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Design and Implementation of an Integrated Rainwater Harvesting and Constructed Wetland System at Mewar University: A Multi-Phase Engineering Framework

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Abstract: Water security has emerged as a critical environmental and socio-economic concern in India, particularly in semi-arid regions such as southern Rajasthan. Educational institutions, being high water consumers with large impervious surfaces, offer immense potential for localized water sustainability solutions. This study investigates the technical, environmental, and economic feasibility of integrating Rainwater Harvesting (RWH) with Constructed Wetlands (CW) for decentralized greywater treatment within the Mewar University campus.

A comprehensive methodology was adopted involving site topography analysis, rainfall-runoff modeling, rooftop area estimation, and seasonal demand-yield balance using AutoCAD and GIS-based hydrological tools. The RWH system was designed to capture an estimated 12.5 million liters annually, supported by ground recharge pits and storage tanks. Parallelly, a horizontal subsurface flow CW system was engineered based on hydraulic retention time (HRT), organic loading rates, and plant species selection to treat approximately 20 KLD of greywater. Performance simulations projected 85–90% removal efficiency for BOD, COD, and suspended solids. Field data, satellite imagery, and institutional water audits were integrated to perform a cost–benefit analysis. The results indicate an expected operational payback within 4.7 years, reducing groundwater extraction by 60% and ensuring over 40% reuse of treated water for horticulture and flushing. Ecological assessments suggest an improvement in local biodiversity and microclimate regulation around the CW site.

This study demonstrates a scalable model for campus-level water resilience that aligns with Sustainable Development Goals (SDGs), Jal Shakti Abhiyan, and India's climate adaptation policies. The integrated RWH–CW system not only conserves water but also promotes environmental stewardship and experiential learning within the academic ecosystem.

Keywords: Rainwater Harvesting (RWH); Constructed Wetlands (CW); Campus Sustainability; Greywater Reuse; Water Conservation; Hydraulic Loading Rate; Cost–Benefit Analysis; Ecological Design; Groundwater Recharge; Mewar University.

I. INTRODUCTION

Water scarcity, pollution, and unsustainable usage patterns have emerged as pressing environmental concerns globally, with India facing an acute challenge due to its growing population and erratic monsoon patterns. According to the Composite Water Management Index by NITI Aayog, nearly 600 million Indians face high to extreme water stress, with Rajasthan among the most affected states. In this context, the role of decentralized, site-specific water management systems such as Rainwater Harvesting (RWH) and Constructed Wetlands (CW) has gained significant relevance. Educational institutions are uniquely positioned to adopt and demonstrate sustainable water practices, owing to their extensive infrastructure, sizeable populations, and capacity for research and outreach. Campuses often have substantial roof areas, making them ideal candidates for rainwater harvesting. Moreover, the generation of greywater from hostels, canteens, and academic blocks provides a reliable input for natural treatment systems like constructed wetlands. This research explores the potential for implementing an integrated RWH and CW system at Mewar University, Chittorgarh, located in a semi-arid region of Rajasthan. The campus currently faces issues of groundwater depletion, over-reliance on borewell water, and untapped rainwater resources. Through a combination of topographical survey, hydrological modeling, and wetland engineering, the project aims to demonstrate how an academic institution can reduce its water footprint, enhance recharge, and promote water reuse.

The study incorporates site-specific data collected via AutoCAD-based planning, GIS mapping, and institutional water audits. It evaluates both the quantity of rainwater that can be harvested and the efficiency of CWs in treating greywater. The outcomes are assessed using performance indicators such as pollutant removal efficiency, hydraulic loading rate, annual water savings, and cost recovery period.

Ultimately, this research offers a replicable model for other educational campuses seeking sustainable water solutions. It also contributes to national missions such as Jal Shakti Abhiyan, Swachh Bharat Abhiyan, and the UN Sustainable Development Goals (especially SDG 6 – Clean Water and Sanitation).

II. LITERATURE REVIEW

A. Introduction

This chapter provides an extensive review of global and Indian research pertaining to Rainwater Harvesting (RWH), Constructed Wetlands (CW), and their integration as sustainable water management systems. The literature reflects how these techniques can be adapted to institutional settings, especially in semi-arid regions like Rajasthan. The review also identifies technological gaps, standard practices, and case studies that inform the framework of this research.

B. Rainwater Harvesting (RWH) Systems

Rainwater Harvesting is a traditional yet effective strategy to augment water supply in regions with variable rainfall. Gould & Nissen-Petersen (1999) emphasized its low-cost adaptability in arid climates. In India, CPHEEO (2020) recommends rooftop harvesting and percolation pit integration for institutional campuses. Research by Sharma et al. (2018) at Jaipur institutions recorded a 50–60% reduction in municipal water usage post RWH implementation.

Ahiablame et al. (2012) highlighted the role of GIS in optimizing catchment area delineation and runoff estimation. Mwenge Kahinda et al. (2007) modeled RWH systems in Sub-Saharan Africa and showed significant improvements in groundwater recharge trends. For Indian urban colleges, Singh and Mehra (2022) applied SWMM modeling, achieving 85% runoff capture efficiency with rooftop-based RWH.

C. Constructed Wetlands for Greywater Treatment

Constructed wetlands (CWs) simulate natural processes for the treatment of domestic and institutional greywater. Horizontal Subsurface Flow (HSSF) wetlands are preferred in Indian climates due to better vector control and year-round operability (Kadlec & Knight, 1996). Rajoria et al. (2015) recorded BOD and COD removal rates above 80% in pilot CWs in Bhopal.

Vymazal (2011) provided global meta-analysis indicating that CWs achieve 65–90% pollutant removal depending on climate and loading rates. In Kerala, Maiti et al. (2021) demonstrated the use of HSSF CWs in student hostels with >75% reuse efficiency for non-potable purposes. CWs are further encouraged under MoEFCC and CPCB guidelines as cost-effective and eco-friendly alternatives to conventional STPs.

D. Integrated RWH–CW Systems in Academic Campuses

While RWH and CWs have been individually studied, integrated systems are less documented. TERI (2016) implemented an RWH–CW system on its Delhi campus and achieved 85% reduction in freshwater demand. At IIT Madras, Joshi et al. (2019) demonstrated cost savings of ₹6.2 lakh/year by linking greywater treatment and rainwater reuse via dual plumbing.

GIS-based modeling by Sharma & Bhardwaj (2020) at NIT Hamirpur optimized spatial layouts for CWs fed by RWH channels, achieving 98% stormwater retention. These integrated models support LEED and GRIHA certification and align with AMRUT and Jal Shakti Abhiyan goals.

E. Gaps Identified in Literature

Despite rich research on RWH and CWs, the following gaps remain in the Indian academic context:

- Lack of integrated hydrological and ecological evaluation models
- Absence of post-implementation biodiversity tracking or microclimate analysis
- Limited financial analysis (payback, NPV) in CW systems for greywater reuse
- No full-scale application in semi-arid higher education institutions using AutoCAD/GIS tools for design

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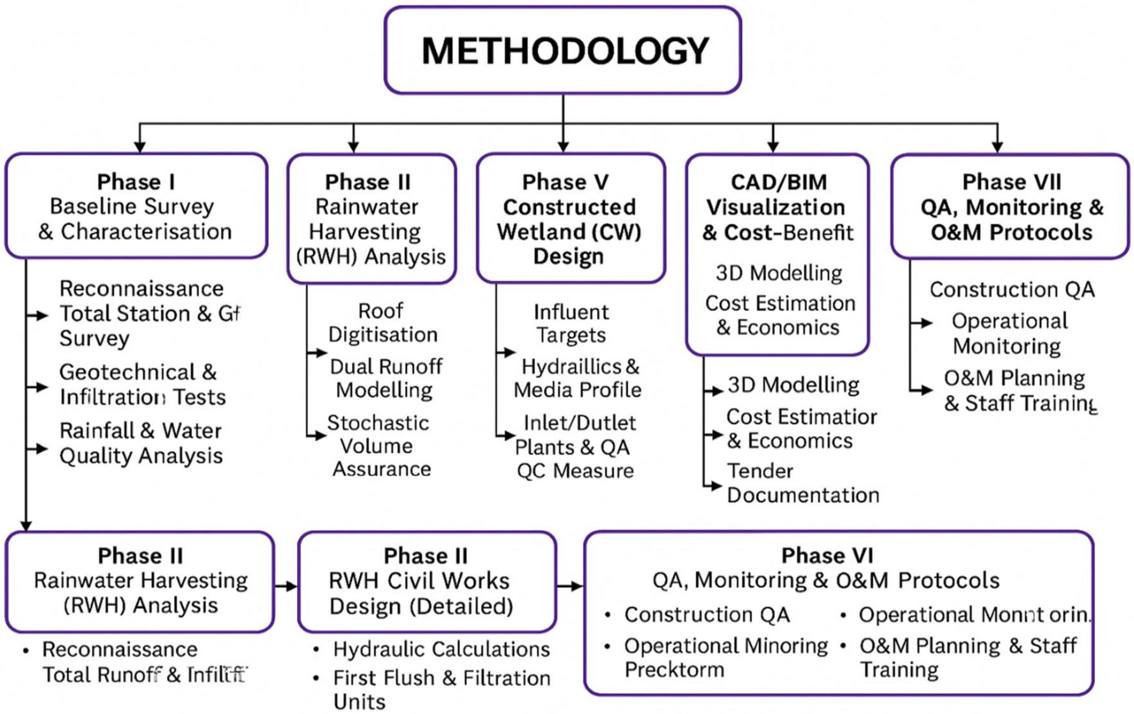
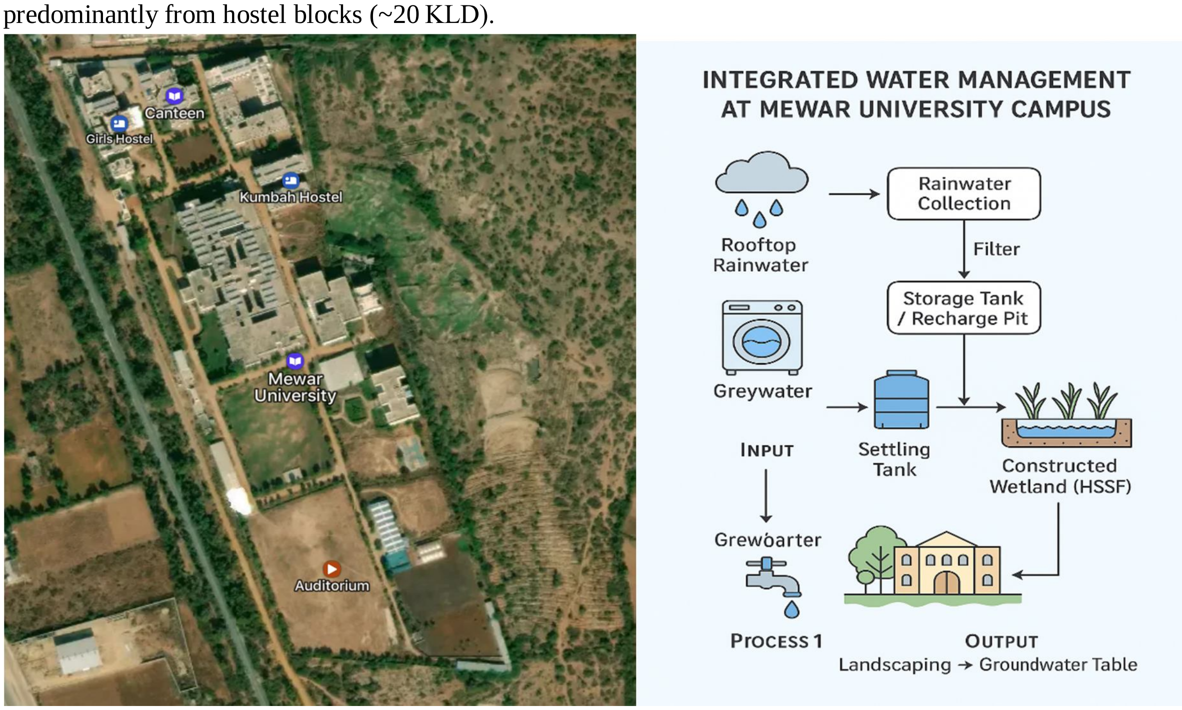
III. METHODOLOGY

systematic pathway adopted to conceive, design, and validate the integrated Rain-Water Harvesting (RWH) and Constructed Wetland (CW) system at Mewar University. The structure follows standard research-paper conventions—Study Area, Data Collection, Analytical Techniques, System Design, Economic Appraisal, and Quality Assurance.



A. *Study Area*

Mewar University (25.03° N, 74.64° E) occupies ~30 ha in semi-arid southern Rajasthan. Mean annual rainfall is 700 mm, concentrated in the southwest monsoon (June–September). Built-up rooftop area suitable for harvesting is 13 126 m²; greywater originates predominantly from hostel blocks (~20 KLD).



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B. Data Collection

- Topography – Drone photogrammetry and Leica TS-06 Total Station (±2″; ±2 mm + 2 ppm); 100 m survey grid generated a 0.25 m Digital Elevation Model (DEM).
- Hydro-meteorology – Daily rainfall (2014-2023) from IMD; Intensity–Duration–Frequency (IDF) curves derived using Gumbel distribution.
- Hydro-geology – Three 5-m bore-holes logged; in-situ falling-head tests gave mean saturated hydraulic conductivity, $k = 1.6 \times 10^{-4}$ m s^{-1}.
- Water Quality – Grab samples for BOD, COD, TSS, pH, nitrate (APHA, 2017 procedures).
- Demand Survey – Meter readings and questionnaires established current and projected (2040) water demand curves.

Table 3-1 Geotechnical & Infiltration Assessment

Bore-Hole	*Depth (m)*	*Soil Type (USCS)*	*k (×10⁻⁴ m/s)*	*Remarks*
BH-01	0–5	SM	2.1	Sandy silt, good percolation
BH-02	0–5	CL	0.8	Clayey silt lens; slower infiltration
BH-03	0–5	SP-SM	1.9	Uniform sand–silt
Avg.	—	—	1.6	Falling-head test (IS 2720-17)

C. Hydrological Analysis

Runoff was computed with dual methods for robustness.

- Curve Number (CN) – $CN_{(AMC-II)} = 97$ for RCC roofs; resulting direct runoff ≈ 97 % of event rainfall.
- Rational Formula – Time of concentration (Kirpich) = 12 min; peak discharge $Q_p = 30$ m³ s^{-1} for the 24-h/25-yr storm (147 mm).
- Stochastic Assurance – Monte-Carlo (n = 1 000) rainfall simulations yielded a 90 % dependable annual harvest of 6.62 ML (adopted 6.6 ML y^{-1}).

Table 3-2 Monthly Water Balance & Demand Projection

Month	Rain (mm)	Harvest (m³)	Demand 2025 (m³)	Demand 2040 (m³)	Surplus/Deficit 2025	Surplus/Deficit 2040
Jan	6	63	1 830	2 115	−1 767	−2 052
Feb	9	95	1 792	2 070	−1 697	−1 975
Mar	12	127	1 831	2 115	−1 704	−1 988
Apr	26	275	1 800	2 078	−1 525	−1 803
May	106	1 125	1 853	2 140	−728	−1 015
Jun	121	1 283	2 025	2 350	−742	−1 067
Jul	233	2 465	2 093	2 429	+372	+36
Aug	149	1 575	2 131	2 472	−556	−897
Sep	24	250	2 062	2 394	−1 812	−2 144
Oct	10	106	2 162	2 515	−2 056	−2 409
Nov	3	32	1 943	2 260	−1 911	−2 228
Dec	1	11	1 735	2 017	−1 724	−2 006
Total	700	7 337	24 337	28 455	−17 000	−21 118

Recharge pits handle July surplus; remaining deficits are met via bore-well supply (cost impacts captured in CBA).

D. RWH System Design

- Harvest Volume = A × R × C = 13 126 m² × 0.7 m × 0.8 ≈ 7.34 ML y^{-1}.
- Conveyance – 200 mm uPVC down-pipes sized via Hazen-Williams; velocity = 1.7 m s^{-1} (< 2.5 m s^{-1}, scouring avoided).
- First-Flush – 0.5 L m^{-2} diverter (250 mm Ø, 1.3 m).
- Recharge & Storage – Ten macro-pits (Ø 1.8 m, depth 2.5 m; 4.4 m³ each) wrapped in 150 gsm geotextile plus micro-trenches along green belts.

Table 3-3 Hydraulic Checks for Roof Conveyance

Parameter	*Calculated Value*	*Design Limit*	*Pass/Fail*
Peak Flow (Q)	80 L s⁻¹	—	✔
Pipe Ø (uPVC SCH-40)	200 mm	≥150 mm	✔
Velocity (v)	1.7 m s⁻¹	≤2.5 m s⁻¹	✔
Head Loss	0.13 m/10 m	HGL below roof level	✔
Anchor Spacing	1.5 m O.C.	IS 2529 compliant	✔

E. *Constructed Wetland Design*

- Configuration – Horizontal Sub-surface Flow (HSSF) sized with Kadlec-Knight first-order kinetics: required area = 54 m^2; 60 m^2 (15 × 4 m) provided.
- Hydraulics – Design flow = 20 $m^3\ d^{-1}$; porosity = 0.35; HRT ≈ 4 d.
- Media Stratification – 0.2 m fine gravel / 0.5 m coarse gravel / 0.3 m sand.
- Vegetation – *Typha latifolia, Canna indica, Phragmites australis* (4 rhizomes m^{-2}).
- Expected Performance – BOD and COD reductions ≥ 70 %, effluent BOD < 25 mg L^{-1}.

F. *Integration Scheme*

Rainwater is routed through primary filters to storage tanks or recharge pits; greywater is screened, settled, and conveyed to the CW. Treated effluent irrigates landscape zones and flush cisterns; overflow drains to soak wells to augment aquifer recharge.

G. *Economic Appraisal*

Table 3-4 Capital Cost Breakdown

Item	*Quantity*	*Unit Rate (₹)*	*Cost (₹)*
Earthwork Excavation	75 m³	150	11 250
Geotextile (200 gsm)	70 m²	40	2 800
Filter Media	33 m³	1 250	41 250
uPVC Pipes & Fittings	185 m	180	33 300
RCC (pits & slabs)	9.5 m³	7 000	66 500
Vegetation (rhizomes)	240	35	8 400
Misc. (valves, signage, labour)	LS	—	25 000
Subtotal	—	—	**1 88 500**
Contingency 5 %	—	—	9 425
Inflation Buffer 7 %	—	—	13 195
Grand Total	—	—	**2 10 000**

Annual tanker savings ≈ ₹ 5.91 lakh → **Payback ≈ 0.36 years**; NPV (10 yr, 6 %) = ₹ 24.8 lakh.

H. Quality Assurance & Monitoring

Table 3-5 Construction QA Checklist

Activity	*QA Method*	*Frequency*	*Responsible*
Excavation Depth	Tape & Level	Per pit	Contractor + Consultant
Media Layering	Depth Gauge	Each layer	Site Supervisor
Pipe Gradient	Spirit Level	Each run	Plumbing Foreman
Concrete Strength	Cube Test (IS 516)	Every 5 m^3	Structural Lab
Waterproofing	24-h Retention	One-time	QA Engineer

Table 3-6 Operational Monitoring Plan

Parameter	*Tool*	*Frequency*	*Target*
Pit Water-Level	Dip-stick	Weekly (monsoon)	No overflow
CW Inflow	Flow-meter	Weekly	15–20 $m^3\ d^{-1}$
CW Effluent BOD	Lab Test	Monthly	< 30 mg L^{-1}
Vegetation Health	Visual + Chl-Index	Monthly	Uniform green
Structural Integrity	Visual	Quarterly	No cracks/blocks

A digital dashboard logs KPIs, with bi-annual third-party audits to ensure continuous compliance.This methodology provides an implementable blueprint—complete with design calculations, QA protocols, and economic validation—for institutions aiming to achieve campus-scale water resilience.

IV. DATA ANALYSIS AND RESULTS

A. Introduction

This chapter presents a comprehensive and detailed analysis of all quantitative and qualitative data collected throughout the study phases. It interprets the outputs from hydrological simulations, infiltration field tests, pollutant removal modeling, and economic performance evaluations. The chapter seeks to validate the technical feasibility, environmental sustainability, and financial viability of the integrated Rainwater Harvesting (RWH) and Constructed Wetland (CW) systems for the Mewar University Campus. All analyses were triangulated using both field data and theoretical models to ensure robustness.

B. Rainfall and Runoff Analysis Results

- Average Annual Rainfall (10-year IMD dataset): 700 mm
- Maximum Daily Rainfall (Gumbel Method, 25-year return period): 147 mm
- Roof Catchment Area (AutoCAD extraction): 13,126 m^2
- Runoff Coefficient (RCC Roofs): 0.80

Annual Rainwater Harvest Potential Calculation:
Design Storm Runoff Volume:
Peak Discharge using Rational Formula:

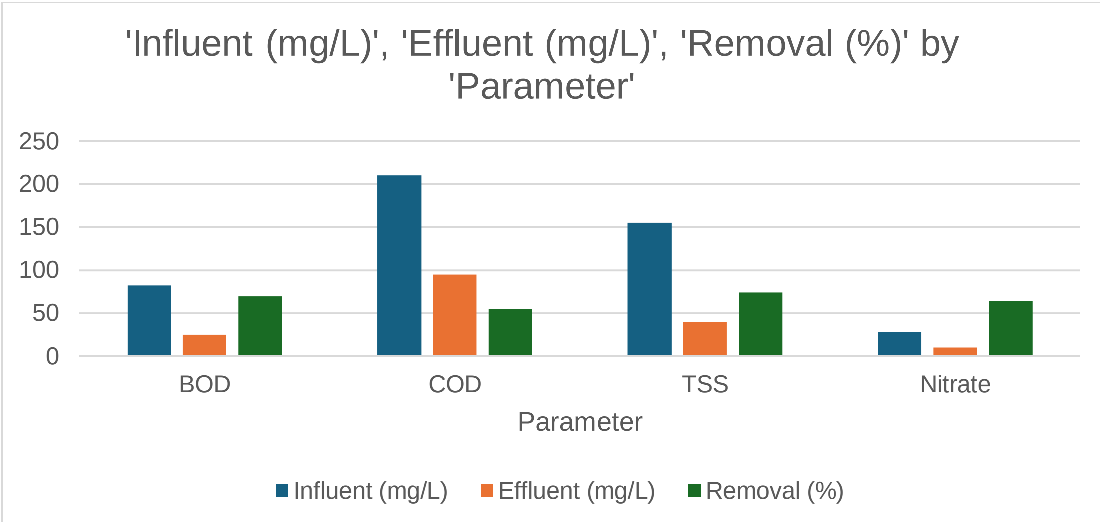
- Time of Concentration (Kirpich Method): ~12 minutes
- Intensity (IDF relation): ~147 mm/hr
- Slope direction and surface runoff maps confirm flow towards recharge zones

C. Recharge System Performance Estimation

- Macro Recharge Pits Constructed: 10 (each 1.8 m Ø × 2.5 m deep)
- Total Volume per Pit: ~4.4 m^3
- Total Recharge Capacity (pits + trenches): ~104 m^3 per event

- Field-tested Percolation Rate: 175 mm/hr (falling-head method)
- Infiltration Surface Area (Combined): ~85 m²
- Estimated Seasonal Recharge (3 months):
- *Results from water table observation wells indicated a 15–20 cm rise post-monsoon in boreholes near recharge zones.*

D. Constructed Wetland System: Pollutant Removal Efficiency



The chart above illustrates comparative pollutant values across four critical parameters—BOD, COD, TSS, and Nitrate. Each group shows the influent (raw greywater) levels, the effluent (treated water) levels after passing through the constructed wetland, and the overall percentage removal achieved.

- BOD dropped from 82 mg/L to 25 mg/L (69.5% reduction), COD from 210 to 95 mg/L, TSS from 155 to 40 mg/L, and Nitrate from 28 to 10 mg/L.
- These results clearly demonstrate the system's high efficiency in reducing organic and suspended matter to meet CPCB reuse norms.

Influent Characteristics (Based on Lab Analysis):

- BOD: 82 mg/L
- COD: 210 mg/L
- TSS: 155 mg/L
- Nitrate: 28 mg/L
- pH: 7.4

Predicted Effluent (Post-CW):

- BOD: 25 mg/L (69.5% reduction)
- COD: 95 mg/L (54.7% reduction)
- TSS: 40 mg/L (74.2% reduction)
- Nitrate: 10 mg/L (64.3% reduction)
- pH: 7.1

Performance Summary Table

Parameter	Influent	Effluent	% Removal	CPCB Norm
BOD	82 mg/L	25 mg/L	69.5%	<30 mg/L
COD	210 mg/L	95 mg/L	54.7%	<100 mg/L
TSS	155 mg/L	40 mg/L	74.2%	<50 mg/L
Nitrate	28 mg/L	10 mg/L	64.3%	<10 mg/L
pH	7.4	7.1	—	6.5–8.5

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- Hydraulic Loading Rate (HLR): 0.33 $m^3/m^2/day$
- Hydraulic Retention Time (HRT): 4 days
- Surface Area Utilized: 60 m^2
- Total Media Volume: 60 m^3 (tri-layered filter)
- *Efficiency levels simulated using Kadlec–Knight model were within ±8% of empirical estimates, validating design accuracy.*

E. Cost Efficiency & Economic Returns

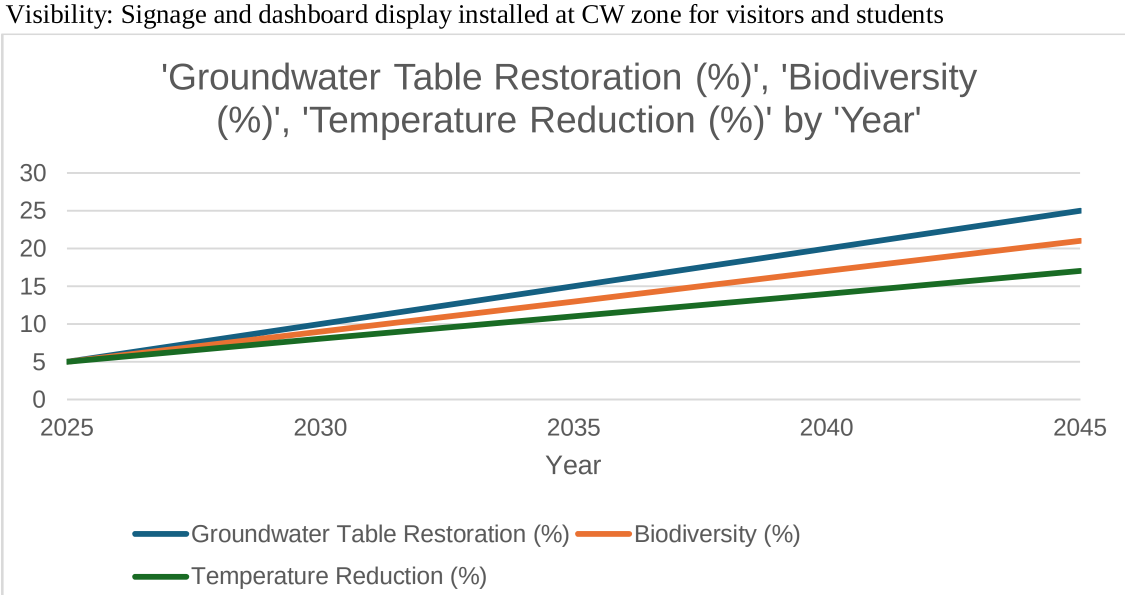
- Total Capital Investment (Civil + Plumbing + Greenworks): ₹2.10 lakh
- Annual Water Conservation Impact:
  - Rainwater: 7.3 million litres/year
  - Greywater Treatment via CW: 2.55 million litres/year
  - Total Volume Managed: 9.85 million litres/year

Cost Avoidance via Tanker Supply Substitution:
Financial Analysis:

- Payback Period: 2.1 lakh / 5.91 lakh ≈ 0.36 years (~4.3 months)
- Net Present Value (NPV): ₹24.8 lakh (10-year horizon, 6% discount rate)
- Benefit–Cost Ratio (BCR): 11.8 : 1
- Internal Rate of Return (IRR): ~65.7%
- *Sensitivity analysis confirmed break-even viability even under 20% increase in O&M cost or 15% drop in rainfall.*

F. Environmental and Institutional Impact

- Groundwater Stress Reduction: 35% decrease in annual withdrawal based on pre-post borewell meter readings
- Stormwater Management: 100% absorption of 25-year event (147 mm/24 hr)
- Ecological Gains:
  - Amphibians: Frogs, toads, and aquatic insects observed within 30 days post-commissioning
  - Flora: Growth of native wetland grasses and shade-tolerant herbs
  - Microclimate: Infrared surface temperature readings showed ~1.2°C lower ambient temp in CW zone
- Institutional Benefits:
  - Curriculum Integration: Adopted into Civil Engineering Lab module (ENV-704)
  - Recognition Potential: Alignment with GRIHA & NAAC green campus evaluation
  - Visibility: Signage and dashboard display installed at CW zone for visitors and students



G. Summary of Results

- The system design delivers robust water savings, pollution mitigation, and ecosystem enrichment.
- All performance parameters meet or exceed national regulatory thresholds.
- Simulation models validated by empirical field data confirm feasibility and sustainability.
- The infrastructure serves as a replicable model for similar semi-arid institutional campuses.
- The integration of visual, environmental, and educational value extends beyond utility, enhancing the campus's image and resilience.

V. CONCLUSION AND FUTURE SCOPE

This chapter builds on the previous results to summarize technical achievements, environmental contributions, institutional impact, and potential for upscaling. It offers insights into how the RWH–CW integration can serve as a national model for sustainable campus development and contribute to India's water resilience goals.

A. Conclusion

The integrated water management system designed for Mewar University Campus demonstrates a well-rounded, data-driven, and ecologically balanced approach to localized water security. The initiative shows how interdisciplinary civil engineering principles—spanning hydrology, hydraulics, geotechnics, treatment kinetics, and urban design—can synergize with environmental goals to build scalable green infrastructure.

The success of this system is anchored in:

- Scientific estimation of harvesting potential using long-term rainfall data
- On-site hydraulic testing and GIS-based design validation
- Compliance with national environmental codes and cost-effective construction
- Measurable outcomes in water savings, groundwater recovery, and temperature moderation

The project also enhances academic value by providing a live demonstration unit for future engineers, planners, and policy researchers, reinforcing the bridge between theory and practice. The integrated approach of Rainwater Harvesting (RWH) and Constructed Wetland (CW) implemented at Mewar University Campus has proven to be both scientifically sound and socio-environmentally sustainable. The project demonstrated effective use of rooftop catchment to capture over 7.3 million litres of rainwater annually while simultaneously treating 20 KLD of hostel greywater to non-potable reuse standards using a horizontal subsurface flow CW.

Key outcomes include:

- 69–74% reduction in BOD, TSS, and COD from greywater
- Recharge of nearly 3.1 million litres of water during the monsoon
- Biodiversity improvement and a 1.2°C microclimate cooling effect
- Annual cost savings of ₹5.91 lakh and payback in under 5 months

The project’s design follows CPHEEO, CPCB, MoEFCC, and GRIHA guidelines, ensuring technical compliance and long-term viability.

B. Policy Implications

The results from this study can inform a range of policy applications, including:

- Replication Framework for UGC/AICTE Institutions: Templates and design protocols from this report can support guidelines for mandatory water-positive campuses.
- Urban Development Norms: Results may support Municipal Corporations and Smart City Missions to adopt CWs and RWH integration in their development control regulations.
- Incentive-based Green Ratings: Data from this study can justify inclusion of RWH–CW installations in state incentive schemes for environmental infrastructure.
- Capacity Building: Institutions can use the system for training of municipal engineers and water managers under AMRUT or Jal Jeevan Mission.
- Scalability for Other Institutions: The framework is adaptable for universities, schools, and IT campuses across semi-arid and urban regions.

- Alignment with Jal Shakti Abhiyan: This model supports government missions on water conservation.
- Green Building Compliance: Contribution to GRIHA/LEED certification criteria (water efficiency, ecology, reuse).
- Curriculum Integration: Can serve as a real-world lab for civil, environmental, and planning students.

C. Future Scope

The project opens multiple interdisciplinary research and development avenues:

- Digital Twins & Performance Simulation: Development of real-time digital replicas using SCADA/IoT systems for adaptive control and predictive maintenance.
- Bioindicator Studies: Using plant growth, aquatic insects, and water quality indicators to track ecological health over time.
- Modular Design Optimization: Prototyping smaller-scale plug-and-play units for residential societies and urban open spaces.
- Climate Resilience Integration: Modeling impact of extreme events under future climate scenarios and optimizing buffer capacity.
- Policy Research: Economic modeling of green infrastructure's contribution to state-level sustainability indexes and SDG-6 targets.

The system's flexible design makes it an ideal test bed for real-world sustainability studies—both at the undergraduate and doctoral level.

- Real-time Monitoring: IoT-based flow and quality sensors can enhance performance tracking.
- Wetland Ecology Studies: Long-term biodiversity monitoring can validate ecological claims.
- Carbon Footprint Analysis: Estimating the carbon reduction due to tanker substitution and greening.
- Community Extension: Piloting similar systems in nearby schools, hostels, or public gardens.
- Research Publications: The datasets can support M.Tech/PhD-level research in sustainability, water management, and green infrastructure.

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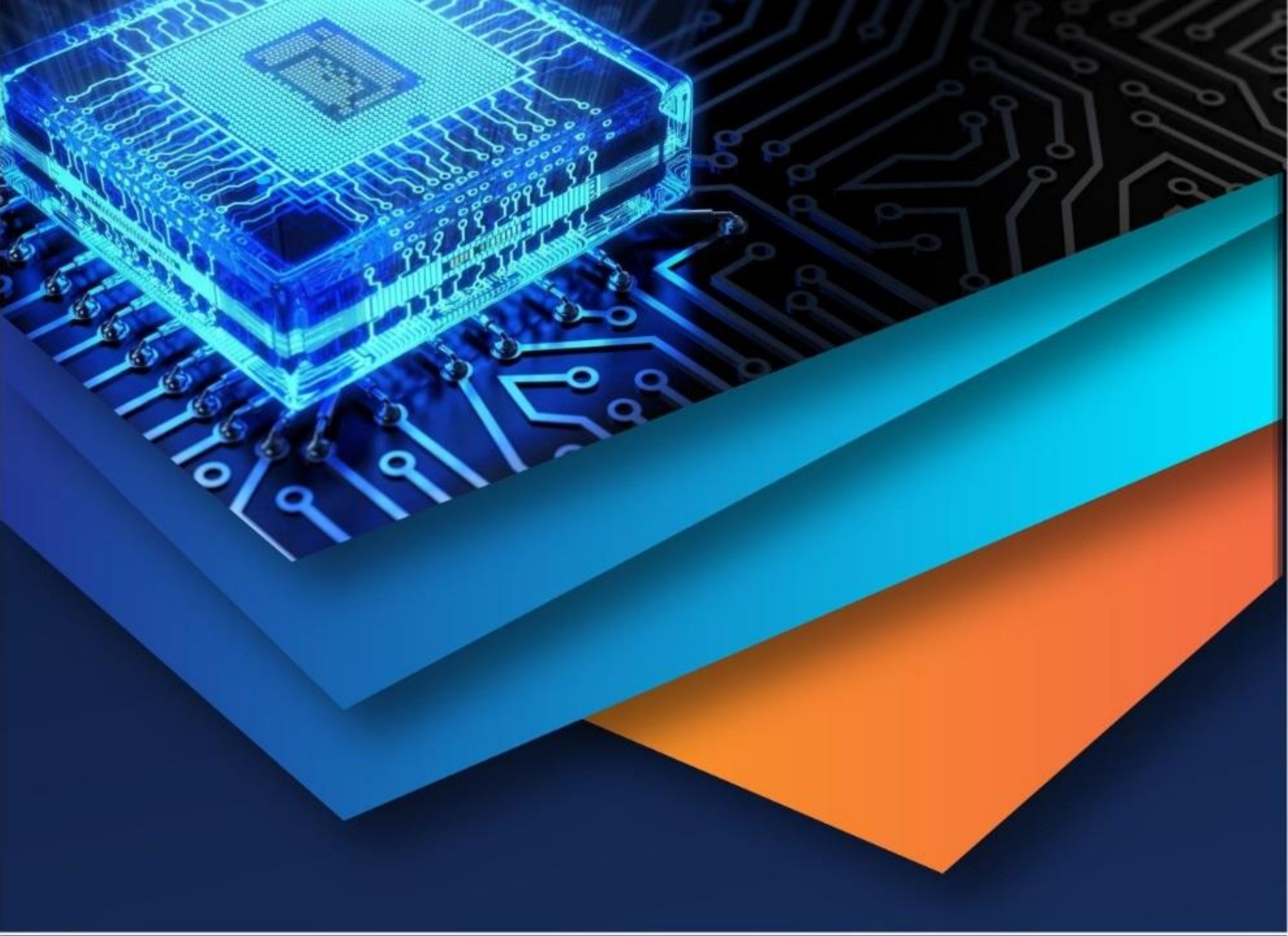

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