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"Rainwater Harvesting in Urban Residential Buildings: A Case Study-Based Economical and Hydrological Assessment"

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Abstract:

The rise in urban water demand, coupled with climate change effects, has put increasing stress on traditional water supply infrastructure. Rainwater harvesting (RWH), in this regard, offers a stable supplemental supply that can decrease reliance on centralized networks and support long-term water security. Its significance extends beyond household water demand satisfaction to lowering utility bills, minimizing urban floods, and maximizing sustainability through optimal utilization of resources. The primary goals of this research are to evaluate the technical effectiveness of RWH systems, determine their economic viability, and examine their place in aggregate urban water management plans. To meet these objectives, the research uses an approach that integrates hydrological evaluation, Building Information Modelling (BIM), water balance modelling, and cost–benefit analysis. The application of case studies in various residential typologies reveals that RWH can provide between 30% and 50% of annual non-potable requirements and payback varies between 3 to 7 years with factors like investment price, tariff design, and rainfall conditions. The article emphasizes the importance of local context in system performance, specifically concerning water quality and policy support. Generally, the study opines that RWH is technically viable and economically economical, and large-scale utilization can only be achieved with effectively framed policies, incentives, and community participation.

Keywords: *Rainwater Harvesting, Urban Water, Sustainability, Water Management, Economic Analysis, Building Information Modeling (BIM), Policy Framework.*

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Introduction:

Water scarcity represents one of the most critical 21st-century global issues, fueled by intense urbanization, population increase, and the effects of climate change. Traditional water supply infrastructure, based on centralized networks and large-scale treatment plants, is increasingly being overwhelmed by urban demand. Against this backdrop, alternative and decentralized sources of water are becoming popular as likely solutions.

Rainwater harvesting (RWH) is one of these alternatives. As a very old activity once more recognized and rediscovered in contemporary water management, RWH entails the collection and storage of rainwater from rooftops or catchment surfaces for domestic, commercial, and even small-scale potable purposes. RWH decreases pressure on centralized supply infrastructures, decreases water bills for households, and assists in managing stormwater by curbing peak runoff volumes in urban settings.

The value of RWH transcends water saving. It helps build sustainable city development through the improvement of drought resilience, facilitation of groundwater recharge, and encouragement of decentralized infrastructure strategies. Nevertheless, though technically viable, RWH uptake is not uniform in cities. This paper assesses the technical and economic efficiency of RWH systems and examines the policy environments required to facilitate their optimal integration into city water policies.

Literature Review:

Rainwater harvesting (RWH) has been comprehensively researched across technical, economic, environmental, and policy aspects, with studies cutting across various geographies and urban environments.

Technical Performance and Water Quality

Early research was largely focused on the technical viability of RWH and rainwater quality. Sazakli et al. (2007) [7] assessed RWH in Greece and made the assessment that rainwater untreated is not

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appropriate for potable purposes but suitable for non-potable uses including flushing toilets and irrigation. Silva et al. (2015) [8] simulated RWH performance in Portugal to show that houses with single families could fulfill a considerable portion of non-potable household needs. Parallel results were documented by Rahman and Khan (2012) [5] in Bangladesh, where the authors emphasized RWH's cost-effectiveness to alleviate pressure on municipal networks.

Economic Assessments

The theme of economic feasibility has been a core article in RWH literature. Abdulla and Al-Shareef (2009) [1] demonstrated the pivotal position of rooftop RWH in water-deficient Jordan, most notably the alleviation of household reliance on central systems. Lani et al. (2018) [2] compared Southern Italy and found that tariff structures have a direct impact on payback periods and system adoption. A case study on a commercial building in Malaysia (Johor Bahru) found that designing RWH from the start greatly enhanced economic parameters like Net Present Value (NPV), Return on Investment (ROI), and reliability over retrofitted systems Johor Bahru study, (2021) [15]. By the same token, a university-scale study in Turkey Kılıç & Kılıç, (2025) [14] estimated an average annual potential of 2045 m^3 with a payback of ~15 years, showing the difference in feasibility between residential and institutional scenarios.

Integrated Approaches: RWH with Greywater and Hybrid Systems

Current studies have focused on integrating RWH with greywater reuse for increased sustainability. Ghisi and Freitas (2024) [12] researched a Brazilian multifamily building and concluded that hybrid systems enhance water savings and enhance economic viability, particularly in scenarios of escalating water tariffs. They also noted potential for decreased energy consumption and stormwater drainage advantages.

Advanced Modeling and Design Tools

Technological advancements have broadened RWH evaluation beyond basic water balance models. Maqsoom et al. (2021) [4] incorporated Building Information Modeling (BIM) for optimizing tank dimensions, catchment mapping, and system visualization. Patil et al. (2023) [17] integrated GIS

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and BIM for urban rainwater management and showed enhanced accuracy in detecting catchments and communicating with stakeholders. Trindade and Reed (2017) [9] proposed multi-objective optimization under uncertainty, considering climate variability and policy reforms. Together, these studies indicate a digital revolution in RWH planning, with BIM and GIS facilitating more accurate and flexible designs.

Environmental and Lifecycle Assessments

In addition to water yield and finances, environmental effects are now also considered. Teston et al. (2022) [13] summarized worldwide evaluations of RWH systems, pointing out that embodied energy of storage tanks, filtration systems, and pumping infrastructure can affect sustainability performance. Lifecycle analyses indicate that while the initial investment might involve carbon expenses, long-term municipal treatment and pumping savings overcome such impacts, especially if systems are well managed.

Policy and Governance Contexts

Policy regimes have a significant impact on rates of adoption. Van Roon (2007) [10] located RWH as an integral component of "low-impact urban design" and connected it with stormwater management in the urban environment. China's "Sponge City" program illustrates how RWH, implemented at the municipal level, is able to provide flood protection, groundwater replenishment, and ecological benefits Li et al., (2023) [3]. In India, there are mandatory RWH policies for big buildings in cities like Bengaluru, Chennai, and Delhi, although there is inconsistency in enforcement. The success of such policies justifies the need for clarity in regulations, subsidies, and awareness campaigns in order to propel adoption.

Justification:

Deployment of Rainwater Harvesting (RWH) in urban residential buildings is economically, technically, environmentally, and socially warranted.

1. Technical Importance RWH offers an immediate decentralized remedy to close demand-supply gaps in cities. As growing stress on traditional supply sources, rooftop catchments and storage tanks

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provide consistent auxiliary supply for non-potable purposes. In addition, through the use of sophisticated software like Building Information Modeling (BIM) and GIS, system sizing and catchment optimization are now possible with greater precision so that long-term operational effectiveness is guaranteed.

2. Economic Feasibility The economic justification for RWH is in its ability to minimize household reliance on costly municipal supply. Payback times range from 3 to 7 years, depending on local water rates, rainfall characteristics, and costs of installation. In high-cost areas, the household recovers investment quickly, and in low-cost areas, government subsidies and tax benefits enhance viability considerably. Therefore, RWH is both a cost-reducing option and a cushion for future tariff increases.

3. Environmental Gains Aside from direct water savings, RWH has a significant role in the management of stormwater by curtailing peak flows of runoff and mitigating urban flooding hazards. In areas where groundwater tables are decreasing, harvested rainwater can be put to recharge, ensuring aquifer sustainability in the long term. Lifecycle analyses also reveal that while tank and filter construction has embodied energy, these are counterbalanced by lower energy requirements for centralized pumping and treatment.

4. Policy Relevance and Governance Several cities, including Bengaluru, Chennai, and Delhi, have already made RWH mandatory for large buildings. However, the effectiveness of such mandates depends on compliance and long-term maintenance. The adoption of RWH, therefore, aligns with national and municipal policy frameworks that promote sustainable urban water management. Strengthening these policies through incentives, subsidies, and awareness programs ensures wider acceptance.

5.Social and Community Effect At the community and household level, RWH increases resistance to drought and water scarcity. It offers a secondary water supply in case of interruptions in supply and promotes water-saving culture. Crucially, social acceptance of reused water and confidence in quality are vital to its large-scale adoption. Informative awareness campaigns can overcome reluctance towards non-potable uses.

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Research Gap:

Notwithstanding the expanding body of evidence attesting to rainwater harvesting (RWH) technical feasibility and environmental advantages, numerous critical research gaps persist that impede their widespread application in urban areas. To begin with, most current research centers on autonomous RWH systems are adopted at the individual household or building scale. These investigations, although useful, tend not to have a wider context for integrating RWH within urban water planning at the community or municipal level. There is sparse investigation on how decentralized systems can be balanced with centralized networks to enhance overall water security and resilience.

Secondly, although hydrological Modeling and water balance simulations are extensively described, it is clear that there is little research where these models have been integrated with real-time building information and dynamic usage patterns. Building Information Modeling (BIM) integration with hydrological analysis is in its infancy, and additional investigation is required to uncover how digital Modeling can be used to feed back into more efficient and responsive RWH system designs.

Thirdly, the economic appraisals of RWH systems are specific to cases and hardly extrapolated to other climatic zones or across tariff conditions. Comparative research on analyzing RWH system financial performance under various policy setups, including subsidized, tax-break, or compulsory adoption policies, is scarce. Additionally, the long-term operational and maintenance expenditure is normally underestimated or oversimplified, which results in optimistic payback periods. Another less researched domain is the behavioral and social aspect of RWH adoption. Although a few studies refer to awareness and public perception as drivers, few explore how socio-cultural mindsets, water quality trust, and user intent to operate systems influence long-term adoption and performance. Without addressing these behavioral elements, the scalability of RWH cannot be assured.

Lastly, the influence of climate variability and urban heat island phenomena on RWH potential is not comprehensively examined in most of the existing research. Future rainfall patterns due to climate change might drastically change the dependability of RWH systems. Nonetheless, few studies use climate models or uncertainty analysis to evaluate system robustness under such changing conditions.

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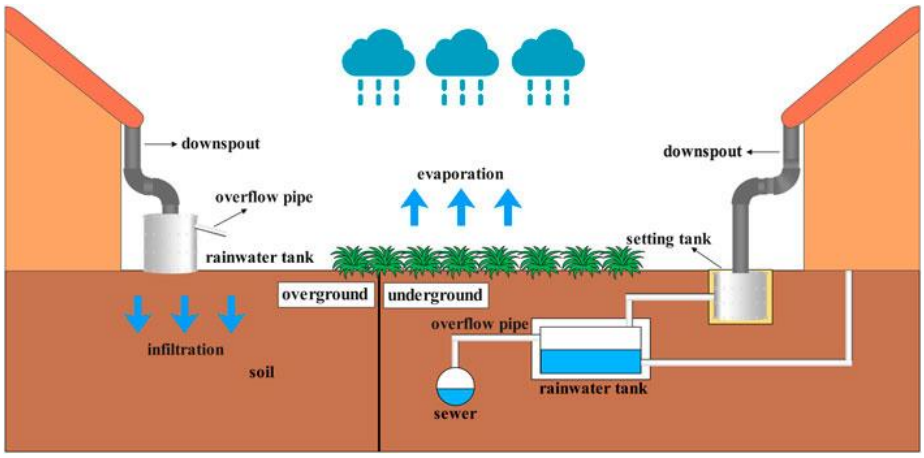
Methodology:

The study employs a multi-step methodology combining hydrological, technological, and economic tools with policy analysis.



Source:(Frontiers)

Figure 1. Urban Rainwater utilization

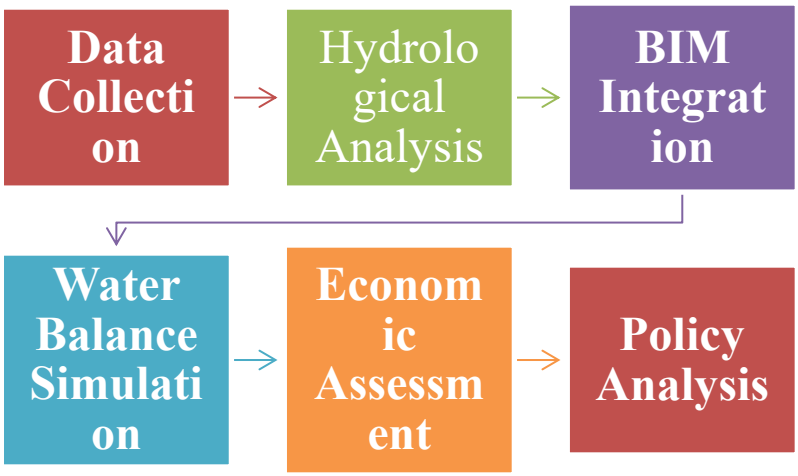


Figure 2. Flow chart representing methodology of hydrological and technological analysis

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- **Data Collection:** The research starts with the gathering of primary and secondary data. Daily and monthly local rainfall data were obtained from the Indian Meteorological Department (IMD) and cross-checked with accessible local weather station records. Household water use data were gathered from surveys and secondary data collections, organized by housing type (apartments, independent houses, and gated communities). Information on building design, such as roof area, slope, and material, was taken from architectural plans and site measurements.
- **Hydrological Analysis:** Based on data gathered, possible rainwater yield was determined using the formula:

$$Q=R\times A\times C$$

where Q = amount of water collected, R = depth of rainfall, A = catchment area, and C = runoff coefficient (determined by roof material). Patterns in daily rainfall were also examined to determine seasonal variation, reliability, and deficit conditions. This task set the benchmark potential for rainwater harvesting for various types of buildings.

- **Integration with Building Information Modeling (BIM):** For attaining correct system design, Building Information Modeling (BIM) was used to virtually model the residential buildings. BIM enabled accurate characterization of roof catchment areas, runoff routes, and potential storage sites. Pipe network designs and tank sizing were maximized in the model to minimize costs of construction and space needs. This phase also allowed a visual representation of how the RWH system fits into current building infrastructure.
- **Water Balance Simulation:** A single-day water balance model was constructed to estimate system performance for a year. The model considered rainfall input, household needs, tank capacity to store water, occasions where overflow occurred and deficits. Simulation enabled comparison of small, medium, and large storage tanks, thus determining the most economical capacity per building type. Sensitivity tests were also run to analyse the impact of different rainfall levels and demand patterns.
- **Economic Assessment:** A cost–benefit analysis was conducted in detail to evaluate the economic viability of RWH systems. The analysis involved initial capital cost (tanks, filters,

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gutters, and plumbing), operation and maintenance costs, and replacement cycles. Benefits were estimated as municipal water bill savings, lowered reliance on tanker water, and indirect benefits including stormwater management. Primary financial metrics like Net Present Value (NPV), Benefit–Cost Ratio (BCR), and payback period were calculated. Sensitivity analyses were conducted to see the impact of varying water tariff structures and government subsidy on system viability.

- **Policy and Scenario Analysis:** In addition to technical and financial analysis, the research also assessed the influence of policy support in terms of adoption. Various scenarios were simulated, namely:

  •Base case: No incentives, regular municipal tariffs.

  •Government subsidy model: Addition of government subsidy on tank installation.

  •Mandatory model: Enactment of compliance of building code with RWH.

  •Tariff escalation model: Modeling future rising water tariffs.

  This allowed for an evaluation of how governance mechanisms can change adoption rates and economic viability.

Results and Discussion:

Case study experiences indicate that RWH systems are capable of supplying 30–50% of the domestic water requirement annually, depending on the rainfall in the specific area and tank capacity. Those with bigger catchments and sized tanks performed better in terms of reliability. Economic evaluation revealed significant variability in payback periods ranging from a mere 2.4 years for areas where there were high tariffs to over ten years for regions where water was low-cost. This supports the need for tariff structures and incentives to spur adoption. Rainwater quality was generally adequate for non-potable applications, although roof materials and air pollution affected results, requiring simple filtration. Aside from technical and economic viability, the analysis

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highlights the need for governance and social acceptance. Targeted subsidies, compulsory building regulations, and public awareness campaigns were highlighted as possible drivers for scaling RWH adoption.

In general, the findings underscore that although RWH is a sustainable urban water management strategy, its success in the greater scheme depends on context-based policy as well as synergy with other water-saving strategies like greywater reuse.

Summary:

Urban centers are experiencing intensified water pressure from expanding populations, accelerated urbanization, and climate change. Conventional, centralized water supply systems are finding it difficult to cope with this rising pressure. In this regard, rainwater harvesting (RWH) is a viable, sustainable solution to complement water supply, lower utility bills in households, and better control stormwater. This research investigates the technical efficiency, economic viability, and policy implications of adopting RWH systems in urban residential areas. By integrating hydrological analysis, Building Information Modeling (BIM), daily water balance modeling, and cost–benefit analysis, the study evaluates the performance of RWH in various types of housing and climatic conditions. The results indicate that RWH has the potential to supply 30% to 50% of annual non-potable water requirements, for example, for toilet flushing and irrigation. The cost recovery time depends on local water charges and the cost of installation and ranges from 3 to 7 years. In areas with high water prices, RWH systems become more financially compelling. While rainwater quality is typically acceptable for non-potable use, simple filtration will usually be required because of considerations such as roof composition and urban air pollution.

Conclusion:

RWH has high potential to minimize urban reliance on centralized water supply, decrease household expenses, and alleviate stormwater issues. Using BIM-based design, hydrological simulation, and economic analysis, this research shows the technical and economic viability of RWH in varied conditions. Nevertheless, tariff, climate fluctuation, and public adoption uncertainties require a

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comprehensive strategy that integrates technology with adaptive policy. Subsequent research needs to look outward to city-wide model implementation, integrate behavioral adoption studies, and consider synergies with RWH and other decentralized water management approaches.

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