non-linear relationships between rainfall intensity, antecedent conditions, drainage capacity, and flood occurrence than conventional models (Tan et al., 2021; Kundu & Sinha, 2022). The performance gain achieved by integrating live sensor data confirms Hypotheses H1 and H2 and underscores the critical role of real-time inputs in improving predictive reliability under highly variable rainfall regimes associated with climate change.

Flood Early-Warning Lead Time Improvement

One of the most critical performance indicators was the improvement in warning lead time. The IoT–AI system generated alerts significantly earlier than conventional response approaches.

Table 4: Comparison of Flood Warning Lead Time

Warning Approach	Mean Lead Time (minutes)
Conventional monitoring	18
IoT sensor threshold alerts	32
Integrated IoT–AI system	54

One of the most significant contributions of this study is the demonstrated improvement in flood warning lead time. The integrated IoT–AI system provided an average lead time of over 50 minutes, nearly three times that of conventional monitoring approaches. Global disaster risk literature consistently emphasises that even modest increases in lead time can substantially reduce flood-related mortality and damage by enabling timely evacuation and protective actions (UNDRR, 2022). The lead-time gains observed here are comparable to those reported in pilot smart flood systems in Mumbai and Jakarta, where AI-enhanced warnings translated into measurable improvements in emergency response coordination (Sharma & Rao, 2022; Kundu & Sinha, 2022). This confirms Hypothesis H3 and demonstrates the practical value of smart technologies for urban flood resilience in Ibadan.

Stakeholder Evaluation of System Effectiveness

Stakeholder validation workshops and interviews assessed system usability, clarity of alerts, and perceived usefulness for disaster response.

Table 5: Stakeholder Evaluation of the IoT–AI Flood Warning Prototype (n = 25)

Evaluation Criterion	Mean Score (1–5)	Interpretation
Ease of use	4.4	High
Alert clarity	4.6	Very High
Timeliness of warnings	4.5	Very High
Decision-support usefulness	4.3	High
Overall system effectiveness	4.5	Very High

The strong positive evaluations from disaster management officials and community representatives indicate high perceived usefulness, clarity, and operational relevance of the prototype. Stakeholder acceptance is a critical yet often overlooked factor in the success of early-warning systems, as technically robust solutions may fail if they are not trusted or understood by end users. The high usability scores reported in this study align with findings from community-centric flood warning initiatives in developing contexts, which stress the importance of clear alerts, local relevance, and institutional ownership (Olayemi & Ogunleye, 2023).

Conclusion

This study demonstrates the practical feasibility and effectiveness of integrating Internet of Things (IoT) and Artificial Intelligence (AI) technologies for real-time flood early-warning and resilience management in the Ibadan metropolitan area. The empirical findings confirm that Ibadan's flood vulnerability is strongly driven by a combination of intense rainfall, low-lying topography, dense drainage networks, and rapid urbanisation. The deployed IoT sensor network successfully captured real-time hydrological data with high reliability, while the artificial neural network model effectively transformed these data into accurate flood predictions. The integrated IoT–AI system significantly outperformed conventional flood monitoring approaches in terms of prediction accuracy and warning lead time, offering substantial improvements in disaster preparedness and response capacity.

Recommendations

Based on the results of this study, the following recommendations are proposed:

1. State and local disaster management agencies should adopt and scale the IoT–AI flood early-warning system across other high-risk zones in Ibadan and similar urban centres in Southwest Nigeria.
2. Flood-risk maps and real-time data generated by the system should be integrated into land-use planning, drainage design, and urban development control to reduce long-term flood exposure.
3. Government and development partners should invest in expanding sensor networks, improving communication infrastructure, and supporting data analytics capacity for smart disaster management.
4. Early-warning messages should be disseminated through multiple channels, including SMS, community leaders, and local media, to ensure inclusivity and rapid response.

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