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IoT-Based intelligent system for headwater phenomenon detection and alerts using ESP32

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ABSTRACT

Headwater phenomena, characterised by rapid increases in river levels and flow velocity, pose significant risks to downstream communities. This study presents an Internet of Things (IoT)-based intelligent monitoring and alert system for detecting headwater phenomena in real time. The proposed system integrates multiple ESP32 microcontrollers with water level and rainfall sensors to monitor environmental parameters continuously. Data are transmitted to Firebase for cloud storage and further processed using Google Sheets for visualisation and analysis. A decision-making algorithm correlates rainfall intensity with water level changes to classify potential hazards and trigger appropriate alerts. Notifications are issued through an LCD display, buzzer, and Telegram alerts, ensuring timely responses. The system enhances early warning capabilities, minimises damage risks, and improves public safety in flood-prone regions. The integration of cloud computing and IoT technology ensures real-time monitoring, remote access, and automated data-driven decision-making. Experimental results demonstrate the system's effectiveness in accurately detecting and responding to headwater-related hazards, making it a viable solution for disaster preparedness and mitigation.

1. INTRODUCTION

The media frequently highlights tragic cases of individuals drowning or going missing due to sudden rises in river levels and swift currents. These events are often associated with the headwater phenomenon, where a rapid increase in water level and flow velocity in the upper sections of a river create serious risks for those downstream. Various factors, such as heavy rainfall, flash floods, landslides, dam breaches, and glacial lake outbursts, can contribute to this phenomenon [1]. One of the few cases that caused extensive damage was

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the flash floods and headwater event that occurred in Kedah's Yan district due to heavy rain in the highland areas covered by Bernama, 2021 [2] . In addition, the Ulu Bendul Recreational Forest, located along the Linggi River in Negeri Sembilan, is a key area where effective monitoring is essential. Unexpected shifts in the river's characteristics necessitate advanced monitoring systems to predict and respond to headwater events efficiently [3].

Headwater phenomena pose serious risks to communities, especially those living near rivers and vulnerable areas. The main challenges include the lack of monitoring systems and early warnings to alert nearby residents, leaving them unprepared for potential dangers. There is also no real-time measurement of rainfall and river levels, which are essential for accurate monitoring. Additionally, the relationship between rainfall and river levels is also insufficiently analysed, making it harder to predict and respond effectively. A system capable of monitoring these events and delivering early warnings is critical for enhancing safety [4]. An Internet of Things (IoT) based real-time monitoring system, integrated with multiple sensors such as water level sensors, is proposed as an effective solution for assessing and monitoring headwater characteristics [2].

This study aims to develop an IoT-based monitoring and warning system that tracks headwater conditions, such as rainfall and water levels in real-time as shown in Fig. 1. The system will also provide early warning through sirens and Telegram notifications to security guards or officers, enabling them to take timely action in affected areas. Additionally, the system will include a user-friendly dashboard that displays real-time data and alerts, allowing officers to monitor the conditions remotely. Google Apps Script and Firebase will be employed to store and analyse the collected data in Google Sheets, improving data automation and its overall utility [5]. This proactive approach will enhance response times, minimise potential damage, and improve overall safety in regions vulnerable to flooding or other water-related hazards.

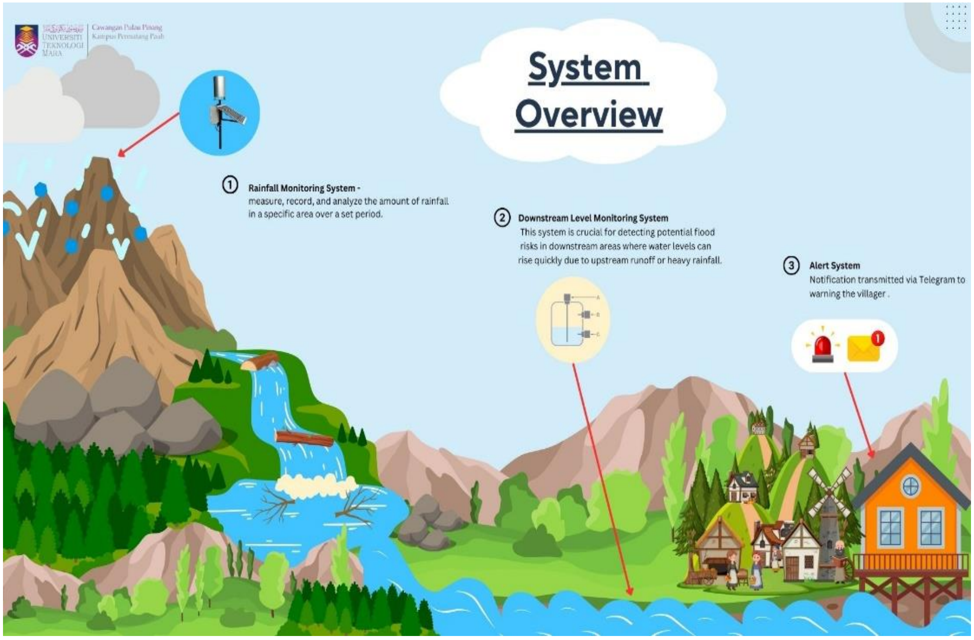

Fig. 1. System overview

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2. LITERATURE REVIEW

Early warning systems for floods have been widely developed, but studies on headwater detection remains limited. Existing flood monitoring systems, such as InfoBanjir [6], Flood Alert Notification System (FANoS) [7], and Flood Warning and Monitoring System (FWMS) [8].

The InfoBanjir website [6], developed by the Hydrology and Water Resources Division under Malaysia's Irrigation and Drainage Department (DID), serves as a comprehensive flood monitoring platform. It provides real-time data on flooded areas and rainfall statistics. The system relies on rainfall and water level sensors, which are placed in remote locations to collect data. This information is automatically transmitted to the Ministry of Agriculture, where it is processed by the DID National Flood Monitoring Center. Once analysed, the data are published online to keep the public informed about flood conditions.

The Flood Alert Notification System (FANoS) [7] operates using two main components, which are the detection system and the action system. The detection system includes flood sensors that monitor three water levels: Level 1, Level 2 and Level 3. When the water reaches Level 3, the flood sensors trigger the microcontroller, activating the action systems. The system then displays the river status on an LCD screen, turns on a red LED indicator, and activates a siren to warn residents. Additionally, an SMS alert is sent to notify people of the critical flood level.

The Flood Warning and Monitoring System (FWMS) [8] is another flood detection system that uses GSM technology to send alerts to users and authorities when water levels rise. FWMS is built using an Arduino Uno microcontroller, ultrasonic sensor (HC-SR04), and a GSM SIM900A module. This system allows users to check flood status via SMS and receive automatic warnings when water reaches critical levels. The system has three alert levels: normal, warning, and danger. At the warning levels, users receive an SMS notification, while at the danger level, both an alarm and SMS are activated. Additionally, FWMS sends alerts to the Fire and Rescue Department to ensure a quick response in emergencies.

While these systems are effective in general flood detection, they are not designed to detect sudden headwater surges, which require faster response times and more localised monitoring. To improve the headwater monitoring, research has proposed the Headwater Phenomenon Warning and Monitoring System (HWMS) [4], which uses water level and moisture sensors connected to a Raspberry Pi to provide real-time updates. This IoT-based system was developed to replace the manual monitoring method used by the Forestry Department and to help reduce risks associated with sudden headwater events. HWMS enables real-time water level monitoring, allowing users to check river conditions before visiting. The system provides updates on headwater occurrences, helping users and staff track trends and patterns of the phenomenon.

Similarly, Affandi et al. [9] developed an ESP32-based Early Warning System for Headwater (EWSH). This system is designed to detect and monitor sudden increases in river water levels, which can lead to dangerous headwater events. The system is built using an ESP32 microcontroller and incorporates ultrasonic, turbidity, and water flow sensors to continuously track changes in water conditions. When the water level rises beyond a critical threshold, the system triggers alarms and LED warning lights to alert people nearby. It transmits real-time data to ThingSpeak, an IoT analytics platform, where users can monitor water conditions remotely. The system also utilized ThingTweet to send automatic alerts via Twitter, ensuring that the public and relevant authorities are quickly informed. This technology improves safety by providing early warnings that allow for timely evacuation and response to potential headwater surges.

Headwater events remain a serious threat due to their sudden and unpredictable nature. While existing monitoring systems have improved early detection, they still face challenges in accurately predicting rapid

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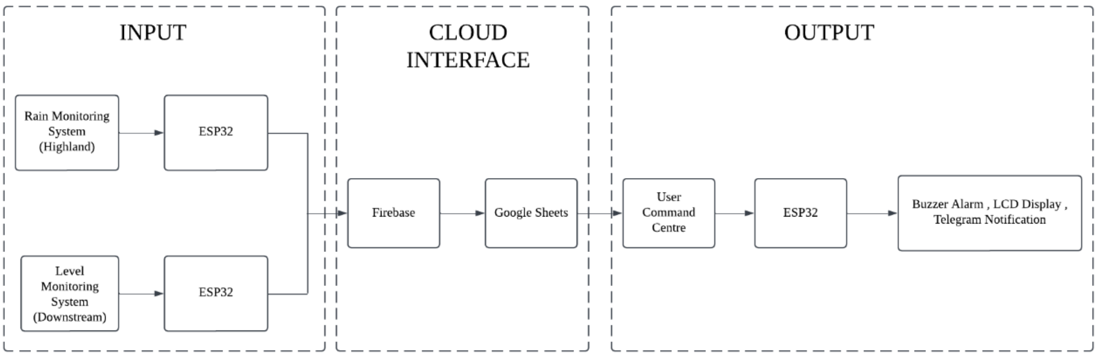
water surges. Advancements in IoT technology and real-time monitoring are essential to develop a more effective and reliable warning system for headwater events.

3. METHODOLOGY

3.1 System design

This project utilises three ESP32 microcontrollers to measure rainfall intensity and monitor water flow from the highlands to the downstream areas to identify headwater. The system block diagram is displayed in Fig. 2. The user interface is managed by one ESP32, which notifies villagers or visitors by turning on an LED buzzer and displaying alarm information on an LCD. The remaining two ESP32s, placed in the highland and the downstream areas, form the core of the detection system. This system provides a comprehensive solution for water level monitoring and early warning, enhancing safety and raising awareness of headwater phenomena.



Fig, 2. System block diagram

As the project's main controller, the ESP32 microcontroller receives data from the water level (limit switches) and rain gauge sensors and transmits it to the cloud (Firebase) together with real-time data. This setup enables data analysis and remote monitoring. To warn villagers or tourists about possible headwater occurrences, another ESP32 displays information alerts on an LCD and activates the buzzer and LED. Overall, the ESP32s ensure smooth communication, real-time monitoring, and timely notifications for efficient headwater detection.

Google Sheets is used in this project as a platform for data analysis and visualisation. In a cloud-based spreadsheet, it displays the timestamp, rainfall status, water level status, and decision after reading data from Firebase. Furthermore, by reading rainfall and water level data, Google Sheets makes it easier to detect headwater occurrences and to monitor and analyse data by observing variations in rainfall intensity in highland and water level downstream. This helps users monitor the level of safety for visitors and locals around the river.

The ESP32 devices at the highland and downstream locations provide data to Firebase. It monitors the timing of changes in the water level and collects data from the switches. The headwater detection system's data transmission and storage are made smooth by sending this data to Google Sheets for additional analysis and visualisation.

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3.2 System flowchart

In modern environmental monitoring systems, real-time data acquisition and cloud integration play a crucial role in ensuring efficient decision-making. Referring to Fig. 3, this system is designed to monitor rainfall and water levels while providing users with a centralised command interface.

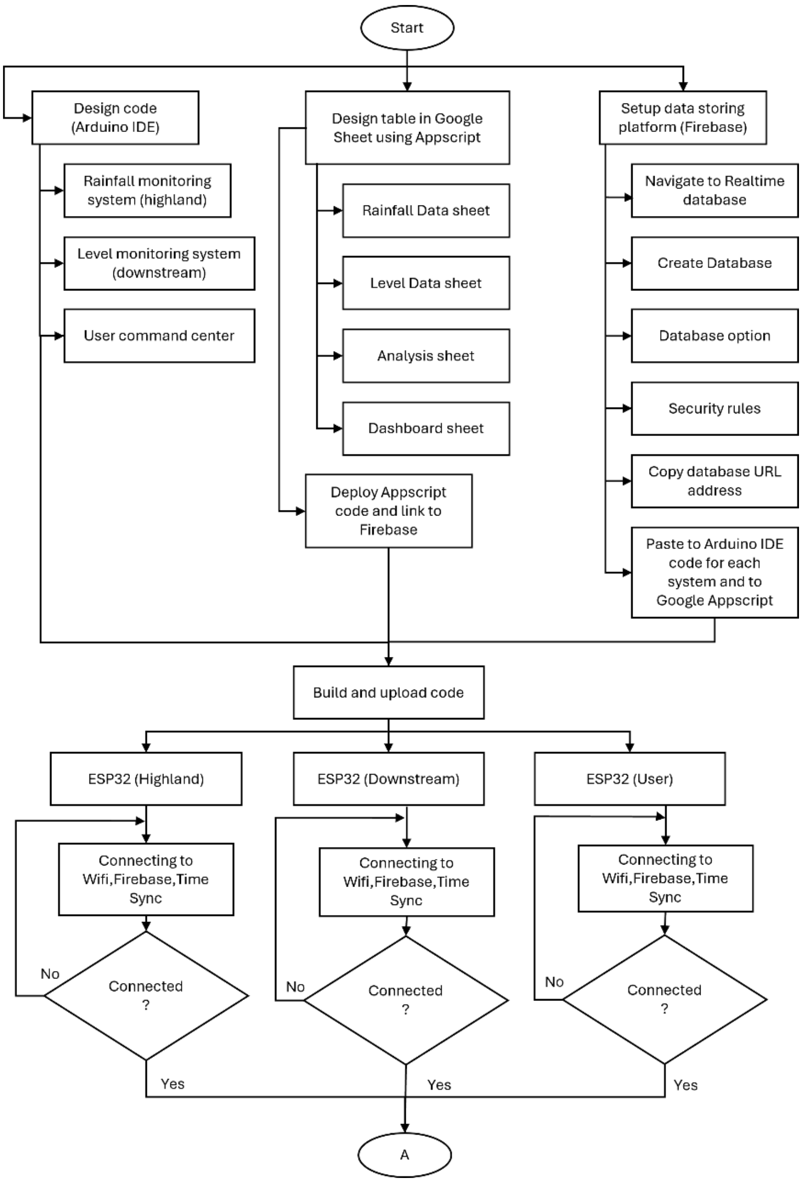

Fig. 3. System initialisation flowchart

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The system begins with the setup and initialisation phase, where the required code for three subsystems—Rainfall Monitoring System (Highland), Water Level Monitoring System (Downstream), and the User Command Centre—is developed using Arduino IDE. Simultaneously, a Google Sheet is designed using Apps Script to store data in various sheets, including Rainfall Data, Water Level Data, Analysis, and Dashboard. To manage real-time data storage and retrieval, Firebase is set up by creating a database, configuring security rules, and obtaining a database URL. This URL is then embedded into both the Arduino IDE code for the ESP32 devices and the Google Apps Script to enable seamless integration between hardware and cloud-based data storage.

Once the setup is complete, the firmware is compiled and uploaded to the ESP32 microcontrollers, each responsible for different monitoring tasks. The ESP32 (Highland) monitors rainfall, the ESP32 (Downstream) tracks water levels, and the ESP32 (User Control System) processes alerts and notifications. After the code is deployed, each ESP32 device attempts to establish a connection to WiFi, Firebase, and a time synchronisation server. If the connection is successful, the system proceeds with data collection; otherwise, it retries until a stable connection is established.

In the data collection phase, real-time monitoring begins. The ESP32 (Highland) measures rainfall intensity using a tipping bucket rain gauge equipped with a Hall Effect Sensor (A3114). Every tip of the bucket represents 0.70 mm of rainfall, and each tip triggers a signal recorded and sent to Firebase. Simultaneously, the ESP32 (downstream) monitors water levels using switch sensors (SW1, SW2, and SW3). When any of these switches are activated, the system registers a water level change and logs the data. At the same time, the ESP32 (User Control System) reads decision data from Google Sheets to assess whether an alert condition has been met.

If an alert condition is triggered, the system evaluates changes in rainfall intensity and water level. When a significant change is detected, the User Command Centre takes action by updating the LCD display, activating a buzzer, and sending a Telegram notification to alert relevant users. This ensures that users are informed of potential hazards, such as flooding or upstream blockages.

Throughout the process, the system continuously monitors the ESP32's connectivity to Firebase, ensuring that all devices stay online. All collected data is stored in Firebase and Google Sheets for real-time access and further analysis. If a disconnection occurs, the system attempts to reconnect automatically. Once a data collection cycle is completed, the updated information is logged in the respective Google Sheets, enabling ongoing monitoring and trend analysis.

The system operates continuously in a real-time loop, ensuring that rainfall and water level changes are monitored efficiently. By leveraging IoT-based solutions, this system provides an automated, cloud-connected, and highly responsive approach to headwater phenomenon monitoring, enhancing early warning capabilities for potential floods or upstream blockages.

This explanation is based on the flowchart depicted in Fig. 4, which illustrates the seamless integration of hardware, software, and cloud-based systems to achieve real-time monitoring and alerting for headwater phenomena. Fig. 3 effectively captures the workflow and interactions between the ESP32 devices, sensors, and cloud platforms, ensuring a robust and reliable monitoring system.

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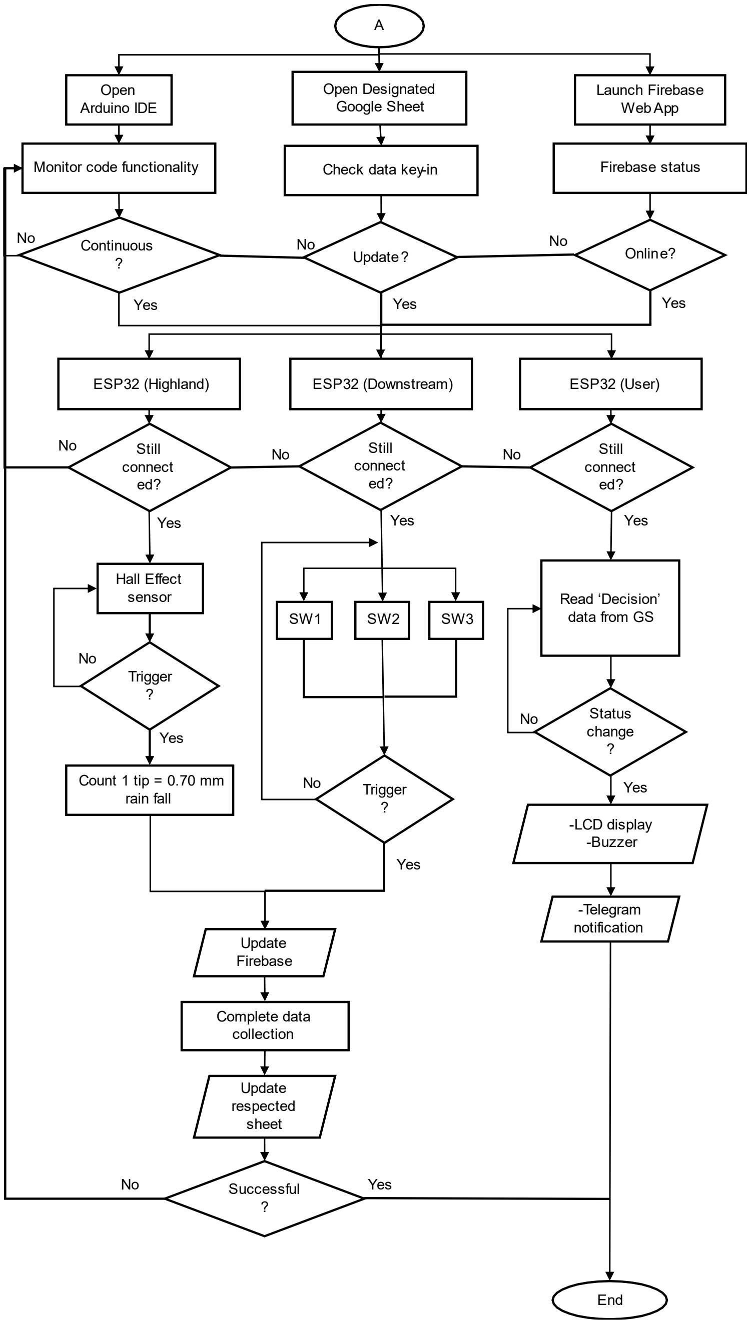

Fig. 4. Overall system's flowchart

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3.3 Rainfall monitoring system design

Fig. 5 shows the system's prototype, designed to measure rainfall and rainfall intensity using a tipping bucket rain gauge mechanism. This prototype follows the same measurement principle as commonly used tipping bucket rain gauges in the market, ensuring compatibility with existing systems. The primary goal of this design is to create a user-friendly and widely integrable rainfall monitoring system that can seamlessly connect with various tipping bucket rain gauge models available in the industry.

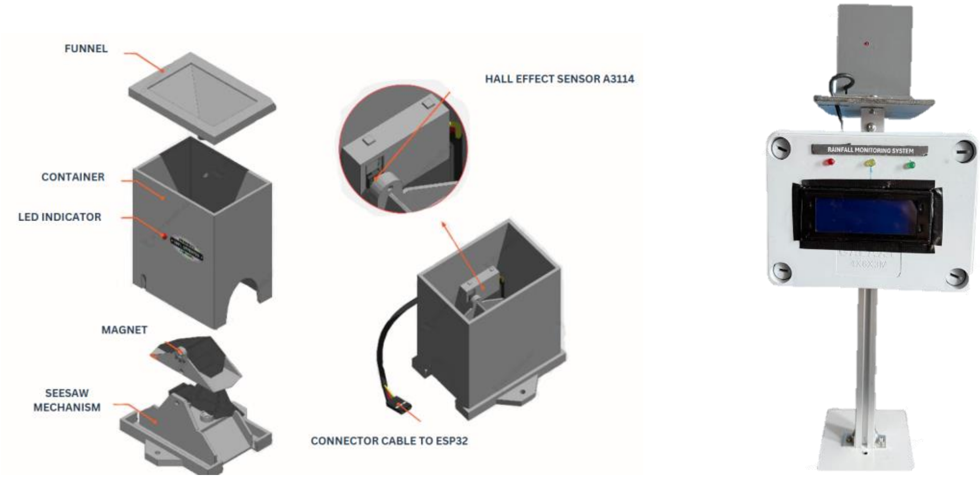

Fig. 5. (left) Rain gauge prototype design; (right) Rain monitoring system prototype

To achieve accurate rainfall measurement, the sensor is first calibrated to determine the amount of rainfall registered per tip. During the calibration process, a controlled volume of 100 mL of water is poured into the system, resulting in 70 recorded tips. By dividing the total volume of water by the number of tips, the calculated volume per tip is determined as follows (Eq. (1):

$$Rain\ volume\ per\ tip = \frac{100mL}{70\ tips} = 1.42mL/tip \tag{1}$$

Next, the corresponding rainfall per tip is calculated by dividing the volume per tip by the area of the prototype's funnel (collector). The area of the funnel is given in Eq. (2):

$$Funnel\ Area = 5.5cm \times 3.5cm = 19.25cm^2 \tag{2}$$

Since 1 mL = 1 cm^3, the rainfall per tip is calculated as in Eq. (3):

$$Rainfall\ per\ tip = \frac{1.42cm^3}{19.25cm^2} = 0.7mm/tip \tag{3}$$

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This means that each time the bucket tips due to accumulated rainwater, the system registers 0.7 mm of rainfall. The total accumulated rainfall is then calculated by multiplying the number of tips by this fixed value, ensuring an accurate record of total rainfall over time (Eq. (4)):

$$Total\ rainfall = (Number\ of\ tips) \times 0.7mm \tag{4}$$

Rainfall intensity, on the other hand, is calculated based on the time interval between consecutive tips. Each time the bucket tips, the system captures the timestamp and compares it with the previous tip to compute the rainfall intensity in mm per hour using the formula (Eq. (5)):

$$Rain\ intensity = \left(\frac{3600000}{Time\ difference\ between\ tips}\right) \times 0.70 \tag{5}$$

where 3,600,000 milliseconds (1 hour) are used to scale the value to an hourly rate. If rain falls at a high rate, the bucket tips occur more frequently, resulting in a higher intensity value. Conversely, if the time between tips is long, the calculated intensity will be lower.

The rainfall intensity thresholds in the system are predefined values set in the Arduino IDE using the #define directive as shown in Fig. 6. These thresholds categorise rainfall intensity into different levels to ensure accurate monitoring and timely responses. In the code, the ALERT_THRESHOLD is set to 500 mm/h, indicating the transition from light to medium rain, while the WARNING_THRESHOLD is set to 900 mm/h, marking the threshold for heavy rain. These values are based on standard meteorological classifications and practical observations of rainfall patterns.

```
// Rainfall intensity thresholds (mm/h)
#define ALERT_THRESHOLD 500.0
#define WARNING_THRESHOLD 900.0
```

Fig. 6. Predetermined rainfall intensity threshold in Arduino IDE.

To ensure the reliability of the rainfall monitoring system, a manual testing method is conducted using a syringe to simulate rainfall. This is necessary since the prototype is not yet ready for real-world application. This test is crucial in verifying the system's ability to measure rainfall accurately and transmit real-time data to the Firebase cloud. By using a syringe, the volume of water injected into the tipping bucket can be precisely controlled. Each tip of the bucket occurs when 1.4 mL of water is added, ensuring consistency in measurements.

To evaluate the system's response to different rain intensity classifications, the time interval between each water injection is varied. By controlling the speed at which water is added, the system can simulate different rainfall intensities. A longer interval between bucket tips corresponds to Light Rain, while shorter intervals result in Medium Rain or Heavy Rain, depending on the predefined intensity thresholds. This method thoroughly tests the system's classification logic, ensuring that the displayed rain status accurately reflects the expected conditions. Additionally, by monitoring the data transmission to Firebase, the test

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confirms that the system reliably updates real-time rainfall data, allowing for accurate remote monitoring and analysis.

Additionally, if no rain is detected for an hour (i.e., no tipping occurs for 3,600,000 milliseconds), the system automatically resets the intensity to 0 mm/h and updates the status to No Rain to ensure old data does not affect real-time monitoring.

The system continuously updates and displays total rainfall, intensity, and rain status on an LCD screen while also transmitting data to Firebase for cloud storage and remote access. The stored data includes the number of tips, total rainfall, intensity, and categorised rain status. This structured approach ensures real-time monitoring accuracy and responsiveness, allowing for timely alerts based on rain intensity levels.

3.4 Water level monitoring system design

Effective water level monitoring is essential for flood prevention and water resource management. This system utilises micro limit switches and ESP32 microcontrollers to detect and respond to changes in downstream water levels. Three sets of micro limit switches are used in the design of the downstream sensor poles in the headwater detection system, and each set is coupled to its corresponding ESP32 microcontroller, as illustrated in Fig. 7 [5].

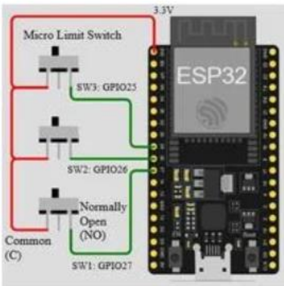

Fig. 7. Diagram of ESP32 connected to micro limit switch

These switches (SW1, SW2, and SW3) are used to monitor various water levels. The ESP32's 3.3V power supply is linked to the Common (C) terminal of each switch, while GPIO27, GPIO26, and GPIO25 are connected to their Normally Open (NO) terminals. The ESP32 reads HIGH when a switch that is activated by the water level shuts, enabling current to flow from the 3.3V supply to the corresponding GPIO pin. With this configuration, the ESP32 can monitor water levels, send the data to Firebase for cloud storage, and do additional processing, including making decisions about the amount of rain and changes in downstream water levels and notifying people via a buzzer, LED, and display.

The sensor prototype is seen in the Fig. 8 two pipes make up the design: a smaller inner pipe and a bigger outer pipe. Because it is supported by a roller system, the inner pipe can move and float freely inside the outer pipe. The inner pipe floats in accordance with the rising water level. With their levers pointing inward and positioned across from the inner pipe, three roller lever switches are mounted on the outer pipe. These switches serve as sensors to measure the river's water level, are progressively pushed as the inner pipe rises in tandem with the water level. To provide real-time monitoring and notify users via an LCD display, LED, and buzzer, the closed switches instruct the ESP32 microcontroller to read the water levels and transmit the information to Firebase.

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Fig. 8. Downstream sensor pole

3.5 User command centre system design

The system design for the user command centre, as shown in Fig. 9 integrates an ESP32 microcontroller, a buzzer, and an LCD display to provide comprehensive monitoring and emergency response capabilities. The LCD display acts as the primary interface, providing detailed and actionable information to the users. It displays the highland rainfall intensity, measured using a rain gauge, categorised into four levels: “No Rain,” “Light Rain,” “Medium Rain,” and “Heavy Rain”. Additionally, it presents downstream water levels classified into Level 0, Level 1, Level 2, and Level 3. The display further indicates the overall system status, ranging from normal to critical conditions, and provides actionable decision prompts such as "Normal," “Warning,” “Flood Alert,” “Clog Warning,” and “Evacuate,” based on the correlation between rainfall intensity and water levels. The buzzer is programmed with three distinct alert patterns to indicate varying levels of severity, with the fastest pattern representing the most critical conditions.

Fig. 9. Prototype of the user command centre system

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By consolidating all critical parameters into a single interface, the system ensures that command centre operators can monitor river conditions effectively, interpret alerts accurately, and implement timely and informed decisions. Fig. 10 and 11 illustrate the integration of these features, demonstrating the system's capability to enhance decision-making and risk mitigation.

Fig. 10. (left) LCD display clog warning condition; (right) LCD display warning condition

Fig. 11. (left) LCD display flood alert condition; (right) LCD display evacuate condition

3.6 Working principle

The working principle of the system is designed to monitor and track headwater conditions by correlating rainfall status and water level status to determine the appropriate decision promptly. The system utilises sensors to categorise rainfall into four distinct statuses: “No Rain,” “Light Rain,” “Medium Rain,” and “Heavy Rain,” while water levels are classified into four levels: Level 0, Level 1, Level 2, and Level 3. Based on Table 1 below by combining these parameters, the system delivers real-time updates on headwater conditions, displaying prompts on the LCD screen and recording them in Google Sheets.

When there is “No Rain” and the water level status is Level 0 or Level 1, the system identifies the condition as “Normal”, indicating safe headwater levels. However, if the water level rises to Level 2, the system issues a “Warning”, and at Level 3, it escalates to a “Flood Alert”, signaling significant risks. In “Light Rain” conditions, the system also maintains a “Normal” prompt for Levels 0 and 1, upgrades to a “Warning” at Level 2, and escalates to a “Flood Alert” at Level 3.

For “Medium Rain” the system begins to detect potential drainage issues. At Level 0, the system issues a “Clog Warning”, highlighting possible blockages in water flow. For Level 1, the system generates a “Warning” while Level 2 triggers a “Flood Alert”. At Level 3, the system recommends immediate evacuation with an “Evacuate” prompt, reflecting the dangerous rise in water levels. Similarly, during “Heavy Rain”, the system raises significant concerns about headwater overflow. At both Level 0 and Level

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1, a “Clog Warning” is issued due to drainage risks. For Level 2, the system advises immediate evacuation with an “Evacuate” prompt, and at Level 3, the “Evacuate” prompt remains active, emphasising the critical risk of severe headwater overflow.

Table 1. Table of rainfall and water level conditions with recommended actions

Rainfall	**Water Level**			
	Level 0	Level 1	Level 2	Level 3
No Rain	Normal	Normal	Warning	Flood Alert
Light Rain	Normal	Normal	Warning	Flood Alert
Medium Rain	Clog Warning	Warning	Flood Alert	Evacuate
Heavy Rain	Clog Warning	Warning	Evacuate	Evacuate

This systematic approach ensures accurate and timely tracking of headwater conditions, enabling users to respond effectively to evolving situations. From routine monitoring during "Normal" conditions to urgent evacuation measures during emergencies, the system provides a reliable tool for safeguarding the surrounding environment and communities from headwater-related hazards.

4. RESULT

Accurate rainfall monitoring is crucial for weather forecasting, flood management, and environmental analysis. This subsystem collects and analyses real-time rainfall data to classify rainfall intensity and provide meaningful insights.

The Rainfall Monitoring Collected Data in Fig. 12 for this sub-system tracks several key parameters, including Status, Intensity, Tips, and Rainfall (volume in millimeters). Real-time data in the Timestamp column will be synchronised with the time recorded in this monitoring data. The Rainfall Monitoring system will assess the level of rainfall based on these factors. Four different output types are available for this status: “NO_RAIN” for rainfall of 0 mm/h, “LIGHT_RAIN” for rainfall of 500 mm/h or less, “MEDIUM_RAIN” for rainfall of 500 mm/h to 900 mm/h, and “HEAVY_RAIN” for rainfall exceeding 900 mm/h.

The Water Level Monitoring Collected Data in Fig. 13 (left) for this sub-system monitors a few important parameters, including real-time synchronised data in column Timestamp, Water Level (height in cm), and Status. The Water Level Monitoring system will assess the level of water based on these factors. Four (4) different conditions of water level are available for this status: “NO_WATER” for a water level of 0cm to 71 cm, "LEVEL_1" for a water level of 72 cm to 83 cm, "LEVEL_2" for a water level of 84 cm to 95 cm, and "LEVEL_3" for a water level exceeding 96 cm. Fig. 13 (right) visualised that the relationship between the output status of the Rainfall Monitoring System and the Water Level Monitoring System.

The Headwater Phenomenon Monitoring and Detection System Alert is displayed in Fig. 12 which combines information obtained from the Rainfall Monitoring System and Water Level Monitoring System to evaluate operational states based on present conditions. The command center processes real-time data from both subsystems and evaluates their relationship to classify the situation into one of five possible status levels: Operational levels include “Normal” for stable conditions plus “Warning” for anticipated water level or rainfall changes followed by “Clog Warning” for blocked water flow reports and “Flood Alert” for water rise risks and “Evacuate” when serious floods require immediate evacuations. The command center uses this information to create reliable risk evaluations. After determining the risk status, the system transfers alerts automatically through Telegram to authorities along with the population, enabling prompt execution of preventive actions alongside response team deployments and evacuation strategies. Real-time flood monitoring aligned with automated status evaluation through efficient

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communication systems helps the Headwater Monitoring System create effectiveness. disaster preparedness alongside flood risk reduction (Fig. 14).

Timestamp	Tips	Rainfall	Intensity	Status
1/24/2025 8:52:53	1	0.7	0	NO_RAIN
1/24/2025 8:52:57	2	1.4	677.96606	MEDIUM_RAIN
1/24/2025 9:08:25	1	0.7	0	NO_RAIN
1/24/2025 9:08:29	2	1.4	556.16858	MEDIUM_RAIN
1/24/2025 9:08:36	3	2.1	394.11948	LIGHT_RAIN
1/24/2025 9:08:40	4	2.8	559.75122	MEDIUM_RAIN
1/24/2025 9:08:42	5	3.5	1452.44958	HEAVY_RAIN
1/24/2025 9:16:18	6	4.2	5.53163	LIGHT_RAIN
1/24/2025 9:16:47	7	4.9	86.31615	LIGHT_RAIN
1/24/2025 9:16:48	8	5.6	2079.20776	HEAVY_RAIN
1/24/2025 9:48:33	9	6.3	1.3226	LIGHT_RAIN
1/24/2025 10:08:02	1	0.7	0	NO_RAIN
1/24/2025 10:08:15	2	1.4	203.42267	LIGHT_RAIN
1/24/2025 10:08:19	3	2.1	661.59094	MEDIUM_RAIN
1/24/2025 10:08:19	4	2.8	3234.9165	HEAVY_RAIN
1/24/2025 10:17:41	1	0.7	0	NO_RAIN
1/24/2025 10:17:45	2	1.4	652.17389	MEDIUM_RAIN
1/24/2025 10:18:51	3	2.1	37.89189	LIGHT_RAIN
1/24/2025 10:26:40	4	2.8	5.37637	LIGHT_RAIN
1/24/2025 10:26:43	5	3.5	895.5224	MEDIUM_RAIN
1/24/2025 10:26:51	6	4.2	301.47147	LIGHT_RAIN
1/24/2025 10:36:30	7	4.9	4.35096	LIGHT_RAIN
1/24/2025 10:36:31	8	5.6	2153.84619	HEAVY_RAIN
1/24/2025 10:36:32	9	6.3	3076.9231	HEAVY_RAIN
1/24/2025 10:36:33	10	7	2055.46484	HEAVY_RAIN
1/24/2025 10:36:34	11	7.7	3000	HEAVY_RAIN
1/24/2025 10:36:35	12	8.4	2326.86987	HEAVY_RAIN
1/24/2025 10:36:36	13	9.1	3569.40503	HEAVY_RAIN
1/24/2025 10:36:37	14	9.8	3065.69336	HEAVY_RAIN
1/24/2025 10:36:39	15	10.5	1465.11621	HEAVY_RAIN
1/24/2025 10:39:57	16	11.2	12.7247	LIGHT_RAIN
1/24/2025 11:09:18	1	0.7	0	NO_RAIN
1/24/2025 11:09:20	2	1.4	1108.17944	HEAVY_RAIN
1/24/2025 11:24:57	3	2.1	2.68826	LIGHT_RAIN

Fig. 12. Rainfall Monitoring Collected Data

Timestamp	Water Level (cm)	Status
1/24/2025 8:51:56	84	LEVEL_2
1/24/2025 8:51:57	0	NO_WATER
1/24/2025 8:56:52	84	LEVEL_2
1/24/2025 8:56:59	0	NO_WATER
1/24/2025 11:08:35	84	LEVEL_2
1/24/2025 11:08:37	0	NO_WATER
1/24/2025 11:23:01	84	LEVEL_2
1/24/2025 11:23:03	96	LEVEL_3
1/24/2025 11:24:03	84	LEVEL_2
1/24/2025 11:26:45	84	LEVEL_2
1/24/2025 15:03:28	96	LEVEL_3
1/24/2025 15:03:30	0	NO_WATER
1/24/2025 15:19:27	84	LEVEL_2
1/24/2025 15:22:48	84	LEVEL_2
1/24/2025 15:22:50	0	NO_WATER
1/24/2025 15:22:53	70	LEVEL_1
1/24/2025 15:22:54	84	LEVEL_2
1/24/2025 15:34:12	70	LEVEL_1
1/24/2025 15:34:13	0	NO_WATER

	A	B	C	D
1	Timestamp	Rainfall Status	Water Level Status	Decision
2	2025-01-24 08:51:56	NO_RAIN	LEVEL_2	Warning
3	2025-01-24 08:51:57	NO_RAIN	NO_WATER	Normal
4	2025-01-24 08:52:53	NO_RAIN	NO_WATER	Normal
5	2025-01-24 08:52:57	MEDIUM_RAIN	NO_WATER	Clog Warning
6	2025-01-24 08:56:52	NO_RAIN	LEVEL_2	Warning
7	2025-01-24 08:56:59	NO_RAIN	NO_WATER	Normal
8	2025-01-24 09:08:25	NO_RAIN	NO_WATER	Normal
9	2025-01-24 09:08:29	MEDIUM_RAIN	NO_WATER	Clog Warning
10	2025-01-24 09:08:36	LIGHT_RAIN	NO_WATER	Normal
11	2025-01-24 09:08:40	MEDIUM_RAIN	NO_WATER	Clog Warning
12	2025-01-24 09:08:42	HEAVY_RAIN	NO_WATER	Clog Warning
13	2025-01-24 09:16:18	LIGHT_RAIN	NO_WATER	Normal
14	2025-01-24 09:16:47	LIGHT_RAIN	NO_WATER	Normal
15	2025-01-24 09:16:48	HEAVY_RAIN	NO_WATER	Clog Warning
16	2025-01-24 09:48:33	LIGHT_RAIN	NO_WATER	Normal
17	2025-01-24 10:08:02	NO_RAIN	NO_WATER	Normal
18	2025-01-24 10:08:15	LIGHT_RAIN	NO_WATER	Normal
19	2025-01-24 10:08:19	MEDIUM_RAIN	NO_WATER	Clog Warning
20	2025-01-24 10:17:41	NO_RAIN	NO_WATER	Normal
21	2025-01-24 10:17:45	MEDIUM_RAIN	NO_WATER	Clog Warning
22	2025-01-24 10:18:51	LIGHT_RAIN	NO_WATER	Normal
23	2025-01-24 10:26:40	LIGHT_RAIN	NO_WATER	Normal
24	2025-01-24 10:26:43	MEDIUM_RAIN	NO_WATER	Clog Warning
25	2025-01-24 10:26:51	LIGHT_RAIN	NO_WATER	Normal
26	2025-01-24 10:36:30	LIGHT_RAIN	NO_WATER	Normal
27	2025-01-24 10:36:31	HEAVY_RAIN	NO_WATER	Clog Warning
28	2025-01-24 10:36:32	HEAVY_RAIN	NO_WATER	Clog Warning
29	2025-01-24 10:36:33	HEAVY_RAIN	NO_WATER	Clog Warning
30	2025-01-24 10:36:34	HEAVY_RAIN	NO_WATER	Clog Warning
31	2025-01-24 10:36:35	HEAVY_RAIN	NO_WATER	Clog Warning
32	2025-01-24 10:36:36	HEAVY_RAIN	NO_WATER	Clog Warning
33	2025-01-24 10:36:37	HEAVY_RAIN	NO_WATER	Clog Warning
34	2025-01-24 10:36:39	HEAVY_RAIN	NO_WATER	Clog Warning
35	2025-01-24 10:39:57	LIGHT_RAIN	NO_WATER	Normal

Fig. 13. (left) water level monitoring collected data; (right) headwater phenomenon data analysis

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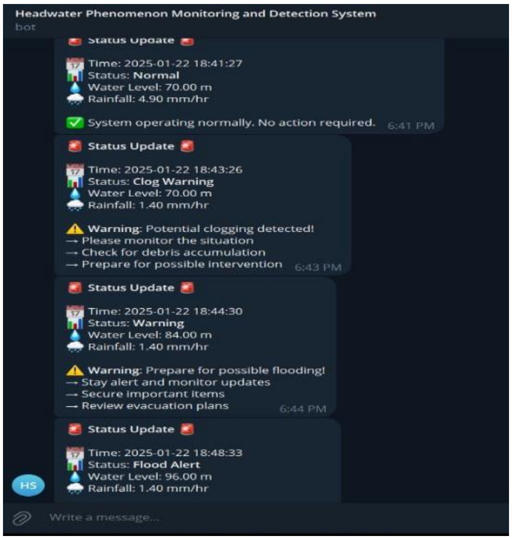

Fig. 14. Headwater phenomenon monitoring and detection system alert via telegram

Lastly, a simple real-time monitoring dashboard has been developed to provide an intuitive and efficient way for responsible personnel to track live data from both the Rainfall Monitoring System and the Water Level Monitoring System as shown in Fig. 15. This dashboard fetches data in real-time and displays it in user-friendly charts that clearly indicate the time and date of each status change. The Live Rainfall Trending Data chart visualises rainfall accumulation over time, while the Live Water Level Trending Data chart monitors changes in water levels.

By integrating these real-time updates, the dashboard allows users to quickly assess current conditions and detect potential risks. Any significant increase in rainfall or water level can be observed immediately, enabling early preparation and response to abnormal phenomena such as potential flooding. The straightforward visual representation enhances decision-making efficiency, ensuring that appropriate actions can be taken to mitigate risks in a timely manner.

In conclusion, the project has effectively developed a system for early detection and alerts of headwater phenomena by monitoring both rainfall intensity and water levels. The rainfall monitoring system utilises a Hall effect magnet sensor to measure precipitation by detecting each tip of the rain gauge, ensuring accurate rainfall data collection. Simultaneously, the water level monitoring system employs micro limit switches to detect changes in water levels, providing real-time updates on downstream conditions. These sensors work in conjunction with ESP32 microcontrollers, which process and transmit the collected data. Through Firebase, the system efficiently stores and organises information, while Google Sheets visualises the data, analyses the relationship between rainfall and water levels, and triggers alerts based on predefined conditions. Additionally, the user interface, featuring an LCD display and a buzzer, delivers immediate feedback and warnings for different danger levels, also sending the warning through applications such as Telegram. This integrated approach ensures precise and timely monitoring, enabling quick responses to potential headwater events and enhancing public safety. The seamless transmission of data and the efficient operation of the inner pipe mechanism further validate the project's effectiveness in addressing headwater-related challenges [5].

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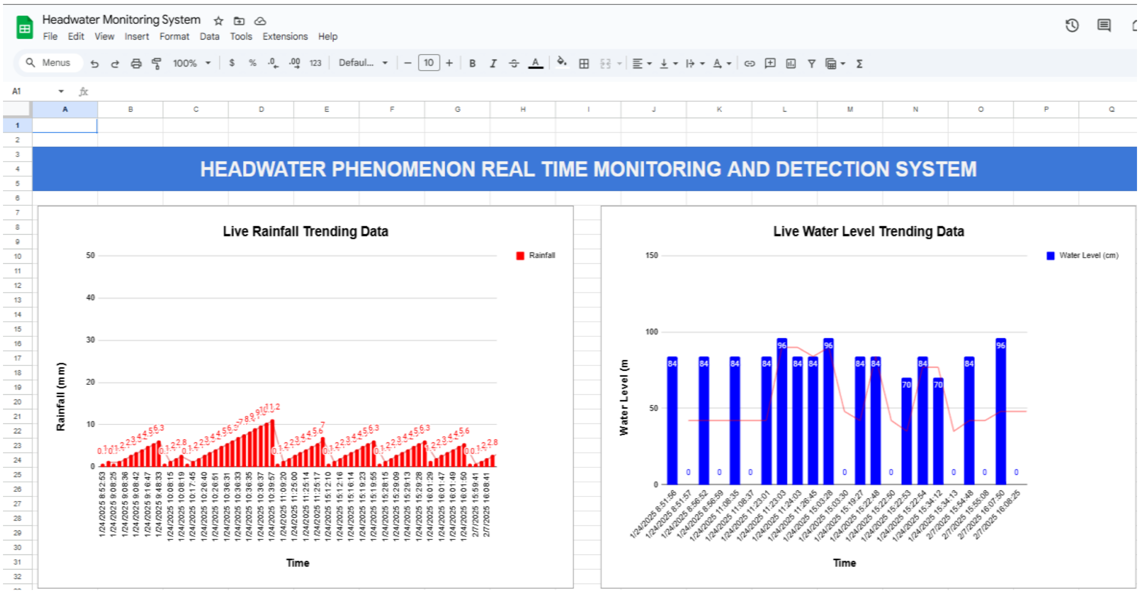

Fig. 15. Headwater phenomenon real time monitoring dashboard

5. CONCLUSION

An IoT-Based Intelligent System for Headwater Phenomena Detection and Alerts highlights an effective methodology for tracking rainfall intensity in real-time and assessing its connection to downstream water flow. The system implements three ESP32 microcontrollers to achieve unified data collection together with analytical processing and response capabilities. The system consists of two ESP32 microcontrollers, with one devoted to rainfall intensity measurement and another dedicated to downstream water level assessment. The third ESP32 operates as a controller that combines data from both systems and then sends processed measurements to a central database for final processing. Real-time data collection becomes efficient through the operational combination of sensors and both Firebase and Google Sheets storage platforms. Processed data shows the water flow relationship to rainfall intensity which helps produce early warning signals based on established safe levels. The LCD display works in conjunction with a buzzer in the user interface to both show immediate feedback and trigger alerts, which enable quick reactions when dealing with critical events.

This execution system successfully manages the problems created by high rainfall quantity and changing downstream water volumes. The system proves its effectiveness for public safety protection by providing precise environmental measurement capabilities and a robust warning system that reduces exposure to headwater hazards.

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7. CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper. The research was conducted without any commercial or financial relationships that could be construed as potential conflicts of interest.

8. AUTHORS' CONTRIBUTIONS

Nur Raihah: Conceptualisation, methodology, formal analysis, data collection, and writing—original draft; **Wan Izzat Hakimi**: Conceptualisation, methodology, hardware integration, experimental validation, and formal analysis; **Muhammad Adly Hisyam**: Data analysis, validation, software development, and result interpretation; **Afif Luqmanulhakim:** Conceptualisation, system design, writing review, editing, and validation. **Rozan Boudville:** Supervision, technical guidance, manuscript review, and final validation.

9. REFERENCES

[1] A. Radhika, G. Manochitra, K. Keerthanen, K. Mahendran, R. M. Kumar, and N. M. Sarath, "Low-cost IoT-based early detection of flood monitoring and alert system using GPS and GSM," 2022, p. 040007. Available: https://doi.org/10.1063/5.0108131

[2] M. A. H. Razian, H. A. Kadir, A. A. A. Muttalib, M. A. M. Razi, and B. S. K. K. Ibrahim, "Design of vibration and turbulence alert system for headwater phenomena," *J. Adv. Res. Appl. Mech.*, vol. 119, no. 1, pp. 174–192, Jul. 2024. Available: https://doi.org/10.37934/aram.119.1.174192

[3] A. A. M. Faudzi, M. M. Raslan, and N. E. Alias, "IoT-based real-time monitoring system of rainfall and water level for flood prediction using LSTM network," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1143, no. 1, p. 012015, Feb. 2023. Available: https://doi.org/10.1088/1755-1315/1143/1/012015

[4] M. A. M. Kameel et al., "A development of headwater phenomenon warning and monitoring system," in *Proc. 2020 IEEE 5th Int. Symp. Telecommun. Technol. (ISTT)*, IEEE, Nov. 2020, pp. 174–179. Available: https://doi.org/10.1109/ISTT50966.2020.9279394

[5] R. Boudville, J. B. M. Tapah, A. A. F. B. M. Yuzi, N. A. I. B. A. Johan, M. I. Bin Daing, and N. A. S. B. Aliastar, "Development of IoT-based headwater phenomenon monitoring and warning system," in *Proc. 2024 IEEE 14th Int. Conf. Control Syst., Comput. Eng. (ICCSCE)*, IEEE, Aug. 2024, pp. 232–236. Available: https://doi.org/10.1109/ICCSCE61582.2024.10696835

[6] "Laman Web Rasmi Public InfoBanjir." Available: https://publicinfobanjir.water.gov.my/?lang=en

[7] H. A. Kadir, M. H. A. Wahab, M. F. M. Mohsin, H. Hashim, H. bin Hashim, and A. N. bin A. Tajuddin, "Flood alert notification system (FANoS)," 2009. [Online]. Available: https://www.researchgate.net/publication/274458098

[8] N. M. Zain, L. S. Elias, Z. Paidi, and M. Othman, "Flood warning and monitoring system (FWMS) using GSM technology," 2020. [Online]. Available: https://jcrinn.com

[9] R. Affandi, Z. Omar, and M. F. Lee, "Development of the headwater early signs by using Internet of Things (IoT)," 2023. [Online]. Available: http://myjms.mohe.gov.my/index.php/ijear

https://doi.org/10.24191/esteem.v21iMarch.4936.g3086