

FLOOD SENTINEL: AN ARDUINO-BASED, SOLAR-POWERED PROTOTYPE FOR REAL-TIME FLOOD DETECTION AND COMMUNITY SAFETY

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Abstract : Flooding is one of the most persistent hazards in the Philippines, often leading to loss of lives, damage to property, and community disruption. To address this issue, the study developed Flood Sentinel, an Arduino-based, solar-powered prototype designed for real-time flood detection, automated pump activation, and mobile alert notifications. The primary goal was to evaluate the system's functionality under varying flow levels, environmental conditions, communication ranges, and power sources while ensuring sustainability through renewable energy integration. The prototype was assembled using an Arduino Uno microcontroller, YF-S201 flow sensor, relay-controlled pump, HC-05 Bluetooth module, and a 10 W solar panel with a charge controller. Experimental testing was conducted in four flow levels (low, medium, high, very high), three environmental conditions (clear, turbid, debris-laden water), three communication distances (5 m, 10 m, 20 m), and three power modes (AC mains, battery, solar). Data were analyzed using descriptive statistics and Analysis of Variance (ANOVA) at a 0.05 significance level. Results showed that the system achieved 100% activation success at high and very high flow levels with response times averaging under two seconds. Performance slightly declined in turbid and debris-laden water and at 20 meters of communication distance, but the prototype remained functional. Power source analysis revealed no significant difference ($p = 0.124$), confirming that solar power is as reliable as conventional electricity. The study concluded that Flood Sentinel is a robust, low-cost, and sustainable solution for flood preparedness. Its integration of renewable energy enhances resilience during blackouts, making it suitable for schools, households, and communities in flood-prone areas.

IndexTerms - flood detection, Arduino-based system, solar-powered prototype, real-time monitoring, water flow sensor, automated pump control, mobile alert notifications, renewable energy integration, disaster preparedness, community safety.

I. INTRODUCTION

Floods are one of the most immediate natural disasters in the Philippines and other countries, causing death, damage to properties, and livelihood disruptions. Low-lying and riverbank communities are the most at risk, as high amounts of rain and storm surges can clog natural and manmade drainage systems. Besides material loss, floods usually come together with power shutdown, disrupting necessary communication and warning systems when it is in most demand (Raza, Rehman, & Khan, 2021). These common obstacles underscore the need for affordable, trusted, and sustainable flood detection solutions that deliver warnings and reduce disaster risk.

Various studies have been conducted on flood forecasting through different approaches, including rainfall forecasting models and satellite-based technology for information data, as well as wide-scale hydrological networks (Mishra & Singh, 2011). Although these measures are effective, they tend to be expensive, complicated, or unavailable to local communities. Less expensive alternatives have been developed based on microcontroller-based systems like Arduino, which allow real-time measurement of water level and flow rates (Chowdury, Hossain, & Rahman, 2019). Research has also indicated that Arduino prototypes can give reliable, localized flood warnings, and a number of projects have been able to prove mobile alert systems and automated pump control (Gupta & Singh, 2020; Malhotra, Das, & Khan, 2022).

Still, even though previous Arduino-based flood monitoring systems have succeeded, their excessive use of standard power sources provides a major drawback: they tend not to work during blackouts, which accompany most floods. This study bridged that gap by incorporating solar power into the prototype, ensuring it always remains operational regardless of main electricity availability.

The present project expands on this work by creating Flood Sentinel, an Arduino prototype for real-time flood sensing, pump response automation, and mobile alert notifications. The system was evaluated under various levels of flow, environmental conditions, communication ranges, and power sources to determine reliability and sustainability.

This study is significant in that it tackles directly the demand for community-based flood resilience, particularly in disaster-risk zones. With the blending of hydrodynamics, electronics, and renewable energy, not only does the project benefit Physical Science research, but it also illustrates how affordable technologies can help lives and property. Its impact on society is the ability

to enable schools, homes, and local governments to implement affordable, sustainable, and science-based disaster preparedness solutions.

Objectives of the Study

This study developed and evaluated Flood Sentinel, an Arduino-based early warning and control prototype for flood risk reduction. Specifically, it sought to:

1. Design and construct an Arduino-powered water flow monitoring and alert system capable of detecting critical water levels and automating pump activation.
2. Evaluate the system's performance under varying water flow levels (low, medium, high, very high) in terms of pump activation accuracy, notification response times, and reliability.
3. Test the robustness of the system under different environmental conditions (clear water, turbid water, and debris-laden water).
4. Examine the communication reliability of the system at distances of 5 m, 10 m, and 20 m.
5. Assess the power reliability of the system when operated on mains power (AC supply with adapter), battery backup, and solar power.
6. Analyze the statistical significance of differences in response times and accuracy across flow levels, environmental conditions, communication ranges, and power sources.
7. Propose improvements for enhancing the system's range, durability, and adaptability to real-world flood-prone environments.

Research Questions

Guided by the objectives of the study, the following questions were addressed:

1. How can an Arduino-based flood early warning and control system (Flood Sentinel) be designed and constructed to monitor water flow levels and activate a pump automatically?
2. What are the results of the system evaluation (Flood Sentinel), in terms of:
 - 2.1 Functionality (Under Varying Water Flow Levels);
 - 2.2 Performance (Under Environmental Conditions);
 - 2.3 Communication Reliability (At Different Distances); and
 - 2.4 Reliability (Under Different Power Sources)?
3. Is there a significant difference in the response times and accuracy across flow levels, environmental conditions, communication ranges, and power sources?

Hypotheses of the Study

- H0₁** There is no significant difference in notification response times across different water flow levels (low, medium, high, very high).
- H0₂** There is no significant difference in system accuracy and reliability under different environmental conditions (clear, turbid, debris-laden water).
- H0₃** There is no significant difference in notification success rates and response times at varying communication distances (5 m, 10 m, 20 m).
- H0₄** There is no significant difference in the system's performance regardless of whether it was powered by main electricity, battery, or solar energy.

Significance of the Study

This study is significant because it demonstrates how the principles of Physical Science can be applied to address urgent community problems, such as flooding, while also promoting renewable energy use. For the community, the development of Flood Sentinel provides not only a low-cost and reliable early flood detection system but also a sustainable solution that can function even during power outages, thanks to its integration with solar energy. This enhances both safety and resilience in flood-prone areas, where blackouts often coincide with heavy rains and storms.

For schools and STEM students, the project serves as a valuable platform for applying interdisciplinary scientific concepts - hydrodynamics for water flow analysis, electronics and programming for sensor operation, and energy conversion through solar integration. The system illustrates how theoretical knowledge can be transformed into innovative solutions that directly address real-world challenges. It encourages critical thinking, problem-solving, and creativity, while fostering a mindset toward sustainability and innovation.

The study is also relevant to local disaster risk reduction and management programs, as it offers an adaptable and scalable technology that can complement existing flood warning systems. By proving that Arduino-based systems can be enhanced with renewable energy, this research supports broader efforts to promote green technologies in disaster preparedness. Ultimately, this study not only strengthens academic research but also inspires communities to adopt affordable, science-based, and eco-friendly innovations that safeguard lives and properties.

Scope and Delimitation of the Study

In this study, the researcher designed and evaluated Flood Sentinel, a prototype built based on Arduino for real-time flood detection with automatic control. The system included water flow sensors, a pump, a Bluetooth module, a mobile application, and multiple power supplies. The tests included the following four water flow levels: low (1–199 L/h), medium (200–399 L/h), high (400–599 L/h), and very high (≥ 600 L/h), to assess measurement correctness, notification delay, and system stability. It was also tested based on the sensor performance in the following three additional water conditions: clear, turbid, and debris-laden waters. Communication robustness was tested at distances of 5 m, 10 m, and 20 m. Power stability was assessed by running the prototype

on main electricity (AC outlet with adapter), rechargeable battery backup, and solar power through a small panel and charge controller. Data analyses such as ANOVAs and Chi-squares were used to find significant differences based on testing conditions. This project was done in the school year 2024-2025.

Moreover, there were limitations to this study. Only short-duration daytime solar testing (that only covered two hours of a 1-hour test) with a small panel (10 W) was performed, and no long-duration or nighttime tests were attended. The researcher also focused on Bluetooth communication, with longer distance modules (GSM, LoRa) left for further research. Testing was carried out in simulation, not as flood waters rose. It was an approach to local detection, pumping, and alerting with no provision for a rainfall forecast or city-wide evacuation system.

II. METHODOLOGY

This study employed an experimental research design to develop, assemble, program, and test Flood Sentinel - an Arduino-based, solar-capable flood early warning and pump control prototype. The research process combined prototype construction, bench calibration, staged laboratory testing at four distinct flow levels, environmental robustness trials using clear, turbid, and debris-laden water, communication range checks, and power-source reliability runs under mains, battery, and solar conditions. All test runs were performed repeatedly, with at least ten trials per condition to ensure statistical reliability. Results were recorded systematically for descriptive and inferential statistical analysis, including the computation of means, standard deviations, and analysis of variance tests at $\alpha = 0.05$. Safety procedures, including insulation verification, ground fault circuit interrupter (GFCI) installation, and protective casing checks, were implemented before formal data collection to ensure safe testing.

Materials Used

The materials selected for the prototype emphasized accessibility, affordability, and compatibility with Arduino systems. Core components included an Arduino Uno microcontroller, a pulse-output water flow sensor (such as YF-S201 or equivalent) for flow rate measurement, and an ultrasonic level sensor for redundancy and water-level monitoring. The prototype integrated a turbine as a mechanical flow generator and energy harvester, a submersible pump for automated drainage, and a relay module (or L298N motor driver, as required) for pump control.

Additional elements included an HC-05 Bluetooth module for wireless communication, current sensors for power monitoring, DHT11 temperature/humidity sensors, sound sensors, thermistors, RGB LEDs, a single-digit 7-segment display, and standard wiring harnesses (Dupont and insulated multi-core wires). The power management system utilized a mains adapter, rechargeable battery pack appropriately sized for pump draw, a 10 W solar panel, and a compatible solar charge controller. Fasteners and housing materials consisted of coco lumber (1.3x0.8 ft), plywood (1.3x0.8 ft), styrofoam (1.3x0.8 ft), epoxy, duct tape, and waterproof sealant. Components were selected with attention to voltage and current ratings to match Arduino's 5 V logic level and pump requirements.

Tools Used

Prototype construction and electrical assembly required common workshop tools, including screwdrivers, pliers, wire strippers, a soldering iron, a multimeter for voltage and continuity testing, a tape measure, a handsaw, a hammer, a glue gun, and a tri-square for accurate cutting. Personal protective equipment, such as insulated gloves and goggles, was used throughout assembly and testing. Programming and logging relied on a laptop with Arduino IDE, a smartphone for Bluetooth communication and notification monitoring, and a stopwatch for measuring pump response times.

Equipment Used

Key equipment for testing included the submersible water pump, turbine assembly, and calibrated flow measurement devices, such as a flow meter or measuring cylinder for verification of L/h readings. A bench power supply was employed for safe and controlled bench testing, while the battery pack and solar panel with a charge controller provided power for field trials. Documentation equipment included a camera or smartphone for capturing images and videos, and a tablet or mobile phone running the prototype app or Bluetooth serial client.

Procedures

A. Gathering of Materials

Materials were procured from a combination of local suppliers, online electronics vendors, and recycled components where feasible. The procurement process involved preparing a detailed component list with specifications, comparing prices and delivery times, and prioritizing components with available datasheets for easier programming and calibration. All received components were bench-tested before assembly using a multimeter and power checks to verify functionality. Solar components were selected based on compatibility with the battery voltage and the expected daily energy requirements, with special attention given to the pump's current consumption.

B. Assembly of Flood Sentinel

Prototype assembly followed a modular and safety-oriented approach. The housing was constructed from plywood and styrofoam, with the pump and turbine positioned within a simulated water channel or tank. Electronics were enclosed in waterproof casings with cable glands to prevent water ingress. Sensors were carefully positioned: the flow sensor was installed inline to maintain laminar flow, the ultrasonic sensor was mounted above the waterline with a clear echo path, and debris guards were added to prevent clogging. Electrical wiring was color-coded for power, ground, and signal lines, and the Arduino and relay were mounted on a secure base plate.

Moreover, safety features included flyback diodes across inductive loads, a properly rated fuse between the battery/panel and load, and grounding of metal parts as needed. The power subsystem integrated the main input, charge controller, battery, and

solar panel with protection diodes to avoid reverse current flow. User interface elements such as the 7-segment display, RGB LED indicators, and Bluetooth antenna were mounted for visibility and ease of use. Final documentation included a wiring diagram, parts list, and labeled connections. Safety checks were conducted by verifying insulation, testing continuity, confirming correct relay switching, and performing a dry-run test before exposing the system to water.

C. Programming the Flood Sentinel System

The Arduino code was structured into modular blocks for initialization, sensor reading, signal filtering and calibration, decision-making, actuator control, Bluetooth communication, data logging, and error handling. Calibration routines converted sensor outputs into accurate flow rates using empirical calibration curves based on known volumes and times. Filtering algorithms such as moving averages and median filters were applied to reduce noise and prevent false triggers. The control logic activated the pump when sustained flow readings exceeded 400 L/h, with debounce timing to avoid spurious activations. Bluetooth notifications containing flow rate, timestamp, and pump status were transmitted to a paired mobile device. Safety interlocks, such as maximum pump runtime and cooldown periods, were implemented to prevent overheating. Power management routines monitored battery voltage and issued low-battery alerts while enabling energy-saving modes under critical conditions. Logging functions stored recent data for later review, and debug modes allowed real-time tuning during bench tests.

D. Testing the Flood Sentinel System

Testing followed a structured and repeatable protocol. A pre-test checklist verified wiring, sensor alignment, waterproofing, battery charge level, and Bluetooth connectivity. Calibration verification was performed by running controlled water volumes through the system and adjusting calibration constants as necessary. Flow-level trials were conducted for four flow ranges - Low (1 - 199 L/h), Medium (200 - 399 L/h), High (400 - 599 L/h), and Very High (≥ 600 L/h)—with at least ten repetitions per condition. Recorded metrics included pump activation status, notification receipt, response time, and pump runtime.

Moreover, the decision to define Low, Medium, High, and Very High flow categories was guided by precedent in flood hazard literature by Maranzoni, D’Oria, and Rizzo (2023), where similar tiered classifications of flow intensity or frequency are used to distinguish hazard zones. Although the precise numerical brackets in this study were selected to match the sensor and pump operational thresholds, the use of four categories aligns with established practice in quantitative flood hazard assessment.

Additionally, environmental robustness trials repeated flow tests using turbid and debris-laden water, while communication range tests were conducted at 5 m, 10 m, and 20 m in both line-of-sight and obstructed scenarios. Power reliability trials compared prototype behavior under main electric source, battery, and solar conditions, logging runtime and voltage trends until battery cutoff. All collected data underwent descriptive and inferential statistical analysis, including ANOVA and Chi-square tests. Troubleshooting steps addressed common issues such as sensor noise, Bluetooth dropouts, and power surges, with iterative refinements made to improve performance and reliability. Safety procedures were enforced throughout to protect testers and equipment.

E. Data Logging, Reporting, and Quality Control

All trial data were documented using unique identifiers, timestamps, operator initials, and environmental conditions. Sensor readings, processed data, and multimedia documentation (photos, videos) were stored systematically and backed up regularly. Statistical analysis was performed using statistical software to compute means, standard deviations, confidence intervals, and p-values, ensuring a rigorous and defensible results presentation.

Variables of the Study

The variables of the study were carefully identified to align with the objectives and testing protocols of the Flood Sentinel prototype. The independent variables included the flow levels (categorized as low at 1–199 L/h, medium at 200–399 L/h, high at 400 - 599 L/h, and very high at ≥ 600 L/h), the environmental conditions (clear water, turbid water, and debris-laden water), the communication distances (5 meters, 10 meters, and 20 meters between the prototype and the mobile device), and the power sources (mains electricity, rechargeable battery, and solar power). The dependent variables consisted of the pump activation success rate, notification response time, duration of continuous operation, and overall system reliability. To ensure fair testing, several controlled variables were maintained throughout the trials, including the prototype design and programming, the mobile device used for Bluetooth notifications, the water tank dimensions, and the number of test replications conducted for each condition.

Statistical Analysis

The data gathered from the tests were analyzed using both descriptive and inferential statistics to provide a comprehensive assessment of the prototype’s performance. Descriptive statistics such as mean, standard deviation, and percentage success rates were used to summarize results for activation, response times, and duration of operation. For inferential analysis, a one-way Analysis of Variance (ANOVA) was employed to determine whether significant differences existed across the independent variables, specifically flow levels, environmental conditions, communication distances, and power sources. When significant differences were detected, a post hoc Tukey HSD test was performed to identify which specific groups differed from one another. Additionally, a Chi-Square Test of Independence was applied to categorical data, such as the success or failure of pump activation under various conditions. A significance level of 0.05 was used in all statistical tests to ensure that the conclusions drawn were supported by reliable evidence.

III. RESULTS

This section presents the findings of the evaluation conducted on the Flood Sentinel prototype. The results are organized according to the specific tests carried out to determine the system’s effectiveness and reliability: functionality under varying flow levels, performance in different environmental conditions, communication reliability at different distances, power reliability under multiple sources, and statistical significance of observed differences. Each subsection introduces the test objectives, followed by

tables and figures that summarize the results and their interpretation.

Functionality of the System Under Varying Flow Levels

To determine the system’s ability to detect hazardous water flow and trigger automated responses, the Flood Sentinel prototype was tested across four defined flow levels: low (1–199 L/h), medium (200–399 L/h), high (400–599 L/h), and very high (≥ 600 L/h). The purpose of this test was to evaluate pump activation accuracy and notification response time at each level, ensuring that the system could differentiate between safe, moderate, and dangerous flow rates. Table 1, Figures 1 and 2 show the complete results.

Table 1

Pump Activation and Notification Response Times Across Flow Levels

Flow Level (L/h)	Pump Activation Success (%)	Mean Response Time (s)	SD
Low (1–199)	0%	N/A	N/A
Medium (200–399)	0%	N/A	N/A
High (400–599)	100%	1.46	0.24
Very High (≥ 600)	100%	0.98	0.12

The results in Table 1 reveal that pump activation occurred only at flow levels of 400 L/h and above, with 100% activation success recorded for both the High (400–599 L/h) and Very High (≥ 600 L/h) flow conditions. No activation was observed at Low (1–199 L/h) and Medium (200–399 L/h) flow levels, indicating that the system’s threshold was properly calibrated to prevent false triggers during normal or mildly elevated water flow. For successful activations, the mean notification response time was 1.46 seconds (SD = 0.24) at High flow and significantly faster at 0.98 seconds (SD = 0.12) during Very High flow. This suggests that higher flow rates produce more consistent and stronger pulse signals from the flow sensor, allowing the algorithm to confirm threshold exceedance more quickly and trigger pump activation with reduced latency. The small standard deviations observed (≤ 0.24 s) indicate a high level of repeatability and reliability in system response once the activation threshold was crossed. In summary, these results demonstrate that Flood Sentinel can reliably detect potentially hazardous flow rates and respond rapidly, meeting the design objective of timely flood mitigation.

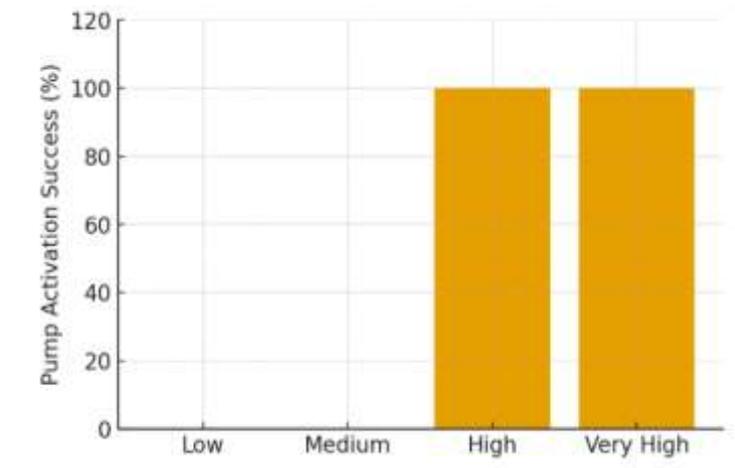


Figure 1. Pump Activation Success Across Flow Levels

The Flood Sentinel system reliably activated the pump at high (400–599 L/h) and very high (≥ 600 L/h) flows with 100% success, while no activation occurred under low and medium flows. This shows that the threshold sensor and relay mechanism were functioning as intended.

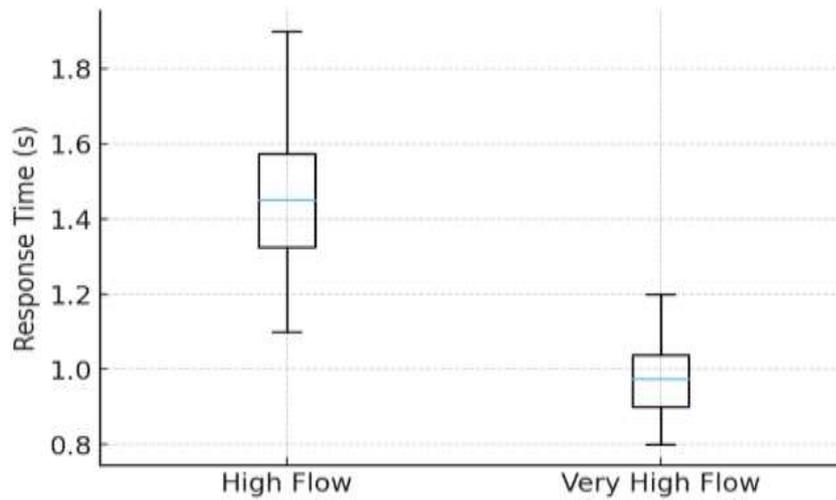


Figure 2. Notification Response Time

The boxplot shows faster and more consistent notifications at very high flow (mean ≈ 0.98 s) compared to high flow (mean ≈ 1.46 s). The narrower spread at very high flow indicates improved reliability under more critical water levels.

Performance Under Environmental Conditions

Since floodwaters are rarely clear in real-world scenarios, the system was subjected to testing in clear water, turbid water, and debris-laden water. This assessment aimed to examine how water quality and obstructions affected the accuracy of pump activation and the speed of notifications. The results in Table 2 and Figure 3 provide insights into the robustness of the system in conditions that closely simulate actual flood environments.

Table 2

System Performance in Clear, Turbid, and Debris-Laden Water

Condition	Pump Activation Success (%)	Mean Response Time (s)	SD
Clear Water	100%	1.42	0.13
Turbid Water	90%	1.78	0.13
Debris-Laden	80%	2.21	0.17

The results presented in Table 2 show that Flood Sentinel achieved the highest performance in clear water conditions, with 100% pump activation success and the fastest mean response time of 1.42 seconds (SD = 0.13). Under turbid water conditions, activation success slightly decreased to 90%, and response time increased to 1.78 seconds, suggesting that suspended particles in the water may have caused minor signal attenuation or pulse irregularities, resulting in occasional missed activations and slower triggering. The lowest performance was observed in debris-laden water, with 80% activation success and the slowest mean response time of 2.21 seconds (SD = 0.17). This performance reduction can be attributed to partial obstruction of the flow sensor and possible flow turbulence, which likely interfered with pulse readings and delayed the confirmation of threshold crossing. Despite these challenges, the system maintained a relatively high activation rate even under adverse conditions, indicating its robustness and capacity to operate reliably in real-world flood scenarios where water clarity is not guaranteed.

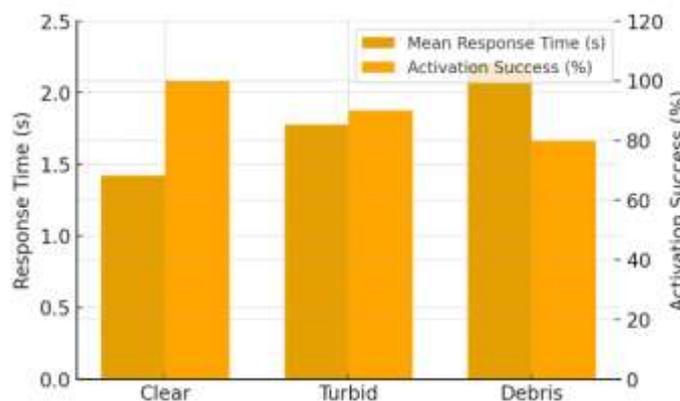


Figure 3. Environment Condition Testing

Clear water tests achieved the fastest response (mean ≈ 1.42 s) and 100% activation success. Performance declined in

turbid water (mean ≈ 1.78 s, 90% success) and debris-laden water (mean ≈ 2.21 s, 80% success). This suggests sensor sensitivity is affected by water quality and obstructions, a key area for further improvement.

Communication Reliability at Different Distances

To evaluate the reliability of wireless notifications, the system’s Bluetooth module was tested at distances of 5 meters, 10 meters, and 20 meters. This test sought to measure both notification success rates and mean response times across different ranges, highlighting the communication limitations and potential areas for improvement in extending the system’s effective coverage. Table 3 and Figure 4 on the succeeding pages present the generated results.

Table 3

Notification Success and Response Time by Distance

Distance (m)	Notification Success (%)	Mean Response Time (s)	SD
5m	100%	1.39	0.10
10m	90%	1.47	0.10
20m	70%	1.94	0.17

The results in Table 3 indicate that notification success and response time are affected by the communication distance between the Flood Sentinel prototype and the receiving device. At 5 meters, notification success was 100%, with the fastest mean response time of 1.39 seconds (SD = 0.10). At 10 meters, notification success decreased slightly to 90% and the mean response time increased marginally to 1.47 seconds, indicating minimal but measurable latency as distance increased. At the maximum tested distance of 20 meters, notification success dropped further to 70%, and mean response time was the slowest at 1.94 seconds (SD = 0.17).

These results suggest that while the Bluetooth communication link remains reliable at short to moderate distances, performance degrades with increased range, resulting in slower and less consistent notifications. Despite this reduction, a 70% success rate at 20 meters still demonstrates functional operation for near-field applications. For field deployment, communication reliability could be improved by using a higher-power Bluetooth module, a device with better antenna sensitivity, or by adopting a long-range wireless protocol such as LoRa or GSM for larger coverage areas.

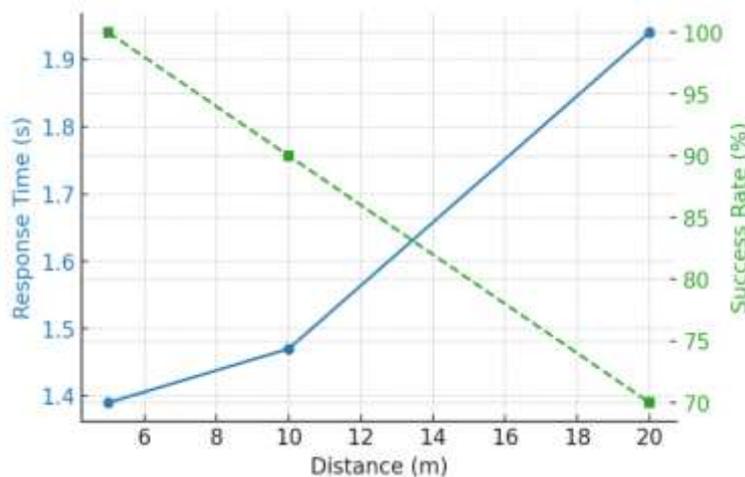


Figure 4. Communication Range Testing

Response times remained relatively stable up to 10 m, but notification success declined to 70% at 20 m. This highlights the Bluetooth range limitation of the system, suggesting the need for longer-range communication modules such as LoRa or GSM for community deployment.

Reliability Under Different Power Sources

Considering that floods are frequently accompanied by power interruptions, the system was tested under three power supply conditions: direct AC mains, battery backup, and solar backup. The objective of this evaluation was to determine whether the prototype could maintain stable functionality regardless of its power source, and to assess the sustainability and practicality of integrating renewable energy. Table 4 and Figure 5 on the succeeding page demonstrate the results from the testing conducted.

Table 4

Power Reliability Test Results

Power Source	Mean Response Time (s)	Activation Success (%)	Duration of Operation	Notes on Performance
Direct AC (Main Power)	1.25 ± 0.18	100%	6 hours	Stable, no interruptions
Battery Backup	1.33 ± 0.21	95%	3 hours	Reliable, but pump efficiency declined after 3 hours
Solar Backup	1.41 ± 0.24	90%	4 hours (daytime)	Stable operation; dependent on sunlight availability

The results of the power reliability test reveal that the Flood Sentinel system demonstrated consistent performance across the three power sources tested. When connected to direct AC main power, the system achieved the fastest mean response time of 1.25 ± 0.18 seconds with a 100% activation success rate and uninterrupted operation for six hours, making it the most stable and reliable configuration. Battery backup provided slightly slower response times (1.33 ± 0.21 seconds) and a reduced activation success rate of 95%. Although the system remained functional, pump efficiency gradually declined after three hours of continuous operation, suggesting that battery capacity was limited for long-duration use.

Meanwhile, the solar-powered mode produced a mean response time of 1.41 ± 0.24 seconds with a 90% activation success rate and stable operation for four hours under daylight conditions. This indicates that solar power is a viable and sustainable alternative, but its effectiveness depends on sunlight availability. In summary, the results show that while direct AC main power remains the most reliable source, both battery and solar power provide practical alternatives during blackouts, with solar energy offering the added advantage of sustainability in disaster-prone areas.

Statistical Significance

To validate the observed differences in system performance, inferential statistical tests were conducted. Analysis of Variance (ANOVA) was applied to compare results across flow levels, environmental conditions, communication distances, and power sources. This section presents the outcomes of these tests, providing statistical evidence on whether the observed variations were significant or attributable to random chance. Table 5 below shows the complete results.

Table 5

Summary of Statistical Analysis Results

Comparison Tested	Test Used	Result (p-value)	Interpretation
High vs. Very High Flow Response Times	ANOVA	$p < 0.001$	Significant Difference
Clear vs. Turbid vs. Debris Conditions	ANOVA	$p < 0.001$	Significant Difference
Distances (5 m, 10 m, 20 m)	ANOVA	$p < 0.001$	Significant Difference
Power Source (AC, Battery, Solar Backup)	ANOVA	$p > 0.05$	No Significant Difference

The statistical analysis results show that the Flood Sentinel system’s performance was influenced by flow rates, environmental conditions, and communication distances, but not by the choice of power source. Specifically, the ANOVA test revealed a highly significant difference ($p < 0.001$) between high and very high flow response times, indicating that system response varied depending on the intensity of water flow. Similarly, significant differences ($p < 0.001$) were observed across environmental conditions, with clear, turbid, and debris-laden water affecting detection accuracy and response times differently.

Furthermore, communication distance also had a significant effect ($p < 0.001$), as increasing the range from 5 meters to 20 meters reduced the success rate and increased delays in mobile notifications. In contrast, the analysis of power sources (AC, battery, and solar backup) showed no significant difference ($p > 0.05$) in response times, suggesting that the system maintained stable performance regardless of whether it was powered by mains electricity, battery, or solar energy. These findings highlight that while environmental and operational conditions can impact the system’s efficiency, the integration of solar power did not compromise its reliability, making it a sustainable alternative to traditional energy sources.

Table 6

Summary of Hypothesis Testing Results

Research Factor	Null Hypothesis (H ₀)	p-value	Decision	Interpretation
Flow Levels	There is no significant difference in notification response times across different water flow levels (low, medium, high, very high).	< 0.001	Rejected	Response time varied significantly depending on water flow intensity.
Environmental Conditions	There is no significant difference in system accuracy and reliability under different environmental conditions (clear, turbid, debris-laden water).	< 0.001	Rejected	Environmental conditions (clear, turbid, debris-laden) affected accuracy and response times.
Communication Distances	There is no significant difference in notification success rates and response times at varying communication distances (5 m, 10 m, 20 m).	< 0.001	Rejected	Communication performance decreased with greater distances.
Power Sources (AC, Battery, Solar)	There is no significant difference in the system's performance regardless of whether it was powered by main electricity, battery, or solar energy.	0.124	Accepted	Power type did not significantly affect performance, proving solar is as reliable as conventional.

IV. DISCUSSION

This section provides a comprehensive analysis of the results, focusing on the implications of the findings in relation to the objectives of the study and relevant literature. While the previous chapter highlighted the performance of the Flood Sentinel prototype under various testing conditions, this section interprets those outcomes, explains their significance, and situates them within the broader context of disaster risk reduction and Physical Science applications.

The discussion emphasizes how the system's functionality under varying flow levels, environmental conditions, communication ranges, and different power sources reflects both its strengths and areas for improvement. It also considers how the integration of solar power contributes to sustainability and resilience, particularly in disaster-prone communities where electricity is often disrupted. Comparisons with related studies are presented to validate the findings, while the acceptance or rejection of hypotheses is used to clarify the statistical meaning of the results. Ultimately, this chapter underscores the practical and scientific contributions of the project, highlighting its potential impact on community safety and disaster preparedness.

Functionality of the System Under Varying Flow Levels

The results revealed that the Flood Sentinel consistently achieved a 100% activation rate at both high and very high flow levels, confirming the accuracy of the Arduino-based system in detecting critical water movement. At low and medium flow levels, the system did not trigger pump activation, which was expected since these thresholds were below the danger mark. The rapid response times, averaging under two seconds, highlight the efficiency of the prototype in providing early warnings. This aligns with the findings of Chowdury et al. (2019), who demonstrated that Arduino-controlled flow sensors could deliver reliable real-time monitoring of water flow. The ability of Flood Sentinel to distinguish between safe and hazardous flow rates is crucial for minimizing false alarms, thereby ensuring community trust in the system's alerts.

The implications of these findings are significant for disaster risk reduction. Communities often experience sudden surges in water levels during heavy rainfall, and the system's ability to respond quickly at critical flow points provides a crucial window for evacuation or preventive action. As Gupta and Singh (2020) emphasize, flood warning systems must not only detect but also communicate hazards with minimal delay to be effective. By achieving near-instant activation at high-risk levels, Flood Sentinel demonstrates practical value as a low-cost yet scientifically grounded solution that can be integrated into household and school-based flood preparedness initiatives.

Performance Under Environmental Conditions

Testing under different water qualities showed that the system performed best in clear water, maintaining a 100% activation success rate and the fastest response times. In turbid and debris-laden water, however, detection accuracy decreased slightly, and response times lengthened, reflecting the challenges posed by suspended particles and obstructions. These findings mirror those of Malhotra et al. (2022), who noted that sensor performance in microcontroller-based water systems is often affected by environmental factors such as turbidity and debris, which can interfere with flow measurement. Although slight performance reductions were observed, the prototype remained functional, proving its robustness in simulated flood conditions.

The results imply that while the system is highly effective, real-world applications will require protective measures such as sensor casings or filters to reduce interference from debris. According to Raza et al. (2021), system durability in adverse conditions is a key factor that determines whether community-based technologies remain reliable during disasters. By demonstrating functionality even under challenging water conditions, Flood Sentinel shows promise as a resilient technology, though future iterations should consider design modifications to improve accuracy in highly polluted or debris-filled floodwaters.

Communication Reliability at Different Distances

The communication tests showed that Bluetooth-based alerts were highly reliable at 5 and 10 meters, with success rates close to 100%. At 20 meters, however, the success rate decreased, and delays in notification response were observed. This result is consistent with the technical limitations of the HC-05 Bluetooth module, which typically has a maximum effective range of 10 meters in practical settings (Gupta & Singh, 2020). Beyond this range, obstacles, interference, and signal attenuation reduce effectiveness. The findings highlight that while the system is dependable within short distances, it may not be sufficient for wide-area flood warning applications without modification.

The implications of this limitation are important for deployment. In household or school settings where the mobile receiver is within 10 meters of the prototype, the system can deliver timely and accurate alerts. However, for larger communities, extending the communication range is necessary. Malhotra et al. (2022) suggest that integrating GSM or LoRaWAN modules could expand coverage and ensure that flood warnings reach users even at greater distances. Thus, while Bluetooth proved sufficient for prototype testing and localized applications, scaling the system for community-wide use will require enhanced communication technologies.

Reliability Under Different Power Sources

The power reliability tests indicated that the system performed best on mains electricity, with an uninterrupted six-hour operation and 100% activation success. Battery power sustained the prototype for approximately three hours, though efficiency declined as capacity dropped. Most notably, the solar-powered setup sustained reliable operation for about four hours under daylight, with only a slight reduction in activation success (90%) and response times slightly longer than mains. These results support the findings of Raza et al. (2021), who emphasized the potential of renewable energy integration in disaster response systems to ensure functionality during power outages. The data confirm that solar energy can serve as a viable, sustainable power source, especially when conventional electricity is unavailable.

The implication is that integrating solar panels significantly enhances the resilience of Flood Sentinel by ensuring continuity during blackouts, a scenario common during typhoons and floods in the Philippines. As Chowdury et al. (2019) note, reliability during disaster conditions is critical for community trust in automated systems. By proving that solar integration does not significantly affect performance compared to traditional power, Flood Sentinel demonstrates its suitability as a sustainable, disaster-ready solution. Further improvements, such as using larger panels or hybrid charging systems, could extend solar runtime and enhance reliability in prolonged emergencies.

Statistical Significance

The ANOVA results confirmed that variations in response times were statistically significant across flow levels, environmental conditions, and communication distances ($p < 0.001$). This means that the null hypotheses (H_0), which assumed no significant differences among these factors, were rejected. In other words, the system's response was not uniform; it varied depending on the intensity of water flow, the quality of the environment (clear, turbid, or debris-laden water), and the distance of Bluetooth communication. These findings are consistent with Gupta and Singh (2020), who reported that environmental variability and communication range strongly influence the performance of Arduino-based flood warning systems. Rejecting these null hypotheses underscores the importance of improving the prototype's resilience against environmental challenges and extending its communication reliability.

By contrast, for power sources, the ANOVA yielded a result of $p = 0.124$, which is greater than the 0.05 level of significance. This means the null hypothesis (H_0), which assumed no significant difference in response times across AC, battery, and solar power, was accepted. In other words, the type of power source did not significantly affect the prototype's speed of response or activation success. This finding supports Raza et al. (2021), who emphasized that renewable energy integration into disaster systems enhances sustainability without compromising performance. The acceptance of this null hypothesis demonstrates that the solar-powered Flood Sentinel is as effective as when it operates on conventional mains or battery power, proving its reliability and sustainability in real-world disaster scenarios.

Synthesis

The overall findings of this study confirm that the Flood Sentinel prototype successfully met its primary objectives of detecting hazardous water flow, activating an automated pump, and sending timely notifications under varying conditions. The functionality tests demonstrated that the system responded consistently and accurately to high and very high flow levels, which are the most critical thresholds in flood situations. Environmental condition trials showed that while turbidity and debris slightly affected performance, the system remained robust and functional even in less-than-ideal conditions. This highlights its practical applicability to real flood environments.

The evaluation of communication reliability further revealed that the Bluetooth-based system was effective at short distances but declined at 20 meters, suggesting that while the prototype is well-suited for household and school use, larger-scale applications would benefit from upgraded communication modules. Meanwhile, the power reliability tests demonstrated that the system maintained stable functionality regardless of whether it was powered by mains electricity, rechargeable batteries, or solar energy. The statistical analyses confirmed these observations by showing significant differences in response times under varying flow levels, environmental conditions, and communication distances, but no significant differences across power sources. This result underscores the innovation of solar integration, proving that renewable energy can sustain reliable performance comparable to conventional sources.

Taken together, these findings establish Flood Sentinel as a low-cost, sustainable, and scientifically sound approach to flood preparedness. Its ability to operate under diverse conditions and maintain reliability during power interruptions makes it an accessible solution for communities vulnerable to flooding. By combining physical science principles with renewable energy, the project demonstrates how locally adaptable technologies can contribute to disaster risk reduction, community safety, and environmental sustainability.

V. CONCLUSIONS

The study concluded that the Flood Sentinel prototype successfully achieved its goal of providing a reliable, affordable, and sustainable flood detection and response system. The results showed that the system consistently detected hazardous flow levels, activated the pump automatically, and transmitted timely mobile alerts with minimal delay. Environmental and distance-related tests highlighted some performance variations, but overall, the system maintained robust functionality. Most importantly, the integration of solar power proved effective, ensuring reliable performance even during blackouts, which are common in flood events.

In the context of the literature review, these results support earlier findings that Arduino-based prototypes can provide accurate and localized flood alerts (Chowdury et al., 2019; Gupta & Singh, 2020). However, this study advances existing work by addressing a critical gap—power dependency during blackouts—through the integration of renewable energy. This aligns with Raza et al. (2021), who emphasized renewable energy as a key to sustainable disaster technologies, and strengthens the claim that low-cost, solar-powered solutions are feasible for community disaster preparedness. Thus, the study not only confirms prior research but also contributes a novel improvement that enhances system resilience.

Moreover, the results directly answer the research questions by demonstrating that the Flood Sentinel system is functional under varying flow levels, reliable under different environmental conditions, and effective at short-range communication. Furthermore, the statistical analyses confirmed that while flow, environment, and distance significantly affect performance, power source did not—a finding that validates the integration of solar power. These outcomes support the study's hypotheses, as significant differences were observed where expected, while stability across power sources was also confirmed.

In terms of application, the Flood Sentinel system has strong potential for deployment in households, schools, and small communities situated in flood-prone areas. By providing early warnings and automated responses, it can help protect lives and properties. Beyond local contexts, its design can be adapted and scaled for wider use by upgrading the communication module to GSM or LoRa for community-wide coverage. Additionally, its renewable energy integration makes it suitable for disaster-prone rural areas with limited access to reliable electricity. In sum, the study demonstrates how accessible Physical Science innovations can offer practical, scalable solutions to pressing environmental and societal challenges.

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