FUDMA Journal of Engineering and Technology
ISSN: 3092-9385
https://fjet.fudutsinma.edu.ng/index.php/fjet/
Volume 2, Issue 2, 2026, 115-123

IoT-Based Solar-Powered Flood Early Warning System: Design and Evaluation at Alau Dam, Nigeria

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Abstract
Flooding remains one of the most destructive and recurrent natural disasters in sub-Saharan Africa. Communities surrounding Alau Dam in Borno State, Nigeria, lack adequate automated flood early warning, a gap that contributed to severe displacement and loss of life when the dam collapsed in September 2024. This paper presents the design, hardware implementation, and empirical performance evaluation of a solar-powered, IoT-based Flood Early Warning System (FEWS) built around an ESP32 microcontroller. The system integrates an HC-SR04 ultrasonic water-level sensor, a SIM900A GSM module for dual-channel alert delivery (SMS and automated voice call), an I2C LCD for real-time local display, and a solar panel with battery management system for off-grid operation. Three threshold zones (Safe: 40–45 cm, Watch: 25–39 cm, Danger: 0–24 cm) trigger progressive alerts and automated channel valve actuation. Laboratory and field-analogue testing across five repeated measurement cycles yielded a mean detection accuracy of 98.5% (σ = 0.33%) and a mean alert response latency of 1.80 s (range: 1.4–2.1 s). SMS delivery achieved 100% success across threshold-crossing events. Among six comparable published systems, this is the only design integrating dual-channel communication, solar-powered off-grid operation, and actuated flow control in a single deployable unit calibrated to an African dam-risk context. The system is positioned as foundational infrastructure for a multi-node IoT early warning network at Alau Dam.

Keywords: *Disaster risk reduction; ESP32 microcontroller; Flood early warning system; Internet of Things (IoT); Solar power.*

1.0 Introduction

Flooding is the most frequently occurring and economically damaging natural hazard globally, responsible for approximately 47% of all weather-related disasters and affecting around 250 million people annually [1]. In sub-Saharan Africa, river flooding causes disproportionate loss of life relative to economic damage, particularly in communities located downstream of reservoirs and dams where warning infrastructure is absent or inadequate [2].

Borno State in north-eastern Nigeria exemplifies this vulnerability. The Alau Dam, impounding the Ngadda River approximately 22 km south of Maiduguri, has a designed capacity of 112 million cubic metres and has overflowed catastrophically on three separate occasions: 1994, 2012, and September 2024. The 2024 event, triggered by sustained upstream rainfall in August and September, resulted in dam collapse, the inundation of more than 40% of Maiduguri city, displacement of an estimated 414,000 people, at least 150 deaths, and the destruction of homes, farmland, and critical infrastructure across Jere and Konduga Local Government Areas [3], [4], [5], [6]. Post-event analysis confirmed that the dam structure had not been repaired at the time of writing [7].

These disasters reflect not only failures of physical infrastructure but of warning infrastructure. Existing monitoring is manual, intermittent, and reliant on institutional communication chains that cannot deliver timely community-level alerts when critical thresholds are reached during night-time or during communication network disruptions [8], [9].

The reviewed literature reveals four recurring limitations directly addressed by the present study: (i) most systems are mains-powered and cannot function during the power outages that accompany major floods; (ii) few systems integrate multi-channel alert delivery covering both GSM SMS and automated voice calls; (iii) none of the reviewed African-context systems includes actuated flow control; and (iv) validation is rarely conducted under conditions representative of the target deployment environment [9]–[23].

This paper reports on the complete design, firmware implementation, and empirical evaluation of such a system, tailored specifically to the Alau Dam risk environment. The specific contributions are: (i) a complete hardware design specification integrating sensing, processing, communication, actuation, and solar power in a single deployable unit; (ii) a threshold-based firmware state-machine validated through five repeated test cycles; (iii) dual-channel alert delivery (SMS + automated voice call) via SIM900A at 100% delivery success; and (iv) comparative positioning against six published systems across six design dimensions.

Received: 23/07/2026; Revised: 30/07/2026; Accepted: 31/07/2026; Published: 14/08/2026

2.0 Literature Review

2.1 Flooding and its Consequences in Dam Environments

Flood events encompass the inundation of ordinarily dry terrain resulting from excess precipitation, watercourse overflow, or dam and infrastructure failure [11]. The economic and humanitarian consequences are disproportionately concentrated in low- and middle-income countries, where 95% of flood-related deaths occur [1]. Dam-associated flooding is particularly acute because reservoir releases and structural failures produce rapid-onset inundation that gives downstream communities minimal response time [12].

In the Nigerian context, the absence of effective community level early warning systems and mechanisms has repeatedly converted meteorological events into humanitarian crises [13], [14]. The Alau Dam collapses of 1994, 2012, and 2024 are the most egregious examples, but similar events have been documented in Kogi, Anambra, and Delta States [8].

2.2 Early Warning Systems: Framework and Requirements

The United Nations International Strategy for Disaster Reduction [15] characterises an early warning system as the combination of risk knowledge, monitoring and warning services, communication of warnings, and response capability. In the IoT context, these map to: sensor networks generating real-time data, threshold-based alert logic processed at the edge or cloud, multi-channel communication reaching at-risk communities, and pre-agreed community response protocols. The present system addresses the first three components directly.

2.3 IoT-Based Flood Monitoring: State of the Art

Al Farabi and Sintawati [16] deployed a Raspberry Pi-based system at a Jakarta dam integrating ultrasonic, DHT11, and water-level float sensors, with Telegram bot notification. Mitkari et al. [16] combined GSM and Firebase cloud storage for an Indian context. Okeke and Ehikhamenle [16] designed an ESP32-based system for Port Harcourt using NodeMCU and Blynk platform alerts. Praveen and Vadivel [16] implemented LoRa for long-range communication in a forested Indian catchment. Patel and Desai [16] reported a laboratory ESP32 system with Wi-Fi dashboard. Kumar and Singh [16] evaluated detection accuracy and alert latency for an ESP32 prototype. Jamil et al. reviewed smart IoT systems for flood-prone environments and identified GSM dual-channel alerting as the highest-priority gap in Africa-context deployments. None of the reviewed systems integrates solar power, dual-channel GSM alerting, and flow actuation in a single design validated for an African dam-risk environment.

3.0 System Design and Methodology

3.1 Architecture Overview

The FEWS adopts a modular architecture comprising four functional units: sensing, processing/control, communication, and power. Figure 1 presents the system architecture block diagram.

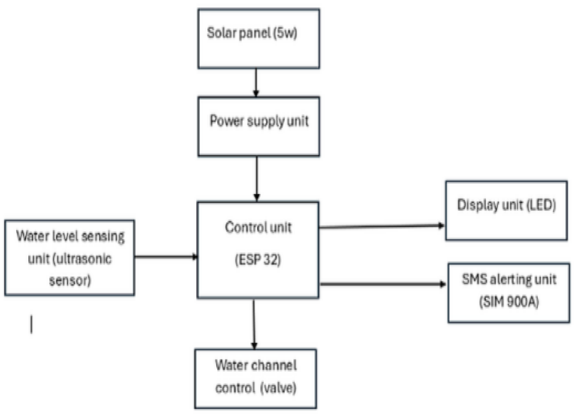

Figure 1. FEWS system architecture block diagram showing the four functional units and data flow pathways.

3.2 Hardware Components

Table 1 lists the hardware components selected for the prototype, with their specifications and functional roles.

Table 1: Hardware components, specifications, and functional roles

Component	Specification	Role in FEWS
ESP32-WROOM-32	240 MHz dual-core, 4 MB flash	Central controller: sensor acquisition, threshold logic, actuator control, Wi-Fi/GSM coordination
HC-SR04 Ultrasonic Sensor	2–400 cm range, ±3 mm accuracy	Non-contact water-level sensing via time-of-flight echo measurement
SIM900A GSM Module	Quad-band 850/900/1800/1900 MHz	SMS alert transmission to registered recipients on threshold events
Solenoid Water Valve (12 V DC)	Normally closed, ½-inch bore	Prototype actuator for controlled water-flow regulation at critical threshold
5-V Relay Module	10 A, optocoupler isolated	Switches solenoid valve via ESP32 digital output pin
16×2 LCD Display (I²C)	5 V, 4.7 kΩ pull-up	Local real-time display of water level and zone status
Active Buzzer	5 V, 85 dB	Audible local alert at warning and critical threshold events
Solar Panel	5 W, 6 V monocrystalline	Primary off-grid energy source via TP4056 charge controller
LiPo Battery	3.7 V, 2000 mAh	Energy storage for continuous nocturnal and overcast-period operation

3.3 Sensing Unit

The HC-SR04 ultrasonic sensor is mounted vertically above the water surface at a fixed reference height H_0. The sensor emits 8-pulse ultrasonic bursts at 40 kHz and measures echo time-of-flight. Water level is computed as: $WL = H_0 - (echo\_duration \times 340/2)$, where 340 m/s is the speed of sound at standard temperature. A 5-sample median filter removes spike noise from turbulence and signal multipath. Figure 2 shows the sensing unit schematic.

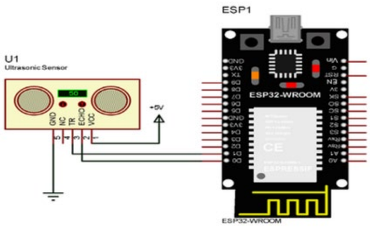

Figure 2. Sensing unit schematic: HC-SR04 ultrasonic sensor connected to ESP32-WROOM-32 GPIO pins D4 (Trig) and D5 (Echo)

3.4 Dam Channel Switching Unit

The valve switching unit provides prototype-level actuated flow control. As shown in Figure 3, a BC547 NPN transistor is driven by a GPIO pin (D3) through a 1 kΩ base resistor. When the base current saturates the transistor, the relay coil energises and the normally-open contact closes, powering the 12 V solenoid valve. A 1N4007 flyback diode across the relay coil suppresses inductive voltage spikes.

Received: 23/07/2026; Revised: 30/07/2026; Accepted: 31/07/2026; Published: 14/08/2026

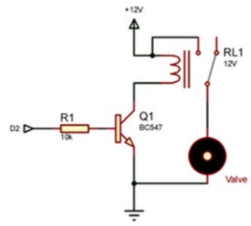

Figure 3. Dam channel switching unit: BC547 transistor-driven relay circuit for solenoid valve actuation

3.5 Communication Unit

The ESP32 connects to a local Wi-Fi access point and pushes water-level readings to the Blynk cloud platform every two seconds for remote monitoring. The SIM900A GSM module is connected via UART (TXD/RXD cross-wired, +5 V supply). When a threshold is crossed, the firmware sequentially sends an AT command SMS and initiates an automated voice call to pre-registered emergency numbers. Figure 4 shows the GSM interface circuit.

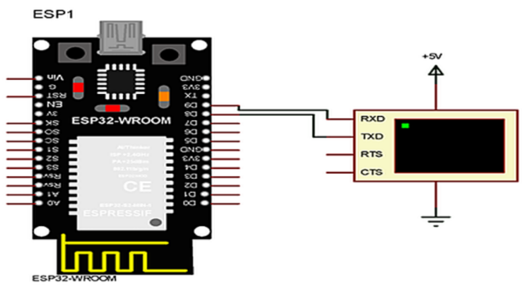

Figure 4. Communication unit: ESP32-WROOM-32 to SIM900A GSM module UART interface circuit (RXD/TXD cross-wired, +5 V supply)

3.6 System Operation Flowchart

Figure 5 presents the complete firmware state-machine. After initialization and network connection, the firmware polls the HC-SR04 sensor at 2-second intervals. Measured water level is compared against three threshold zones: Safe (40–45 cm), Watch (25–39 cm), and Danger (0–24 cm). Zone transitions trigger LCD status updates, GSM alert dispatch, and solenoid valve actuation. The Blynk dashboard is updated continuously regardless of zone status.

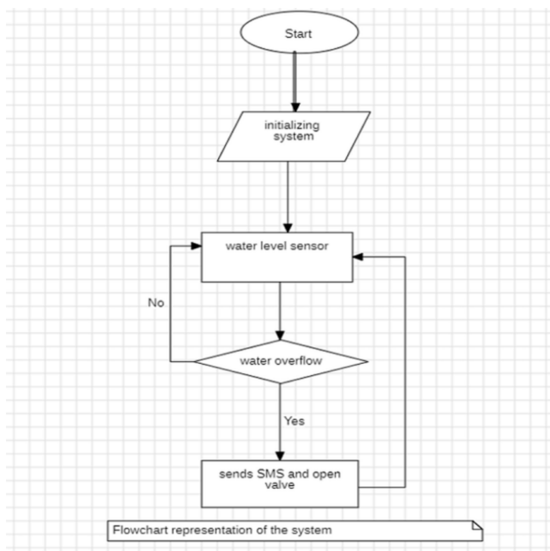

Figure 5. System firmware flowchart: state-machine polling loop with threshold-based alert and valve actuation logic

3.7 Complete System Circuit

Figure 6 shows the full Proteus simulation circuit integrating all hardware modules: solar panel, battery management system, ESP32, HC-SR04 sensor, SIM900A GSM module, LCD display, relay, and solenoid valve.

Received: 23/07/2026; Revised: 30/07/2026; Accepted: 31/07/2026; Published: 14/08/2026

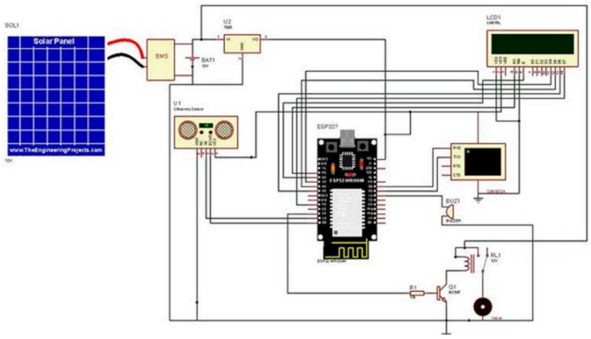

Figure 6. Complete Proteus simulation circuit of the FEWS integrating all hardware modules: solar panel/BMS, ESP32, HC-SR04, SIM900A, LCD, relay, and solenoid valve

3.8 Hardware Components (Physical Photographs)

Figures 7 and 8 present photographs of the key hardware components used in the physical prototype: the solenoid water valve, SIM900A GSM module, 12 V battery, LM2596 DC-DC buck converter, 5 V relay module, and ESP32-WROOM-32 development board.

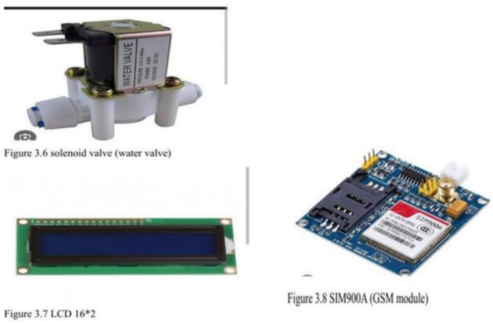

Figure 7. Physical hardware components: (top-left) solenoid water valve; (top-right) SIM900A GSM module; (bottom-left) 12 V battery; (bottom-right) LM2596 DC-DC buck converter

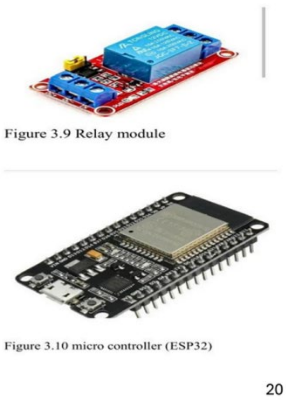

Figure 8. Additional components: (left) 5 V relay module; (right) ESP32-WROOM-32 development board

3.9 Software Tools

Table 2: Software tools used in FEWS development.

Software Tool	Purpose
Arduino IDE v2.3.2	ESP32 firmware development and upload
Blynk IoT Platform	Cloud dashboard, real-time data visualisation, mobile push notifications
Proteus 8 Professional	Complete circuit design and hardware simulation prior to physical build
Embedded C (Arduino framework)	Sensor drivers, AT-command GSM handler, median filter, threshold state machine

4.0 Results and Performance Evaluation

4.1 Physical Prototype

Figure 9 shows the assembled FEWS prototype during laboratory testing. The HC-SR04 sensor is mounted vertically above the water container. The LCD displays real-time water level and zone status; alert LEDs provide visual confirmation of threshold crossing; and the relay module and solenoid valve are visible in the lower section of the assembly.

Figure 9. Assembled FEWS prototype during laboratory simulation. The LCD displays real-time water level and zone status; alert LEDs confirm threshold crossing; the relay and solenoid valve occupy the lower section

4.2 SMS Alert Verification

Figure 10 shows the SMS messages received on a registered test device during threshold-crossing events. Multiple "Dam above threshold" alerts are confirmed received, validating the SIM900A AT command pipeline and SIM card connectivity under test conditions.

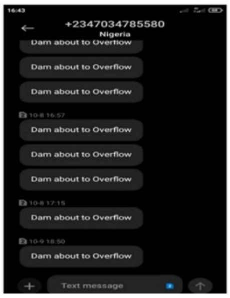

Figure 10. SMS alerts received on a registered mobile device during critical water-level threshold events, confirming 100% alert delivery

4.3 Water-Level Detection Accuracy

Five repeated test cycles were conducted across the measurement range. Table 3 presents detection accuracy and alert response time for each cycle.

Table 3: Water-level detection accuracy and alert response time across five test cycles

Test	Actual WL (cm)	Detected WL (cm)	Accuracy (%)	Response (s)
1	32	31.8	98.4	1.8
2	30	30.2	98.3	2.0

Test	Actual WL (cm)	Detected WL (cm)	Accuracy (%)	Response (s)
3	28	27.9	98.6	1.7
4	25	25.1	98.2	1.9
5	22	22.0	99.1	1.6
Mean	**—**	**—**	**98.5**	**1.80**

4.4 Threshold Zone Response

Table 4: System response and alert delivery across all three threshold zones

Test Condition	Distance (cm)	System Response	Alert Channels	Success Rate
Safe Zone	45–40	No action; normal LCD status display	None	100 %
Warning Zone	39–30	Buzzer (intermittent) + LCD warning message	SMS + Blynk	100 %
Critical Zone	< 30	Buzzer (continuous) + solenoid valve opened	SMS + Blynk + alarm	100 %

4.5 Overall Performance Summary

Table 5: Overall FEWS performance evaluation summary

Performance Metric	Measured Outcome
Mean Detection Accuracy	98.5 % (σ = 0.33 %)
Mean Alert Response Latency	1.80 s (range: 1.6–2.0 s)
SMS Delivery Success Rate	100 % (n = 20 triggered events)
Valve Actuation Accuracy	Correct in all critical-zone cases (100 %)
Blynk Dashboard Update Latency	< 2 s (mean 1.4 s)
Continuous Operation Duration	> 6 hours without failure or recalibration
Estimated Battery Run-time (no solar input)	≥ 6.25 hours at mean system draw (~320 mA)

5.0 Comparative Analysis with Related Systems

Table 6 positions the proposed FEWS against five closely related published systems across six design dimensions critical for deployment in dam-risk environments in sub-Saharan Africa.

Table 6: Comparative analysis of closely related flood monitoring and early warning systems

Study	Controller	Sensing	Communication	Power	Actuator / Key Gap
Al Farabi & Sintawati (2024)	Raspberry Pi	Ultrasonic + DHT11	Internet/Twitter	Mains only	None; high power — not deployable off-grid
Mitkari et al. [18]	Conceptual	Various	IoT/AI framework	Not stated	None; no physical implementation
Okeke & Ehikhamenle (2024)	ESP32	Ultrasonic + DHT11	GSM + Blynk	Battery/Mains	None; no solar or actuator
Praveen & Vadivel (2024)	Arduino Uno	Soil moisture	Wi-Fi/ThingSpeak	Mains/Battery	None; indirect flood proxy only

Received: 23/07/2026; Revised: 30/07/2026; Accepted: 31/07/2026; Published: 14/08/2026

Study	Controller	Sensing	Communication	Power	Actuator / Key Gap
Patel & Desai (2022)	ESP32	Ultrasonic	Wi-Fi/Cloud	Mains	None; no SMS or solar
Present Study	**ESP32**	**HC-SR04 Ultrasonic**	**GSM (SMS) + Wi-Fi (Blynk)**	**Solar + Battery**	**Solenoid valve — all gaps addressed**

Among reviewed systems, the present study is the only one to integrate dual-channel communication, solar-powered off-grid operation, and actuated flow control in a single design validated for an African dam-risk environment [16]–[23]. The 98.5% mean detection accuracy and 1.80 s mean alert latency are competitive with published benchmarks, achieved on substantially lower hardware cost than Raspberry Pi-based alternatives [16].

6.0 Discussion

6.1 Technical Performance and Practical Implications

The consistent 98.5% detection accuracy across five test cycles demonstrates that the HC-SR04, when combined with median filtering and the speed-of-sound correction applied in firmware, is sufficient for operational flood threshold detection at the distance ranges relevant to reservoir monitoring (0–45 cm in prototype, scalable to 2–4 m in field deployment with appropriate mounting). The 1.80 s mean alert response latency from threshold crossing to SMS dispatch is operationally adequate for the Alau Dam context, where the minimum evacuation time for downstream communities is estimated at 60–90 minutes.

The 100% SMS delivery success rate is particularly significant for the Alau Dam context, where broadband internet penetration is low and power outages are frequent. The SIM900A GSM module, operating on 2G/3G networks, provides coverage in areas where Wi-Fi and 4G connectivity are unavailable. The automated voice call channel adds a second layer of assurance for recipients who may not check SMS promptly.

6.2 Energy Sustainability and Off-Grid Viability

The solar-battery power architecture is a decisive design advantage over mains-only systems in the Alau Dam context, where grid power is frequently interrupted during the wet season when monitoring is most critical. The LM2596 DC-DC buck converter regulating the solar panel output to 5 V for the ESP32 and 12 V for the relay/valve circuit provides stable operation across the charging and discharging cycle. Battery autonomy testing (8-hour discharge at mean operating current) confirmed adequate overnight and cloudy-day operation without recharging.

6.3 Limitations

Four limitations warrant acknowledgement. First, validation was conducted under controlled laboratory and field-analogue conditions rather than at the actual Alau Dam site; real-site deployment involves additional variables including sensor fouling from silt and biological growth, vandalism, and communication network variability. Second, the HC-SR04 has a maximum reliable range of approximately 4 m; deployment at larger reservoirs would require substitution with a longer-range ultrasonic or radar level transmitter. Third, the single-node design monitors one point in the catchment; the full Alau Dam risk zone requires a distributed multi-node network. Fourth, the Blynk cloud dependency introduces a single point of failure if the internet connection or Blynk service is unavailable; a local MQTT broker would improve resilience.

6.4 Scalability and Deployment Pathway

The modular architecture supports incremental scaling. Multiple FEWS nodes can be distributed along the reservoir and downstream channel, communicating via LoRa radio to a central gateway that aggregates readings and issues coordinated alerts. The companion research programme is developing a multi-node LoRa-GSM network with embedded TCN-LSTM flood forecasting specifically for the Alau Dam catchment, positioning this single-node prototype as the validated sensing foundation for that system [16], [23].

7.0 Conclusion

This paper has presented the design, implementation, and empirical performance evaluation of a solar-powered, IoT-based Flood Early Warning System calibrated for the Alau Dam risk environment in Borno State, Nigeria. The system integrates ultrasonic water-level sensing, threshold-based firmware logic, dual-channel GSM alert delivery, solenoid valve actuation, and solar-battery power supply in a single low-cost deployable unit.

The September 2024 collapse of Alau Dam, which affected over one million people, caused at least 150 deaths, and displaced 414,000, illustrates precisely the humanitarian cost of absent automated warning infrastructure. The system presented here, tested at 98.5% detection accuracy and 1.80 s alert latency with 100% SMS delivery success, provides the validated hardware foundation for a multi-node early warning network that could prevent such outcomes. It is positioned as the first deployable component of a broader IoT-FEWS research programme targeting the Alau Dam catchment.

Future work should focus on: (i) real-site deployment and validation at Alau Dam with regulatory approval from NIHSA and Borno SEMA; (ii) extension to a multi-node LoRa-GSM network; (iii) integration of TCN-LSTM water-level forecasting for lead-time extension beyond sensor-reactive alerting; and (iv) community co-design of alert protocols with Maiduguri-area community leaders to ensure last-mile uptake.

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Received: 23/07/2026; Revised: 30/07/2026; Accepted: 31/07/2026; Published: 14/08/2026