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Rainwater Harvesting System Analysis for Semi-Arid Climate: A Daily Linear Programming Model

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ABSTRACT

Rainwater harvesting has proven to be an alternative water supply scheme for sustainable water management of regions with limited water resources. In this paper, a linear programming (LP) model with daily time steps, which minimizes a rooftop rainwater harvesting system (RWHS) cost, is developed and used to calculate the optimum RWH tank size. The developed LP model is applied to the semi-arid Northern Cyprus in the Eastern Mediterranean. The analysis is carried out for 33 sites which receive average annual rainfall ranging from 292 mm to 548 mm to evaluate the spatial effect of rainfall characteristic and the water cost on the financial feasibility and performance of the RWHS. At 29 out of 33 sites, RWHS investments are found to be financially feasible with discounted payback periods ranging from 12 to 28 years. The optimum RWH tank sizes are determined to be between 2 m^3 and 6 m^3 resulting in up to 20 % reliability with more than 50 m^3 of average annual water savings per house. It is observed that the cost of water is a critical factor that affects the financial feasibility and water savings of a RWHS, especially in regions with limited rainfall. The comparison of the developed daily LP model with an LP model with monthly time steps demonstrates that the financial feasibility and the optimum tank size can only be assessed realistically when daily time steps are used. Finally, the sensitivity analysis shows that the discounted payback period is highly sensitive to the collector area.

Keywords: Sustainable water use, rainwater harvesting, optimum tank size, spatial analysis, semi-arid climate, Northern Cyprus.

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1. INTRODUCTION

Water, intertwined with sustainable development, is vital to the continuity of healthy life and ecosystems [1]. However, water resources are finite and need to be sustainably managed. Rainwater harvesting is an old and sustainable water resources management technique employed to collect and use rainwater to improve the accessibility of water where it is scarce. Systems that harvest, store, and bring rainwater into the service are called rainwater harvesting systems (RWHSs). Harvested rainwater is stored in a tank or a cistern. Some of the water demand can be supplied using RWHSs, especially at water-stressed islands [2-8]. Moreover, RWH is expected to reduce damages related to urban floods [9], can mitigate the effects of urbanization and climate change on water resources and is necessary for sustainable urban water management [10].

Tank size is one of the main concerns in designing RWHSs since it directly affects the financial feasibility of the system and performance indicators such as reliability, resilience, and vulnerability [11-15]. Generally, approaches based on a water balance model are used to identify the best tank size. A set of alternative tank sizes are selected and the water balance model is executed for each alternative tank size to evaluate the corresponding financial feasibility [16-24] and the performance of the systems [25-29]. However, in the analysis of a high number of sites, water balance models are time-consuming since they require solving the model once for each tank size in a trial and error approach. On the other hand, when linear programming (LP) models are used the whole domain is searched and the optimum tank size is identified in a single run.

Mixed-integer, linear and non-linear optimization models have recently been used for optimal RWHS design. Bocanegra-Martínez et al. [30] and [31] developed multi-objective non-linear optimization models to design water supply networks in a residential complex for reusing reclaimed water and harvested rainwater. Their models aimed to minimize total cost and freshwater consumption. Sample, D. J., & Liu, J. [32] investigated minimizing costs of RWHSs for supplying water and capturing runoff. Emami Javanmard et al. [33] developed a multi-objective mixed-integer LP model to optimize energy and water use of dwellings and to decrease CO_2 emissions. Their results showed that the amount of water provided from the local water grid was reduced at least 20% through RWH and greywater recycling. Zhang, L. et al. [34] proposed a mixed-integer LP model to optimize water tank size and operation of pumps for the minimum potable water consumption and electricity cost. Their results indicated that electricity price, discount rate, rainfall intensity, and water demand all impact the size of the water tank but only water demand has a significant impact on the cost-effectiveness of the system. LP models are simpler in comparison with other optimization models and guarantees to find the optimum tank size if there exists one. To the best of the authors' knowledge, work of Okoye, C. O. et al. [35] is the first study in which LP is used to identify the optimum tank size. Then, Ruso, M. et al. [36] identified optimum tank sizes by minimizing total costs using the LP approach with monthly time steps. Both studies concluded that utilization of monthly time steps affects the optimum tank size and the financial benefit of the system considerably. Furthermore, in studies where the effect of hourly, daily and yearly time steps are compared, the use of smaller time steps is recommended to evaluate the performance more accurately [37-41]. Large time steps (e.g. monthly) caused oversized tank designs and misleading reliability evaluations [39]. Zhang, S. et al.[41] showed that monthly time steps ended in inaccurate results, while hourly and daily time steps resulted in similar performances and water savings. Thus, in this study, the LP model in [36] is modified to run with daily time steps (LP-Daily Model) and inflation rates are used to estimate future costs for a more realistic cost-benefit analysis.

A spatial performance assessment of RHWSs was conducted in various studies [25, 42- 47] and dependence of the performance on the climatic characteristics of the site were highlighted. [25] investigated the potable water savings potential of the residential areas in 62 cities in Brazil. Equations were developed to correlate the potential for water savings with rainfall and water demand. Potable water savings ranged from 34% to 92% for the 62 cities. Campisano, A., & Modica, C. [42] introduced a dimensionless methodology to determine the optimum tank size for 17 rainfall gauging stations on the island of Sicily, Italy. Water saving and overflow discharges were evaluated using simulation results of the daily time step water balance model. The optimum tank size was selected based on cost efficiency. It was reported that the net revenue decreases when tank size increases and rainfall decreases. Ali, S., et al. [47] developed a daily water balance model and applied it to five climatic regions of Pakistan. Water saving, stormwater capture efficiency and financial feasibility of RWHSs were assessed for different tank sizes up to 100 m^3. They founded financially feasible systems could be achieved in a warm, semi-arid climate with 667 mm of average annual rainfall, while RWHS investments were found to be financially infeasible in a cold, semi-arid climate with 238 mm of average annual rainfall. Preeti, P., & Rahman, A. [48] investigated the reliability of RWHSs for eight cities in Australia with average annual rainwater ranging from 510 mm to 1176 mm using a daily water balance modelling approach. Reliability was found to range from 88% to 99% for toilet and laundry uses for tank sizes ranging from 10 m^3 to 100 m^3. They concluded that RWHS investments were not economically viable in most of the investigated cities.

This study aims (i) to introduce a single-objective *LP model with daily time steps* to optimize tank sizes by minimizing costs and (ii) to investigate the *spatial effect of rainfall characteristics and water costs* on the financial feasibility and performance of RWHSs. The developed LP-Daily Model determines optimum RWH tank sizes for 33 case study sites selected from the semi-arid Northern Cyprus, located in the Eastern Mediterranean Sea.

2. METHOD

In this study, a single-objective *LP model with daily time steps* is developed to identify the best RWH tank size by minimizing municipal water, wastewater, and tank costs. Optimum supply strategy of daily water demand of a single residential unit is determined using historical daily rainfall data. Musayev, S. et al. [46] showed that climate change will have a negligible impact on the feasibility of RWHSs in semi-arid regions. Thus, it is assumed that the rainfall pattern in the near future will be similar to that of the simulation period and the optimum RWH tank size will be efficient in the near future as well.

2.1. LP-Daily Model

The developed LP-Daily model uses the yield-before-spillage algorithm. First, the daily water demand is supplied, and then the current day's rainfall is harvested. The excess rainwater is spilled if the capacity of the tank is exceeded. Our model allows the use of water from the RWH tank or the municipal water supply network (MWSN) in supplying the daily water demand of a residential unit according to the region's water tariff scheme to ensure maximum financial benefits. The mathematical formulation of the proposed LP-Daily model is given below:

$$Min.Z = a \times T_{cap} + \sum_{t=1}^{T} \sum_{j=1}^{J} \frac{(b_{tj} \times P_{tj} + (P_t - U_t) \times c_{wt})}{(1+im)^t} \quad (1)$$

s.t.

$$Id_i^t = Id_{i-1}^t + rd_i^t - Ud_i^t \qquad \forall t, i \in t \quad (2)$$

$$Id_0^1 = 0 \quad (3)$$

$$Id_0^t = Id_I^{t-1} \qquad t = 1,2, \dots, T \quad (4)$$

$$Id_i^t \le T_{cap} \qquad \forall t, \forall i \quad (5)$$

$$Ud_i^t \le T_{cap} \qquad \forall t, \forall i \quad (6)$$

$$rd_i^t \le \min\{Rd_i^t, T_{cap}\} \qquad \forall t, \forall i \quad (7)$$

$$T_{cap} \le S_{max} \quad (8)$$

$$Pd_i^t + Ud_i^t = D_{daily} \qquad \forall t, \forall i \quad (9)$$

$$T_{cap}, Id_i^t, rd_i^t, Ud_i^t, Pd_i^t \ge 0 \qquad \forall t, \forall i \quad (10)$$

where Z is the objective function in Turkish Lira (TL), a is the unit cost of the RWH tank (TL/m^3), T_{cap} is the optimum RWH tank size (m^3), t is the index for months of the simulation period, T is the total number of months in the simulation period, j is the index for the price level, J is the total number of the price levels in the water tariff scheme, i is the index for the days of a month, b_{tj} is the unit municipal water cost supplied from the MWSN in month t at price level j (TL/m^3), P_{tj} is the municipal water volume that is purchased in month t from the MWSN at price level j (m^3), P_t is the total municipal water volume supplied from the MWSN in month t (m^3), U_t is the total rainwater volume used from the RWH tank in month t (m^3), c_{wt} is the unit wastewater cost in month t (TL/m^3), and im is the monthly discount rate. The unit municipal water costs incurred due to the water supply from the MWSN and unit wastewater costs throughout the simulation period are estimated assuming that their current unit costs will increase with the inflation rate.

The constraints of the LP-Daily are given in Eqs. (2) to (10) where Id_i^t is the inventory level of the RWH tank at the end of day i of month t (m^3), Ud_i^t is the amount of rainwater used from the RWH tank on day i of month t (m^3), rd_i^t is the amount of harvested rainwater on day i of month t (m^3), $i \in t$ states that index i is for all the days in month t, Rd_i^t is the maximum amount of rainwater that could be harvested on day i of month t (m^3), S_{max} is the maximum allowable RWH tank size (m^3), D_{daily} is the daily water demand (m^3), and Pd_i^t is the municipal water volume purchased from the MWSN on day i of month t (m^3).

Eq. (1) is the objective function that is composed of the summation of the net present value of the total municipal water and wastewater costs and the RWH tank cost. The simulation period is chosen as the lifetime of the RWHS. The amount of rainfall that will be collected and stored in the RWH tank is calculated using historical daily rainfall data. Eq. (2) is the daily water balance equation of the RWH tank. Eq. (3) states that the inventory level of the RWH tank is zero at the beginning of the first day of the simulation period. Eq. (4) ensures that the inventory level of the last day of month $(t-1)$ in the RWH tank is equal to the inventory level of the RWH tank at the beginning of the first day of month t. Constraints (5) and (6) ensure that the inventory level of the RWH tank on day i of month t and the amount of rainwater used from the RWH tank on day i of month t cannot be greater than the volume of the RWH tank. Constraint (7) guarantees that the amount of harvested rainwater on day i of month t cannot exceed both the maximum amount of rainwater that could be harvested on day i of month t and the volume of the RWH tank. Constraint (8) confirms that the optimum tank size cannot be higher than the maximum allowable RWH tank size (m^3). Eq. (9) states that the daily water demand is supplied from the RWH tank or the MWSN or both. Finally, Eq. (10) is the sign restrictions and ensures that all the decision variables are positive.

The total municipal water volume supplied from the MWSN in month t, P_t, is calculated by summing the municipal water volume purchased from the MWSN in each day of month t:

$$P_t = \sum_{i \in t} Pd_i^t \qquad \forall t \tag{11}$$

Assuming the total amount of water purchased from the MWSN in month m^* is P_{m^*} and three price levels are used, (i.e., the first V_1 m^3 is purchased from b_1 TL/m^3, the amount between V_1 and V_2 m^3 is purchased from b_2 TL/m^3 and the remaining is purchased from b_3 TL/m^3), the water cost that should be paid to the municipality, C, is calculated as follows:

$$\begin{aligned} &\text{If } P_{m^*} \le V_1 \text{ then } C = b_1 P_{m^*} \\ &\text{If } V_1 \le P_{m^*} \le V_2 \text{ then } C = b_1 V_1 + (P_{m^*} - V_1) b_2 \\ &\text{If } V_2 \le P_{m^*} \text{ then } C = b_1 V_1 + b_2 V_2 + (P_{m^*} - V_1 - V_2) b_3 \end{aligned} \tag{12}$$

The maximum amount of rainwater that could be harvested on day i of month t, Rd_i^t, is calculated using the equation of [49]:

$$Rd_i^t = c_f \times A_{col} \times p_i^t \times 10^{-3} \qquad \forall t, \forall i \tag{13}$$

where c_f is the runoff coefficient for the roof, A_{col} is the collector area at the roof (m^2), and p_i^t is the measured rainfall depth on day i of month t (mm).

The total rainwater volume used from the RWH tank in month t, U_t, is calculated by summing the amount of rainwater used from the RWH tank in each day of month t:

$$U_t = \sum_{i \in t} Ud_i^t \qquad \forall t \tag{14}$$

The daily water demand, D_{daily}, is calculated using:

$$D_{daily} = W_d \times n \tag{15}$$

where W_d is the average daily water demand per capita (m^3/cap/day), and n is the number of residents.

The monthly demand for month t, D_t, is calculated using:

$$D_t = D_{daily} \times I \qquad \forall t \tag{16}$$

where I is the total number of days in month t.

2.2. Cost-Benefit Analysis

After the optimum RWH tank size is obtained, the cost-benefit analysis of the RWHS is carried out. Maintenance, wastewater, and municipal water supply costs are increased using the inflation rate for each year of the simulation period. The net present value of all costs are calculated using the discount rate. The cost-benefit analysis compares the net present value of the case where a RWHS is installed and supplies some part of the total water demand to the case where all water demand is supplied from the MWSN. The total cost of the RWHS, C_{total}, is calculated using:

$$C_{total} = Z_{opt} + C_{fixed} \tag{17}$$

where Z_{opt} is the optimum value of the objective function Z (TL), and C_{fixed} is the summation of the fixed costs (TL) which is calculated using:

$$C_{fixed} = C_{inst} + C_{maint} \tag{18}$$

where C_{inst} is the RWHS installation cost (TL) and C_{maint} is the total RWHS maintenance cost that occurs throughout the simulation period (TL) which is calculated using:

$$C_{maint} = \sum_{t=1}^{T} \frac{c_m}{(1+im)^t} \tag{19}$$

where c_m is the base monthly RWHS maintenance cost (TL). The maintenance cost throughout the simulation period is estimated assuming that the base cost will increase with the inflation rate. The cost of supplying the whole water demand from the MWSN throughout the simulation period, C_{net} (TL), is calculated using:

$$C_{net} = \sum_{t=1}^{T} \sum_{j=1}^{J} \frac{b_j}{(1+im)^t} P_{tj} + \sum_{t=1}^{T} \frac{c_w}{(1+im)^t} D_t \tag{20}$$

The net financial benefit of the RWHS, NFB, is defined as the difference between the cost of supplying the whole water demand from the MWSN and the total cost of the RWHS:

$$NFB = C_{net} - C_{total} \tag{21}$$

When the NFB is negative, the RWHS ends in financial loss, and the RWHS is found to be infeasible. In addition to the NFB, the discounted payback period of the RWHS investment, which is the year at which cumulative discounted net cash-flow becomes zero, is calculated.

2.3. Water Balance Simulation Model

Tank size, daily rainfall, daily water demand, daily rainwater supply, daily tank spillage, and municipal water supply from the network are taken into account in the water balance simulation model (WBSM). The daily water balance of the RWH tank is carried out for a set of selected alternative tank sizes. The WBSM uses the yield-before-spillage algorithm.

Daily inflow to the RWH tank is calculated using Eq. (13). If the sum of daily inflow and the inventory level of the RWH tank at the end of the previous day is smaller than the daily water demand, daily rainwater supply from the RWH tank equals the sum of daily inflow and the inventory level of the RWH tank at the end of the previous day. Otherwise, daily rainwater supply from the RWH tank equals the daily water demand. Spill is the excess rainfall that exceeds the RWH tank size. Spill on day i of month t, SP_i^t (m^3), is calculated using Eqs. (22) or (23) [28]:

$$\text{If } Rd_i^t + Id_{i-1}^t - D_{daily} > T_{max} \text{ then } SP_i^t = Rd_i^t + Id_{i-1}^t - D_{daily} - T_{max} \tag{22}$$

$$\text{If } Rd_i^t + Id_{i-1}^t - D_{daily} \leq T_{max} \text{ then } SP_i^t = 0 \tag{23}$$

where T_{max} is the RWH tank size (m^3).

If spill on day i is calculated to be smaller than or equal to zero, the RWH tank inventory level at the end of day i is determined by subtracting the amount of rainwater supplied from the RWH tank on day i from the inventory level at the end of the previous day plus inflow on day i. Otherwise, the RWH tank inventory level at the end of day i is equal to the RWH tank size. For the detailed methodology of the WBSM on a daily scale, see [28]. Cost-benefit analysis of the RWHS is carried out to calculate the NFB for each alternative tank size using Eq. (21).

2.4. Performance Indicators: Resilience, Vulnerability, Reliability, and Water Saving

Resilience is the inverse of the mean value of the time the system spends in an unsatisfactory state [50]. In this study, the unsatisfactory state is considered to be the days in which water demand is not fully supplied by the RWHS. Such days are referred to as deficit events. Resilience, Res, is calculated using [50]:

$$Res = \left\{\frac{1}{M}\sum_{k=1}^{M} d_k\right\}^{-1} \tag{24}$$

where d_k is the duration of the k^{th} failure event and M is the total number of failure events.

Vulnerability is an indicator of the severity of RWHS failure. In this study, vulnerability is estimated as the mean value of the deficit events (i.e., the total amount of water supplied from the MWSN during deficit events divided by the total number of deficit events) as suggested by [51]. Vulnerability, Vul, is calculated using [50]:

$$Vul = \frac{1}{M}\sum_{k=1}^{M} v_k \tag{25}$$

where v_k is the deficit volume of the k^{th} failure event.

Reliability is a widely used indicator to evaluate the rainwater supply performance of a RWHS. In this study, water demand is supplied either by the RWHS, the MWSN or both and a failure event does not occur throughout the simulation period. Therefore, the volumetric reliability of the RWHS which is the percent of the water demand that can be supplied from the RWHS is considered for reliability calculations. Reliability, Rel, is calculated using [12]:

$$Rel = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} Ud_i^t}{D_{daily} \times N} \times 100 \tag{26}$$

where N is the total number of days in the simulation period.

Finally, water saving, Ws (m^3), is the average annual rainwater used to supply the demand:

$$Ws = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} Ud_i^t}{A} \tag{27}$$

where A is the total number of years in the simulation period.

2.5. Sensitivity Analysis

The sensitivity analysis is carried out to investigate the effects of collector area and average daily water demand per capita on the optimum tank size and the discounted payback period. In the sensitivity analysis, each of these two parameters is varied while keeping all other parameters constant. The LP model is run repeatedly between the limits of the analysed parameters.

2.6. Study Area and Rainfall Characteristics

Cyprus is an island in the Eastern Mediterranean region with a semi-arid climate where summers are hot and long, and winters are warm and short. Water resources are limited and water scarcity problems are encountered. December and January are the rainiest months on the island, while July and August are the driest months. The rainy period is usually from November to March. In this study, 33 case study sites are selected in Northern Cyprus. The rainfall characteristics throughout these sites vary significantly.

The European Standard suggests that large and complex RWHS projects need to be designed using at least five years of daily rainfall data series [52]. This study uses daily rainfall records of 33 meteorological stations from 1985 to 2015 obtained from the Meteorological Department of Northern Cyprus.

The average annual rainfall between 1985- 2015 at the study area is 386 mm. The average annual rainfall between 1985- 2015 are calculated as 470 mm for Girne (Kyrenia), 309 mm for Lefkoşa (Nicosia), 346 mm for Mağusa (Famagusta), 554 mm for Lapta, and 291 mm for Güzelyurt (Morphou). In order to demonstrate the rainfall regime at the study area, the average monthly rainfall between 1985- 2015 at the selected sites, such as Girne, Lefkoşa, Mağusa, Lapta, and Güzelyurt are presented in Fig. 1.

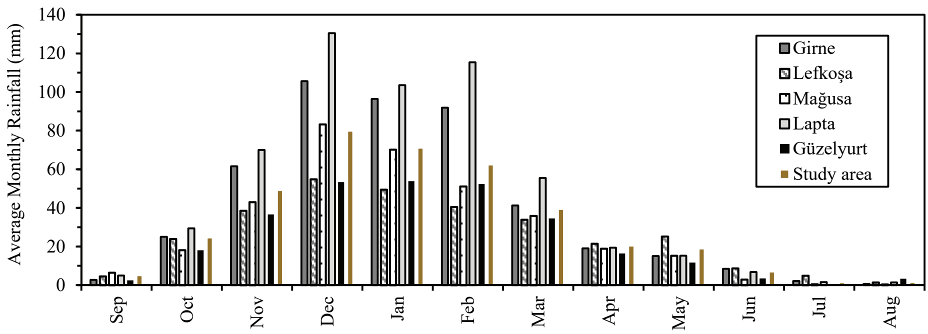

Fig. 1 - Average monthly rainfall between 1985- 2015 at the selected sites and the average in the study area

2.7. Input Data

The simulation for LP-Daily and LP-Monthly models and the WBSM is performed for a period of 30 years ($N = 10957$ days or $T = 360$ months). Accordingly, the lifetime of the RWHS is assumed to be 30 years. The wastewater collection and treatment networks are not available in all urban areas in the study area. However, the design and construction of new wastewater network projects are on the agendas of many municipalities. Despite the lack of a wastewater collection network in some sites, the wastewater tariff is included in the analyses for the sake of generalization. For the first year of the simulation period, each unit of water supplied from the MWSN is assumed to be charged an additional wastewater cost of 1 TL/m^3 ($c_w = 1$ TL/m^3). The wastewater cost is increased according to the average annual inflation rate between 2005 and 2021 which is taken as 11.3% [53] throughout the simulation duration.

Many municipalities at the study area employ an increasing block rate water tariff to promote water savings, while others use a fixed water charge. For example, Lapta Municipality employs a fixed municipal water charge of 5 TL/m^3. In an increasing block rate water tariff, the unit water cost increases as the water volume purchased from the MWSN increases. For example, Dipkarpaz Municipality sets the unit cost of water as 5 TL/m^3 up to 20 m^3 and 6 TL/m^3 when the amount exceeds 20 m^3 within a month [54]. Current water tariffs of each study site that are used as inputs for the models are obtained by directly contacting the municipalities or from the local newspaper Havadis, issued on May 15th, 2017. The inflation rate is used to estimate the future prices of the simulation duration.

A rooftop RWHS is assumed to supply the domestic water demand of a single house with four residents ($n = 4$). The average daily domestic water (i.e., tap water) demand per capita in Northern Cyprus is taken as 250 liters ($W_d = 0.25$ m^3/cap/day) [55]. It is assumed that tap water is not used for drinking purposes so the cost of a simple filter but no treatment cost is included. The roof of the single house is assumed to be a flat concrete roof with a runoff coefficient, c_f, of 0.9 [56]. Rainwater is assumed to be harvested through a 200 m^2 collector ($A_{col} = 200$ m^2) at the roof. Some municipalities prohibit building a water tank size larger than 20 m^3 for private use, so the maximum allowable tank size is set to 20 m^3 ($S_{max} = 20$ m^3).

The existing MWSN of the single house is assumed to be retrofitted for the RWHS installation. The existing water pump that is already connected with the single house's MWSN system to transfer municipal water from the main water tank to the single house is assumed to be used to transfer the harvested rainwater. Commonly, a water pump is used in residential units in Northern Cyprus to pressurize the water supplied from the MWSN. The user is responsible for the electricity consumption cost of the water pump. It is assumed that the same water pump will be used for the harvested rainwater, so that water pump's electricity cost is not included in the cost-benefit analysis.

Current installation (i.e., retrofitting the existing MWSN of the single house for the RWHS installation) and base annual maintenance costs of the RWHS are taken as 1500 TL ($f_{ini} =$ 1500 TL) and 102 TL ($c_m = 8.5$ TL/month), respectively. These costs are provided by a local plumbing service supplier (Olcay Uzuçar Plumbing Service, Personal communication in December 2019). The maintenance cost is estimated using the inflation rate. Above-ground water tanks in gardens are common in Northern Cyprus. Therefore, in this study it is assumed that the RWH tank is positioned above-ground; so the excavation cost is neglected. This assumption is realistic for Northern Cyprus but excavation cost may need to be considered for other regions. The tank is assumed to be made of polyethylene and the unit cost is taken as 600 TL/m^3 ($a = 600$ TL/m^3) [57]. The net present values of the costs are calculated using an average annual discount rate of 11.7% which is estimated using 2005-2021 data ($im =$ 0.98% per month) [58].

3. RESULTS AND DISCUSSION

The validation of the LP model with the WBSM, a comparison of LP with daily and monthly time steps, the spatial evaluation of RWHS performances, and finally, sensitivity analysis are provided below.

3.1. Comparison of LP-Daily Model and WBSM

Our model differs from the water balance model approach since there is no need to specify alternative tank sizes beforehand and to individually evaluate the feasibility of each alternative tank size. The LP model searches the whole domain and finds the optimum tank size resulting in the maximum revenue in a single run. To validate the LP-Daily model, the results are compared to those obtained from the WBSM. This analysis is carried out for Lapta, which receives an average annual rainfall of 554 mm. The WBSM is run on tank sizes from 1 m^3 to 10 m^3 with increments of 1 m^3. As seen in Fig. 2, the maximum net financial benefit occurs at a tank size between 4 m^3 and 5 m^3.

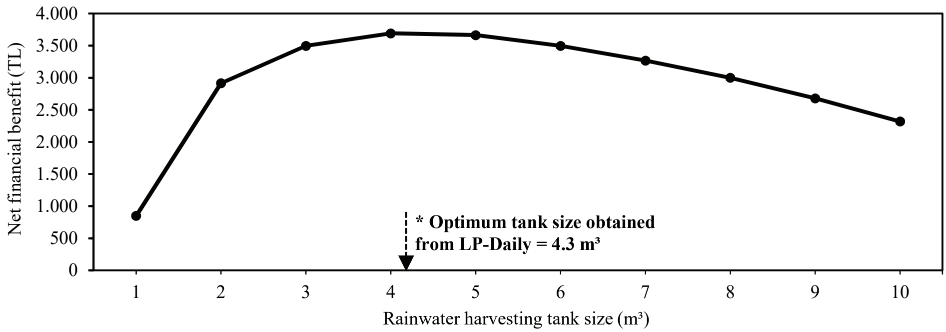

Fig. 2 - Results of the WBSM for Lapta

The optimum tank size is identified as 4.3 m^3 with the LP-Daily model in a single run. On the other hand, a single run of the WBSM provides the net financial benefit associated with the chosen tank size. Thus, the WBSM is run 10 times to obtain the maximum net financial benefit curve given in Fig. 2. As can be seen from Fig. 2, The WBSM results indicate that the optimum tank size (i.e., the tank size with the highest net financial benefit) is between 4 m^3 and 5 m^3 which contains the LP-Daily model result of 4.3 m^3. Hence, identifying the tank size with the highest net financial benefit is a trial and error procedure when the WBSM is used. Moreover, the WBSM is not as accurate as the LP model. LP is an alternative approach to the WBSM and will save time, especially when the RWH analysis is required at numerous sites with varying characteristics.

3.2. Comparison of LP-Daily and LP-Monthly Models

The results of LP-Daily and LP-Monthly models for Lapta are compared. The time required to solve LP-Daily and LP-Monthly for the 30-year simulation period differ significantly. For example, while the LP-Monthly model runs in 2 minutes, the LP-Daily model requires 1.5 hours to complete each run with OpenSolver software Ver. 2.9.0 installed on a computer with Intel® Core™ i5-9400F CPU @ 2.90GHz and 16 GB RAM. The results of LP-Monthly [36] and LP-Daily models for Lapta are given in Table 1.

As seen in Table 1, a larger tank size is obtained, and the system is assessed as an infeasible investment (i.e., a negative NFB value) when monthly time steps are used. Consequently, the total cost of the RWHS could not be paid back within the simulation period. On the other hand, the discounted payback period of the RWHS is calculated as less than 17 years when daily time steps are used. The difference in the amount of water savings between the models' results affects the financial feasibility calculations considerably since that difference is compensated using municipal water.

Table 1 - Comparison of LP-Monthly [36] and LP-Daily models' results for Lapta

Model	Optimum tank size (m^3)	Tank cost (TL)	Cost of water savings (TL)	Municipal water and wastewater costs (TL)	Net financial benefit (TL)	Discounted payback period (year)
LP-Monthly	8.4	5,065	7,380	46,700	-1,700	-
LP-Daily	4.3	2,600	10,350	43,730	3,730	16.6

When both models are investigated in detail, it is observed that the amount of rainwater harvested and utilized is underestimated when monthly time steps are used. Utilization of daily time steps simulates the RWH tank (i.e., filling and emptying) more realistically. The average monthly water supply and demand relations of the two models throughout the simulation period are presented in Fig. 3.

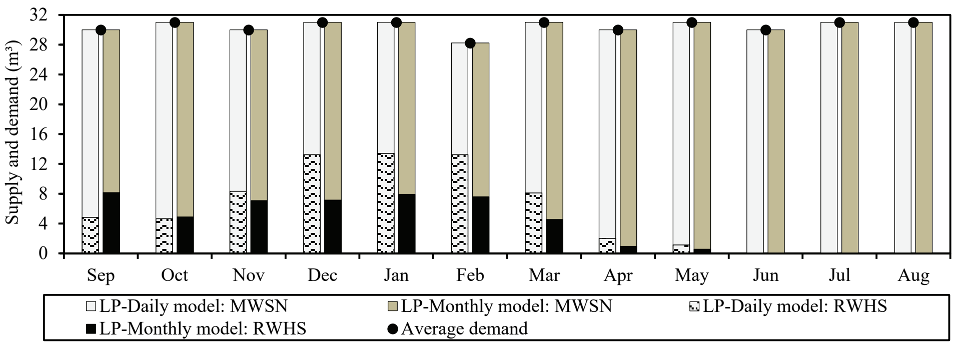

Fig. 3 - Average monthly water supply and demand relations of LP-Daily and LP-Monthly models throughout the simulation period for Lapta

As seen in Fig. 3, higher percentages of the monthly demands - other than for September - are supplied by the RWHS in the daily model compared to that of the monthly model. For example, around 13 m^3 of the total average demand of 31 m^3 is supplied by the tank in January when LP-Daily is used. This shows that, according to LP-Daily, the tank (i.e., 4.3 m^3 as given in Table 1) is filled and emptied multiple times on the average to supply the demand in January. However, when monthly time steps are used, the water balance equation is satisfied for each month. Thus the tank can only be filled and emptied once. This causes the part of the average demand supplied by the tank to be at most 8.4 m^3 (i.e., the optimum RWH tank size for LP-Monthly as given in Table 1). Similar underestimations of water savings occur in the other months as well. The water balance given in Eq. (2) is satisfied for each day in LP-Daily while it is satisfied for each month in LP-Monthly. Thus in LP-Monthly, the maximum amount of water demand that can be supplied by the tank is equal to the optimum tank size. Once the tank is filled with rainwater in a month, rainfall received in the remaining days of that month cannot be harvested and utilized, but wasted as overflow. The reader may refer to [35] and [36] for detailed explanations of LP-Monthly results.

Average annual water saving at Lapta is calculated as 69 m^3 with the LP-Daily model, whereas it is 49 m^3 with the LP-Monthly model. It is concluded that the utilization of monthly time steps leads to the incorrect judgment of the less efficient use of the RWH tank capacity. For realistic results, daily time steps should be used as also suggested by [39, 40, 41].

3.3. Spatial Evaluation of the Performance of the Rainwater Harvesting Systems

The LP-Daily model is configured and run for each site. The results are shown in Table S1. The optimum RWH tank sizes range from 2.1 m^3 to 5.4 m^3. NFBs at 33 sites vary and result in the discounted payback periods ranging from 12 years to 28 years. The minimum discounted payback period (i.e., 12.4 years) is obtained at Beylerbeyi, which receives 500 mm of average annual rainfall and has a relatively high average water cost (i.e., 43.6 TL/m^3).

As given in Section 2.4 in detail, resilience, vulnerability, and reliability are commonly used performance indicators of water supply systems. The resilience values of RWHSs at 33 sites range from 0.061 (day/failure event)$^{-1}$ to 0.111 (day/failure event)$^{-1}$ while the vulnerability values range from 8.75 m^3/failure event to 16.02 m^3/failure event (see Table S1). Higher resilience means the RWHS returns to supplying the water demand state quickly and higher vulnerability means the average deficit volume (i.e., demand that the RWHS cannot supply) is high. The highest resilience and the lowest vulnerability are achieved at Tatlısu which receives an average annual rainfall of 511 mm, while Dörtyol which receives 273 mm average annual rainfall has the minimum resilience and the maximum vulnerability. For Tatlısu, the total duration of failure events is 9180 days and the total number of failure events is 1019. Thus, the resilience for Tatlısu is 1019/9180=0.111 (day/failure event)$^{-1}$. On the other hand, for Dörtyol, the total duration of failure events is 10118 days and the total number of failure events is 616; and its resilience is 616/10118=0.061 (day/failure event)$^{-1}$. Although the total number of failure events are less for Dörtyol, the average duration of each failure event is longer, meaning it takes longer to recover (i.e. it takes longer to go back to non-failure state). Thus, as the average duration of the failure event increases the resilience decreases. Vulnerability, on the other hand is related with the average amount of deficit. For Tatlısu, the total deficit volume of all failure events is 8917 m^3, thus its vulnerability is 8917/1019=8.75 m^3/failure event; while for Dörtyol, total deficit volume of all failure events is 9866 m^3, thus its vulnerability is 9866/616=16.02 m^3/failure event. As expected, when the average duration of the failure event is longer the deficit is higher and the vulnerability is higher. Except for Lapta, vulnerability values are lower (i.e. range from 8 m^3/failure event to 9 m^3/failure event) at the sites which receive higher than 480 mm average annual rainfall. As the performance indicators address, RWHSs should be used as auxiliary water supply systems at semi-arid regions due to low rainfall periods lasting for 4- 5 months and irregular rainfall pattern by months.

The RWHS reliability range is between 10% and 20% for the study area (Table S1). This means that at most 20% of the total demand can be supplied by the harvested rainwater. Although reliabilities higher than 20% cannot be maintained for the semi-arid Northern Cyprus, at 29 of the 33 sites, RWHSs are found to be financially feasible (i.e., resulted in net financial benefit). Low reliability values are mainly due to low rainfall and its non-uniform distribution throughout the year. As can be seen in Fig. 4, as the average annual rainfall decreases, the reliability decreases almost linearly. The maximum reliability of 20% is observed at Kantara which receives 562 mm average annual rainfall whereas Dörtyol has the minimum reliability of 10% and its average annual rainfall is 273 mm. These results are in agreement with literature. Reliabilities between 10% and 20% in supplying non-potable water demands between 360 L and 720 L were obtained using rainwater collector areas between 120 m^2 and 240 m^2 and tank sizes between 1 m^3 and 5 m^3 for Tabriz, Iran which receives an average annual rainfall of 288 mm [59]. Additionally, similar to our results, [29] calculated reliabilities between 12% and 23% in Central and South-West Melbourne, Australia, receiving 465 mm and 374 mm of average annual rainfalls in dry years, respectively using a roof area of 200 m^2, a non-potable water demand of 600 L and tank sizes ranging from 1 m^3 to 10 m^3.

It is observed that there is a significant difference in rainfall amounts between the rainy period (i.e., from November to March) and the whole year for Northern Cyprus. When the reliabilities are calculated only for the rainy period, significantly higher values are obtained (i.e., 18% - 37%), sometimes overflows of tanks are observed. For example, for Lapta, the reliability of the RWHS for the rainy period is 37%, while it is only 19% when the whole year is considered. This is due to the semi-arid climatic characteristics of the study area where little rainfall is received outside the rainy period. The long dry period between June and September (see Fig. 1) decreases the reliability. In line with our findings, [62] concluded that the rainfall distribution is a major variable on non-potable water savings via RWH in Beit-Dagan, Tel Aviv, Israel where roughly 90% of the rainfall occurs between November and March and less than 1% between May and September.

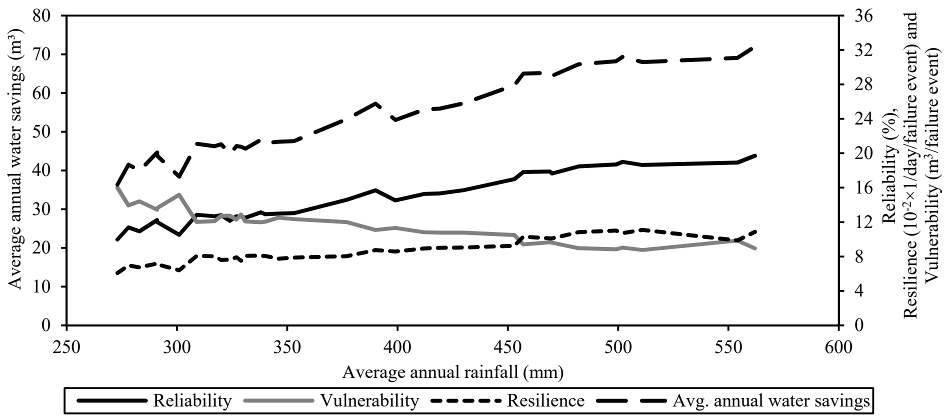

Fig. 4 - Water savings, reliability, resilience, vulnerability and annual rainfall relations

Rainfall contours together with financial feasibilities of RWHSs are shown in Fig. 5. The RWHS investments are found to be financially feasible at 29 of the 33 sites. We find that the range of the optimum tank sizes in this study is similar to those of [47] where financially feasible tank sizes are between 1 m^3 and 5 m^3 for warm semi-arid Lahore, Pakistan, which receives 667 mm average annual rainfall. We also find that average annual water savings of a single house range from 36 m^3 to 72 m^3 and are close to the water savings of combined water use in household and irrigation obtained across Australia for tank sizes between 1 m^3 and 5 m^3 [60, 48].

To conclude, when the average annual rainfall is more than 300 mm, RWH tank sizes larger than 2.5 m^3 can provide more than 12% of the domestic water demand of a single house in Northern Cyprus. If widespread rainwater harvesting is realized, domestic water savings will contribute to sustainable water resources management of water-scarce Northern Cyprus. RWH may offer additional benefits such as stormwater collection and reducing energy, maintenance and operational costs of existing water supply systems, but these are out of the scope of this study [61].

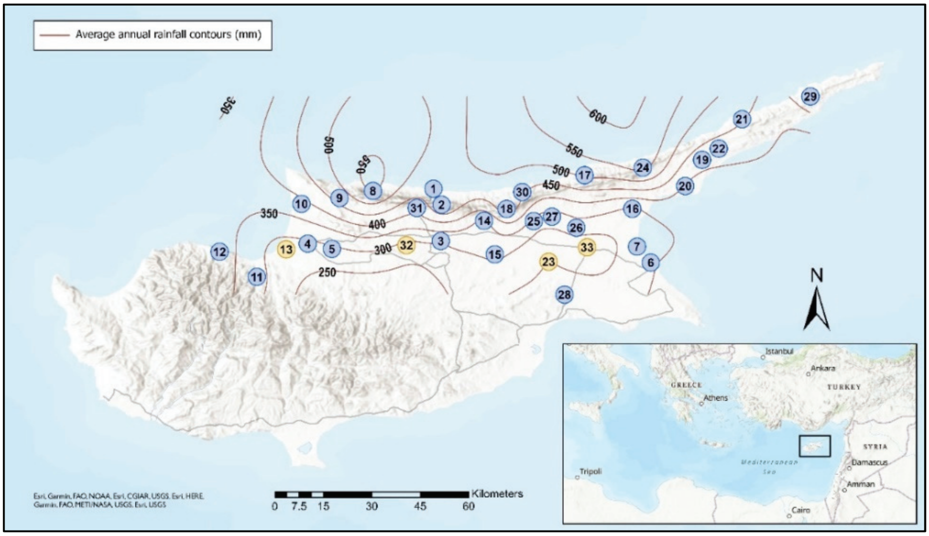

Fig. 5 - Map of the case study sites in Northern Cyprus. Blue marked sites are the locations where the RWHS is financially feasible, while the financially infeasible locations are marked with yellow.

The combined effect of rainfall characteristic and the water cost on the net financial benefit is shown in Fig. 6. The average annual rainfall is used as an indicator of the rainfall characteristic. As seen in Fig. 6, at the sites where water cost and rainfall are high, RWHSs have positive NFBs. Except for Lefkoşa, all the sites where the RWHSs' initial investment costs are compensated in less than 17 years are located at the north and northeast shores of the island, which receive higher than average annual rainfall of 390 mm. At Lefkoşa, the average annual rainfall throughout the 30-year simulation period is one of the lowest (i.e., 309 mm) whereas the average unit water cost is the highest (i.e., 45.1 TL/m^3). The RWHS is found to be financially feasible for Lefkoşa. Kantara, on the other hand, has the highest average annual rainfall (i.e., 562 mm), but the average municipal water supply cost is relatively low (i.e., 26.8 TL/m^3), resulting in a lower NFB than that of Lefkoşa. As also noted by [63], the economic feasibility of RWH relies on many elements such as water price, amount of rainfall, and capital cost; our results demonstrate that both water cost and amount of rainfall become critical for Northern Cyprus in the financial feasibility of the RWHS.

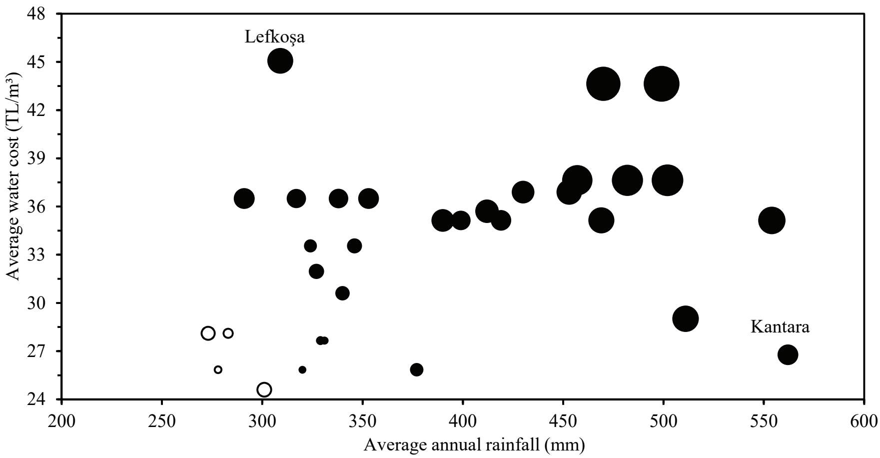

Fig. 6 - Net financial benefits of RWHSs with respect to average water costs and average annual rainfalls for 33 sites. Filled black circles represent positive net financial benefit while empty circles represent negative net financial benefit

3.4. Sensitivity Analysis

In this section, sensitivity analysis results of the LP-Daily model for Lapta are given. Effects of the collector area and the average daily water demand per capita on the optimum RWH tank size and the discounted payback period are investigated. The sensitivity analysis results for the collector area are given in Fig. 7. The discounted payback periods range from 28 years to 13.5 years when the collector area changes from 75 m^2 to 500 m^2. The RWHS is not financially feasible for collector areas of less than 75 m^2 for Lapta with the assumptions explained in Section 2.7. This indicates that although the RWHS with a collector area of less than 75 m^2 can supply some portion of the water demand at Lapta, costs associated with the RWHS exceeds its benefits, resulting in financial loss. As the collector area increases, the optimum tank size also increases to accommodate larger amounts of harvested rainwater, and consequently, the discounted payback period decreases. Likewise, [35] analyzed roof areas between 80 m^2 and 300 m^2 as rainwater collectors and found that optimum tank sizes increased from around 1 m^3 to 3 m^3, while financial benefits increased from 600 TL to 740 TL for Girne.

The following analysis is carried out for Lapta by changing the average daily domestic water demand per capita between 50 lt/cap/day and 650 lt/cap/day. The results are given in Fig. 8. For daily domestic water demand per capita of 150 lt/cap/day and higher, the discounted payback period is calculated to be between 15 to 19 years. The RWHS ends in financial losses at Lapta if daily domestic water demand per capita is less than 50 lt/cap/day. For Girne, [35] found that the RWHS is financially infeasible for daily water demand of less than 100 lt/cap/day using a monthly time-step LP model. These results show the effect of water demand on financial feasibility.

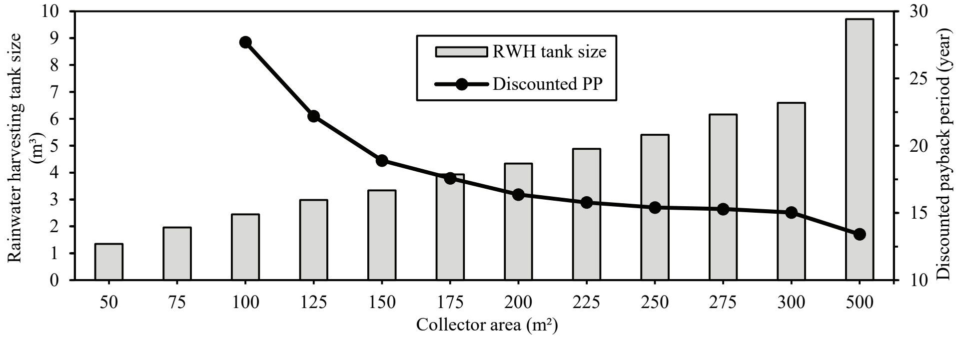

Fig. 7 - Effects of collector areas on rainwater harvesting tank sizes and discounted payback periods for Lapta

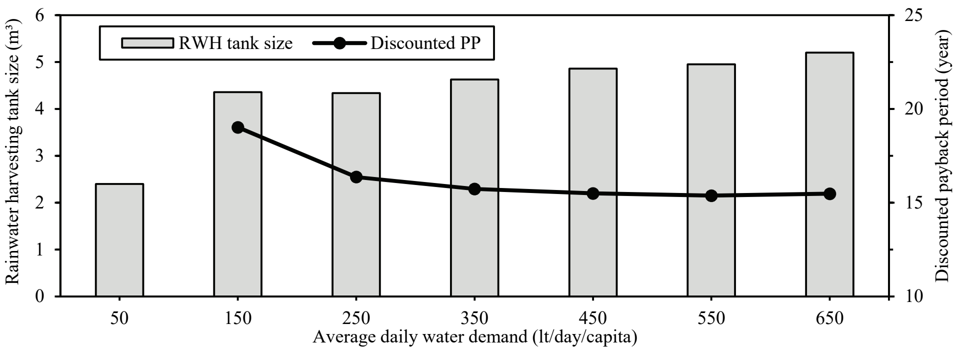

Fig. 8 - Effects of average daily water demand per capita on rainwater harvesting tank sizes and discounted payback periods for Lapta

As expected, when daily water demand per capita increases, the discounted payback period decreases until 550 lt/cap/day then levels off for larger values. This implies that the use of a larger tank size is unfavorable with respect to the increase in the benefits of the RWHS serving for a single house. Unlike [25], our sensitivity analysis results show that water demand does not significantly affect the optimum tank size for a single house at Lapta. In the current study, the average annual rainfall ranges from 273 mm to 562 mm at the study area and rainfall is mostly received during a short rainy period while the annual average rainfall is over 1000 mm in [25]. We believe that the amount of rainfall and its distribution throughout the year is the main reason for the differing effects of water demands on optimum tank sizes. At Lapta, due to limited availability of rainfall, increasing the water demand over 350 lt/cap/day does not significantly affect the optimum tank size.

Sensitivity analysis results demonstrate that the collector area plays a significant role in the optimum tank size and the financial feasibility is more sensitive to the collector area than water demand for Lapta. Thus, the RWHS should be designed to allow rainwater harvesting from the maximum possible area to maximize the benefits and reliability of the system. Similar conclusions were also reached for Australia, Iran, and Pakistan [29, 57, 47].

4. CONCLUSION

In this study, a single objective *LP model with daily time steps* is introduced to find the optimum RWH tank size by minimizing costs. The proposed model is run for the selected 33 sites from semi-arid Northern Cyprus in the Eastern Mediterranean region where average annual rainfalls ranging from 273 mm to 562 mm. The significant conclusions of this study are given as follows:

- Comparison of the LP-Daily model and WBSM reveals that both models generate consistent optimum tank sizes but the LP-Daily model saves time since it requires a single run.
- It is demonstrated that 29 of the 33 studied sites RWHSs are feasible (i.e., have positive financial benefits). However, it is pertinent to note the relatively low reliability of RWHSs, indicating their auxiliary role vis-à-vis the existing municipal water supply network. Beyond financial considerations, RWHS desirability is contingent upon factors such as uncertainties in sources of existing municipal water supply and tariffs. Given these circumstances, rainwater harvesting emerges as a potential alternative of existing water sources, warranting governmental incentives for its adoption. Such incentives may facilitate RWHS implementation among homeowners, notwithstanding extended payback periods.
- RWHSs' initial investment costs are generally compensated in less than 15 years at the north and northeast shores of the island, where the average annual rainfall is higher than 390 mm.
- The LP-Daily model yields a notably reduced optimum tank size and provides a more accurate assessment of financial feasibility compared to the LP-Monthly model. The utilization of monthly time steps may lead homeowners to incorrect investment decisions.

The main contribution of this study lies in its spatial analysis of the assessment of RWHSs feasibility for the first time in water-scarce Northern Cyprus. The outcomes of this research hold promise for informing the development of sustainable water resource management frameworks, particularly pertinent to Mediterranean islands and semi-arid regions. In future investigations, our aim is to integrate environmental cost metrics into the existing LP-Daily model, thereby facilitating a comprehensive evaluation of the environmental advantages associated with RWHS implementation.

List of Symbols

<u>Acronyms</u>

LP	Linear programming
MWSN	Municipal water supply network

RWHS	Rainwater harvesting system
TL	Turkish Lira
WBSM	Water balance simulation model
Indexes	
A	Total number of years in the simulation period
i	Days of a month
I	Total number of days in month t
j	Price level
J	Total number of the price levels in the water tariff scheme
N	Total number of days in the simulation period
t	Months of the simulation period
T	Total number of months in the simulation period
Parameters	
a (TL/m^3)	Unit cost of the RWH tank
A_{col} (m^2)	Collector area at the roof
b_j (TL/m^3)	Unit municipal water cost supplied from the MWSN at price level j
c_f	Runoff coefficient for the roof
C_{fixed} (TL)	Summation of the fixed costs
C_{inst} (TL)	RWHS installation cost
c_m (TL/month)	Base monthly RWHS maintenance cost
C_{maint} (TL)	Total RWHS maintenance cost that occurs throughout the simulation period
C_{net} (TL)	Cost of supplying the whole water demand from the MWSN
C_{total} (TL)	Total cost of the RWHS
c_w (TL/m^3)	Unit wastewater cost
D_{daily} (m^3)	Daily demand
d_k	Duration of the k^{th} failure event
D_t (m^3)	Total demand in month t
im	Monthly discount rate
k	Failure event
M	Total number of failure events
NFB	Net financial benefit
n	Number of residents
p_i^t (mm)	Measured rainfall depth on day i of month t

P_t (m^3)	Total municipal water volume supplied from the MWSN in month t
P_{tj} (m^3)	Municipal water volume that is purchased in month t from the MWSN at price level j
Rd_i^t (m^3)	Maximum amount of rainwater that can be harvested on day i of month t
Rel	Reliability
Res	Resilience
S_{max} (m^3)	Maximum allowable RWH tank size
SP_i^t (m^3)	Spill on day i of month t
T_{max} (m^3)	RWH tank size
U_t (m^3)	Total rainwater volume used from the RWH tank in month t
v_k	Deficit volume of the k^{th} failure event
Vul	Vulnerability
W_d (m^3/cap/day)	Average daily water demand per capita
Ws (m^3/year)	Average annual water saving
<u>Variables</u>	
Id_i^t (m^3)	Inventory level of the RWH tank at the end of day i of month t
Pd_i^t (m^3)	Municipal water volume purchased from the MWSN on day i of month t
rd_i^t (m^3)	Amount of harvested rainwater on day i of month t
T_{cap} (m^3)	Optimum RWH tank size
Ud_i^t (m^3)	Amount of rainwater used from the RWH tank on day i of month t
Z (TL)	Objective function
Z_{opt} (TL)	Optimum objective function value

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Table S1 - Characteristics of the stations and the linear programming model results for each site.

Station number	Study site	Avg. annual rainfall (mm/year)	Avg. unit water cost[1] (TL/m^3)	Optimum tank size (m^3)	Reliability[2] (%)	Avg. annual water saving[3] (m^3/year)	Resilience (10^{-2}×1/day/failure event)	Vulnerability (m^3/failure event)	Net financial benefit (TL)	Discounted payback period (year)
1	Girne	470	43.6	5.1	18	64	10.1	9.6	5,811	12.5
2	Beylerbeyi	499	43.6	5.4	19	68	11.0	8.8	6,342	12.4
3	Lefkoşa	309	45.1	3.4	13	47	8.1	12.0	3,302	16.0
4	Güzelyurt	291	36.5	2.8	12	45	7.2	13.4	2,147	17.6
5	Zümrütköy	291	36.5	2.7	12	44	7.1	13.6	2,009	18.0
6	Mağusa	346	33.6	3.5	13	47	7.8	12.5	1,115	22.7
7	Salamis	324	33.6	3.2	12	44	7.7	12.7	837	24.3
8	Lapta	554	35.1	4.3	19	69	9.9	9.9	3,729	16.4
9	Çamlıbel	469	35.1	4.0	18	65	10.1	9.6	3,346	17.0
10	Akdeniz	390	35.1	3.4	16	57	8.8	11.1	2,552	17.0
11	Lefke	320	25.8	2.5	13	47	7.6	12.7	306	27.6
12	Yeşilırmak	377	25.8	2.8	15	53	8.1	12.0	885	26.1
13	**Gaziveren**	**278**	**25.8**	**2.3**	**11**	**42**	**7.0**	**14.0**	**-222**	-
14	Değirmenlik	338	36.5	3.6	13	48	8.1	12.0	1,897	19.5
15	Ercan	317	36.5	3.3	13	46	8.0	12.1	1,836	19.3
16	İskele	340	30.6	3.1	13	47	8.1	12.1	1,021	24.0
17	Tatlısu	511	29.0	4.5	19	68	11.1	8.8	3,451	16.5
18	Alevkaya	482	37.6	4.9	18	67	10.8	9.0	4,812	14.8
19	Mehmetçik	419	35.1	3.8	15	56	9.0	10.8	2,092	19.8
20	Çayırova	399	35.1	3.4	15	53	8.6	11.3	1,883	19.8
21	Yeni Erenköy	453	36.9	4.3	17	62	9.3	10.5	3,164	16.6
22	Ziyamet	430	36.9	4.1	16	57	9.1	10.8	2,558	17.5

Table S1 - Characteristics of the stations and the linear programming model results for each site. (Continue)

Station number	Study site	Avg. annual rainfall (mm/year)	Avg. unit water cost[1] (TL/m^3)	Optimum tank size (m^3)	Reliability[2] (%)	Avg. annual water saving[3] (m^3/year)	Resilience (10^{-2}×1/day/failure event)	Vulnerability (m^3/failure event)	Net financial benefit (TL)	Discounted payback period (year)
23	**Vadili**	**301**	**24.6**	**2.1**	**11**	**38**	**6.4**	**15.2**	**-938**	-
24	Kantara	562	26.8	4.2	20	72	10.9	8.9	2,110	19.0
25	Serdarlı	329	27.7	3.0	13	46	7.5	12.9	398	27.2
26	Geçitkale	327	32.0	3.2	13	46	7.9	12.3	1,155	22.4
27	Gönendere	331	27.7	3.0	13	46	8.1	12.1	326	27.5
28	Beyarmudu	353	36.5	3.5	13	48	7.9	12.3	2,124	19.8
29	Dipkarpaz	502	37.6	5.0	19	69	10.7	9.0	4,948	13.9
30	Esentepe	457	37.6	4.7	18	65	10.3	9.4	4,539	15.0
31	Boğaz	412	35.7	3.6	15	56	8.9	10.8	2,727	17.7
32	**Alayköy**	**283**	**28.1**	**2.3**	**11**	**40**	**6.7**	**14.4**	**-418**	-
33	**Dörtyol**	**273**	**28.1**	**2.4**	**10**	**36**	**6.1**	**16.0**	**-847**	-
	Max	562	45.1	5.4	20	72	11.1	16.0	6,342	27.6
	Min	273	24.6	2.1	10	36	6.1	8.8	-938	12.4
	Avg.	386	33.7	3.6	15	53	8.6	11.6	2,151	19.2

[+] Bold rows represent the locations where RWHSs are identified as financially infeasible.

[1] Average values are calculated using the average inflation rate from 2005 to 2021 for the simulation duration by assuming that a four-person family's average monthly domestic water consumption is 31 m^3 (i.e., 1 m^3 per day).

[2] Ratio of the rainwater supply to the water demand throughout the simulation period.

[3] Per single house. This is the amount of water supplied from the RWHS instead of the MWSN in a year.