Development of a Portable LoRa-Based Data Logger System for Enhanced Flash Flood Monitoring in Remote Upstream Catchments of Sarawak

Diana Ringgau*, Samsawi Bujang, and Natasha Subang Tawie

Department of Electrical Engineering,
Politeknik Mukah,
Jalan Oya, 96400 Mukah, Sarawak, Malaysia.

*Corresponding Author's Email: dianaringgau@pmu.edu.my

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Abstract

In Sarawak, flash floods are often triggered by intense rainfall over hilly and upland catchments, causing rapid runoff into major rivers and their tributaries. These events pose significant risks to downstream towns, particularly when they coincide with high tides. Although Automatic Weather Stations (AWS) provide essential environmental data for the National Flood Forecasting and Warning System (PRAB), their fixed locations result in limited coverage in remote tributaries. This creates spatial data gaps that reduce the accuracy of flood prediction and early warning. This project aimed to develop a low-cost, portable data logger system to complement existing AWS infrastructure by enabling real-time monitoring in remote upstream areas. The proposed system is equipped with a LoRa communication shield and a micro-SD card to allow efficient data transmission and storage while operating independently of internet access and the power grid. It also includes locally processed alerts, enabling immediate early warning in the surrounding area with the same data forwarded to the nearest AWS or server for further dissemination via PRAB. Sensor modules were calibrated to maintain accuracy within a 1% error margin. The system was validated through flood simulation tests and performance evaluation of the LoRa 915 MHz communication module, which demonstrated a strong linear correlation between transmission distance and received signal strength (RSSI). Preliminary analysis using SRTM-derived Digital Elevation Model (DEM) data and hydrological tools in QGIS supported strategic data logger placement. Long Banga was selected as a representative site due to its location in a flash flood-prone sub-catchment with limited AWS coverage. Overall, the proposed system enhances localised flood detection, supports PRAB data requirements, and cost-effective solution for strengthening early warning capabilities in remote river basins.

Keywords: Automatic Weather Station, Digital Elevation Models, LoRa, Monitoring System, Warning System

1.0 Introduction

In Sarawak's upstream river basins, heavy rainfall over upland terrain generates rapid surface runoff due to steep slopes and limited soil infiltration. This fast-moving runoff quickly enters tributaries and main rivers, and when combined with downstream rainfall or tidal influences, the effects are a significant risk of flash flooding in lower-elevation areas. Hydrological modelling studies, such as the Danjiang River analysis [1], confirmed that hilly and upland catchments produced short-lag, high-peak discharge events following intense rainfall, underscoring the need for upstream monitoring and early warning systems. Kuching, for example, is situated in a coastal lowland area bordered by upland terrain approximately 10 to 30 kilometres away. During periods of heavy rainfall, runoff originating from the Penrissen Highlands, Bau Hills, and Matang Range can rapidly flow into Sungai Sarawak and its tributaries. When this upstream runoff coincides with high tides, the probability of flash flooding in Kuching increases substantially. A study on the flow behaviour of Sungai Sarawak following the construction of the Matang Bypass Channel further highlighted the challenges of managing excess water during such events [2].

Currently, Malaysia's flood monitoring and warning framework relies heavily on the national telemetry network and Automatic Weather Stations (AWS). The telemetry network is strategically installed along main rivers and accessible locations, utilising industrial-grade data loggers that contribute to relatively high installation and maintenance costs [3]. Malaysia's Department of Irrigation and Drainage (DID) depends primarily on its AWS network, supported by the National Flood Forecasting and Warning System (PRAB), which provides flood prediction models across 41 major river basins. These AWS stations play a central role in monitoring weather conditions and supplying real-time data to PRAB, enabling the translation of rainfall measurements into actionable flood thresholds and public advisories [4].

However, AWS installations are fixed [5] and unable to capture localised rainfall or river-level variations occurring in remote tributaries far from their coverage zones. Additionally, AWS require reliable power and stable internet connectivity to transmit real-time data—conditions often unavailable in rural Sarawak. As a result, deploying and maintaining AWS in remote upstream catchments is challenging, and gaps in spatial coverage may lead to reduced accuracy and reliability in PRAB-generated outputs. Therefore, this paper aims to develop a portable data logger capable of delivering real-time monitoring and alerts in response to heavy rainfall occurring in tributaries and upstream rivers during the monsoon season. To achieve this goal, three project objectives were defined: (1) identify suitable upstream monitoring locations using a Digital Elevation Model (DEM), (2) fabricate a low-cost, portable real-time flood monitoring and warning system, and (3) test its performance. By meeting these three objectives, deployed data loggers in upstream river basins can capture high-resolution meteorological and hydrological data well before floodwaters reach downstream communities. These loggers complement existing AWS infrastructure by filling critical coverage gaps.

2.0 Methodology

The main concept of the proposed Flood Monitoring and Warning System is illustrated in Figure 1, where data loggers were installed in tributaries and upstream river catchments. Each data logger was connected to transducers and other data sources to record hydrological and meteorological parameters over time. The recorded data was processed and analysed locally to support early warning efforts in the surrounding area, while also being transmitted to a local server or the nearest AWS.

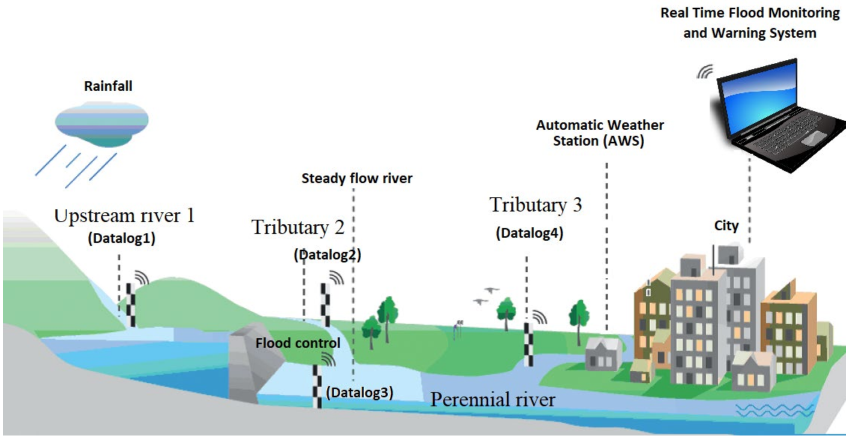

Figure 1: Design concept of a flash flood monitoring system for upstream remote catchments of Sarawak

Data logger placement was guided by DEM analysis and hydrological factors with particular attention to high-elevation, high-rainfall zones characterised by rapid-response catchments [6]. The selected DEM location was intended for the early detection of flash floods [7] in the Baram River basin, particularly those affecting the Marudi and Miri regions. In this case, Long Banga (approximately 3.20°N, 115.39°E) was chosen as a representative site due to its position within a flash-flood-prone sub-catchment and the limited coverage of existing AWS. This site was expected to monitor the upper Baram tributaries that contributed to downstream flooding [8] toward Marudi.

The data logger was implemented with selected transducers, data acquisition components and communication modules. Figure 2 illustrates the block diagram of the data logger. The DHT22 temperature sensor, GY-652 atmospheric pressure sensor, air humidity sensor, HC-SR04 water level sensor and soil moisture sensor were selected, tailored to the specific needs of the system. The DHT22 operated within a temperature range of –40°C to 80°C. The GY-652 sensor, which integrated the HMC5983 and BMP180 chips, used the I²C communication protocol and measured atmospheric pressure from 300 to 1100 hPa and relative humidity from 0% to 100%. An Atmel ATmega2560 microcontroller was selected to manage the transducers and modules while supporting multiple bus protocols, including I²C, SPI, and TTL. The DS3231 was used as the Real-Time Clock (RTC) to maintain accurate time and date, and it was chosen to prevent loss of the time base in the event of a system power supply failure. The SIM900 GSM module was used in this project to enable cellular communication, allowing the data logger to send and receive information through the mobile network. It was programmed to deliver warning messages via Short Message Service (SMS) to authorities such as the Rukun Tetangga, the Fire and Rescue Department (BOMBA), and the National Security Council (JPAM). The system also incorporated Dragino LoRa Shields operating on the LoRaWAN protocol [9].

The shields were stacked onto the Arduino Mega boards, providing ultra-long-range spread-spectrum communication with high interference immunity [10]. The shield consumed approximately 10.3 mA of current, with only 200 nA required for register retention [11]. Two LoRa modules were required for communication at the 915 MHz frequency band, with the baud rate set to 9600 and the UART pins connected in a cross arrangement to the microcontroller.

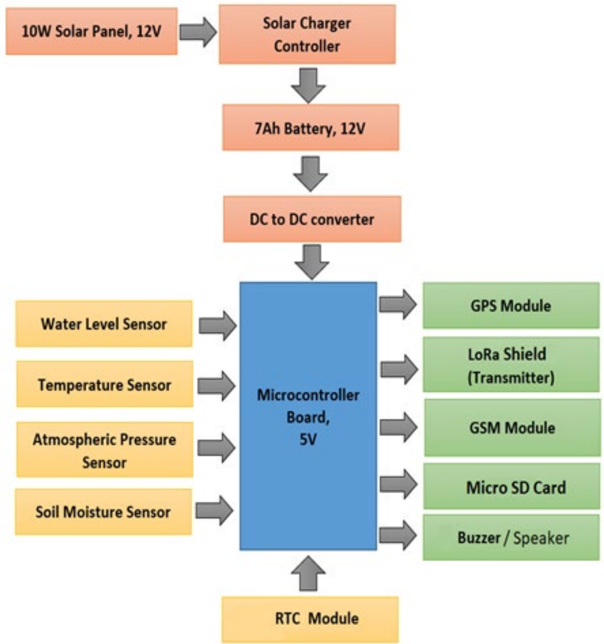

Figure 2: The data logger block diagram

By combining both the SIM900 GSM module and the Dragino LoRa Shield in a data logger, it provides the ability to use alternative communication channels if one communication channel fails. If both the GSM and LoRaWAN networks are unavailable, the data logger can store the data on a Micro-Security Disk (SD) card until the networks become available again. Once the networks become available, the data logger can transmit the stored data to the local server. This feature is important in flood monitoring systems to ensure that data can be transmitted reliably even in strict conditions. The micro-SD card used in this project required 0.2 - 200mA of current and was able to support up to 2GB of data storage.

Further, Figure 3 illustrates the flowchart of the data logger programme. The process starts with the initialisation of the transducers' status, GSM, RTC module, and LoRa shield. Then, the datalog1.csv is created by utilising the SD.open() function, whereas the myFile.read() function will read from the file and display data on the serial monitor. Once a file was created, the microcontroller processed the signals from transducers. The variable port index and baud rate were set to match the port and the baud rate used by the microcontroller board and the LoRa shield transceiver. Once the receiver was detected, Arduino IDE was programmed to read the recorded data inside the

SD card and print it on a serial monitor, allowing it to transmit the stored data to the local server.

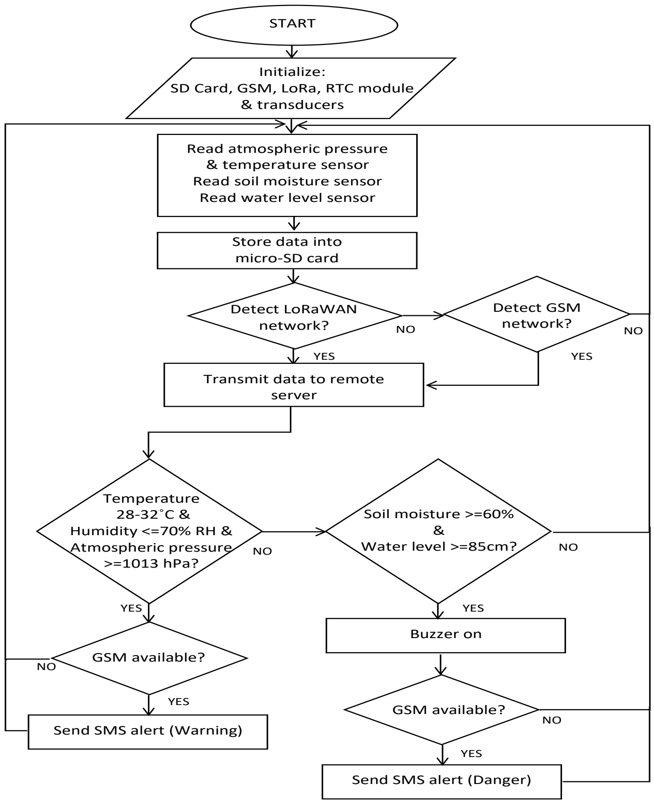

Figure 3: Flowchart of the data logger program

The data logger was not calibrated to the weather conditions specific to Long Banga, as the testing was conducted at Politeknik Mukah (2.8952° N, 112.0914° E). Therefore, the configuration and threshold settings were based on environmental conditions typical of a lowland region rather than those of the intended upland deployment site. As part of the test setup during the monsoon season, the data logger was programmed to send warning messages via SMS when the temperature ranged between 28°C and 32°C and the atmospheric pressure approached 1013.25 hPa [12], [13]. This temperature range and pressure level were selected because heavy rainfall typically occurred within 1 to 3 hours after these conditions were met. Once rainfall began, the temperature and atmospheric pressure no longer fell within the specified threshold values. Therefore, the logger was designed to subsequently monitor water level and soil moisture instead. When the threshold values for water level and soil moisture were reached, the system triggered a danger message, indicating a potential risk of flooding.

The GY-652 atmospheric pressure sensor was tested by comparing its readings with known atmospheric pressure values obtained from online sources such as MetMalaysia. For temperature calibration, the sensor readings were compared with a known and reliable reference thermometer [14]. The ultrasonic sensor's accuracy was evaluated by comparing its measurements with a known, precise distance. For the soil moisture sensor, raw voltage outputs were recorded while watering the soil for 30 seconds, and the change between the initial and final voltage readings was used to determine the corresponding change in soil moisture. The performance of the LoRa 915 MHz communication modules was evaluated through field tests measuring signal strength (RSSI) and packet delivery success over increasing distances in an open environment [15]. The transmitter was programmed to send data packets at 5-second intervals, while the receiver logged the RSSI values of received packets. During testing, the transmitter remained fixed while the receiver was moved from 1 km to 10 km away. At each distance, RSSI and packet reception were observed using the serial monitor.

3.0 Results and Discussion

The preliminary analysis using the DEM revealed promising insights for future data logger placement. The catchment boundary delineation was completed using SRTM-derived DEM data and hydrological tools in QGIS [16]. The delineated area shown in Figure 4 represents the Upper Baram sub-catchment, with its main outlet near Long Lama in northern Sarawak. The boundary follows natural topographic ridgelines, accurately enclosing upstream tributaries that contribute to the Baram River system above Long Lama. This catchment includes important headwaters near Long Banga, Long Laput, and the surrounding highlands close to the Sarawak-Kalimantan border.

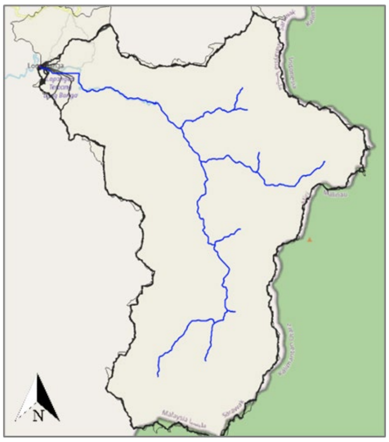

Figure 4: The Upper Baram sub-catchment

Figure 5 displays the Upper Baram River catchment overlaid on a hill-shaded DEM. The elevation gradient is clearly visible, with the southern and central parts of the catchment exhibiting the highest elevations. Steep slopes are especially concentrated in these zones, suggesting a rapid surface runoff response during intense rainfall events. Such terrain characteristics are typical of flash flood-prone basins [17], where rainfall quickly converts to surface runoff due to limited infiltration capacity. The blue lines represent multiple tributaries that converge into the main Baram River channel. These tributaries traverse steep-sided valleys and form dendritic drainage patterns, which are common in upstream basins. Given the steep topography, the catchment is likely to experience short lag times between rainfall and peak streamflow, increasing the risk of flash flooding. This highlights the importance of installing early-warning systems and real-time monitoring stations in upstream areas such as Long Banga.

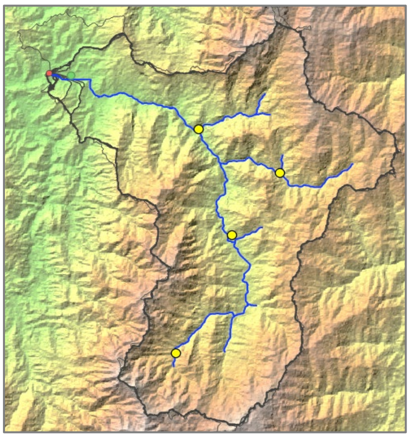

Figure 5: The Upper Baram River catchment overlaid on a hill-shaded DEM

Therefore, Data Logger 4 is planned to be located along a steep upper tributary near the ridgeline, south of Long Banga. This placement aims to monitor the uppermost headwaters and capture early runoff. Data Logger 3 will be deployed along a curved mountainous river channel draining from the eastern slope to monitor midstream tributary flows from the eastern hills. Data Logger 2 is positioned near a key confluence where multiple tributaries merge before the main river flows northward. Its purpose is to monitor the junction of these tributaries for cumulative flow assessment. Data Logger 1 will be installed near the river outlet before Long Lama to observe the lower-elevation steep river segment just before discharge into the downstream section. Additionally, an Automatic Auxiliary Weather Station (AAWS) is expected to be installed at Long Banga Airport to provide supporting meteorological data. These results provide a strong foundation for the next phase of field validation and deployment of the data logger system.

Figure 6 shows the complete setup of a single data logger unit. This data logger consumed 76 mAh of power. When the logger ran continuously for 24 hours, the 7Ah battery powered it for 3 days and 20 hours before requiring recharging. With an 80% charging efficiency, it took approximately 10.5 hours for the 10W solar panel to fully charge the battery. However, to sustain the operation of the data logger, the solar panel requires at least 3 hours of direct sunlight per day, thereby making it independent from power grids. The data logger without its base and pole was light in weight, weighing approximately 0.75 kg. It had a compact size with a volume of 0.005m^3, making it highly portable and easy to transport. It could be installed in remote areas without requiring extensive infrastructure. The data logger has four channels, and the sampling rate is 1 S/s. Since the high data rate of transfer was required, the logger executed 96 times of data reading and recording per day. For each reading, the logger captured 30 samples per reading with a 15-minute interval within 24 hours. Hence, for every reading, the data consumed 1.5K bytes of SD card capacity, which comes to about 144K bytes per day. Therefore, for a capacity of 2GB, the storage was estimated to save data for up to 19 months. If a 32GB SDHC card was used, it could save data for up to 25 years.

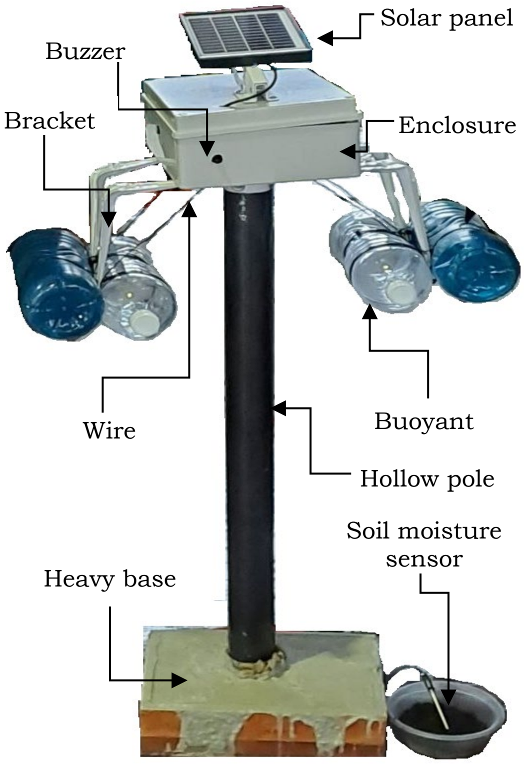

Figure 6: Complete setup of a single data logger unit

Figure 7 shows the testing of the flood monitoring and warning system's performance. A ground pool was used to simulate flood conditions and record the logger's performance. By simulating flood conditions in a controlled environment, the test conditions can be easily replicated and modified as necessary. Buoyant materials, such as foam or bottles, were added side by side to the enclosure to ensure that it remained afloat on the water's surface.

Figure 7: Testing the flood monitoring and warning system's performance

The data loggers provided real-time monitoring, which allowed timely responses to flood events. Figure 8 shows the system's local server displaying the data received from the data logger, which is located 10 km away. In this test, the module was programmed to send multiple SMS messages to several designated phone numbers when the water level and soil moisture reached or fell below 85 cm and 60%, respectively. While Figure 9 shows the SMS received by one of the designated phone numbers.

```
TEMPERATURE SENSOR READING:
Temperature = 30.20 *C

ATMOSPHERIC SENSOR READING:Pressure = 101316 Pa
Altitude = 1.00 meters
Pressure at sealevel (calculated) = 101309 Pa
Real altitude = 0.67 meters

SOIL MOISTURE SENSOR READING:
Analog output:571

ULTRASONIC MOISTURE SENSOR READING:
Distance: 85 cm

(THIS IS A FLOOD DRILLS)WARNING! Prepare for any evacuation
message sent to mobile No.2
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Wednesday 30 . 11 . 2022 - - 05 : 48 : 37
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Figure 8: The local server's data display

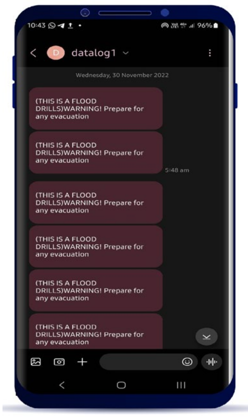

Figure 9: The SMS alert received by the community

The accuracy tests were performed on the atmospheric pressure sensor, temperature sensor, ultrasonic sensor, and soil moisture sensor. The results, as shown in Figure 10, indicate that the average percentage error for the atmospheric pressure sensor was 0%, demonstrating excellent accuracy. While industrial-grade devices such as the Vaisala PTB330 or Bosch BMP388 are commonly used, the tested sensor's performance aligns with the industry-acceptable deviation of ±1 hPa for environmental monitoring applications, confirming its reliability under test conditions.

The temperature sensor results, presented in Figure 11, showed an average percentage error of 0.73%, equivalent to around ±0.2°C. Industry-standard devices such as the Vaisala HMP110 and DS18B20 offer typical accuracies of ±0.5°C to ±1.0°C, which are commonly accepted in field-based meteorological and hydrological monitoring. The results validate the DHT22 sensor's suitability for real-time environmental monitoring, especially in remote locations where low-power, cost-effective solutions are needed. For both the ultrasonic water level sensor and the soil moisture sensor, initial tests identified systematic errors. To compensate, correction factors were applied.

As shown in Figure 12, the ultrasonic sensor (HC-SR04) initially had a percentage error of 6.05%, which was reduced to 0.056% after applying a correction factor of 1.0638. Industrial-level sensors like the Senix ToughSonic 100 and Microsensor MPM489W typically operate within an average error margin of ±1%. The corrected value achieved by the low-cost sensor in this study falls well within that range. Similarly, Figure 13 shows that the soil moisture sensor's initial error of 2.62% was reduced to 0.007% using a correction factor of 1.0268. Professional-grade sensors such as the Meter Teros 12 and Decagon EC-5 maintain an accuracy of ±2% to ±3% VWC (Volumetric Water Content) in field conditions. The proposed sensor, after calibration, surpassed these standards, highlighting its capability for reliable field data collection. To monitor the complete operation of the system, the data logger was operated for seven hours at the ground pool, located at Politeknik Mukah.

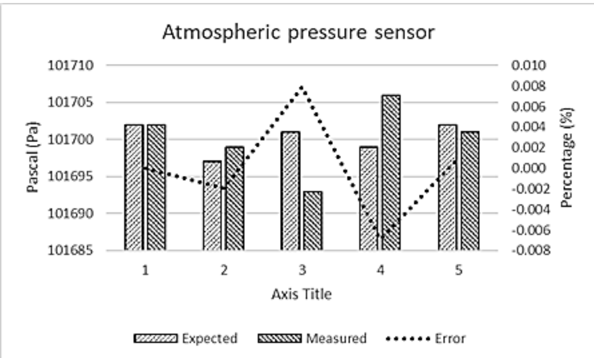

Figure 10: The accuracy tests of atmospheric pressure sensors

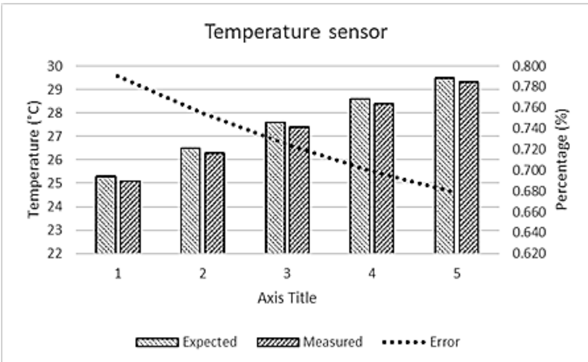

Figure 11: The accuracy tests of temperature sensors

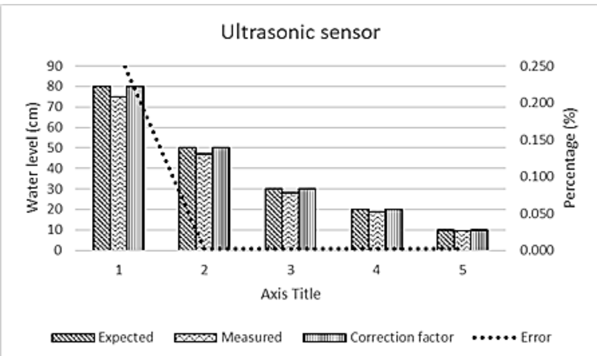

Figure 12: The accuracy tests of ultrasonic sensors

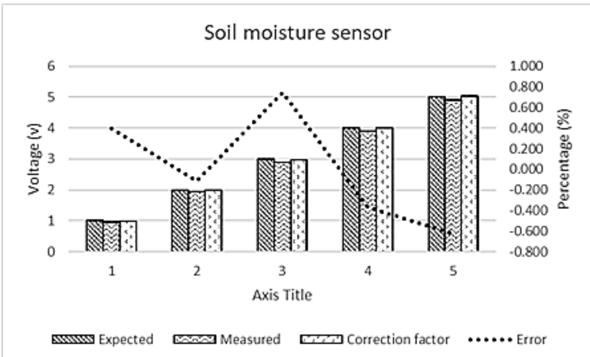

Figure 13: The accuracy tests of soil moisture sensors

Further, Figure 14 shows the temperature and atmospheric pressure as a function of time. Based on the graph's readings, the average temperature was 27.5°C, and the atmospheric pressure was 1013 hPa. Figure 15 shows the water level and soil moisture as a function of time. The graph shows that the average water level was 42 cm, and the soil moisture was 53.6%. The data logger was demonstrated by the acceptable behaviour and accuracy of transducers' readings. The test results confirmed that the sensors, once calibrated, provided accurate and consistent readings within or below the acceptable error range for field-based environmental monitoring. This highlights the data logger's reliability for use in flood-prone regions where sensor accuracy is essential for timely warnings.

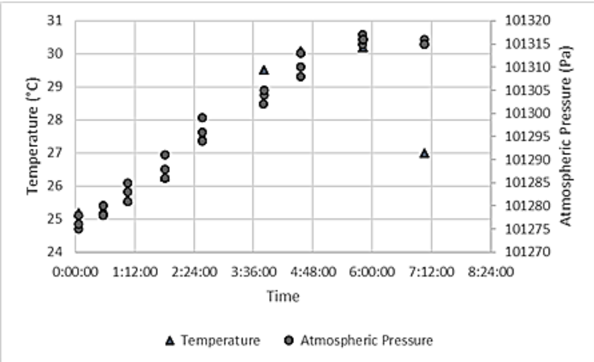

Figure 14: Data logger temperature and pressure measurements

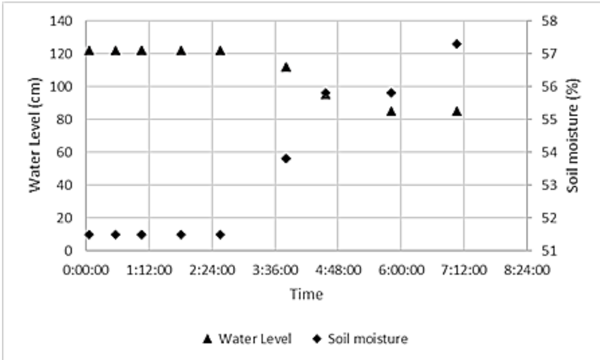

Figure 15: Real-time readings from ultrasonic and soil moisture sensors

Additionally, the signal performance of the LoRa 915 MHz module was evaluated by measuring the Received Signal Strength Indicator (RSSI) over increasing transmission distances, ranging from 1 km to 10 km. As illustrated in Figure 16, the measured RSSI consistently decreased as the distance increased, indicating signal attenuation with range. The linear regression line, defined by the equation RSSI = –2.85 × Distance + 17.53, shows a signal loss rate of approximately 2.85 dBm per kilometre. This strong linear relationship confirms the stability and predictability of LoRa signal degradation in open environments. Even at 10 km, the RSSI remained above –45 dBm, which is within the operational threshold for reliable data transmission.

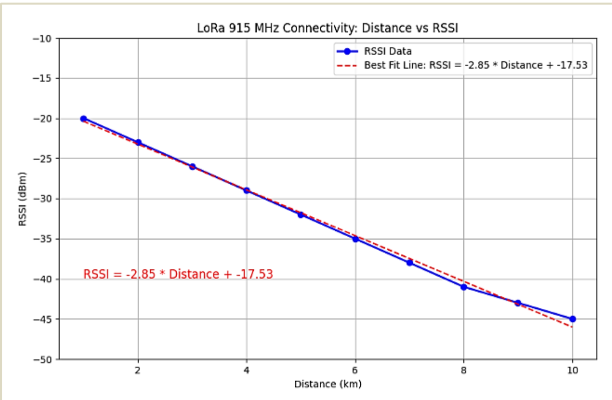

Figure 16: Measured RSSI values during data logger transmission test

Table 3 presents a comparative summary of the sensor error values obtained during experimental testing against established industry-acceptable accuracy thresholds. It can be observed that the proposed sensing and communication modules meet or exceed industry-acceptable accuracy thresholds after calibration, confirming the system's operational suitability for flash-flood early warning in remote catchments. The marginally larger relative error for the temperature sensor is nevertheless acceptable for early-warning applications where detection of rapid trends is more important than absolute precision, a trade-off commonly reported in recent low-cost IoT flood monitoring studies [18]. The atmospheric pressure sensor's negligible deviation under controlled conditions and the marked reduction in water-level and soil-moisture errors post-calibration verify findings that calibration and correction factors substantially improve low-cost sensor reliability for hydrological monitoring [19], [20].

Table 3: Comparison of proposed sensor error rates with industry-acceptable benchmarks

Parameters	Proposed Sensor Error Rate	Industry-Acceptable Error Rate	Remarks
Temperature	±0.73% (≈ ±0.2°C at 27.5°C)	±0.1°C to ±0.2°C	Slightly higher relative error, but acceptable for early warning purposes
Atmospheric Pressure	±0% under test conditions (1013 hPa)	±0.1 to ±0.3 hPa	Meets industry standard, likely due to stable test conditions
Water Level	Reduced to ±0.056% after calibration	±0.1% to ±0.25% of full scale	Performance matches or exceeds benchmark following calibration
Soil Moisture	Reduced to ±0.007% after calibration	±2% to ±3% volumetric water content (VWC)	Exceeds typical accuracy requirements after applying correction factor
LoRa Communication (RSSI)	~2.85 dBm/km path loss, RSSI > –45 dBm at 10 km	Reliable above –120 dBm; ~2–3 dBm/km loss	Satisfies long-range communication performance expectations

Significantly, the measured LoRa path-loss and RSSI behaviour align with empirical performance reported for LoRa deployment in hydro-environment monitoring, indicating the communication link can sustain long-range telemetry in topographically complex areas [21]. Collectively, the quantitative outcomes in Table 3 validate the proposed system's robustness and its potential to mitigate spatial data gaps in national flood-warning schemes when deployed as a complementary upstream sensing layer [18], [19], [20].

4.0 Conclusion

The project successfully identified suitable upstream monitoring locations using a Digital Elevation Model (DEM), demonstrating that hydrological and catchment characteristics strongly influenced flood behaviour in the Baram River basin, contributing to downstream flooding toward Marudi. The study also highlighted that strategic data logger deployment was essential to complement AWS. The system provided a viable solution for areas with limited internet and grid infrastructure, enabling effective monitoring and localised flood alerts. Its low power consumption allowed operation with approximately three hours of sunlight per day. With a total hardware cost of RM307.10, the system proved portable and scalable for deployment in remote areas. Following calibration, the data logger performed comparably to industrial benchmarks, with transducers achieving an average error of less than 1%. Preliminary field testing conducted at Politeknik Mukah confirmed the successful integration of environmental sensors and reliable wireless data transmission. However, since the testing environment was in a lowland coastal region, key meteorological parameters, such as temperature and atmospheric pressure, were not representative of upstream catchments like the Baram River. As a result, the system remained in a proof-of-concept phase, and future in-situ deployment and calibration in upstream catchment areas were required to validate its performance under actual flash flood conditions.

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Author Contributions

Diana Ringgau: Conceptualisation, Methodology, Data Curation, Analysis, Data Validation, Visualisation, Writing –Review & Editing; **Samsawi Bujang**: Investigation, Resources, Writing-Review & Editing; **Natasha Subang Tawie**: Conceptualisation, Methodology, Software, Data Validation.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have reviewed and approved the manuscript, consent to its submission, and declare that there are no conflicts of interest.

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