Cost-Benefit Analysis and Life Cycle-Assessment of Rainwater Harvesting in a Commercial Building

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Abstract*: This study examines the economic viability and environmental sustainability of implementing a rainwater harvesting (RWH) system in a six-story commercial office building through the integration of Cost–Benefit Analysis (CBA) and Life Cycle Assessment (LCA). Rapid urbanization, increasing water demand, and rising utility costs have intensified the need for alternative water management strategies in commercial developments. The proposed RWH system captures rooftop runoff, treats it through filtration units, and reuses the collected water for non-potable applications such as toilet flushing and landscape irrigation. The Cost–Benefit Analysis evaluates capital, operational, maintenance, and end-of-life costs against long-term financial benefits, including reduced municipal water consumption, lower wastewater fees, and resilience against future water tariff increases over a 20-year project life. Meanwhile, the Life Cycle Assessment assesses environmental impacts across manufacturing, installation, operation, and disposal phases. Results indicate that although the system entails significant upfront investment, the long-term economic savings outweigh total costs, yielding a favorable benefit–cost ratio. Environmental analysis further demonstrates net positive outcomes through reduced potable water use, lower energy consumption for water treatment, and decreased wastewater generation. Overall, the findings support rainwater harvesting as a practical, cost-effective, and environmentally responsible solution for commercial office buildings, contributing to sustainable urban water management and long-term operational efficiency.

***Keywords*: Rainwater harvesting, Cost–Benefit Analysis, Life Cycle Assessment, Sustainable engineering, Water management.**

1. Introduction

Engineering decision-making increasingly requires the integration of economic feasibility and environmental sustainability, particularly in the design and operation of urban infrastructure. Commercial office buildings are significant consumers of potable water, largely due to non-potable demands such as toilet flushing, landscape irrigation, janitorial services, and cooling-related processes. As urban populations grow and climate change intensifies rainfall variability and water scarcity, centralized municipal water systems face mounting pressure to meet demand reliably and affordably.

In many developing and highly urbanized regions, rising water tariffs, energy-intensive treatment processes, and aging distribution infrastructure further exacerbate operational challenges for building owners and facility managers. These conditions necessitate alternative water management strategies that can reduce dependence on municipal supply while maintaining service reliability and regulatory compliance. Engineers are therefore tasked not only with technical system design but also with evaluating long-term economic performance and environmental impacts of infrastructure solutions.

Rainwater harvesting (RWH) has gained recognition as a sustainable engineering practice that captures and reuses precipitation for non-potable applications. By utilizing rooftop catchment areas and on-site storage systems, rainwater harvesting can significantly reduce potable water consumption, lower wastewater discharge volumes, and decrease the energy required for centralized water treatment and distribution.

Despite these advantages, the adoption of rainwater harvesting in commercial buildings is often hindered by concerns over initial capital costs, system maintenance requirements, and uncertainties regarding long-term performance. A comprehensive evaluation that considers both financial returns and environmental impacts over the system's entire life cycle is therefore essential to support informed engineering and management decisions.

This study addresses these challenges by applying Cost–Benefit Analysis (CBA) and Life Cycle Assessment (LCA) to a rainwater harvesting system implemented in a six-story commercial office building. By examining economic costs, operational savings, and environmental outcomes across a 20-year life span, the research aims to demonstrate whether rainwater harvesting represents a viable and sustainable solution for commercial developments. The findings are intended to guide engineers, facility managers, and decision-makers in adopting water-efficient technologies that balance economic practicality with environmental responsibility.

2. Methodology

A. Case Description

The subject of this study is a six-story commercial office building located in a densely populated urban business district. The building accommodates administrative offices, conference rooms, shared service facilities, and limited recreational areas. It features a wide rooftop area suitable for rainwater collection. Prior to the project, the building relied entirely on municipal water, resulting in high utility costs and a substantial environmental footprint.

The proposed rainwater harvesting system collects rooftop runoff, filters it through first-flush diverters and filtration units, stores it in underground tanks, and distributes it via a dedicated non-potable plumbing network for toilet flushing and landscape irrigation. Semi-automated pumps and control systems manage water levels and supplement supply with municipal water when required.

B. Organizational Context

The building is managed by an organization focused on cost optimization, regulatory compliance, and sustainability initiatives. Rising water tariffs and corporate environmental targets motivated the exploration of alternative water management strategies. The adoption of rainwater harvesting aligns with green building certification goals, enhances operational resilience, and supports long-term sustainability objectives.

C. Problem Statement

The increasing dependence of commercial office buildings on municipal water supply presents both economic and environmental challenges. Rising water tariffs, growing demand, and the environmental impacts associated with centralized water treatment and distribution highlight the need for alternative and sustainable water management solutions. Despite the recognized potential of rainwater harvesting systems, uncertainty remains regarding their long-term financial feasibility and environmental performance, particularly when applied to medium-scale commercial buildings.

This study seeks to determine whether the implementation of a rainwater harvesting system in a commercial office building is economically viable and environmentally sustainable when evaluated over its full life cycle.

Specifically, it seeks to answer the following questions:

1. What are the total life-cycle costs associated with the installation, operation, maintenance, and end-of-life of a rainwater harvesting system in a six-story commercial office building?
2. What financial benefits can be realized from reduced municipal water consumption, wastewater charges, and long-term operational savings through the use of rainwater harvesting?
3. How does rainwater harvesting system yield a favorable cost–benefit ratio over a 20-year project lifespan compared to full reliance on municipal water supply?
4. What are the environmental impacts of the rainwater harvesting system across its life cycle, including manufacturing, installation, operation, and disposal stages?
5. How does rainwater harvesting compare with alternative water management options in terms of economic performance, environmental sustainability, and operational resilience?

By addressing these research problems, the study aims to provide evidence-based guidance for engineers, facility managers, and decision-makers considering sustainable water infrastructure solutions.

D. Research Instrument

This study utilized a combination of qualitative and quantitative research instruments to support comprehensive economic and environmental analysis. The primary research instruments include:

1) Water Consumption Records

Historical and projected water usage data from the commercial office building were analyzed to determine baseline demand and estimate potential savings from rainwater harvesting.

2) Cost Data Collection Sheets

Detailed cost records were used to capture capital expenditures, operation and maintenance costs, and projected end-of-life expenses associated with the rainwater harvesting system.

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4) Life Cycle Assessment Framework

An LCA framework based on ISO 14040 standards was employed to assess environmental impacts across the system's life cycle stages.

5) Technical Documentation and Design Specifications

Engineering plans, system layouts, and manufacturer specifications were reviewed to ensure accurate assessment of system capacity, performance, and operational requirements.

6) Expert Consultation and Project Records

Inputs from facility managers, engineers, and project stakeholders were utilized to validate assumptions, operational practices, and maintenance requirements.

These research instruments ensured data accuracy, methodological rigor, and reliability of results, supporting evidence-based conclusions regarding the feasibility and sustainability of the rainwater harvesting system.

E. Statistical Treatment of Data

This study employed quantitative analytical techniques to evaluate the economic and environmental performance of the rainwater harvesting system. Statistical treatment of data was applied to ensure objective comparison between the baseline scenario and the proposed system over a 20-year period.

1) Cost–Benefit Analysis (CBA)

The Cost–Benefit Analysis was used as the primary statistical tool to assess the economic feasibility of the rainwater harvesting system. Financial data were organized and analyzed using spreadsheet-based models. Capital costs, operation and maintenance expenses, and end-of-life costs were aggregated to compute total project costs. Benefits were quantified through reductions in municipal water consumption, wastewater charges, and projected savings from avoided tariff increases.

Key financial indicators calculated include total costs, total benefits, benefit–cost ratio (BCR), and payback period. Comparative analysis was conducted between the baseline (municipal water only) and project (rainwater harvesting) scenarios to determine net economic advantage

2) Life Cycle Assessment (LCA)

Life Cycle Assessment served as the statistical framework for evaluating the environmental impacts of the rainwater harvesting system. Data were categorized according to four life-cycle stages: manufacturing, installation, operation, and end-of-life. Quantitative indicators such as potable water savings, energy consumption reduction, wastewater volume reduction, and emissions mitigation were measured and compared across stages.

Environmental impact data were normalized and interpreted to determine net environmental performance over the system's life span. The results enabled comparison between conventional water supply reliance and rainwater harvesting, supporting evidence-based evaluation of sustainability outcomes**.**

The Life Cycle Assessment evaluates the environmental impacts of the rainwater harvesting system across four stages: manufacturing of components, installation and construction, operation and maintenance, and end-of-life disposal or recycling. Environmental indicators considered include potable water savings, energy consumption, emissions associated with water treatment and distribution, and wastewater reduction.

3. Results and Discussion

A. Results

The results of this study are presented in accordance with the identified research problems, focusing on both economic and environmental performance of the rainwater harvesting system.

1) Life-Cycle Costs of the Rainwater Harvesting System

Analysis of cost data shows that the rainwater harvesting system entails substantial initial capital investment, including expenses for storage tanks, filtration units, pumps, control systems, plumbing modifications, and installation. Additional costs include periodic maintenance, energy consumption for pumping, and eventual end-of-life disposal or component replacement. However, when distributed over the 20-year life span, the annualized cost of the system becomes manageable and predictable, supporting long-term financial planning.

2) Financial Benefits and Cost Savings

The results indicate significant financial benefits resulting from reduced municipal water consumption and lower wastewater discharge fees. The system supplies a considerable portion of non-potable water demand, leading to consistent utility cost savings. Over time, these savings increase as water tariffs rise, further enhancing the economic value of the rainwater harvesting system.

3) Cost–Benefit Performance

Cost–Benefit Analysis demonstrates that total benefits exceed total costs, yielding a benefit–cost ratio greater than one. The calculated payback period falls within the system's operational life, confirming that the investment is economically justified when evaluated over the long term.

4) Environmental Impacts Across the Life Cycle

The Life Cycle Assessment results show that while the manufacturing and installation stages contribute to initial environmental impacts, these are offset during the operational phase. The system significantly reduces potable water demand, energy use associated with water treatment and distribution, and wastewater generation. Over its life cycle, the rainwater harvesting system exhibits net positive environmental performance.

5) Comparison with Alternative Water Management Options

Comparative evaluation reveals that rainwater harvesting outperforms alternatives such as exclusive reliance on municipal water, water-efficient fixtures alone, or greywater reuse systems in terms of combined economic and environmental benefits. Rainwater harvesting provides greater operational resilience and long-term sustainability, particularly when integrated with conservation measures.

B. Discussion

The results confirm that rainwater harvesting represents a viable solution to the economic and environmental challenges associated with water use in commercial office buildings.

Although the system requires high upfront investment, long-term cost savings from reduced municipal water dependence justify the expenditure. The favorable benefit–cost ratio and reasonable payback period indicate strong economic feasibility.

From an environmental perspective, the Life Cycle Assessment demonstrates that rainwater harvesting contributes to sustainable water management by reducing potable water consumption, lowering energy use for centralized treatment, and minimizing wastewater discharge. These benefits align with sustainable engineering principles and organizational environmental objectives.

The comparison with alternative strategies highlights the importance of adopting integrated water management solutions rather than relying solely on efficiency measures. Rainwater harvesting not only provides direct resource savings but also enhances resilience against supply disruptions and regulatory changes.

Overall, by directly addressing each research problem, the findings reinforce the value of combining economic and environmental analysis in engineering decision-making. The results provide strong empirical support for the adoption of rainwater harvesting systems in commercial buildings seeking long-term operational efficiency, sustainability, and compliance with evolving environmental standards.

The integration of Cost–Benefit Analysis and Life Cycle Assessment provided a comprehensive evaluation framework that supports sustainable engineering management decisions. Although the system requires a high initial capital investment, long-term financial and environmental benefits justify implementation. Leadership, proper system design, staff training, and performance monitoring were critical to project success.

Technology integration—including rooftop catchments, filtration units, storage tanks, automated pumps, and dedicated plumbing—enabled efficient operation with minimal human intervention. Continuous monitoring and adaptive management ensured sustained system performance throughout its life cycle.

4. Conclusion

This study comprehensively evaluated the implementation of a rainwater harvesting system in a six-story commercial office building using an integrated Cost–Benefit Analysis (CBA) and Life Cycle Assessment (LCA). The findings confirm that rainwater harvesting is both economically viable and environmentally sustainable when assessed over its full life cycle. Although the system requires a relatively high initial capital investment, the long-term financial benefits—such as reduced municipal water consumption, lower wastewater charges, and protection against future water tariff increases—clearly outweigh the initial costs, demonstrating a strong economic case for adoption.

From an environmental perspective, the Life Cycle Assessment reveals that rainwater harvesting substantially reduces potable water demand, energy consumption associated with centralized water treatment and distribution, and wastewater generation. While the manufacturing and installation stages introduce some initial environmental impacts, these are effectively offset during the operational phase, leading to a net positive environmental outcome over the system's projected 20-year life span. Additionally, the system contributes to enhanced stormwater management, mitigating urban flooding risks, and strengthens resilience against potential water supply disruptions, which is particularly relevant in regions facing water scarcity.

This study provides evidence-based support for rainwater harvesting as a practical and responsible engineering solution for commercial buildings. The results underscore the importance of adopting life-cycle thinking in engineering and infrastructure planning, ensuring that both economic performance and environmental responsibility are integral considerations in decision-making. First, rainwater harvesting aligns with global sustainability initiatives, including water conservation, climate adaptation, and green building standards. Second, the successful integration of such systems can improve organizational reputation, foster stakeholder trust, and serve as a model for other commercial and institutional developments. Finally, the study emphasizes that early planning, appropriate design, and careful system maintenance are crucial to maximizing both economic and environmental benefits over the system's lifetime.

Ultimately, widespread adoption of rainwater harvesting systems in urban commercial buildings can enhance operational efficiency, support sustainability goals, and promote responsible resource management. These insights can serve as a valuable reference for engineers, facility managers, and policymakers seeking to implement sustainable water infrastructure solutions, encouraging a shift toward more resilient, efficient, and environmentally conscious urban development.

5. Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Integration in Early Design Stages – Rainwater harvesting systems should be considered during the early planning and design phases of commercial buildings to optimize system sizing, reduce retrofitting costs, and ensure seamless integration with building infrastructure.
2. Policy and Incentive Support – Building owners and policymakers should promote rainwater harvesting through incentives, regulatory support, or inclusion in green building standards to encourage wider adoption in urban developments.
3. Regular Monitoring and Maintenance – Proper operation and maintenance programs should be implemented to ensure long-term system efficiency, water quality, and reliability. Periodic performance evaluations can help maximize economic and environmental benefits.
4. Integration with Other Water Conservation Measures – Rainwater harvesting should be combined with water-efficient fixtures, behavioral conservation programs, and smart monitoring systems to further enhance water savings and operational resilience.
5. Future Research and System Optimization – Further studies are recommended to evaluate system performance under varying climatic conditions, expand analysis to different building types, and incorporate advanced technologies such as real-time monitoring and automation

These recommendations aim to guide stakeholders in maximizing the benefits of rainwater harvesting systems while supporting sustainable and resilient urban water management practices.

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[7] Key Finding: Confirms RWH has a higher "Benefit-Cost Ratio" (BCR > 1.0) compared to more complex on-site recycling, making it more economically feasible for long-term use.

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