

Rainwater harvesting as a sustainable solution for the production of urban hydroponic crops

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ABSTRACT

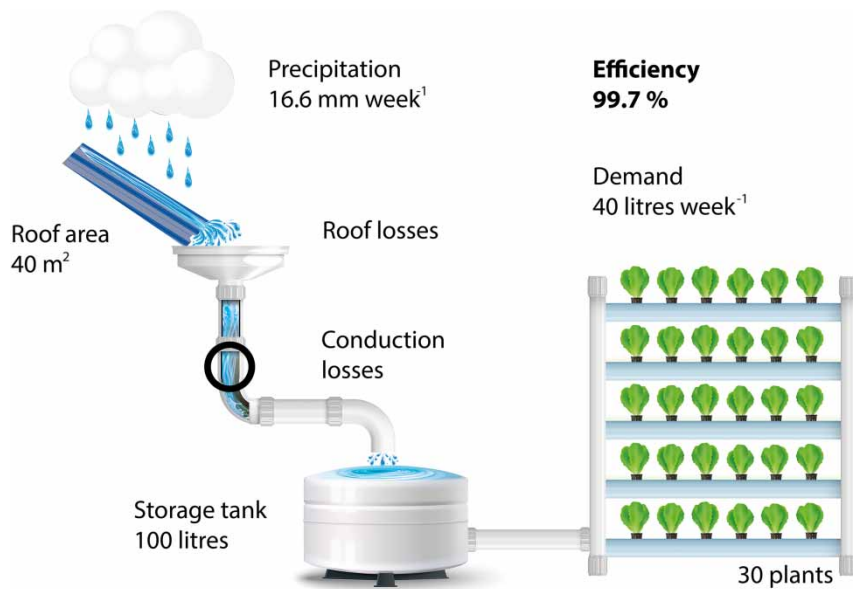
Population growth and poor agricultural practices demand an improvement in the efficiency of food production. Urban hydroponic crops represent a potential solution to this challenge. However, the use of drinking water for urban agriculture is not a priority. Consequently, rainwater harvesting can reduce the use of drinking water for other purposes than human consumption. This study evaluated the efficiency of rainwater harvesting for the production of hydroponic crops in an Andean city. We developed a rainwater harvesting model to analyze the efficiency and optimization of two hydroponic production scenarios: (1) domestic production (30 plants) and (2) small-scale commercial production (200 plants). We found an efficiency of 99.71 and 75.79%, for scenarios 1 and 2, respectively. The 75.79% efficiency is given by the presence of low precipitation periods, which in the case of the study area are sporadic. Furthermore, scenario 2 could reach efficiencies of 100% if the roof capture area increases up to 40 m². Rainwater harvesting in Andean cities, with sustained precipitation throughout the year, is enough to supply water for domestic and small-scale commercial hydroponic production with basic household modifications. We show promising results by combining rainwater harvesting and hydroponic crops for improving urban food and water security.

Key words: Andean cities, food security, hydroponic crops, rainwater harvesting, urban agriculture, water security

HIGHLIGHTS

- Rainwater harvesting can support small-scale urban hydroponic crops.
- The combination of rainwater harvesting and hydroponic crops is a potential solution to improve water and food security.
- Rainwater harvesting has promising results in Andean urban areas.
- Development of a conceptual rainwater harvesting model for hydroponic crops.
- New combination of rainwater harvesting and small hydroponic crops.

GRAPHICAL ABSTRACT



INTRODUCTION

Food security on the planet has been under debate since 1798, with the foundation that the population will exceed the capacity of the earth to feed us (Odorico *et al.* 2018). This is caused by accelerated population growth (Kopittke *et al.* 2019) and the inefficient use and distribution of resources (Bruinsma 2003). On the other hand, climate change scenarios suggest a reduction in agricultural production by 2050, along with increased competition for irrigation water, posing threats to agricultural practices (Collinson 2000; Wiebe *et al.* 2019). Furthermore, poor farming practices disrupt ecosystems, reduce biodiversity, alter soil processes (Piñeiro *et al.* 2020), and affect water quality (Li *et al.* 2018), leading to heightened pressure on ecosystems and socio-economic conflicts (Bogardi *et al.* 2012).

Applied agricultural research is crucial for tackling challenges like increasing crop production amid water scarcity, and emphasizes optimizing water use for higher yields (Elliott *et al.* 2014; Jägermeyr *et al.* 2015; Hunter *et al.* 2017). Hydroponic production systems offer a solution, particularly in areas with soil issues, such as degraded, unproductive, or contaminated soils (Sambo *et al.* 2019; Sharma *et al.* 2019), making agriculture available for diverse family scales (Sheikh 2006).

Urban hydroponic crops are a partial solution for the world population of 9.7 billion inhabitants projected for 2050, especially concentrated in urban areas (United Nations 2022). This sustainable approach reduces family expenses, minimizes food imports, and lowers agrochemical contamination (Romeo *et al.* 2018). However, the prioritization of water use prohibits potable water for agriculture (Namwata *et al.* 2015). To address this, rainwater in urban hydroponics is a potential option to simultaneously improve food and water security (Velasco-Muñoz *et al.* 2019; Amos *et al.* 2020), reducing dependence on other water resources (Jurga *et al.* 2021). Rainwater harvesting positively impacts water security, reducing the pressure on the ecosystems from which this resource is extracted for the city (Ranaee *et al.* 2021), and easing strain on urban stormwater systems (Freni & Liuzzo 2019).

The performance of rainwater harvesting depends on precipitation patterns and design factors such as roof capture area, maximum storage capacity and water demand (Rahman 2017). Seasonal precipitation patterns determine available water, while roof capture and maximum storage influence collection and the storage of the system. The water demand determines the required amount of water required (Campisano *et al.* 2013). All these factors determine the volume of water in the storage and its dynamic. As these factors depend on climatological, infrastructural, socio-economic and water management characteristics specific to each region, models have been developed to simulate rainwater harvesting systems and evaluate their efficiency (Rahman 2017). These models address several aspects, such as household use, (Semaan *et al.* 2020) potable water savings (Abdulla 2019), optimization of storage tanks (Campisano & Modica 2015), economic efficiency (Domínguez *et al.* 2017), carbon emission reductions (Dallman *et al.* 2021), and reduce peak flows in storm water systems and runoff

volume to prevent flooding at a larger scale such as at neighborhood level (Freni & Liuzzo 2019; Snir & Friedler 2021). Additionally, the application of rainwater harvesting has been socially well accepted, improving the application of these techniques in the cities.

However, the assessment of rainwater harvesting for urban hydroponic crops production still needs to be explored (Campisano *et al.* 2017). Rainwater harvesting and urban hydroponic crops enable food production in urban areas without relying on additional water from traditional sources. The integration of both strategies addresses food and water security at the user level, extending accessibility to the entire population. Furthermore, the installation of these compact systems imposes minimal structural modifications to buildings compared to other rainwater harvesting applications, enhancing appeal for average households.

In this paper, we evaluated the efficiency of rainwater harvesting for urban hydroponic crops production in an Andean city. We developed a conceptual model to simulate rainwater harvesting and storage based on precipitation input and demand outflow. Subsequently, the reliability of the system was assessed in covering the water demand of two urban hydroponic crops systems: the first scenario representing a household production level (30 plants), and the second representing a small-scale commercial production at micro-entrepreneurship level (200 plants). To optimize the efficiency, we simulated rainwater harvesting under varying design conditions for hydroponic production, developing design guidelines to identify the most favorable conditions. This research serves as a necessary step in establishing a sustainable water-food nexus in urban centers.

METHODOLOGY

Study area

The study was conducted in the city of Cuenca (Figure 1), located in the southern Ecuadorian Andes, at an elevation of approximately 2,550 metres above sea level (m a.s.l.). Cuenca is considered the third most important city in Ecuador due to its population and economic activity. The canton covers an area of ~3,665 km² and has 636,996 inhabitants according to the 2020 population projection (INEC 2010). Therefore, identifying new forms of local food production for this medium city is a challenge that supports food sustainability. The city is situated in an inter-Andean valley surrounded by steep slopes, a typical characteristic of Andean cities (Céleri & Feyen 2009). According to the Köppen-Geiger climate

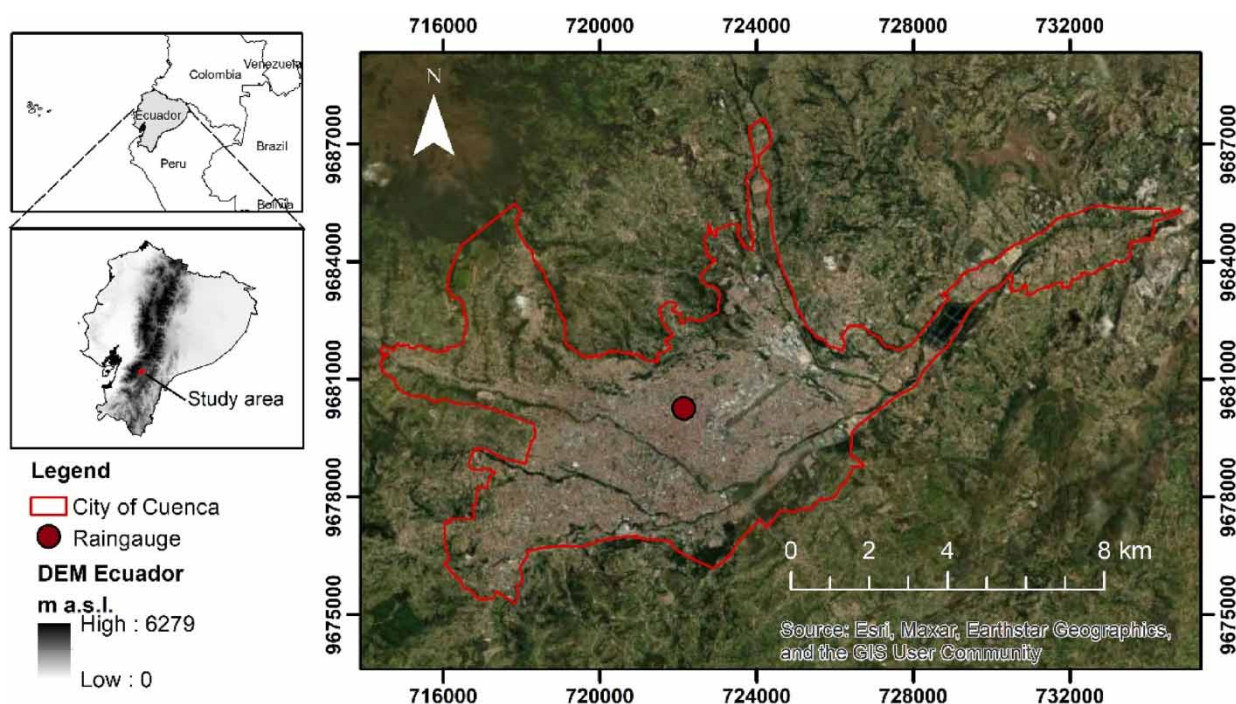


Figure 1 | Study area and precipitation monitoring point.

classification, the city has a warm temperate climate, fully humid, with cool summers and cold winters (climate code: Cfc, Kotttek *et al.* 2006). However, it exhibits significant variability due to the influence of the Andes Mountain range, the Inter-tropical Convergence Zone, Amazonian air masses, and the Pacific coast regime (Vuille *et al.* 2000). The average annual precipitation was 869 mm during the period 2015 to 2019. It has a bimodal rainfall seasonality with a marked dry season from June to August and two rainy periods in March to May and October (Céleri *et al.* 2007). The average temperature in Cuenca is 14 °C (Córdova *et al.* 2016).

Precipitation data

The precipitation input data for the rainwater harvesting model were obtained using an automatic tipping-bucket rain gauge located in the center of the city of Cuenca (Figure 1). The data cover the period from March 15, 2014, to December 5, 2020, with a total of 6 years and 8 months. The data recorded every 5 min were aggregated on a weekly timescale (352 weeks) to adjust them to the timescale of the hydroponic crops water demand, explained in the following section. Annual precipitation has a behavior similar to the historical variability compared to a station with 22 years of information (1999 to 2020) located at the exit of the city, 7 km away (Figure 2).

Design factors of rainwater harvesting and hydroponic crops

The rainwater harvesting model mainly depends on four design factors: precipitation (water availability), roof capture area, storage volume (storage tank), and water demand (Semaan *et al.* 2020). Water availability is determined by the amount of precipitation in each location and, as a result, it cannot be altered. On the other hand, roof capture area, storage volume and water demand are factors that depend on the requirements and conditions of the users, and can be modified to find an optimal design.

The production scenarios were based on a nutrient film hydroponic system (Sharma *et al.* 2019). This production system consists of PVC pipes of 75 mm diameter and 1.5 and 3 m long for the first and second scenarios, respectively. Plant seedlings with 4 weeks of development are placed at intervals of 25 cm along the pipes. A nutrient solution prepared according to the formulation of 'Steiner' (Steiner 1961) circulates through the pipes, which forms a film of 2–3 cm that is in contact with the roots of the plants. The nutrient solution is pumped from a reservoir at a constant flow rate of 0.1 L s⁻¹. The species produced in these systems are lettuces of different types, chard, kale, arugula, celery, cilantro, parsley, and basil. The production cycle is 6 weeks, starting when the plants are transplanted and ending when they are harvested. After harvesting and cleaning the pipes, another batch of plants can be transplanted to initiate a new production cycle.

Production scenarios of hydroponic crops

Two hydroponic crop production scenarios, based on real cases, were proposed. The first one was for domestic food production scale and the second one was for small-scale commercial production at the micro-entrepreneurship level. Their characteristics were provided by a local entrepreneurship dedicated to the installation of these production systems. A scheme of the scenarios is shown in Figure 3.

The first scenario aimed to produce 30 plants per production cycle, requiring 40 L of water per week. The system had a pyramidal configuration with five levels and occupied a space of 1.5 m in length and 0.8 m in width. The roof area of the

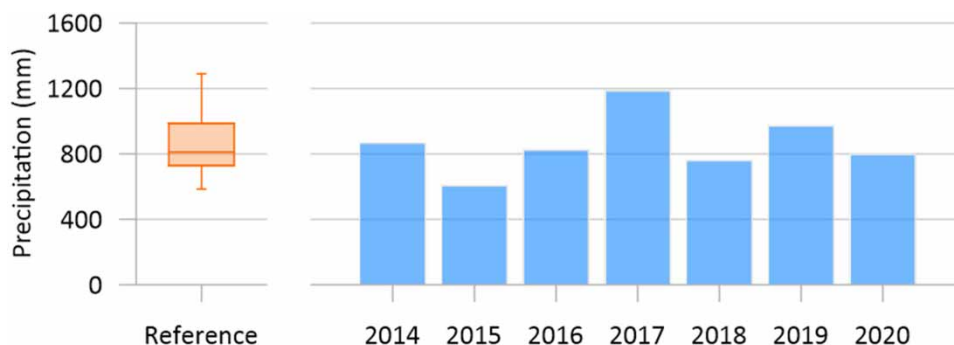


Figure 2 | Reference annual precipitation (from 1999 to 2020, orange box plot) compared to annual precipitation used in this study (from 2014 to 2020, blue bar plot).



Figure 3 | Real scenarios of urban hydroponic crops: (a) scenario 1 (E1): domestic production and (b) scenario 2 (E2): small-scale commercial production.

home was 40 m² (8 m × 5 m, in horizontal projection). The tank size was set at 100 L because it is a common size in the local market and suitable for the installation in a house.

The second scenario aimed to produce 200 plants per production cycle, requiring 160 L of water per week. It consisted of four systems arranged in a two-level bench configuration. Each system occupied an area of 3.0 m in length by 0.9 m in width. The roof area of the microenterprise was 12 m² (3 m × 4 m, in horizontal projection). This roof area was smaller than scenario 1 because it only corresponds to the roof protecting the plants. The tank size was set at 500 L due to the greater availability of physical space compared to scenario 1.

As can be observed, scenario 2 had a smaller roof area and higher demand compared to scenario 1. However, these initial baseline characteristics were not changed in order to evaluate the performance of rainwater harvesting under two extremes of water demands. The difference in weekly water demand per plant (litres of water per plant) between scenarios 1 (1.33 L plant⁻¹) and 2 (0.8 L plant⁻¹) was due to the minimum head required for pumping operation. As result, the larger the hydroponic crop system is, the lower the amount of water per plant.

Conceptual rainwater harvesting model

A conceptual model based on water balance was developed to evaluate the performance of the rainwater harvesting system. This balance is a function of the water input as precipitation and the water output as demand. The remaining water after the use of the demand is stored in a reservoir (storage tank). A scheme of the conceptual model is shown in Figure 4.

The model computes the collected rainwater volume (RW), which is the amount of precipitation that actually is captured by the roof and reaches the storage tank. This RW is calculated as a function of precipitation (P, in mm), roof capture area (A, m²) and two efficiency factors, rl and cl (Equation (1)). These efficiency factors represent all potential water losses that occur in the roof (rl) and in the pipelines (cl). They range between 0 and 1, where 0 means that all water is lost and 1 means that all precipitation falling on the roof can be stored. These factors are mostly related to the construction materials. In our case they were set at 0.9 each, representing a loss due to the initial wetting of the roof and the water splashing.

The RW is added to the storage reservoir of the previous week or previous time step (STO_{i-1}, in litres), increasing the available water storage (AW) in the present week (Equation (2)). However, the volume calculated for the present week, in Equation (2), can exceed the maximum storage capacity (VolMAX, in L). When the available water exceeds the VolMAX, it is set to the maximum storage capacity of the tank. This replacement is done to avoid including the water that cannot be stored as available water for the demand. Finally, the water demand (D, in litres) is extracted from storage, after fulfilling the previous condition (Equation (3)).

$$RW_i = P_i * A * rl * cl \quad (1)$$

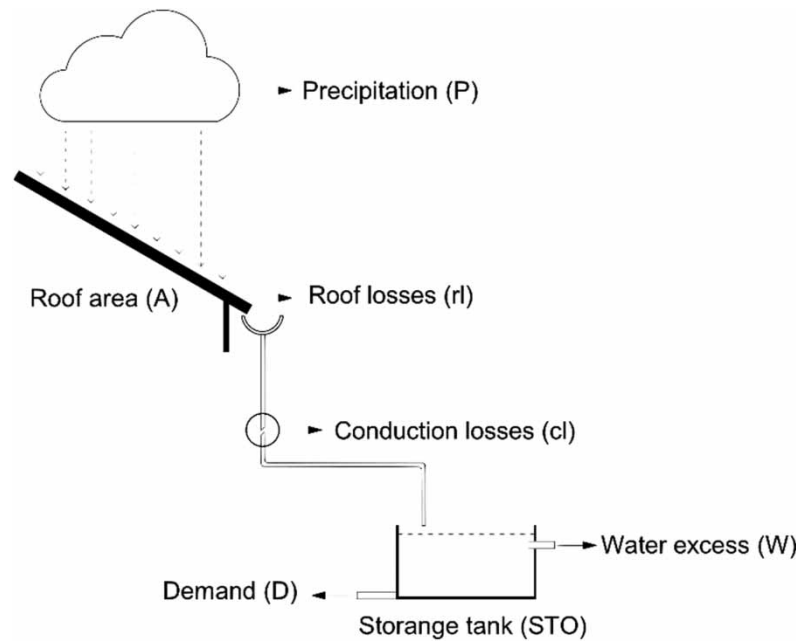


Figure 4 | Scheme of the conceptual rainwater harvesting model.

$$AW_i = \min(STO_{i-1}) + RW_i ; VolMAX \quad (2)$$

$$STO_i = AW - D \quad (3)$$

where i represents each timestep, in this case, 1 week.

Evaluation of rainwater harvesting for hydroponic crop production scenarios

The rainwater harvesting model was used to analyze whether the observed precipitation covers the water demand of the two hydroponic crop scenarios. To achieve this, weekly precipitation data was used as input to the model. Then, the rainwater collected, the water stored, the water used to cover the demand and the water that remained after the demand were simulated. The quantity of precipitation data was extensive (>6 years) and, therefore, it was possible to analyze the performance of rainwater harvesting under low and high precipitation conditions.

The performance of rainwater harvesting to meet the demand of the hydroponic crop scenarios was quantified using two indices suggested by Hashimoto *et al.* (1982) and used for example in Chadwick *et al.* (2021). The volume-based reliability, hereafter called efficiency index (Eff.), represents in percentage the mean rainwater used compared to the demand over the entire study period (Equation (4)). The weekly temporal variability of the efficiency index was obtained using the same equation for each week of the study period. The index ranges from 0 to 100%, where 100% means that all demand for the period was covered. The second index is called time-based reliability (RelT). The RelT estimates the percentage of time (in weeks) that the demand was met. This index is estimated by subtracting from one the fraction of weeks the demand was not met compared to the total number of weeks of the study period and expressed as percentage (Equation (5)). NSD is the number of weeks that the demand was not met (Equations (6) and (7)).

$$Eff = \frac{\sum_{i=1}^n \frac{URW_i}{D} * 100}{n} \quad (4)$$

$$RelT = \left(1 - \frac{NSD}{n} \right) * 100 \quad (5)$$

$$\text{aux}_i = \begin{cases} 0 & \text{if } \text{URW}_i < D \\ 14 & \text{if } \text{URW}_i = D \end{cases} \quad (6)$$

$$\text{NSD} = \sum_{i=1}^n \text{aux}_i \quad (7)$$

where n is number of weeks of the study period; URW_i is the water used from storage (l) at time i ; D is the weekly water demand of hydroponic crops and aux_i is the counter when the demand was not covered for time i .

Optimization of design factors of rainwater harvesting system for hydroponic crop production scenarios

The optimization of hydroponic production scenarios was conducted by simulating rainwater harvesting performance with different values of design factors. The evaluated design factors included roof capture area, storage volume, and water demand. The range of variation for these factors was chosen to maintain a relatively small system suitable for urban and peri-urban areas. The roof capture area remained constant according to the two aforementioned scenarios (12 and 40 m). A third area of 80 m² was added to represent the average roof area of the city (Godoy 2015) and establish general guidelines. The storage volume ranged from 10 to 2,500 L by increments of 10 L. The water demand ranged from 10 and 1,000 L week⁻¹ by increments of 10 L. The 10-L increment was selected to provide detailed results of rainwater harvesting performance.

The rainwater harvesting efficiency (Equation (4)) was calculated using all combinations of the aforementioned design factors. This process generated a matrix for each roof capture area, containing the rainwater harvesting efficiency for each increment in storage volume and demand. Finally, this matrix was plotted to identify efficiency contour lines. These lines were delimited from 0% to 100% for each 10% change in efficiency. The NSD index was not used in this part of the study because we only wanted to evaluate the overall functionality of the system.

This process is similar to Snir & Friedler (2021). It provides a range of design options rather than a single optimization value. These options can be analyzed to match user needs and are often referred to as design guidelines (Rahman *et al.* 2020).

RESULTS

Evaluation of rainwater harvesting for hydroponic crop production scenarios

The performance indices obtained for the study period and for each scenario are presented in Table 1. Additionally, the weekly water storage, before the allocation of the water demand, and the efficiency calculated based on this storage, is presented in Figure 5.

The mean efficiency of scenario 1 was 99.71%, showing that the rainwater captured was enough to cover the demand. According to the time-based reliability (99.15%), almost all the weeks the demand was covered. In just 3 out of 352 weeks the demand was not covered by the system. The lowest weekly efficiency of these 3 weeks was 50%, and the storage tank was never empty (Figure 5(a)). Moreover, there were no consecutive weeks where storage was below the demand threshold, implying that the decrease in efficiency toward the end of 2015, 2017, and 2020 was due to punctual periods of low precipitation input. The system reliability depended not only on weekly precipitation but also on stored water to mitigate normal precipitation variations.

The mean efficiency for scenario 2 reached 75.79%, ~24% lower than scenario 1. Although the efficiency was lower compared to scenario 1, an average demand of 121.6 L week⁻¹ was covered, which means 42,684.3 L in potable water consumption during the 6.6 years of the study period. Although the demand was fully covered 61.36% of the weeks, the efficiency dropped to 0% only in 7 non-consecutive weeks. Another feature of this scenario is that water storage is more variable than in scenario 1. A decline in storage level, often below the demand threshold, was typical in mid-year (June, July, and

Table 1 | Performance indices for the study period (352 weeks)

Scenario	Eff. (%)	NSD (# weeks)	RelT (%)	Eff = 0% (# weeks)	Mean water demand covered (L week ⁻¹)
1	99,71	3	99.15	0	39,88
2	75,79	136	61.36	7	121,6

Eff. is the percentage of the demand covered, and NSD is the number of weeks where the demand is not fully covered.

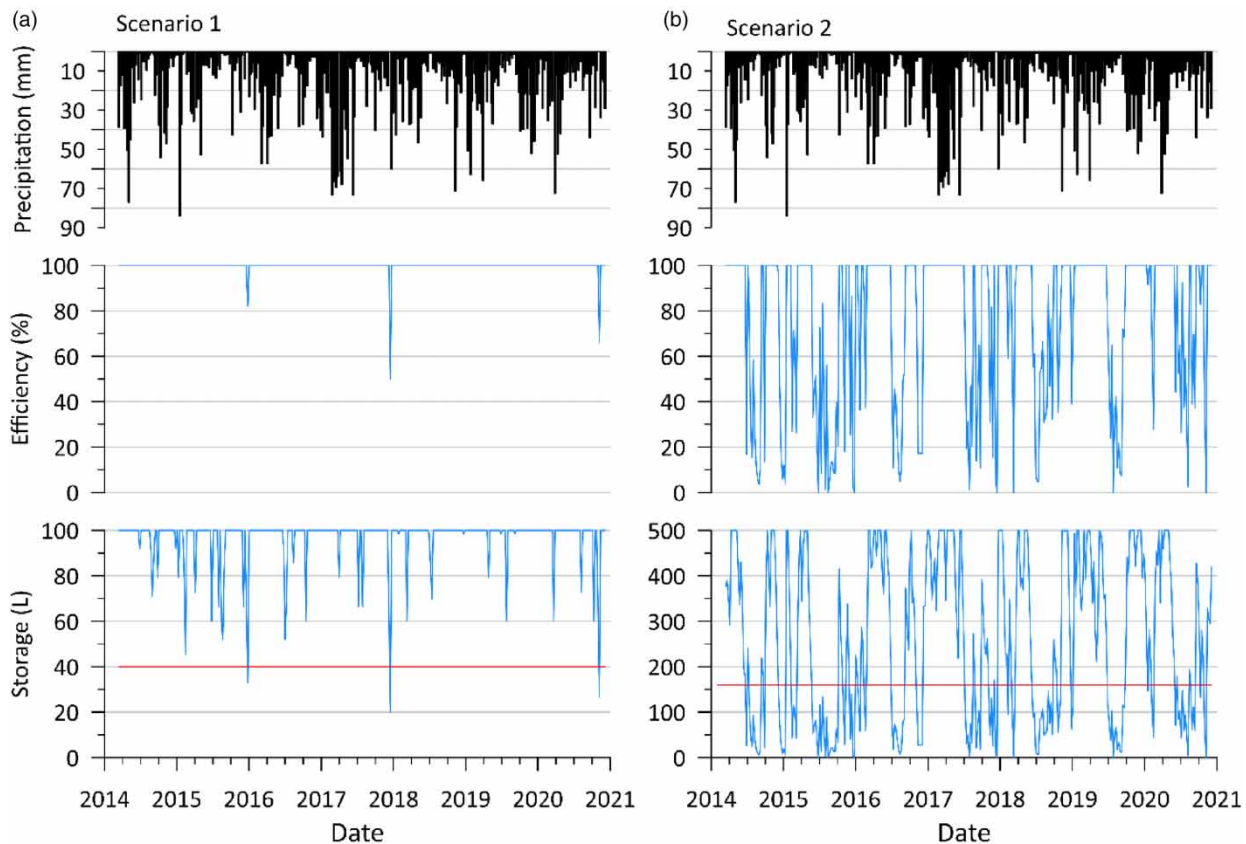


Figure 5 | Simulated water storage and efficiency for each hydroponic crop scenario. The bar plot at the top represents the weekly rainfall used as the input to the model. The red line indicates the water demand (L week^{-1}) for each scenario. (a) Scenario 1: domestic production and (b) scenario 2 (E2): small-scale commercial production.

August) (Figure 5(b)). Notably, in 2015, 2017, and 2020, the storage tank remained unfilled by the end of the year (September, October, and November), unlike in other years. Nonetheless, storage during these months is rarely empty and is often close to the demand threshold. Indicating that stored water partially covers the demand, even in years with extreme variations in precipitation.

Optimization of design factors for rainwater harvesting systems in hydroponic production scenarios

The initial design conditions of scenario 1 obtained an efficiency of 99.71% (Table 1), already exceeding the 90% contour line (Figure 6(b)). However, 100% efficiency can be achieved by increasing the storage volume to 120 L or decreasing the water demand to 30 L. In this case, the first option is recommended because increasing storage volume by 20 L did not result in a significant cost change. Furthermore, the robust performance of this scenario offered several options to ensure an efficiency above 90% and even increase the demand. For example, the maximum demand that could be achieved with an efficiency above 90% was 420 L, increasing by three times the original demand.

For scenario 2 (Figure 6(a)), the maximum achievable efficiency was 94.27% with a maximum storage of 2,500 L. However, this option was not the most convenient because reducing the storage to 1,480 L would result in an efficiency of 90%. Thus, a difference of 1,020 L only increases the efficiency by 4%. Two options were possible to achieve 100% efficiency, decrease the demand from 160 to 130 L or increase the roof capture area to 40 m^2 . In this case, the second option is recommended, as it increases the maximum demand covered with an efficiency of 100% from 130 to 250 L (using the largest storage tank of 2,500 L). Additionally, with the capture area of 40 m^2 , an efficiency of above 90% can be achieved using a storage tank of 260 L for this demand of 160 L week^{-1} . This change is significant compared to the storage of 1,480 L needed with the roof capture area of 12 m^2 to obtain the same efficiency of 90%.

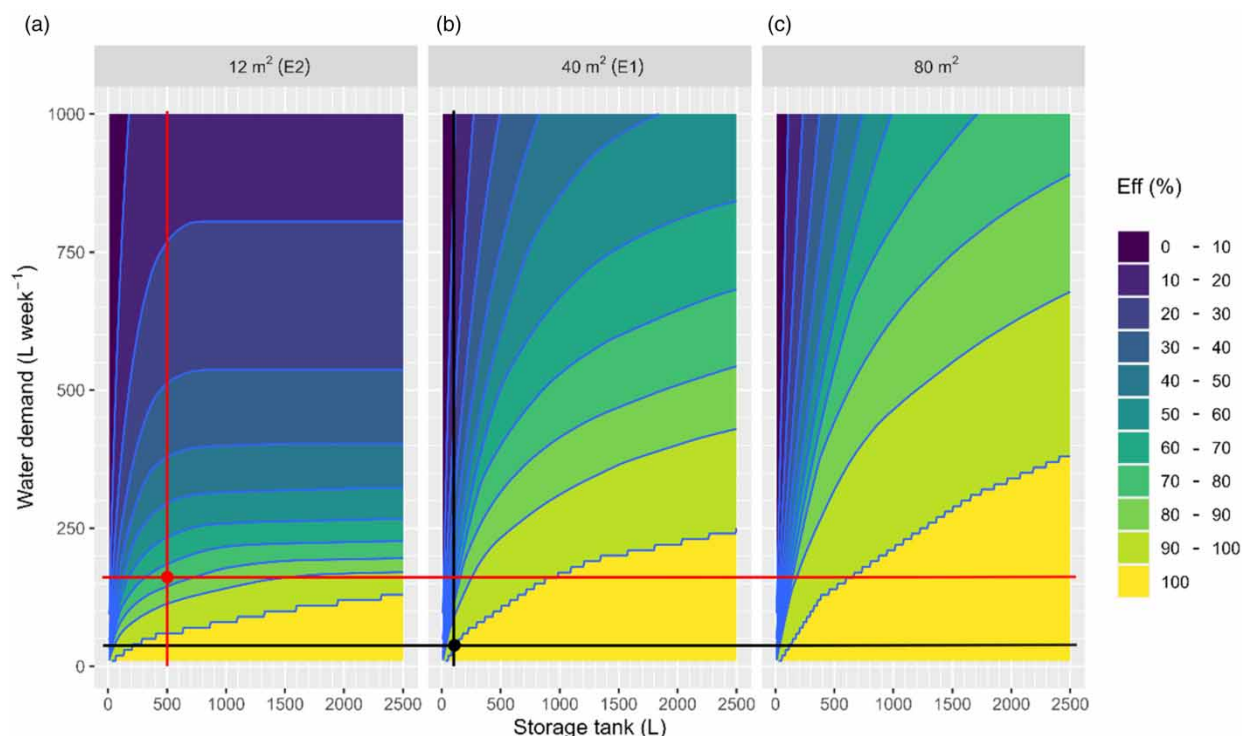


Figure 6 | Contour lines of rainwater harvesting efficiency for areas of: (a) 12 m², scenario 2; (b) 40 m², scenario 1; and (c) 80 m². Each band represents the efficiency within the low and high efficiency level in the legend. The band color represents the efficiency level by increments of 10%. The black and red lines represent the initial efficiency obtained in scenarios 1 and 2, respectively.

For the mean roof capture area of the city (80 m², Figure 6(c)) and considering storage tanks of 100 and 500 L, a demand of 100 and 310 L week⁻¹ can be covered with an efficiency above 90%, respectively. With this water availability (100 and 310 L week⁻¹), 76 and 238 plants could be produced considering the water consumption of scenario 1 (1.3 L week⁻¹) and the production cycle of 6 weeks. Meanwhile, 125 and 387 plants could be produced considering scenario 2 (0.8 L week⁻¹). These results highlight the potential of combining rainwater harvesting and hydroponic crops in the city because water availability is enough to cover the demand, and the storage tanks are small for a house. The maximum demand that could be covered with an efficiency above 90% is 670 L week⁻¹, using a storage tank of 2,500 L.

The design guidelines (Figure 6) enabled further analysis. Increasing storage guarantees higher demand coverage. However, this relation is not always the most efficient considering the space and economic conditions of the user. For instance, in scenario 1 ($A = 40$ m²), doubling the demand (200 L) increases the storage by about five times (500 L) to maintain an efficiency close to 100%. But, four times the demand (400 L) leads to a storage increase of approximately 25 times (2,500 L). This is because the initial stages of the curves display a linear relationship, indicating that with each incremental rise in storage, there is a proportionate increase in demand. However, as demand escalates to higher levels, progressively larger increments in storage become necessary.

DISCUSSION

Performance of rainwater harvesting for urban hydroponic crops production

Precipitation in the study area was enough to cover the water demand of the hydroponic crops at domestic level (Eff. = 99.71%), due to the constant inputs of precipitation throughout the year. In studies such as Abdulla (2019) and Aladenola & Adeboye (2010), the well-marked dry seasons in the precipitation input was the most important variable to establish the objective, temporal scale of the water demand and storage size of the rainwater harvesting. In our results, the seasonality of the study site only affected scenario 2 due to the small roof capture area of the system. The water deficit was generated by the normal variation of precipitation which coincided with the lowest precipitation period (Céleri *et al.* 2007).

Nevertheless, an efficiency of 75.79% was achieved. This value is higher compared to the study of Jurga *et al.* (2021) conducted in Wrocław, Poland, where an average efficiency between 36.8 and 39.8% was found. Although the conditions of the scenarios in this study were different in demand and storage, there are few urban rainwater harvesting studies oriented to hydroponic crop production (Campisano *et al.* 2017; Semaan *et al.* 2020).

Comparing this study with other purposes of rainwater harvesting, the demand at a weekly scale for the hydroponic crops played an important role in the high efficiency values obtained (Fernandes *et al.* 2015; Semaan *et al.* 2020). This temporal scale allowed us to reduce the temporal variability of precipitation and to store enough water to cover the water demand (Figure 5). In contrast to the study of Snir & Friedler (2021), who used an hourly scale to reduce stormwater runoff effectively but covering only an average of 18% of their domestic water demand. In this way, the high water efficiency of hydroponic crops produced a very low water demand and high production value (Barbosa *et al.* 2015; Ragaveena *et al.* 2021). However, the different timescales of other rainwater harvesting uses must be considered to make a fair comparison. For example, hydroponic crops use water once a week compared to the daily use in toilets. Without using a single timescale, this can lead to errors in the calculation of storage and efficiency. Other rainwater uses can be analyzed using the same model and modifying the timescale of rainfall input and water demand. In this way, the efficiency of rainwater harvesting can be studied under different scenarios with combined water uses and operation rules.

Overall, the presence of precipitation throughout the year, the weekly periodicity of demand, and the water use efficiency of the hydroponic crop systems contributed to the strong performance of the rainwater harvesting system. These factors were favorable for exploring design optimization options. The design guidelines generated using efficiency contour lines presented in Figure 6 were used similarly to the efficiency curves by Rahman *et al.* (2020) and Snir & Friedler (2021). This figure demonstrates that scenario 2 could achieve efficiencies above 90% by increasing the roof capture area to 40 m². These adjustments require minimal structural changes compared to rainwater harvesting for sanitation purposes (Domínguez *et al.* 2017).

Furthermore, considering the average roof capture area of the city of 80 m², the system was able to cover a maximum demand of 670 L week⁻¹ with 90% efficiency and a tank of 2,500 L. This represents 59.82% of the average weekly consumption of 1,120 L per person calculated from the daily average of 160 L per person in the city (Primicias 2023). These results are in agreement with the study of Islam (2023), which shows that rainwater could generate incomes at household levels. A clear example of the application of rainwater harvesting at large urban scale is China, where it helped to reduce water scarcity and floodings (Zhou *et al.* 2023). However, detailed studies of roof size distribution are needed to generalize the results. Further studies on the spatial variability of precipitation and efficiency parameters could be analyzed to establish city-level guidelines and to study the uncertainty of the model. Despite this, the model is accessible and can be used to analyze a variety of conditions.

On the other hand, water quality is the characteristic that most concerns the population in order to use rainwater harvesting (Portman *et al.* 2022). This analysis is recommended for future studies because a complex sampling strategy needs to be developed. Factors to be studied are the pollutants that could accumulate on the roofs and in the storage tank, nutritional composition of the vegetables and the wastewater. In addition, with a circular economy approach, the impacts of the entire production system can be analyzed, including energy and social factors that were not taken into account in this study.

Comparing a weekly consumption of 7.6 L plant⁻¹ for traditional row crops (González-Esquiva *et al.* 2017) with the weekly consumption of the hydroponic crop scenarios employed (1.3 and 0.8 L plant⁻¹ for scenario 1 and 2, respectively), the water demand of only five and nine plants could be covered, respectively. Considering the water efficiency of hydroponic crops and their minimal space requirements (Rufi-Salís *et al.* 2020), this becomes a promising option for urban spaces. Furthermore, during the experimentation process with the hydroponic crops it was observed that during short periods of water scarcity (up to 1 week), plants did not wilt due to the remaining water in the pipes. Subsequently, the plants tended to recover as long as water was present in the system. This can mitigate the risk of crop loss during weeks when the water demand is not fully covered. The performance of rainwater harvesting under conditions of precipitation shortage is still complex due to the uncertainty of climate change scenarios at weekly precipitation timescales used in this study. Instead, the use of synthetic rainfall scenarios could inform the influence of changes in rainfall amount. Short periods of water scarcity can also be mitigated with strategies such as using alternative water sources, using additional reservoirs exclusively for these times and reducing crop production during the months of the year when the precipitation is expected to be low. However, under extreme drought scenarios it is not recommended to use this system with tap water in order to avoid the competition with population and increase the water stress. One way to address this problem is to have access to drought forecasts that allow us to store more water before these periods.

CONCLUSIONS

This study evaluated the efficiency of rainwater harvesting systems to cover the water demand of urban hydroponic crops. For this purpose, the operation of these systems was simulated using a conceptual rainwater harvesting model. The input data for the model were based on the observed local precipitation and real conditions from two urban hydroponic crop scenarios. The collected rainwater was enough to fulfill the water demand (Eff. = 99.71%) of the hydroponic crop at the domestic level (30 plants) with a roof capture area of 40 m² and a storage tank of 100 L. For larger crop systems, such as microenterprises (~200 plants), the demand was covered completely using the roof capture area of 40 m² and a storage tank of 500 L. Moreover, considering the average roof capture area of the city (80 m²) and employing a tank of 500 L, a demand of up to 310 L week⁻¹ can be covered with an efficiency above 90%. This means water was available for a hydroponic system of up to 387 plants. The model and approach used here can be replicated for diverse water roof capture area conditions and objectives.

On the other hand, the combination of rainwater harvesting and hydroponic crops could be implemented mainly in places with constant rainfall over the year. Therefore, in semi-arid locations it is a constraint that requires other parameters to be evaluated. The strategy is also recommended for locations with limited space, even in locations with high land prices, due to the small space required. In addition, the use of design guidelines, containing water demand, tank size, efficiency and roof area, is a simple way to communicate the results to users and make design decisions. Finally, this combination is promising to promote urban food security by reducing negative impacts on water security.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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