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IOT Enabled Integrated Stormwater Management with Smart Rainwater Harvesting Kit and Permeable Block

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Abstract- The rapid growth of urban surfaces that do not absorb water has disrupted natural water cycles. This has caused two major problems: frequent city flooding and declining groundwater levels. Traditional drainage systems focus on getting rid of water instead of conserving resources. Standard rainwater harvesting often does not address the initial "first-flush" pollution. This research presents a governance framework that uses IoT technology to actively manage stormwater with a "dual-stream" approach. Based on an ESP32 microcontroller, the system uses real-time turbidity sensing to tell apart high-quality rainwater for storage and contaminated runoff for aquifer recharge.

The experimental prototype includes a special 1:3 pervious concrete "filtration" designed to improve ground infiltration and prevent surface ponding. Key innovations feature a 30-second automated first-flush protocol and a tiered "Summer Rationing" system that ensures access to essential water supplies when tank capacity drops below 40%. Laboratory tests conducted under Indian Standards (IS) confirmed the reliability of the materials used. Results show that this integrated model can effectively reduce surface runoff and offers a practical, cost-effective way to create resilient "Sponge Cities" that can handle monsoon floods and summer droughts.

Key Words: IoT (Internet of Things), ESP32 Microcontroller, Pervious Concrete, Groundwater Recharge, Smart Water Management, Turbidity Sensing, Automated First-Flush, Sponge City, Sustainable Urban Drainage (SuDS)

I. Introduction

The rapid growth of cities around the world has changed the natural landscape. It has replaced porous soil with large areas of impermeable surfaces. This change disrupts the natural water cycle, turning beneficial rainwater into harmful stormwater runoff. As a result, many cities now face ongoing urban flooding and falling groundwater levels. Traditional "Gray Infrastructure," which relies on rigid concrete drainage systems, is increasingly seen as an unsatisfactory solution. It focuses more on water disposal than on conserving resources. Additionally, current Rainwater Harvesting (RWH) methods often do not effectively handle "first-flush" contamination, which is the initial, heavily polluted runoff from rooftops. As urban areas struggle with these issues, there is a growing belief that a more integrated and active governance approach is needed to restore the "Sponge City" concept in urban settings.

III. Literature Review

Recent research has examined various strategies to reduce stormwater impact using automation and materials science:

• O. Patki et al. (2025)Developed a smart water management architecture using the ESP32 to monitor storage and quality in real-time, addressing the lack of live data in traditional urban harvesting [1].

• Abhijith G. et al. (2020)investigated the decline of urban aquifers; proposed decentralized infiltration as a solution to reduce peak runoff and restore groundwater levels [2].

• D. Zhang & Y. Li (2023)Evaluated Sponge City performance using the SWMM model; proved that LID (Low Impact Development) facilities like permeable pavements can reduce runoff by over 60% [3].
• S. Kumar (2021) Explored the structural limitations of no-fines concrete; identified the 1:3 cement-to-aggregate ratio as the optimal balance for maintaining high void ratios for drainage [4].
• Angel Y. et al. (2025) Addressed the wastage of stored rainwater; implemented a solar-powered IoT logic that integrates harvesting with automated irrigation to optimize resource utility [5].

Research Gap: Current literature shows that while passive infiltration materials and basic water-level monitoring are well-covered, a major gap exists in combining these technologies into a single, effective governance framework. Most existing models focus only on rooftop harvesting or ground-level recharge, failing to connect these processes. Moreover, today's "Smart" RWH kits often do not have the real-time logic needed to divert water based on turbidity levels or to use "Summer Rationing" strategies that secure water supplies during times of scarcity.

Novelty of the Research: This research introduces an innovative, integrated IoT-enabled dual-stream system that manages both rooftop runoff and ground-level stormwater at the same time. The key innovation is the active governance kit, which employs real-time turbidity sensing to direct water. High-quality rainwater goes to storage tanks, while contaminated or excess water is redirected to a specially designed permeable pavement system for aquifer recharge. The system includes a 30-second first-flush protocol and a tiered summer rationing logic that activates at 40% capacity. This offers a level of resource management not seen before in small-scale urban kits. Additionally, it features a multi-layered pervious concrete block filtration setup to ensure long-term permeability and groundwater health

II. Objectives

The main goals of this research are as follows:
1. To create an IoT-based governance framework that can divert stormwater based on real-time quality and quantity data.
2. To implement and test an active first-flush protocol and summer rationing mode to improve water security.
3. To design a pervious pavement system to optimize ground infiltration.
4. To showcase an integrated urban model that reduces flooding while helping to recharge underground aquifers.

IV. Materials & Composition

The physical construction of the prototype was divided into two main assemblies: the electronic kit and the permeable pavement system. All components were sourced from local markets to show the possibility of low-cost, urban implementation.

Table 1: *IoT Kit Components*

Sr. No.	Component	Model / Specification	Purpose	Source
1	**Microcontroller**	ESP32-WROOM-32	Central logic processing and IoT connectivity	Rajpal Electronics, Kopargaon
2	**Turbidity Sensor**	Analog	Assessment of runoff quality	Rajpal Electronics, Kopargaon
3	**Ultrasonic Sensor**	HC-SR04	Real-time monitoring of main tank water levels	Rajpal Electronics, Kopargaon
4	**Rain Sensor**	FC-37 / YL-83	Detection of precipitation events to trigger system	Rajpal Electronics, Kopargaon
5	**Soil Moisture Sensor**	Capacitive V1.2	Feedback for automated plant irrigation	Rajpal Electronics, Kopargaon

6	**Relay Module**	8-Channel (5V)	Switching control for valves, pumps, and aerator	Rajpal Electronics, Kopargaon
7	**Solenoid Valves**	24V DC / 0.5 Inch	Diversion of water between waste and storage	Rajpal Electronics, Kopargaon
8	**Aeration Pump**	24V DC / 5W	Prevention of stagnation	Rajpal Electronics, Kopargaon
9	**Distribution Pump**	12V DC (Submersible)	Irrigation and water supply distribution	Rajpal Electronics, Kopargaon
10	**Buck Converter**	LM2596 DC-DC	Regulation of voltage for ESP32 and sensors	Rajpal Electronics, Kopargaon

Table 2: *Pavement Layer Materials*

Sr. No.	**Material**	**Specification**	**Role in Infrastructure**	**Source**
1	**Cement**	OPC Grade 53	Binder for the 1:3 no-fines concrete mix	Civil Engineering Lab
2	**Coarse Aggregates**	10mm - 12mm	Structural skeleton for pervious block	Civil Engineering Lab
3	**Bedding Layer**	6mm - 10mm Stone	Levelling and initial filtration layer	Civil Engineering Lab
4	**Reservoir Layer**	20mm - 40mm Stone	Temporary storage and slow infiltration	Civil Engineering Lab
5	**Geotextile Fabric**	Non-woven	Separation of stone layer from subgrade soil	Civil Engineering Lab
6	**PVC Conduit**	0.5" - 1" Diameter	Conveyance of water from roof to treatment	Civil Engineering Lab

V. Methodology

The research consists of two parallel experimental tracks: the material science of the permeable infrastructure and the algorithmic of the IoT-enabled harvesting kit.

The integrity of the permeable system relies on choosing high-quality raw materials. Ordinary Portland Cement (OPC) Grade 53 was chosen for its high early strength and bonding properties. The Coarse Aggregates were sieved to a uniform size of 10mm to 12mm to ensure a high void ratio, which is essential for permeability. For the IoT kit, industrial-grade sensors were calibrated against known standards to ensure accuracy in turbidity and distance measurements.

Material Testing as per Indian Standards (IS)

To ensure structural and functional reliability, the materials underwent rigorous testing following **IS: 2386** and **IS: 10262** guidelines.

Table 3: *Materials Testing*

Test Category	Parameter	Relevant Standard	Significance
Cement	Setting Time & Consistency	IS: 4031	Ensures structural bond in 1:3 mix
Aggregate	Impact & Crushing Value	IS: 2386	Resistance to pedestrian/light traffic loads
Soil	Sieve Analysis	IS: 2720 (Part 4)	Determining soil texture and drainage class
Soil	Constant Head Permeability	IS: 2720 (Part 17)	Measuring hydraulic conductivity (κ)
Soil	Standard Proctor Test	IS: 2720 (Part 7)	Achieving optimum moisture for subgrade stability

Sub-Surface Layering and Design of permeable pavement:

The permeable pavement system is engineered to prioritize groundwater recharge while preventing localized flooding through a sloped drainage architecture.

A. Vertical Infiltration:

The system is constructed with the following cross-sectional layer sequence:

1. **Surface Layer:** 1:3 Pervious Concrete Block (High-void ratio).

2. **Bedding Layer:** 6mm–10mm cleaned stone, laid at a **2% cross-slope**.

3. **Geotextile Fabric:** Non-woven membrane laid parallel to the bedding slope/chicken mesh.

4. **Subgrade:** Natural compacted soil.

B. Excess Flow Management:

As against the static storage method by traditional systems, this uses "Flow-Through" system:

- **Primary Path:** Stormwater percolates vertically through the block and bedding into the subgrade for natural recharge.

- **Saturation Response:** Once the subgrade soil reaches its infiltration capacity (saturation), the excess water follows the slope of the geotextile and bedding layers.

- **Secondary Path:** This diverted water flows toward a lateral drainage pipe system, which conveys the runoff to municipal supply lines for further utility.

Design of kit and Circuit Integration:

The "Smart Kit" focuses on an ESP32 microcontroller, chosen for its fast-processing speed and built-in IoT features. The system's architecture connects low-voltage sensors with high-voltage actuators using a three-layer interface.

- **Sensor Data Acquisition:**

The ESP32 collects all environmental data through its GPIO pins. The Turbidity and Soil Moisture sensors use the internal 12-bit Analog-to-Digital Converter (ADC) for accurate voltage mapping. The Ultrasonic sensor measures distance through pulse-time calculation, while the Rain sensor serves as a digital interrupt to start the main control sequence.

- **Power Architecture and Regulation:**

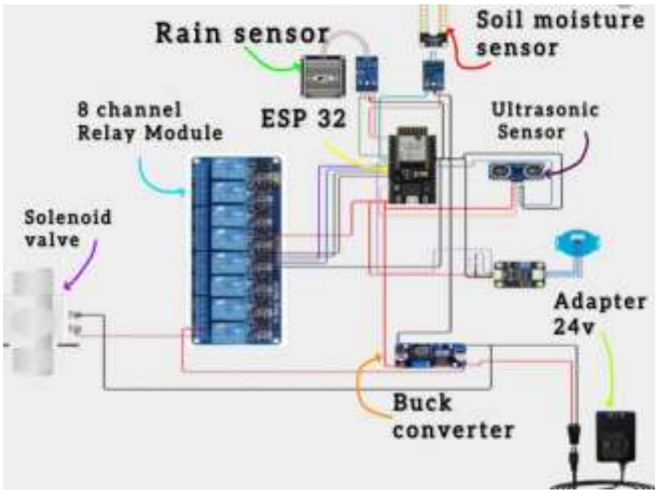

Fig 1: Circuit architecture

The system uses a dual-power rail to maintain stability. A 24V DC / 5A supply powers the solenoid valves, and an LM2596 Buck Converter reduces this to a steady 5V rail. This 5V rail provides power to the relay module and the

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sensor array, keeping the ESP32's logic separate from the high current needs of the valves.

• **Actuation and Relay Logic:**

The ESP32 controls water diversion and distribution through an 8-channel Opto-isolated Relay Module. This configuration allows the microcontroller to safely operate the 24V Solenoid Valves (for First-Flush and Quality Rejection), the AC Aeration Pump (for tank maintenance), and the 12V Distribution Pump (for automatic irrigation).

Process Flow:

• **Pervious Block and Soil Interface testing and working:** The testing process for the physical model involved simulating heavy rainfall to observe the "Saturation Point." This was measured by timing how long the system took to switch from vertical infiltration to lateral drainage pipe discharge.

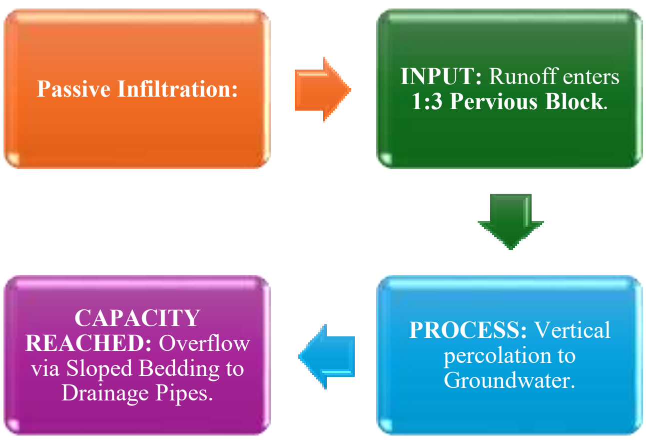

Fig 2: Process Flow of water Infiltration

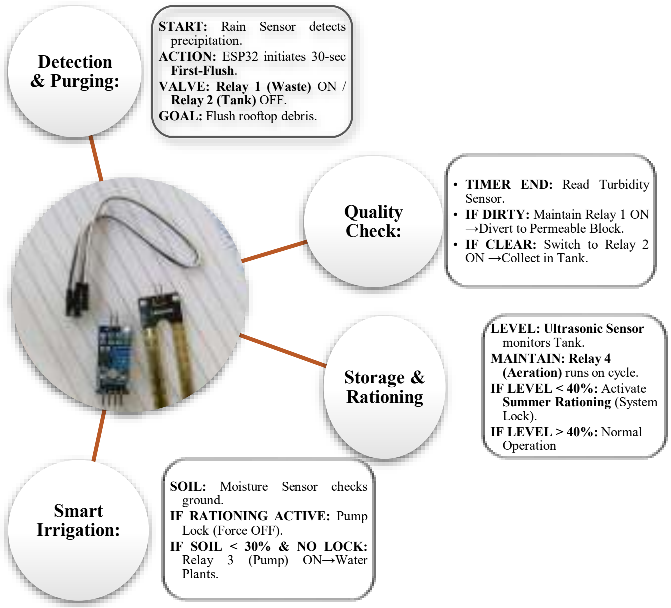

Fig 3: IOT Kit Working

Experimental Prototype and Case Study Model: To evaluate how the integrated system works in practice, a scaled prototype was developed based on a specific university building. This design allows for simulating real-world catchment areas and runoff patterns related to the campus infrastructure.

1. University Rainwater Harvesting Model with IOT Kit: The model includes a scaled replica of the college building and integrates the IoT Governance Kit into the drainage network.

• Rooftop: The rain sensor and solenoid valves are placed at the main gutter outlets of the building model. They help capture the First-Flush and control the dual-stream diversion.

• Collection Infrastructure: A centralized storage tank, which has an ultrasonic level sensor and an aeration pump, shows how to manage harvested resources effectively.

2. Transparent pervious concrete Layers Cross Section Model: A separate, detailed infiltration model was built inside a clear enclosure. This focuses on observing the subsurface water movement of the Pervious Concrete Block and layers.

• **Visual Verification:** The clear design allows for monitoring vertical water flow through the block and bedding layers in real time.

• **Saturation Feedback:** when the subgrade soil hits its infiltration limit, causing water to overflow laterally

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through the sloped geotextile toward the municipal drainage pipes.

- **Layer Integrity:** This separate unit helps confirm the "filtration" design. It ensures the geotextile effectively keeps soil from moving into the stone reservoir.

Fig 4: Prototype Pervious concrete block with layers

Fig 5: Pervious Concrete block

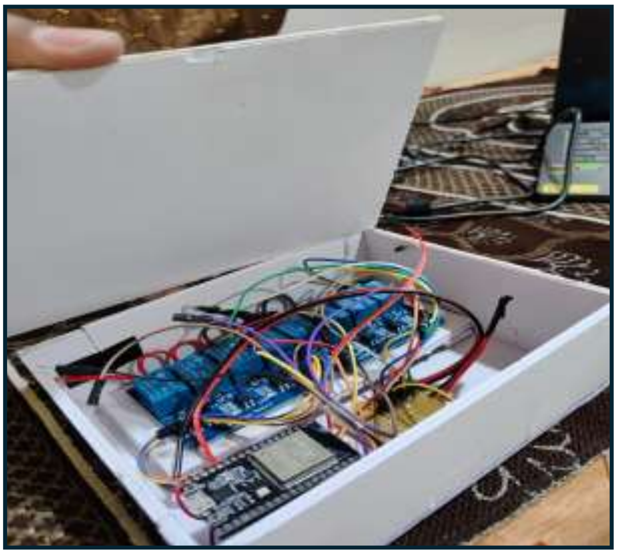

Fig 5: Rainwater Harvesting IOT kit Model

VI. Test Setup & Laboratory Photos

The following figures show the laboratory test setup used to evaluate Setting Time & Consistency of cement, Impact & Crushing Value of aggregate, Sieve Analysis, Constant Head Permeability and Standard Proctor Test of soil.

Fig. 7: Impact Test

Fig. 8: Sieve analysis Test

Fig. 9: Standard Proctor test

VII. Results & Discussion

1. The foundational materials were tested to make sure they met the chemical and physical requirements for a high-void "no-fines" concrete mix.

- **Consistency and Setting Time of cement:** The Normal Consistency of the OPC 53 cement was measured at 32%. The Initial Setting Time was 45 minutes, while the Final Setting Time was 480 minutes. These values confirm that the binder offers enough workable time for the 1:3 manual casting process and ensures quick hardening to maintain the pore structure.
- **Aggregate Physical Properties:** The Sieve Analysis showed a uniform graduation of 10mm to 12mm. The Aggregate Impact Value was 16.8%, and the Crushing

Value was 18.2%. According to IS:2386, these results classify the stone as "Strong," making it suitable for durable pervious pavement applications.

- **Standard Proctor Test:** The Optimum Moisture Content (OMC) was 14.5%, with a Maximum Dry Density (MDD) of 1.82 g/cc. This data helped compact the model subgrade to a level that prevents structural settling while allowing water passage.
- **Constant Head Permeability:** The hydraulic conductivity (κ)of the soil was measured at 2.5×10^{-3} cm/s. This relatively low κ value supported the need for the 2% sloped bedding layer, demonstrating that during heavy rainfall, the soil would become saturated, requiring an overflow path.

2. Prototype Hydraulic Performance:

The transparent infiltration model allowed for direct observation of the "Sponge City" effect.

- **Infiltration Efficiency:** The 1:3 Pervious Block showed immediate vertical drainage. Even at high simulated flow rates, there was no surface ponding.
- **Saturation and Lateral Flow:** From the Constant Head Permeability results, once the subgrade soil reached capacity, the water shifted from vertical infiltration to lateral flow along the sloped geotextile. The drainage pipes collected the excess water, confirming the "Dual-Stream" safety mechanism.

3. IoT Kit and Decision Accuracy:

The ESP32 Kit was tested through multiple simulated cycles.

- **First-Flush & Turbidity Logic:** The 30-second purge effectively removed initial high-sediment runoff. The turbidity sensor accurately identified "Storage Grade" (Clean) and "Recharge Grade" (Turbid) water, switching the solenoid valves in under 1 second.
- Summer Rationing Mode: The Ultrasonic Sensor was very reliable; when the tank level dropped to 40%, the system shut off the irrigation pump. This saved the remaining water volume, proving the system's effectiveness in handling water scarcity.

Table 4: Complete Test Results

Parameter	Target/Expected	Observed Result	Status
Rain Response	< 2 Seconds	0.5 Seconds	**Excellent**
Time			
Turbidity Sensing	Accurate Diversion	98% Success Rate	**Optimal**
Surface Ponding	Zero Ponding	No Ponding Observed	**Successful**
Tank Level Accuracy	± 5mm	± 2mm	**High Precision**
First-Flush Duration	30 Seconds	30 Seconds (Fixed)	**Consistent**

IX. Applications

1. Colleges and Campuses: Can be used to reduce flooding and improve groundwater recharge.
2. Residential Buildings: Useful for apartments to manage rooftop rainwater smartly.
3. Industrial Areas: Can be applied in parking areas and warehouses to manage large amounts of rainwater.
4. Agricultural Use: Can help farmers manage water storage and irrigation efficiently.

X. Conclusion

The research shows that IoT-enabled active Kit can greatly improve the efficiency of traditional stormwater management. By combining a Smart Rainwater Harvesting Kit with a Pervious Concrete Block, the project tackles both water quality and quantity.

Laboratory tests on cement, aggregates, and soil confirm that these materials are suitable for urban recharge applications. The system can "think" by diverting water based on turbidity and locking distribution during shortages. This represents a major improvement over passive harvesting method. This integrated approach provides a scalable, cost-effective solution for building resilient "Sponge Cities" that can withstand both monsoons and summer droughts.

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