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Development of Buoy-based Observation Module (B.O.M.) for Headwater Monitoring and Early Warning System

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Abstract

Recreation areas and waterfalls are often visited to experience the peace of nature. In recreational areas and waterfalls, headwater disasters can occur; this disaster often worries visitors and residents. This study aims to reduce human casualties and help mitigate the public by developing an early warning system, namely the Buoy-based Observation Module (B.O.M.). Evacuation and emergency planning activities get underway faster with a trustworthy early warning system. Therefore, developing technologies like this can help monitor and provide early warning signs based on LoRa and IoT technologies. This system aims to improve the preparedness of recreational area controllers to face disasters in recreational areas. This module is designed to monitor environmental changes such as vibration, rain, temperature, humidity, and orientation, such as significant changes in angle to the installed module. With various sensors, it allows the system to provide early warning of potential water disasters. Among the additional technologies that have been improved from previous technologies are LoRa and IoT communication technology. It is used to ensure efficient and fast data transmission in real time. Construction of the B.O.M. was structured to withstand heavy rain. By being equipped with solar panels, the B.O.M module can ensure sufficient energy, and there is backup energy. Findings from this study also evaluate aspects such as function, performance, visualization, data communication, and the warning system. At the end of the study, it was found that this system showed that it works well in various environmental conditions and is effective in early warning of disasters in watershed areas.

1. Introduction

Threats to the lives of residents who have occurred at the top of Gunung Jerai due to the headwater phenomenon in 2021. This phenomenon has not only claimed lives but has also swept away everything that was submerged by the headwater flow, including the Neo Era Chalet, and the incident was considered an extraordinary event by local residents, who had not witnessed such an event in over two decades [1]. Following the disasters, public safety and disaster preparedness need to be strengthened. By developing an effective monitoring system in the headwater areas and recreational areas, it can provide early warning if there are signs of headwaters, such as a sudden and rapid increase in the volume and velocity of water in the upper reaches of the river. This is a feature that is often observed for headwater disaster events. Among the changes that can be signs of headwaters are climate change, water abstraction, and land changes that have increased the flow of existing small rivers and the number of temporary streams [2].

The development of an Internet of Things (IoT)-based monitoring system is an effort to overcome the challenges of developing an early hazard detection system. For example, some previous studies, Assendelft and van Meerveld [2] introduced a system to monitor transient flow dynamics in a mountain catchment area, which is a multi-sensor low-cost system. While Mahmud et al. [3] specifically for tropical waterfalls in Johor Eco Park, which has developed an early warning system. Meanwhile, an integrated monitoring and warning system using IoT to address upstream phenomena in river recreation areas is proposed by Boudville et al. [4]. In addition, a system using LoRa communication to monitor river flow speed and debris movement developed by Aiman et al. [5] BUOY ONE, demonstrates the potential of long-range wireless monitoring in remote locations. A warning system based on vibration and flow turbulence sensing using acceleration, vibration and rain sensors was also designed by Razian et al. [6]. Affandi et al. [7] early warning system using ESP32 with ultrasonic sensors implemented, it displays data on the ThingSpeak platform and sends notifications via Twitter. The Upstream Phenomenon Warning and Monitoring System (HWMS) by Kameel et al. [8] is introduced, which combines on-site monitoring devices and mobile applications, and leverages platforms such as InfoBanjir, FANoS and Firebase for real-time data management.

However, electronic-based systems face problems with unstable power, limited internet and uneven geographical conditions in mountainous areas. Standard risk classification, leading to inconsistent warnings and public confusion are shortcomings in the current system. This project proposes a portable and energy-efficient technology to address the problems associated with mountainous areas. The energy-efficient and portable Buoy-Based Observation Module (B.O.M.) is specifically designed for pond and waterfall areas. The system integrates a variety of sensors including vibration, rain, temperature, humidity and orientation (tilt/angle) sensors, and uses a LoRa communication module. It is powered by a rechargeable battery via a solar panel and is equipped with a sleep mode function to save energy consumption. The main objective of this project is to develop a prototype B.O.M. for the purpose of upstream monitoring and real-time early warning. The system is designed to detect environmental risks more accurately through the integration of various sensors and wireless communication. This study evaluates the functionality, performance and buoyancy of the prototype B.O.M. There are two environments, namely an open environment (lake) and a controlled environment. The B.O.M. will be tested to evaluate its operational reliability, communication stability and real-time response capability to simulated upstream conditions.

2. Methodology

The B.O.M. development consists of several parts: a) Microcontroller b) Rain sensor c) Temperature and humidity sensor d) Antenna e) Photovoltaic (PV) module f) Battery charger g) Orientation sensor h) Battery management system (BMS) i) Vibration sensor j) Six 21700 lithium-ion batteries (5000mAh each). The integration of a Heltec WiFi LoRa 32 (V3) development board as the central microcontroller, along with multiple environmental sensors including the MPU6050 sensor detects tilt and acceleration. The SW-18010P vibration sensor for strong hit detection. The rain sensor module measures rainfall levels percentage. The DHT11 sensor measures temperature and humidity. The system is powered by six 21700 lithium-ion batteries arranged to support extended field operation, and the batteries are rechargeable via an external solar panel system. A buzzer module is included to trigger local audio alarms when critical thresholds are detected. For wireless data transmission, a built-in LoRa antenna enables long-range communication with the receiver unit. Fig. 1 shows the overall wire connection of the B.O.M.

Fig. 2 shows the block diagram of the transmitter unit, which was responsible for collecting data from connected sensors and transmitting it via LoRa communication. Fig. 3 shows the block diagram of the receiver unit, which was also based on the Heltec WiFi LoRa 32 V3 microcontroller. This unit receives the transmitted sensor data via LoRa and processes it for further use, such as displaying the WiFi address, received data packet, and Received Signal Strength Indicator (RSSI). Fig. 4 shows a schematic of the B.O.M. circuit.

Fig. 5 shows the flowchart of the B.O.M. system, which detects environmental conditions and triggers a warning. All of the sensors will be initialized when the device was turned on. It collects data from three sensors, which are orientation, rainfall, and vibration. If the conditions are met, the system activates a warning which includes an audible alarm and Thingspeak lamp indicator. If the conditions are not met, the system continues monitoring. The receiver module will receive data collected via LoRa communication. The receiver will constantly be ready to receive the data that has been transmitted. The system will upload the data to the internet using the ground station's WiFi. Lastly, the ThingSpeak platform allows for real-time data monitoring. Fig. 6 shows the enclosure design for the electronic parts for the Buoy-based Observation Module (B.O.M.) and receiver module.

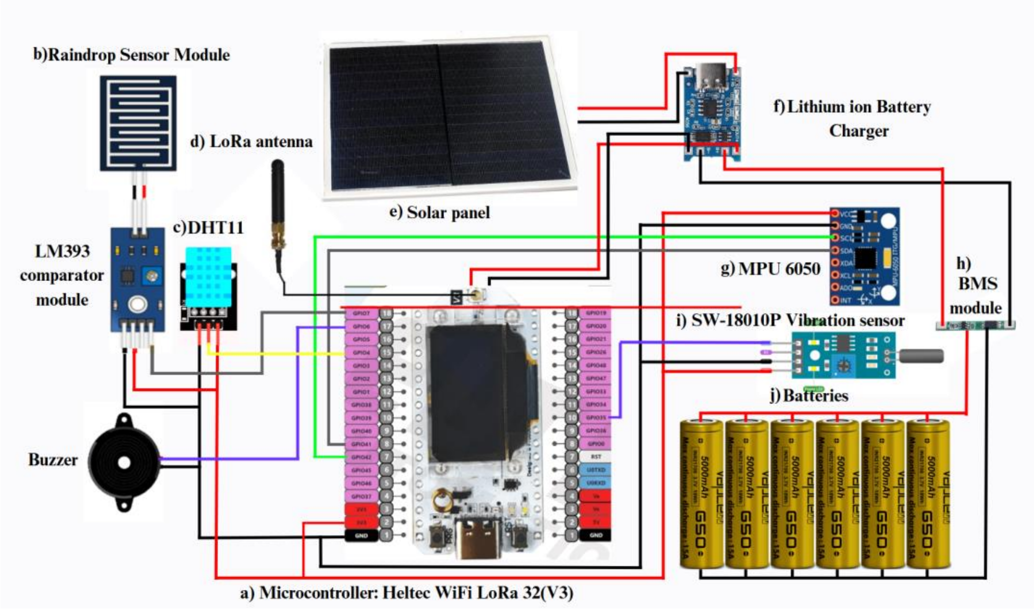


Fig. 1 *Wire connection B.O.M. system*

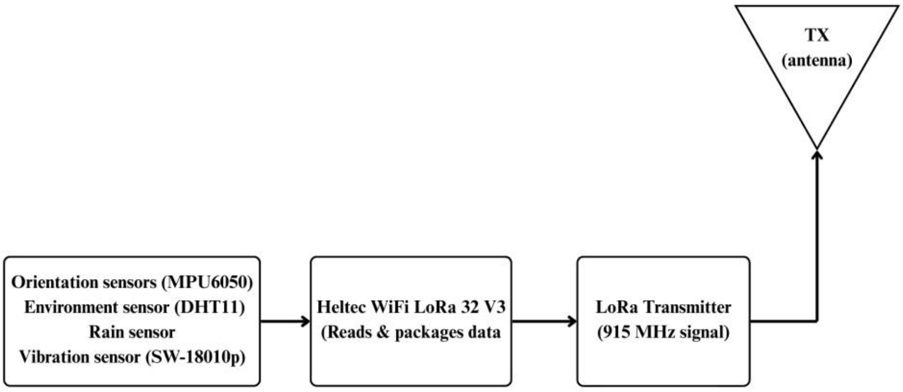


Fig. 2 *Transmitter block diagram*

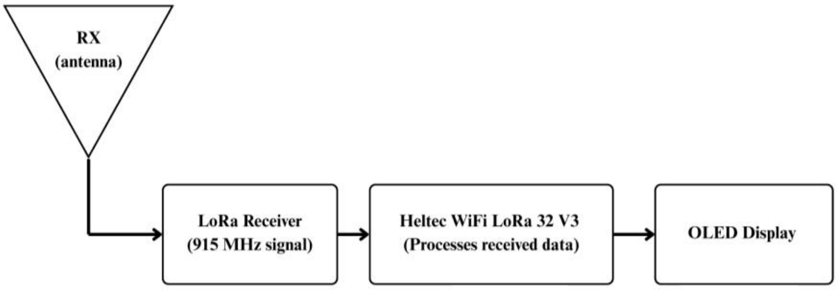


Fig. 3 *Receiver block diagram*

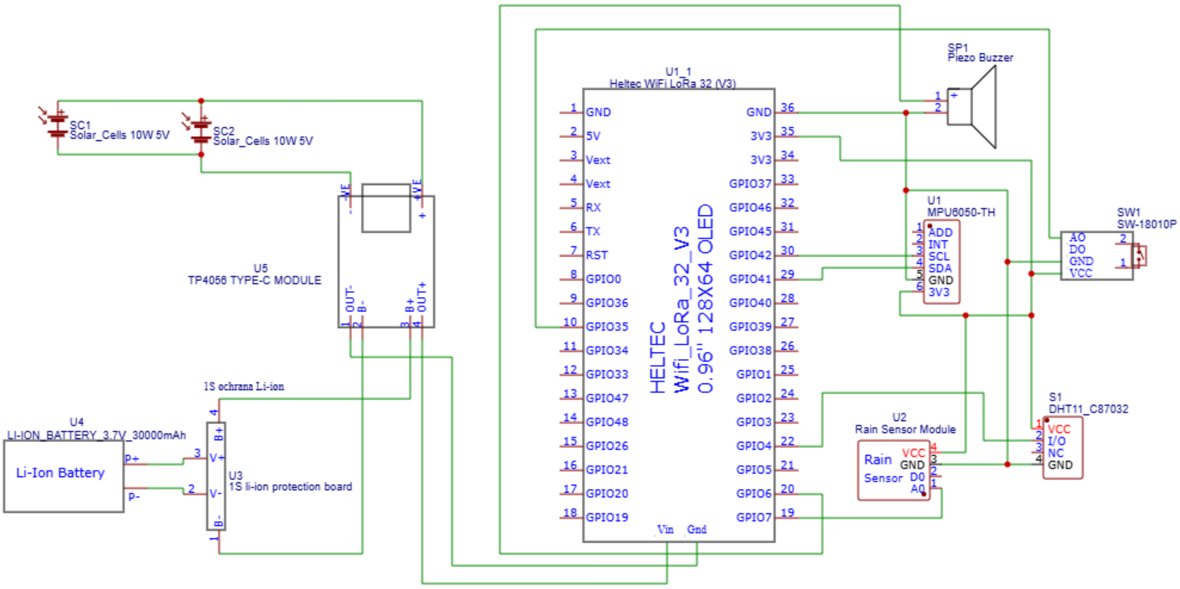


Fig. 4 *Schematic circuit diagram*

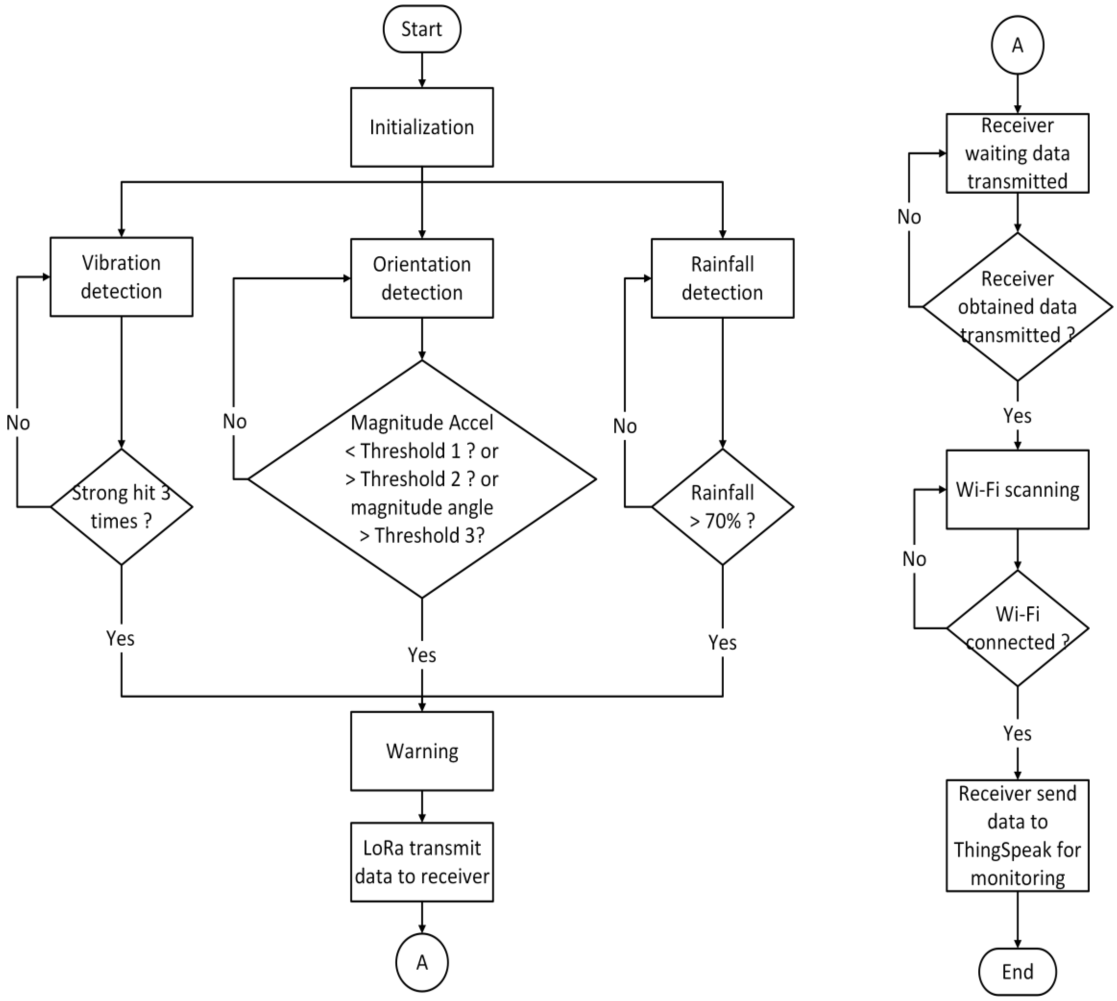
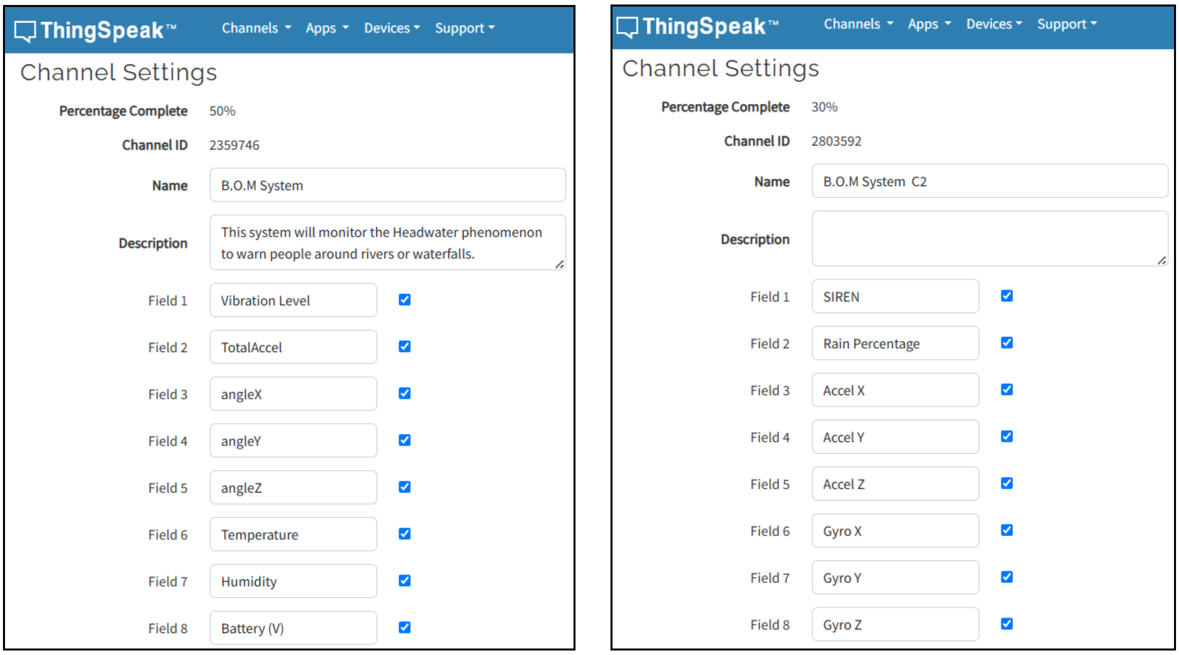


Fig. 5 *Flowchart of headwater detection*

Fig. 6 *B.O.M. prototype*

Monitoring through the Internet of Things (IoT) was a key feature of this system, enabling real-time data transmission and remote tracking of environmental conditions at potential headwater locations. Fig. 7 shows that two dedicated ThingSpeak channels were used to manage and display the sensor data collected by the receiver unit.



Channel Settings

Percentage Complete 50%
Channel ID 2359746
Name B.O.M System
Description This system will monitor the Headwater phenomenon to warn people around rivers or waterfalls.
Field 1 Vibration Level ☑
Field 2 TotalAccel ☑
Field 3 angleX ☑
Field 4 angleY ☑
Field 5 angleZ ☑
Field 6 Temperature ☑
Field 7 Humidity ☑
Field 8 Battery (V) ☑

a) Channel 1

Channel Settings

Percentage Complete 30%
Channel ID 2803592
Name B.O.M System C2
Description
Field 1 SIREN ☑
Field 2 Rain Percentage ☑
Field 3 Accel X ☑
Field 4 Accel Y ☑
Field 5 Accel Z ☑
Field 6 Gyro X ☑
Field 7 Gyro Y ☑
Field 8 Gyro Z ☑

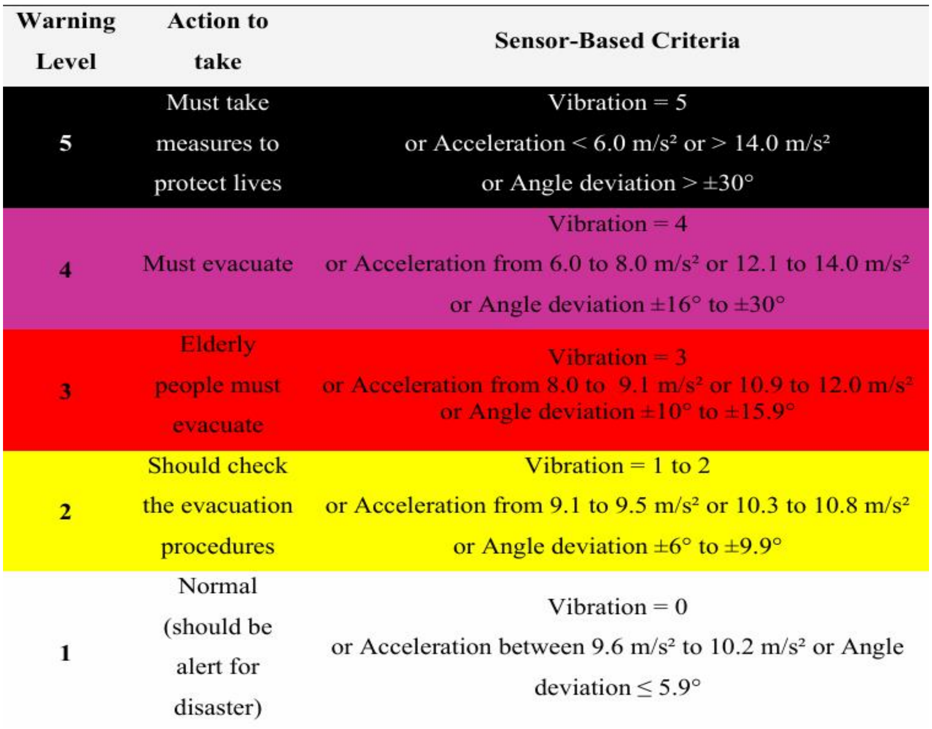
b) Channel 2

Fig. 7 *Channel settings for ThingSpeak Channel 1 and 2*

Table 1 shows the overall five-tier risk classification system used in the Buoy-based Observation Module (B.O.M.) to classify the severity of detected environmental disturbances. Each warning level was based on three types of sensor data, which are vibration level, total acceleration, and angle deviation. The early warning system is divided into five levels that reflect increasing levels of danger related to disasters occurring in upstream river areas. These levels are determined based on sensor readings involving ground vibration, movement speed, and changes in slope position. The first level represents a normal condition where the environment is stable, but monitoring should continue and individuals should remain alert for any unusual changes. When early signs such as slight ground movement or small shifts in slope position are detected, the system advances to the second level.

At this point, it is recommended to review and prepare evacuation procedures. The third level indicates a higher risk where the environment shows more noticeable changes. During this stage, vulnerable groups such as older individuals are advised to begin evacuation due to stronger vibrations and more irregular motion. The fourth level indicates a serious condition that requires everyone in the area to evacuate immediately. This is due to strong vibrations and significant instability in both movement and slope direction. The fifth and highest level represents a critical condition, where the sensor readings show severe vibrations, rapid movement changes, and major shifts in slope position. At this stage, immediate action is necessary to protect lives, as the possibility of a disaster such as a flood, slope failure, or ground collapse is very high.

Table 1 *Five-tier risk classification*



Warning Level	Action to take	Sensor-Based Criteria
5	Must take measures to protect lives	Vibration = 5 or Acceleration < 6.0 m/s² or > 14.0 m/s² or Angle deviation > ±30°
4	Must evacuate	Vibration = 4 or Acceleration from 6.0 to 8.0 m/s² or 12.1 to 14.0 m/s² or Angle deviation ±16° to ±30°
3	Elderly people must evacuate	Vibration = 3 or Acceleration from 8.0 to 9.1 m/s² or 10.9 to 12.0 m/s² or Angle deviation ±10° to ±15.9°
2	Should check the evacuation procedures	Vibration = 1 to 2 or Acceleration from 9.1 to 9.5 m/s² or 10.3 to 10.8 m/s² or Angle deviation ±6° to ±9.9°
1	Normal (should be alert for disaster)	Vibration = 0 or Acceleration between 9.6 m/s² to 10.2 m/s² or Angle deviation ≤ 5.9°

3. Results and Discussions

Fig. 8 shows the Buoy-based Observation Module (B.O.M.) being tested in three different locations to evaluate its functionality, performance, buoyancy, wireless communication, and system stability. The first image shows the device being tested in a pool, which provided a stable and calm setting to verify sensor readings and floatation stability. The second image displays testing in a narrow drainage channel, allowing assessment of the module's performance in confined water flow and interaction with man-made infrastructure. The third image captures the device deployed in a natural pond, where environmental factors such as wind, surface ripples, and vegetation were present, offering insight into the system's real-world functionality in more dynamic and unpredictable conditions.

a) UTHM pool **b) UTHM ECO-HYTECH** **c) UTHM pond**

Fig. 8 *Field testing*

3.1 Functionality test

The experiment was conducted indoors focused on battery lifetime and stability of the 6 Degrees of Freedom (6DoF) sensor readings. This test provides a basic estimate of the system's energy efficiency during standby mode. Fig. 9 shows the estimated battery voltage of the Buoy-based Observation Module (B.O.M.), which dropped to 3.2V after sustaining continuous operation for 9 days.

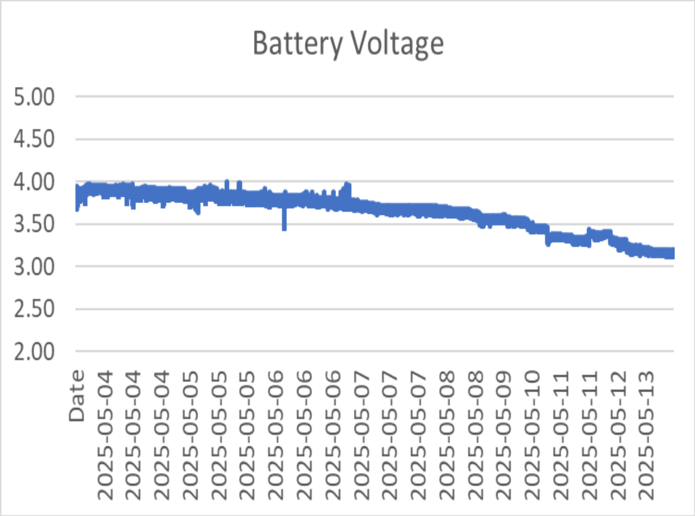


Fig. 9 *Estimated battery voltage dropping to 3.2V after 9 days of operation.*

During the experiment, the prototype was fully charged and left to operate continuously in a stationary state to evaluate the durability of the lithium-ion battery under minimal load conditions. This test provided an estimate of the system's energy efficiency during standby mode. The prototype, powered by six lithium-ion batteries, operated for approximately 9 days from the initial charge. Although theoretical calculations suggested a shorter runtime, the actual duration was extended due to several contributing factors. The integration of a Battery Management System (BMS) and a charge controller enhanced power regulation and reduced energy loss. Furthermore, the microcontroller was programmed with a deep sleep mode, which significantly reduced power consumption during idle periods. Operating at a low voltage also allowed the system to perform effectively over a longer discharge cycle. These combined factors contributed to the extended operational time observed during the experiment. Fig. 10 confirms that all sensor readings were successfully transmitted and displayed on the ThingSpeak dashboard.

Fig. 10 *Successful transmission and display of all sensor data on the ThingSpeak dashboard.*

3.2 Performance test

The objective of this test was to assess the B.O.M. system's sensor stability while floating in a static indoor pool. Table 2 summarizes the data collected, confirming that all sensors operated reliably in a disturbance-free environment. Environmental readings such as temperature and humidity remained stable, while total acceleration closely matched the gravitational constant, indicating the system maintained a static position. Orientation angles showed only minor tilt, consistent with natural buoy movement. The battery voltage remained above the minimum threshold, ensuring uninterrupted operation. No rain or vibration events were recorded, and statistical analysis revealed minimal variation across all parameters. These results validate the system’s reliability and consistent performance in a controlled aquatic setting.

Table 2 *Calculation of all parameters observed in the field test*

Total reading = 120	Total Acceleration	Angle X	Angle Y	Angle Z	Temperature	Humidity	Vibration level	Rain percentage	Battery Voltage
Mean	9.808	-1.380	0.604	1.538	31.930	63.133	0	0	3.486
Median	9.810	-1.460	0.790	1.590	31.900	63.000	0	0	3.480
mode	9.810	-1.460	0.790	1.650	31.800	64.000	0	0	3.470
Standard deviation	0.036	0.820	0.857	0.756	0.153	0.948	0	0	0.019
Variance	0.001322	0.672127	0.733734	0.571465	0.023267	0.898889	0	0	0.000344

3.3 Buoyancy test

Fig. 11 shows the B.O.M. prototype floating stably on the water surface. The visible waterline aligns with the center of buoyancy, indicating that the system was well-balanced and structurally supported without sinking or tilting. This confirms the buoy's effective buoyancy and stable performance under real-water conditions.

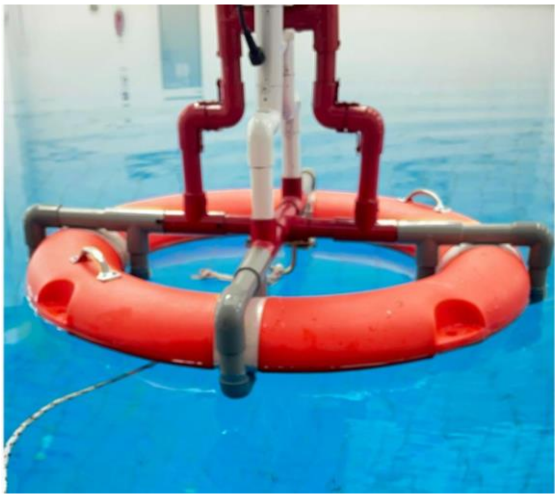


Fig. 11 *Stable floating position of the B.O.M. prototype*

3.4 LoRa distance test

The LoRa communication test was conducted to evaluate signal stability across increasing distances. At short ranges of 1 to 5 meters, the RSSI values were strong, ranging from -40 dBm to -59 dBm, indicating excellent signal quality with minimal loss. At 10 meters, the signal slightly weakened with a median RSSI of -64 dBm. At 15 meters, the signal remained stable with a median of -65 dBm. By 20 meters, RSSI values averaged around -66 dBm, and at 25 meters, they ranged close to -68 dBm. At 30 meters, the signal approached the lower threshold for stability, with a median RSSI of -70 dBm and occasional drops to -73 dBm. Despite the gradual decline, all readings remained within acceptable levels for reliable LoRa communication. These results confirm stable performance up to 30 meters, though further testing is recommended to determine the system's maximum effective range under outdoor or line-of-sight conditions.

Fig. 12 *RSSI testing setup in open space*

3.5 System test

The analysis of Readings 20 to 33, as referred to in Table 3 of the appendix, was conducted using the five-tier risk classification in Table 1, which defines thresholds for vibration, acceleration, and angular deviation. Each reading was evaluated based on these criteria to determine the corresponding warning level.

In general, the assigned warning levels were consistent with the sensor data. Readings with high vibration values, particularly those with a value of five, triggered Level 5 warnings regardless of other parameters. In several cases, high acceleration or significant angle deviation alone justified higher levels. For example, Readings 22, 23, 28, and 32 were assigned Level 5 due to extreme acceleration or angle values, even when vibration was low or absent. Other readings, such as 24 and 33, were classified as Level 4 based on vibration alone, while moderate readings like 26 and 29 were categorized as Level 2 or 3.

This evaluation confirmed that the warning levels accurately reflected the sensor-based criteria and effectively identified varying levels of environmental risk.

4. Conclusion

Based on the overall test findings, it was confirmed that the system is reliable, functional and suitable for real-world environmental monitoring applications. Different field environments, such as an enclosed pond, a drainage channel and a natural pond, demonstrated that the system was able to maintain stable buoyancy, structural balance and operate without interruption in both controlled and dynamic environments.

The B.O.M. was operated continuously for nine days, which demonstrated that the functional test was successful. The integration of the Battery Management System, charge controller and deep sleep mode in the microcontroller helped the B.O.M. to operate for a long time. Sensor data was successfully transmitted throughout the experiment, as verified via the ThingSpeak dashboard. In the performance test, all sensors operated consistently under static water conditions, confirming the stability of the system and minimal variation in sensor output. The buoyancy test further validated the design, as the floating body remained balanced with the water line aligned at the center of buoyancy, ensuring that the system could support its weight without tipping or sinking.

LoRa communication tests demonstrated reliable data transmission up to 30 meters, with RSSI values remaining within acceptable limits for stable operation. Meanwhile, system tests confirmed the effectiveness of the alerting framework. All recorded sensor readings were accurately classified using a five-level risk criterion, reflecting the system's ability to detect and respond to changes in environmental conditions. In conclusion, the prototype B.O.M. successfully met its design objectives, offering a robust, low-power, and responsive monitoring solution for headwater detection in a variety of aquatic environments.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Azwar Hakim, Herdawatie;* ***data collection:*** *Azwar Hakim;* ***analysis and interpretation of results:*** *Azwar Hakim, Herdawatie;* ***draft manuscript preparation:*** *Azwar Hakim, Herdawatie. All authors reviewed the results and approved the final version of the manuscript.*

Appendix A:

Table 3 *Readings during operation and additional external disturbance*

No	Time	Vibration level	Total Acceleration	Angle X	Angle Y	Angle Z	Temperature	Humidity	Rain percentage	Warning level	Validated
20	15:40:45	2	13.85	-10.49	6.59	-3.35	32.4	62	0	4	☑
21	15:41:00	5	9.53	6.28	1.16	-3.17	32.5	63	0	5	☑
22	15:41:15	2	6.28	-7.01	-56.83	-11.34	32.4	63	0	5	☑
23	15:41:33	3	14.69	-0.55	-10.55	1.34	32.4	64	0	5	☑

24	15:41:48	4	10.16	-16.52	-15.12	11.34	32.5	64	0	4	☑
25	15:42:04	5	10.86	5.67	1.46	6.71	32.4	65	0	5	☑
26	15:42:19	0	9.82	0.55	9.09	1.95	32.4	66	0	2	☑
27	15:42:34	5	12.68	13.6	13.48	5.3	32.4	67	0	5	☑
28	15:42:50	2	15.01	-0.61	-2.56	11.83	32.4	68	0	5	☑
29	15:43:07	3	10.78	-4.94	2.68	15.12	32.4	70	0	3	☑
30	15:43:23	5	10.3	-1.28	4.21	4.63	32.4	71	0	5	☑
31	15:43:39	5	11	7.56	-8.9	8.23	32.4	72	0	5	☑
32	15:43:57	0	9.78	-36.83	-24.15	-1.52	31	70	0	5	☑
33	15:44:13	4	9.83	-1.71	0.55	1.4	23.3	95	0	4	☑
34	15:44:29	0	9.83	-1.4	0.85	1.59	28.1	95	0	1	☑
35	15:44:45	0	9.81	-1.04	0.73	1.71	28.1	95	0	1	☑
36	15:45:00	0	10.05	4.33	-1.65	2.93	28.3	95	0	1	☑

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