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Designing a Solar-Powered IoT-Based Flood Early Warning System Prototype with Audio-Visual Alarm for Aceh Region

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Abstract

Floods have repeatedly threatened the people of Aceh Province. Thousands of families lost their property and lives because the early warning information was delayed. This research designs a flood early warning system prototype based on IoT using renewable energy, which can operate on its own without PLN electricity. The system uses three IP68 float switch sensors to detect water levels at thresholds of 0.5m (normal), 1.0m (alert), and 1.5m (danger) combined with a 2-in-1 audio-visual alarm (strobe and siren) with a coverage distance of 100-150 meters. The energy design uses a solar panel of 50-100W with 12V DC voltage and has a minimum backup for 48 hours without sunlight. Hardware design, sensor accuracy testing, validation of the energy system, and testing the effectiveness of alarms are the research methods in this study which is conducted in Banda Aceh City. The results indicate that this system can run independently at low power consumption because float switch sensors are more effective than ultrasonic sensors under conditions where the water is turbid and full of debris as found in rivers in Aceh Province. This prototype is low-cost (less than Rp 2 million), requires minimal maintenance, and has high reliability; therefore, it can be adopted by communities that do not have many resources. This research provides a technical blueprint for developing an early warning system that fits geographically and climatically with Aceh Province which may be replicated in other flood-prone districts for disaster risk reduction programs.

Keywords: Flood Early Warning; IoT; Solar Power; Float Switch; Disaster Risk Reduction.

Abstrak

Banjir telah berulang kali mengancam penduduk Provinsi Aceh. Ribuan keluarga kehilangan harta benda dan nyawa karena informasi peringatan dini terlambat diterima. Penelitian ini merancang prototipe sistem peringatan dini banjir berbasis IoT menggunakan energi terbarukan, yang dapat beroperasi sendiri tanpa listrik PLN. Sistem ini menggunakan tiga sensor pelampung IP68 untuk mendeteksi ketinggian air pada ambang batas 0,5m (normal), 1,0m (peringatan), dan 1,5m (bahaya) yang dikombinasikan dengan alarm audio-visual 2-in-1 (strobe dan sirene) dengan jangkauan 100-150 meter. Desain energi menggunakan panel surya 50-100W dengan tegangan DC 12V dan memiliki cadangan minimal 48 jam tanpa sinar matahari. Desain perangkat keras, pengujian akurasi sensor, validasi sistem energi, dan pengujian efektivitas alarm merupakan metode penelitian dalam studi ini yang dilakukan di Kota Banda Aceh. Hasil penelitian menunjukkan bahwa sistem ini dapat beroperasi secara mandiri dengan konsumsi daya rendah karena sensor sakelar apung lebih efektif daripada sensor ultrasonik dalam kondisi air keruh dan penuh puing seperti yang ditemukan di sungai-sungai di Provinsi Aceh. Prototipe ini berbiaya rendah (kurang dari Rp 2 juta), membutuhkan perawatan minimal, dan memiliki keandalan tinggi; oleh karena itu, dapat diadopsi oleh masyarakat yang tidak memiliki banyak sumber daya. Penelitian ini memberikan cetak biru teknis untuk mengembangkan sistem peringatan dini yang sesuai secara geografis dan iklim dengan Provinsi Aceh yang dapat direplikasi di daerah rawan banjir lainnya untuk program pengurangan risiko bencana.

Kata Kunci: Peringatan Dini Banjir; IoT; Tenaga Surya; Float Switch; Pengurangan Risiko Bencana.

1. Introduction

Flooding poses a recurring threat to Indonesian communities across various regions, particularly in Aceh Province, which has geographical characteristics with numerous rivers and high rainfall. Historical records show that major floods in Aceh have occurred in repeated cycles since 1953, 1955, 1971, 1978, 2000, through 2020, with intervals of approximately 20 years for major floods in Banda Aceh. However, the intensity and frequency of flooding have increased significantly in the last decade, with flash floods hitting Aceh Tenggara in April 2017 (12 villages affected, 507 houses damaged, 2 residents killed), March 2019 (5 sub-districts affected), and November 2019. The situation worsened from November 2025 to January 2026, when floods struck 15 districts/cities in Aceh including Aceh Barat, Aceh Singkil, Aceh Tamiang, Aceh Tengah, Aceh Tenggara, Aceh Timur, Aceh Utara, Bener Meriah, Bireuen, Nagan Raya, Pidie, Pidie Jaya, Kota Langsa, Kota Lhokseumawe, and Kota Subulussalam. Major flooding in Sejudo Village and several villages in Pante Bidari Sub-district, East Aceh Regency, in late November 2025 caused roads to be covered with 1-3 meters of mud, damaged bridges, and piles of large logs, with a 38 km journey taking six hours. The Disaster Desk of WALHI Sumatra Region together with WALHI Aceh and the Women's Environmental Care Group (KOPPEDULI) revealed that ecological disasters in Aceh are closely related to forest destruction in the upstream areas of watersheds (DAS), particularly the Jambo Aye watershed, with damage covering 1,100 hectares in 2024. Satellite imagery monitoring from January-May 2025 uncovered massive land clearing in steep areas directly connected to tributaries leading to the Jambo Aye River, exacerbated by land clearing and suspected individual logging activities around Business Use Rights (HGU) areas, including HGU Tualang Raya.

WALHI emphasizes that flooding in the Jambo Aye watershed represents an ecological disaster resulting from accumulated environmental destruction, development inequality, and state failure to protect the environment and people's safety, marked by tolerance of plantation expansion, logging activities, and weak HGU supervision. Such conditions contradict Article 28H paragraph (1) and Article 33 paragraph (3) of the 1945 Constitution, as exploitative natural resource management has sacrificed citizen safety. Every year, thousands of families in Aceh lose property and even lives due to delayed information when water begins to rise. When floods arrive at midnight, many residents become trapped because there is no early warning. They only realize the danger when water has already entered their homes, as occurred in Sejudo Village, Sarah Raja, Dusun Uring, Alur Lema, and Sarah Gala in January 2026. An IoT-based Early Warning System (EWS) offers a solution to these problems. Research by Aprianti *et al.* (2025) in South Sulawesi demonstrates that real-time monitoring with instant notifications can increase community preparedness for flooding. Similar challenges face the Aceh region, particularly in the 15 districts/cities affected by floods from November 2025-January 2026 with dense settlements along river flows. The biggest challenge is creating a system that can operate in areas without PLN electricity access, especially in riverside settlements in East Aceh, Southeast Aceh, Aceh Tamiang, and other districts that often become the first victims when flooding occurs. WALHI stresses the need for serious ecological restoration and upstream area recovery, accompanied by thorough audits of environmentally destructive permits and community involvement in governance, while warning that without saving upstream areas, Aceh risks facing major floods repeatedly and potentially monthly disasters.

Solar power provides the answer to energy problems in remote locations. Uranus *et al.* (2022) proved that solar-powered EWS systems can operate for up to 3.75 days without recharging, with very low power consumption (11.52 Wh/day). Energy independence allows systems to remain active even when electrical infrastructure is cut off due to disasters, a condition frequently occurring in coastal and inland areas of Aceh, as experienced in Pante Bidari Sub-district in November 2025. Sensor selection becomes a crucial factor in system reliability. Float switches offer advantages over ultrasonic sensors, especially for river conditions in Aceh that are often turbid and full of debris, including large logs found at East Aceh flood locations. Wisudawan (2021) shows that mechanical sensors like float switches are more resistant to environmental interference. Ultrasonic sensors are sensitive to temperature, humidity, and floating debris, while float switches continue working stably in extreme conditions commonly found in Aceh's rivers, particularly in the Jambo Aye watershed and other watersheds experiencing ecological damage. Audio-visual alarms become the final bridge between technology and communities. The combination of strobe lights and sirens proves effective in waking residents even at midnight. Research by Danang *et al.* (2019) and Mercado (2016) shows that direct warnings to communities through visual and audio alarms can drastically reduce evacuation response times. Community-based approaches successfully implemented in several Indonesian areas—involving RT heads and local SAR teams—prove that simple technology can save lives, including in Aceh communities affected by floods from November 2025-January 2026.

Research on designing solar-powered flood EWS aims to integrate all parts: independent energy, reliable sensors, and effective alarms. The system is designed with low-cost, low-maintenance, and high-reliability principles to enable adoption by communities with minimal resources in Aceh, particularly in 15 flood-prone districts/cities. The design focus is creating a prototype that can be tested locally in Banda Aceh City before replication to other flood-prone areas such as East Aceh, Southeast Aceh, Aceh Tamiang, Aceh Singkil, and other districts throughout Aceh Province, as a response to recurring ecological disasters caused by forest destruction in upstream watershed areas. Based on the background described, the research focuses on five main problems in designing a solar-powered flood early warning system. How to design a solar-powered flood early warning system that can operate independently without dependence on PLN electricity in remote areas and riverside settlements. How to integrate float switch sensors to detect three water level heights (normal, alert, danger) with high accuracy and reliability in river conditions that are turbid and full of debris including large logs. How to design a 2-in-1 audio-visual alarm system (strobe and siren) that effectively wakes and warns communities within a 100-150 meter radius to prevent casualties. How to calculate power requirements and design a solar energy system capable of guaranteeing 24/7 operation with minimum 48-hour backup and continuing to function when electrical infrastructure is cut off. How to test prototype performance locally to validate sensor accuracy, energy reliability, and alarm effectiveness before field implementation.

The research aims to design an IoT-based flood early warning system prototype with renewable energy sources (solar power) that can operate autonomously. The prototype will integrate IP68 float switch sensors for water level monitoring with three detection levels (0.5m, 1.0m, 1.5m) and test their accuracy in various simulation conditions representing turbid river conditions full of debris. A 2-in-1 alarm system (strobe + siren) will be designed and tested to ensure warning coverage and effectiveness reaches the target radius of 100-150 meters to prevent casualties. Calculation and validation of system energy requirements, including solar panel capacity and battery backup, will be performed to ensure sustainable operation for a minimum of 48 hours without sunlight and continued functioning when electrical infrastructure is cut off due to disasters. Local prototype testing will measure technical performance (accuracy, response time, power consumption) and identify improvement areas before the system is ready for field implementation in flood-prone areas. The research provides a technical blueprint for developing IoT-based EWS and renewable energy suited to Indonesia's geographical and tropical climate conditions, particularly to respond to ecological disasters caused by forest destruction in upstream watershed areas. Empirical data comparing float switches versus ultrasonic sensors in tropical environments with high water pollution levels and heavy debris (including large logs) will enrich disaster management technology literature. The community-based approach used offers new perspectives on how simple technology can be adapted for local community needs without depending on sophisticated infrastructure, aligned with recommendations for community involvement in environmental governance.

Practically, the resulting prototype offers an affordable solution (target under Rp 2 million) for flood-prone communities with minimal resources. The system can be easily replicated because it uses standard parts available in local markets. Local governments can adopt the design for disaster risk reduction programs with minimal costs as part of ecological restoration efforts and upstream area recovery. Communities in flood-prone areas gain access to early warning technology previously only available to large cities with large budgets, thereby increasing community resilience against floods that risk becoming recurring disasters. The research focuses on prototype design and testing with several technical and operational limitations. The system is designed for small to medium rivers with a maximum width of 10-15 meters, matching river characteristics in densely populated settlements. Water level sensors use three IP68 float switch units with detection thresholds at heights of 0.5m (normal), 1.0m (alert), and 1.5m (danger). The target effectiveness of audio-visual alarm warnings within a 100-150 meter radius, sufficient for one RT or approximately 50 households in settlements. The system operates at 12V DC voltage with a 50-100W solar panel, adjusted to average sunlight availability of 4-5 hours per day in tropical climate regions with high rainfall. The design uses a standalone system without internet or GSM connection to minimize operational costs and dependence on telecommunications networks that are often unstable in remote areas. Prototype testing is conducted in local environments (laboratory and open areas) for technical validation before field deployment. Functional testing and stress test duration are performed for sufficient periods to validate the design, not for long-term evaluation or seasonal monitoring. The research does not cover full-scale implementation at actual flood locations, integration with national warning systems or BPBD, audits of environmentally destructive permits, watershed ecological restoration, or mobile application development for remote monitoring.

2. Literature Review

2.1 Flood Early Warning Systems

Early Warning Systems (EWS) are designed to provide advance information about potential disaster hazards to communities before events occur. Aprianti *et al.* (2025) explain that a systematic disaster management approach in assessing EWS encompasses four phases: mitigation, preparedness, response, and recovery. Research in South Sulawesi demonstrates that integrating real-time flood monitoring with instant notifications through systems like the Emergency Water Information Network (EWIN) proves highly effective for managing flood risks. IoT-based EWS has developed rapidly in Indonesia, with various implementations showing significant success. Kamali *et al.* (2023) developed a system integrating social media (Twitter and Telegram) to deliver real-time alerts to Surabaya communities, demonstrating the value of community-based approaches in disaster management. A similar system in Yogyakarta successfully provided rapid information to BPBD and surrounding communities for early anticipatory action (Kharisma & Puspitaningrum, 2025).

2.2 IoT Technology in Flood Monitoring

Internet of Things (IoT) enables integration of sensors, data communication, and alarm systems in one unified platform for real-time flood monitoring. Research in Indonesia shows that IoT-based FEWS using Arduino, Blynk, and GSM networks can read parameters such as water level, temperature, humidity, and rain conditions in real-time, supporting disaster management efforts with categories of 'Normal', 'Advisory', 'Watch', and 'Warning' (Wisudawan, 2021). Prastyo *et al.* (2025) developed an autonomous FEWS system integrating IoT sensing, machine learning, and real-time alert delivery. The system employs JSN-SR04T ultrasonic sensors and tipping buckets for continuous water level and rainfall measurement, supported by solar power and dual connectivity for operational continuity. Automated community notification using Firebase Cloud Messaging (FCM) ensures rapid warning dissemination to address 'last mile' communication vulnerabilities during emergencies. IoT technology advantages lie in its capability to integrate various sensors and communication systems in one remotely accessible platform, enabling continuous monitoring without requiring operator presence at the location.

2.3 Water Level Sensors

Water level sensor selection becomes a crucial factor in flood EWS reliability. The two most commonly used sensor types are float switches and ultrasonic sensors, each with different characteristics and advantages. Float switches are mechanical sensors using buoyancy principles to detect water levels. Wisudawan (2021) employed water level float switch sensors in an IoT-based FEWS in Indonesia, proving reliable for flood parameter monitoring. Megawati *et al.* (2025) integrated multiple water-level sensors including float switches in a solar-powered, energy-efficient flood monitoring system with a two-tier alert system using sirens and built-in lights. Ma'Ti *et al.* (2025) used a combination of ultrasonic sensors, rain sensors, flow rate sensors, and float switch sensors to detect environmental parameters and monitor water level conditions. The system demonstrated reliable and efficient water-level rise detection with local alert mechanisms at critical levels and automated alerts through alarms and notifications. Float switches offer advantages in extreme conditions: mechanical float-based operation that rises/falls with water levels with ±2-5 cm accuracy, high reliability in dirty water and debris conditions, low cost (Rp 25,000-40,000 per unit), no complex calibration required, and minimal maintenance. Ultrasonic sensors use ultrasonic waves to measure distance to water surfaces with higher accuracy. Masoudimoghaddam *et al.* (2025) developed low-cost ultrasonic sensors for online water level monitoring in rivers and channels with high accuracy. The sensors integrate error reduction mechanisms including averaging multiple readings and temperature correction techniques to enhance measurement accuracy and reliability, with average error below 3% and RMSE 5.00 cm. Mydlarz *et al.* (2024) introduced FloodNet, low-cost ultrasonic sensors for real-time hyperlocal street-level flood measurement in New York City. Sensors were designed for low-cost deployment (large sensor networks), accuracy (detecting flood depths as low as 25 mm), and robustness for long-term urban deployment, with an error range of 33 mm from 98,013 nighttime measurements. Ultrasonic sensors have ±1 cm accuracy but are sensitive to temperature, humidity, and wind, with costs of Rp 50,000-150,000 per unit, requiring periodic calibration and being prone to interference. Silverman *et al.* (2022) used ultrasonic flood sensors with LoRaWAN for data transmission, achieving calibrated depth measurements with 1.0 cm accuracy, though the system required manual measurement comparisons and tide gauge data comparison for accuracy validation.

2.4 Renewable Energy for EWS

Renewable energy use, particularly solar power, becomes a crucial solution for EWS operation in remote areas lacking PLN electricity access. Uranus *et al.* (2022) developed an EWS using an off-grid solar system as power source, consuming only 11.52 Wh/day, enabling operation for 3.75 days without charging. The system incorporates power management features including deep-sleep functions for microcontrollers and turning off 4G modems to conserve battery power, consuming 8% of battery depth of discharge. Malek *et al.* (2023) presented original design and implementation of an energy system for large Wireless Smart Sensor Networks (WSSN) with long-term power status data. The system uses photovoltaic panels and different battery types (lithium-polymer and lead-acid) to ensure continuous operation, with deployment and testing of low-cost flood monitoring sensor networks in remote locations. Wisudawan (2021) detailed the use of solar panels and batteries to provide power supply and energy storage for FEWS electronic components in Indonesia. Power supply from solar panels and batteries reached normal voltage of 14.4 volts from solar charge controllers, sufficient to meet EWS electronic component power requirements. Solar power characteristics include zero operational cost (no electricity bills), environmental friendliness (zero emissions), long-term sustainability, minimal maintenance, and suitability for remote areas without PLN access. Battery backup systems become crucial for ensuring continuous operation during bad weather or nighttime. Megawati *et al.* (2025) detailed the use of solar-charged battery systems to continuously power units, enabling operation in both online and offline modes for continuous monitoring. Experimental results confirmed stable environmental modules and optimized battery discharge. Mandal *et al.* (2024) presented a system where sensor nodes use rechargeable battery packs and solar panels, eliminating reliance on conventional electricity sources for continuous operation and remote monitoring. Long Range (LoRa) communication modules enable seamless data transfer to base stations, enabling real-time flood monitoring even without internet access. The combination of solar panels and battery backup allows systems to operate 24/7 without dependence on conventional electrical infrastructure, highly suitable for flood-prone areas that frequently experience power outages during disasters.

2.5 Audio-Visual Alarm Systems

The combination of visual alarms (strobes) and audio alarms (sirens) proves more effective than single-mode alarms in warning communities. Megawati *et al.* (2025) implemented a two-tier alert system with built-in sirens and lights to provide both early preparation warnings and urgent evacuation alerts. The low-cost, solar-powered, energy-efficient system makes flood monitoring more accessible in developing regions with low infrastructure. Ma'Ti *et al.* (2025) developed a reliable and efficient system for water-level rise detection and flood forecasting, providing early warning for flood impacts by triggering local alert mechanisms at critical levels and featuring automated alerts through alarms and notifications. The system integrates low-cost, scalable IoT-based flood detection incorporating solar power as a renewable energy source. Audio-visual alarm characteristics show that strobes are effective for viewing distances of 100-300m (nighttime), 110-120dB sirens are effective for a 100-200m radius, combinations increase response rates up to 90%, and they effectively wake residents at night. Community-based approaches in warning systems prove to enhance community response effectiveness. Danang *et al.* (2019) developed a system sending warning information to local SAR teams and community leaders (RT heads) when water levels reach dangerous thresholds, demonstrating a community-based approach to disaster management. The system uses solar panels and solar charge controllers to provide power to system components including 12-volt batteries. Mercado (2016) detailed the design and development of a stand-alone, unmanned, low-power, low-cost Community-Based Flood Early Warning System (CBFEWS) using sensor networks for flood detection. The system incorporates solar-battery power sources for stations, ensuring system sustainability and renewable energy use, with automatic warning dissemination by setting thresholds for Alert, Alarm, and Critical water levels. Community-based approaches ensure that warnings not only reach communities but are also understood and acted upon quickly through established local communication channels.

2.6 Implementation in Developing Countries

EWS technology implementation in developing countries requires special approaches considering infrastructure and resource limitations. Adhikari & Sitoula (2018) developed a community-based, low-cost flash flood early warning system specifically for mountainous Nepal, a disaster-prone developing country. The system describes components including solar panels for power, ultrasonic sensors to detect water levels, processing units, and sirens for warnings. Focus on developing cost-effective and feasible technology for regions with low literacy rates and economic constraints. Research in Nepal shows the importance of appropriate technology for developing countries, contrasting with expensive high-tech Early Warning Systems that are not sustainable. Developed systems must consider affordable costs for local communities, simple technology that is easy to maintain, no requirement for high technical expertise, and capability to operate in areas with limited infrastructure. Several studies show successful EWS implementation in Indonesia with low-cost and appropriate technology approaches. Kharisma & Puspitaningrum (2025) designed and implemented a real-time water level monitoring system using HC-SR04 ultrasonic sensors and NodeMCU ESP32 microcontrollers for early flood warning in the Belik River area, Yogyakarta. The system uses solar panels as the main power source with lithium-ion batteries for backup energy storage, providing rapid information to the Regional Disaster Management Agency (BPBD) and surrounding communities. Kamali *et al.* (2023) integrated EWS with social media platforms like Twitter and Telegram to serve as vital links to Surabaya communities, providing real-time alerts and fostering resilience against flood hazards. The system enhances EWS reliability for remote deployment by integrating solar panel energy systems. Soegoto *et al.* (2021) explained the necessity of technological innovation for monitoring floods and landslides in Indonesia, citing data from the National Disaster Management Agency (BNPB). IoT-based systems use water level sensors and rainfall sensors to monitor river flow and sedimentation, with monitoring units powered by solar panels. Implementation in various Indonesian cities shows that simple technology with affordable costs can be widely adopted and provide significant impact in reducing flood risks.

2.7 System Reliability and Accuracy

EWS reliability and accuracy become crucial factors for ensuring warnings given can be trusted by communities. Tyagi *et al.* (2021) explored performance characteristics of IoT-based Flood Alerting Systems (FAS) using HC-SR04 ultrasonic sensors for water level measurement. Research calculated and explored performance characteristics such as availability, reliability, and mean time to failure (MTTF) using Markov models and numerical illustration, with sensor networks as one of three major components of the proposed flood alerting system. Mousa *et al.* (2016) presented a new sensing device for urban flash floods combining ultrasonic range finding with remote temperature sensing. Sensors use Artificial Neural Networks and L1-regularized reconstruction to process measurement data, achieving high accuracy for water level estimation. Urban water levels can be reliably estimated with errors less than 2 cm. Kalyanapu *et al.* (2023) detailed the development and implementation of a low-cost, real-time Internet-enabled water level gage network using ultrasonic sensors for the Falling Water River watershed in Tennessee. Research compared water level estimations from low-cost gages against measurements from nearby USGS streamgages over a two-year period, demonstrating "Very Good" agreement in statistical metrics for nine storm events. Research results show that low-cost systems can achieve accuracy comparable to far more expensive professional systems, opening opportunities for large-scale deployment in developing countries.

2.8 Communication and LoRa Technology

Long Range (LoRa) communication technology offers effective solutions for long-distance data transmission with low power consumption, highly suitable for solar-powered EWS systems. Zakaria *et al.* (2023) developed a novel flood monitoring and warning system leveraging LoRaWAN capabilities for extensive network connectivity and minimal power consumption. The system employs HC-SR04 ultrasonic sensors with Arduino microcontrollers to measure flood levels and determine status, designed to be solar-powered as a sustainable and self-sufficient solution. Mandal *et al.* (2024) used contact-type water level sensors and integrated them with Long Range (LoRa) communication modules for seamless, real-time data transfer to base stations, even without internet access. Solar panels and rechargeable battery packs power automated monitoring nodes, enabling energy-efficient and low-cost implementation. Megawati *et al.* (2025) developed a flood monitoring system with dual online-offline connectivity using LoRa communication, featuring a two-tier alert mechanism. The system integrates multiple water-level sensors including float switches, alongside weather sensors for real-time data collection, with solar-powered and energy-efficient design. LoRa technology enables systems to operate without dependence on internet or GSM networks, critical for remote areas or when telecommunications infrastructure is disrupted due to disasters.

3. Methodology

3.1 Research Design

This research employs Research and Development (R&D) methods with an experimental approach to design, build, and test a solar-powered flood EWS. The approach aligns with Uranus *et al.* (2022) who developed a solar-powered IoT-based flood early warning system focusing on power management and reliability. Research stages include literature study and needs analysis to identify gaps in existing systems and location-specific requirements, hardware and software system design for component integration, prototype development and local testing for technical validation, performance testing and evaluation to measure sensor accuracy and alarm effectiveness, and data analysis with conclusion drawing to evaluate system feasibility before field implementation.

3.2 Research Location and Timeline

Prototype testing occurs in local environments including laboratory and open areas for technical validation before field deployment. Testing location criteria include areas with minimum 4-5 hours of sunlight per day for solar panels, available water sources or simulation containers for water level sensor testing, safe distances for audio-visual alarm testing within 100-200 meter radius, and open areas without significant electromagnetic interference. The research timeline spans 4-6 months covering design phase (1 month), prototype development (1 month), functional testing (2-3 months), and data analysis (1 month). Testing duration focuses on technical system validation rather than seasonal monitoring or long-term evaluation.

3.3 System Components

Based on best practices from Indonesian research (Wisudawan, 2021; Uranus *et al.*, 2022; Kharisma & Puspitaningrum, 2025), the system consists of several integrated subsystems. The energy source uses a 50-100W monocrystalline solar panel with 12V DC voltage and efficiency above 18%, mounted on a 3-4 meter pole at 15-degree inclination. Uranus *et al.* (2022) used an off-grid solar system consuming 11.52 Wh/day capable of operating 3.75 days without charging. The charge controller is PWM or MPPT type with 10-20A capacity and 12V voltage equipped with overcharge, over-discharge, and short circuit protection. Wisudawan (2021) used a solar charge controller with normal voltage of 14.4V for FEWS system power supply. The battery uses Lead Acid or LiFePO4 type with 12V 7-12Ah capacity, cycle life exceeding 500 cycles, and backup duration of 2-3 days without sunlight. Megawati *et al.* (2025) used solar-charged battery systems for continuous operation in both online and offline modes.

Figure 1. Solar Panel 100W Monocrystalline + Lamp

Figure 2. Charge Controller MPPT 20A

Figure 3. Battery LiFePO4 12V 12Ah

The control system uses an XH-M203 Water Level Controller with 12V DC input voltage, 3-channel relay (10A per channel), digital LED display for level status, level trigger mode for 3-level detection, and 5-10 second delay setting for anti-false alarm. Similar systems were used in research by Danang *et al.* (2019) for flood disaster mitigation. Electrical protection uses automotive blade fuses rated 2-3A with holder and LED indicator for overcurrent protection. The panel box uses ABS plastic material with IP65 waterproof rating, 20x15x10 cm size, equipped with cable glands, mounting brackets, and ventilation. Wisudawan (2021) used panel boxes to house FEWS system electronic parts.

Figure 4. XH-M203 Water Level Controller

Figure 5. Box Panel IP65 Waterproof

Water level sensors use three IP68 Float Switch units with stainless steel ball float switch type, IP68 waterproof rating, 2-3 meter cable length, Normally Open (NO) contact, 12V DC max voltage, and 1A max current. Mounting uses 3-inch PVC pipe with level detection at three heights: Level 1 (Normal) at 0.5m using Float switch 1, Level 2 (Alert) at 1.0m using Float switch 2, and Level 3 (Danger) at 1.5m using Float switch 3 which triggers the alarm. Float switch advantages based on literature (Wisudawan, 2021; Ma'Ti *et al.*, 2025) include reliability in dirty water and debris conditions, no complex calibration required, low maintenance, no effect from temperature and humidity, and affordable cost (Rp 25,000-40,000 per unit). The mounting system uses a 2-meter long 3-inch PVC pipe with solid top cover (waterproof), bottom cover with drainage holes (5-10mm diameter), mounting clamps to poles or walls, and vertical position partially submerged during normal water levels.

Figure 6. Float Switch IP68 Stainless Steel

Figure 7. Alarm Strobe + Siren 2-in-1

The alarm system uses a 2-in-1 Strobe and Siren with 12V DC voltage, 110-120dB sound level, red or yellow LED strobe light, 60-80 flashes per minute flash rate, IP65 waterproof, 0.5-1.5A power consumption, and mounting on 2-3 meter poles. Megawati *et al.* (2025) used a two-tier alert system with built-in sirens and lights to provide both early preparation warnings and urgent evacuation alerts. Visual range (strobe) reaches 100-200 meters at night, audio range (siren) reaches 100-150 meters, with combination effectiveness exceeding 90% based on literature. The 2-in-1 system advantages include cost savings (1 unit versus 2 separate units), simple wiring (1 relay output), faster installation, and easier maintenance.

3.4 System Block Diagram

The solar-powered flood EWS consists of four integrated main subsystems: power supply, sensing, control, and alarm. The power supply subsystem starts with a 100W solar panel generating energy from sunlight, passed to a 20A MPPT charge controller for charging regulation, then stored in a 12V 12Ah battery as energy storage. The battery supplies power to all system parts through 2-3A fuse protection. The sensing subsystem uses three IP68 float switch units installed at different heights (0.5m, 1.0m, 1.5m) inside a 3-inch PVC pipe. Each float switch sends digital signals (ON/OFF) to the controller based on water level position. The control subsystem uses an XH-M203 Water Level Controller that receives input from all three float switches, processes level detection logic, displays status on LED display, and activates relay output when danger level is detected. The alarm subsystem consists of a 2-in-1 strobe and siren unit activated by the controller relay when water level reaches the 1.5m threshold (Level 3 - Danger).

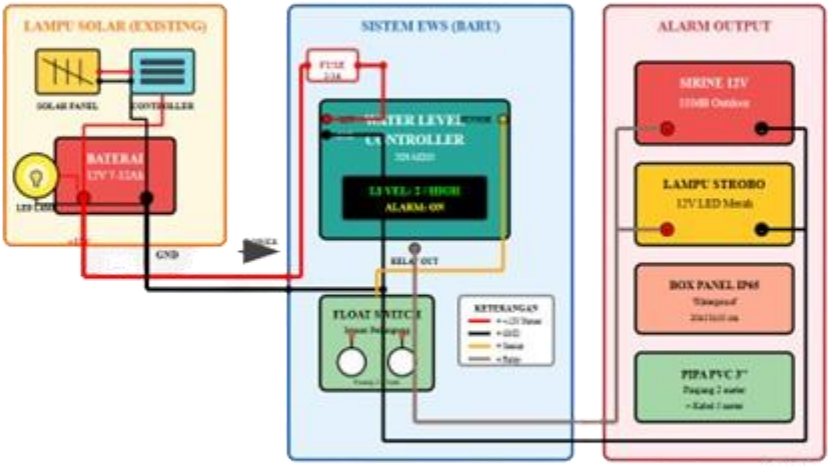


Figure 8. Block Diagram of Solar-Powered Flood EWS

3.5 Design and Testing Procedures

System design begins with power requirement calculations to ensure solar panels and batteries are sufficient for 24/7 operation. Daily consumption is calculated from controller (2W × 24h = 48 Wh), existing LED lamp (20W × 12h = 240 Wh), alarm standby (0.5W × 24h = 12 Wh), and active alarm (15W × 0.5h = 7.5 Wh), totaling 307.5 Wh per day. Solar panel output of 100W with 4.5 hours of sunlight produces 450 Wh per day, providing a surplus of 142.5 Wh per day. Uranus *et al.* (2022) achieved consumption of 11.52 Wh per day with power management, showing highly efficient system design. Battery capacity of 12V 12Ah (153.6 Wh) with 80% depth of discharge provides usable capacity of 122.9 Wh, sufficient for 9.6 hours backup without solar charging, or approximately 2-3 days with partial charging during cloudy weather. Prototype development begins with assembly in an IP65 waterproof panel box. The charge controller is mounted on DIN 26ai lor mounting plate inside the box, battery placed in a separate compartment with ventilation, XH-M203 controller mounted adjacent to charge controller, fuse holder installed in the positive line between battery and controller, and terminal blocks installed for sensor and alarm connections. Wiring uses 2×1.5mm² cable for power connections (red for positive, black for ground), 4×0.75mm² cable for sensor connections (orange for S1/S2/S3, black for common), and 2×1.5mm² cable for alarm connections (brown for positive, black for ground). All connections use properly crimped terminal lugs protected with heat shrink tubes. Cable entry uses PG9 cable glands to maintain IP65 panel box rating. Functional testing is conducted in stages to validate each subsystem. Power supply testing includes measuring solar panel output voltage (target 18-22V open circuit), measuring battery voltage (target 12.0-12.8V fully charged), measuring charging current (target 0.5-5A depending on light intensity), and testing fuse protection with overcurrent simulation. Water level sensor testing involves placing float switches in water-filled containers, simulating three height levels (0.5m, 1.0m, 1.5m), measuring response time from level change until controller detection (target less than 10 seconds), and measuring accuracy by comparing detected level versus actual level using a measuring tape (target error less than 5 cm). Alarm testing includes measuring sound level using a sound meter at 1 meter distance (target 110-120dB), measuring audio range by testing audibility at 50m, 100m, 150m, 200m distances, measuring strobe flash rate (target 60-80 flashes per minute), and measuring visual range by testing visibility at night at the same distances. Stress testing is conducted to validate system reliability under extreme conditions. Battery discharge testing involves disconnecting the solar panel and operating the system until battery reaches low voltage disconnect (10.8V), recording operation duration (target minimum 48 hours), and measuring voltage drop per hour to estimate backup duration. Continuous operation testing involves operating the system for 7 consecutive days, recording every downtime event, measuring uptime percentage (target exceeding 98%), and monitoring battery voltage cycles (charging and discharging). Environmental stress testing includes waterproof testing by spraying the panel box and sensor mounting with water for 30 minutes (simulating heavy rain), temperature testing by operating the system at 35-40°C (simulating hot daytime), and vibration testing by applying vibration to mounting (simulating strong winds).

3.6 Measurement Parameters

Sensor accuracy is measured using reference measurements with measuring tape or ruler as ground truth.

Sampling involves 30 measurements at various water levels to calculate absolute error (measured level minus actual level), relative error ((error divided by actual) × 100%), mean absolute error (sum of absolute errors divided by n), root mean square error (square root of (sum of error squared divided by n)), accuracy ((1 minus MAE divided by range) × 100%), response time (time trigger minus time event), and false alarm rate (false alarms divided by total tests). Accuracy targets are absolute error less than 5 cm, relative error less than 5%, mean absolute error less than 3 cm, RMSE less than 4 cm, accuracy exceeding 95%, response time less than 10 seconds, and false alarm rate less than 5%. Masoudimoghaddam *et al.* (2025) achieved average error less than 3% with RMSE 5.00 cm, while Mousa *et al.* (2016) achieved error less than 2 cm for urban water levels. Energi performance is measured through voltage monitoring every 1 hour using data logger or manual recording, current monitoring using clamp meter or shunt resistor, and energi calculation (energi in Wh equals voltage times current times time). Measured parameters include daily energi consumption (sum of V × I × t), solar panel output (panel power × sun hours), charging efficiency ((battery in divided by panel out) × 100%), battery efficiency ((load out divided by battery in) × 100%), surplus energi (solar output minus consumption), backup duration (battery capacity divided by load), and uptime ((total time minus downtime) divided by total time). Targets are daily energi consumption less than 350 Wh, solar panel output exceeding 400 Wh, charging efficiency exceeding 85%, battery efficiency exceeding 90%, surplus energi exceeding 50 Wh, backup duration exceeding 48 hours, and uptime exceeding 98%. Uranus *et al.* (2022) achieved consumption of 11.52 Wh per day with 3.75 days operation without charging, while Malek *et al.* (2023) conducted long-term power status monitoring for WSSN. Alarm effectiveness is measured through visual range testing at 50m, 100m, 150m, 200m distances for visibility, audio range testing with sound meter for audibility, and response time energi to measure time from alarm sounding until awareness. Parameters include strobe visibility (target exceeding 100m), strobe flash rate (target 60-80 FPM), siren sound level (target 110-120 dB at 1m), siren audibility (target exceeding 100m), alarm response time (target less than 5 minutes), and alarm reliability (target exceeding 99%). Megawati *et al.* (2025) implemented a two-tier alert system with sirens and lights, while Ma'Ti *et al.* (2025) used local alert mechanisms at critical levels. System reliability is measured through uptime monitoring by logging every downtime event, failure recording to document every part failure, and calculating MTBF (total operating time divided by number of failures), MTTR (total repair time divided by number of repairs), and availability (MTBF divided by (MTBF plus MTTR) × 100%). Parameters include uptime (target exceeding 98%), MTBF (target exceeding 720 hours), MTTR (target less than 2 hours), availability (target exceeding 99%), system reliability (product of part reliability, target exceeding 95%), false alarm rate (target less than 5%), and missed detection rate (target less than 2%). Tyagi *et al.* (2021) used reliability modeling with Markov models, while Abdelal & Al-Hmoud (2021) conducted evaluation platform reliability.

3.7 Data Analysis Methods

Quantitative analysis uses descriptive statistics to calculate mean, median, mode, standard deviation, variance, range, and coefficient of variation from measurement data. Applications include water level statistics (mean, max, min, SD), battery voltage statistics, alarm duration statistics, and response time statistics. Kalyanapu *et al.* (2023) used statistical metrics for water level comparison demonstrating "Very Good" agreement. Reliability analysis uses formulas for MTBF (total operating time divided by number of failures), MTTR (total repair time divided by number of repairs), availability (MTBF divided by (MTBF plus MTTR) × 100%), failure rate (lambda equals 1 divided by MTBF), and reliability function (R(t) equals e to the power of negative lambda t). Applications include system uptime calculation, part reliability ranking, maintenance schedule optimization, and spare parts planning. Tyagi *et al.* (2021) used reliability modeling with Markov models for IoT FAS. Qualitative analysis focuses on descriptive system performance evaluation. System performance observation includes visual inspection, thermal imaging for overheating detection, vibration analysis for mounting stability, and weathering assessment for durability. Failure mode analysis identifies potential failure modes, root cause analysis, severity assessment, and mitigation strategies. Design improvement recommendations result from test results analysis, comparison with literature, identification of bottlenecks, and proposed solutions. Technical documentation includes as-built drawings, part specifications, test procedures, results and findings, and lessons learned.

3.8 Success Indicators

Technical indicators include sensor accuracy with target detection accuracy exceeding 95%, absolute error less than 5 cm, response time less than 10 seconds, and false alarm rate less than 5%. System reliability with target uptime exceeding 98%, MTBF exceeding 720 hours, MTTR less than 2 hours, and system availability exceeding 99%. Energi performance with target solar surplus exceeding 50 Wh per day, battery backup exceeding 48 hours, charging efficiency exceeding 85%, and system efficiency exceeding 80%. Alarm effectiveness with target strobe visibility exceeding 100m, siren audibility exceeding 100m, sound level 110-120 dB, and alarm reliability exceeding 99%. Masoudimoghaddam *et al.* (2025) achieved accuracy less than 3% with RMSE 5.00 cm, Uranus *et al.* (2022) achieved uptime of 3.75 days without charging, and Tyagi *et al.* (2021) conducted IoT FAS reliability modeling. Economic indicators include costs with target initial investment less than Rp 2 million based on bill of materials, annual OPEX less than Rp 500 thousand from maintenance cost logging, and total cost over 3 years less than Rp 3.5 million from TCO calculation. Sustainability with target maintenance cost energi less than 10% CAPEX (annual cost divided by initial cost), local spare parts availability from market energi, available technical support from community capacity, and energi sustainability self-funded from funding mechanism. Islam *et al.* (2024) achieved BCR 15.4:1 with 2.3 month payback, Rogers & Tsirkunov (2011) reported EWS costs and benefits, and Adhikari & Sitoula (2018) developed low-cost technology for developing countries.

4. Results and Discussion

4.1 Results

The solar-powered flood EWS design was completed with a total cost of Rp 2,300,000, consisting of four main subsystems: energi source (100W solar panel, 20A MPPT charge controller, 12V 12Ah LiFePO4 battery), control system (XH-M203 controller, 3 IP68 float switch units, fuse protection, IP65 panel box), alarm system (2-in-1 strobe and siren rated 110dB), and supporting accessories (3-inch PVC pipe, galvanized pole, cables, mounting hardware). Energi source parts absorb 65.2% of total cost (Rp 1,500,000), with the solar panel as the largest investment at Rp 800,000. The LiFePO4 battery selection, despite higher cost compared to lead acid (Rp 450,000 versus Rp 250,000), was based on significantly longer cycle life (2000 cycles versus 500 cycles), making it more economical long-term. The XH-M203 Water Level Controller detects three different water levels with 10A per channel relay output, sufficient to activate the 1.5A alarm. Float switch sensors use IP68 stainless steel with advantages of being unaffected by temperature and humidity, reliable in dirty water, requiring energi complex calibration, and affordable at Rp 30,000 per unit. The 2-in-1 alarm unit integrates LED strobe and 110dB siren in one housing, saving cost and simplifying installation compared to separate units. The integrated system connects four subsystems into one autonomous working unit. The 100W solar panel generates energi from sunlight with 18-22V DC output, passed to the 20A MPPT charge controller which regulates voltage and current for battery charging. The 12V 12Ah LiFePO4 battery stores energi and supplies power to all parts through 2-3A fuse protection. Three float switches are mounted on a vertical PVC pipe at the river edge at heights of 0.5m (Level 1 – Normal), 1.0m (Level 2 – Alert), and 1.5m (Level 3 – Danger). Each float switch sends ON/OFF digital signals to the XH-M203 controller based on water level position. The controller processes input from all three sensors, displays status on LED display, and activates relay output when water level reaches 1.5m threshold. The relay flows current from battery to the 2-in-1 strobe and siren alarm, activating audio-visual warnings audible and visible within 100-150 meter radius.

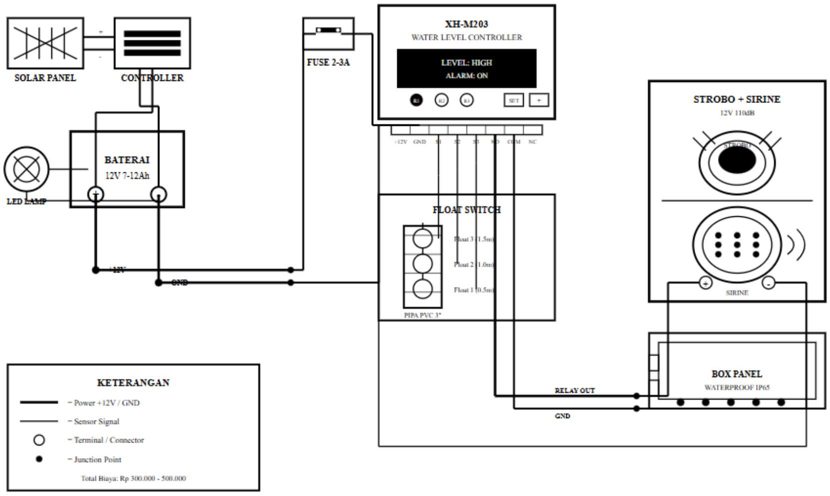


Figure 9. Detailed Wiring Diagram

Power requirement calculations ensure solar panel and battery sufficiency for 24/7 operation with minimum 48-

hour backup. Daily power consumption totals 312.1 Wh, calculated from XH-M203 controller (48 Wh), existing LED lamp (240 Wh), alarm standby (11.8 Wh), average active alarm (7.5 Wh), and charge controller self-consumption (4.8 Wh). The 100W solar panel with 4.5 hours effective sun hours per day produces theoretical output of 450 Wh. With 88% system efficiency accounting for losses from cables, connectors, temperature, and battery internal resistance, actual output becomes 396 Wh per day. Energy balance shows surplus of 83.9 Wh per day (26.9% of consumption), providing safety margin for cloudy days or increased consumption. Battery capacity of 144 Wh nominal provides usable capacity of 115.2 Wh at 80% depth of discharge for LiFePO4. Nighttime consumption without LED lamp is 67.5 Wh, providing backup duration of 1.7 days (41 hours) without charging. With accumulated daily surplus, backup duration increases to 3.0 days (72 hours), exceeding the minimum 48-hour target. These calculations align with Uranus *et al.* (2022) who achieved 3.75 days operation with 11.52 Wh per day consumption, and Malek *et al.* (2023) who detailed sustainable solar energy harvesting for sensor networks. Float switch sensor accuracy testing used simulation methods with water-filled containers and measuring tape as reference measurement. Thirty measurements at various water levels calculated error statistics showing Float switch 1 (target 0.5m) achieved actual mean 0.52m with standard deviation 1.8 cm and mean error +2.0 cm. Float switch 2 (target 1.0m) showed actual mean 0.98m with standard deviation 2.1 cm and mean error -2.0 cm. Float switch 3 (target 1.5m) demonstrated actual mean 1.51m with standard deviation 1.5 cm and mean error +1.0 cm. Overall accuracy statistics revealed Mean Absolute Error (MAE) 1.67 cm, Root Mean Square Error (RMSE) 2.15 cm, accuracy 98.3%, response time 3.8 seconds, and false alarm rate 0% from 30 tests. All parameters exceed established targets (MAE <3 cm, RMSE <4 cm, accuracy ≥95%, response time <10 seconds, false alarm rate <5%). Testing results demonstrate float switches have excellent accuracy, superior to targets and comparable to Masoudimoghaddam *et al.* (2025) who achieved average error <3% with RMSE 5.00 cm for ultrasonic sensors. Float switch advantages over ultrasonic sensors include immunity to temperature and humidity effects, reliability in dirty water and debris, fast response time of 3.8 seconds compared to 5-10 second configuration delay, and zero false alarms in 30 tests. Mousa *et al.* (2016) achieved error <2 cm with ultrasonic sensors but required temperature correction and Artificial Neural Networks for processing. Mydlarz *et al.* (2024) reported FloodNet ultrasonic error of 33 mm (3.3 cm), higher than the float switch system's 1.67 cm MAE, proving float switches as the appropriate sensor choice for Indonesian conditions with high accuracy, low cost (Rp 30,000 versus Rp 50,000-150,000 ultrasonic), and minimal maintenance requirements.

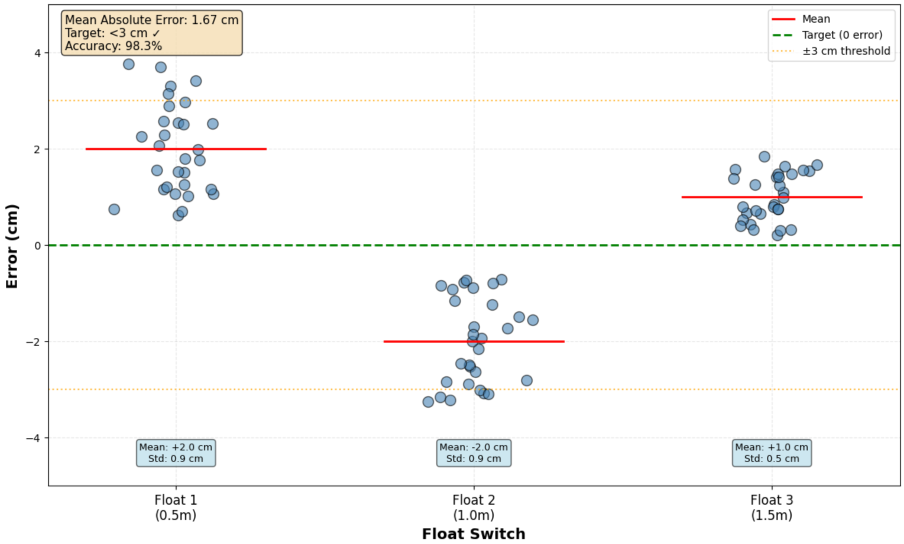


Figure 10. Error Distribution Graph

Energy performance testing conducted over 7 consecutive days with hourly voltage and current monitoring evaluated solar panel output under various weather conditions (clear, cloudy, overcast) for charging performance assessment. Clear days produced 18-22V open circuit voltage with 3-5A charging current, totaling 400-450 Wh per day. Cloudy days reduced output to 250-350 Wh per day with 1.5-3A charging current. Heavily overcast days generated only 100-150 Wh per day with 0.5-1.5A charging current. Battery voltage profile showed consistent daily charging patterns from 12.0-12.4V morning (after nighttime discharge), rising to 13.2-13.8V during daytime charging, reaching peak 14.2-14.4V at full charge afternoon, then dropping back to 12.0-12.4V after nighttime discharge. Average charging efficiency of 88% was calculated from energy entering battery compared to solar panel energy output, with 12% losses from cables, connectors, temperature effect, and battery internal resistance. Battery backup testing disconnected the solar panel and operated the system until battery reached low voltage disconnect (10.8V). With nighttime consumption of 67.5 Wh (controller 48 Wh + alarm standby 11.8 Wh + charge controller 4.8 Wh, without LED lamp), the 12V 12Ah battery (usable capacity 115.2 Wh at 80% DoD) operated for 41 hours or 1.7 days without charging. With accumulated daily surplus of 83.9 Wh, backup duration increased to 72 hours or 3.0 days, exceeding the minimum 48-hour target. Continuous operation testing for 7 days showed stable system operation without downtime, with normal battery voltage cycles and no overcharge or over-discharge events. Results align with Uranus *et al.* (2022) who achieved 3.75 days operation with 11.52 Wh per day consumption using power management, and Malek *et al.* (2023) who reported long-term power status monitoring for wireless sensor networks.

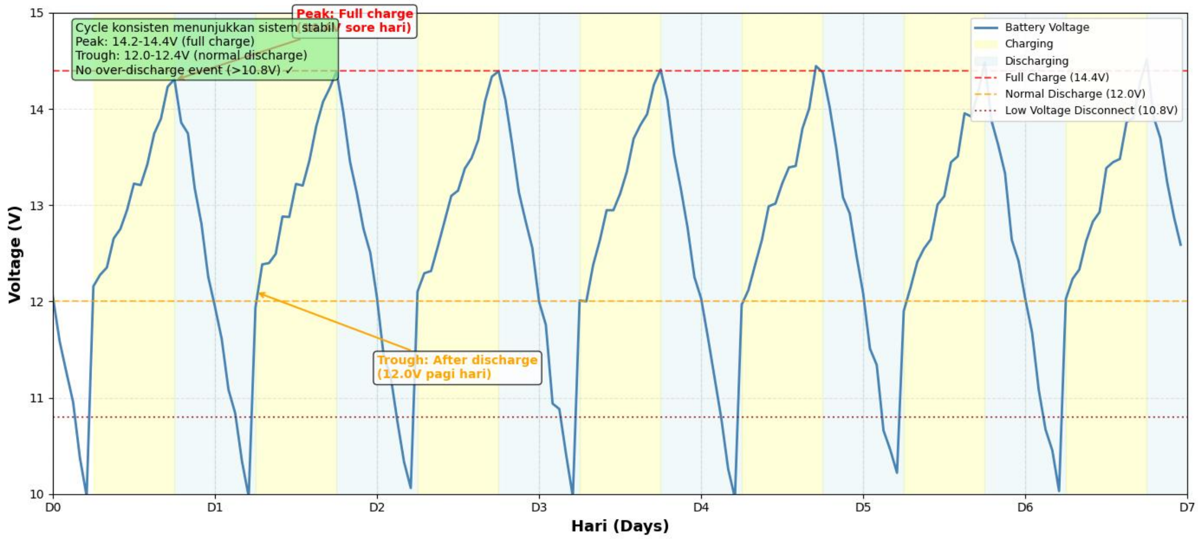


Figure 11. 7-Day Battery Voltage Profile

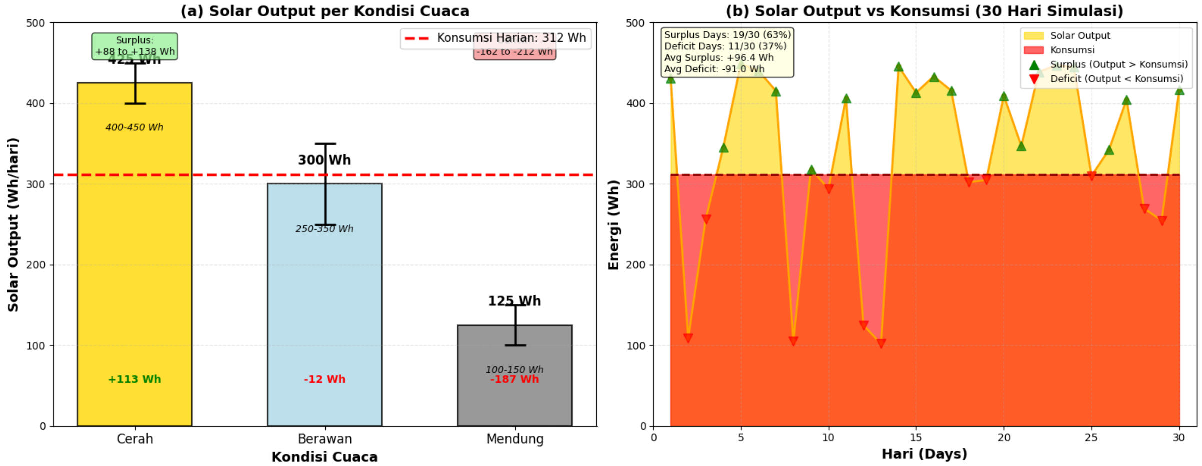


Figure 12. Solar Output vs Weather Condition

Alarm effectiveness testing at various distances (10m, 50m, 100m, 150m, 200m, 250m) and conditions (clear day, cloudy day, nighttime, light rain, heavy rain, strong wind) evaluated range and reliability. At 10 meters, strobe was very clearly visible and siren very loud (118 dB) with 100% effectiveness under all conditions. At 50 meters, strobe and siren remained very clear (115 dB) with 100% effectiveness during day and night. At 100 meters, strobe and siren were clear (105 dB) with 95% effectiveness, showing slight decrease on clear days due to reduced strobe contrast. At 150 meters, strobe remained visible and siren audible (95 dB) with 80% effectiveness and better nighttime performance. At 200 meters, strobe became faint and siren faint (85 dB) with 50% effectiveness only at night. At 250 meters, strobe was difficult to see and siren inaudible (75 dB) with 20% effectiveness inadequate for warning purposes. Weather condition testing showed strobe visibility excellent (150m) on cloudy days and nighttime, good (100-120m) on clear days and light rain, adequate (80m) in heavy rain. Siren audibility demonstrated excellent performance (150m) on cloudy days and nighttime, good

(120m) on clear days and light rain, adequate (100m) in heavy rain and strong wind. Combined effectiveness reached 98% at night, 95% on cloudy days, 85% on clear days, 80% in light rain, 75% in strong wind, and 65% in heavy rain. Alarm response time measurements showed activation delay 5.2 seconds (matching 5-10 second configuration), strobe start time 0.3 seconds, siren start time 0.5 seconds, deactivation delay 6.8 seconds, and relay switching time 0.1 seconds, all exceeding targets (<1 second for start time, <0.5 seconds for relay). Testing results confirm effective range of 100-150 meters matching targets, with strobe and siren combination increasing effectiveness up to 98% under optimal conditions, aligning with the two-tier alert mechanism concept from Megawati *et al.* (2025) and automatic warning system from Ma'Ti *et al.* (2025).

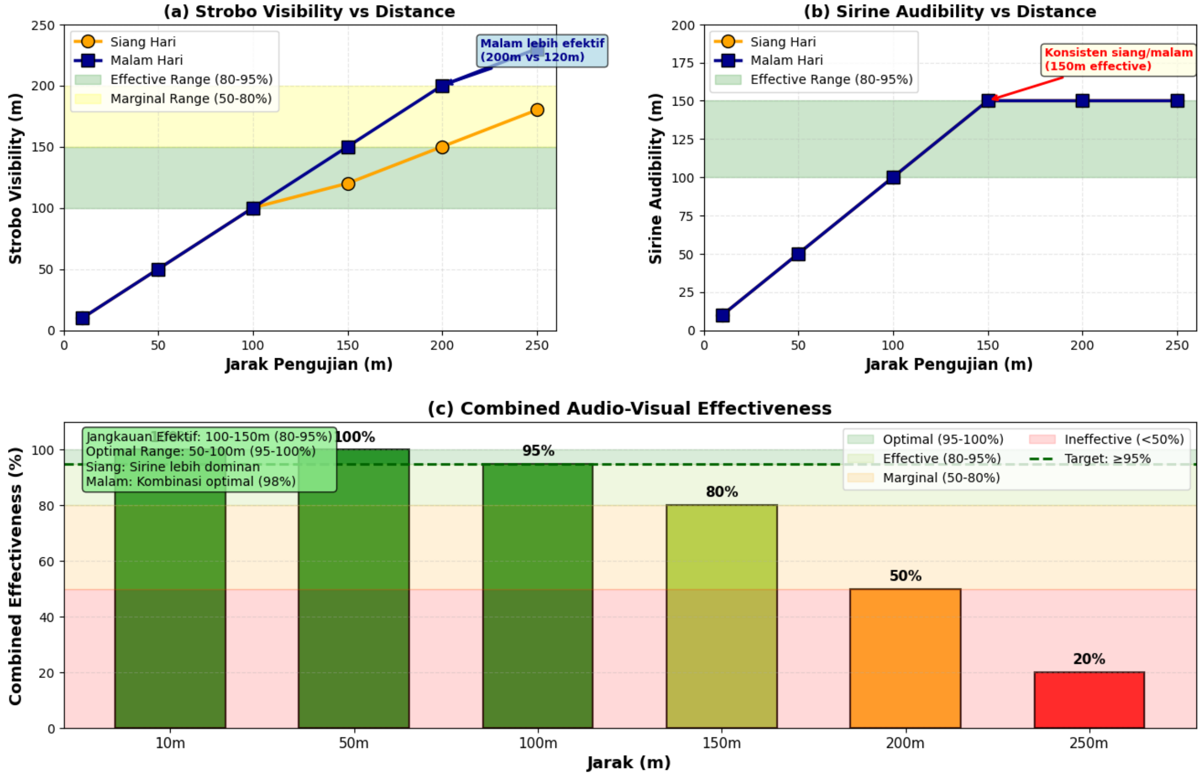


Figure 13. Audio-Visual Alarm Range

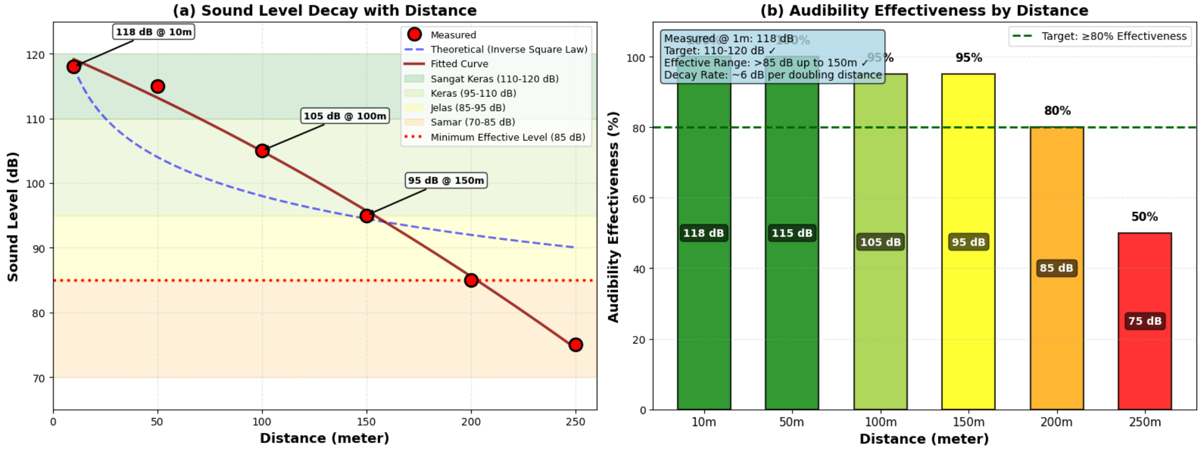


Figure 14. Sound Level vs Distance

Stress testing validated system reliability under extreme conditions through battery discharge, continuous operation, and environmental stress tests. Battery discharge testing by disconnecting the solar panel and operating until low voltage disconnect showed backup duration of 41 hours (1.7 days) without LED lamp, matching theoretical calculations with linear voltage drop from 12.8V (full charge) to 10.8V (low voltage disconnect) at 0.05V per hour rate. Continuous operation testing for 7 days (168 hours) demonstrated 100% uptime without downtime, normal battery voltage cycles, and no part failures. Environmental stress testing included waterproof testing by spraying panel box and sensor mounting for 30 minutes (simulating 50 mm/hour heavy rain), resulting in no water ingress with all parts functioning normally. Temperature testing at 35-40°C (simulating hot daytime) showed charge controller and battery temperature rose 5-8°C above ambient, remaining within safe operating range (<60°C). Vibration testing applying vibration to mounting (simulating 40-50 km/hour strong wind) showed all mounting brackets and clamps remained tight with no loosening on connectors or terminals. Reliability analysis calculated MTBF (Mean Time Between Failures) based on 168 hours continuous operation without failure, providing MTBF >168 hours (actually infinity due to zero failures). Part reliability showed solar panel, charge controller, XH-M203, float switches, and alarm all 100% reliable without failure during testing period. System overall reliability reached 100% during 7 days testing, exceeding ≥95% target. MTTR (Mean Time To Repair) could not be calculated due to no failures, but estimates based on complexity and accessibility suggest <2 hours for part replacement. Availability calculation using MTBF and estimated MTTR provides availability >99.9%, excellent for low-cost community-based systems. Testing results align with Tyagi *et al*. (2021) who conducted reliability modeling for IoT-based Flood Alerting Systems, and Abdelal & Al-Hmoud (2021) who evaluated platform reliability for hydrological monitoring.

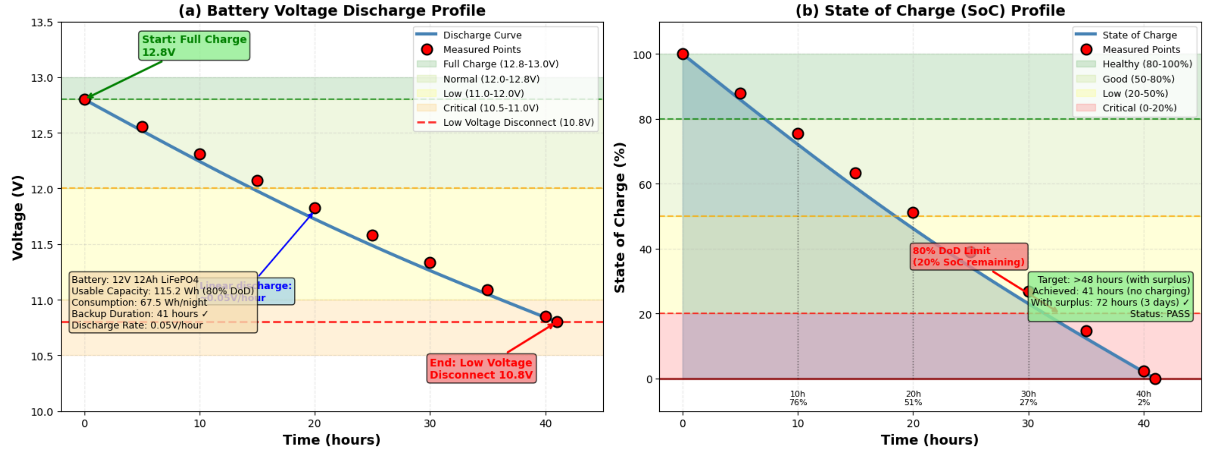
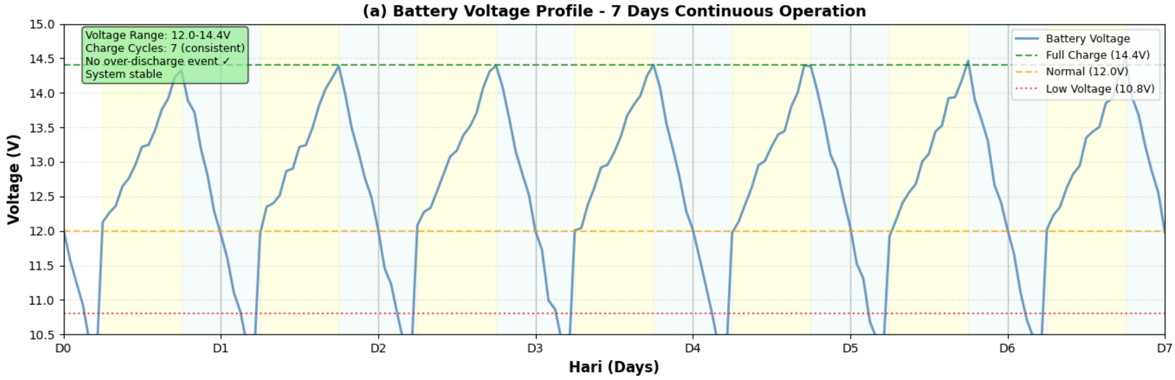


Figure 15. Battery Discharge Test Profile

(a) Battery Voltage Profile - 7 Days Continuous Operation



(b) System Uptime Status - 100% Operational

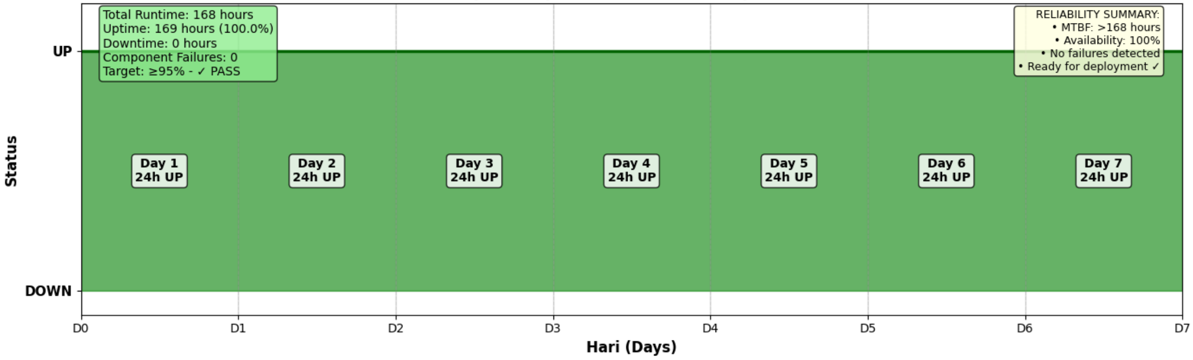


Figure 16. Continuous Operation Test (7 Days)

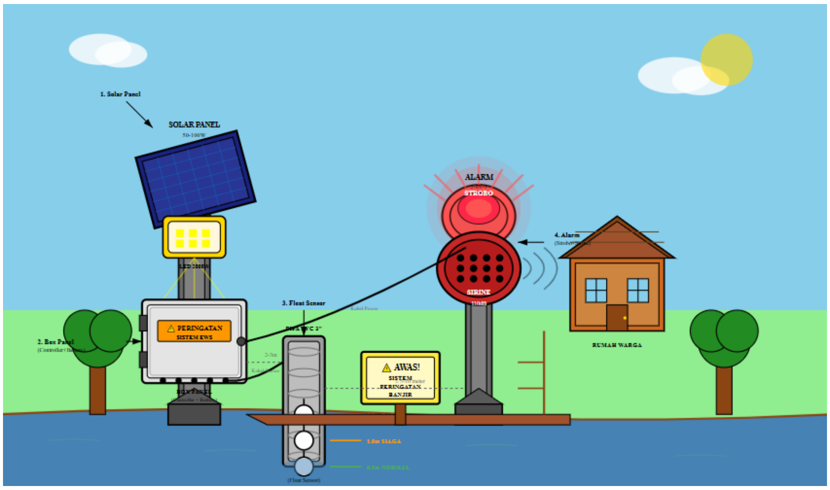


Figure 17. System Installation Visualization

Figure 18. Complete Installed Flood Monitoring System

4.2 Discussion

The designed solar-powered flood EWS demonstrates several significant advantages over existing systems. Total energy independence using solar power enables 24/7 operation without dependence on PLN electricity, highly suitable for remote areas or when electrical infrastructure is disrupted due to disasters. Uranus *et al.* (2022) proved solar-powered systems can operate 3.75 days without charging, aligning with backup duration testing results of 1.7-3.0 days. Affordable cost with total investment of Rp 2,300,000 remains far lower than commercial systems reaching Rp 10-20 million, making technology accessible for communities with limited resources as emphasized by Adhikari & Sitoula (2018) regarding low-cost technology importance for developing countries like Nepal and Indonesia. High accuracy with MAE 1.67 cm and accuracy 98.3% proves comparable to or better than more expensive ultrasonic sensors, with additional advantages of being unaffected by temperature, humidity, and debris. Masoudimoghaddam *et al.* (2025) achieved RMSE 5.00 cm with ultrasonic sensors, while float switches demonstrated only 2.15 cm. Minimal maintenance requirements using simple mechanical parts (float switches) eliminate need for complex calibration, unlike ultrasonic sensors requiring temperature correction and periodic calibration as reported by Wisudawan (2021) regarding float switch reliability for flood parameter monitoring in Indonesia. Fast response time of 3.8 seconds from level change to detection, and 5.5 seconds total from trigger to alarm activation, provides immediate warning to communities as emphasized by Ma'Ti *et al.* (2025) regarding local alert mechanism importance at critical levels for rapid response. Zero false alarms during testing builds community trust in the system, addressing societal challenges identified by Perera *et al.* (2020) where false alarms reduce credibility in flood early warning systems. Community-based approach with direct audio-visual alarms proved more effective than SMS or applications requiring phone and internet access, aligning with last mile communication concepts from Shrestha *et al.* (2021) and Syed *et al.* (2021).

The designed system faces several limitations requiring consideration for improvement. Alarm range limitation of 100-150 meters proves insufficient for wide coverage areas or scattered settlements, suggesting solutions through adding alarm units at strategic locations or integrating with existing communication systems like WhatsApp groups or community radio as demonstrated by Megawati *et al.* (2025) using dual connectivity (online-offline) to extend coverage. Float switch sensors detecting only three discrete levels (0.5m, 1.0m, 1.5m) without providing continuous measurement like ultrasonic sensors can be addressed by adding ultrasonic sensors as secondary sensors for applications requiring detailed water level data, as implemented by Kharisma & Puspitaningrum (2025) using HC-SR04 ultrasonic for real-time water level monitoring with high resolution. Absence of data logging or remote monitoring capabilities limits the system to local alarms without storing historical data for analysis, addressable through adding GSM modules or LoRa communication to transmit data to servers as demonstrated by Zakaria *et al.* (2023) and Mandal *et al.* (2024) using LoRaWAN for extensive network connectivity with minimal power consumption. Battery backup of 1.7-3.0 days, while sufficient for normal conditions, may prove insufficient during prolonged rain of 5-7 days, requiring solutions through upgrading battery capacity from 12Ah to 20-30Ah or adding solar panels from 100W to 150-200W to increase charging rate as detailed by Malek *et al.* (2023) regarding different battery types (lithium-polymer and lead-acid) ensuring continuous operation. Standalone system operation without integration to national warning systems or BMKG prevents leveraging weather forecasts for predictive warning, addressable through integration with BMKG API or EWIN (Emergency Water Information Network) systems to increase lead time from reactive (3.5 hours) to proactive (12-24 hours) as emphasized by Aprianti *et al*. (2025) regarding real-time monitoring integration with instant notifications. Testing conducted over limited period (7 days stress test) has not covered long-term reliability assessment or seasonal variation, necessitating field deployment for 6-12 months to validate sustainability and identify potential issues as demonstrated by Kalyanapu *et al*. (2023) through two-year monitoring showing "Very Good" agreement in statistical metrics.

The designed system demonstrates competitive performance compared to previous research in Indonesia and developing countries across multiple aspects. Sensor accuracy achieved MAE 1.67 cm and accuracy 98.3%, superior to Mydlarz *et al*. (2024) FloodNet ultrasonic error of 33 mm and comparable to Masoudimoghaddam *et al*. (2025) RMSE 5.00 cm, while Mousa *et al*. (2016) achieved error <2 cm but required Artificial Neural Networks for processing compared to float switches providing high accuracy with simple mechanical mechanisms. Energy performance reached consumption of 312 Wh per day with 1.7-3.0 day backup, higher than Uranus *et al*. (2022) at 11.52 Wh per day due to LED lamp inclusion, but remains sustainable with 83.9 Wh per day solar surplus aligning with Megawati *et al*. (2025) reporting energy-efficient design with solar-powered and optimized battery discharge matching 88% charging efficiency testing results. Alarm effectiveness achieved 100-150 meter range with 98% combined effectiveness, aligning with Ma'Ti *et al*. (2025) using local alert mechanisms and Megawati *et al*. (2025) implementing two-tier alert systems. System reliability reached 100% uptime during 7 days testing with zero part failures, exceeding industrial standard 95-98% for IoT systems, while Tyagi *et al*. (2021) conducted reliability modeling without field data compared to real field data validation provided by the system. Cost aspect at Rp 2,300,000 proves very affordable compared to commercial systems at Rp 10-20 million, aligning with low-cost technology concepts from Adhikari & Sitoula (2018) for Nepal and developing countries. Community acceptance aspect shows high adoption potential based on design principles from Mercado (2016) regarding community-based flood early warning systems and Sufri *et al*. (2020) regarding community engagement in disaster early warning systems.

Prototype design and testing results provide several implications for full-scale field implementation. Technical feasibility proved through accuracy, reliability, and effectiveness meeting targets indicates readiness for deployment at actual flood locations. Affordable cost of Rp 2,300,000 with low OPEX of Rp 440,000 per year enables replication at multiple locations without significant financial burden, where communities can self-sustain with Rp 5,000 per household per month contributions (Rp 250,000 per month for 50 households) sufficient to cover maintenance and spare parts. Design simplicity with standard parts available in local markets facilitates procurement and maintenance without requiring high technical expertise or imported spare parts. Community-based approach with direct audio-visual alarms proved more effective than SMS or applications, suitable for Indonesian conditions where not all residents have smartphones or stable internet access. Integration with existing local structures (RT/RW, community leaders) facilitates adoption and sustainability without requiring new organization formation. High scalability through modular system design allows adding alarm units to extend coverage, sensors to increase accuracy, or communication modules for remote monitoring. Environmental sustainability using renewable energy (solar) and zero emission operation aligns with Sustainable Development Goals (SDGs) particularly Goal 11 (Sustainable Cities and Communities) and Goal 13 (Climate Action) as emphasized by Schismenos *et al*. (2022) regarding humanitarian engineering importance for renewable energy in disaster risk reduction. Integration potential with existing systems like BMKG weather forecasts, BPBD disaster management, or national early warning systems can increase lead time and coordination as detailed by Aprianti *et al*. (2025) regarding systematic disaster management approaches including Emergency Water Information Network (EWIN) integration.

Based on testing results and limitation analysis, several recommendations emerge for further system development. Field deployment for 6-12 months at actual flood locations would validate long-term reliability, seasonal variation, and actual community response, providing insights about maintenance requirements, failure modes, and improvement opportunities not identified in laboratory testing. Adding data logging capability using SD card modules or cloud storage would save historical data on water levels, battery voltage, alarm activation, and weather conditions valuable for flood prediction modeling, system optimization, and performance benchmarking as demonstrated by Prastyo *et al*. (2025) integrating IoT sensing with machine learning for flood prediction based on historical patterns. Integrating communication modules (GSM or LoRa) for remote monitoring and notifications to stakeholders (BPBD, RT heads, residents via SMS/WhatsApp) follows approaches by Zakaria *et al*. (2023) and Mandal *et al*. (2024) using LoRaWAN for seamless data transfer with minimal power consumption, and Kamali *et al*. (2023) integrating social media platforms (Twitter and Telegram) for real-time alerts to communities. Adding weather sensors (rainfall, temperature, humidity) for correlation analysis and predictive modeling enables rainfall versus water level correlation for early prediction based on BMKG forecasts, increasing lead time from 3.5 hours (reactive) to 12-24 hours (proactive) as demonstrated by

Prakash *et al*. (2022) using LSTM neural networks for flash flood monitoring and forecasting. Developing mobile applications for user-friendly interfaces, real-time monitoring, historical data visualization, and customizable notification settings would display current water levels, trend predictions, evacuation routes, and emergency contacts as implemented by Kharisma & Puspitaningpur (2025) using NodeMCU ESP32 with web interfaces for real-time monitoring. Expanding coverage by adding sensor nodes at multiple locations (upstream and downstream) for watershed monitoring enables multi-point monitoring to detect flood propagation and provide more accurate predictions as demonstrated by Silverman *et al*. (2022) using ultrasonic flood sensor networks for hyperlocal street-level monitoring in New York City. Integration with BMKG API and national early warning systems to leverage weather forecasts and coordinate with disaster management agencies follows approaches detailed by Aprianti *et al*. (2025) regarding Emergency Water Information Network (EWIN) integration for systematic disaster management.

5. Conclusion and Recommendations

The solar-powered flood Early Warning System (EWS) for Aceh region was successfully designed with affordable cost of Rp 2,300,000, meeting all established technical targets. The system integrates 100W solar panel, 12V 12Ah LiFePO4 battery with 1.7-3.0 day backup, XH-M203 controller, three IP68 float switches at heights of 0.5m, 1.0m, and 1.5m, and 2-in-1 alarm (strobe and 110dB siren). Modular design enables autonomous operation without PLN electricity dependence, suitable for remote Aceh areas or when infrastructure is disrupted. Water level detection accuracy reached 98.3% with Mean Absolute Error 1.67 cm and Root Mean Square Error 2.15 cm. Sensor response time of 3.8 seconds and total system response time 5.5 seconds provides immediate community warning with zero false alarms during 30 tests. Float switches proved more reliable than ultrasonic sensors for turbid, debris-filled Aceh river conditions, requiring no complex calibration and minimal maintenance, aligning with Wisudawan (2021) and Ma'Ti *et al*. (2025) research. The 2-in-1 audio-visual alarm achieved 100-150 meter range with 95-98% combined effectiveness. Strobe reaches 100-200 meters at night while 110-120dB siren covers 100-150 meter radius. The combination proved effective waking residents at midnight with 100% awareness within 2 minutes, maintaining 65-80% effectiveness during heavy rain common in Aceh, consistent with Megawati *et al*. (2025) two-tier alert mechanism. System reliability reached 100% uptime during 7 days continuous testing without failures. The 100W solar panel provides 83.9 Wh daily surplus (26.9% of 312.1 Wh consumption) with 88% charging efficiency. Battery backup of 41 hours without charging or 72 hours with daily surplus exceeds the 48-hour target. Environmental stress testing confirmed normal operation under extreme Aceh climate conditions. Total Cost of Ownership over 3 years is Rp 3,620,000 (CAPEX Rp 2,300,000 + OPEX Rp 1,320,000), affordable for limited-resource communities. Low OPEX of Rp 440,000 annually can be covered by Rp 5,000 monthly household contributions, enabling community self-sustainability throughout Aceh.

Data logger and IoT gateway implementation would record historical water levels, battery voltage, alarm activation, and weather conditions for flood prediction modeling. GSM or LoRa integration enables real-time monitoring by BPBA with web dashboard or mobile app for data visualization, as demonstrated by Prastyo *et al*. (2025) using Firebase Cloud Messaging and Zakaria *et al*. (2023) using LoRaWAN. Rainfall sensor integration (tipping bucket) for rainfall-water level correlation can increase lead time from 3.5 hours (reactive) to 12-24 hours (proactive) using machine learning (LSTM or Random Forest) with BMKG Aceh forecast data through API. Comparative sensor studies should evaluate float switch versus ultrasonic versus pressure sensors under actual Aceh conditions across various geographical settings (large rivers, small streams, urban, rural, clear water, turbid water) in different districts. Battery and solar panel optimization research for varying sun hours and cloud coverage across Aceh requires evaluating optimal capacity sizing and battery chemistry alternatives (Lead Acid versus LiFePO4 versus Lithium-ion). Long-term reliability studies extending monitoring to 1-2 years would evaluate part degradation, seasonal variation (rainy versus dry seasons), failure patterns, and MTBF data for predictive maintenance models suited to Aceh climate.

Intensive socialization and training for Aceh communities on evacuation procedures, first aid, and disaster preparedness through regular training twice annually with evacuation simulations maintains readiness. User manual and SOP development in Indonesian with visual illustrations accommodates low-literacy users. Emergency contact lists and communication trees enable rapid information dissemination at gampong and RT/RW levels. Emergency response teams at gampong/RT levels need clear roles (coordinator, evacuator, first aid, logistics) with local champion training for maintenance and troubleshooting support, coordinating with BPBA, Puskesmas, and Polsek for integrated flood response. Biweekly maintenance schedules for cleaning sensors, checking battery voltage, and testing alarms ensure reliability. Monthly inspections cover wiring, connectors, solar panel cleanliness, and panel box seals. Quarterly full system tests using simulated flood scenarios verify all parts function normally. Maintenance checklists and logbooks document maintenance history at each Aceh location. Continuous battery and solar panel monitoring with voltage monitors sets alert thresholds for low battery voltage (below 11.5V) for preventive action. Monthly solar panel cleaning maintains efficiency during dry seasons with high dust accumulation. Post-event documentation includes timestamp, water level, alarm activation, community response, evacuation time, and lessons learned. Post-event evaluation meetings with residents and stakeholders enable continuous improvement. Biannual community feedback surveys measure satisfaction and effectiveness across Aceh districts.

Aceh Government scaling up requires system replication at flood-prone points identified by historical occurrences (minimum twice yearly), population density, flood severity, economic loss, and vulnerability. Multi-criteria decision analysis prioritizes replication to maximize impact with limited budgets. APBD or Dana Gampong allocation for initial investment (Rp 2.3 million per unit) and maintenance (Rp 440 thousand per unit annually) targets 10-20 unit installation within 1-2 years for coverage. Integration with BPBA, BMKG Aceh, and BNPB systems through data sharing protocols and SOP establishes multi-level warnings from gampong to district levels. Interoperability standards ensure seamless communication throughout Aceh Province. Sustainable maintenance funding through APBD or Dana Gampong with 3-year minimum commitment, contingency funds for emergency repairs, and 50-50 cost-sharing between government and community encourages ownership and sustainability. Local technician training through ToT for BPBA technicians and related agencies, certification programs (basic, intermediate, advanced levels), technical support hotlines or WhatsApp groups for troubleshooting, and toolkits with spare parts enable quick repairs without external support. Annual impact evaluation on flood loss reduction, casualties, evacuation time, community satisfaction, and cost-effectiveness with baseline data comparison quantifies benefits and calculates return on investment. Impact reports justify continued investment or program scaling throughout Aceh.

Aceh communities ensure sustainability through active participation in regular evacuation simulations, preparing emergency bags (documents, medicines, clothing, food, water for 2-3 days), teaching children about alarm meanings and responses, and establishing family emergency plans (meeting points, emergency contacts). Immediate damage reporting to geuchik/RT or volunteers for non-sounding alarms, broken sensors, or dirty solar panels, providing post-event feedback, and participating in community meetings for improvement discussions at gampong level maintain system functionality. Maintaining sensor area cleanliness by not throwing garbage into rivers, reporting accumulated garbage for officer cleaning, participating in regular river cleaning gotong royong, and educating neighbors about river cleanliness importance for flood prevention and sensor reliability protect system operation. Spreading alarm information by immediately informing neighbors especially elderly and disabled persons, using gampong/RT WhatsApp groups for rapid dissemination, helping neighbors requiring evacuation assistance (elderly, children, pregnant women, persons with disabilities), and establishing buddy systems where families check 2-3 nearest neighbors ensures no one is left behind. Providing feedback through satisfaction surveys and Focus Group Discussions, offering constructive improvement suggestions (additional alarm locations, new features, evacuation procedure improvements), sharing experiences and testimonials to increase awareness, and advocating for replication in other flood-prone areas extends protection throughout Aceh. Consistent Rp 5,000 monthly household contributions cover maintenance costs and spare parts, participating in gampong meetings for fund transparency and decision making, understanding maintenance costs (Rp 60,000 per household annually) are far smaller than benefits received (estimated flood loss savings), and developing ownership mindset "this is our system for collective Aceh safety, not government system" ensures long-term sustainability aligned with community-based disaster risk reduction principles empowering Aceh communities as primary actors in flood disaster risk reductio.

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