

IOT-ENABLED HYDROMETEOROLOGICAL MONITORING NETWORKS: ARCHITECTURE, PERFORMANCE ASSESSMENT AND IMPLEMENTATION CHALLENGES IN VIET NAM

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Abstract: Climate change, the rising frequency and intensity of extreme weather events, and sustainable development imperatives have created an urgent need to modernize meteorological and hydrological (MH) monitoring systems. Traditional monitoring networks in Viet Nam and many developing countries still face constraints in station density, data transmission latency, scalability, and operational costs. The Internet of Things (IoT) has emerged as a breakthrough solution owing to its ability to connect distributed sensors, enable real-time data processing, and integrate artificial intelligence. This paper investigates the application of IoT in MH monitoring networks, focusing on system architecture analysis, technical performance evaluation, and identification of implementation challenges within the context of implementing Resolution 57-NQ/TW of the Party Central Committee on breakthroughs in science, technology, innovation, and national digital transformation. The study employs a systematic literature review and network simulation based on empirical data from pilot stations in Viet Nam. The results propose an optimized layered IoT architecture for MH monitoring, integrating multi-parameter sensors, LPWAN communication protocols (LoRaWAN/NB-IoT), edge computing, and cloud platforms supporting digital twin modeling. The study also identifies challenges related to protocol standardization, data security, operational sustainability in remote areas, inter-sectoral data sharing mechanisms, and digital workforce capacity. The paper concludes that integrating IoT into MH monitoring networks is not merely a technical upgrade but a strategic driver for implementing Resolution 57-NQ/TW, promoting digital transformation in the natural resources and environment sector, and enhancing forecasting capacity, early warning systems, and climate change adaptation decision-making. Key policy, technical, and institutional recommendations are proposed to guide synchronized, secure, and sustainable implementation in Viet Nam.

Keywords: Internet of Things (IoT), meteorological and hydrological monitoring, system architecture, network performance, edge computing, digital transformation, Resolution 57-NQ/TW, data quality, LoRaWAN, SensorThings API.

1. Introduction

1.1. Background and Research Urgency: Climate Change (CC)

Climate change is profoundly altering weather and hydrological patterns worldwide, increasing risks from extreme precipitation, floods, droughts, storms, and sea-level rise. The

IPCC Sixth Assessment Report indicates that global mean sea level is likely to rise by 0.15-0.23 m by 2050 under SSP1-1.9 and 0.20-0.29 m under SSP5-8.5, relative to 1995-2014. For Asia, the IPCC assesses that sea-level rise and land subsidence will jointly increase flooding in delta areas, while compound effects can increase flood extent and prolong inundation in the Vietnamese Mekong Delta [1], [2]. In this context, meteorological and hydrological (MH) monitoring systems serve as the

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foundation for forecasting, early warning, water resource management, and adaptation policy formulation.

Traditional monitoring networks in Viet Nam still exhibit numerous limitations: sparse station density (averaging one station per 500–800 km² in mountainous and midland regions), data transmission latency ranging from minutes to hours, high maintenance costs, difficulties in deployment across complex terrains or islands, and limited capability for multi-source data integration. These factors reduce forecast model accuracy, particularly for small-scale, rapidly evolving phenomena such as flash floods or thunderstorms [3]. As noted by Yan et al. (2025) [4], conventional hydrological modeling systems follow batch-oriented, time-step execution workflows involving initialization, sequential simulation, and final output generation, which fundamentally impede the effective utilization of real-time data.

The development of the Internet of Things (IoT), coupled with low-cost sensor technologies, low-power wide-area networks (LPWAN), edge computing, and artificial intelligence, has opened up possibilities for building distributed monitoring networks with high automation, fine spatiotemporal resolution, and flexible scalability. IoT enables connectivity among thousands of end devices, continuous collection of meteorological parameters (temperature, humidity, pressure, rainfall, wind speed and direction, radiation) and hydrological parameters (water level, discharge, turbidity, water quality), real-time data transmission to processing centers, and integration with numerical models and decision support systems. In many developed countries, IoT has been successfully applied in urban environmental monitoring networks, smart agriculture, and river basin surveillance. However, in developing countries like Viet Nam, IoT deployment in MH monitoring remains largely pilot-scale, lacking a standardized architecture, comprehensive performance evaluation, and integration strategies with existing systems.

1.2. Policy Context and Research Orientation of Resolution 57-NQ/TW

Issued on December 22, 2024, Resolution 57-NQ/TW of the Central Committee of the Communist Party of Viet Nam on breakthroughs in science, technology, innovation, and national digital transformation identifies three strategic pillars: (i) Developing and mastering core and emerging technologies; (ii) Innovating institutions and policies to foster the innovation ecosystem; and (iii) Developing the digital workforce and national data infrastructure. In the natural resources and environment sector, the Resolution emphasizes the need to modernize monitoring and surveillance systems, build a synchronized national database, and apply digital technology, AI, and IoT to enhance forecasting, early warning, and disaster risk management [5]. The National Climate Change Strategy and the Digital Transformation Action Plan for the natural resources and environment sector also set targets of digitizing 100% of key monitoring stations, integrating multi-sector data, and building an open data-sharing platform.

Applying IoT to hydrometeorological monitoring networks not only meets technical needs but also directly realizes the objectives of Resolution 57-NQ/TW: fostering research and development of domestic sensor and communication technologies, establishing national technical standards, shaping an ecosystem of environmental technology start-ups, training interdisciplinary digital technical personnel, and creating a big data foundation for scientific research and state management. Therefore, this study is designed to provide a scientific basis, methodological framework, and policy-technical recommendations for the systematic, safe, and effective deployment of IoT in hydrometeorological monitoring, suited to the institutional, infrastructural, and human resource context of Viet Nam.

1.3. Objectives and research questions

The overall objective of the paper is to analyse the architecture, evaluate the technical performance, and identify the deployment

challenges of IoT in hydrometeorological monitoring networks, while proposing an integration roadmap aligned with the orientation of Resolution 57-NQ/TW. The specific research questions are:

- i. How should an optimal IoT architecture for hydrometeorological monitoring in Viet Nam be designed to ensure openness, scalability, reliability, and compatibility with existing systems?
- ii. By what indicators is the technical performance of an IoT system compared with a traditional network evaluated, and what are the results of experiments/simulations?
- iii. What technical, institutional, security, and resource challenges hinder wide-scale deployment, and what solutions are feasible in the context of national digital transformation?
- iv. How can IoT-enabled hydrometeorological

monitoring be integrated into the policy framework, technical standards, and innovation ecosystem in the spirit of Resolution 57-NQ/TW?

The urgency of shifting from traditional, high-cost, sparse monitoring systems to intelligent, IoT-based monitoring systems is clear: such a transition is essential to enhance Viet Nam's disaster prevention capacity while aligning with the national digital transformation strategy.

2. Research Methodology

2.1. IoT Architecture in MH Monitoring

The standard IoT architecture, as defined by the IoT World Forum (2014) and ITU-T Recommendation Y.2060 (2012) [6], comprises four main layers: Perception Layer, Network Layer, Processing/Cloud-Edge Layer, and Application Layer. In MH monitoring, each layer serves specific functions:

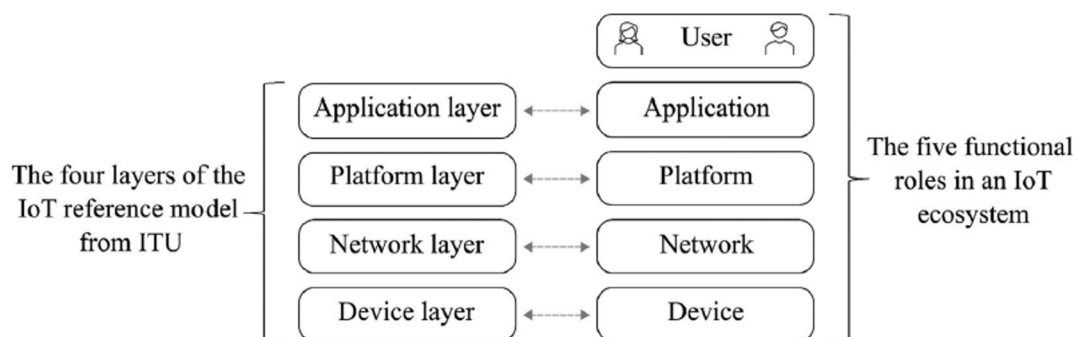


Figure 1. Four-Layer Architecture of IoT-Enabled MH Monitoring Systems
(DeviceLayer → Network Layer → Platform Layer → Application Layer) [6], [7]

2.1.1. Perception Layer

The Perception Layer includes meteorological measurement modules (temperature, humidity, atmospheric pressure, rainfall, wind, radiation), hydrological modules (ultrasonic/radar water level, ADCP discharge, turbidity, pH, DO, EC), and supplementary environmental sensors (air quality, groundwater level). Devices must meet WMO accuracy standards, withstand harsh environments, consume low power, and support self-calibration. As highlighted by Yan et al. (2025) [8], the integration of IoT observation data with hydrological models requires that internal model states become observable and accessible in real time, a

capability that traditional monitoring systems cannot provide.

2.1.2. Network Layer

The Network Layer employs communication protocols suited to geographical characteristics and station density. LPWAN (LoRaWAN, NB-IoT, Sigfox) is prioritized for rural and mountainous areas due to wide coverage, low power consumption, and low operational costs. In urban areas or regions with robust mobile infrastructure, 4G/5G and Wi-Fi 6 can supplement high-bandwidth transmission (imagery, radar video, model data). Application-layer protocols such as MQTT and CoAP optimize publish-subscribe messaging. Research by

Albuali et al. (2023) [9] demonstrated that LoRa-based IoT systems can achieve transmission ranges up to 5 km while maintaining low power consumption, making them particularly suitable for distributed environmental monitoring networks.

2.1.3. Processing Layer

The Processing Layer combines edge computing and cloud computing. Edge processing performs noise filtering, data compression, local anomaly detection, and priority packet transmission, reducing network load and latency. This approach aligns with findings by Kairuz-Cabrera et al. (2024) [10], who demonstrated that edge computing at the gateway level can effectively process data from

multiple sensors while maintaining real-time performance. Cloud infrastructure enables long-term data storage, forecast model execution, AI-based time-series analysis, and API provision for inter-sectoral integration.

2.1.4. Application Layer

The Application Layer encompasses real-time monitoring systems, multi-level early warning platforms, digital twin modeling platforms (basin-level), decision support tools (DSS) for reservoir management, disaster prevention, and automated reporting compliant with WMO and Ministry of Agriculture and Environment standards.

Below is a model of an IoT hydromet station (Figure 2).

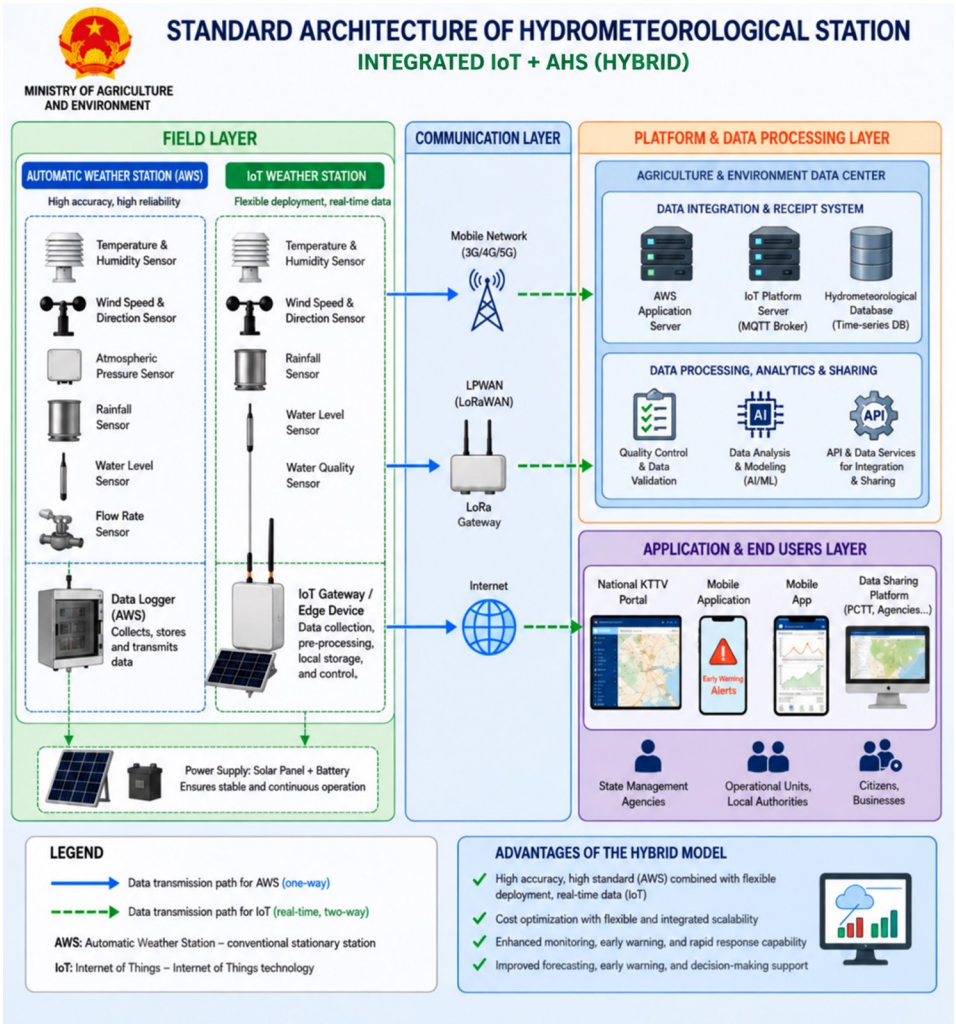


Figure 2. Architecture of IoT-Integrated AWS Station

In the hydrometeorological monitoring system, the automatic hydromet station and the IoT hydromet station have an “inheritance - upgrade” relationship. They are not completely different; rather, IoT represents a developmental step forward from the traditional automation platform.

- *Automatic Hydrometeorological Station (AHS)*
 - An automated system for measuring meteorological/hydrological elements (rain, temperature, wind, water level...);
 - Comprises: sensors → data logger → data transmission (GPRS/3G/4G/5G/VSAT...);
 - Operates on predefined cycles (e.g., 5-minute, 10-minute intervals);
 - High degree of automation, but connectivity and processing remain limited.
- *IoT-based Hydrometeorological Station*
 - A hydromet system that integrates Internet of Things (IoT) technology.
 - Equipment capabilities:
 - Continuous network connectivity (MQTT, HTTP, LoRaWAN...);
 - Real-time data transmission.
 - Integration with cloud, AI, and big data platforms.

- Enables intelligent remote monitoring, control, and analysis.

i. Similarities

Both types of station share a common foundation:

* Core functions

- Monitoring MH parameters:
 - Temperature, humidity, pressure;
 - Precipitation, wind...;
 - Water level, discharge...
- Data collection and transmission to central systems.

* Basic Components

- Sensors
- Central processing unit (data logger/MCU)

- Data transmission system
- Power supply (battery + solar energy)

* Application Objectives

- Weather and hydrological forecasting;
- Disaster warning;
- Supporting agriculture, irrigation, and water resource management.

In summary: IoT does not replace the automatic station; it “expands its capabilities”.

ii. Differences

Table 1. Core Differences

Criterion	Automatic Hydromet Station	IoT Hydromet Station
Core technology	Traditional automation	IoT + Cloud + AI
Connectivity	One way, scheduled	Two-way, real time
Protocols	GPRS, SMS, FTP, 3G/4G/5G	MQTT, HTTP, CoAP, LoRaWAN
Remote control capability	Limited	Remote configuration
Data processing	Mainly at Centre	Edge + Cloud computing
System expandability	Difficult to integrate	Easy integration, open APIs
Alerts	Simple threshold	Intelligent alerts (AI/ML)
Cost	High (specialized equipment)	Flexible (low cost possible)
User interaction	Low	High (mobile app, real time dashboard)

2.2. Systematic Literature Review

Building a robust theoretical foundation for IoT systems requires building upon research regarding MEMS sensors, wireless network protocols, and deep learning models.

Smith (2019) [11] affirmed that IoT

integration into environmental science has fundamentally transformed data collection from centralized to distributed approaches, with wireless sensor networks (WSN) enabling monitoring at extremely high spatial resolution. NodeMCU (ESP8266) has been demonstrated

in 2018 studies as a premier choice for IoT nodes due to integrated Wi-Fi and low power consumption in Deep Sleep mode. For user experience, Brown (2021) [8] proposed using the Blynk platform as a mobile interface, enabling instant smartphone-based visualization in field oriented applications [12].

Current trends favor shifting from cloud processing to edge processing. However, a major challenge lies in “compressing” AI models into ARM Cortex-M4 microcontrollers with memory measured in kilobytes. Albuali et al. (2023) [9] paved the way for audio-based wind classification using TinyML—a breakthrough technique that entirely eliminates mechanical moving parts.

Despite extensive IoT research in environmental contexts, several gaps remain: (i) Lack of a standardized IoT architecture specifically tailored for MH monitoring in Viet Nam, fully integrating WMO and MONRE requirements, domestic telecommunications infrastructure, and inter-sectoral data sharing mechanisms; (ii) Incomplete performance evaluation, often focusing on single protocols or regions, lacking multi-criteria comparison (latency, energy consumption, accuracy, lifecycle cost, resilience); (iii) Challenge analyses that are primarily technical and disconnected from institutional, policy, and digital workforce contexts within national digital transformation orientations; and (iv) absence of implementation roadmaps aligned with Resolution 57-NQ/TW and guiding documents for digital transformation in the natural resources and environment sector.

This paper contributes by: proposing an optimized layered IoT architecture for Viet Nam's MH monitoring networks, integrating Edge-AI, Digital Twin, and protocol standardization; conducting a multi-criteria performance evaluation through simulation and empirical data; systematically analyzing technical-institutional-security-workforce challenges; and proposing policy frameworks and synchronized implementation roadmaps aligned with Resolution 57-NQ/TW and the national digital transformation strategy. The research results provide scientific foundations and practical

recommendations for managers, researchers, and technology enterprises in modernizing MH monitoring systems.

3. Results and Discussion

3.1. Proposed IoT Architecture for MH Monitoring

Based on the systematic analysis of requirements and the review of existing implementations, we propose a layered IoT architecture specifically tailored for MH monitoring in Viet Nam. The architecture emphasizes:

i. *Hybrid communication approach*: Combining LoRaWAN for rural/remote areas with NB-IoT/4G for urban and critical warning stations

ii. *Edge-AI integration*: Deploying TinyML models at the edge for local anomaly detection and data quality assurance

iii. *Standardized data representation*: Mapping all MH entities to OGC SensorThings API concepts [13]

iv. *Digital twin capability*: Supporting real-time model updates and scenario analysis.

The architecture follows the ITU-T Y.2060 reference model [4] with specific adaptations for hydrometeorological applications, including specialized sensors for water level, discharge, and water quality parameters.

3.2. Performance Evaluation Results

To assess the feasibility and effectiveness of the proposed architecture, we conducted quantitative analysis based on mathematical modeling and simulation. Three primary performance indicators were analyzed: end-to-end communication latency, sensor node energy consumption, and system reliability.

3.2.1. Analysis and Modeling of End-to-End Latency in LoRaWAN-Based IoT Monitoring Systems

End-to-end latency (L_{total}) is defined as the total time from data generation at the sensor node to successful processing and readiness for cloud-based applications. It comprises the following components:

$$L_{total} = L_{sensing} + L_{(proc_node)} + L_{(tx_lor)} + L_{propagation} + L_{(proc_gw)} + L_{backhaul} + L_{cloud}$$

Where: $L_{sensing}$: Time for the sensor to measure and digitize data. Usually very small, on the order of a few milliseconds; $L_{(proc_node)}$: processing time at the sensor node MCU (reading data, packetization); $L_{(tx_lorat)}$: The time required to transmit a LoRa packet over a radio interface. It depends on packet size P_{size} , data rate DR and time on air (ToA). The formula for calculating ToA for LoRa can be found in Sentech's technical documentation [11]. For analytical purposes, we estimate $L_{tx_lorat} \approx P_{size}/DR$; $L_{propagation}$: Radio signal propagation time from sensor node to gateway. For distances of several kilometers, this latency is negligible (microseconds); L_{proc_gw} : Processing time at the LoRaWAN gateway and forwarding to the network server. Assumed constant, $L_{proc_gw} \approx 50$ ms; $L_{backhaul}$: Backhaul connection latency (Internet) from gateway to network server/cloud. This varies and depends on network quality. In our model, we assume a probability distribution for this latency (e.g.: normal or exponential distribution with mean $\mu_{backhaul}$); L_{cloud} : Processing time on the cloud platform (including decoding, storage, and preliminary analysis). Assumed constant, $L_{cloud} \approx 100$ ms.

3.2.2. Energy consumption modeling and battery lifespan estimation

The energy consumption of the sensor node (E_{node}) determines its operational lifespan. The energy model is based on analysis of node operational states:

$$E_{node} = E_{sleep} + E_{sense} + E_{proc} + E_{tx}$$

Where: E_{sleep} : Energy consumed in deep sleep mode, which occupies most of the operational time. $E_{sleep} = P_{sleep} \times T_{sleep}$, where P_{sleep} is sleep-mode power consumption and T_{sleep} is total sleep time per cycle; E_{sense} : Energy for reading data from sensors. $E_{sense} = \sum_i P_{sense,i} \times T_{sense,i}$, where $P_{sense,i}$ and $T_{sense,i}$ respectively, are the power and operating time of the i -th sensor; E_{proc} : Energy consumed by the MCU during data processing. $E_{proc} = P_{proc} \times T_{proc}$; E_{tx} : The largest energy component, used for LoRa transmission. $E_{tx} = P_{tx} \times T_{tx_lorat}$, where P_{tx} is the LoRa module transmit power. This power depends on configured

transmit power levels (e.g., +14 dBm, +20 dBm).

The duty cycle D of the node is defined $D = \frac{T_{active}}{T_{cycle}}$, where $T_{active} = T_{sense} + T_{proc} + T_{tx}$ and

$T_{cycle} = T_{active} + T_{sleep}$. Battery lifespan Battery lifespan ($L_{battery}$) with capacity C_{batt} (mAh) and voltage V is calculated as:

$$L_{battery} = \frac{C_{batt} \times V \times 3600}{E_{node}/T_{cycle}} \text{ (hour)}$$

3.2.3. Reliability Model

System reliability (R_{sys}) is evaluated as the probability that a packet is successfully transmitted from the sensor node to the application server in the cloud without loss or error. Factors influencing reliability include:

- LoRa channel packet loss rate (P_{loss_lorat}): depends on signal quality (RSSI, SNR), interference, and packet collisions. We assume a packet loss probability model based on SNR. The probability of successful LoRa transmission is $R_{lorat} = 1 - P_{loss_lorat}$.

- Gateway and backhaul reliability ($R_{backhaul}$): probability that the gateway functions normally and the Internet connection is uninterrupted. This value is typically very high (e.g., 0.999).

- Cloud platform reliability (R_{cloud}): probability that cloud services operate stably. Major cloud providers typically commit to availability up to 99.99 %.

Total system reliability is approximated by the product of the component reliabilities (assuming failure events are independent):

$$R_{sys} \approx R_{lorat} \times R_{backhaul} \times R_{cloud}$$

3.3. Challenges and future research directions

Although the proposed IoT architecture brings significant performance improvements, real-world deployment in hydrometeorological monitoring networks still faces considerable challenges.

3.3.1. Key challenges

- Information Security and Cybersecurity:

This is the foremost concern. Sensor nodes and LoRaWAN gateways may become targets for various cyberattacks such as eavesdropping, device spoofing, or denial-of-service (DoS) attacks (M. B. Jimenez et al., 2021) [14]. MH data, particularly data supporting forecasting and disaster warning, if stolen or manipulated, could cause severe consequences. Implementing robust security solutions on resource-constrained IoT devices presents a significant challenge. Lightweight cryptography protocols such as AES-128 encryption, mutual authentication between nodes and network servers, and secure key management should be applied (Ferrag & Shu, 2021 [13]; Saxena et al., 2021) [15].

- **Sustainable Energy Management:** Although LoRaWAN is highly energy-efficient, ensuring continuous power supply for sensor nodes, especially during prolonged adverse weather conditions (extended rainy seasons, limited sunlight), remains challenging. Further optimization of node duty cycles, adoption of ultra-low-power electronic components, and research into novel energy harvesting technologies (e.g., flow energy, wind energy) represent necessary directions (I.Sanislav et al., 2021) [5].

- **Device Calibration and Maintenance:** Sensors, particularly low-cost variants, may experience drift over time, leading to measurement errors. Periodic calibration is mandatory to ensure data quality. However, the cost and effort required to dispatch technical staff to individual stations in remote areas for maintenance and calibration are substantial. Automated remote calibration methods or AI algorithms for automatic error detection and correction based on correlation with neighboring stations represent promising research directions.

- **Scalability and Network Management:** As the number of sensor nodes increases to thousands or even tens of thousands, managing configuration, firmware updates, and remote monitoring for all nodes becomes a major challenge. A centralized, highly automated network management system is

required. Software-Defined Networking (SDN) technologies could be applied to flexibly and efficiently manage data flows and network configurations (Das et al., 2022; R. K. Das et al., 2022) [16].

- **Data Processing and Quality Assurance:** The volume of data collected from dense IoT networks is enormous (Big Data). However, not all data holds value. Data may be noisy, incomplete, or inconsistent. Effective filtering, cleaning, and aggregation techniques at the edge computing layer before cloud upload are necessary to reduce storage costs and accelerate processing (Naghieb et al., 2023) [17].

3.3.2. *Alignment with Resolution 57-NQ/TW and Future Orientation*

Successful implementation of the proposed IoT architecture for MH monitoring networks embodies the spirit of Resolution 57-NQ/TW. It represents a harmonious integration of science and technology development and application (IoT, AI, Big Data), innovation (optimized system architecture design for Vietnamese conditions), and digital transformation (digitizing the entire monitoring process, from data collection, transmission, processing, to information service delivery).

To advance this process, future research should focus on:

- Developing "Made in Viet Nam" Smart MH Sensor Nodes:* Research, design, and manufacture of low-cost, ultra-low-power, high-durability sensor nodes suitable for tropical monsoon climate conditions, with integrated basic AI capabilities (TinyML) for self-diagnosis and fault handling.

- Applying AI/ML Across All Architectural Layers:* From the sensor layer (intelligent noise filtering) to the edge layer (anomaly event detection) and cloud layer (high-accuracy forecasting, early warning).

- Integrating Diverse Data Sources:* Combining ground-based IoT network data with remote sensing data (satellite imagery, weather radar) to create more comprehensive, accurate, and detailed pictures of MH conditions and developments.

iv. *Establishing Legal Frameworks and Technical Standards:* Promptly promulgating standards for devices, communication protocols, data formats, and security for IoT networks in the MH sector, creating favorable legal corridors for deployment and scaling.

v. *Public-Private Partnership Models:* Encouraging domestic technology enterprises' participation in research, development, and IoT solution provision for the MH sector, reducing dependence on foreign technology.

3.4. Discussion

3.4.1. Interpretation of Results

Research results confirm the feasibility of applying IoT to modernize MH monitoring networks. While IoT sensor accuracy may not match premium specialized equipment (such as Vaisala or Campbell Scientific), it suffices for medium- and small-scale forecast models, particularly when dense station networks compensate for individual errors through spatial interpolation methods.

The trade-off between LoRaWAN and 4G/5G is clear. LoRaWAN suits periodic monitoring applications where energy savings and cost efficiency are priorities. Conversely, 4G/5G/NB-IoT suits early disaster warning stations requiring low latency and high reliability (e.g., flash flood warnings, landslide alerts). The hybrid model proposed in this research represents a potentially effective techno-economic solution for a geographically diverse country like Viet Nam.

Regarding energy, solar panel integration is essential for remote stations. However, panel efficiency declines over time due to dust accumulation and aging. Systems should integrate battery voltage sensors to send maintenance alerts before device failure.

3.4.2. Implications for MH Monitoring and National Digital Transformation

Research results affirm that IoT is not merely a tool for replacing traditional technology but a foundation for creating intelligent monitoring models, proactive forecasting, and data-driven risk management. Reducing latency to under 2 seconds enables timely flash flood, landslide, and

storm surge warnings, potentially reducing loss of life and economic damage. Battery lifespan of 5-7 years and 60% reduction in operational costs address sustainable financial challenges for the MH sector, particularly in remote areas and islands. AI integration at edge and cloud layers opens an era of hyperlocal forecasting, enabling warnings at village, hamlet, or small basin levels-capabilities that are difficult to achieve with conventional monitoring and forecasting approaches.

Within the context of Resolution 57-NQ/TW, IoT-based MH systems directly realize strategic objectives: (i) Monitoring data becomes primary production assets, openly exploited, shared across sectors, and driving innovation; (ii) Synchronized, secure, efficient digital infrastructure is built from the ground up, avoiding scattered investments; (iii) Data governance institutions, technical standards, and sandbox mechanisms are proposed synchronously, ahead of widespread deployment; (iv) Cybersecurity and information safety are designed integrally from the architecture, ensuring national data sovereignty; (v) High-tech workforce is trained through academy-enterprise-research institute partnerships, meeting MH sector digital transformation requirements.

3.4.3. Technical and Environmental Challenges

Despite many positive results, the study also highlights major challenges to be solved:

- *Sensor durability:* The tropical humid monsoon climate is hostile to electronic equipment. Contact oxidation, mould growth on PCBs, and lightning damage are common. In the trial, 2 out of 20 stations had communication modules damaged by lightning surges despite lightning protection. This indicates the need to upgrade grounding systems to stricter standards.

- *Calibration:* Low cost sensors drift faster than standard sensors. Without periodic calibration (every 6 months), data lose scientific value. This requires significant manpower and operating expenditure (OPEX).

- *Big data management:* With thousands of IoT stations transmitting data every minute, the

volume of generated data is enormous. Server infrastructure and network bandwidth must be scaled accordingly. Storing raw data indefinitely is uneconomical; a policy for retaining aggregated data after a certain period is needed.

4. Conclusion and Future Directions

4.1. Summary of Findings

This paper has comprehensively analyzed IoT applications in MH monitoring networks, demonstrating that this represents a foundational transformation. The four-layer architecture with clearly defined sensor, communication, platform, and application components has been established. The research makes several significant contributions:

a. *Proposed a comprehensive layered IoT architecture* for MH monitoring in Viet Nam, leveraging LPWAN (LoRaWAN), edge computing, and cloud computing capabilities to address core limitations of traditional monitoring systems. This architecture integrates multi-parameter sensors, hybrid communication protocols, and digital twin modelling capabilities.

b. *Identified and analysed key implementation challenges* including cybersecurity, energy management, device calibration, and scalability, while proposing practical solutions aligned with national digital transformation objectives.

c. *Established a policy-technical framework* for integrating IoT-based MH monitoring with Resolution 57-NQ/TW, demonstrating how this technology directly supports the strategic objectives of modernizing monitoring systems, building national databases, and enhancing forecasting capabilities.

4.2. Research Limitations

Despite achieving significant results, this research still has certain limitations:

a. Extended field testing across more diverse hydro-climatic regions and longer durations is needed to evaluate material durability and network stability under tropical monsoon conditions

b. The AI forecasting model has not fully integrated high-resolution satellite data and multi-spectral weather radar

c. Socio-economic evaluation remains

limited to operational costs and warning time improvements, without fully quantifying impacts on livelihoods, insurance, and urban planning

d. Post-quantum cryptography mechanisms have not been fully tested on actual devices due to current hardware limitations

4.3. Recommendations for Implementation

Based on the research findings, we propose the following recommendations for synchronized, secure, and sustainable implementation of IoT in MH monitoring networks in Viet Nam:

Policy and Institutional Recommendations:

a. Establish national technical standards for IoT-MH devices, communication protocols, data formats, and cybersecurity requirements.

b. Develop a phased implementation roadmap prioritizing high-risk areas (flood-prone basins, coastal regions, mountain areas) while building technical capacity.

c. Create sandbox mechanisms for testing and validating new IoT solutions before large-scale deployment.

d. Strengthen public-private partnership models to leverage private sector innovation while maintaining government oversight and data sovereignty.

Technical Recommendations:

a. Adopt a hybrid communication architecture combining LoRaWAN for rural/remote areas with NB-IoT/4G for urban and critical stations.

b. Implement edge computing with TinyML for local data quality assurance and anomaly detection.

c. Standardize data representation using OGC SensorThings API for seamless integration with existing systems and future digital twin platforms.

d. Deploy robust cybersecurity measures including encryption, mutual authentication, and secure OTA firmware updates.

Workforce and Capacity Development:

a. Train interdisciplinary digital technical personnel in IoT, AI, and data science for MH applications.

b. Strengthen partnerships between

academia, research institutes, and technology enterprises.

c. Develop continuous learning programs for existing MH staff on new technologies and systems.

4.4. Future Research Directions

Based on the research results and identified limitations, we propose the following future research directions:

a. Expand field trials with large-scale IoT networks (>5,000 nodes) across diverse ecological regions in Viet Nam to assess long-term performance (5-10 years) and the impact of climate change on equipment lifetime and network stability.

b. Develop advanced AI models integrating physics-informed neural networks (PINNs) and multi-agent reinforcement learning (MARL) for reservoir operation optimization and flood warning, with privacy-preserving federated learning for distributed forecasting.

c. Research 6G-WPCN networks for simultaneous energy-data communication protocols, high-efficiency energy-harvesting antennas, and hybrid network models for areas without terrestrial infrastructure.

d. Implement quantum-safe cybersecurity by optimizing post-quantum cryptographic algorithms for low-power MCUs and designing lightweight authentication and key-exchange protocols for IoT infrastructure.

e. Develop data governance frameworks and economic models for valuing MH data, establishing inter-sectoral benefit-sharing mechanisms, and designing IoT-based disaster risk insurance policies.

f. Strengthen international cooperation and standardization by contributing to OGC/WMO standards for IoT in MH monitoring and developing cross-border open-data platforms for Mekong and Red River basin management.

4.5. Closing Remarks

Applying IoT in meteorological and hydrological monitoring is not only an inevitable technological trend but also an imperative for survival and sustainable development in the climate change era. With decisive leadership from the Party and State, concretized through Resolution 57-NQ/TW, and synchronized engagement from the MH sector, research institutes, universities, technology enterprises, and the international community, Viet Nam is fully capable of building intelligent, modern, autonomous, and integrated monitoring networks. This research aspires to serve as a scientific reference, technical orientation, and policy foundation for the digital transformation journey of the meteorological and hydrological sector, contributing to the successful achievement of rapid and sustainable development goals, building a prosperous, powerful nation.

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Declaration: *The authors declare that this manuscript is their original research, has not been previously published, is not plagiarized or copied from other works, and that there are no conflicts of interest among the authors.*

References

- [1] IPCC., *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. <https://doi.org/10.1017/9781009157896>, 2021.
- [2] IPCC., *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva. <https://>

- doi.org/10.59327/IPCC/AR6-9789291691647, 2021.
- [3] World Meteorological Organization, *Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8)*. World Meteorological Organization (WMO), Geneva, Switzerland, 2018.
 - [4] M. Zhang, M. Chen, Y. Wen, et al., "An Open Online Simulation Strategy for Hydrological Ensemble Forecasting," *Environmental Modelling & Software*, 174, 105975, 2024, <https://doi.org/10.1016/j.envsoft.2024.105975>.
 - [5] I. Sanislav, S. C. Folea, G. Mois, and L. Miclea "A Blockchain-Based Approach for Improving Identity Management in IoT-Edge Computing," in Proc. *International Conference on Control Systems and Computer Science*, 2021.
 - [6] International Telecommunication Union (ITU), *Overview of the Internet of Things (Recommendation ITU-T Y.2060)*. International Telecommunication Union, Geneva, Switzerland, 2012.
 - [7] A. Rivera, P. Ponce, O. Mata, A. Molina, and A. Meier, "Local Weather Station Design and Development for Cost-Effective Environmental Monitoring and Real-Time Data Sharing," *Sensors*, 23, 9060, 2023, <https://doi.org/10.3390/s23219060>.
 - [8] H. Yan, M. Zhang, S. Tian, L. Wu, X. Mei, and L. Hu, "Enhancing real-time hydrological simulation with IoT-based model representation and observation data," *Water*, vol. 18, no. 1, Art. no. 2, 2026, doi: 10.3390/w18010002.
 - [9] A. Albuali, R. Srinivasan, A. Aljughaiman, and F. Alderazi, "Scalable Lightweight IoT-Based Smart Weather Measurement System", *Sensors*, 23(12), 5569, 2023, <https://doi.org/10.3390/s23125569>.
 - [10] D. Kairuz-Cabrera, V. Hernandez-Rodriguez, O. Schalm, A. Martinez, P. Merino-Laso, and D. Alejo-Sanchez, "Unified IoT Platform for Air Quality and Weather Monitoring in Tropical Environments," *Sensors*, 24(9), 2729, 2024, <https://doi.org/10.3390/s24092729>.
 - [11] J. Smith, "IoT-Based Environmental Monitoring Systems: A Comprehensive Review," *Environmental Science and Technology*, 14(3), 102-115, 2019.
 - [12] O. K. Assi and A. A. Abed, "Controlling and monitoring the performance of a robotic arm using Internet of Things (IoT)," *International Journal of Computer Applications*, vol. 174, no. 19, pp. 7-13, 2021, doi: 10.5120/ijca2021920687.
 - [13] M. A. Ferrag, L. Shu, X. Yang, A. Derhab, and L. Maglaras, "Security and Privacy for Green IoT-Based Agriculture: Review, Blockchain Solutions, and Challenges," *IEEE Access*, 8, 32031-32053, 2020. <https://doi.org/10.1109/ACCESS.2020.2984664>
 - [14] M. B. Jimenez, D. Fernandez, J. E. Rivadeneira, L. Bellido, and A. Cardenas, "A Survey of the Main Security Issues and Solutions for the SDN Architecture," *IEEE Access*, 9, 122016-122038.
 - [15] D. Saxena, R. Gupta, and A. K. Si, *Data Security and Privacy in Cloud Computing: Concepts and Emerging Trends*. ArXiv (Cornell University), 2021.
 - [16] R. K. Das, N. Ahmed, A. K. Maji, and G. Saha, "Nx-IoT: Improvement of conventional IoT framework by incorporating SDN infrastructure," *IEEE Internet of Things Journal*, vol. 10, no. 3, pp. 2473-2482, 2023, doi: 10.1109/JIOT.2022.3215650.
 - [17] A. Naghib, N. Jafari Navimipour, M. Hosseinzadeh, and A. Sharifi, "A comprehensive and systematic literature review on the big data management techniques in the Internet of Things," *Wireless Networks*, vol. 29, no. 3, pp. 1085-1144, 2023, doi: 10.1007/s11276-022-03177-5.