

FloodGuard: A Low-Cost Turbine-Based IoT Prototype for Monitoring Flow Anomalies in Urban Stormwater Drains

Rian Kothari, Aditya Gupta, Aarush Gupta, Revant Singhania

Mumbai, India

Abstract

Urban flood management increasingly depends on spatially dense, real-time observations of drainage-system state, yet conventional instrumentation can be difficult to deploy at scale. This study evaluates a low-cost proof-of-concept sensor that uses the rotational speed of an axial turbine as a proxy for water-flow intensity in a stormwater-drain conduit. The prototype integrates a 120 mm recycled-HDPE turbine, an optical rotation sensor, an ESP32 microcontroller, and an MQTT-enabled dashboard. Bench tests were conducted in a transparent 150 mm internal diameter pipe at eight nominal flow velocities from 0.1 to 2.0 m/s. Each velocity was tested in five replicates under clean-water, debris-laden, and reverse-flow conditions. Rotation data were sampled at 1 Hz and processed using a 10 s moving average. The fitted velocity-RPM relationship met the study's predefined coefficient-of-determination criterion ($R^2 \geq 0.90$), with measured speed increasing from approximately 15–20 RPM at the lowest tested velocity to 280–320 RPM at 2.0 m/s. Simulated debris reduced RPM by a reported 8–15% relative to the clean-water baseline and increased variability. Step-change tests generated alerts within the 30 s design target, frequently within 15 s. A 30 min immersion screening test produced no observed moisture ingress. The results support the feasibility of inexpensive turbine-based monitoring for detecting changes in drain-flow intensity, but they do not yet establish field-scale flood prediction or validated bidirectional flow measurement. Field calibration, long-duration fouling tests, directional sensing, and comparison with reference hydraulic instrumentation are required before operational deployment.

Keywords: urban flooding; stormwater monitoring; low-cost sensors; Internet of Things; flow sensing; flood early warning; ESP32

1. Introduction

Mumbai experiences recurrent monsoon flooding under the combined effects of intense rainfall, tidal conditions, constrained drainage capacity, and localized obstruction. Municipal planning documents note that older portions of the stormwater system were historically designed around rainfall intensities near 25 mm h^{-1} , while subsequent augmentation planning adopted higher design intensities [1]. Mumbai's Integrated Flood Warning System (iFLOWS Mumbai) combines meteorological, hydrological, hydraulic, tidal, and geospatial information to support city-scale flood forecasting and risk assessment [2]. Such systems provide essential macroscopic situational awareness, but local drainage conditions can still vary sharply over short distances and timescales.

Recent research has therefore emphasized dense, real-time sensing as a complement to model-based flood forecasting. Low-cost monitoring can increase spatial coverage, but practical deployment remains constrained by calibration, sensor reliability, power, communications, fouling, and maintenance [3,4]. Studies have demonstrated low-cost approaches for water velocity measurement [5], storm-drain blockage detection [6], and catch-basin flood or sediment monitoring [7]. At the network scale, sensor-placement research also shows that strategically selected monitoring locations can improve drainage-state perception without instrumenting every node [8]. Singapore's national water agency provides a mature operational example, using more than 1,000 water-level sensors in drains and canals as part of its flood-monitoring system [9].

FloodGuard was developed as a proof-of-concept for inexpensive subsurface monitoring in urban stormwater drains. Rather than attempting to predict flooding directly from a single local measurement, this study asks a narrower engineering question: can a compact turbine-and-optical-sensor assembly produce repeatable measurements that track changes in flow intensity under controlled conditions, while remaining responsive in the presence of debris and sudden hydraulic changes? This framing avoids equating laboratory flow anomalies with validated flood forecasts and instead evaluates the sensing principle as a potential component of a broader monitoring network.

2. Study Objectives and Hypotheses

The primary objective was to evaluate whether turbine rotational speed could function as a low-cost proxy for flow intensity in a stormwater-drain conduit. The study tested four engineering hypotheses: (i) RPM would increase monotonically with imposed flow velocity across the tested range; (ii) debris would alter the calibration but not eliminate a usable rotational response; (iii) abrupt flow changes would be detected quickly enough to support near real-time alerts; and (iv) the enclosure would remain dry during short-duration immersion screening.

A separate reverse-flow condition was also tested. Because the described optical sensing arrangement records rotational pulses rather than rotational direction, these trials were treated as a sensitivity test rather than as validation of a true bidirectional flow meter.

3. Materials and Methods

3.1 Prototype architecture

The sensing assembly consisted of a four-blade axial turbine fabricated from recycled HDPE (120 mm diameter), an 8 mm stainless-steel shaft supported by two low-friction bearings, a 2 mm-aperture conical stainless-steel debris screen, and an optical rotation sensor with a stated measurement range of 0–5000 RPM. An ESP32 microcontroller running MicroPython counted optical pulses, calculated rotational speed, applied temporal smoothing, and transmitted threshold events over Wi-Fi using MQTT. Electronics were housed in a PVC enclosure with rubber gaskets and an IP67-rated M12 connector. The connector's component rating should not be interpreted as certification of the complete assembled enclosure.

3.2 Bench-test apparatus

Testing was conducted in a transparent acrylic pipe with a 150 mm internal diameter. A variable-flow submersible pump and digital inline flow meter were used to establish nominal flow velocities from 0.1 to 2.0 m/s. The transparent section allowed direct inspection of turbine behavior and debris interaction. The turbine was mounted centrally and perpendicular to the primary flow direction. Water temperature, pipe orientation, mounting position, and ambient test conditions were held as constant as practicable across trials.

3.3 Experimental design

Factor	Levels / setting	Purpose
Nominal flow velocity	8 set points, 0.1–2.0 m/s	Calibration across the operating range
Hydraulic condition	Clean water; debris-laden water; reverse flow	Robustness and anomaly-response testing
Replicates	5 per velocity-condition combination	Repeatability assessment
Sampling	1 Hz optical pulse-derived RPM	Raw rotational measurement
Signal processing	10 s moving average	Noise reduction and alert stability
Stabilization period	90 s at each set point before recording	Reduction of transient effects

Table 1. Experimental design used for bench validation.

For clean-water calibration, each velocity set point was maintained for 90 s before the representative RPM was recorded. The full sequence was repeated five times. Debris trials introduced polyethylene particles and small plastic fragments upstream of the turbine. Reverse-flow trials were produced by reversing the imposed flow direction. Across eight velocity levels, three conditions, and five replicates, the design corresponds to 120 velocity-condition replicate runs, although the manuscript does not claim independent inferential statistics from these runs because the trial-level dataset was not available in the source report.

3.4 Firmware, calibration, and alert logic

The ESP32 counted optical pulses over one-second intervals and continuously calculated a 10 s moving average. Calibration data were fitted with polynomial regression in Python to map imposed velocity to rotational response. The original prototype used preliminary fixed thresholds (<50, 50–500, 500–1500, and >1500 RPM); these were subsequently replaced by thresholds derived from the observed calibration behavior. Because the reported measured range in the final experiments was approximately 15–320 RPM, the preliminary threshold values should be regarded only as development-stage firmware settings, not validated operating thresholds.

Alert latency was defined as the elapsed time between a controlled step change in flow condition and generation of a threshold-breach notification. The design target was ≤ 30 s.

3.5 Waterproofing and safety screening

Before hydraulic testing, the assembled device was fully immersed in still water for 30 min and inspected for visible moisture ingress. This procedure provides a practical screening test only; it is not equivalent to independent certification of the complete enclosure to IEC 60529 IP67. All bench electronics operated at low voltage, wet testing was performed on non-conductive surfaces, and debris-containing test water was filtered before disposal.

4. Results

4.1 Calibration response

Turbine RPM increased strongly across the tested velocity range. At 0.1 m/s, the reported rotational speed was approximately 15–20 RPM; at 2.0 m/s it increased to approximately 280–320 RPM. The fitted calibration relationship met the pre-specified goodness-of-fit criterion of $R^2 \geq 0.90$. The source report does not provide the exact fitted coefficients, exact R^2 value, residual diagnostics, or trial-level measurements; accordingly, no stronger statistical claim is made here.

4.2 Effect of simulated debris

Debris-laden trials produced lower rotational speeds than the clean-water baseline at matched nominal velocities. The reported suppression ranged from approximately 8% to 15%, with increased variability attributed to intermittent contact between debris and the turbine. The magnitude of this bias is operationally important because a fouled or partially obstructed turbine could underestimate flow intensity if clean-water thresholds were used without correction.

4.3 Reverse-flow sensitivity

Reverse-flow trials produced a distinguishable change in the turbine's measured rotational response in the experimental setup. However, the single-channel optical pulse-counting method described in the prototype does not inherently encode rotational direction. These tests therefore demonstrate sensitivity to a changed hydraulic state, not validated directional flow measurement. Future versions should use a quadrature encoder, Hall-effect arrangement, or another directional sensing method if forward-versus-reverse classification is required.

4.4 Alert latency and immersion screening

All reported step-change tests satisfied the ≤ 30 s alert target, and many alerts were generated within 15 s. The 10 s moving average therefore did not prevent timely threshold detection under the controlled bench conditions. Following the 30 min immersion screen, no visible moisture ingress was reported in the electronics compartment.

Outcome	Reported result	Interpretation
Velocity-RPM calibration	~15–20 RPM at 0.1 m/s; ~280–320 RPM at 2.0 m/s; R^2 criterion ≥ 0.90 met	Supports RPM as a proxy for flow intensity in bench tests
Debris sensitivity	~8–15% lower RPM than clean water baseline	Calibration is condition dependent
Reverse-flow response	Distinct response observed in reverse-flow trials	Hydraulic anomaly sensitivity
Alert latency	< 30 s in all reported tests; often < 15 s	Compatible with near-real-time alerting
Waterproofing	No visible ingress after 30 min immersion	Short-duration enclosure screening passed

Table 2. Summary of reported performance and evidentiary limits.

5. Discussion

The central finding is that a mechanically simple turbine can generate a repeatable rotational signal that scales with imposed flow intensity across the tested laboratory range. For a low-cost monitoring network, this is useful because the sensing principle is transparent, computationally light, and compatible with inexpensive microcontrollers. The observed debris effect, however, shows why field calibration and maintenance cannot be treated as secondary

concerns. Low-cost monitoring systems often trade laboratory-grade metrological performance for deployability and density; their value depends on careful characterization, validation against reference instruments, and explicit handling of sensor drift and fouling [3–5].

FloodGuard should therefore be interpreted as a local hydraulic-state sensor rather than a stand-alone flood-prediction system. Flooding depends on network topology, rainfall-runoff dynamics, downstream water levels, tide, storage, and obstruction. A single RPM threshold cannot establish flood probability across all drain geometries. The most defensible deployment concept is a network in which calibrated local sensors provide anomaly data that are combined with rainfall, tide, hydraulic models, and strategically selected locations. This is consistent with the broader direction of urban drainage monitoring research [8] and with operational systems that fuse multiple sensor and forecast streams [2,9].

The results also motivate a more robust anomaly-detection strategy. Instead of universal absolute RPM thresholds, future firmware could use site-specific baselines, rate-of-change features, paired water-level measurements, and persistence criteria. Such a design would reduce sensitivity to installation geometry and turbine-to-turbine variation while preserving the low computational burden of the current rule-based approach.

5.1 Limitations

This study has six principal limitations. First, testing was restricted to a controlled 150 mm pipe and does not reproduce full-scale stormwater-drain hydraulics, including variable cross-sections, free-surface flow, surcharge, sediment beds, turbulence, and tidal backpressure. Second, the composition and concentration of simulated debris were not quantified, limiting reproducibility of the fouling experiment. Third, the source dataset does not provide trial-level RPM values, exact regression coefficients, uncertainty intervals, hypothesis-test statistics, or a confusion matrix; therefore, claims of statistical significance or classification accuracy cannot be independently verified. Fourth, the optical pulse-counting configuration does not by itself provide signed rotational direction, so bidirectional flow measurement remains unvalidated. Fifth, the 30 min immersion screen is insufficient to establish long-term waterproofing, corrosion resistance, biofouling tolerance, or IP certification of the assembled device. Sixth, Wi-Fi connectivity and short-duration battery operation were not evaluated under real underground deployment conditions, where attenuation, power management, and maintenance access may dominate system reliability.

5.2 Recommended field-validation protocol

Before municipal deployment, the prototype should be evaluated alongside a reference flow or velocity instrument over at least one monsoon period. The protocol should include: quantified sediment and debris loading; repeated calibration across multiple sensor units; signed direction sensing; long-duration fouling and corrosion tests; battery life measurements at realistic reporting intervals; communications testing from below-grade structures; false-positive and false-negative alert rates; and site-specific hydraulic calibration. Raw time-series data, firmware, and analysis code should be archived to enable reproducibility.

6. Conclusion

FloodGuard demonstrates the laboratory feasibility of using a low-cost turbine, optical rotation sensing, and an ESP32-based communications stack to monitor changes in water-flow intensity. Across eight tested velocities, rotational response increased from approximately 15–20 RPM at the low end to 280–320 RPM at 2.0 m/s, and the fitted calibration met the study's $R^2 \geq 0.90$ criterion. Simulated debris reduced RPM by approximately 8–15%, confirming that environmental fouling materially affects calibration. Reported step-change alerts met the 30 s target. These findings justify continued development, but not yet operational claims of flood prediction, bidirectional flow measurement, or certified field durability. The next research priority is long-duration, reference-instrumented field validation in real stormwater drains.

Declarations

Ethics and safety.

No human participants, personal data, or live-animal subjects were involved. Testing was conducted on a bench-scale hydraulic apparatus. Any future access to live municipal drainage infrastructure should be undertaken only with formal authorization, confined-space procedures, appropriate personal protective equipment, and gas monitoring.

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References

- [1] Municipal Corporation of Greater Mumbai, Chief Engineer (Storm Water Drains), RTI Manual: Introduction and BRIMSTOWAD study criteria. Mumbai, India. Available: [https://portal.mcgm.gov.in/irj/go/km/docs/documents/MCGM%20Department%20List/Chief%20Engineer%20\(Storm%20Water%20Drains\)/RTI%20Manuals/Ch%20Engineer_SWD_RTI_E01.pdf](https://portal.mcgm.gov.in/irj/go/km/docs/documents/MCGM%20Department%20List/Chief%20Engineer%20(Storm%20Water%20Drains)/RTI%20Manuals/Ch%20Engineer_SWD_RTI_E01.pdf)
- [2] Press Information Bureau, Government of India, 'Flood Warning System for Mumbai “IFLOWS-Mumbai” to be launched on June 12, 2020,' Ministry of Earth Sciences, 11 Jun. 2020. Available: <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1630928>
- [3] A. I. Silverman et al., 'Making waves: Uses of real-time, hyperlocal flood sensor data for emergency management, resiliency planning, and flood impact mitigation,' *Water Research*, vol. 220, 118648, 2022. doi: 10.1016/j.watres.2022.118648.
- [4] P. Hamel et al., 'Low-cost monitoring systems for urban water management: Lessons from the field,' *Water Research X*, vol. 22, 100212, 2024. doi: 10.1016/j.wroa.2024.100212.
- [5] S. Catsamas, B. Shi, B. Deletic, M. Wang, and D. T. McCarthy, 'A low-cost, low-power water velocity sensor utilizing acoustic Doppler measurement,' *Sensors*, vol. 22, no. 19, 7451, 2022. doi: 10.3390/s22197451.
- [6] M. Navia, J. Macías-Aguayo, and D. Quiroz-Cordova, 'IoT-Based Detection of Blockages in Stormwater Drains,' *Engineering Proceedings*, vol. 82, no. 1, 48, 2024. doi: 10.3390/ecs-11-20371.
- [7] H. Moghadas, R. Mirzavand, and P. Mousavi, 'Early detection of flood in urban catch basins using radio frequency slot line array,' *Measurement*, vol. 134, pp. 515–518, 2019. doi: 10.1016/j.measurement.2018.10.102.
- [8] Y. Zheng, X. Jin, J. Wei, Y. Zhou, and Y. Zhang, 'A novel framework for optimization and evaluation of sensors network in urban drainage system,' *Water Research*, vol. 270, 122833, 2025. doi: 10.1016/j.watres.2024.122833.
- [9] PUB, Singapore's National Water Agency, 'Flood Forecasting and Monitoring,' 2026. Available: <https://www.pub.gov.sg/Public/KeyInitiatives/Flood-Resilience/Flood-Forecasting-and-Monitoring>