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Development of a Solar-Powered IoT-Based Flood Monitoring and Early Warning System with LoRa32 and TTN Integration for Remote Area Applications

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Abstract

The recent increase in flooding across Malaysia is partly because of climate change and faster urbanization, mostly where drainage systems are not well developed. Poorly maintained and old flood sensors like in Klang Valley in 2021 meant warnings were slow to reach people and many were cut off from rescue help. Because of a weak monitoring system and limited communication, rural areas are more vulnerable and many have stopped listening to real alarms after multiple false ones. For this reason, this project establishes a solar-powered sensor network system for flood monitoring and early warning in rural communities using LoRa32 and The Things Network (TTN). It gathers environmental data with an ultrasonic water level sensor and a rain sensor which sends information via LoRaWAN and is checked in real time on a monitor. As soon as system levels reach critical amounts, Telegram notifications are sent out. Even without a power source, this system will not stop since it is charged by a solar panel and battery. Using green energy and wireless communication allows this solution to address the problems of disconnected rural communities facing floods. The purpose of this project is to make it easier for people to face floods by providing a more reliable and faster warning system.

1. Introduction

Flooding has become one of Malaysia's most serious natural disasters in recent years, with events happening more often and hitting harder due to changing rainfall patterns, rapid land development, and urban growth. Weak drainage systems and increased surface runoff lead to widespread floods, especially in low-lying and rural areas during the Northeast Monsoon season. Major floods in 2024 and 2025 forced over ten thousand people to evacuate across various states, with many finding shelter in temporary relief centres. These floods also disrupted schools and exams, such as when more than 300 SPM students in Perak had to be relocated because their facilities were unsafe. They caused serious problems for transportation and infrastructure, damaging key roads and services. These extreme floods are connected to climate variability and changing rainfall patterns, resulting in significant social and economic impacts. This highlights the urgent need for better flood management and adaptation strategies to protect communities in Malaysia [1], [2].

Despite the implementation of various flood monitoring and early warning initiatives, Malaysia's existing systems still face significant challenges. Reports indicate that outdated sensors, poor maintenance, limited coverage, and slow warning dissemination have led to ineffective alerts during major floods like the 2021 Klang Valley floods [3], [4]. Rural and remote areas are even more vulnerable due to unreliable power and communication infrastructure. Moreover, frequent false alarms and inconsistent warning delivery had reduced public trust in early warning systems, leading to poor community responses during actual flood emergencies [4].

Previous studies have explored various flood monitoring and early warning systems using different technologies and communication methods. An SMS-based flood warning system utilizing ultrasonic sensors and solar power was developed for basic water level alerts in remote areas, but it lacked real-time monitoring and cloud integration [5]. Another study implemented an IoT-based flash flood warning system using LoRa communication, multiple sensors, and artificial intelligence to improve flood risk classification and early alerts, particularly in high-risk and mountainous regions [6]. In addition, an IoT-based embankment monitoring system combined water level and turbidity sensors with cloud platforms to provide continuous real-time monitoring, although its reliance on Wi-Fi limited its effectiveness in rural areas [7].

Other IoT-based flood monitoring systems employed platforms such as NodeMCU and Raspberry Pi to deliver real-time data, mobile notifications, and visual alerts to users, improving flood preparedness and response [8], [9]. However, most existing systems still depend heavily on stable internet connectivity, consume higher power, or are unsuitable for remote and off-grid locations. These limitations highlight the need for a low-power, long-range, and solar-powered flood monitoring system using LoRaWAN, which can provide reliable real-time monitoring and early warnings for rural and flood-prone areas.

To address the challenges of ineffective flood monitoring in Malaysia, this project designed and developed a solar-powered IoT-based flood monitoring and early warning system integrated with LoRa32 and The Things Network (TTN) for remote area applications. The system use ultrasonic water level and rain sensors to continuously monitor environmental conditions, transmitting data wirelessly via LoRaWAN for real-time observation. Alerts were delivered instantly via Telegram, providing a low-cost, sustainable solution that enhanced flood preparedness, improved response times, and increased safety for communities in rural, flood-prone areas. The system also demonstrated how renewable energy and IoT technologies could be combined to create resilient and responsive early warning mechanisms, aligning directly with the project's objectives to develop a functional prototype and evaluate its reliability, power efficiency, and suitability for remote or off-grid locations.

Although the IoT-based system worked effectively during testing, several limitations appeared during setup and evaluation. Its reliance on solar energy which is optimized for sunny regions was problematic in cloudy and rainy weather, which often coincides with flooding. This reduced solar panel efficiency and could disrupt continuous operation. Consequently, the system's reliability in emergency situations where quick alerts are critical may be affected. To address these issues, future improvements could include integrating hybrid power sources or energy storage options to ensure operation during adverse weather conditions.

2. Methodology

This section described the methodology used to develop and evaluate the solar-powered IoT-based flood monitoring and early warning system. The methodology covered the overall system design, hardware and software implementation, data transmission, and alert mechanisms to ensure reliable operation in remote and flood-prone areas.

2.1 System Design and Architecture

The system was designed to monitor environmental conditions related to flooding using a combination of sensing, communication, and power management modules. An ultrasonic water level sensor measured the distance between the sensor and the water surface, while a rain sensor detected the presence of rainfall. Both sensors were connected to a LoRa32 (Heltec WiFi LoRa 32 V3) microcontroller, which processed the sensor data and prepared it for transmission.

The collected data were transmitted wirelessly via LoRaWAN to a LoRaWAN gateway and forwarded to The Things Network (TTN) server. The data were then visualized in real time using the TagoIO platform, allowing continuous monitoring of water level and rainfall conditions. Predefined safety thresholds were set within the system to determine critical flood levels. Fig. 1 shows the schematic diagram of the project. The system consists of several components working together to be functioned.

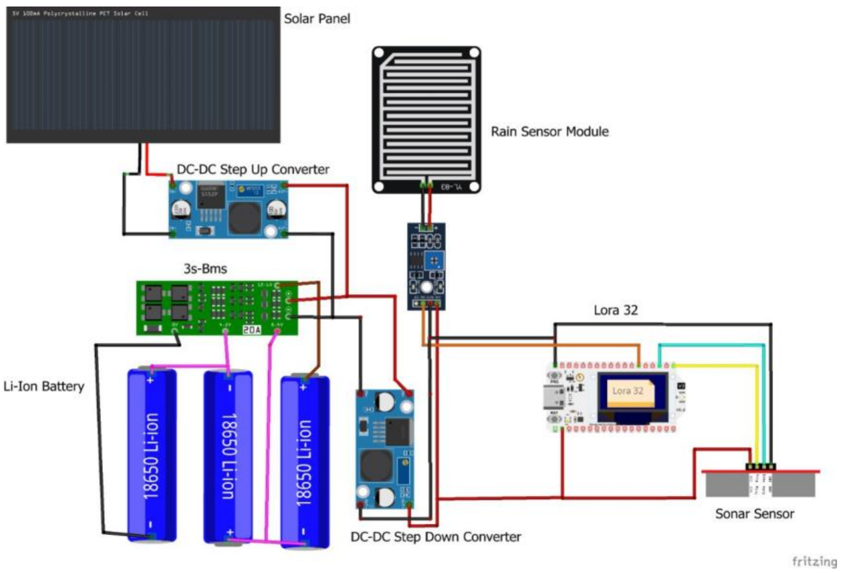

Fig. 1 *Schematic Diagram of the project*

2.2 System Operation and Alert Mechanism

During operation, the system continuously read data from the ultrasonic water level sensor and rain sensor at predefined intervals. The processed data were sent to TTN through LoRaWAN, where they were stored and displayed on a real-time monitoring dashboard. When the measured water level exceeded the predefined safety threshold, the system automatically triggered an alert mechanism.

Flood warning notifications were sent to users through a Telegram bot to ensure fast and reliable communication. The system was powered by a solar panel and a rechargeable battery, enabling continuous operation even in locations without access to a main power supply. This power management approach ensured low energy consumption and long-term deployment suitability for remote area applications.

Fig. 2 illustrates the comprehensive operational workflow of the flood monitoring system, starting with the initialization of the microcontroller and the subsequent reading of data from the water level and rain sensors. The captured information is transmitted via LoRaWAN to The Things Network (TTN) and then sent to the TagoIO cloud platform through a Webhook integration. When the data is received, the system updates the System Dashboard in real-time and compares the water level distance against a predefined safety threshold. If the distance is less than 25cm, TagoIO automatically triggers a Telegram alert to notify the user of a potential flood, ensuring continuous data logging and an immediate emergency response before concluding the process.

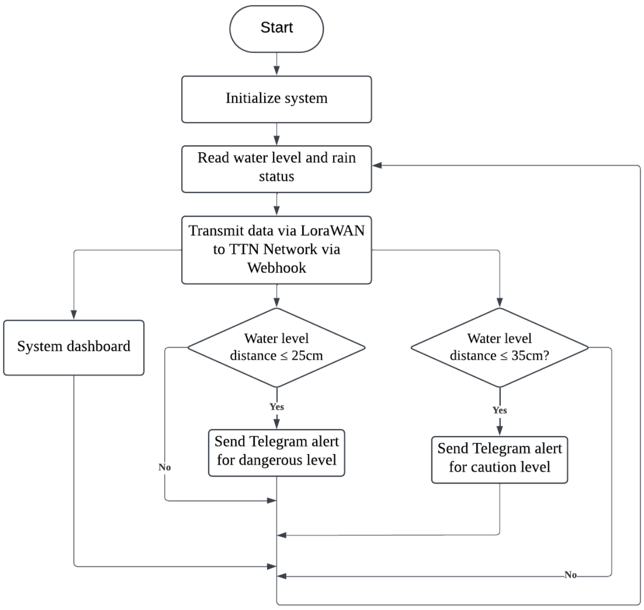

Fig. 2 *System Flowchart*

Progress in Engineering Application and Technology Vol. 7 No. 1 (2026) p. 396-403

3. Results and Discussion

This section outlines the systematic approach undertaken to develop and evaluate the solar-powered IoT-based flood monitoring and early warning system. The methodology is structured to address each research objective sequentially, ensuring comprehensive coverage from design conceptualization through prototype development to performance evaluation. The research employs a mixed-methods approach combining hardware integration, software development, and experimental testing to validate the system's effectiveness for remote area applications.

3.1 System Design for Remote Area Applications

The system was designed to operate as a sustainable, solar-powered environmental monitor tailored for remote areas where traditional power grids and internet connectivity were often unavailable. A comprehensive system block diagram was developed to outline the interaction between hardware components, starting with a 5V solar panel that served as a clean, renewable power source for the entire setup. The design integrated a Heltec LoRa32 V3 microcontroller to process environmental data and utilized the Dragino DLOS8N LoRaWAN Gateway as a bridge to transmit packets to The Things Network (TTN). This architectural layout ensured long-range communication capabilities while maintaining low power consumption, which was critical for off-grid deployment.

(a) **(b)**

Fig. 3 *Figure description (a) External view of the hardware (b) Top view of the hardware*

Fig. 3 (a) and (b) illustrates the external components of the prototype, including the solar panel and the rain sensor. The solar panel provides a sustainable energy source, helping to maintain battery charge and extend the operational life of the system during prolonged deployment. Meanwhile, the rain sensor complements water level measurements by detecting rainfall events, adding another layer of environmental awareness. These external components together enable the prototype to respond effectively to changing conditions in real-time, supporting the overall reliability of the monitoring system.

3.2 Functional Prototype Development and Data Transmission

The functional prototype was built by combining several essential hardware components, including a JSN-SR04T ultrasonic sensor to measure water levels and an MH-RD rain sensor to detect rainfall. The software was created using the Arduino IDE and C++ to manage sensor functions and process long-range wireless data. To enable real-time monitoring, a communication link was established between the LoRa32 device and the TagoIO cloud platform through Webhook integration. An early warning system was also set up with a Telegram bot, which automatically sent flood alerts to users' mobile devices when the water level dropped below the safe threshold of 25cm for dangerous and below 35cm for caution. These thresholds were used to assess the system's ability to detect rising water levels and trigger alerts accordingly correctly. The value for threshold serve to demonstrate how the alert mechanism would function once field calibration is performed.

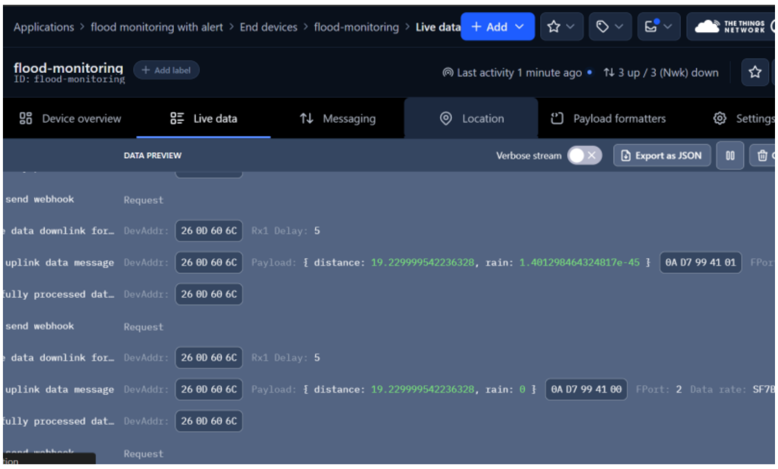

Fig. 4 *Data distance and rain status from The Things Network*

Fig. 4 shows data collection from The Thing Network for rain status and distance. Rain status displayed in the live data interface gives the rain detection: 0 means it rained, whereas any value higher than 1.4 reflects dry conditions. The Distance value is equivalent to the reading of the water level which helps officials detect and forecast possible flooding. When these information sources are collected, the system can give early flood warnings with greater certainty.

Fig. 5 *Notification for water level alert via Telegram application*

As shown in Fig. 5, the bot successfully delivered consecutive alerts based on the real-time sensor data received from the LoRa32 gateway. When the system detects a critical water level, it immediately sends the data. When the water level reach below 25cm, alert notification will tell user that the water level is in dangerous level. While for the caution level, notification will be sent when water level between 26cm to 35cm.

3.3 Performance Evaluation and Reliability Analysis

The performance of the system was rigorously evaluated through controlled testing and data analysis to ensure its reliability in harsh conditions. Sensor validation was conducted by measuring water levels at various distances specifically at 20 cm, 30 cm, and 40 cm to confirm the accuracy and consistency of the ultrasonic readings. Additionally, the system's power efficiency was assessed by calculating the average power consumption of approximately 222 mW against the 4800 mAh battery capacity to estimate operational longevity. Finally, the suitability for rural deployment was verified by observing the stability of the solar-powered setup and the success of data transmission via the LoRa module during simulated flood conditions.

Table 1 *Table Data for Sensor Reliability Analysis*

Test Condition (cm)	Sensor Reading 1 (cm)	Sensor Reading 2 (cm)	Average Reading (cm)	Threshold Level (cm)	Alert Status	Alert Level
20	19.21	19.30	19.26	≤ 25cm	Triggered	Dangerous
30	28.25	28.17	28.21	≤35cm	Triggered	Caution
40	38.59	37.08	37.84	>35cm	Not triggered	Not triggered

Based on Table 1, the repeated sensor readings showed minor variations at each water level, which was expected. For example, at the 20 cm test, readings of 19.21 cm and 19.30 cm averaged 19.26 cm (±0.05 cm). At 30 cm, variations were ±0.04 cm, and at 40 cm, readings ranged from 37.08 cm to 38.59 cm, averaging 37.84 cm. These small fluctuations reflected normal sensor noise but overall demonstrated reliable performance. Alerts behaved as configured: they triggered at 20 cm and 30 cm for early warnings, but not at 40 cm. The minor variations did not affect reliability and confirmed the sensor could detect water level changes accurately within a narrow tolerance.

The difference between caution level and dangerous level pertains to the severity of the risk and the urgency of response needed. A caution level signals that conditions are nearing a critical point and acts as an early warning for preventive measures. It indicates the situation should be observed carefully but is not yet harmful. Conversely, a dangerous level signifies a critical state where the threshold has been breached, presenting a high risk and demanding immediate action to avert damage or harm. Essentially, the caution level serves as a warning stage, whereas the dangerous level constitutes an emergency.

Other than that, the reliability was measured through the battery capacity as it represents the amount of electrical charge that a battery can store, typically expressed in mAh, while voltage indicates the electrical potential of the battery. To determine the actual energy available, the battery capacity Li-ion 18650, 4800mAh and 3.7V is converted into energy (Wh) using the following equation:

$$Energy(Wh) = Voltage(V) \times Capacity(Ah) \quad [10]$$

$$Energy\ in\ battery(Wh) = 3.7V \times 4.8Ah = 17.76Wh$$

For a Li-ion 18650 battery with a nominal voltage of 3.7 V and a capacity of 4800 mAh (4.8 Ah), the total stored energy is 17.76 Wh. This value is used as a reference for estimating the system's operating time and power efficiency.

$$Battery\ life(hours) = \frac{Battery\ energy(Wh)}{Average\ power(W)} \quad [11]$$

$$Battery\ life(hours) = \frac{17.76\ Wh}{0.222W} = 80\ hours$$

Based on the estimated battery life of approximately 80 hours which is around 3.3 days using a 3.7 V, 4800 mAh Li-ion 18650 battery, the flood monitoring system demonstrates the ability to operate for several days without frequent recharging. In actual operation, the system transmits data at 30-minute intervals and enters sleep mode when idle, which helps to reduce overall power consumption and further extend battery life beyond the estimated continuous-operation value.

4. Conclusion

In all, the project succeeded in developing an IoT system for flood monitoring and early warning using LoRa32 and TTN integration. It was shown that the system could track water levels right away, pass data through LoRa communication across great distances and offer early warnings using an IoT software platform. The system takes advantage of solar energy, making it able to stand alone in regions where infrastructure is missing. Despite some setbacks such as less solar power when it rains a lot and the need for more durable waterproofing, the project reveals that sustainable flood monitoring systems with little power can be used in rural areas facing disasters. From the study, improvements can be planned like smarter power management systems, protecting enclosures from weather and better use of data analytics. In conclusion, the work done in this project supports the development of larger-scale and budget-friendly flood monitoring systems for the real world.

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Conflict of Interest

Author declares that there is no conflict of interest regarding the publication of the paper.

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