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Original Article

Comparative Analysis of Roof Geometries for Rainwater Harvesting using CAD Modeling in Autodesk Inventor

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Abstract *- This study proposes a geometric optimization approach for rooftop rainwater harvesting systems using parametric three-dimensional modeling. The study addresses the influence of roof shape on hydraulic efficiency under controlled conditions, holding constant slope, projected area, runoff coefficient, and precipitation parameters. Three common configurations: a gable roof, a mono-pitched roof, and a butterfly roof, are modeled using Autodesk Inventor to compare their potential harvesting volumes. The analysis isolates the geometric effect by applying a uniform runoff coefficient to each model and calculating the theoretical annual volume based on the effective sloped area. The results show that the butterfly roof significantly improves hydraulic performance, with an 18 percent increase over the reference flat model, while the other configurations show equivalent improvements of 6.35 percent. The methodology allows efficiency prediction without the need for physical prototyping and highlights the value of CAD-assisted conceptual design in stormwater harvesting systems. These findings provide a replicable framework for optimizing performance in rural regions with high rainfall and guide future research with CFD simulations and experimental validations.*

Keywords *- Autodesk inventor, Roof geometry, Runoff efficiency, Rainwater harvesting systems, Structural typologies.*

1. Introduction

Water scarcity is one of the most pressing challenges of the 21st century. It is estimated that nearly 4 billion people face severe water scarcity at least one month a year [1], and that by 2050, this figure could reach 6 billion [2]. This phenomenon is exacerbated by population growth, uncontrolled urbanization, and the effects of climate change, which alter precipitation patterns and increase the frequency of droughts and floods [3]. In this context, Rainwater Harvesting (RWH) is presented as a sustainable, decentralized, and low-impact strategy to complement water supply, especially in rural or peri-urban areas with limited infrastructure [4].

In Latin America, and particularly in Peru, the situation is critical: more than 50% of the population lives on the coast, but this region only has 2% of the country's fresh Water [5]. Furthermore, an estimated 15 million Peruvians lack safe and consistent access to drinking water [6]. In high Andean regions such as Pasco, where annual rainfall exceeds 1,200 mm, efficient rainwater harvesting represents a tangible opportunity to improve local water security [7].

Among the many forms of RWH, Rooftop Rainwater Harvesting (RRWH) stands out for its simplicity, low cost, and adaptability to different scales. Several studies have shown that this technique can reduce pressure on groundwater sources, improve domestic water security, and contribute to the climate resilience of communities [8, 9]. Furthermore, its implementation can be integrated with sustainable urban drainage systems, mitigating flood risk and promoting aquifer recharge [10]. Given this situation, the use of three-dimensional design and computational simulation tools allows exploring geometric alternatives that optimize harvesting efficiency from the project's conceptual stage, without the need for physical prototypes. This digital approach reduces costs and implementation times and facilitates objective comparisons between different roof configurations, which is key to maximizing hydraulic performance in high-rainfall environments.

Several studies have addressed this issue from empirical, territorial, and technical-scientific perspectives. Nnaji [11] evaluated the suitability of concrete, galvanized zinc, and aluminium roofs for rainwater harvesting, concluding that non-reactive metal roofs exhibit greater hydraulic efficiency and better harvested water quality.

In a large-scale case study, Naik et al. [12] designed a rainwater harvesting system for an industrial complex comprising 16 buildings, successfully collecting over 59,000 m³ annually from galvanized roofs with an effective runoff coefficient of 0.68. Wahyuningsih et al. [13] experimentally compared asbestos, clay tile, and zinc roofs, analyzing the physical and chemical parameters of the collected Water and its suitability for non-potable use in tropical climates.

Taking an integrative approach, Bañas et al. [9] analyzed more than 1,100 indexed articles and highlighted roof slope, shape, and materials as critical factors for efficiency, sustainability, and water quality. Finally, Radzali et al. [14] implemented a geospatial model based on satellite imagery and digital segmentation to classify urban roofs according to their hydraulic and sanitary potential, empirically validating that metal roofs in good condition generate higher-quality Water in dense urban environments.

Despite the growing number of studies on rainwater harvesting, a methodological gap persists in the systematic comparison of different roof geometries from a digital design perspective. Most research focuses on experimental conditions with existing roofs or on analyzing water quality and material behavior, neglecting the impact that geometric shape can have on the harvested volume and overall hydraulic efficiency.

In this context, a three-dimensional approach based on CAD modeling is proposed, specifically using the Autodesk Inventor platform, to evaluate the potential behavior of three roof configurations: gable (triangular), single-pitched (sloped plane), and butterfly (inverted V). The analysis focuses on geometric efficiency to maximize the harvested volume, integrating real runoff coefficients taken from the scientific literature without resorting to physical prototypes. The article begins by presenting the three-dimensional modeling of three roof types, describing their geometric characteristics and boundary conditions. The potential harvesting volumes are then calculated from the data.

2. Literature Review

Rooftop Rainwater Harvesting (RRWH) has been widely studied in recent decades, with emphasis on three main areas: the influence of roofing materials on the quality of the collected Water, hydraulic efficiency under real empirical conditions, and the relevance of geometric design as a critical factor in the conceptual phase of the system.

2.1. Roof Material and Quality of Collected Water

Nnaji [11] compared concrete, galvanized zinc, and aluminium roofs installed on real buildings under tropical conditions, evaluating physicochemical parameters such as pH, turbidity, and heavy metal concentrations. The study concluded that non-reactive aluminium performed better in both hydraulic efficiency and water quality, with an estimated runoff coefficient of 0.85. Additionally, Wahyuningsih et al. [13] analyzed asbestos, clay tile, and zinc roofs in Indonesia, finding that the material's shape, roughness, and composition significantly affected the suitability of Water for non-potable domestic use. In line with these findings, Radzali et al. [14] combined satellite spectral analysis and physicochemical testing on urban concrete, asbestos, and metal roofs with a 20° slope, concluding that new metal roofs were the most suitable for RWH adoption from a sanitary perspective.

These works agree that the selection of materials influences not only the quantity of Water collected but also its quality, which supports the proposed digital modeling approach, based on metal covers with high efficiency.

2.2. Hydraulic Performance in Real-Life Implementations

A relevant case study is that of Naik et al. [12], who designed and implemented a rainwater harvesting system in an industrial complex of 16 buildings with galvanized zinc pitched roofs. The system managed to collect approximately 59,671 m³ annually from 60,062 m² of roofed area, with a composite runoff efficiency of 68%. This work is particularly useful for validating simulated results and estimating expected volume ranges in comparable systems, such as those proposed in this article, using CAD modeling.

2.3. Geometric Design and System Efficiency

Bañas et al. [9] conducted a systematic review of over 1,100 indexed scientific articles, identifying that roof geometry, material, and slope are determining factors in collection efficiency, pollutant accumulation, and system viability.

The lack of studies exploring comparisons between structural forms from the digital design stage is notable. In this regard, this paper seeks to contribute through a comparative three-dimensional analysis of typical configurations (gable roof, single roof, and butterfly roof), with the aim of estimating their potential efficiency before the construction stage. Table 1 shows the relevant studies on hydraulic efficiency in rainwater harvesting systems according to the types of roofs.

3. Methodology

This section describes the technical procedure adopted to compare the hydraulic efficiency of three roof geometric configurations using parametric modeling in a CAD environment. A replicable three-dimensional approach, with controlled slope, area, and precipitation conditions, is used to evaluate the impact of roof shape on the volume of Rainwater Harvesting in RRWH systems.

Table 1. Relevant studies on hydraulic efficiency in roof-based rainwater harvesting systems

Author (Year)	Roof type evaluated	Area (m²)	Precipitation (mm/year)	Runoff coefficient	Parameters	Contribution
Nnaji (2019)	Concrete, zinc, aluminum	Not specified	Tropical (not precise)	≈0.85 (aluminum)	pH, turbidity, heavy metals	Non-reactive material improves efficiency and water quality
Naik et al. (2024)	Sloped metal roofs (galvanized)	60,062	1,461	0.68 (composite)	Actual collection volume, efficiency	Empirical basis for validating simulated volumes
Wahyuningsih et al. (2020)	Asbestos, clay tile, zinc	6 prototypes	~2,920	Not reported	pH, metals, color, coliforms	Comparison of materials under tropical conditions
Bañas et al. (2023)	Literature review (flat, sloped, green roof, etc.)	Global studies	640–4,239	0.4–0.9 (depending on source)	Design, sustainability, quality, efficiency	Theoretical basis for comparing geometries from design

3.1. Three-Dimensional Design of Roofs

The geometric models were developed using the Autodesk Inventor platform, which was selected for its ability to generate accurate and controlled parametric representations. Each design was built with a constant projected area of 100 m² and a uniform slope of 20°, to isolate the effect of geometry on hydraulic efficiency.

The three configurations evaluated were:

- Gable roof (triangle roof).
- Single-pitched roof (single slope).
- Inverted gable roof (butterfly roof)

Figure 1 shows the CAD model of the gable roof. The isometric view 1(a) shows the symmetry of both inclined slopes, and the side view 1(b) shows the 20° slope and the bidirectional flow of runoff towards the opposite ends.

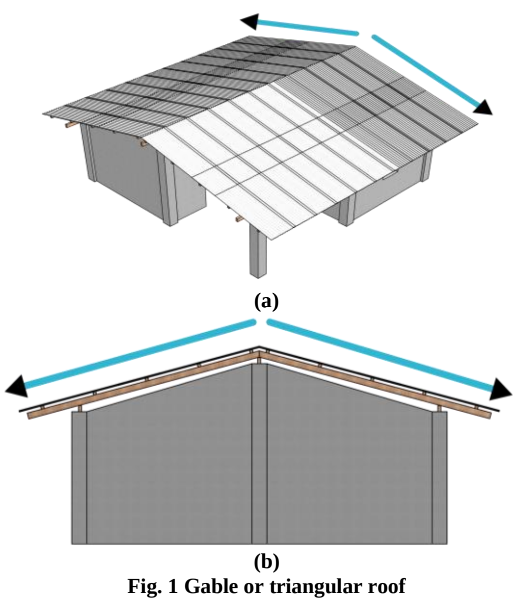


Fig. 1 Gable or triangular roof

Figure 2 shows the CAD model of the single-pitched roof. The isometric view 2(a) shows the entire sloped plane in a unidirectional orientation, while the side view 2(b) reveals the single 20° slope that directs runoff toward the lower edge of the design.

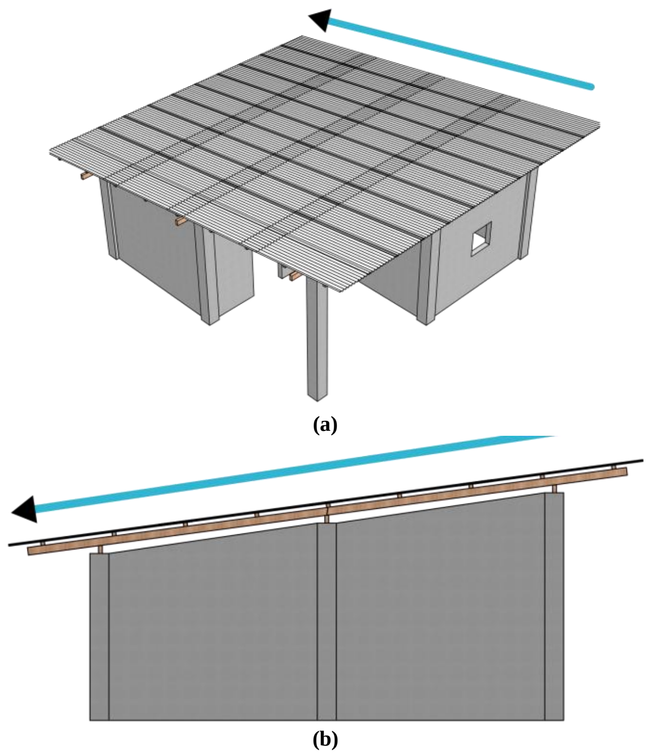
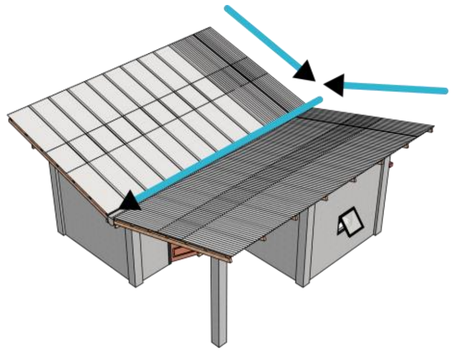
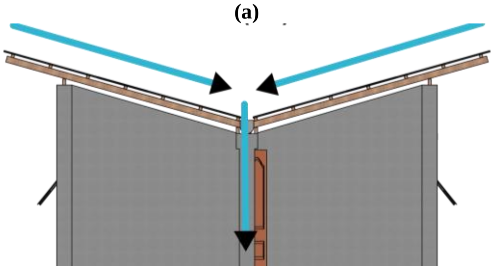


Fig. 2 Single-pitched or single-slope roof

Figure 3 shows the CAD model of the butterfly roof. The isometric view 3(a) shows the inverted "V" shape, and the side view 3(b) shows the central drainage channel facilitated by the double slope oriented towards the lower line.



(a)



(b)

Fig. 3 Inverted gable or butterfly roof

In each figure, the natural direction of surface runoff under ideal conditions is indicated by arrows, based on the sloped geometry. These representations do not correspond to a hydraulic simulation, but rather a conceptual visualization of the geometric behavior of the flow.

The effective catchment area was defined as the horizontal projection of the roof surface, which corresponds to the rainfall intercepting surface, following criteria established in previous studies on rainwater harvesting (Salinas-López et al., 2016; FAO, 2012). This parameter is essential for estimating the potential volume of collected Water.

3.2. Calculation of Collected Volume

Equation (1) calculates the theoretical annual catchment volume, where V is the volume of Water collected, P is the average annual precipitation, A is the projected roof area, and C is the runoff coefficient.

$$V = P \times A \times C \tag{1}$$

This formula provides a base volume of 102 m^3/year on a flat surface. The adjusted volume of each model is then determined based on its actual sloped area, without modifying the coefficient or precipitation. This isolates the effect of geometry on hydraulic efficiency.

It should be noted that, although Equation (1) uses the projected area as the base collection parameter (100 m^2), the final volume collected by each configuration depends on its sloped surface area, which varies according to the roof geometry. This difference is considered the geometric effect on hydraulic efficiency, holding the other calculation parameters constant.

Furthermore, the analysis does not include evaporation losses, initial runoff (first flush), surface fouling, or storage system efficiency, as the objective is only to compare the relative geometric efficiency of each configuration.

3.3. Assumptions and Calculation Parameters

To maintain a constant slope (20°) in all three configurations, each model's front and rear heights were adjusted using elementary trigonometry, maintaining the rectangular base of 10 × 10 m. In the case of the butterfly roof, two slopes converging towards a linear central gutter were simulated, which would function as the main collection line under ideal laminar runoff conditions.

4. Results

Based on the CAD model and the parameters defined in Section 3, the estimated collection volumes for each roof configuration were calculated using the base hydraulic equation.

Applying Equation (1) defined in the previous section, the estimated annual volume of rainwater collected for each geometric configuration was calculated using the previously defined parameters: average annual rainfall of 1,200 mm, constant projected area of 100 m^2, and a runoff coefficient of 0.85, corresponding to new metal roofs.

$$V = P \times A \times C$$

For this study, $= 1.2m$, $A = 100m^2$ were assumed and a runoff coefficient of 0.85 was adopted, representative for new metal roofs on steep slopes, as reported in previous studies [11, 14], which generates a reference base volume of $V = 102m^3/year$.

The differences observed between models are exclusively attributed to the effective inclined surface and its collection geometry.

4.1. Hydraulic Comparison between Configurations

Table 2 shows the three models, which have different inclined surfaces due to their geometries, which directly influence the collection volume:

Table 2. Estimated annual volume of rainwater according to roof geometry under homogeneous parameters

Roof Configuration	Total sloped area (m^2)	Estimated volume (m^3/year)	Variation from plane (%)
Gable	106.4	108.48	+6.35 %
Single-pitched	106.4	108.48	+6.35 %
Butterfly	118.1	120.44	+18.06 %

4.2. Technical Interpretation

The butterfly model presented the highest collection volume, with an efficiency 18% higher than the planned flat roof and nearly 10% higher than the other two designs. This performance is attributed to:

- The increase in the exposed sloped roof surface.
- The flow converges toward the central gutter, which facilitates collection and reduces lateral losses.

The gable and single-slope models show equivalent hydraulic performance, sharing inclined area and slope, suggesting that the plane's bilateral or unilateral distribution does not significantly affect the catchment if the structural parameters are constant.

These results indicate that surface geometry can optimize the design of RRWH systems from the conceptual stage, without requiring physical tests or prototypes, as long as the rigor in the modeling and calculation parameters is maintained.

4.3. Percentage Comparison of Hydraulic Performance

Considering a base reference volume of 102 m³/year corresponding to a flat surface with homogeneous parameters, it is observed that configurations with sloped surfaces increase hydraulic efficiency depending on their geometry. The butterfly roof achieved a volume of 120.44 m³/year, representing an 18.06% improvement compared to the flat roof. Meanwhile, the gable and single-pitched roofs achieved 108.48 m³/year, equivalent to a 6.35% improvement.

These differences demonstrate that the increase in the sloped area and geometric orientation directly impacts the potential water catchment of the RRWH system. The estimated additional efficiency is attributed exclusively to the geometry of the receiving surface, since the precipitation, runoff coefficient, and projected area parameters remained constant.

4.4. Effect of Surface Convergence on Capture

The superior performance of the butterfly roof is related to its double-slope design converging toward a lower central gutter. This arrangement favors the direction of surface runoff toward a focal point, minimizing lateral dispersion and optimizing effective collection.

The CAD figures illustrate this with arrows representing flow under ideal laminar runoff conditions. In contrast, the gable and single-slope configurations feature bidirectional or unidirectional runoff, respectively, which distributes the flow to opposite ends without concentrating it. Although they share a sloping area and uniform slope, their geometric orientation does not significantly contribute to the additional hydraulic efficiency observed in the butterfly model.

As discussed in the following section, these results serve as a basis for comparative discussion with previous studies and reinforce the value of CAD modeling as a predictive tool in water resources management systems.

5. Discussion

The results obtained through three-dimensional modeling show that the butterfly configuration presented the highest hydraulic efficiency, reaching an estimated volume of 120.44 m³/year, representing an 18% improvement compared to the base volume projected on a flat surface. This difference is attributed to the increase in the effective sloped surface (118.1 m²) and the central runoff channeling, which favors efficient collection with less lateral dispersion.

This behavior partially coincides with the study by Naik et al. [12], who reported a composite runoff efficiency of 68% on sloped metal roofs under realistic conditions, collecting more than 59,000 m³ annually in a large-scale system. Although the present work was conducted in a simulated environment with idealized parameters, the applied runoff coefficient (0.85) aligns with ranges observed on new roofs according to Nnaji [11] and Radzali et al. [14]. Furthermore, Raimondi et al. [15] assert that roof geometry directly influences the performance of rainwater harvesting systems, especially in the early stages of conceptual design, and suggest that approaches such as the one proposed based on digital simulation can contribute to meeting the Sustainable Development Goals in vulnerable areas. This theoretical support reinforces the value of three-dimensional modeling as a decision-making tool for scalable water harvesting projects.

On the other hand, Hamidi et al. [16] demonstrated, using a hybrid experimental and multicriteria approach, that roof selection directly influences the hydraulic efficiency of rainwater harvesting systems. Their study evaluated various materials and slopes, concluding that metal roofs with well-oriented runoff geometry offer the highest harvested volumes and the most stable water quality. Although the present work focused on geometry and three-dimensional simulation, the findings of Hamidi et al. are consistent with the behavior observed in the butterfly model, especially regarding central flow direction and utilization of the sloped surface.

The technical review by Bañas et al. [9] also highlights the scarcity of studies comparing configurations from the design stage. The gap is addressed through a replicable virtual approach, demonstrating that the roof's geometric shape significantly impacts the captured volume, even under homogeneous area and slope conditions. The novelty of this study lies in its parametric modeling approach, which isolates the geometric effect on hydraulic efficiency under controlled conditions. Unlike previous research that relies on empirical observations or post-construction evaluations, this work enables early-stage optimization of roof configurations without physical prototyping. By integrating CAD-based simulations with realistic runoff parameters, the study provides a replicable framework for sustainable design in high-rainfall regions, contributing to the advancement of digital methodologies in water resource engineering. The limitations of this study are acknowledged, as listed below:

- No analysis of the collected water quality or post-treatment was included.
- Environmental disturbances such as wind, evaporation, or surface fouling were modeled.
- Efficiency was estimated under ideal conditions, without direct experimental validation.

Despite this, the results provide a useful conceptual basis for designers, communities, and policymakers. The integration of CAD modeling with hydraulic criteria provides an effective, replicable, and accessible tool for optimizing water resources systems from their technical conception.

6. Conclusion

This study demonstrated that the geometric shape of the roof significantly influences the potential volume of rainwater harvested, even under homogeneous projected area, slope, and material conditions. Three common configurations were compared using three-dimensional modeling with Autodesk Inventor and realistic hydraulic parameters: gable, single-pitched, and butterfly. The results showed that the butterfly roof achieved 18% higher performance than the reference flat surface due to its larger effective sloped area and convergent design, which favors central runoff channeling. The gable and single-pitched configurations performed similarly, with improvements of 6.35%, confirming that bilateral or unilateral orientation does not significantly alter performance if structural parameters remain constant.

These findings support the use of CAD tools in the conceptual stage of rainwater harvesting projects, especially in high Andean areas with high rainfall, such as Peru. The proposed approach allows geometry optimization from the initial design, without the need for physical prototypes or expensive tests, contributing to sustainable, replicable and adaptable systems to the local environment.

For future research, it is recommended:

- Integrate CFD simulations to evaluate surface runoff and turbulence patterns.
- Validate the results with full-scale experimental tests.
- Consider water quality, sediment clogging, and behavior under extreme events.

The research provides a solid basis for improving the hydraulic efficiency of RRWH systems through intelligent geometric design, providing sustainable solutions to the growing demand for Water in vulnerable rural and peri-urban contexts.

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