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Development of a Sensor-Based Flood Early Warning System with Rainfall and Water Level Monitoring

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Abstract Floods are one of the most frequent and destructive natural hazards, with their intensity and frequency expected to increase under climate change and rapid urbanization. Accurate and timely detection of rainfall and rising water levels is crucial for reducing disaster risk at the community level. This study aims to develop a low-cost and sensor-based Flood Early Warning System (FEWS) that integrates a tipping-bucket rainfall sensor and an ultrasonic water level sensor with a web-based monitoring platform. The system was designed, implemented, and evaluated through calibration, sensitivity testing through accuracy analysis, and Root Mean Square Error (RMSE) calculation. Experimental results showed that the rainfall sensor achieved an average accuracy of 96% with an RMSE of 2.38, while the water level sensor demonstrated 100% accuracy with an RMSE of 0 under controlled testing conditions. These results confirm that both sensors can provide reliable measurements for real-time flood monitoring. The integration of rainfall and water level observations in a single system enhances the capacity for early detection, enabling rapid dissemination of alerts through online platforms. The findings highlight the feasibility of deploying affordable and flexible FEWS prototypes to strengthen disaster preparedness and resilience in flood-prone communities.

Keywords Flood, Early Warning System, Rainfall Sensor, Water Level Sensor, Monitoring

1. Introduction

The problem of climate change poses a threat to all aspects of human life, including social, economic, and environmental aspects, and determines its impact on human life in the future. This unprecedented global climate change phenomenon increases vulnerability to the impacts of climate change [1]. Climate change will have a significant impact on agriculture due to the increasing frequency of extreme weather events. Although the impact of climate change on the agricultural sector and its mitigation depends on the specific context and location, in general, developing countries are highly vulnerable to climate change [1], [2], [3]. Climate change affects energy production, vegetation, development, and water availability. Water availability is the resource most affected by climate change, as it is closely related to extreme hydrometeorological events such as droughts and floods [4].

Floods are among the most frequent and damaging natural hazards worldwide. The incidence of floods and their severity are increasing under changing climatic conditions and rapid urbanization [5], [6]. In an attempt to reduce loss of life and property, accurate and timely detection of flood-generating conditions, particularly intense rainfall and rising water levels in rivers or drainage channels, is essential. Traditional large-scale forecasting systems provide valuable regional forecasts but often lack the site-level resolution and real-time responsiveness required for community-scale early warning and local operational decision-making [7].

Site-level Early Warning Systems (EWS) that combine rainfall measurements with direct water-level sensing have proven effective for producing rapid alerts for flash floods and urban pluvial flooding. Hardware for such systems typically integrates rain gauges (tipping-bucket or weight-based), water-level sensors (ultrasonic, pressure transducers, float switches or optical methods), data-loggers/microcontrollers, and communication modules (GSM, LoRaWAN, or cellular IoT) to transmit observations to a cloud or local processing node [8].

Research related to flood management as a result of climate change was carried out by providing information on flood-prone areas using surface/remote sensing aerial mapping methods [9], [10]. This method is carried out by disaggregating statistical rainfall data and presenting ID-2D urban flood model data [10]. The information is surface mitigation through aerial mapping. This application will certainly be very helpful as information on disaster-prone areas, but sub-surface information related to environmental events is needed in real time. This real-time information is very important to be processed into early detection information for disaster events with a set threshold, so that people can save themselves. Sub-surface/ground-based monitoring for flood disasters has been carried out [11] and by measuring water levels, and through measuring water levels and rainfall [12]. However, there is a lack of integrated, low-cost, real-time monitoring systems at the community level. A monitoring system is very important for generating and disseminating timely warning information so that communities at risk can prepare and act quickly and appropriately to reduce danger or loss [13]. Laboratory performance assessments of low-cost sensors indicate that several off-the-shelf sensors can achieve consistent measurements under controlled conditions, but performance may deteriorate in field deployments due to environmental factors and installation variability [14]. However, robust validation protocols—including co-location with reference instruments and controlled lab bench tests—are still not consistently applied across published projects. Besides, few works present a full-stack validation where hardware performance, such as accuracy and sensor errors, is tested together to quantify the end-to-end system performance in realistic deployments.

This study aims to present a low-cost and flexible flood early warning system integrating rainfall and water level sensors with web-based monitoring for information dissemination, and to evaluate its performance. This study is limited in the laboratory performance in terms of sensitivity through accuracy and RMSE (Root Mean Square Error) tests.

2. Materials and Methods

The methodology of this study was designed to ensure that the development and evaluation of the Flood Early Warning System (FEWS) followed a systematic and replicable approach. A combination of rainfall and water level sensors was employed to provide real-time monitoring of flood-inducing parameters. The research framework consists of system design and development, followed by laboratory testing and performance validation. The evaluation process included calibration, sensitivity testing through accuracy analysis, and Root Mean Square Error (RMSE) calculation to determine the reliability of the sensors under experimental conditions. This structured methodology provides a comprehensive basis for assessing the capability of the proposed system to deliver timely and accurate flood warnings at the community level.

2.1. System Design and Development

The Early Warning System for flood consists of two primary sensing modules, i.e., a rainfall sensor and a water level sensor. The rainfall sensor is a tipping-bucket rain gauge, which was selected for rainfall measurement due to its established performance and ease of calibration. The device was housed in an aluminium enclosure to ensure durability under tropical conditions. Meanwhile, the water level sensor is an ultrasonic sensor that was employed for non-contact measurement of water level. The sensor was mounted above the water surface and protected with an aluminium casing to prevent mechanical damage and minimize temperature-related drift. The design of the system is shown in Figure 1.

Figure 1 shows the system design of flood EWS. The technology is a flood monitoring prototype consisting of a Mounting Unit, Power Unit, Controller Unit, and Sensor Unit. This product is a stand-alone client device in the form of a station with a solar-powered stand-alone power supply equipped with sensors and an online server hosted on a cloud server. The sensors used in the flood monitoring system are a rainfall sensor and a water level sensor. The rainfall sensor is made with a tipping bucket model or a water container. The water level sensor is based on the principle of emitting high-frequency sound waves toward the water surface and measuring the time required for the waves to return after being reflected. Data from the sensor is processed in a Raspberry Pi microcontroller and sent in real-time to the server with a website address. The data will be displayed on a 7” TFT screen.

Figure 2 shows the flood EWS developed in the research. The rainfall sensor type is a reed switch, and the water level sensor works based on detecting the level of water from the sensor. Both sensors have an RS-485 interface. The integration between the sensor and the monitoring website will produce an information display on the website monitoring at www.ewsbanjir.ewspolines.com, accessible via a device or computer connected to the internet. This prototype is equipped with a siren to provide warnings to the public (Figure 3).

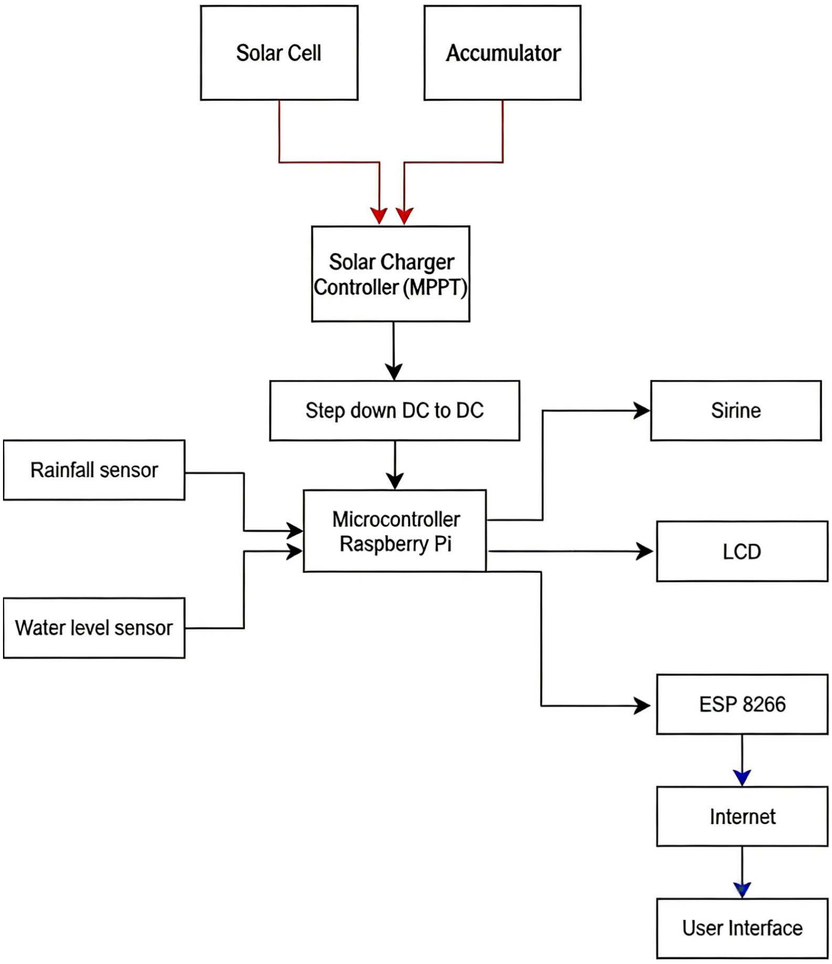
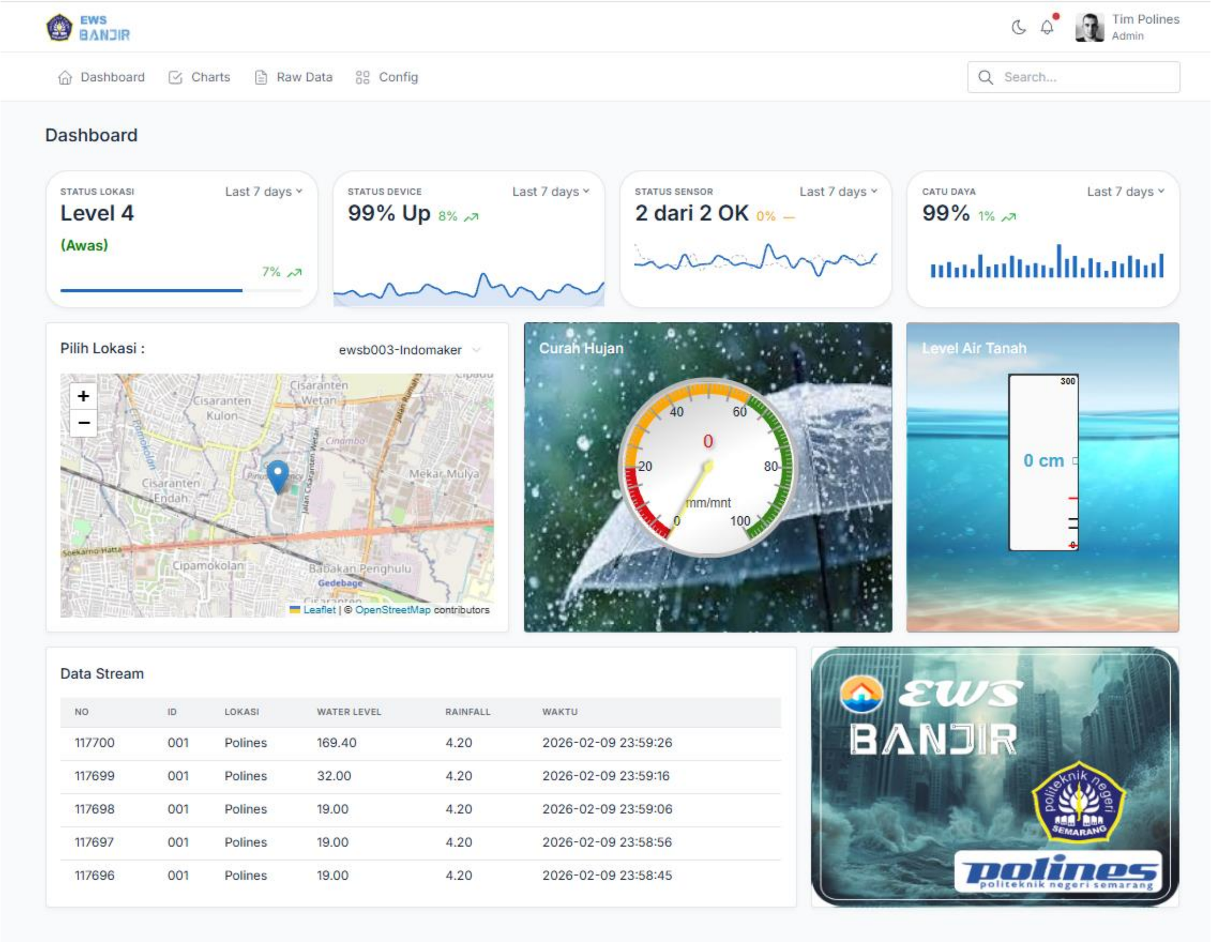


Figure 1. System Design

Figure 2. Flood EWS Development



Data Stream

NO	ID	LOKASI	WATER LEVEL	RAINFALL	WAKTU
117700	001	Polines	169.40	4.20	2026-02-09 23:59:26
117699	001	Polines	32.00	4.20	2026-02-09 23:59:16
117698	001	Polines	19.00	4.20	2026-02-09 23:59:06
117697	001	Polines	19.00	4.20	2026-02-09 23:58:56
117696	001	Polines	19.00	4.20	2026-02-09 23:58:45

Figure 3. Website Monitoring

Figure 3 shows the Flood Early Warning System (FEWS) website, which serves as a centralized monitoring and visualization platform for real-time flood-related data. The dashboard integrates rainfall intensity, water level measurements, device status, and location information to support early warning and decision-making processes.

2.2. Laboratory Testing and Performance Validation

The evaluation conducted in this study involved a sensitivity test, supported by accuracy analysis and Root Mean Square Error (RMSE) calculation to validate the performance of the system. Sensor sensitivity testing aims to evaluate the sensor's ability to detect any changes and ensure proper and accurate sensor function. Rainfall sensor sensitivity testing involves creating artificial rainfall of varying intensity to observe the sensor's response and comparing the sensor's output with manual rainfall measurements. Artificial rainfall was generated without the use of a nozzle by maintaining a steady water flow from a tap. The flow rate was kept constant during each measurement cycle and was only adjusted between cycles to produce different rainfall intensities. For each rainfall intensity level, the water flow was first adjusted from the tap opening, allowing the flow to reach a steady state. Then, the rainfall intensity was measured manually and subsequently recorded by the rainfall sensor under identical flow conditions. To generate a different rainfall intensity, the tap opening was adjusted slightly to increase the flow rate, and the same procedure—manual measurement followed by sensor measurement—was repeated. This approach ensured that manual and sensor measurements were obtained under the same flow velocity and water delivery conditions, allowing the manual calculation to serve as the ground truth reference under controlled laboratory settings.

The water level sensor also compared manual readings with the sensor's readings. The higher the percentage, the better the sensor's accuracy. The accuracy was measured using (1).

$$\text{Accuracy (\%)} = 100\% - \text{Error rate (ER)} \qquad (1)$$

The error rate was measured using (2).

$$\text{ER} = |\text{Observed value–Actual Value}|/\text{Actual Value} \times 100 \qquad (2)$$

Meanwhile, the calculation of RMSE was measured using (3).

$$\text{RMSE}=\sqrt{\left(\sum_{I=1}^{N}(\hat{y}i-yi)\right)^2/n} \qquad (3)$$

where $\hat{y}i$ is the predicted value and yi is the observed value.

Figure 4. Setting of Rainfall Sensor Test

Figure 4 shows the setting of rainfall sensor test, i.e. the accuracy testing which was performed by calculating the sensor's mm/tick. Accuracy testing of the rainfall sensor was performed by calculating the sensor's mm/tick. Accuracy testing was performed using the following method: 1) The same water flow rate (from the tap) was measured using a 100 ml measuring cup, 2) The water flow was transferred to the measuring cylinder, and the volume and time were recorded using stopwatch, 3) The resulting volume per time was converted to mm^3/10 minutes, 4) The mm^3 units were converted to mm by dividing by the area of rainfall sensor diameter i.e. d = 16 cm (phi d^2/4), 5) The final rainfall units were now mm/10 minutes, 6) The experiment was conducted 2-3 times to determine the consistency of the flow, 7) The same flow rate was measured with the rainfall sensor and waited for 10 minutes, 8) The results of the manual measurements and the rainfall sensor were compared, 9) The second and subsequent experiments were conducted in the same manner, gradually increasing the water flow rate. The tests on the rainfall sensor also evaluate its performance in terms of the amount of collected rain in millimeters per tick (mm/tick).

Figure 5. Setting the Accuracy Test of the Water Level Sensor

Figure 5 shows that the water level sensor test was performed by comparing manual measurements with sensor readings. This test is performed from 0 to 25 cm in 5 cm intervals. The manual measurement used the actual calculation using a measuring tape.

3. Results

Before presenting the results, it is essential to highlight that the proposed *Flood Early Warning System (FEWS)* was developed and tested through a series of systematic procedures, including sensor calibration and sensitivity test through accuracy and RMSE evaluation. Data obtained from the rainfall and water level sensors were compared with the reference of manual measurements. Furthermore, the sensitivity of the system was examined through accuracy assessment and Root Mean Square Error (RMSE) analysis. The following section presents the experimental findings and discusses their implications in the context of early flood detection and disaster risk reduction.

3.1. Accuracy

In rainfall sensors, "tick/mm" or "tip/mm" refers to the number of **tipping buckets** that tip for every millimeter of collected rainfall. Table 1 shows the result of evaluating the tick/mm of the rainfall sensor developed.

Table 1. Evaluation of Rainfall Sensor’s Tipping Bucket

ml	mm^3	Sensor area	mm/tick
6.5	6500	314 cm^2	0,2
		31.400 mm^2	

Table 1 shows that the rainfall sensor has a tipping bucket calculation of 0.2 mm/tick. This result was obtained from the first tick; the water that poured out, measured with a measuring cup, amounted to 6.5 ml. By calculation, with a sensor diameter of 20 cm, the sensor's area was 314 cm^2 or 31,400 mm^2 Then, 6.5 ml was converted to mm^3 giving 6,500 mm^3 Next, the volume/area was calculated, yielding a value of 6,500 mm^3 divided by 31,400 mm^2 resulting in 0.2 mm^2 This means that the rainfall sensor has a tipping bucket specification of 0.2 mm/tick. It means when a bucket fills with a specific amount of rain, 0.2 mm, its weight causes it to tip, emptying its contents and moving a fresh bucket into position to collect more rain.

The test of the accuracy of the rainfall sensor was conducted 3 times to collect the average value of accuracy. The result is shown in Table 2 and picturized in Figure 6.

The results of the rainfall sensor accuracy test with 3 trials obtained an average accuracy of 96%.

Table 3 shows the water level sensor results of the experiment. The results of the water level sensor accuracy test obtained a measured accuracy of 100% under controlled conditions.

Table 2. Accuracy of Rainfall Sensor

Experiment	Sensor reading (mm/10 min)	Manual Calculation	Accuracy (%)
I	80	82	97
II	60	63	95
III	90	88	97

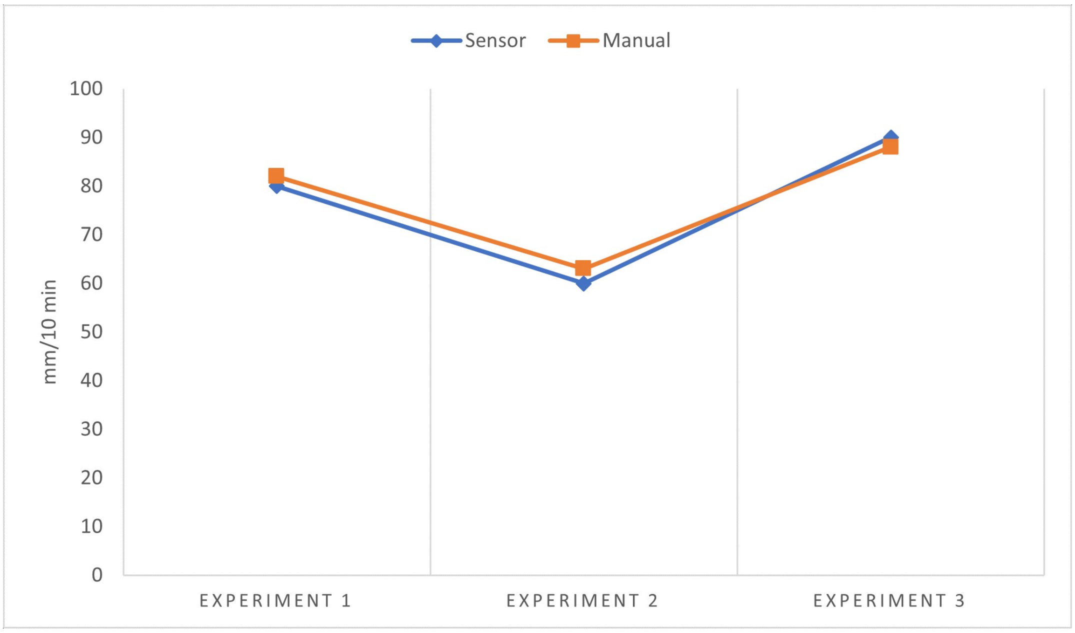


Figure 6. Rainfall Sensor Accuracy

Table 3. Accuracy of Water Level Sensor

Manual Measurement (cm)	Detection of Sensor (cm)
0	0
5	5
10	10
15	15
20	20
25	25
Accuracy	100%

3.2 RMSE

To ensure the reliability of the proposed *Early Warning System (EWS)*, a quantitative evaluation was performed by comparing sensor measurements with reference data. The Root Mean Square Error (RMSE) was employed as the primary statistical indicator to assess the accuracy of both the rainfall and water level sensors. RMSE provides an effective measure of the deviation between observed values and reference measurements, where lower values indicate higher precision. In this study, RMSE analysis was conducted separately for rainfall intensity and water level data to validate the performance of each sensor under field conditions. For the rainfall intensity, the value of the readings, either from sensor or manual calculation, was converted to mm/hour. Therefore, the results are as shown in Table 4.

Table 4. Conversion of Rainfall Intensity Unit

Sensor reading		Manual calculation	
mm/10 min	mm/hour	mm/10 min	mm/hour
80	480	82	492
60	360	63	378
90	540	88	528

The results of RMSE for rainfall and water level sensors are shown in Table 5.

Table 5. Results of RMSE

Sensor Statistics	Rainfall	Water level
Sample size (n)	3	6
Unit	mm/hour	cm
Mean error	−6.0	0
Standard deviation	15.87	0
RMSE	14.28	0
95% CI mean error	[-45.4, 33.4]	[0,0]

According to Table 5, the statistical analysis was performed using paired sensor and manual rainfall intensity data (n = 3). The mean error was −6.0 mm/hour with a standard deviation of 15.87 mm/hour. The RMSE value was 14.28 mm/hour, indicating relatively low deviation under extreme rainfall intensity conditions. The 95% confidence interval for the mean error ranged from −45.4 to 33.4 mm/hour, reflecting the limited sample size and laboratory-based nature of the experiment. Meanwhile the statistical analysis of the water level sensor was conducted using six paired observations (n = 6). The sensor readings showed very high agreement with manual measurements across all tested levels. The RMSE of the water level sensor was below the detectable resolution of the instrument and can be considered negligible under controlled laboratory conditions. Further validation under field deployment scenarios is required to assess performance under dynamic water surface conditions.

4. Discussion

The experimental results demonstrate that the developed Flood Early Warning System (FEWS) achieved satisfactory measurement performance. The rainfall sensor obtained an average accuracy of 96% with an RMSE of 14.28 mm/hour, while the water level sensor achieved 100% accuracy with an RMSE of 0 cm. These values indicate that the system can provide reliable hydrometeorological data for real-time flood monitoring and early warning.

The rainfall sensor results are comparable to previous studies using tipping-bucket rain gauges in field deployments. For example, Dunn et al. [15] reported that the tipping bucket rain gauge is widely used for climate change. However, the device is susceptible to errors that affect the trends and lead to the mismanagement of disasters due to a multitude of errors by 5–40% [16]. Similarly, Arno et al. [17] found that tipping-bucket sensors, although sensitive to high-intensity rainfall and mechanical limitations, still achieved accuracy above 90% after calibration. These findings confirm that the error observed in this study is consistent with the expected performance of low-cost rainfall monitoring systems.

The water level sensor showed near-perfect accuracy, with no deviation between manual and sensor readings within the 0–25 cm range tested. Comparable results were obtained by Pereira et al. [18], who reported that the combination of Arduino and ultrasonic sensor obtained an error of <0.020 m, which indicates that the measurement is valid. Recent advancements in ultrasonic-based sensing technologies further confirm their robustness for flood monitoring applications, especially when protected against environmental interference [19], [20].

Rainfall intensity and water level are fundamental and complementary parameters for flood detection and early warning [21], [22]. Rainfall measurements indicate the *forcing* that generates runoff, while water-level (stage) observations directly measure the hydrological response that poses immediate risk to communities and infrastructure [23]. Monitoring both parameters in real time allows threshold-based warnings (rainfall thresholds, stage thresholds, or combined criteria) that improve lead time and reduce false alarms compared with single-parameter systems [24], [25]. Moreover, international guidance and assessments emphasize that effective FEWS rely on timely precipitation and stream/river stage observations, combined with robust communication and forecasting, to translate measurements into actionable alerts [26]. Finally, recent sensor technology and operational reviews show that affordable rainfall gauges and non-contact water-level sensors, such as ultrasonic, when properly sited, calibrated, and quality-controlled, can provide sufficiently accurate inputs for community-scale EWS and can be integrated to further improve reliability [27].

The combination of rainfall and water level sensing is particularly important for enhancing early flood detection capability. Studies in the past five years have emphasized the role of multi-parameter monitoring systems in reducing false alarms and improving lead times [28], [29]. Our findings support this approach, as the system provides consistent and reliable measurements across two critical flood indicators.

Despite promising results, certain limitations should be noted. The rainfall sensor showed minor deviations at varying intensities, likely caused by tipping-bucket mechanical tolerance and splashing effects, consistent with observations by Munoz et al. [30]. In real-world deployments, factors such as debris, extreme rainfall intensity, or temperature variation may affect long-term accuracy. For the water level sensor, although laboratory results were ideal, field deployments often encounter turbulence, floating debris, or sensor alignment issues that may introduce error [31], [32]. Research on an ultrasonic sensor for monitoring water level in a river obtains an average error below 3%, with the errors having been solved by averaging multiple readings and temperature correction techniques [33]. So, the performance of the water level with under 3% of error shows that it is an efficient tool for measuring water level in streams, especially during floods. Therefore, further long-term testing under actual hydrological conditions is required to fully validate performance robustness.

Although this study was conducted under controlled laboratory conditions, the developed EWS is designed to operate in real-world flood environments. In field deployment scenarios, factors such as debris accumulation, water turbulence, and extreme rainfall may affect sensor readings. In addition, real-world deployment requires continuous power availability, robust communication networks, and regular maintenance to ensure system reliability. These challenges highlight the need for extended field validation and system adaptation before large-scale implementation. However, comprehensive field validation under natural flood conditions is required and will be addressed in future studies. Besides, the tipping bucket rainfall sensor and water level sensor require periodic calibration to maintain measurement accuracy and reliability. Regular calibration is necessary to minimize measurement errors caused by mechanical wear, environmental changes, and long-term operational conditions. Despite these limitations, the proposed EWS provides a foundational framework for flood monitoring and can be further enhanced through real-case field deployment and long-term evaluation.

Overall, the results of this study strengthen the evidence that low-cost rainfall and water level sensors, when properly calibrated, can serve as reliable components of community-scale FEWS. The integration with real-time monitoring and online information dissemination ensures that the developed prototype not only measures environmental parameters accurately but also fulfills the essential function of timely risk communication to local communities.

5. Conclusions

This study successfully developed and evaluated a low-cost Flood Early Warning System (FEWS) that integrates rainfall and water level sensing for real-time monitoring and alert dissemination. The rainfall sensor achieved high accuracy (96%) with an RMSE of 14.28 mm/hour, while the water level sensor achieved perfect agreement with manual measurements (100% accuracy, RMSE = 0 cm). These findings demonstrate that affordable off-the-shelf sensors, when properly calibrated and validated, can provide sufficiently precise hydrometeorological data to support community-scale flood monitoring. The integration of rainfall and water level parameters proved effective in enhancing early detection capability, consistent with recent studies emphasizing the benefits of multi-parameter monitoring. Despite the promising results, further long-term field testing is required to validate performance under diverse hydrological and environmental conditions, including extreme events. Future work should also address system robustness, including communication reliability, power autonomy, and resilience to environmental interference in field deployment. Overall, the proposed FEWS shows strong potential as a practical and scalable solution for reducing flood risks and strengthening local disaster preparedness.

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