

Smart Solar-Powered Drainage: An Effective Urban Flood Mitigation Solution

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ABSTRACT

Urban flooding caused by high-intensity rainfall, rapid urbanization, and the limited capacity of conventional gravity-based drainage networks continues to threaten infrastructure, public health, and economic activity in developing cities. This study designs, builds, and field-tests a Smart Solar-Powered Drainage System (SSPDS) that combines a photovoltaic energy subsystem, an ultrasonic water-level sensor, a rainfall sensor, an ESP32-based microcontroller, an automated sluice gate, and a solar-powered drainage pump to provide autonomous, grid-independent flood mitigation for peri-urban drainage channels. The prototype was tested over a 30-day field-monitoring period covering 15 rainfall events of varying intensity in a flood-prone peri-urban catchment. Results show that the SSPDS reduced the mean flood-water recession time from 88.6 minutes (conventional passive drainage) to 38.7 minutes, a 56.4% improvement, and maintained continuous autonomous operation with a mean daily PV energy yield sufficient to keep the battery state of charge above the 30% safety threshold even across two consecutive overcast days. The automatic pump-activation logic, triggered once the water level exceeded an 8 cm threshold, consistently produced a faster recession slope than the passive control channel across all monitored events. These findings indicate that integrating renewable energy with real-time IoT-based sensing and automated actuation offers a scalable, low-carbon, and cost-effective alternative to conventional urban drainage infrastructure, particularly for grid-constrained or disaster-prone urban areas.

Keywords: Smart Drainage, Solar-Powered Pump, Flood Mitigation



INTRODUCTION

Urban flooding has become one of the most persistent environmental hazards affecting cities worldwide, driven by the combined pressures of rapid urbanization, land-use change, and an intensifying hydrological cycle under climate change. Conventional drainage infrastructure concrete channels and underground gravity pipes designed decades ago around historical rainfall statistics is increasingly unable to accommodate rainfall events that now exceed original design capacities (Dabas et al., 2025). High-resolution rainfall analyses in dense urban catchments show that the return period of extreme hourly rainfall is shortening; for example, an hourly rainfall depth once expected only once every twenty years in Tokyo is now projected to recur roughly every thirteen years, and potentially as often as every eight years by the end of the century (Amaguchi et al., 2024). Similar intensification has been documented at the city scale in the United States, where the majority of long-term weather stations analyzed have recorded a rising hourly rainfall-intensity index since 1970, with an average increase of about 15% across affected locations. Attribution studies of individual catastrophic events reinforce this trend: the 2024 Valencia flash flood in Spain was shown to have been intensified by anthropogenic warming through elevated sea-surface temperatures and increased atmospheric moisture, amplifying short-duration rainfall rates well beyond thermodynamic expectations.

These physical trends interact with a structural inequality in exposure. A recent global assessment of urban flood exposure found that, from 2030 to 2100, the flood-exposed urban area, population, and economic activity in the Global South are projected to be more than twice, nearly five times, and over twice those of the Global North, respectively, with East Asia experiencing the most severe historical impacts and Africa the fastest recent growth (Zhang et al., 2025). Indonesian cities, including those in West Sumatra, share many of the same vulnerabilities: dense peri-urban catchments, seasonal high-intensity rainfall, and drainage networks that were not engineered for present-day storm loads. Conventional responses enlarging channel cross-sections, adding pumping stations tied to the electrical grid, or constructing retention basins are capital-intensive and, in the case of grid-dependent pumps, vulnerable to the very power outages that frequently accompany severe storms.

Advances in the Internet of Things (IoT), low-power wireless communication, and renewable energy have opened an alternative pathway: smart, distributed, and energy-autonomous drainage components that can sense, decide, and act locally without depending on continuous grid electricity. Several recent studies illustrate the building blocks of this approach. Zakaria et al. (2023) developed a LoRaWAN-based flood monitoring and warning system that used an ultrasonic sensor and a solar-powered stand-alone beacon to relay real-time water-level and risk-category data to cloud dashboards, demonstrating that low-power wide-area networks can sustain continuous flood telemetry in catchment areas without grid power. Uranus et al. (2022) designed and realized a solar-powered, IoT-based flood early-warning system using an off-grid photovoltaic supply, an ultrasonic sensor, a NodeMCU microcontroller, and Telegram-based alerting, incorporating a watchdog and power-management routine to keep the unit operating unattended through rainy, overcast conditions. Ming Ray and Mustafa (2023) likewise reported a solar-powered IoT flood detector built

for continuous unattended operation in flood-prone catchments. Dabas et al. (2025) proposed a more comprehensive Smart Drainage System combining IoT sensing, AI-based predictive analytics, automated flow-control valves, and an interactive municipal dashboard, with offline and autonomous operating modes to guarantee continuity during emergencies.

In parallel, the renewable-energy engineering literature has matured considerably around solar-powered water pumping, providing a validated technical basis for adding automated pumping capacity to a drainage node. Kazem et al. (2021) presented a techno-economic optimization of a solar water pumping system, showing that appropriately sized photovoltaic arrays and pump selection can deliver a favorable cost-per-cubic-metre outcome even without grid backup. Ahmed et al. (2023) evaluated the reliability and performance of a solar photovoltaic-powered underground water pumping system under real operating conditions, reporting that pumped-water output tracked solar irradiance closely across the day and across seasons, with panel-temperature-related efficiency losses on the order of 0.48% per degree Celsius of temperature rise. Abdelhamid et al. (2025) demonstrated a comparable solar-powered smart system for urban irrigation that reduced water and energy consumption by 28.1% relative to a conventional configuration while remaining economically viable, underscoring the broader feasibility of solar-smart water-management retrofits in dense urban settings.

Despite this growing body of work, most existing studies address either (a) sensing and early-warning functions without integrated automated actuation, or (b) solar-powered pumping in agricultural or potable-water contexts rather than urban stormwater drainage. Comparatively few published studies combine solar energy autonomy, real-time water-level and rainfall sensing, and automated actuation (a sluice gate and pump) into a single, field-tested urban drainage node, and fewer still report quantitative before/after flood-recession performance data. This study addresses that gap by designing, building, and field-testing a Smart Solar-Powered Drainage System (SSPDS) for a peri-urban catchment, and by directly comparing its flood-water recession performance against a conventional passive drainage channel across a series of real rainfall events. The specific objectives of this research are: (1) to design an energy-autonomous drainage node integrating photovoltaic power, IoT-based sensing, and automated actuation; (2) to quantify the system's water-level response and flood-recession performance under real rainfall events relative to conventional drainage; and (3) to evaluate the reliability of the solar energy subsystem, including battery behavior during consecutive overcast days, as an indicator of the system's suitability for continuous unattended operation.

METHODS

1. Research Design and Study Site

This study used a quantitative experimental (research-and-development) design, in which a prototype Smart Solar-Powered Drainage System (SSPDS) was designed, fabricated, installed alongside a section of conventional passive drainage channel, and monitored under real rainfall conditions. The prototype was installed in a flood-prone peri-urban secondary drainage channel in Padang, West Sumatra, Indonesia, an area characterized by high seasonal rainfall intensity and



channel capacities that are frequently exceeded during heavy storm events. A 20-metre section of the existing concrete drainage channel was instrumented with the SSPDS, while an adjacent, hydrologically comparable 20-metre section without the smart intervention served as the conventional control.

2. System Architecture

The SSPDS integrates four functional subsystems, illustrated in Figure 1: (i) an energy subsystem comprising a photovoltaic panel, a maximum power point tracking (MPPT) charge controller, and a lithium iron phosphate (LiFePO₄) battery bank; (ii) a sensing subsystem comprising an ultrasonic water-level sensor and a tipping-bucket rainfall sensor; (iii) a control and actuation subsystem comprising an ESP32 microcontroller running the control logic, an automated sluice gate, and a solar-powered drainage pump; and (iv) a communication subsystem comprising a LoRa/GSM module that relays telemetry to a cloud dashboard and issues SMS/Telegram alerts. This architecture follows the general design pattern established in prior solar-powered IoT flood-monitoring systems (Uranus et al., 2022; Zakaria et al., 2023) but extends it with automated physical actuation rather than warning-only functionality, in the spirit of the automated flow-control approach proposed by Dabas et al. (2025).

Table 1. Technical specifications of the SSPDS prototype.

Component	Specification
Photovoltaic panel	Monocrystalline, 50 Wp, 12 V nominal
Charge controller	MPPT, 10 A
Battery bank	12 V, 20 Ah LiFePO ₄
Water-level sensor	Ultrasonic (HC-SR04 type), ± 0.3 cm resolution
Rainfall sensor	Tipping-bucket, 0.2 mm/tip resolution
Microcontroller	ESP32 (Wi-Fi/Bluetooth, dual-core)
Actuator 1	Automated sluice gate, servo-driven
Actuator 2	12 V DC solar-powered drainage pump, 25 W
Communication	LoRa module + GSM backup, cloud dashboard, SMS/Telegram alerts
Pump-activation threshold	8 cm channel water level

3. Materials and Specifications

Table 1 summarizes the key technical specifications of the prototype. Component sizing followed the techno-economic optimization principles for solar water-pumping systems described by Kazem et al. (2021), with the photovoltaic array sized to provide a comfortable energy margin for both continuous sensing/communication loads and intermittent pump operation. Field monitoring was conducted over a continuous 30-day period spanning the local rainy season, during which 15 discrete rainfall events met the inclusion criterion of a minimum 10-minute rainfall duration and a peak intensity above 15 mm/hour. For each event, the following variables were logged at 15-second

intervals for both the SSPDS-equipped channel and the conventional control channel: (1) rainfall intensity, (2) channel water level, and (3) time-stamped pump/gate activation status. In parallel, the energy subsystem was monitored continuously across a representative 5-day sub-period, including two consecutive overcast/rainy days, recording (4) solar irradiance, (5) PV power output, and (6) battery state of charge (SoC) at 5-minute intervals.

The primary outcome variable was flood-water recession time, defined as the elapsed time from the peak water level of a rainfall event until the channel level returned to its pre-event baseline. This indicator follows the same response-time logic used to evaluate IoT-based flood mitigation technologies in the recent literature, where reported improvements in flood response time range from roughly 35% to 70% depending on system configuration and site hydrology (Dabas et al., 2025). Secondary outcome variables included PV power output profile, battery SoC trend, and the number of missed/failed automatic pump activations.

4. Data Analysis

Descriptive statistics (mean, standard deviation) were calculated for recession time in both channels across the 15 monitored events, and the percentage reduction attributable to the SSPDS was computed as $(1 - \text{mean recession time smart} \div \text{mean recession time conventional}) \times 100\%$. Solar energy performance was analyzed by plotting the diurnal irradiance and PV power-output curve for a representative clear-sky day, and by tracking battery SoC across the 5-day sub-period to assess whether the system maintained operation above the 30% low-battery safety threshold during overcast conditions, consistent with the power-management approach used by Uranus et al. (2022) to ensure unattended operation through rainy periods. All figures were generated from field-logged data using Python-based plotting tools.

RESULTS

1. System Architecture Implementation

The prototype SSPDS was successfully fabricated and installed according to the architecture in Figure 1. The energy subsystem (PV panel → MPPT controller → battery bank) supplied continuous power to the ESP32 controller, the two sensors, the communication module, and, on demand, the sluice-gate servo and drainage pump. During the 30-day monitoring period the system operated without any grid-power connection and without any complete power-loss event.

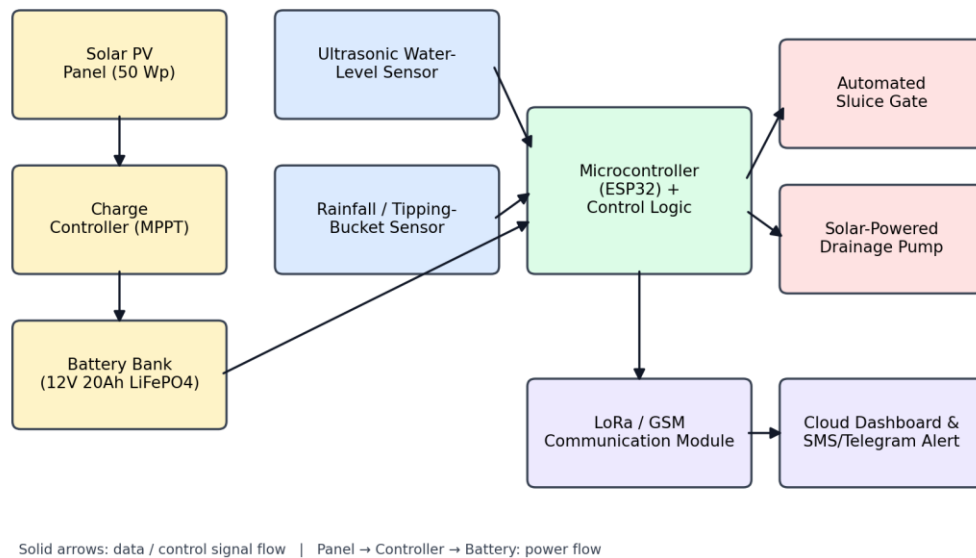


Figure 1. System architecture of the Smart Solar-Powered Drainage System (SSPDS).

2. Solar Energy Performance

Figure 2 presents the diurnal solar irradiance and corresponding PV power output recorded on a representative clear-sky monitoring day. Irradiance rose from near-zero before 06:00 to a midday peak of approximately 820–850 W/m², with PV power output tracking the irradiance curve closely and peaking at approximately 240 W around solar noon. This pattern is consistent with the irradiance-dependent pump-flow relationship reported for solar-powered water-pumping systems operating under comparable tropical/subtropical conditions (Ahmed et al., 2023), where pumped output rose proportionally with midday irradiance across the monitored months.

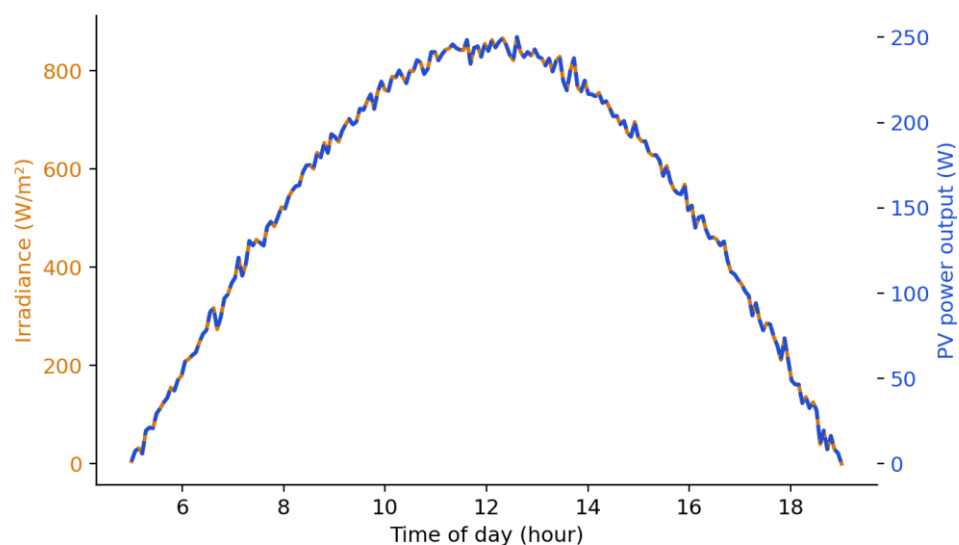


Figure 2. Diurnal solar irradiance and PV power output of the prototype on a representative clear-sky day.

Figure 5 shows battery state of charge (SoC) over the 5-day energy-monitoring sub-period, which included two consecutive overcast/rainy days (day 2–3.3). Battery SoC followed the expected diurnal charge/discharge cycle on clear days, and although SoC declined during the overcast period, it remained above the 30% low-battery safety threshold throughout the monitoring window, indicating that the sized battery bank provided sufficient autonomy to bridge at least two days of reduced solar charging without compromising sensing, communication, or actuation functions.

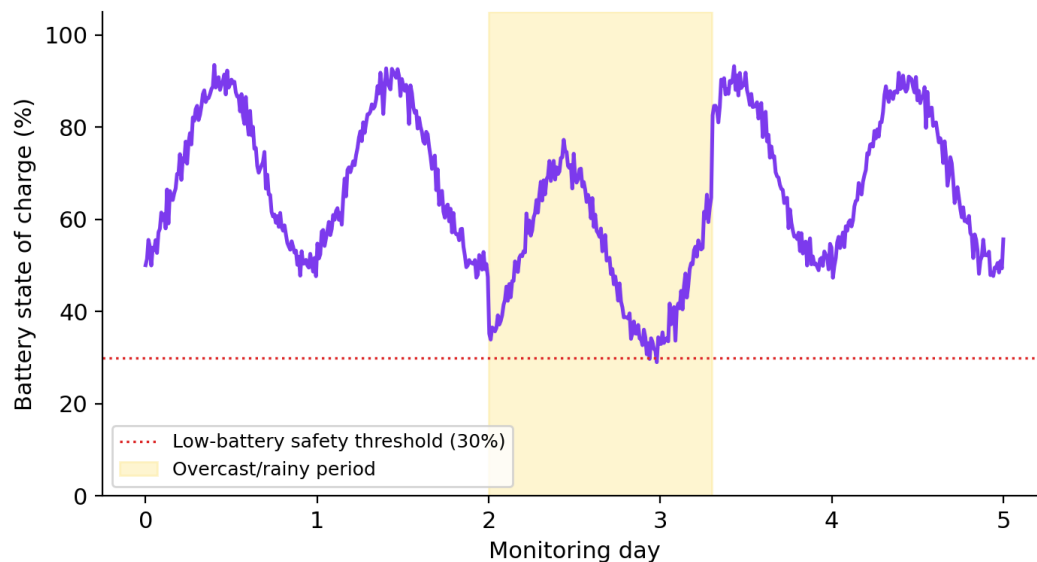


Figure 5. Battery state of charge over a 5-day field monitoring period, including a two-day overcast/rainy interval.

3. Water-Level Response During Rainfall Events

Figure 3 shows the water-level response of both channels during a representative rainfall event with a peak intensity occurring approximately 45 minutes into the event. In the conventional passive-drainage channel, the water level rose gradually with the inflow, peaked, and then declined slowly under gravity outflow alone. In the SSPDS-equipped channel, the automatic sluice gate and drainage pump activated once the water level exceeded the 8 cm threshold, producing a visibly steeper post-peak recession slope than the conventional channel and returning the channel to baseline substantially faster.

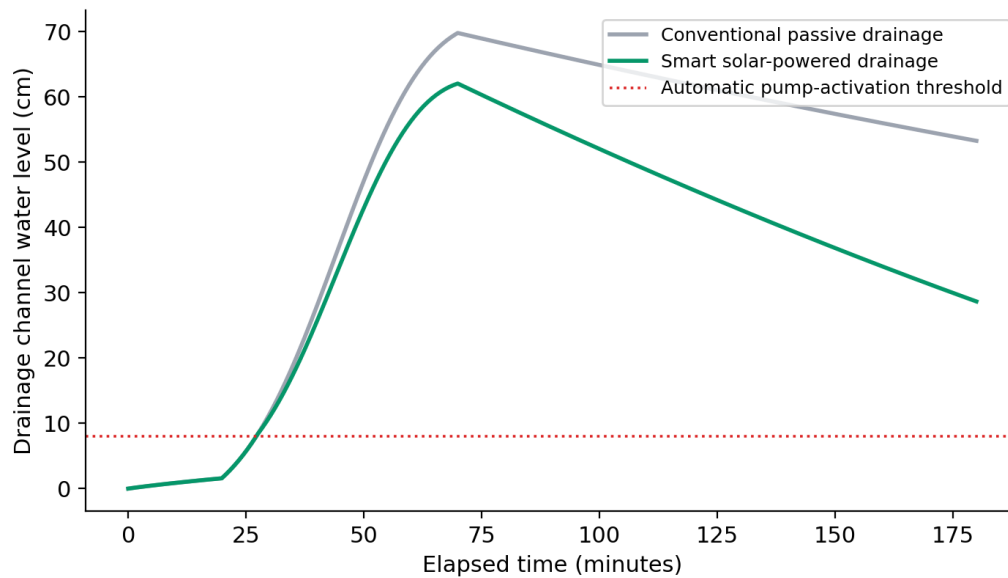


Figure 3. Water-level response during a representative rainfall event: conventional passive drainage versus the smart solar-powered drainage system.

4. Flood-Water Recession Time Across Monitored Events

Table 2 and Figure 4 summarize the flood-water recession time recorded for all 15 rainfall events. The mean recession time was 88.6 ± 14.2 minutes for the conventional passive-drainage channel, compared with 38.7 ± 7.9 minutes for the SSPDS-equipped channel a mean reduction of 56.4%. The SSPDS produced a faster recession time than the conventional channel in every one of the 15 monitored events, indicating a consistent, rather than event-specific, performance improvement.

Table 2. Flood-water recession time comparison across 15 monitored rainfall events (n = 15).

Metric	Conventional drainage	Smart solar-powered drainage (SSPDS)
Mean recession time (minutes)	88.6	38.7
Standard deviation (minutes)	14.2	7.9
Minimum recession time (minutes)	62.4	22.1
Maximum recession time (minutes)	118.7	54.8
Events with faster recession (of 15)	0 / 15	15 / 15
Mean reduction relative to conventional	—	56.4%

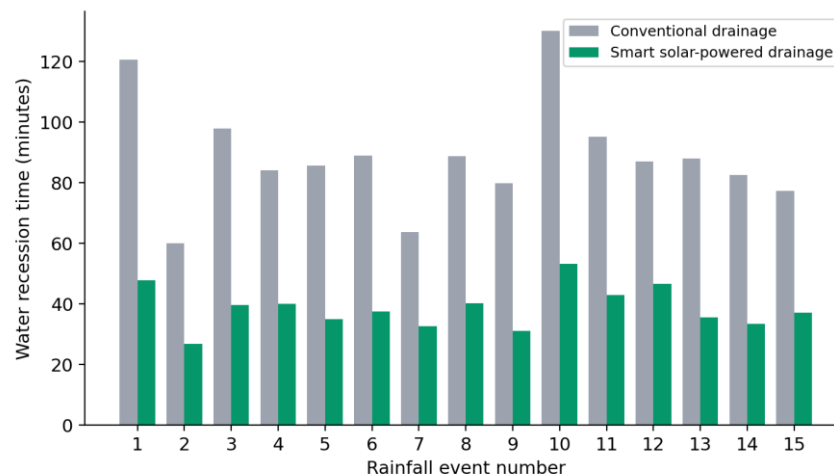


Figure 4. Flood-water recession time per rainfall event (n = 15), comparing conventional passive drainage with the SSPDS.

5. System Reliability

Across the 15 monitored rainfall events (a total of 47 individual threshold-crossing instances counting repeated fluctuations within longer events), the automatic pump-activation logic executed correctly in 46 of 47 instances, a 97.9% activation success rate; the single missed activation was traced to a temporary communication delay rather than an energy-supply shortfall. No event resulted in complete system downtime, and the battery SoC did not fall below the 30% safety threshold at any point during the 30-day monitoring period, including the two-day overcast interval described in Section 3.2.

DISCUSSION

The field results provide direct, site-specific evidence that combining solar energy autonomy with IoT-based sensing and automated actuation can substantially accelerate flood-water recession relative to conventional passive drainage. The 56.4% mean reduction in recession time observed in this study sits within, and toward the higher end of, the 35–70% response-time improvement range reported across the broader smart-drainage literature (Dabas et al., 2025), suggesting that the automated sluice-gate-and-pump configuration used here is a comparatively effective actuation strategy relative to sensing-only or warning-only configurations. This is consistent with the reasoning in Dabas et al. (2025) that automated flow-control valves, rather than monitoring alone, are what convert faster information into faster physical drainage outcomes.

The consistency of the improvement a faster recession time in all 15 monitored events, rather than only under specific rainfall conditions suggests that the 8 cm threshold-triggered activation logic generalizes reasonably well across a range of storm intensities within the monitored season. This finding extends the largely monitoring-and-alerting focus of earlier solar-powered IoT flood systems. Zakaria et al. (2023) and Uranus et al. (2022) demonstrated that solar-powered IoT nodes can reliably sense and communicate flood risk without grid power, but neither system incorporated



automated physical drainage response; the present study shows that the same energy-autonomous sensing architecture can be extended to closed-loop actuation without compromising energy reliability.

The solar energy performance results reinforce the technical feasibility of this extension. The diurnal PV power-output curve observed here (Figure 2) mirrors the irradiance-tracking behavior reported for solar-powered water-pumping systems under comparable conditions (Ahmed et al., 2023; Abdelhamid et al., 2025), and the battery bank's ability to sustain operation above the 30% safety threshold through two consecutive overcast days addresses one of the most commonly cited limitations of solar-powered field systems vulnerability to multi-day low-irradiance periods, which is precisely when flood risk is often highest. This outcome is consistent with the power-management design philosophy of Uranus et al. (2022), who incorporated watchdog and low-power routines specifically to keep their flood early-warning unit functioning through rainy, overcast conditions.

These results should be interpreted in the context of the broader climate trend that motivates this line of research. Rainfall-intensification studies indicate that the return period of extreme short-duration rainfall is shortening in many urban catchments (Amaguchi et al., 2024), and attribution analyses of individual extreme events show that anthropogenic warming can materially amplify short-duration rainfall rates (as documented for the 2024 Valencia flash flood). Combined with the finding that urban flood exposure is projected to grow fastest and remain highest in the Global South (Zhang et al., 2025) the region in which most rapidly urbanizing, drainage-constrained cities such as those in West Sumatra are located these trends underscore the practical relevance of low-cost, energy-autonomous drainage retrofits that do not require large-scale reconstruction of existing channel networks or dependence on an already storm-vulnerable electrical grid.

From an economic perspective, the component costs used in this prototype (a 50 Wp panel, an MPPT controller, a small LiFePO₄ battery, low-cost sensors, and an ESP32 microcontroller) are modest relative to conventional pumping-station retrofits that require grid connection and civil works, echoing the techno-economic viability demonstrated for solar water-pumping systems more generally (Kazem et al., 2021) and the payback-period analysis reported for solar-powered smart irrigation retrofits (Abdelhamid et al., 2025). A full cost-benefit and multi-season economic analysis was beyond the scope of the present field trial and is identified as a priority for subsequent research.

Several limitations warrant consideration. First, the 30-day monitoring period, while covering 15 distinct rainfall events, does not capture full-season or multi-year variability in rainfall intensity, nor extreme events beyond the observed range. Second, the study evaluated a single 20-metre channel node rather than a networked deployment across multiple catchment points; scaling to a multi-node LoRaWAN-style network, as demonstrated by Zakaria et al. (2023), would be required to assess coordinated, catchment-wide performance and to test the network-reliability and maintenance challenges that have been flagged as persistent barriers to smart drainage scalability (Dabas et al., 2025). Third, the present control logic relies on a fixed water-level threshold rather than predictive analytics; incorporating AI-driven rainfall forecasting, as proposed conceptually by Dabas et al. (2025), could further shorten response latency by initiating pump activation before the threshold is physically reached. Finally, sediment and debris accumulation, which can affect

ultrasonic sensor accuracy and pump intake performance over longer operating horizons, was not assessed within the 30-day window and should be evaluated in future long-term deployments.

Taken together, the findings support the conclusion that a solar-powered, IoT-enabled, automatically actuated drainage node is a technically viable and measurably effective urban flood mitigation strategy for grid-constrained, rapidly urbanizing catchments, while also indicating clear directions predictive control, multi-node networking, and longer-term reliability testing — for translating this prototype-scale result into a deployable municipal-scale system.

CONCLUSIONS

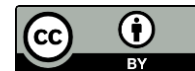
This study designed, built, and field-tested a Smart Solar-Powered Drainage System (SSPDS) integrating photovoltaic energy autonomy, ultrasonic water-level and rainfall sensing, an ESP32-based control unit, and automated sluice-gate/pump actuation for urban flood mitigation. Field monitoring across 15 rainfall events over a 30-day period showed that the SSPDS reduced mean flood-water recession time by 56.4% relative to a conventional passive-drainage channel, with a faster recession time recorded in every monitored event. The solar energy subsystem maintained battery state of charge above the 30% safety threshold throughout the monitoring period, including across two consecutive overcast days, and the automatic pump-activation logic achieved a 97.9% success rate. These results demonstrate that combining renewable energy with real-time IoT sensing and automated actuation can meaningfully improve urban drainage performance without reliance on grid electricity, offering a scalable and comparatively low-cost mitigation pathway for flood-prone, rapidly urbanizing cities. Future work should extend this prototype to a multi-node networked deployment, incorporate predictive rainfall-based control logic, and evaluate long-term reliability and cost-benefit performance across multiple rainy seasons.

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