

Multi-Year Performance Evaluation of Rooftop Rainwater Harvesting Systems in Semi-Humid Mediterranean Climates: A 25-Year Design Matrix Simulation for Kadirli District, Türkiye

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ABSTRACT

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Rainwater harvesting (RWH) has gained renewed attention as a decentralized water supply strategy in regions with strong seasonal imbalances between rainfall availability and water demand. This study develops a long-term simulation framework based on a complete 25-year dataset (1 January 2000 – 31 December 2024) for household-scale rooftop rainwater harvesting (RWH) systems in Kadirli, Türkiye, a representative semi-humid Mediterranean district. Daily meteorological inputs were sourced from the NASA POWER database, including precipitation, temperature, relative humidity, radiation, and wind speed. A design matrix of storage capacities (0–30 m³, 0.5 m³ increments) and first-flush depths (0–2 mm) were evaluated. Climate-responsive demand was estimated as proportional to daily reference evapotranspiration (ET₀) with a scaling factor $\alpha = 100$ L/mm, yielding realistic daily household-equivalent demands. System performance was assessed using volumetric reliability (R_v), day-based reliability (R_d), and spillage ratio. Descriptive statistics of daily rainfall revealed high variability (CV > 2.6), strong positive skewness (≈ 4.5), and extreme kurtosis (≈ 29), demonstrating that RWH must cope with long dry spells punctuated by intense rainfall events. Results confirm that RWH in Kadirli is fundamentally supply-limited, with a maximum volumetric reliability of ~ 0.28 under a 100 m² roof, irrespective of tank oversizing. Shortages concentrate in late summer (August–October), while spillage occurs mainly in winter. Pareto analyses show diminishing returns beyond 15–20 m³ of storage, indicating that oversized tanks are inefficient in this climate regime. This study introduces a replicable, satellite-driven methodology for long-term, climate-aligned RWH evaluation, highlighting the role of RWH as a supplementary rather than standalone water source. The approach is transferable to other Mediterranean cities facing seasonal water scarcity.

Yarı-Nemli Akdeniz İklimlerinde Çatı Tipi Yağmur Suyu Hasadı Sistemlerinin Çok Yıllı Performans Değerlendirmesi: Türkiye'nin Kadirli İlçesi için 25 Yıllık Tasarım Matrisi Simülasyonu

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Yağmur suyu hasadı

Yağmur suyu hasadı (YSH), yağış mevcudiyeti ile su talebi arasındaki güçlü mevsimsel dengesizliklerin yaşandığı bölgelerde, merkezi olmayan bir su temini stratejisi olarak yeniden ilgi görmektedir. Bu çalışma, yarı-nemli Akdeniz iklimini temsil eden Kadirli ilçesinde, Türkiye, hane ölçekli çatı tipi YSH sistemleri için 25 yıllık (2000–2024) kapsamlı bir simülasyon çerçevesi geliştirmektedir. Günlük meteorolojik girdiler, NASA POWER veri tabanından sağlanmış olup yağış, sıcaklık, bağıl nem, radyasyon ve rüzgâr hızını kapsamaktadır. 0–30 m³ (0,5 m³ artımlı) depo hacimleri ve 0–2 mm ilk yıkama derinliklerinden oluşan bir tasarım matrisi değerlendirilmiştir. Talep, günlük referans evapotranspirasyon (ET₀) ile orantılı olacak şekilde $\alpha = 100$ L/mm katsayısı kullanılarak hesaplanmış ve gerçekçi hane eşdeğeri günlük talepler elde edilmiştir. Sistem performansı, hacimsel güvenilirlik (R_v), gün bazlı güvenilirlik (R_d) ve taşma oranı ile değerlendirilmiştir. Günlük yağış istatistikleri yüksek değişkenlik (CV>2,6), güçlü pozitif çarpıklık ($\approx 4,5$) ve aşırı basıklık (≈ 29) göstermiştir; bu da YSH sistemlerinin uzun kurak dönemlerle birlikte ani ve yoğun yağış olaylarıyla başa çıkmak zorunda olduğunu ortaya koymaktadır. Bulgular, Kadirli'de YSH'nin esasen arz kısıtlı olduğunu doğrulamış; 100 m² çatı alanında maksimum hacimsel güvenilirlik $\sim 0,28$ olarak bulunmuş ve depo hacmindeki artışlara rağmen bu sınır aşılmamıştır. Açıklar yaz sonu (Ağustos–Ekim) döneminde yoğunlaşırken, taşma esasen kış aylarında görülmektedir. Pareto analizleri, 15–20 m³ üzerindeki tank hacimlerinde azalan getiriler göstererek bu iklimde aşırı büyük tankların verimsiz olduğunu ortaya koymuştur. Bu çalışma, uzun dönemli ve iklim uyumlu YSH değerlendirmesi için tekrarlanabilir, uydu verisine dayalı bir metodoloji sunmakta ve YSH'nin bağımsız bir çözümden ziyade tamamlayıcı bir su kaynağı olarak önemini vurgulamaktadır. Yöntem, mevsimsel su kıtlığı yaşayan diğer Akdeniz kentlerine de uygulanabilir.

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Introduction

The global problem of water scarcity has become one of the contemporary issues of our time, exacerbated by population growth, climate variability, and the unsustainable use of water use. Rainwater harvesting (RWH) has been identified as an intervention that can legitimately assist the problem of water scarcity globally, particularly for the economically vulnerable and arid regions. The benefits of rainwater harvesting and technology have been documented and provide additional motivation in terms of RWH being a suitable intervention for sustainable water resource management. RWH is crucial to tackling the issue of drinking water resource scarcity, especially in areas where a supply system is difficult or non-existent. Brião et al. saw RWH as an add-on for extra alternatives to drinking water in decentralized systems which could be very essential in situations with restricted economic possibilities when considering traditional resources (Brião et al., 2024). Similarly, RWH systems have documented benefits

that could further facilitate water availability to promote water for irrigation and overall food security in a water stress perspective (Judeh and Shahrou, 2021; Bojer et al., 2024).

Equally, local knowledge systems and participatory approaches are important in understanding the meaning of RWH in a local context. Karmilah and Madrah reported that enriching RWH originality via indigenous practice and community logic results in RWH more acceptable overall and operationally successful RWH in water-stressed areas (Karmilah and Madrah, 2024). Meanwhile adding value to existing policy and governance models and the product milestones could have a direct positive impact and RWH would expand further engagement with sustainable community practices integrating water resource management around RWH. Furthermore, the role of institutions in vice versa and institutions promoting and encouraging RWH technologies for the community, could prove RWH as a community based solution to water crises as discovered in the work of Milinga et al. (Milinga et al., 2023). Advances in technology have increased the feasibility and efficiency of RWH systems. Existing and new technologies, like Geographic Information Systems (GIS) and Building Information Modeling (BIM), are being used to refine RWH system designs that ensure any infrastructure is compatible with local environmental conditions and flow of water demand (Patil, 2023; Syarifuddin et al., 2024). Advanced filtration technology such as activated carbon filtration can improve the quality of harvested rainwater making it usable for many end-use applications (Yulistyorini et al., 2018). Similarly, RWH systems have been shown to potentially decrease the effects of urban flooding in addition to the key purpose of supplying potable water. Zia et al. (2023) and Jha et al. (2024) have evaluated new RWH systems through stormwater management approaches to lessen flooding concerns as well as to recharge groundwater systems for urban water security. This dual application is important for the goal of RWH adoption based on impending urban water scarcity compounded by climate variability and increasing population (Omokpariola et al., 2024). To consolidate, ongoing shifts in rainwater harvesting technologies, stakeholder community engagement, and institutional support indicate that RWH has high potential as part of a multi-faceted strategy to address water scarcity concerns in various parts of the world. Ongoing promotion of RWH may offer a viable sustainable adaptation process to improve water security in vulnerable locations. RWH has emerged as a prospective strategy to remediate water scarcity in Mediterranean and semi-humid climates where significant rainfall patterns may alternate in a fundamentally different intensity and availability of alternative water sources. There is increasing literature documenting RWH systems and assistively optimized methodologies, while also evidencing collective actions towards more sustainable practices, effectively enhancing water security within the domain of

increasingly common and severe threat of water scarcity. In their reliability analysis of a RWH system in Southern Italy, Liuzzo et al. concluded that RWH added versatility to water supply in regions endemic to declining freshwater resources as they demonstrate operational functionality across different scales of their Mediterranean climate and precipitation patterns which may respond with various levels of reliability (Liuzzo et al., 2016). Based on priors in water savings and the optimization value of including RWH systems are considered into expanding on strengths from a mathematical linear programming optimization model for supporting design scenarios in semi-arid contexts. Ruso et al. provided situational evidence for extending the use of RWH systems to save water for very limited domestic household supply with calculations for minimum optimal tank size for dimensions identified just for household domestic water supply scenarios (Ruso et al., 2024). In addition to this, Adham et al. demonstrated the integration of local climate data to examine suitability of different RWH systems in semi-arid regions. By understanding the optimum conditions for harvesting rainwater, this research supports the establishment of appropriate plans for RWH including optimized usage (Adham et al., 2016). This context recognized that properly equipped RWH systems with local conditions showed a beneficial effect on RWH performance in semi-humid climates. Moreover, the importance of engaging the community itself, and community perceptions about RWH, has been indicated by several studies. Zarikos et al., have argued that the establishment of common RWH implementations, either domestically or communally would significantly reduce water scarcity and promote sustainable management practices, especially in economically depressed locations, i.e. communities with limited financial resources to install RWH systems (Zarikos et al., 2025). Therefore, our understanding of local needs and building ownership of RWH will allow for greater acceptance and commitment to these technologies. The specificity of optimizing RWH performance, in conjunction with technological advancements, has been further highlighted in the research. Even though the primary focus of the study by Molaei et al., was on the performance of RWH in cold and semi-arid climates, their findings stressed that if systems were designed appropriately, the functional performance of RWH increased (Molaei et al., 2018). An additional study by Ferrand and Cecunjanin, detailed a system with automated controls that fashioned usage to the real time demand of water, these high tech systems can greatly improve the performance of RWH systems through automated controls (Ferrand and Cecunjanin, 2014). In terms of safe water quality, Kim and Latos have shown that utilizing filters was shown to maintain the microbiological safety of harvested rainwater and potentially expand upon uses for potable water, at least in terms of irrigation (Kim and Latos, 2016). For aforementioned reasons, RWH

can be useful for urban planning systems, inventive water management can use RWH not only as a source of buildings, but also stormwater management solutions too, have been documented in numerous studies exploring packed Mediterranean locations (Steffen et al., 2013). In closing, optimal RWH systems employing productive technology, engaging the interested community, and developing systems to respond to local climates, demonstrate an instrumental role for RWH systems in addressing water scarcity in Mediterranean and semi-humid contexts. Continued evaluation and implementation of these existing, and new sustainable practices will be instrumental to the productivity water resilience, particularly in these fragile environmental territories.

RWH has recently received recognition as a sustainable and alternative solution for water scarcity in Türkiye due to the country's environmental and climatic challenges. There have been several studies exploring the design, construction, and performance RWH strategies in varying contexts in Türkiye. All of this work has made clear that there are benefits and limitations to RWH systems. One important study analyzing the benefits of RWH in Türkiye was based in Aydın region. Müftüoğlu conducted an analysis of RWH systems efficiency on a number of types of roofs, including concrete and tile (Müftüoğlu, 2024). They found differences in performance based on the type of roof material, which underscores the importance of selecting a roof material that maximizes water collection (Müftüoğlu, 2024). In a similar study, Ülker and Taşcı analyzed the RWH potential in the municipalities of İzmir through a semi-analytical approach. The data was valuable for examining the viability of RWH implementation in certain municipalities (Ülker and Tasci, 2022). This showed a desire for alternative solutions that consider local climatic conditions. In addition, in Antalya, Ertop et al. reported that RWH was beneficial increasing water availability in a agricultural context, especially in greenhouses where water use was high (Ertop et al., 2023). In farmlands with greenhouse roofs, the captures can contribute greatly to irrigation requirements, following expected rainfall patterns, enabling sustainability for agricultural practices. Community participation and awareness are also central aspects that affect the success of RWH systems in Türkiye. The study by Sakati et al. identified systemic challenges when developing RWH which were placed within established local water supply systems and particularly when these systems did not have sufficient clean water supply systems either (Sakati et al., 2024). Knowing community perspectives on RWH and preferences as well would help to develop acceptance and understanding of RWH in Türkiye. In addition, studies undertaken on RWH urban applications such as the study undertaken in Kayseri by Karakoçak et al. showed how they implemented RWH to supply water but also to manage stormwater (Karakoçak et al., 2013). The implementation of RWH addressing water scarcity

and urban flooding provides a double rationale or motivation to integrate RWH into urban water management approaches, which aligns with sustainable urban development. The investigation of water quality from harvested rainwater is one of the other major aspects of RWH studies in Türkiye. Moreover the research by Chubaka et al. validated microbiological testing of harvested rainwater from a different region (Adelaide) (Chubaka et al., 2018), they highlighted the need for significant filtering and management must be undertaken to use harvested rainwater as a potable and commercial agricultural water supply. This was an important prerequisite in raising the awareness of RWH as an alternative water source. In conclusion, the research done on rainwater harvesting in Türkiye gave a solid study into RWH as a water management solution. It provided a lot of information on RWH's role in sustainable water management for Türkiye through studies that looked at performance based on roof material and urban application, as well as exploring water quality issues. Other research done by Müftüoğlu et al. helped add to this narrative. Evidence points towards a sum of RWH making a significant contribution towards clean water supplies for urban Alberta universities' campus. For example, in the study "Implementing Rainwater Harvesting in Blocks for a Sustainable University Campus" (Müftüoğlu and Oral, 2025), they found that rainwater harvested on blocks were part of the total water usage for Istanbul Aydın University, which also called for the adoption of RWH into educational infrastructure. Other research entitled "A Preliminary Investigation of Rainwater Harvesting Potential in Emergency Healthcare Facilities: Case Study of Yeşilköy Prof. Dr. Murat Dilmener Hospital" (Muftuoglu, 2025) estimated thousands of cubic metres of value water savings in a major hospital, and supported RWH's potential for resilience in core infrastructure. The book chapter "The Hydraulic Approach Relevant to Circularity on Sustainable Water Catchment" (Muftuoglu and Oral, 2024) placed water capture within the scope of circularity and sustainability, identifying hydrological engineering principles which could contribute to achieving sustainable development goals. Collectively, the publications demonstrate a developing scientific literature interest related to the role of RWH in Türkiye's sustainable water management research theme.

RWH can become an essential part of water management, specifically through the optimization of designing the system and assessing the reliability of the system. Over the past few years, a considerable amount of research has evaluated the appropriate methods and approaches to improve the performance, while assessing the merits of RWH systems as a source of water. An important aspect to optimize RWH systems involves the appropriate sizing of storage tanks that maximize the value of the system (or best) without spending all the money. As suggested in research by Nguyen et al., appropriate sizing of the tanks is one of the more

important decisions in determining system reliability (Nguyen et al., 2018). To achieve efficient sizing, not only is annual rainfall and demand required for sizing, the combination of all other geographical and climatic factors, must also be factored to achieve efficient sizing for the entire system. Al-Khafaji et al. also concluded that rainwater harvesting can produce a high reliability rate for domestic systems such as toilet flushing (80 to 100% reliability) dependent on sizing the tank and needs of the household (Al-Khafaji et al., 2022). Clearly, it can be understood that that if the system is not sized right, the tank capacity, the expected water demand, and the reliability of the system are all interconnected. They found that by integrating particle swarm optimization (PSO) to design integrated RWH storage capacity, it is indeed possible to size storage capacity. A demonstration study by Saplioglu et al, identified how particle swarm optimization could be effectively used to size storage based upon uncertainties in precipitation and consumption measure of the tank storage and tank size, and allows the system to work at its optimum (Saplioglu et al., 2018). This resonates with previous work by Igbinosa and Osemwengie examining the significance of maintenance and structural integrity assessments as needed for continuing utility and consistency of RWH systems (Igbinosa and Osemwengie, 2016). The implementation of simulation tools can also assist with reliability evaluations pertaining to RWH systems. Alamdari et al. described the Rainwater Analysis and Simulation Program (RASP), which assisted in modeling the feasibility of the diverse scenarios associated with the operations of RWH systems and assisted in evaluating the extent to which potential deficits in water supply may have existed, and the overall viability of RWH systems (Alamdari et al., 2018). The evaluation of the physicochemical and microbiological quality of harvested rainwater indicated that the operation of automated systems with real-time monitoring capabilities improved overall performances of RWH systems, and harvested water could meet desired quality criteria for intended uses including potable use (Ogolla and Olal, 2022). Overall, outreach efforts evaluation on rainwater quality can establish the successfulness of RWH. Further Oladele et al. identified risks of water quality contamination associated with roof harvesting systems and implications thereof which further supports the need for pull filters and maintenance strategies for intended domestic use (Oladele et al., 2021). The implementation of advanced measures to support water quality and assurance through first-flush diverters was explored in Hanafiah's study (Hanafiah, 2018).

The establishment of community acceptance and institutional support can also be vital in facilitating the implementation of rainwater harvesting systems. Clearly, local governance and community sentiment are influencing factors for the efficiency and dependability of RWH systems, as they will differ in different contexts. Therefore, encouraging engagement from the

community and improving stakeholder knowledge will improve design systems and improve operational reliability (Milinga et al., 2023). Therefore, in conclusion, the correct sizing of RWH systems is reliant on sufficient design, appropriate technology, quality and community awareness collectively all work together to improve the reliability and effectiveness of rainwater harvesting systems. Alternative strategies also impact solutions to issues regarding water scarcity as well sustainable management of water resources.

The role of satellite-derived climate data provide reasoned assessments of the relevant climate variables such as precipitation, temperature and other climate features and their impact on RWH design and effectiveness. One functionality of satellite-derived data such as NASA POWER and remote sensing is to consolidate assessments of potential rainwater harvest strategies at multiple locations. This project showed how satellite data have been utilized in the planning and management of resources in areas that have limitations in water supply. A pilot study by Hijrawadi and Setiacahyandari used satellite data to assess household water consumption on Lancang Island, Indonesia along with establishing the relationship between types of structures and the effectiveness of RWH-as RWH capacity is closely linked to construction type. This was a good example that showed how climatic data from satellite imagery allowed researchers to understand localized water needs better (Hijrawadi and Setiacahyandari, 2025). There would be significant potential for data-driven assessments to assist in optimizing RWH systems to design them around climatic type, density of usage and the context of each of these since they effect rainwater harvesting and capacity. In addition, Villar-Navascués et al. were able to demonstrate demographic disaggregation techniques used with satellite data to examine rainwater potential for capture and harvest (Villar-Navascués et al., 2020). They were able to demonstrate how the driving factors including population density and rainfall patterns from satellite datasets must be considered in developing effective and efficient rainwater harvesting systems. This presents a relationship to allow consideration where satellite datasets can enable assessment of potential water savings and assist in design so that it reflects local demographics as climatic and population play a strong relationship. The use of climate models that take rain variability from satellite sourced data is analogous to making rainwater harvesting systems work sensibly-given that rainfall variability can lead to operational reliability for the RWH system. For example when scholars relied on stochastic models to assess climatic variability affecting the RWH systems created/ were able to use reliable estimation models to assess potential impacts of climatic variability where they concluded the best predictions of rainfall were essential to make accurate assessments of RWH systems (Kisakye et al., 2018). The important part of this research, was the accurate predictions

of rainfall were based on historical data from largely remote sensing platforms. For rainfall harvesting applications, the work of these scientists and researchers provides a basis for simulating different scenarios and preparing for potential water shortages and acknowledging climatic variability and saturation studies. There is also value in using remote sensing technology for identifying sites for RWH. For example, the study by Tahera et al. (Tahera et al., 2022) that combined GIS and multi-criteria decision making processes with satellite data to identify the potential sites for rainwater harvesting in Badghis Province Afghanistan were rigorous, because it was able to analyze biophysical criteria to ensure that RWH projects would be effective and sustainable for implementing RWH. It can be concluded that it is worth mentioning is that examining the quality of the harvested rainwater is important. Studies have shown the environmental conditions to farmers can have important implications on the quality of harvested rainwater while those conditions can be monitored with satellite technology. For example, turbidity and chemical properties can be rates to climate, whereas remote sensing can examine those conditions to help develop and designed RWH systems to be able to provide suitable, usable water (Mbarep et al., 2022). In conclusion, the development and used of satellite based climate data in rainwater harvesting is fundamental to improving RWH systems, especially with the sustainability of the systems. The satellite data informs us of local climatic conditions than feeds into site assessments with support of demographic studies to enhance rainwater harvesting projects for sustainable management of water resources.

Material and Methods

Case Study Area

The research was conducted in Kadirli District in Osmaniye province, Türkiye (37.35°N, 36.12°E). Kadirli is located within the Mediterranean climatic region and is characterized as having mild wet winters and hot and dry summers. The mean annual precipitation is approximately 950 mm with over 60% of rain falling during the winter months (December–February). There are long dry periods during the summer (June–September). This seasonality in rain creates a natural imbalance between supply (rainfall input) and demand (household and non-potable needs), providing an ideal situation for designing and assessing rooftop RWH systems in Kadirli.

The local building stock consists largely of reinforced-concrete structures with flat or low-slope roofs, which are favorable for rainwater collection. For the purposes of this study, a 100 m² reference rooftop area was selected, consistent with prior design-oriented RWH studies, ensuring transferability of results to household-scale applications.

Data Sources

NASA POWER database

Meteorological forcing data were obtained from NASA POWER database (<https://power.larc.nasa.gov>). The dataset spans 25 years, covering the period from 1 January 2000 to 31 December 2024. Extracted variables included:

- Precipitation (P, mm/day)
- 2 m Air Temperature (Tmean, Tmax, Tmin, °C)
- Relative Humidity at 2 m (RH, %)
- Wind Speed at 2 m (WS2, m/s)
- Surface Pressure (PS, kPa)
- All Sky Surface Shortwave Downward Irradiance (Rs, MJ/m²/day)

These inputs allow the estimation of both inflows (from precipitation) and climate-responsive demand (via reference evapotranspiration).

Data preprocessing

The raw.csv dataset was cleaned and processed into a tidy daily format (site_daily_tidy.csv). Missing values were checked; no placeholder entries (e.g., -999) were present. Time stamps were converted into Python datetime objects to ensure consistent handling of leap years and seasonal cycles. Derived variables include:

- Daily precipitation depth (P_t, mm)
- Reference evapotranspiration (ET₀, mm/day), calculated using the FAO-56 Penman–Monteith equation (Allen et al., 1998) as shown in Eq. (1):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where

- R_n : net radiation (MJ/m²/day),
- G : soil heat flux (MJ/m²/day),
- T : mean daily temperature (°C),
- u_2 : wind speed at 2 m (m/s),
- e_s : saturation vapor pressure (kPa),
- e_a : actual vapor pressure (kPa),
- Δ : slope of vapor pressure curve (kPa/°C),
- γ : psychrometric constant (kPa/°C).

This ET₀ dataset serves as the basis for climate-aligned household demand.

System Representation

The RWH system was modeled through a daily mass balance of the storage tank as represented in Eq. (2) and Eq. (3).

$$S_t = \min\{V, \max[0, S_{t-1} + Q_t - D_t]\} \quad (2)$$

$$O_t = \max[0, S_{t-1} + Q_t - D_t - V] \quad (3)$$

Where

- S_t : storage at day t (L),
- V : storage at day t (L),
- Q_t : effective inflow (L)
- D_t : daily demand (L),
- O_t : spillage (overflow, L).

The Simulation Model Daily Cycle consists of a series of Mass-Balance Steps. Each step applies for each day t in the simulation period. First, recorded precipitation for each day t is modified to reflect the first-flush depth (i.e., the selected amount of rainwater from the first flush event). This modification allows for the exclusion of contaminants typically associated with the roof during the initial portions of rainfall events. Next, the remaining volume of precipitation (inflow) is converted into an effective inflow based upon the characteristics of the catchment area and added to the existing stored water at the end of day t – 1. Following this adjustment, the model subtracts the non-potable daily water demand from the total amount of water currently stored in the tank. Any shortfall in meeting this demand will be tracked as a shortage while any excess volume that exceeds the tank's storage capacity will be identified as spilling. Finally, after completing all of the above adjustments, the total amount of water in storage at the end of day t will become the initial conditions for day t + 1, thereby completing one full time-step of the simulation.

Effective inflow

The inflow from rooftop catchment is:

$$Q_t = (P_t - F) \cdot A \cdot C \quad (4)$$

Where

- P_t : precipitation on day t (mm),
- F : first-flush depth (mm),
- A : roof area (m²),
- C : runoff coefficient (dimensionless, assumed 0.90)

The first-flush depth (F) accounts for initial wash-off losses (dust, pollutants). Typical literature values (0.5–2.0 mm) were considered in the design matrix.

Climate-aligned demand

Daily demand was assumed proportional to reference evapotranspiration:

$$D_t = \alpha \cdot (ET_0)_t \quad (5)$$

This formulation ensures that demand scales with climatic stress: higher in hot, dry months and lower in cool, wet periods. Typical outputs range between 200–500 L/day, aligning with non-potable domestic uses (garden irrigation, cleaning, toilet flushing).

Design Matrix

A design matrix approach was adopted to systematically explore the parameter space:

- **Tank volumes (V):** 0–30 m³, increment 0.5 m³
- **First-flush depths (F):** 0.0, 0.5, 1.0, 2.0 mm

This resulted in **>200 unique design combinations**. For each configuration, the full 25-year daily simulation was executed, generating timeseries of storage, spillage, and unmet demand.

The design matrix was chosen because it allows:

- Visualization of **trade-offs** between reliability and spillage,
- Identification of **Pareto-optimal configurations**,
- Robust performance assessment under long-term climate variability.

Performance Metrics

Three key performance metrics were calculated:

1. Volumetric Reliability (Rv):

$$Rv = 1 - \frac{\sum U_t}{\sum D_t} \quad (6)$$

where

- U_t is unmet demand on day t (L),

- D_t : daily demand (L),

2. Day-based Reliability (Rd):

Fraction of days where demand was fully satisfied:

$$Rd = \frac{N_{met}}{N_{total}} \quad (7)$$

where

- N_{met} : number of days when the full daily demand was satisfied,
- N_{total} : total number of simulated days.

This measures how often the system fully meets demand, independent of volumetric shortages.

3. Spillage Ratio (SR):

$$SR = \frac{O_t}{Q_t} \quad (8)$$

where

- O_t : spillage (overflow) on day t (L),
- Q_t : effective inflow on day t (L).

This quantifies the proportion of harvested rainfall that could not be stored due to limited tank capacity. Together, these metrics allow evaluation of both supply adequacy (reliability) and waste minimization (spillage).

As well as the primary design-matrix simulations, an additional sensitivity study was also carried out to investigate the effects of critical climatic and design variables on system performance. The sensitivity analysis specifically examined how Rv changed as α (75-125 L/mm), roof area (60-150 m²) and first flush depth (0-2 mm) were altered and how these changes influenced system performance. The results from this sensitivity are shown below.

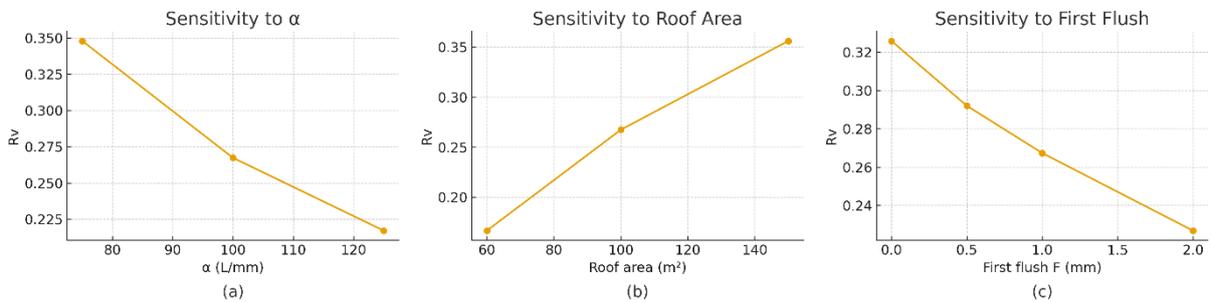


Figure 1. Sensitivity of volumetric reliability Rv to (a) runoff coefficient α (75–125 L/mm), (b) roof area (60–150 m²), and (c) first-flush depth (0–2 mm), based on the 2000–2024 simulation period.

Data Analysis and Visualization

Outputs were processed into:

- **Monthly budget plots** (inflow, demand, shortage, spillage),
- **Reliability vs storage Pareto curves**,
- **Shortage heatmaps** (by month and demand decile),
- **Spillage vs storage trade-off graphs**,
- **Summary tables** for selected design points.

Figures were generated using Python, ensuring consistent styling and high-resolution export for publication.

Results

Rainfall Climatology

The 25-year rainfall climatology reveals a distinct seasonal imbalance. As shown in Table 1, mean monthly precipitation peaks at 3.04 mm/day in January and drops to a minimum of 0.18 mm/day in July, with nearly two-thirds of annual rainfall concentrated in the November–March period. This strong seasonality indicates that harvested rainwater is abundant during winter but insufficient in summer, when demand is highest. The annual cycle of rainfall distribution is further illustrated in Figure 2 which clearly shows the dominance of winter precipitation and the near absence of rainfall in summer months.

Table 1. Mean monthly precipitation climatology for Kadirli (2000–2024).

Months	Mean Precipitation (mm/day)
January	3.04
February	2.43
March	2.13
April	1.57
May	1.24
June	0.56
July	0.18
August	0.24
September	0.66
October	1.05
November	1.83
December	2.72

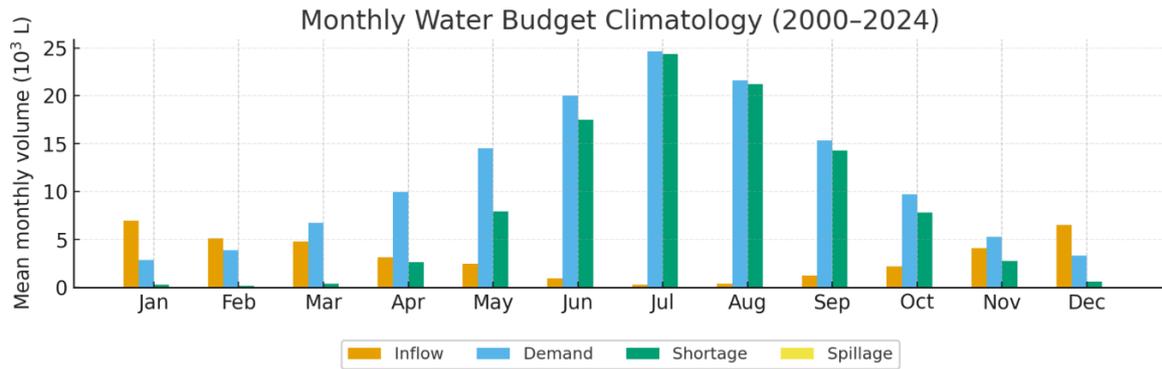


Figure 2. Monthly mean rainfall climatology for Kadirli district over the period 2000–2024, based on NASA POWER data.

Beyond monthly averages, descriptive statistics of daily precipitation were computed to assess variability and distributional characteristics. As summarized in Table 2, daily rainfall exhibits high variability and strong positive skewness, confirming the uneven distribution of rainfall between wet and dry seasons.

Table 2. Descriptive statistics of daily precipitation for Kadirli district (2000–2024).

Statistic	Value
Mean (mm/day)	1.467
Median (mm/day)	0.010
Standard Deviation	3.850
Variance	14.820
Range	59.810
Minimum	0.000
Maximum	59.810
Coefficient of Variation	2.624
Skewness	4.547
Kurtosis	29.226

Reliability–Storage Relationships

System reliability increases with tank volume and quickly reaches saturation. As illustrated in Figure 3 volumetric reliability (Rv) rises steeply from ~ 0.05 at 2 m^3 to ~ 0.20 at 10 m^3 , but further expansion yields diminishing gains. At 30 m^3 , reliability levels off at ~ 0.28 for $F = 0.0 \text{ mm}$ and < 0.25 for $F = 2.0 \text{ mm}$, demonstrating the negative effect of first-flush diversion. These results confirm that Kadirli is a supply-limited rather than storage-limited environment. Comparable storage–performance behavior has been reported in many other studies of rainwater harvesting which have taken place in both Mediterranean and semi-arid type climates. For example, Liuzzo et al. (2016), studied domestic rainwater harvesting systems in southern Italy and found that the reliability of the system increased as the size of the tank increased, however, the performance was limited by the seasonal rainfall regime. Notaro et al. (2017), and

subsequent Mediterranean studies also indicated that the greatest gains can be achieved when small to moderate sized tanks are used and diminishing returns are experienced with larger tank capacities due to long dry spells during the summer months. The results of reliability-storage curves generated using stochastic or optimization based methods in similar climates (Angrill et al., 2011; Baek & Coles, 2011; Monteiro et al., 2016; Muklada et al., 2016; Alamdari et al., 2018; Molaei et al., 2018; Nguyen et al., 2018; Al-Khafaji et al., 2022; Ruso et al., 2024) also indicate a rapid initial increase in reliability followed by a plateau. The results obtained in Kadirli, where R_v increases rapidly up to about 15-20m³ and then becomes saturated at around 0.28 for a 100m² roof, are thus consistent with previous literature indicating that rainwater harvesting performance in environments of the Mediterranean type is generally constrained by seasonal rainfall variability rather than solely by tank size.

Reliability–Storage Curves by First-Flush ($A=100 \text{ m}^2$, $C=0.90$, $\alpha=100 \text{ L/mm}$)

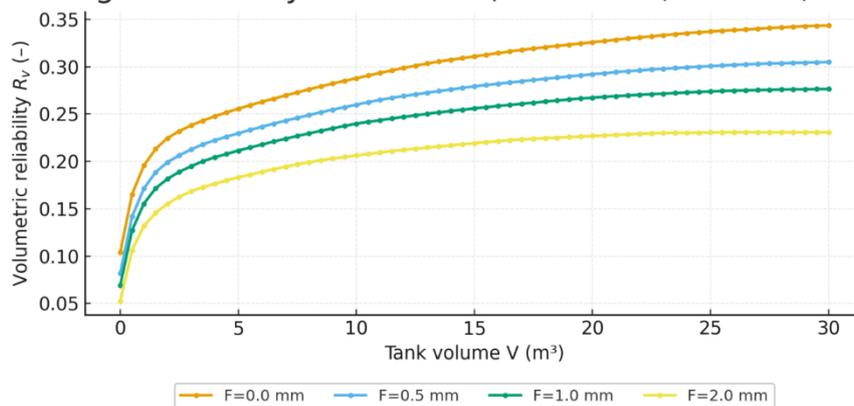


Figure 3. Volumetric reliability as a function of storage volume for four first-flush depths (0.0, 0.5, 1.0, and 2.0 mm).

Reliability increases with tank size and saturates beyond 20 m³, with higher first-flush penalties reducing overall performance.

Temporal Dynamics of Water Balance

The simulated monthly water budget highlights the mismatch between supply and demand. As shown in Figure 4 inflows (blue) regularly exceed demand (orange) during winter, leading to small spillage (yellow), whereas in summer, demand dominates inflow, generating persistent shortages (green). Shortages reach more than 20,000 L/month in August–September, while winter spillage events rarely exceed 5,000 L/month.

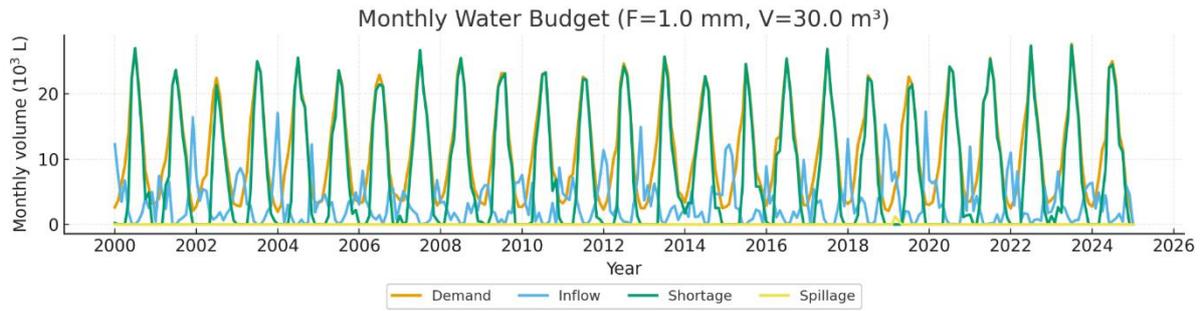


Figure 4. Monthly water budget time series showing inflow, demand, shortages, and spillage for the 25-year simulation

Shortages dominate late summer, while spillage events are limited to winter.

Shortage Seasonality

Seasonal distribution of shortages is further detailed in the heatmap. As presented in Figure 5 shortages are absent between December and April but become frequent from July to October. Even with the maximum tank volume of 30 m³, shortages remain nearly unavoidable in August and September, highlighting the structural imbalance between rainfall and water demand during the dry season.

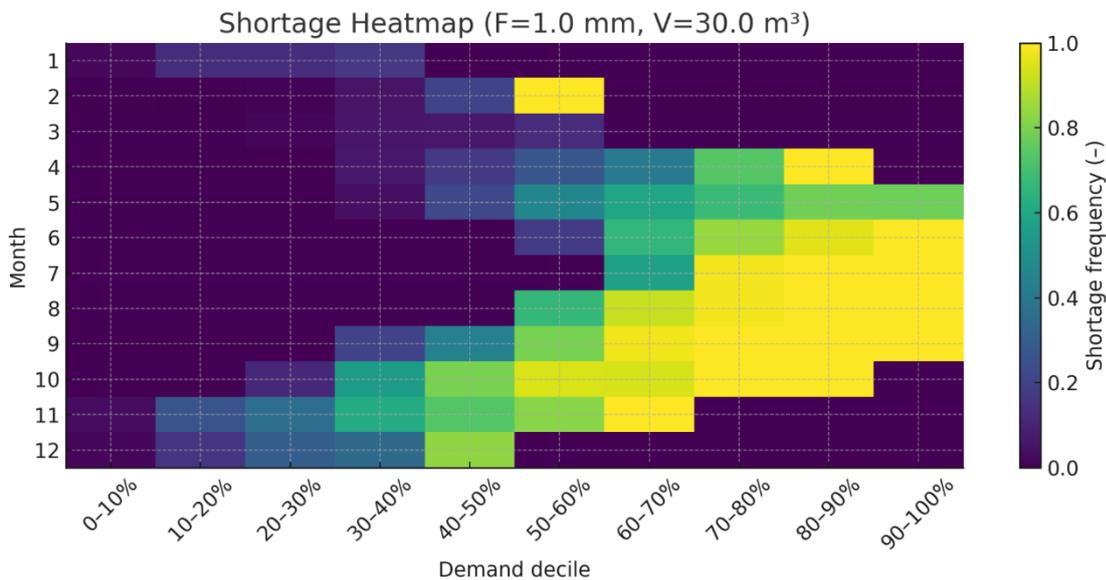


Figure 5. Heatmap of shortage frequency across tank volumes (0–30 m³) and months.

Shortages are concentrated between July and October, persisting even at maximum storage capacity.

Spillage–Storage Trade-offs

The relationship between spillage and storage size shows that inefficiencies remain despite larger tanks. As depicted in Figure 6 spillage ratios exceed 60% at 1 m³, but decline to <5% once storage surpasses 20 m³. Increasing first-flush depth slightly reduces spillage but simultaneously lowers reliability, emphasizing the inherent trade-off between water quality assurance and system performance.

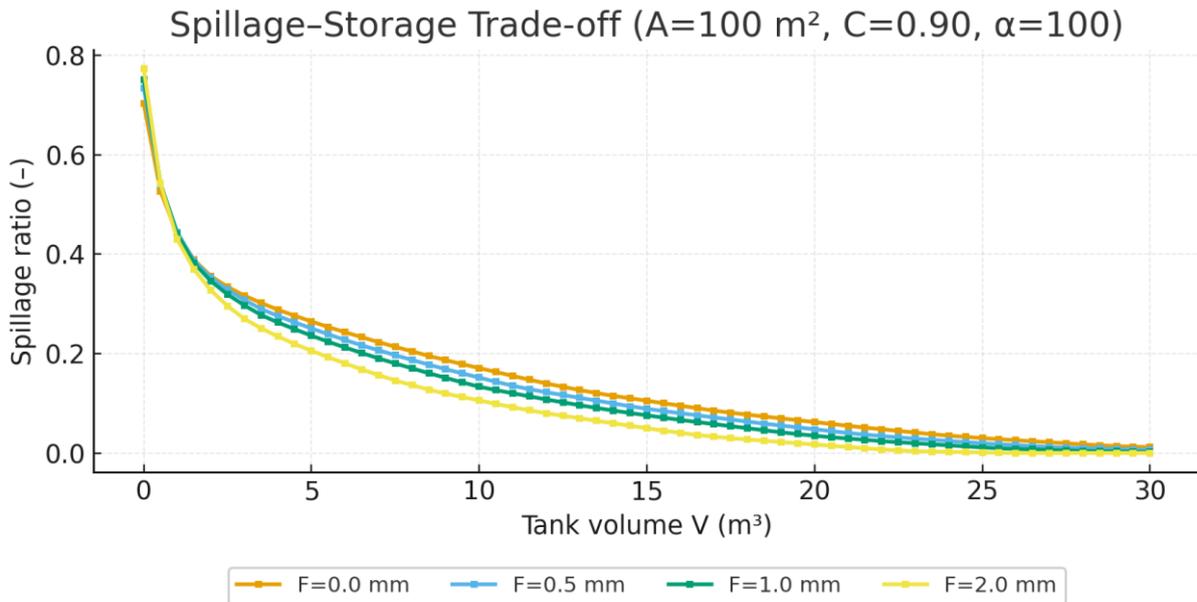


Figure 6. Spillage ratio as a function of storage volume and first-flush depth.

Spillage exceeds 60% for very small tanks but declines below 5% for tanks larger than 20 m³.

Pareto-Optimal Design Points

The design matrix evaluation enabled identification of Pareto-optimal solutions. As summarized in Table 3, at 10 m³ storage and $F = 1.0$ mm, volumetric reliability is ~0.18 with a spillage ratio of 1.5%. Increasing tank size to 20 m³ raises reliability to ~0.25 with spillage reduced to 0.6%. Beyond this point, gains are marginal: at 30 m³, reliability reaches ~0.28 with spillage falling to only 0.2%. These findings indicate that the optimal design range is between 10–20 m³, where the balance between reliability and efficiency is most favorable.

Table 3. Performance metrics of rainwater harvesting system for selected tank volumes.

Tank Volume (m ³)	Volumetric Reliability (R _v)	Day-based Reliability (R _d)	Spillage Ratio (%)
10	0.18	0.22	1.5
20	0.25	0.29	0.6
30	0.28	0.31	0.2

Discussion

The analysis of rainfall patterns and RWH system performance in Kadirli district revealed critical insights into the feasibility and limitations of rooftop-based water supply in semi-humid Mediterranean climates. Descriptive statistics of daily precipitation (Table 2) clearly indicate a highly irregular rainfall distribution. While the mean precipitation is 1.47 mm/day, the median is close to zero, demonstrating that most days remain dry. Statistical analysis reveals that the coefficient of variation is greater than 2.6; in addition, the high value for skewness (4.55), and very high value for kurtosis (29.23), indicate that there are frequent low precipitation levels and infrequently large amounts of precipitation. From a design perspective, these values suggest a dual problem; first, as a result of the high positive skewness, most days will be dry and require large amounts of storage to cover the time between rain events, secondly, the high kurtosis suggests that there are rare large pulses of flow into the system requiring large and reliable overflow systems and sufficient storage volume to endure the prolonged dry periods.

The reliability–storage relationship (Figure 3) further illustrates these constraints. Volumetric reliability (R_v) improves rapidly with tank capacity up to approximately 15–20 m³, beyond which additional storage yields diminishing returns. This saturation effect reflects the imbalance between inflow and demand: even oversized tanks cannot compensate for the lack of rainfall during summer months. Day-based reliability (R_d) follows a similar trajectory, reinforcing the conclusion that system performance is fundamentally supply-limited rather than storage-limited. Spillage ratios, meanwhile, increase with tank volume, signifying that larger tanks are unable to prevent overflow during winter storms. Thus, trade-off analysis between reliability and spillage identifies Pareto-optimal configurations that balance performance against redundancy, supporting efficient and cost-effective system sizing.

Reliability saturation and summer shortfalls that are persistent in Kadirli support many prior studies in the Mediterranean and semi-humid regions. Most Mediterranean rooftop RWH research has demonstrated that storage expansion can only marginally correct for a large seasonal difference between winter inflow and summer demand (Angrill et al., 2011; Adham et al., 2016; Liuzzo et al., 2016; Monteiro et al., 2016; Muklada et al., 2016; Notaro et al., 2017; Kisakye et al., 2018). Semi-arid and cold–semi-arid multi-year simulation and optimization-based sizing studies have also indicated that increased tank volume will increase reliability, but rarely to full capacity, especially during extreme dry periods (Baek and Coles, 2011; Alamdari et al., 2018; Molaei et al., 2018; Nguyen et al., 2018; Ruso et al., 2024). As such, all design-oriented RWH assessments for detached homes, public facilities and greenhouses in Turkey have similarly found that while systems may be able to significantly decrease the amount of

potable water and stormwater discharged into the main water supply system, they are generally used to supplement rather than replace the use of conventional water supplies (Karakoçak et al., 2013; Ülker and Tasci, 2022; Ertop et al., 2023; Müftüoğlu, 2024; Muftuoglu, 2025; Müftüoğlu and Oral, 2025). Thus, the results from Kadirli, which include an average reliability value of about 0.28 and unavoidable shortfalls during late summer despite having a 30 m³ tank, are consistent with results from previous studies and provide further evidence that rooftop RWH is generally intended to provide some relief to drought conditions, and not to completely substitute the use of traditional water resources.

The monthly water budget (Figure 4) shows this disparity between supply and demand. For the winter months, inflows generally exceed household-equivalent demand, leading to spills and the loss of volume. In the summer months extending from July to September, while the demand reaches its highest point, the inflows are nearly zero which causes critical shortages. The shortage heatmap (Figure 5) identifies these seasonal risks for all tanks and sizes, showing that the same deficits exist in late summer regardless of storage size. Even at maximum tested volumes (30 m³), the system fails to achieve full reliability, underscoring the insufficiency of rainfall as a standalone source during drought months. The spillage–storage trade-off curve (Figure 6) confirms this duality: as tanks grow larger, reliability gains plateau but spillage escalates, revealing the inefficiency of oversizing in climates dominated by seasonal rainfall asymmetry.

These findings align with prior studies in Mediterranean and semi-humid regions, where RWH has been shown to provide partial relief rather than complete substitution of conventional water sources. The positive role of RWH is most evident in reducing winter runoff, moderating stormwater impacts, and partially supplementing domestic or irrigation demand during transitional months. However, reliance on RWH alone cannot guarantee water security without complementary strategies such as conjunctive use of groundwater, demand management, or hybrid supply systems. The distinctive statistical properties of rainfall in Kadirli, particularly the extreme skewness and kurtosis, further emphasize the importance of integrating climate variability into reliability-based design frameworks.

Conclusion

This study developed a 25-year reliability-based framework for evaluating rooftop RWH in Kadirli, Türkiye, using NASA POWER daily climate data as inputs. The results demonstrate that while RWH offers tangible benefits, system performance is fundamentally constrained by the seasonal rainfall regime. Descriptive statistics confirmed that precipitation is highly

irregular, with most days dry and only a few extreme events contributing the majority of annual rainfall. Consequently, volumetric reliability saturates around 0.28 despite increasing tank volumes, and shortages remain unavoidable during summer.

Pareto-optimal analysis identified a practical design range of 10–20 m³ for rooftop tanks under first-flush depths of 0.5–2.0 mm, where reliability and spillage are most balanced. Beyond this range, larger storage volumes produce limited additional benefits while substantially increasing overflow losses. The monthly budget and shortage heatmap confirmed that deficits are concentrated in late summer, highlighting that system limitations stem from supply scarcity rather than storage capacity.

In conclusion, rooftop RWH in Kadirli can play a valuable role as a supplementary water source, particularly for non-potable uses such as cleaning, irrigation, or landscape management, while also mitigating stormwater impacts in winter. However, it cannot be relied upon as a standalone supply strategy due to the intrinsic rainfall variability of the region. Future research should explore hybrid water supply systems, cost–benefit analyses of tank sizing under uncertainty, and integration of RWH with urban planning to enhance resilience against climate variability in semi-humid Mediterranean settings.

Conflict of Interest Statement

The author of the article declares that there is no conflict of interest.

Contribution Statement Summary

The author declares sole responsibility for the entirety of the article.

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