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Optimum tank size for a rainwater harvesting system: Case study for Northern Cyprus

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Abstract. The available freshwater is limited on earth. On the other hand, available water resources on earth have been depleting and being polluted due to climate change and population growth. In order to reduce the risk of water scarcity and water resources contamination, Integrated water resources management (IWRM) is required. IWRM is a concept to manage water resources that aims to balance economic efficiency, social equity, and environmental sustainability. When rainwater harvesting systems (RWHS), one of the techniques of IWRM, are implemented, the stress on water resources is reduced. Since the installation cost of rainwater harvesting systems significantly depends on the size of the rainwater storage tanks, in the implementation of rainwater harvesting, the selection of tank size is one of the main concerns for the feasibility of the system. This study aims to investigate the feasibility of domestic rainwater harvesting systems for a single house. In order to find the optimum storage tank size of the rainwater harvesting system, a linear programming (LP) optimization model is employed. As a case study, the LP model is applied to six regions from semi-arid Eastern Mediterranean island Northern Cyprus, where water resources are limited. The model considers thirty-seven years monthly rainfall data, the roof area of the building, the water consumption per capita, the discount rate, the cost of the rainwater storage tank, and the number of residents. The results of the selected study areas show that the implementation of the RWHS for a single house is infeasible due to the substantial installation costs and maintenance expenses. The financial losses caused by the implementation of the RWHS are found higher than the installation costs and maintenance expenses for all regions. In addition to economic analyses, environmental benefits of the RWHS should be included into the feasibility analysis.

1. Introduction

Population growth, rapid urbanization and industrial developments around the world have resulted in increased water demand in municipal, industrial, and irrigational use [1]. Climate change further increases uncertainty and adds stress on existing water resources. As a result, in some regions, the quantity decreases and the quality of water deteriorates [1]. More frequent extreme events and temperature and precipitation variations in seasons are being faced and they boost the tension on limited water resources. At this point, integrated water resources management (IWRM), which will improve and accelerate the adaptation of water resources to climate change, has become an attractive concept to

develop, manage, and distribute water resources equitably without disturbing ecosystems [2]. Furthermore, IWRM is a framework that aims to promote countries concerning economy and social wellbeing, which helps countries to achieve sustainable development goals defined by the United Nations.

Rainwater Harvesting Systems (RWHS), one of the actions of implementation of IWRM and sustainable water resources management, collect rainwater in storage tanks for future consumption such as non-potable household use (washing clothes and dishes, toilet flushing) [3], agricultural irrigation [4], and potable use [5,6]. The fact that the quality of harvested rainwater is expected to be higher than the quality of the surface water and groundwater results in the low treatment cost of harvested rainwater to be used for the potable purpose [7]. Harvested rainwater may decrease storm water runoff and prevent watershed contamination in addition to its multipurpose use and relatively better quality [4]. Rainwater may be stored during high precipitation seasons and supplied to the regions during dry periods.

The traditional rooftop RWHS consist of a roof catchment to receive rainwater, a filter to prevent sediments in harvested rainwater from getting into the system, pipelines to carry rainwater from the roof catchment to the storage tank, and a storage tank called cistern to store harvested rainwater. Depending on RWHS design, a water pump can be necessary to transport harvested water from storage tanks to the desired place. Among these components, the storage tank size is the critical variable that affects the net financial benefit gained from RWHS. Previous studies have analyzed the optimum size of the storage tank for rainwater harvesting based on RWHS design, feasibility analyses, environmental considerations and water conservation [3,6,8,9,10,11,12]. [6] investigated the optimal tank size using a computer program named Neptune to assess potable water savings for nine cities in Brazil. [8] evaluated the cost-effectiveness of RWHS for a single house and apartment building using the Plugrisost software. In a recent study, [9] developed an analytical model to determine the optimal tank size by minimizing the total cost without explicitly considering RWHS' maintenance and electricity costs. In other study, [10] developed a generalized curve to select the optimal tank size for the Greater Melbourne region, Australia. [11] examined four RWHS located in humid North Carolina, USA and underlined that the implementation of RWHS in humid regions is not reasonable. Therefore, rainwater harvesting studies have been conducted for different regions of the world. In line with these studies, [3] proposed an optimization model for Girne, Northern Cyprus that uses a linear programming approach to select the optimal storage tank size of a single house for domestic rainwater harvesting. The model was built in Excel Solver, and the optimum storage tank size was calculated in OpenSolver Software by minimizing freshwater purchase costs [3]. [12] explored the whole-life cost performance of rooftop domestic RWHS at the single-building scale for 16 different storage tank sizes and noted that the rooftop RWHS generally ended up with financial losses because of their high capital cost and maintenance expenses. Most of the time, studies focused on the design, water savings, and environmental aspects of RWHS. However, some variables like electricity and maintenance costs that affects the cost-effectiveness of RWHS were ignored.

In this paper, our objective is to determine the optimum storage tank size for rainwater harvesting to satisfy the domestic water need of a single house and carry out the feasibility analysis of RWHS. As a case study, six different regions in Northern Cyprus, a water-poor country due to the low average annual precipitation regime, are selected. Optimization model developed by [3] is modified according to the new water tariff scheme in the country, new costs, and water consumption values. Our study differs from [3,9,10] such that the maintenance cost of RWHS and electricity cost of pumping, which affect the feasibility of RWHS, are included into the optimization model in addition to the capital cost of RWHS.

In Section 2, the linear programming model is provided. Then, the study area and input data are explained in Section 3. In Section 4, results are demonstrated, and finally, conclusions are provided in Section 5.

2. Linear programming model

The mathematical formulation of the optimum storage tank size determination for the rainwater harvesting problem is developed in this section. It is assumed that harvested rainwater is used to meet the domestic need of a single house. The problem is modeled as a linear programming (LP) problem. Whenever the amount of harvested rainwater is not enough to satisfy the domestic water need, necessary additional water is provided from the utility network. Thus, our goal is to minimize the cost of water supplied from the utility network and the costs of building a RWHS.

The costs of building a RWHS consist of fixed costs and a variable cost. Fixed costs comprise the installation cost and the maintenance cost. The installation cost includes the mounting of a storage tank, two filters, pipelines, and valves. The maintenance cost contains the overhauling cost of the whole system during the useful lifetime of the rainwater storage tank. Since the size of the rainwater storage tank is determined after the LP is solved, the cost of the rainwater storage tank is named as the variable cost. An additional freshwater pump is used in many residential units because freshwater from the utility network has low pressure in Northern Cyprus. Therefore, it is assumed that existing freshwater pumps in residential units can be used to transfer both harvested rainwater and water from the network to the single house. Harvested rainwater is transferred from the rainwater storage tank to the main water tank by the gravitational force. The cost of electricity to transfer harvested rainwater from the rainwater storage tank to the residential unit is neglected because the same cost occurs when water is supplied from the utility network. Figure 1 illustrates the plan of a RWHS for Northern Cyprus in details.
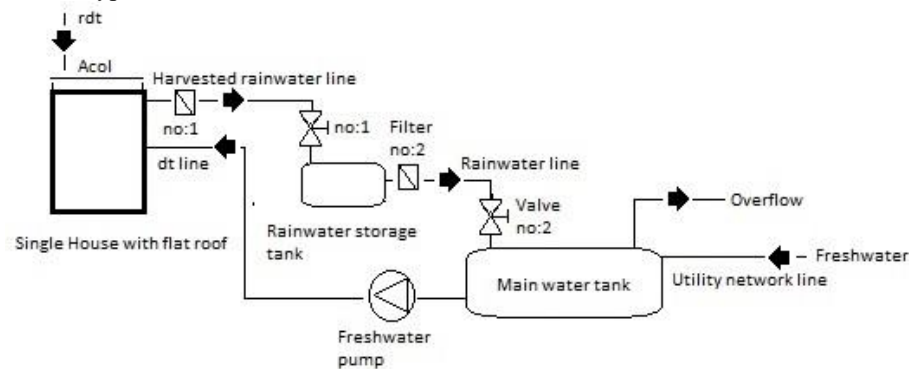

Figure 1. Diagram of a rooftop RWHS for Northern Cyprus.

An increasing block rate (IBR) tariff scheme is used for the water supplied by the utility network to maximize water saving in Northern Cyprus. When the volume of water purchased from the utility network increases, the cost of water per m^3 also increases in the IBR tariff scheme. The cost of water supplied from the utility network can be calculated as follows [3]:

$$CPt = \sum_{j=1}^{k-1} b_{tj}\left(Vj - V_{j-1}\right) + b_{tk}\left(V' - V_{k-1}\right) \tag{1}$$

where k is the highest price level, b_{tj} is the unit cost of water supplied from the utility network in period t at the price level j, J refers to the number of price levels, V_j is the maximum cumulative volume of freshwater that can be supplied at the jth price level, $V = 0$, and V' is water purchased from the utility network at any period t with k. Since there is a direct proportion between the volume of water purchased from the utility network and the unit price of water, $b_{t1} < b_{t2} < \cdots < b_{tj}$ for any period t. For more details see [3]. In addition to the IBR tariff scheme, for each m^3 of water supplied by the utility network a wastewater cost (w_c) is charged by municipalities in Northern Cyprus to support wastewater collection system. The volume of rainwater that can be harvested in period t can be calculated as follows [13]:

$$r_t = c_f \cdot A_{col} \cdot rd_t \cdot 10^{-3} \tag{2}$$

where c_f is the dimensionless runoff coefficient, A_{col} is the area of the rooftop in m^2, and rd_t is the measured rainfall depth in mm in period t (see Figure 1). The monthly domestic household water demand d_t can be calculated as follows [3]:

$$d_t = W_d \cdot n \cdot Nt \tag{3}$$

where W_d is the water usage in $m^3/day/capita$, n is the number of residents, and N_t is the number of days in month t.

By minimizing the objective function, the LP model is designed to find the optimum rainwater storage tank size to be build (T_{cap}), and decision variables are the amount of water purchased from the utility network at the jth price level in period t (P_{tj}), the amount of rainfall stored by the rainwater tank in period t (R_t), the amount of water used from the rainwater tank to satisfy demand in period t (U_t), and the inventory level in the rainwater storage tank at the end of the period t (I_t). LP model is designed for monthly time steps, ranging from $t = 1$ to the end of the useful lifetime of the rainwater storage tank (τ). The mathematical model used in this study is a modified version of [3]:

$$Z = a \cdot T_{cap} + \sum_{t=1}^{\tau} \sum_{j=1}^{J} (b_{tj} \cdot P_{tj} + (Ptj - U_t) \cdot w_c)(1 + i)^{-t} \tag{4}$$

Subject to

$$I_t = I_{t-1} + R_t - U_t \qquad \forall 1 \le t \le \tau \tag{5}$$

$$R_t \le r_t \quad \forall 1 \le t \le \tau \tag{6}$$

$$I_t \le T_{cap} \quad \forall 1 \le t \le \tau \tag{7}$$

$$R_t \le T_{cap} \quad \forall 1 \le t \le \tau \tag{8}$$

$$T_{cap} \le s_{max} \tag{9}$$

$$U_t + \sum_{j=1}^{J} P_{tj} = d_t \quad \forall 1 \le t \le \tau \tag{10}$$

$$P_{tj} \le V_j - V_{j-1} \qquad \forall 1 \le t \le \tau, \ 1 \le j \le J \tag{11}$$

$$I_O = 0 \tag{12}$$

$$T_{cap}, R_t, U_t, P_{tj}, I_t \ge 0 \qquad \forall 1 \le t \le \tau \tag{13}$$

where Z is the objective function in Turkish Lira (TL), a is the unit cost of the rainwater storage tank in TL/m^3, T_{cap} is the optimum size of the rainwater water storage tank in m^3, τ is the useful lifetime of the rainwater storage tank in months, J is the total number of price levels, b_{tj} is the cost of water per m^3 purchased from the utility network in TL in period t in jth price level, P_{tj} is the volume of water purchased from the utility network in TL in period t in jth price level, U_t is the volume of water that is used from the rainwater storage tank in m^3 in period t, w_c is the wastewater cost in TL/m^3, and i is the monthly discount rate, I_t is the inventory level in the rainwater storage tank in m^3 at the end of period t, R_t is the collected water in the rainwater storage tank in m^3 in period t, r_t is the maximum harvested rainwater in m^3 for period t, s_{max} is the maximum allowable rainwater tank size to build in m^3, d_t is the domestic water demand in m^3 in period t, V_j is the maximum volume of water that can be provided from the utility network in jth price level in m^3.

The monthly discount rate (i) is used in the objective function (Equation (4)) to compute the present value of costs because all costs that will occur during the estimated lifetime of the rainwater storage tank should be in the same monetary value. The objective function (4) is the sum of the cost of the rainwater storage tank built, the total cost of water purchased from the utility network, and the total wastewater cost during the useful lifetime of the rainwater storage tank. Starting from period $t = 1$, the water level in the rainwater storage tank, also referred to the inventory level at the end of period t (I_t) is determined using the continuity equation as given in Equation (5). Constraints (6) guarantee that the amount of harvested rainwater cannot be higher than the amount of rainfall for the same period. Constraints (7) ensure that the amount of harvested rainwater saved in the rainwater storage tank cannot be higher than the volume of the rainwater storage tank in any period. Constraints (8) state that the amount of harvested rainwater in the storage tank cannot be higher than the volume of the rainwater storage tank in any period. Constraint (9) guarantees that the volume of the rainwater storage tank cannot be higher than the allowable volume of water tanks for non-commercial use due to the local space restrictions in Northern Cyprus. Constraint (10) emphasize that water purchased from the utility network or rainwater supplied from the rainwater storage tank in a period should satisfy the domestic water demand in that period. Constraint (11) ensure that in any period, water purchased from the utility network at the jth price level cannot exceed the permissible volume of water that can be purchased at that price level. Constraint (12) states that the inventory balance level is zero at the beginning because the rainwater storage tank is assumed to be empty at the simulation period. Finally, constraints (13) express that all decision variables are positive.

We used the open source optimization software for Microsoft Excel named OpenSolver Ver. 2.9.4. to solve the LP problem. OpenSolver is a user-friendly software that can quickly solve large linear and integer problems. It solves instantenously to optimize one instance of the model which has up to 2220 variables.

After obtaining the optimum rainwater storage tank size (T_{cap}) and the objective function (Z), fixed costs, which are the installation costs (f_{ini}) and the maintenance costs (m_c), are added to the optimum objective function value to calculate the total discounted cost of the RWHS. If $T_{cap} > 0$, the net financial benefit of building the RWHS is calculated by subtracting the total discounted cost of the RWHS from the total discounted utility network cost without the RWHS (C_{UN}). The equation of C_{UN} is calculated using:

$$C_{UN} = \sum_{t=1}^{\tau} \sum_{j=1}^{J} (b_{tj} \cdot P_{tj} + d_t \cdot w_c)(1 + i)^{-t} \tag{14}$$

If the net financial benefit ($NFB = C_{UN} - Z - f_{ini} - m_c > 0$) is greater than zero ($NFB > 0$), building the RWHS is considered to be feasible for the selected area; otherwise, it is not.

3. Study areas and input data

LP model has been applied to a number of locations across semi-arid Northern Cyprus located in the Eastern Mediterranean. The average rainfall per month in Northern Cyprus between 1978 and 2009 is calculated as 30 mm using data collected from 19 precipitation stations. Such low precipitation causes extreme water scarcity in the country. Until 2016, the country met its water demand from its limited groundwater resources and insufficient surface water. Currently, water is transferred from the maritime neighbour Anamur, Turkey to the country via pipelines constructed 250 m below the surface of the Mediterranean Sea through a total distance of 80 km [14]. The pipeline system was put into service in 2016, as a result of that, the price of water per m^3 provided from the utility network has slightly increased in Northern Cyprus. Water transferred from Turkey to Northern Cyprus initially enters to a pump station. Then, the water is pumped to Geçitköy Dam in Northern Cyprus. From this reservoir, amount necessary to supply the demand is transported to the treatment plant and then to the network. Electricity is consumed at each step of this procedure. Thus, the unit price of water in Northern Cyprus is directly proportional to the energy price.

In this study, Northern Cyprus has been divided into six regions namely Alevkayası, Dipkarpaz, Girne, Güzelyurt, Lekoşa, and Mağusa (see Figure 2). These areas represent various hydraulic characteristics of Northern Cyprus. Figure 3 illustrates the monthly rainfall data measured in these six regions between 1978 and 2015. Thirty-seven years monthly rainfall data is obtained from precipitation stations located in the selected regions, and used as input for the linear programming model. Box-plots of precipitation for these six regions is given in Figure 3.
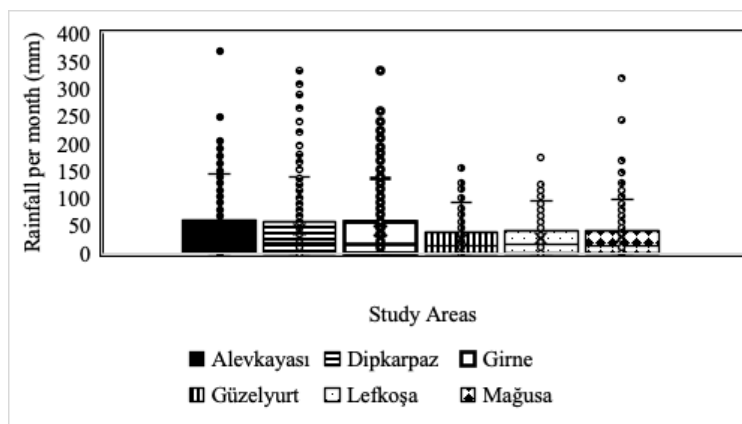

Figure 2. Study areas in Northern Cyprus.

Figure 3. Monthly rainfall data in the study areas measured between 1978 and 2015 (Data provided from the Meteorological Office of Northern Cyprus).

Municipalities in Northern Cyprus adopted water volume sensitive utility network tariff scheme to protect the country's water resources from overuse. The utility network tariff scheme of the study areas for 2017 is illustrated in Figure 4 (Data is retrieved from the local newspaper, Havadis, 2017). Moreover, for each m^3 of water purchased from the utility network a wastewater charge of 1 TL/m^3 is applied. Therefore, implementing RWHS will decrease wastewater cost as well, which will provide an additional financial benefit for the consumers.
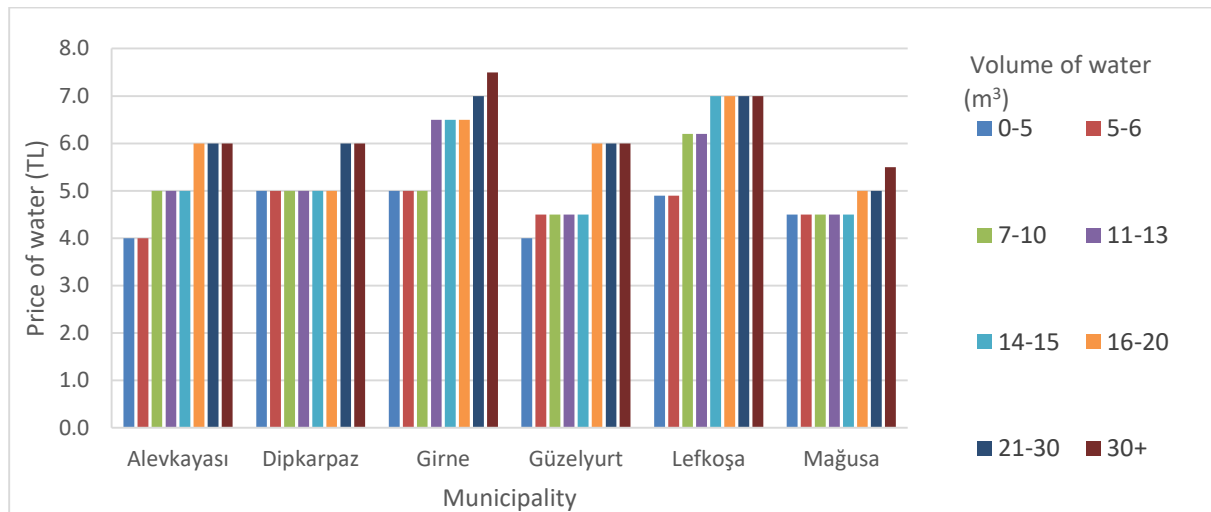
Figure 4. Utility network tariff scheme in the study areas.

In this study, we assume the number of residents (n) living in a single house is four. The flat roof area (A_{col}) of single houses is taken as 200 m^2. The equivalent runoff coefficient (c_f) for a flat roof is selected as 0.90 [15]. The installation cost (f_{ini}), the fixed monthly maintenance cost (m_t), the cost of the storage tank per m^3 (a), and the lifetime of the rainwater storage tank (τ) are taken as 1500 TL, 8.5 TL, 600 TL, and 444 months, respectively, suggested by a local supplier in Northern Cyprus. The fixed monthly maintenance cost occurs throughout the simulation period which is taken as 37 years for this study. Therefore, the present value of 37 years maintenance cost is estimated as 1514 TL using a monthly discount rate (i) of 0.05 % [16]. The maximum storage tank size (s_{max}) is limited up to 20 m^3 because of the local restrictions in the study areas. The average daily water consumption per capita (W_d) in Northern Cyprus is taken as 0.25 m^3 [17].

4. Results

The optimum rainwater storage tank sizes for each region are shown in table 1. As expected, the optimum rainwater tank sizes for different regions vary. According to the input data given in Section 3, the optimum rainwater storage tank sizes in six regions range between 1 and 5 m^3. Since some of these optimum rainwater storage tank sizes are not available in the market, they are revised according to the available water tank sizes sold in the market (see the third column of table 1).

Table 1. Financial assessments of RWHS and optimum rainwater storage tank sizes in the study areas.

Area	Rainwater storage tank size (m^3)	Available tank size in the market (m^3)	NFB in 37 years without fixed costs (TL)	Financial loss in 37 years (TL)
Alevkayası	4.60	5	692	2322
Dipkarpaz	3.83	4	477	2537
Girne	4.77	5	871	2143
Güzelyurt	2.50	2.5	320	2694
Lefkoşa	3.87	4	756	2258
Mağusa	1.36	1.5	297	2716

After obtaining the optimum domestic rainwater storage tank sizes for a single house with 4 residents, we evaluated the feasibility of installing domestic RWHS. Without the maintenance and installation costs, installing the RWHS is found feasible for all cases. However, for all regions, when fixed costs,

which are the installation and maintenance costs, are added to the optimum objective function values, installation of the RWHS becomes infeasible ($NFB < 0$) as shown in the last column of table 1. High maintenance expenses and installation costs is the main reason of infeasibility. For all regions, the economic losses are greater than 2000 TL, which is more than the cost of the installation, 1500 TL, and the maintenance expenses, 1514 TL. This situation supports the conclusions of [12] that without noteworthy incentives, installation of RWHS for domestic uses in a single housing unit results in financial losses.

5. Conclusion
In this study, we have calculated the optimum rainwater storage tank sizes for a single house to meet the domestic water demand of 4 residents. We developed an LP model to minimize the total discounted cost. Then, we analysed the feasibility of installing the RWHS for each case study site located in semi-arid Northern Cyprus. The results show that without the installation and maintenance costs, installation of RWHS are feasible for the regions but when installation and maintenance costs are considered, installation of the RWHS turns out to be not cost-effective. Although currently, RWHS are found out to be infeasible for Northern Cyprus, their feasibility may change with changing electricity prices. As mentioned earlier, since water comes from Turkey to Northern Cyprus, a number of pumping stations are used in the network. Therefore, future changes in electricity price are going to affect the unit cost of water price in Northern Cyprus. Identification of optimum RWHS will become more critical and important as the electricity price increases.

Although the results of this showed that domestic RWHS are infeasible to implement due to economic analysis, we believe that the environmental benefits of RWHS should be considered in this analysis as well. RWHS is a noteworthy tool in integrated water resources management to protect the decreasing water resources around the world as a result of the rising population and climate change. Therefore, as a future study, we plan to integrate the environmental benefits of RWHS into our analysis to provide a complete evaluation.

To conclude, as displayed in the case studies, RWHS may become an attractive option to cope with water scarcity in semi-arid regions if the governments compensates certain portion of the maintenance and capital costs.

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