RAINWATER HARVESTING ANALYSIS FOR NORTHERN CYPRUS

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ABSTRACT

RAINWATER HARVESTING ANALYSIS FOR NORTHERN CYPRUS

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Rainwater harvesting is a sustainable water resources management technique to harvest, store and reuse rainwater through rainwater harvesting systems (RWHSs). This study aims to determine the optimum rainwater storage (RWS) tank size of a RWHS to minimize the cost of water supplied from the utility network, wastewater cost and the RWS tank cost to attain the maximum financial benefit and analyze the rainwater harvesting potential for Northern Cyprus. A Linear Programming (LP) model is developed to achieve this aim. The LP model considers the daily precipitation data, the collector area at the roof of the building, the water consumption per capita, the number of residents, the unit water cost, the unit wastewater cost, the unit cost of the RWS tank and the discount rate as inputs. This model is applied to 33 case study locations (CSLs) selected from semi-arid Northern Cyprus, Cyprus Island, Eastern Mediterranean. Results show that the RWHS investment is financially feasible for almost one-third of the CSLs investigated. The optimum RWS tank sizes at the CSLs are calculated to range from 1.6 m^3 to 3.2 m^3. The financial benefit and the RWS tank size's sensitivity to the number of residents, the collector area, the discount rate, the daily average water consumption per capita and the RWS tank unit cost are further analyzed. Sensitivity analysis results show that the utilization of accurate parameters in the LP model is necessary because the change in the parameters affects the optimum RWS tank size and the net financial benefit of the RWHS considerably. From the environmental point of view, a total annual CO_2 equivalent emission of 444 ton/year, a total annual social carbon cost of nearly 150,000 TL/year (i.e., $18,750/year) and a total annual electrical energy generation cost of 640,000 TL/year (i.e., $80,000/year), resulting from Turkey – Northern Cyprus Water Supply Project, can be avoided if RWHSs are implemented at Girne, Mağusa, İskele and Lefke.

Keywords: Sustainable Water Use, Rainwater Harvesting, Linear Programming, Optimum Tank Size, Cost Minimization

ÖZ

KUZEY KIBRIS İÇİN YAĞMUR SUYU HASADI ANALİZİ

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Yağmur suyu hasadı, yağmur suyununu toplayan, depolayan ve yeniden kullanan sürdürülebilir su kaynakları yönetimi tekniğidir. Bu çalışma, maksimum finansal faydayı elde etmek için şebeke ağından temin edilen su maliyetini, atık su maliyetini ve yağmur suyu depolama tankı maliyetini en aza indirmeyi hedefleyen bir yağmur suyu hasat sisteminin optimum yağmur suyu depolama tankı boyutunu belirlemeyi amaçlamaktadır. Bu amaca ulaşmak için bir doğrusal programlama modeli geliştirilmiştir. Doğrusal programlama modeli girdi olarak günlük yağış verilerini, evin çatısındaki yağmur suyu toplanan alanını, kişi başına düşen su tüketimini, evde yaşayanların sayısını, birim su maliyetini, birim atık su maliyetini, yağmur suyu depolama tankının birim maliyetini ve faiz oranını dikkate almaktadır. Bu model, Doğu Akdeniz'de bulunan yarı kurak iklime sahip Kuzey Kıbrıs’taki 33 çalışma sahasında uygulanmıştır. Sonuçlar, yağmur suyu hasat sistemi yatırımının, çalışma alanının üçte birinde finansal olarak uygun olduğunu göstermektedir. Çalışma sahalarındaki optimum yağmur suyu depolama tank boyutları 1,6 m^3 ile 3,2 m^3 arasında hesaplanmıştır. Bu çalışmada mali fayda ve yağmur suyu depolama tank boyutunun ev sakinlerinin sayısına, toplama alanına, faiz oranına, kişi başına düşen günlük ortalama su tüketimine ve yağmur suyu depolama tankı birim maliyetine duyarlılığı ayrıca analiz edilmiştir. Duyarlılık analizi sonuçları, doğrusal programlama modelinde doğru parametrelerin kullanılmasının gerekli olduğunu çünkü parametrelerdeki değişikliğin optimum yağmur suyu depolama tankı boyutunu ve yağmur suyu hasat sisteminin net finansal faydasını önemli ölçüde etkilediğini göstermektedir. Çevre açısından, Girne, Mağusa, İskele ve Lefke'de eğer yağmur suyu hasat sistemleri uygulanırsa Türkiye – Kuzey Kıbrıs Su Temin Projesinden kaynaklanan yıllık toplam 444 ton CO_2 eşdeğer emisyonu, yaklaşık 150.000 TL toplam yıllık sosyal karbon maliyeti ve 640.000 TL toplam yıllık elektrik enerjisi üretim maliyetinin önlenebileceği hesaplanmıştır.

Anahtar Kelimeler: Sürdürülebilir Su Kullanımı, Yağmur Hasadı, Doğrusal Programlama, Optimum Tank Boyutu, Maliyet Minimizasyonu

To My Country

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LIST OF ABBREVIATIONS

ABBREVIATIONS

CSL	Case study location
LP	Linear programming
MCM	Million cubic meters
METU-NCC	Middle East Technical University Northern Cyprus Campus
NC	Northern Cyprus
PP	Payback period
RWHS	Rainwater harvesting system
RWS	Rainwater storage
TL	Turkish Lira
UN	Utility network

LIST OF SYMBOLS

SYMBOLS

Indexes

I	Total number of days within month t
J	Total number of price levels used by the UN
T	Total number of months in the simulation period
i	Day
j	Index for the price level at which water is purchased from the UN
t	Month

Parameters

A_{col} (m^2)	Collector area at the roof
C_{carbon} ($/year)	Avoided total annual social carbon cost
C_{fixed} (TL)	Summation of the fixed costs
C_{inst} (TL)	RWHS installation cost
C_{maint} (TL)	Total RWHS maintenance cost that occurs during the simulation period
C_{total} (TL)	Total cost of the RWHS
C_{un} (TL)	Cost of supplying the whole water demand from the UN
D_{daily} (m^3)	Daily demand

D_t (m^3)	Total demand in month t
E_{CO_2} (ton CO_2 eq/year)	Avoided total annual ton CO_2 equivalent emission resulting from the transfer of water from the water storage facilities to the main water tanks of single houses
E_{el} (TL/year)	Avoided total annual electrical energy generation cost
E_{fwp} (kWh/year)	Avoided annual electrical energy need of pumps to transfer water from municipal water storage facilities to the main water tanks of single houses
F_o (ton/year)	Amount of the avoided annual fuel to generate electrical energy
P_t (m^3)	Total amount of water purchased from the UN in month t to satisfy the demand
P_{tj} (m^3)	Amount of water purchased from the UN in month t at the j th price level
Rd_i^t (m^3)	Maximum amount of rainwater that can be harvested in the i th day of month t
S_R (ton CO_2 per urban tree planted)	Weighted average carbon sequestered by a medium growth coniferous or deciduous tree, planted in an urban setting and allowed to grow for 10 years
S_{max} (m^3)	Maximum tank size
T_s (urban tree)	Number of trees required for CO_2 sequestration

U_t (m^3)	Total amount of water used from the RWS tank in month t to satisfy the demand
b_j (TL/m^3)	Cost of water per unit volume purchased from the UN at the $j\ th$ price level
c_f	Runoff coefficient
c_m (TL)	Monthly fixed RWHS maintenance cost
c_w (TL/m^3)	Cost per unit volume of wastewater
e_{el} (TL/kWh)	Unit cost of electrical energy generation
e_{fwp} (kWh/m^3)	Unit electrical energy need of pumps
i_{CO_2} (kg CO_2/kWh)	Electricity generation - CO_2 emission intensity
p_i^t (mm)	Measured precipitation depth in the $i\ th$ day of month t
LHV (kWh/ton)	Lower heating value of fuel
NFB (TL)	Net financial benefit
SCC (\$/ton CO_2)	Social cost of carbon
WS (m^3/year)	Total annual water savings using the RWHS at single houses for an average year
Wd (m^3/day/cap)	Average daily water consumption per capita
Z (TL)	Optimum objective function value
a (TL/m^3)	Unit cost of the RWS tank
im	Monthly discount rate
n	Number of residents

Variables

Id_i^t (m^3)	Inventory level of the RWS tank at the end of the i th day of month t
Pd_i^t (m^3)	Amount of water purchased from the UN in day i of month t (m^3)
T_{cap} (m^3)	Volume of the RWS tank
Ud_i^t (m^3)	Amount of rainwater used from the RWS tank in the i th day of month t to satisfy the daily demand
rd_i^t (m^3)	Amount of harvested rainwater in the i th day of month t

CHAPTER 1

INTRODUCTION

The population around the world has been rising, with a percentage of 1.05 annual growth rate (The World Bank, 2020). Besides, human life expectancy has been increasing. A person born in 2020 can reach more than an age of 70, which is nearly double the life expectancy in 1900 (Roser et al., 2013). It is inevitable that as the population increases around the world, the demand for water, which is the fundamental human need for survival, increases. Therefore, more water needs to be abstracted and used to satisfy the growing demand. It is expected that 40% of existing water resources will be exploited by 2030, and this will cause a global water crisis if the necessary actions are not taken to conserve water resources for the next generations (UN, 2018).

In addition to the rising population, climate change is affecting water resources. For example, Parandvash and Chang (2016) estimate that the daily water demand per capita in the Portland metropolitan area, the USA, will increase by approximately 10% in the middle of the 21st century without climate change adaptation. Water availability has been decreasing due to more extreme weather events triggered by climate change like urban floods and droughts. While frequent urban floods disturb water quality, long-term and severe droughts threaten water resources. Water resources need to be sustainably managed, which is an essential strategy to mitigate climate change impacts on water resources. For example, the rainwater harvesting technique, as a sustainable water resources management method to harvest, store, and reuse rainwater through rainwater harvesting systems (RWHSs), is a way to protect water resources and transfer them to the next-generations without being diminished.

This study aims to calculate the optimum rainwater storage (RWS) tank size of a RWHS to minimize the cost of water supplied from the utility network (UN), wastewater cost and the RWS tank cost to attain the maximum financial benefit. The objectives of this study are as follows:

i. Developing a Linear Programming (LP) model to determine the optimum tank size of a RWHS
ii. Application of the LP model to Northern Cyprus (NC)
iii. Carrying out the financial assessment of a RWHS
iv. Carrying out the environmental assessment of a RWHS

In Chapter 2, the general concept of rainwater harvesting is presented, a literature review for the tank sizing and feasibility analyses of the RWHS are provided. Moreover, the theoretical framework of this study is explained and its position in the literature is addressed. In Chapter 3, the country-based features of NC are presented in detail, and the precipitation characteristics and monthly water tariffs are provided for the case study locations (CSLs) selected from NC. In the country, snowfall is rarely observed; thus, precipitation expresses rainfall events throughout the study. The proposed RWHS design for all CSLs is described, and its technical and financial features are explained. In Chapter 4, the mathematical formulation of the LP model is presented, the financial assessment of the RWHS is explained, and the environmental assessment of the RWHS is provided. In Chapter 5, first, the LP model's optimum solution and the result of the financial assessment of the RWHS are demonstrated and discussed for each CSL. Second, water supply and demand patterns, and rainwater harvesting characteristics of the RWHSs that are obtained by solving the LP model are presented and discussed for each CSL. Third, the daily average water supplies and demand pattern throughout the simulation period, the daily water supplies and demand relations for each day of the simulation period, and tank size-based overflow estimations are provided and discussed for the selected CSL. Next, the results of sensitivity analysis carried out are presented. Furthermore, the results of the environmental assessment of the RWHSs for the selected cities are demonstrated and discussed. Finally, in Chapter 6, the study is concluded, and the recommendations for future research are provided.

CHAPTER 2

LITERATURE REVIEW

This chapter provides background information about the studies related to RWHSs. The importance of the sustainable management of water resources through RWHSs is explained. Case studies with different or similar approaches used in this study are reviewed, the research gaps are identified, and the position of this study in the literature is addressed in this chapter.

2.1. Rainwater Harvesting for Sustainable Water Resources Management

Rainwater harvesting is an ancient, simple and environmentally friendly method that is now being used to cope with the water scarcity problem and the effects of climate change on water resources. Systems that harvest, store and reuse rainwater are called RWHSs. Such systems harvest and store rainwater close to the point of use compared to traditional water supply systems, which are located far from most urbanized areas (UN-Habitat, 2005). Harvested rainwater assures reliable access to water and creates an alternative for low-quality water (UN-Habitat, 2005). Moreover, it can reduce rainwater runoff and relief the drainage systems in urban areas. For example, results showed that a RWHS in a planned industrial park in southeastern China could collect and store all surface runoff in the cisterns if the amount of precipitation is less than 135.5 mm (Zhang and Hu, 2014).

The existing structures in urban areas like rooftops, parking lots, parks, etc. can be used as catchments for rainwater harvesting. The harvested rainwater is kept in storage tanks or cisterns (UN-Habitat, 2005). It is mostly used to supply domestic water demand like toilet flushing, laundry, and gardening (EPA, 2013). Moreover, it may be used for potable purposes. Abdulla and Al-Shareef (2009) calculated that the annual potable water savings potential through rainwater harvesting is nearly 19% for Ajlun, Jordan. The authors underline that harvested rainwater needs to be treated before being used for potable purposes. However, the treatment cost of rainwater may affect the financial feasibility of the system. The use of rainwater for domestic purposes may be more feasible than using it for potable purposes.

RHWSs provide the reuse of a portion of rainwater that will otherwise be lost through the drainage systems. Some of the municipal water demand is satisfied by rainwater. This decreases the dependence on the municipal water supply system. Decreasing the municipal water demand, in turn, reduces money spent on the water. However, a financial feasibility analysis still needs to be carried out for the RWHS to determine the cost-benefit of the system.

All RWHSs, regardless of their size, consist of six fundamental components, catchment area, gutters and downspouts, leaf screens and roof washers, cisterns or storage tanks, conveying, and filters (UN-Habitat, 2005). The capital cost of the RWHS includes all the costs of these six components. The cost of the storage tank is a highly decisive parameter for determining the capital cost of the RWHS. Therefore, sizing storage tanks is important in the financial feasibility analysis of the RWHS. In the literature, there are various case studies on sizing the storage tank and cost-benefit analyses of RWHSs. These studies are reviewed in Section 2.2.

2.2. Background on the Tank Sizing and Feasibility Analyses of RWHSs

Sometimes the financial feasibility of the RWHS is ignored in the studies, and only the potential for water savings via rainwater harvesting is determined since the priority is to improve water supply reliability for the locations where supplying water demand is an issue (see Abdulla and Al-Shareef, 2009; Aladenola and Adeboye, 2010; Shadeed and Lange, 2010). Ghisi et al. (2007) used a software called Neptune to decide the tank size for nine cities in Sao Paulo, Brazil. The Neptune software calculates the potential for potable water savings based on changing tank sizes. Then, the user selects the ideal tank sizes for the potential for potable water savings determined by the software. The authors concluded that the tank size needs to be determined according to each resident and location since the tank size is significantly affected by the variables such as water demand, roof area and daily precipitation. Tank sizes are determined based on the desired reliability of the system, and the system’s financial feasibility is neglected in their study.

Morales-Pinzon et al. (2015) developed a software product called Plugrisost to assist in designing RWSHs and greywater systems at different urban scales. Their study is interesting because the developed software can analyze the potential environmental impact of the RWHS in addition to its economic performance. The potential environmental impact of the RWHS was evaluated through life cycle assessment using global warming potential and energy use indicators. The optimum storage volume was found to be 13 m^3 for a single house using the software. However, the authors stated that for a scenario in which the tank volume exceeds 2 m^3, the potential environmental impact of the RWHS exceeds that of the water network. Therefore, sizing the storage tank considering environmental parameters makes the optimum size more conservative than the case where water supply and demand reliability are evaluated.

Ward et al. (2012) analyzed the empirical performance of the non-domestic RWHS in the Innovation Center in Exeter, UK and compare its design performance to its operational performance. It was found that 25 m^3 tank, designed according to the number of estimated occupants, was over-sized for the number of the actual occupants at the office. The capital cost payback period of the RWHS was found to be 11 years. In their study, Ward et al. (2010) calculated the optimum tank size as 9 m^3 for the Innovation Centre using the yield-after-spillage approach in the form of a continuous simulation. They identified that an optimized 9 m^3 tank could show a similar performance of 25 m^3 tank and decreased the payback period of the RWHS to 5 years. The system was designed for the estimated occupants, which lead to possessing a larger tank than the optimum tank for the actual occupants at the office. The authors concluded that the sensitivity analyses need to be carried out for the changing occupants at the office buildings at the design stage of the system to determine the variety of tank sizes and prevent over-sized tank designs.

Roebuck et al. (2011) analyzed the whole life cost performance of domestic RWHSs at a single housing unit for the UK. Climate change was considered, and 37-year sequential daily precipitation data were adjusted accordingly. Daily time steps were used, and the yield-after-spillage approach was implemented to model the flows in the tank. Different scenarios were analyzed for the financial performance of the RWHS, using 16 tank sizes ranging from 1.2 to 15 m^3. The authors concluded that the whole life cost performance of supplying water only from the network is more financially effective than that of the domestic RWHS at a single house for all scenarios investigated when the whole lifetime of the system is considered.

Fernandes et al. (2015) aimed to design a RWHS for the regions with a temperate climate and low water demand. The reservoir volume was obtained using the Ripple method to identify the maximum reservoir volume since the Ripple method gives oversized the reservoir volume. The authors identified that using an optimum water tank volume (i.e., 90% water saving efficiency) could reduce the payback period of the RWHS investment by 5 to 8 years throughout two investigated scenarios compared to a maximum water tank volume (i.e., 100% water saving efficiency). The payback period of the RWHSs in their study highly depended on the user's selection of the type and size of water tank volume.

Khastagir and Jayasuriya (2011) investigated the cost-effectiveness of different size RWS tanks for the locations from the Greater Melbourne area in Australia. Four scenarios, including the tank size in the range of 1-5 m^3, the roof area of 250 m^3, and a variety of discount and inflation rates and network water prices, were investigated for the cost-effectiveness of the tank sizes. The authors found that the network water price, discount and inflation rates are the key parameters that affect the payback period of the RWS tank. In their study, Khastagir and Jayasuriya (2010) developed reliability-centered curves to determine the optimum RWS tank size for the Greater Melbourne area in Australia. In those studies, the RWS tank sizes are selected according to the desired reliability, which may result in unrealistic optimum tank sizes and payback periods at the investigated locations.

Lopes et al. (2017) investigated the effect of the ratio of non-potable water demand and the catchment area of rainwater harvesting on the RWS tank size. Synthetic time series of daily precipitation for a year were developed by employing Markov chain and Gama probability function. They were generated for 1000-years using Monte Carlo simulations. The yield-after-spillage approach was used to simulate tank operations. Furthermore, the economic analysis was carried out for the ideal tank sizes found. Results showed that a 2 m^3 tank calculated for a household with three residents and 150 m^2 roof area has an average payback period of 10.6 years over the system's 25-year lifetime.

The payback period of the systems significantly varies for the studies reviewed within this section. This is because different system design approaches are employed, especially when sizing the RWS tank, and this affects the system's financial feasibility. Furthermore, country-based costs of the components of the RWHS and the significant variations in water usage patterns depending on the location also affect the system's financial feasibility.

In many studies, tank sizes are selected based on the designated supply and demand reliability of systems. In addition, the optimization models have been developed in some previous studies to obtain optimum tank sizes. Bocanegra-Martinez et al. (2014) proposed a multi-objective nonlinear optimization model to identify the optimum RWHS in a residential development. The proposed model was applied to Morelia, Mexico. The two objective functions of the study were the minimization of the total cost and the freshwater consumption. Garcia-Montoya et al. (2015) proposed a multi-objective optimization model to design residential networks for reusing reclaimed water and harvested rainwater. The proposed model had two objective functions; the minimization of the total cost and the freshwater consumption, which was applied to Morelia, Mexico. Garcia-Montoya et al. (2016) extended their study through the consideration of the environmental impacts of the designed residential networks using the life cycle assessment approach.

Pelak and Porporato (2016) developed a mathematical formulation for an optimal cistern design of a domestic RWHS. The optimal cistern was calculated for the minimum total cost. The developed model was tested on a smart home in North Carolina, the USA. In their study, it was demonstrated that there is a linear relationship between the tank cost and size for the plastic above-ground tank. The optimization studies on RWHSs expressed in this section may be implemented in different locations by only adjusting inputs. This may be the main advantage over the studies that are highly dependent on site-specific data.

2.3. Background for Rainwater Harvesting in Relatively Small Islands

RWHS studies are conducted for many different locations in the literature, as mentioned in Section 2.2. Furthermore, there are studies on rainwater harvesting that are carried out for the locations selected from relatively small islands (Wallace et al., 2015; Bailey et al., 2018; Solomon and Smith 2007; Donohue et al., 2017; Han and Ki, 2010; Quigley et al., 2016; Okoye et al., 2015; Ruso et al., 2019). Groundwater is commonly utilized as the primary water resource instead of surface water in most of the islands.

However, over-extraction and seawater intrusion may affect groundwater both quantitatively and qualitatively and cause water shortage in the islands. According to UNESCO-IHP and UNEP (2016), 73% of the small island developing states are at risk of groundwater pollution. United Nations defines the small island developing states as the countries and territories located on islands that face socio-economic and environmental obstacles and have less than 5 million population (UNESCO-IHP and UNEP, 2016).

Climate change puts additional pressure on water resources, while 71% of the small island developing states are at the risk of water scarcity (UNESCO, 2019). This percent can rise to 91% according to the altitude of the islands (UNESCO, 2019). Therefore, sustainable water resources management is essential to protect existing water resources of islands and increases the resilience of island communities towards water scarcity. Rainwater harvesting is an effective climate change adaptation technology and may contribute to the effective use of water in islands (Bush, 2018).

Some studies on rainwater harvesting for the small island developing states are done for the Federated States of Micronesia, which consist of numerous islands, located in the Western Pacific (Wallace et al., 2015; Bailey et al., 2018). Wallace et al. (2015) developed design curves, displaying the relationship between the roof catchment area and the storage tank size, under future climate scenarios. Bailey et al. (2018) used a water balance model to evaluate the performance of the RWHS.

Solomon and Smith (2007) investigated the effects of the compulsory cistern construction law in terms of cost-benefit on water prices and water supply and demand patterns for the Virgin Islands, the USA. Donohue et al. (2017) explored how the perceptions of a community from Hawaii Island, the USA on rainwater catchment practices were affected before and after participating in rainwater catchment workshops. Han and Ki (2010) identified the challenges of already built-in RWHSs on Guja-do Island, South Korea, and made suggestions to improve their technical aspects. Quigley et al. (2016) examined the RWS tank sizes for water supply reliability to increase domestic water supply in Honiara, Solomon Islands.

The following studies are done for the chosen locations from NC which is located in the Eastern Mediterranean. Harb (2015) investigated the rainwater harvesting potential of Middle East Technical University Northern Cyprus Campus (METU-NCC), Güzelyurt, to design a RWHS that supplies the university's irrigation demand. The traditional Soil Conservation Service (SCS) method and the SWMM software were employed to calculate the rainwater runoff from the stormwater network. Three reservoir sizes, 2,300 m^3, 3,500 m^3, and 1,100 m^3, were found to provide 37.8%, 41.3%, and 90.5% efficiencies, respectively. Results showed that rainwater harvesting potential calculated for the campus can supply some of the irrigation demand.

Zuberi et al. (2013) investigated the rainwater harvesting potential of the dormitories of METU-NCC through building the RWHS for domestic water use. Results showed that building a separated RWHS for each dormitory is financially infeasible. The systems' reliabilities were found to be poor for the total water demand of each dormitory. When the holistic approach was employed, the proposed RWHS design to supply water to Dorm 2 was found to result in 4,246 Turkish Lira (TL) water cost savings, with a 93% reliability for toilet flushing. However, it is not clear whether the cost of a proposed RWS tank of 2,831 m^3 was considered in their study.

Okoye et al. (2015) developed a linear programming (LP) model to determine the optimum size of the RWS tank of a rooftop domestic RWHS for a single house. Girne, NC, was selected as the case study for their research. The optimum size of the RWS tank was determined for the maximum net financial benefit (NFB) by minimizing the tank cost and the municipal water supply's cost over the planning horizon of 25 years. The 31-year monthly average precipitation of Girne and monthly time steps were used in their study. The optimum RWS tank and the NFB were found to be 2.2 m^3 and 675 TL, respectively. The authors concluded that the LP model needs to be converted to a daily basis LP model to obtain more accurate optimum tank sizes.

Ruso et al. (2019) modified Okoye et al.'s (2015) LP model by defining one more variable, which is the wastewater cost (i.e., the cost of water discharged to drainage systems). Furthermore, the maintenance cost of the RWHS was added to the NFB

calculation. Monthly time steps were employed in the study, and the 37-year monthly precipitation time series of Girne was used as one of the inputs. The modified LP model was used to determine the optimum RWS tank size of a rooftop domestic RWHS for a single house. Then, the NFB of the RWHS through 37 years was calculated for the case study. The optimum RWS tank size and the NFB, without the maintenance and installation costs, were found to be 4.7 m^3 and 871 TL, respectively. With the maintenance and installation costs, the NFB was calculated as $-2{,}143$ TL (i.e., a loss of 2,143 TL). As a result, the RWHS investment was found to result in a financial loss at the end of the planning horizon. The authors concluded that an environmental cost analysis needs to be carried out for a better evaluation of the system in addition to the financial feasibility analysis of the RWHS. The current study is an extension of Ruso et al. (2019). An overview of the current study and its position in the literature are presented in Section 2.4.

2.4. Theoretical Framework of this Study and Its Position in the Literature

The LP method is used in the latter two studies reviewed in Section 2.3. LP is a technique to find the optimum solution of a linear function, defined as the objective function with linear constraints. The optimum solution is achieved by minimizing or maximizing the objective function.

In this study, we propose an LP model to identify the optimum RWS tank size for a rooftop domestic RWHS. Harvested rainwater is utilized for supplying the domestic water demand of a single house together with the municipal water supplying from the

UN. The daily precipitation data, the collector area at the roof of the building, the daily water consumption per capita, the number of residents, the unit water cost, the unit wastewater cost, the unit cost of the RWS tank, and the discount rate are the inputs of the LP model. The objective of the LP model is the minimization of the total costs associated with the municipal water consumption, wastewater production, and the RWS tank.

A financial assessment is carried out by considering the RWS tank cost, the costs associated with the municipal water consumption and wastewater production, and the RWHS's installation and maintenance costs. The optimum RWS tank size is obtained by solving the LP model. The cost of the optimum RWS tank and the costs associated with the municipal water consumption and wastewater production are calculated as well. Moreover, an environmental assessment of the RWHS is carried out by considering the social cost of carbon (SCC) and the unit cost of electrical energy generation.

The proposed LP model can be implemented to any location by only changing site-specific inputs. Some adjustments may be needed based on the location's water tariff scheme, like disregarding wastewater cost if it is not applied. Since the RWS tank is optimized for the minimum total costs and the water balance model is employed in this study, it differs from the two traditional approaches, determining the RWS tank size with respect to the desired supply or the demand reliability. These approaches originally developed by Jenkins and Pearson (1978) are yield-after-spillage (i.e., the demand is supplied with the desired reliability after spillage at each time step) and yield-before-spillage (i.e., the demand is supplied with the desired reliability before spillage at each time step) (Mitchell, 2007). Our model is similar to the yield-before-spillage approach. However, the whole demand may not be supplied by the RWS tank even if there is enough water in the tank for the current day's demand. Some or all stored water in the tank may be saved to be used later. Thus, the water balance model employed in this study assumes that at each time step, the RWHS supplies some or all water demand of the current day before the current day's precipitation is harvested. To summarize, the water balance model employed is like the yield-before-spillage approach, but the harvested rainwater may be stored for future use, and it may be preferred to purchase municipal water if it is cheap (i.e., at a low level of the unit water price). This is explained in detail in Chapter 4.

The proposed LP model is performed throughout a continuous simulation period of 10957 days (i.e., 30 years) for 33 CSLs selected from NC. Since NC is located in Cyprus Island, the water resources used to be dependent on limited surface water and groundwater. Since 2015, water has been transferred through the NC Water Supply Project from the maritime neighbor Turkey. The characteristics of the CSLs and the project details are explained in Chapter 3. The environmental assessment of the RWHS is performed for the selected cities from NC by determining the avoided economic damage of carbon dioxide emissions and the economic benefits of reducing electrical energy generation required for water transfer. This environmental assessment demonstrates the environmental cost-benefits through RWHSs that could be preliminary research for those countries located in islands that plan to perform similar projects.

CHAPTER 3

CASE STUDY

The optimization problem formulated in this study is used to determine the optimum RWS tank sizes of the RWHSs at the CSLs to minimize the cost of water supplied from the UN, wastewater cost and the RWS tank cost, and to attain the maximum financial benefit. The CSLs found in NC are selected to perform the optimization model developed in this study. First, NC and its characteristics are presented. Second, detailed information about the selected CSLs is provided. Finally, the RWHS designed for all CSLs are explained within this chapter.

3.1. Northern Cyprus

Cyprus, the third-largest island in the Mediterranean Sea, is found between the longitude of 32-34º east and the latitude of 32-35° north. NC is a country located in Cyprus Island, in the Eastern Mediterranean region. It has a semi-arid Mediterranean climate whose summers are hot and dry while winters are mild and rainy.

NC has limited water resources and faces water scarcity problem (EEA, 2009; Ağıralioğlu et al., 2018). The 30-year annual average precipitation, from 1985 to 2015, is obtained using the daily rainfall data measured by 33 meteorological stations distributed throughout the country as 390 mm. The daily precipitation data is obtained from the NC Meteorology Department.

The daily average domestic water consumption per capita in NC is 0.25 m^3/day/cap (i.e., $W_d = 0.25$ m^3/day/cap – The mathematical formulation of the LP model and the definitions of all the parameters are given in Chapter 4 to avoid repetition values of the parameters which are given in parenthesis in this chapter) (Elkiran and Türkman, 2008). Supplying the water demand, until very recently, depended on the irregularly distributed precipitation and groundwater. Groundwater was the primary resource to supply the increasing water demand in the country, but encounters seawater intrusion (Ergil and Günyaktı, 1993; Günyaktı and Akıntuğ, 1999; Ergil, 2000) and overconsumption resulted in a decrease in water table level (Zuberi et al., 2013).

In 2015, the NC Water Supply Project (see Figure 3.1), a water pipeline system between Turkey and NC, became operational and started supplying the water demand of the country. According to SHW (2014), the system consists of a pipeline, a total length of 106 km, 80 km of which is sea passage. The pipes are installed approximately 250 m below the sea level of the Mediterranean Sea. With the project, 75 MCM water is intended to be transferred each year from Turkey to NC to be used for irrigation, potable, domestic, and industrial purposes. The project is designed to meet the country's water demand for the year of 2045. The scheme of the project is presented on a map in Figure 3.1.

Figure 3.1. The NC Water Supply Project Scheme (SHW, 2014)

Water is transferred from the Alaköprü Dam, Mersin, Turkey, where is NC's maritime neighbor, to NC (see Figure 3.1). The coming water from Turkey first arrives at the Güzelyalı Pump Station by gravity, and it is transferred to either the Geçitköy Dam where it is stored or Çamlıbel Treatment Plant where it is monitored and purified for domestic use. From the Geçitköy Dam, the stored water is transferred to the Çamlıbel Treatment Plant via the Geçitköy Pump Station, and then to the UNs.

At Güzelyalı and Geçitköy Pump Stations, electrical energy is consumed to transfer water to the Geçitköy Dam and Çamlıbel Treatment Plant. The total annual electrical energy consumption of Güzelyalı and Geçitköy Pump Stations in 2019 was 24.9 million kWh (CTEA, Personal Communication in September 2020). These pump stations need to transfer of an annual domestic water demand of nearly 37.2 MCM of NC (Elkiran and Ergil, 2006). Therefore, the unit electrical energy need of Güzelyalı and Geçitköy Pump Stations is calculated as 0.67 kWh/m^3 (i.e., $e_{fwp} = 24.9/37.2 = 0.67$ kWh/m^3).

Nearly 70% of the total domestic water consumption in 2002 (i.e., 25 MCM of 37 MCM) was consumed at the houses (Elkiran and Ergil, 2006). For this reason, achieving water savings at the houses via RWHSs can contribute to the decrease in electrical energy demand of Güzelyalı and Geçitköy Pump Stations and carbon dioxide emissions associated with electrical energy generation.

In Cyprus Island, the electricity generation – carbon dioxide (CO_2) emission intensity in 2006 was 677 g CO_2/kWh (i.e., $i_{CO_2} = 0.68$ kg CO_2/kWh) which is higher than the average of 2016 of the European Union member countries' electricity generation –

CO_2 emission intensity (EEA, 2018). The SCC, explained in detail in Section 4.3, is a measure of the long-term damage of a ton of carbon dioxide emissions in dollars in a given year (EPA, 2016). The SCC is used to estimate of climate change damages like changes in human health and energy system costs (EPA, 2016). In 2020, the SCC is estimated as US$ 42/ton CO_2 at a discount rate of 3 percent (EPA, 2016).

In NC, the official currency is TL, and the annual discount rate is approximately 6% (i.e., $im = 0.005$ per month) as of Feb 24th, 2020 (The TRNC Central Bank, 2020b). Due to the utilization of the NC Water Supply System for municipal water supply purposes since 2015, the cost of municipal water has increased in the country.

With limited water resources of the island, an efficient and sustainable water supply for various needs such as municipal, irrigation and industrial is of utmost importance for the country. RWHSs can supply some portion of the domestic water demand in NC. Hence, the country's need for water transfer from Turkey will be reduced, causing some savings for the residents in terms of water costs. Moreover, the electricity consumption at two of the pumping stations will decrease, which in turn will result in a reduction in carbon dioxide emissions caused by electricity generation.

3.2. Case Study Locations

NC is divided into six districts, Lefkoşa, Girne, Mağusa, Güzelyurt, İskele, and Lefke. To reflect the entire precipitation regime of the country, 33 locations are selected as CSLs. The distribution of these 33 CSLs throughout the country is given in Figure 3.2.

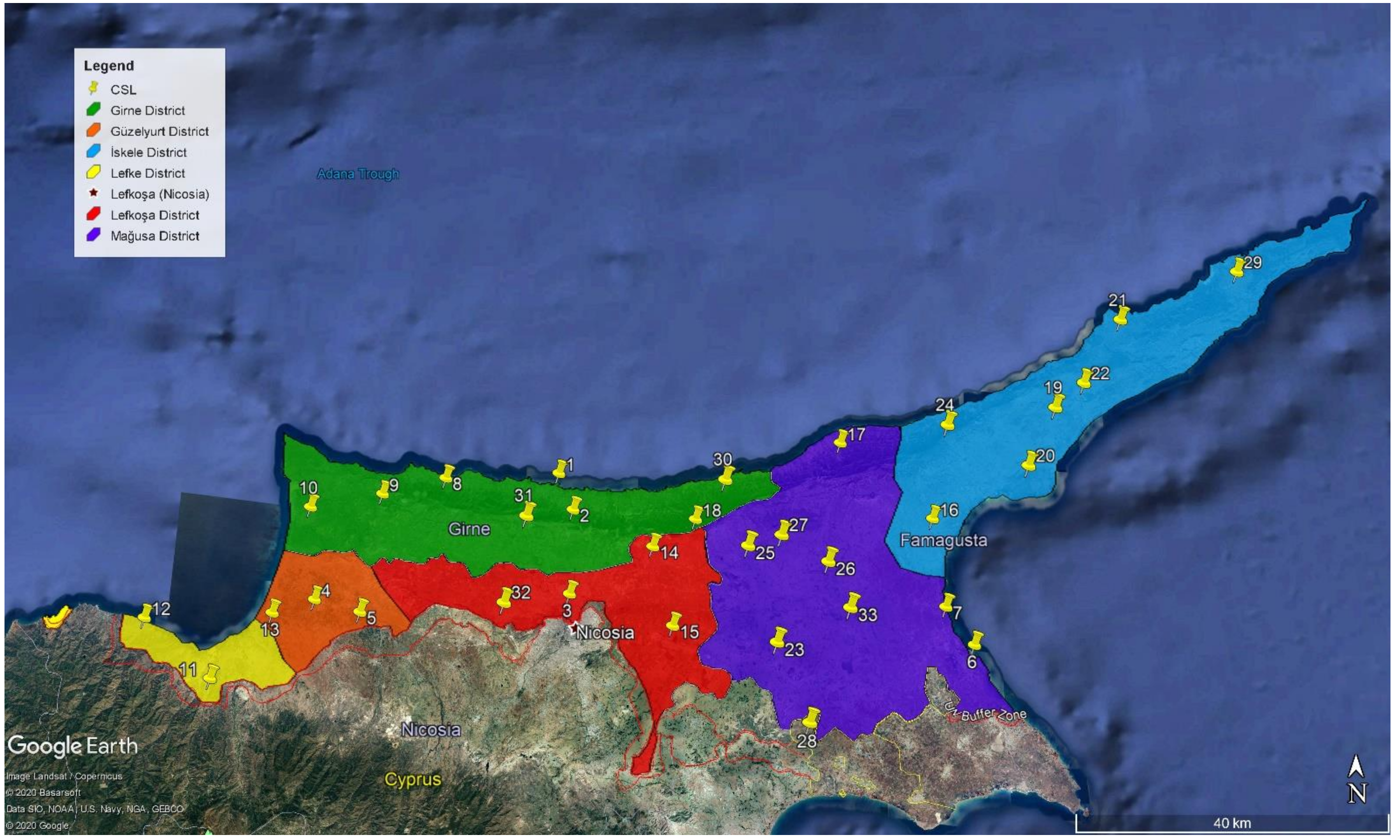


Figure 3.2. Districts and CSLs

The Lefkoşa district is in the center of the country. The Girne district, which includes a considerable portion of the Beşparmak Mountains, is located on the north coast. The Mağusa district extends from the north coast to the south-east coast. The İskele district, comprising the Karpaz Peninsula, is located on the north-east coast. Finally, Güzelyurt and Lefke districts are situated on the south-west coast.

The CSLs are identified based on the locations of the meteorological stations. The geographical coordinates of the meteorological stations are provided from the NC Meteorology Department (see Table 3.1). The daily average precipitation calculated using daily precipitation surveillances between 1985 and 2015 is given in Table 3.1.

Table 3.1. Geographical Coordinates of Meteorological Stations and Daily Average Precipitations (1985-2015)

Station Number	**Station Name**	**Latitude (degree)**	**Longitude (degree)**	**Elevation (m)**	**Daily Avg. Precipitation (mm)**
1	Girne	35.34194	33.33139	10	1.3
2	Beylerbeyi	35.29729	33.35404	225	1.4
3	Lefkoşa	35.19639	33.35194	134	0.8
4	Güzelyurt	35.18889	32.98194	52	0.8
5	Zümrütköy	35.17444	33.04917	129	0.8
6	Mağusa	35.13639	33.93556	10	0.9
7	Salamis	35.18080	33.89734	6	0.9
8	Lapta	35.33575	33.16336	168	1.5
9	Çamlıbel	35.31611	33.07056	277	1.3
10	Akdeniz	35.29972	32.96500	89	1.1
11	Lefke	35.09664	32.84091	129	0.9
12	Yeşilırmak	35.16639	32.73694	20	1.0
13	Gaziveren	35.17306	32.92194	19	0.8
14	Değirmenlik	35.25276	33.47218	168	0.9
15	Ercan	35.15917	33.50194	119	0.9
16	İskele	35.28611	33.88444	39	0.9
17	Tatlısu	35.37972	33.75167	168	1.4
18	Alevkaya	35.28583	33.53472	623	1.3
19	Mehmetçik	35.42222	34.07833	99	1.1
20	Çayırova	35.34949	34.03129	67	1.1
21	Yenierenköy	35.53556	34.18944	123	1.2
22	Ziyamet	35.45350	34.12451	82	1.2
23	Vadili	35.13869	33.65161	54	0.8
24	Kantara	35.40056	33.91361	480	1.5
25	Serdarlı	35.25183	33.61024	111	0.9
26	Geçitkale	35.23333	33.72861	45	0.9
27	Gönendere	35.26417	33.66083	75	0.9
28	Beyarmudu	35.04716	33.69582	87	1.0
29	Dipkarpaz	35.59889	34.37917	136	1.4
30	Esentepe	35.33273	33.57852	183	1.3
31	Boğaz	35.28825	33.28484	300	1.1
32	Alayköy	35.18472	33.25667	166	0.8
33	Dörtyol	35.17889	33.75861	54	0.8
				Average	**1.1**

As seen in Table 3.1, the north and the north-east shores of the country, including the north part of the Girne and Mağusa districts, and the Karpaz Peninsula from the İskele district, have greater average precipitation than the remaining part of the country.

The local municipalities determine the cost of water in NC. The CSLs selected for this study are located at the inside of the boundaries of 21 municipalities of a total of 28 municipalities in the country. Twenty-one municipalities' water tariffs are used as inputs. Some of them are obtained by directly contacting the municipalities’ officers, and some are obtained from the local newspaper Havadis, issued on May 15th, 2017. Table 3.2 presents the monthly water tariffs of the municipalities at the CSLs.

Table 3.2. Monthly Water Tariffs of Municipalities at CSLs

Municipality Number	Municipality	CSL	Water Tariff		
			Price Level	**Water per m^3**	**Water Cost (TL)**
1	Girne	Girne Beylerbeyi	1	0-10	5.0
			2	11-20	6.5
			3	21-30	7.0
			4	31-50	7.5
			5	51-100	8.0
			6	100+	8.5
			Average*		6.2
2	Lefkoşa	Lefkoşa	1	0-6	4.9
			2	7-13	6.2
			3	14+	7.0
			Average*		6.4
3	Güzelyurt	Güzelyurt Zümrütköy	1	0-5	4.0
			2	6-15	4.5
			3	16+	6.0
			Average*		5.2
4	Mağusa	Mağusa Salamis	1	0-15	4.5
			2	16-30	5.0
			3	31+	5.5
			Average*		4.8
5	Lapta	Lapta Akdeniz Çamlıbel	1	1+	5.0
6	Lefke	Lefke Gaziveren Yeşilırmak	1	0-20	3.5
			2	21-40	4.0
			3	41+	5.0
			Average*		3.7
7	Değirmenlik	Değirmenlik Ercan	1	0-25	5.0
			2	26+	6.0
			Average*		5.2

Table 3.2. Monthly Water Tariffs of Municipalities at CSLs (Cont'd)

Municipality Number	Municipality	CSL	Water Tariff		
			Price Level	Water per m^3	Water Cost (TL)
8	İskele	İskele	1	1-15	4.0
			2	16-25	4.5
			3	26-35	5.0
			4	36+	6.0
			Average*		4.4
9	Esentepe	Esentepe Alevkaya	1	0-5	4.0
			2	6-15	5.0
			3	16+	6.0
			Average*		5.2
10	Mehmetçik	Mehmetçik Çayırova	1	1+	5.0
11	Yeni Erenköy	Yeni Erenköy Ziyamet	1	1+	5.2
12	Vadili	Vadili	1	1+	3.5
13	Büyükkonuk	Kantara	1	1+	3.8
14	Serdarlı	Serdarlı Gönendere	1	0-10	3.5
			2	11-25	4.0
			3	26-40	4.5
			4	41+	5.0
			Average*		3.9
15	Geçitkale	Geçitkale	1	0-10	4.0
			2	11-20	4.5
			3	21-30	5.0
			4	31+	6.0
			Average*		4.5
16	Beyarmudu	Beyarmudu	1	0-10	4.5
			2	11-20	5.0
			3	21+	6.0
			Average*		5.0

Table 3.2. Monthly Water Tariffs of Municipalities at CSLs (Cont'd)

Municipality Number	Municipality	CSL	Water Tariff		
			Price Level	Water per m^3	Water Cost (TL)
17	Dipkarpaz	Dipkarpaz	1	0-20	5.0
			2	21+	6.0
			Average*		5.4
18	Tatlısu	Tatlısu	1	0-10	3.2
			2	11-20	4.0
			3	21-30	5.0
			4	31+	6.0
			Average*		4.1
19	Alayköy	Alayköy	1	1+	4.0
20	İnönü	Dörtyol	1	1+	4.0
21	Dikmen	Boğaz	1	0-7	4.5
			2	8-15	5.0
			3	16-25	5.3
			4	26+	5.5
			Average*		5.1
		Average	**4.7 TL/m^3 per Municipality**		

* Average values are calculated, assuming that the monthly domestic water demand for a 4 resident household is 31 m^3 per month. These average values are used for comparison purposes.

As seen in Table 3.2, the average unit water cost is the most expensive in Lefkoşa while the cheapest in Vadili. Most of the municipalities in NC use varying unit water costs. The unit water costs vary depending on the volume of water purchased from the UNs; this is called "The increasing block rate tariff." The increasing block rate tariff is implemented by the municipalities of NC, like by the Lefkoşa Municipality, to enforce water efficiency and increase water savings. On the other hand, some municipalities, such as the Vadili Municipality, employ the fixed-unit rate water tariff.

Furthermore, wastewater cost is charged for the volume of water purchased from the UNs by some municipalities at the locations where wastewater collection systems are constructed. When the RWHS is implemented, the volume of water supplied from the UN will decrease, and this will cause the wastewater cost to decrease as well. Wastewater cost is implemented in other parts of the world, and the financial feasibility of the RWHS was found to be highly sensitive to its change (Sample and Liu, 2014). The number of wastewater collection systems is estimated to increase at the CSLs in the future with population growth and the increase in urbanization throughout the country. Therefore, the unit wastewater cost is assumed to be fixed at 1 TL/m^3 (i.e., $c_w = 1$ TL/m^3) at all CSLs throughout this study.

3.3. Rainwater Harvesting System

In this study, a rooftop RWHS is designed for a residential unit (i.e., a single house) at all CSLs (see Figure 3.3). It is assumed that the single house accommodates a family of four people (i.e., $n = 4$). The daily average domestic water demand of a four-member family (i.e., $D_{daily} = 1$ m^3) is supplied from the RWHS and the UN. The RWHS could enable the user to store harvested rainwater in the RWS tank for future use to minimize monthly water bills, and the whole water demand could be supplied from the UN. This is explained in detail in Section 5.2.3. The RWHS is assumed to be used effectively for 30 years or 360 months (i.e., $N = 30$ years, $T = 360$ months) with regular yearly maintenance.

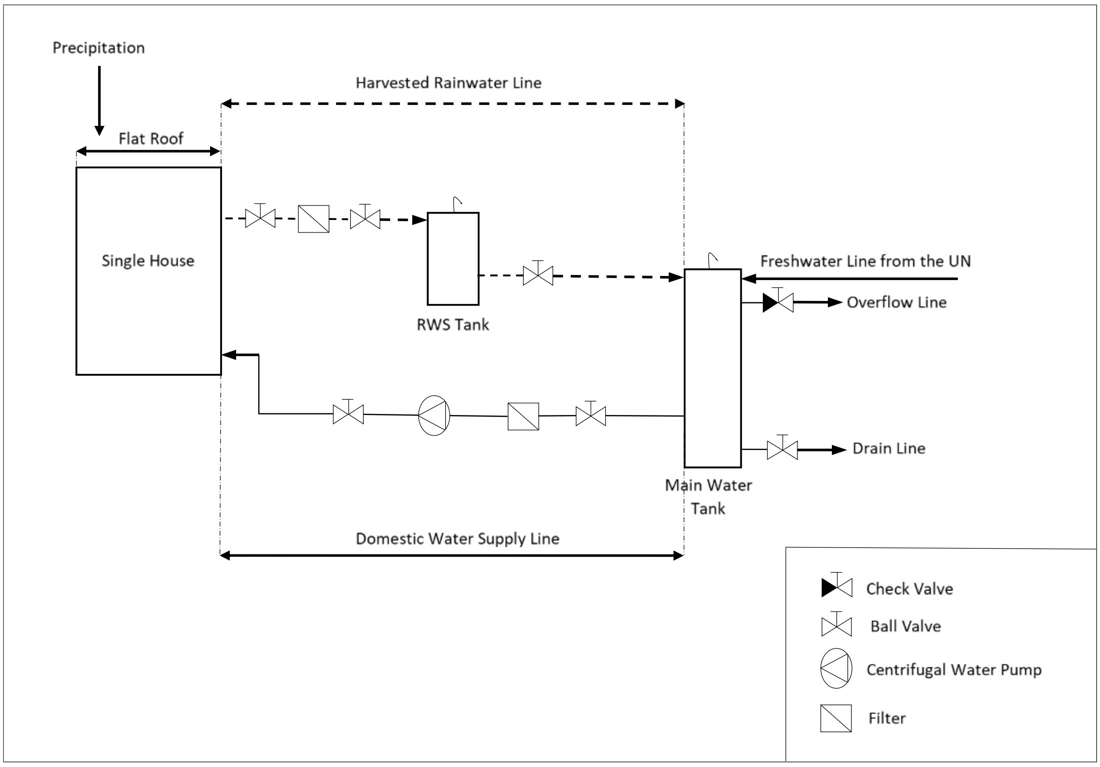


Figure 3.3. Schematic Plan View of the Designed Rooftop RWHS for a Single House

In NC, each residential unit is equipped with a water tank, illustrated as the main water tank in Figure 3.3, and a water pump which is used to transfer municipal water from the main water tank to the residential unit since the water pressure in the UNs' is insufficient. The consumer is liable for the electricity cost of that water pump. It is assumed that the RWHS is connected to the already existing municipal water supply system of the residential unit, and thus, it will not increase the electricity cost of the residential unit.

Storing rainwater in the RWS tank for a long time may affect the quality of water. Using the same pump to transfer rainwater and municipal water and blending rainwater with municipal water in a tank may cause water quality problems. In practice, to maintain water quality standards, disinfection and other necessary treatment operations have to be applied to the stored rainwater. This may bring an additional operating cost. The type of required treatment should be identified based on the quality of collected rainwater and its residence time in the storage tank. However, such studies were left out of this study's scope, and treatment-related costs are ignored.

The RWS tank is designed as an above-ground tank, and the excavation cost is ignored. The RWS tank is positioned at a higher location than the main water tank. Thus, harvested rainwater in the RWS tank feeds the main water tank by gravity, in which rainwater and municipal water are blended (see Figure 3.3). The evaporation loss is not considered in this study since the RWS tank and the main water tank are closed tanks. When the water level in the main water tank gets low on any day, it is filled by the RWHS and the UN. Rainwater is assumed to be harvested through a 200 m^2 collector (i.e., $A_{col} = 200$ m^2) at the roof. The roof is assumed to be a flat concrete roof with a 90% runoff coefficient (i.e., $c_f = 90\%$) (California State Water Resources Control Board, 2011).

Based on the local plumbing service provider, the initial installation cost of the designed RWHS, including the pipes, three ball valves and a filter, is assumed to be

1500 TL (i.e., $C_{inst} = 1500$ TL) (Personal Communication with Olcay Uzuçar in December 2019). The annual maintenance cost is taken as 102 TL/year (i.e., $c_m = 8.5$ TL per month) (Personal Communication with Olcay Uzuçar in December 2019). Additionally, the RWS tank is assumed to be made of polyethylene, and its unit cost is estimated to be 600 TL/m^3 (i.e., $a = 600$ TL/m^3) (Paralik Group, 2020). The maximum RWS tank size is limited to 20 m^3 (i.e., $S_{max} = 20$ m^3) for all CSLs due to the municipal restrictions on the capacity of the storage tanks.

CHAPTER 4

METHODOLOGY

This study aims to calculate the optimum RWS tank size of a RWHS to minimize the cost of water supplied from the UN, wastewater cost and the RWS tank cost to attain the maximum financial benefit. An LP model is developed to achieve that aim. This chapter introduces the LP model developed in this study in detail. First, the mathematical formulation of the LP model is presented. Then, the financial assessment of the RWHS is explained. Finally, the environmental assessment of the RWHS is given.

The LP model in this study is designed for daily time steps, and the simulation period is taken as 30 years. Thus, it is assumed that the precipitation regime will not change significantly, and the optimum tank size will be effective in the near future. The utilization of daily time steps allows a better representation of the real situation. For example, during heavy precipitation, the capacity of the RWS tank may be exceeded, and additional rainwater may overflow. If monthly time steps are used, such details may not properly be represented in the model. For the mathematical formulation of the LP model using monthly time steps, see Appendix A.

In the LP model, it is assumed for each residential unit that the rainwater stored in the RWS tank is used as the municipal water supply for that residential unit. Therefore, the water demand at the residential unit is supplied from the RWHS and the UN. It is assumed that each residential unit has its freshwater pump to distribute municipal water to that residential unit. The same pump is assumed to be used to distribute the harvested rainwater to the residential unit as well. As a result, the same electricity cost occurs when the water demand is only supplied from the UN. Thus, the solution of the LP model is not affected by the electricity cost due to the distribution of the harvested rainwater to the residential unit. Consequently, it is ignored in the LP model.

After calculating the optimum RWS tank size by minimizing the costs, the financial assessment of the RWHS investment is carried out to calculate the NFB at the end of the simulation period. The NFB is an indicator of the RWHS investment's worth through the simulation period. The NFB is the difference between the total cost of supplying the water demand using only the UN and using the UN together with the RWHS (UN&RWHS). The total cost associated with UN&RWHS is calculated by summing up the cost of the RWS tank and the costs of water that is supplied from the UN and wastewater through the simulation period (these two items are the outputs of the LP model), the cost of installation of the RWHS, and the total cost of maintenance of the RWHS through the simulation period. The total water cost associated with the UN is calculated by assuming that all the water demand through the simulation period is supplied from the UN (i.e., no RWHS).

The environmental assessment is carried out using the SCC value, which may vary with respect to the country. The SCC is an economic measure to quantify the cost of the economic damage of climate change due to each additional ton of carbon dioxide emitted into the atmosphere (Rennert and Kingdon, 2019). For instance, for a project that will increase carbon dioxide emissions, the total social carbon cost is calculated by multiplying the SCC with the estimated carbon dioxide emissions resulting from that project. Since the total social carbon cost is calculated in monetary terms, it can directly be added to the total cost of the project. In the environmental assessment of the RWHS, the avoided economic damage due to reduction in carbon dioxide emissions is calculated. The following sections present mathematical formulations of the LP model, the financial assessment of the RWHS and the environmental assessment of the RWHS, respectively.

4.1. Mathematical Formulation of the LP Model

Objective Function

$$Min. Z = a \times T_{cap} + \sum_{t=1}^{T} \sum_{j=1}^{J} \frac{b_j}{(1+im)^t} P_{tj} + \sum_{t=1}^{T} \frac{(P_t - U_t)c_w}{(1+im)^t} \tag{4.1}$$

s.t.

$$Id_i^t = Id_{i-1}^t + rd_i^t - Ud_i^t \qquad \forall t, i \in t \tag{4.2}$$

$$Id_0^1 = 0 \tag{4.3}$$

$$Id_0^t = Id_I^{t-1} \qquad t = 2, \dots, T \tag{4.4}$$

$$Id_i^t \leq T_{cap} \qquad \forall t, \forall i \tag{4.5}$$

$$Ud_i^t \leq T_{cap} \qquad \forall t, \forall i \tag{4.6}$$

$$rd_i^t \le \min\{Rd_i^t, T_{cap}\} \qquad \forall t, \forall i \qquad (4.7)$$

$$T_{cap} \le S_{max} \qquad (4.8)$$

$$P_t + U_t = D_t \qquad \forall t \qquad (4.9)$$

$$T_{cap}, Id_i^t, rd_i^t, Ud_i^t, Pd_i^t \ge 0 \qquad \forall t, \forall i \qquad (4.10)$$

where t is the index for month, $t = 1,2,..,T$, T is the total number of months in the simulation period, j is the index for the price level at which water is purchased from the UN, $j = 1,2,..,J$, J is the total number of price levels used by the UN, i is the index for day, $i = 1,2,...,I$, I is the total number of days within month t (i.e., $I = 28, 29, 30$ or 31), a is the unit cost of the RWS tank (TL/m^3), b_j is the cost of water per unit volume purchased from the UN at the $j\ th$ price level (TL/m^3), Rd_i^t is the maximum amount of rainwater that can be harvested in the $i\ th$ day of month t (m^3), S_{max} is the maximum tank size (m^3), im is the monthly discount rate, c_w is the cost per unit volume of wastewater (TL/m^3), D_t is the total demand in month t (m^3), T_{cap} is the volume of the RWS tank (m^3), Id_i^t is the inventory level of the RWS tank at the end of the $i\ th$ day of month t (m^3), rd_i^t is the amount of harvested rainwater in the $i\ th$ day of month t (m^3), Ud_i^t is the amount of rainwater used from the RWS tank in the $i\ th$ day of month t to satisfy the daily demand (m^3), Pd_i^t is the amount of water purchased from the UN in day i of month t (m^3), P_t is the total amount of water purchased from the UN in month t (m^3) to satisfy the demand, P_{tj} is the amount of water purchased from the UN in month t at the $j\ th$ price level (m^3), U_t is the total amount of water used from the RWS tank in month t to satisfy the demand (m^3). Here,

t, j and i are the sets, $a, b_j, Rd_i^t, S_{max}, im, c_w,$ and D_t are the parameters, and $T_{cap}, Id_i^t, rd_i^t, Ud_i^t,$ and Pd_i^t are the variables.

Equation (4.1) is the objective function that is the summation of the cost of the RWS tank, the present value of the total amount of water supplied from the UN, and the present value of the total wastewater cost. The monthly discount rate is used in Equation (4.1) to bring the costs occurring in the simulation period to the present. Equation (4.2) is the continuity equation for the RWS tank. Equation (4.3) states that the RWS tank's inventory level is at zero in the beginning of the simulation period. Equation (4.4) forces the RWS tank's inventory level in the last day of each month to be equal to the inventory level at the first day of the next month. Constraint (4.5) ensures that the inventory level of the RWS tank does not exceed the volume of the RWS tank through the simulation period. Constraint (4.6) guarantees that the amount of rainwater used from the RWS tank is no greater than the volume of the RWS tank through the simulation period. Constraint (4.7) confirms that during the simulation period, the amount of harvested rainwater in each does not exceed neither the maximum amount of rainwater that can be harvested in a day nor the volume of the RWS tank. Constraint (4.8) guarantees that the volume of the RWS tank is smaller than the maximum tank size. Equation (4.9) ensures that the total demand in each month is satisfied through the RWS tank and/or from the UN. Constraint (4.10) represents the sign restrictions, such that all the decision variables are positive.

The total amount of water purchased from the UN in month t, P_t, is calculated by summing the amount of water purchased from the UN in each day of that month:

$$P_t = \sum_{i \in t} Pd_i^t \qquad \forall t \qquad (4.11)$$

Municipalities of cites may charge different price levels based on the amount of volume purchased from the UN. So the total volume of water purchased from the UN in month t, P_t, is calculated by summing the volumes purchased at different price levels:

$$P_t = \sum_{j \in J} P_{tj} \qquad \forall t \qquad (4.12)$$

For example, when a total of 4 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, the amount between V_2 and V_3 m^3 is purchased from b_3 TL/m^3, and the remaining is purchased from b_4 TL/m^3), the total amount of water purchased from the UN in month m^* is P_{m^*}. The water cost that should be paid to the municipality for the water purchased from the UN, C, is calculated as follows:

$$if\ P_{m^*} \leq V_1\ \ then \begin{cases} P_{m^*1} = P_{m^*} \\ C = b_1 P_{m^*} \end{cases}$$

$$if\ V_1 \leq P_{m^*} \leq V_2\ \ then \begin{cases} P_{m^*1} = V_1,\ P_{m^*2} = (P_{m^*} - V_1) \\ C = b_1 V_1 + (P_{m^*} - V_1) b_2 \end{cases}$$

$$if\ V_2 \leq P_{m^*} \leq V_3\ \ then \begin{cases} P_{m^*1} = V_1, P_{m^*2} = V_2, P_{m^*2} = (P_{m^*} - V_1 - V_2) \\ C = b_1 V_1 + b_2 V_2 + (P_{m^*} - V_1 - V_2) b_3 \end{cases}$$

$$if\ V_3 \leq P_{m^*}$$

$$then \begin{cases} P_{m^*1} = V_1, P_{m^*2} = V_2, P_{m^*3} = V_3, P_{m^*4} = (P_{m^*} - V_1 - V_2 - V_3) \\ C = b_1V_1 + b_2V_2 + b_3V_3 + (P_{m^*} - V_1 - V_2 - V_3)b_4 \end{cases}$$

The maximum amount of rainwater that could be harvested from the roof of the building through collectors in the $i\ th$ day of month t, Rd_i^t, is calculated using Equation (4.13). The modified version of Ghisi et al. (2006) is as follows:

$$Rd_i^t = c_f \times A_{col} \times p_i^t \times 10^{-3} \tag{4.13}$$

where c_f is the runoff coefficient for the roof, A_{col} is the collector area at the roof (m^2), p_i^t is the measured precipitation depth in the $i\ th$ day of month t (mm).

The total amount of water used from the RWS tank in month t to satisfy the demand, U_t, is calculated by summing the amount of water used from the RWS tank in each day of that month:

$$U_t = \sum_{i \in t} Ud_i^t \qquad \forall t \tag{4.14}$$

The total demand in month t, D_t, is calculated by summing the demand in each day of that month, and the daily demand is calculated as follows:

$$D_{daily} = Wd \times n \tag{4.15}$$

where Wd is the daily average water consumption per capita (m^3/day/cap), and n is the number of residents. Thus, D_t, is practically the daily demand, D_{daily}, times total number of days in month t.

4.2. Financial Assessment of the RWHS

After calculating the minimum value of the objective function and the optimum size of the RWS tank, the total cost of the RWHS, C_{total}, is calculated as follows:

$$C_{total} = Z + C_{fixed} \tag{4.16}$$

where Z is the optimum objective function value (TL), C_{fixed} is the summation of the fixed costs (TL) which is calculated as follows:

$$C_{fixed} = C_{inst} + C_{maint} \tag{4.17}$$

where C_{inst} is the RWHS installation cost (TL), C_{maint} is the total RWHS maintenance cost that occurs during the simulation period (TL), and it is calculated as follows:

$$C_{maint} = \sum_{t=1}^{T} \frac{c_m}{(1+im)^t} \qquad \forall t \tag{4.18}$$

where c_m is the monthly fixed RWHS maintenance cost (TL).

Next, the cost of supplying the whole water demand from the UN (i.e., the case where there is no RWHS), C_{un}, is calculated as follows:

$$C_{un} = \sum_{t=1}^{T} \sum_{j=1}^{J} \frac{b_j}{(1+im)^t} P_{tj} + \sum_{t=1}^{T} \frac{c_w}{(1+im)^t} D_t \qquad \forall t, j \le J \tag{4.19}$$

Finally, the NFB is calculated as follows:

$$NFB = C_{un} - C_{total} \tag{4.20}$$

If the NFB is positive, the RWHS investment is feasible; while if the NFB is negative, the RWHS investment results in economic losses. In addition to the NFB analysis, the discounted payback period (PP) of the RWHS investment is also calculated. The discounted PP is the year at which cumulative discounted net cash-flow becomes zero (Ali, 2013).

4.3. Environmental Assessment of the RWHS

Municipal water supply networks (i.e., the UN line as shown in Figure 3.3) distribute water from municipal water storage facilities to storage units (i.e., the main water tank of a single house as shown in Figure 3.3). Water is transferred from the municipal water storage facilities to the main water tanks of single houses using powerful pumps. To operate the powerful pumps, electrical energy is required. Some part of the electrical energy used for water transfer can be avoided by supplying a portion of the water demand through the rooftop RWHS. As a result, as the electrical energy need decreases, emerging carbon dioxide emissions and fuel consumption due to electrical energy generation decrease as well.

High concentrations of carbon dioxide in the atmosphere trigger global warming, cause climate change and harm human health. In other words, in addition to economic benefits, RWHSs introduce environmental benefits as well. Hence, in this study, the economic benefits of reducing electrical energy consumption, which is evaluated as the environmental benefit, are achieved through RWHSs.

The environmental assessment of the RWHS is carried out by calculating the avoided total annual social carbon cost and the avoided total annual electrical energy cost when some of the water demand is supplied by RWHSs. First, the avoided annual electrical energy need of pumps to transfer water from municipal water storage facilities to the main water tanks of single houses, E_{fwp} (kWh/year), is calculated as follows:

$$E_{fwp} = e_{fwp} \times WS \tag{4.24}$$

where e_{fwp} is the unit electrical energy need of pumps (kWh/m^3), and WS is the total annual water savings using the RWHS at single houses for an average year (m^3/year).

Second, the avoided total annual ton CO_2 equivalent emission resulting from the transfer of water from water storage facilities to the main water tanks of single houses, E_{CO_2}, is calculated as follows (modified from Al-Ghussain et al., 2018):

$$E_{CO_2} = i_{CO_2} \times E_{fwp} \times 10^{-3} \tag{4.25}$$

where i_{CO_2} is the electricity generation - CO_2 emission intensity (kg CO_2/kWh).

Third, the avoided total annual social carbon cost, C_{carbon}, is calculated as follows (modified from Al-Ghussain et al., 2018):

$$C_{carbon} = E_{CO_2} \times SCC \tag{4.26}$$

where SCC is the social cost of carbon (\$/ton CO_2).

Next, the number of trees required for CO_2 sequestration, T_s, is calculated as follows (modified from Al-Ghussain et al., 2018):

$$T_s = \frac{E_{CO_2}}{S_R} \tag{4.27}$$

where S_R is the weighted average carbon sequestered by a medium growth coniferous or deciduous tree, planted in an urban setting and allowed to grow for 10 years (ton CO_2 per urban tree planted).

The second environmental benefit is the reduction in the electrical energy consumption using the RWHS. Thus, the avoided total annual electrical energy generation cost, E_{el} (TL/year), is calculated as follows:

$$E_{el} = E_{fwp} \times e_{el} \tag{4.28}$$

where e_{el} is the unit cost of electrical energy generation (TL/kWh).

Finally, the amount of the avoided annual fuel to generate electrical energy, F_o (ton/year), is calculated as follows:

$$F_o = \frac{E_{fwp}}{LHV} \tag{4.29}$$

where LHV is the lower heating value of fuel (kWh/ton).

CHAPTER 5

RESULTS AND DISCUSSION

This chapter demonstrates and discusses the results of the LP model's optimum solutions, the financial assessments of the RWHSs, and the environmental assessment of the RWHSs. One LP model is built for each CSL. Each LP model has its decision variables. They are the harvested rainwater for each day, the rainwater used from the RWS tank for each day, and the water purchased from the UN for each day of the simulation period (i.e., a total of 10967 days). In addition to these decision variables, the monthly water purchased from the UN is a decision variable that is calculated for each month of the simulation period (i.e., a total of 360 months). It is calculated for each month of the simulation period by summing the water purchased from the UN for each day and each price level. When the volume of the RWS tank is added, this results in a total of around 34,000 decision variables for each LP model.

The LP models are developed for each CSL using the already built-in Solver add-in of Microsoft Excel. Because of the restrictions on the number of constraints and the number of decision variables in linear or non-linear models in the Solver add-in, the optimum RWS tank sizes are found by using the OpenSolver for Microsoft Excel software Ver. 2.9.0. OpenSolver is a free linear, integer and non-linear optimizer that can solve large optimization models. It is compatible with the Solver add-in. Thus, it can solve the optimization models developed in the Solver add-in.

The optimum solutions of each LP model are calculated approximately in 1 hour and 30 minutes on a Windows 10 desktop computer, which has Intel® Core™ i5-9400F CPU @ 2.90 GHz and 16 GB RAM. Then, the NFBs at all CSLs are calculated for two cases, which are with and without considering the fixed costs. Next, water supply and demand and rainwater harvesting through RWHSs at the CSLs throughout the simulation period are analyzed and discussed. Finally, the environmental assessment of the RWHS is carried out for the selected cities, and the results are discussed.

5.1. Optimum Solutions of the LP Models and Financial Assessments of the RWHSs for all CSLs

In this section, first, the effect of using different time steps in the LP model on the results of the optimum RWS tank size and the NFB is investigated. For this analysis, the results of the LP model using daily time steps (LP-Daily), developed in this study, and the results of the LP model using monthly time steps of Ruso et al., 2019 (LP-Monthly), provided in Appendix A, are compared. Dipkarpaz is selected for this analysis (see Table 3.1 and Figure 3.2). LP-Daily and LP-Monthly are run using the same parameters presented in Chapter 3 for the simulation period of 30 years, and the results are summarized in Table 5.1.

Table 5.1. Comparison of LP-Daily and LP-Monthly Results for Dipkarpaz

Model	Optimum tank size (m^3)	Tank cost (TL)	Sum of municipal water and wastewater costs (TL)	NFB (TL)
LP-Monthly	3.1	1,860	30,022	-2,603
LP-Daily	2.8	1,680	26,480	1,119

As seen in Table 5.1, the optimum RWS tank sizes and the tank costs obtained from LP-Daily and LP-Monthly are similar. However, the financial assessment of the RWHS results in a different NFB when monthly and daily time steps are used in the LP. When the LP-Monthly model is used, a negative NFB is obtained, and this indicates the financial infeasibility for the RWHS. On the contrary, the financial feasibility of the RWHS is found to be positive when the LP-Daily model is used. The main reason for this difference is that monthly water demand is supplied from the RWHS at the end of the month in the LP-Monthly model. Therefore, LP-Monthly allows the RWS tank to be filled with rainwater only once a month.

On the other hand, when the LP-Daily model is used, the RWS tank is filled with rainwater and used to supply the demand more than once a month if necessary (see Table 5.6). This is explained in detail in Section 5.2.3. As a result, rainwater harvesting and utilization are more realistically modeled by the LP-Daily model. The LP-Monthly model may lead to wrong results in terms of the financial feasibility of the investment for decision-makers. Therefore, the LP model developed in this study which uses daily time steps (i.e., LP-Daily) is run for all CSLs. Table 5.2 illustrates the optimum RWS tank sizes and the NFBs with and without fixed costs for each CSL.

Table 5.2. Optimum RWS Tank Sizes and NFBs of all CSLs

CSL Number	**CSL**	**District**	**Optimum RWS Tank Size, T_{cap} (m^3)**	**NFB without Fixed Costs (TL)**	**NFB with Fixed Costs (TL)**
1	Girne	Girne	3.02	4,542	**1,624**
2	Beylerbeyi	Girne	3.24	4,729	**1,811**
3	Lefkoşa	Lefkoşa	2.32	3,280	362
4	Güzelyurt*	Güzelyurt	2.00	2,814	-104
5	Zümrütköy*	Güzelyurt	1.98	2,672	-246
6	Mağusa*	Mağusa	2.00	2,248	-670
7	Salamis*	Mağusa	2.05	2,138	-780
8	Lapta	Girne	2.70	3,285	368
9	Çamlıbel	Girne	2.52	3,123	205
10	Akdeniz	Girne	2.16	2,930	12
11	Lefke*	Lefke	1.80	1,810	-1,108
12	Yeşilırmak*	Lefke	1.80	2,071	-847
13	Gaziveren*	Lefke	1.62	1,607	-1,310
14	Değirmenlik*	Lefkoşa	2.21	2,437	-481
15	Ercan*	Lefkoşa	2.11	2,509	-409
16	İskele*	İskele	2.00	2,180	-738
17	Tatlısu	Mağusa	2.88	3,215	297
18	Alevkaya	Girne	3.08	3,836	**918**
19	Mehmetçik*	İskele	2.34	2,526	-392
20	Çayırova*	İskele	2.10	2,513	-404
21	Yeni Erenköy	İskele	2.61	3,176	259
22	Ziyamet*	İskele	2.45	2,898	-20
23	Vadili*	Mağusa	1.58	1,241	-1,677
24	Kantara*	İskele	2.42	2,550	-368
25	Serdarlı*	Mağusa	1.89	1,841	-1,076
26	Geçitkale*	Mağusa	2.16	2,197	-721
27	Gönendere*	Mağusa	1.98	1,821	-1,097
28	Beyarmudu*	Mağusa	2.06	2,640	-278

Table 5.2. Optimum RWS Tank Sizes and NFBs of all CSLs (Cont'd)

CSL Number	CSL	District	Optimum RWS Tank Size, T_{cap} (m^3)	NFB without Fixed Costs (TL)	NFB with Fixed Costs (TL)
29	Dipkarpaz	İskele	2.84	4,037	**1,119**
30	Esentepe	Girne	3.01	3,737	**819**
31	Boğaz*	Girne	2.34	2,877	-41
32	Alayköy*	Lefkoşa	1.63	1,500	-1,417
33	Dörtyol*	Mağusa	1.67	1,334	-1,583
		Min.	**1.58**	**1,241**	**-1,677**
		Max.	**3.24**	**4,729**	**1,811**

* The NFB is found negative after the fixed costs are added.

As seen in Table 5.2, the RWS tank sizes range from 1.58 to 3.24 m^3. The optimum RWS tank sizes obtained from the solution of the LP may not be available in the market. Installation of the closest available tank size larger than the optimum size is suggested for practical purposes. The minimum NFB is calculated for Vadili while the maximum is calculated for Beylerbeyi. For all CSLs, investing in RWHSs is found to be feasible before the fixed costs of the RWHS are added. At nearly two-third of the CSLs, investing in RWHS is found to be infeasible after adding the fixed costs (i.e., the negative values in the last column of Table 5.2). The CSLs where the RWHSs are found feasible after adding the fixed costs are shown in Figure 5.1. The results demonstrate that the unit water cost, the daily average precipitation and the precipitation distribution significantly affect the optimum RWS tank size and the feasibility of the RWHSs.

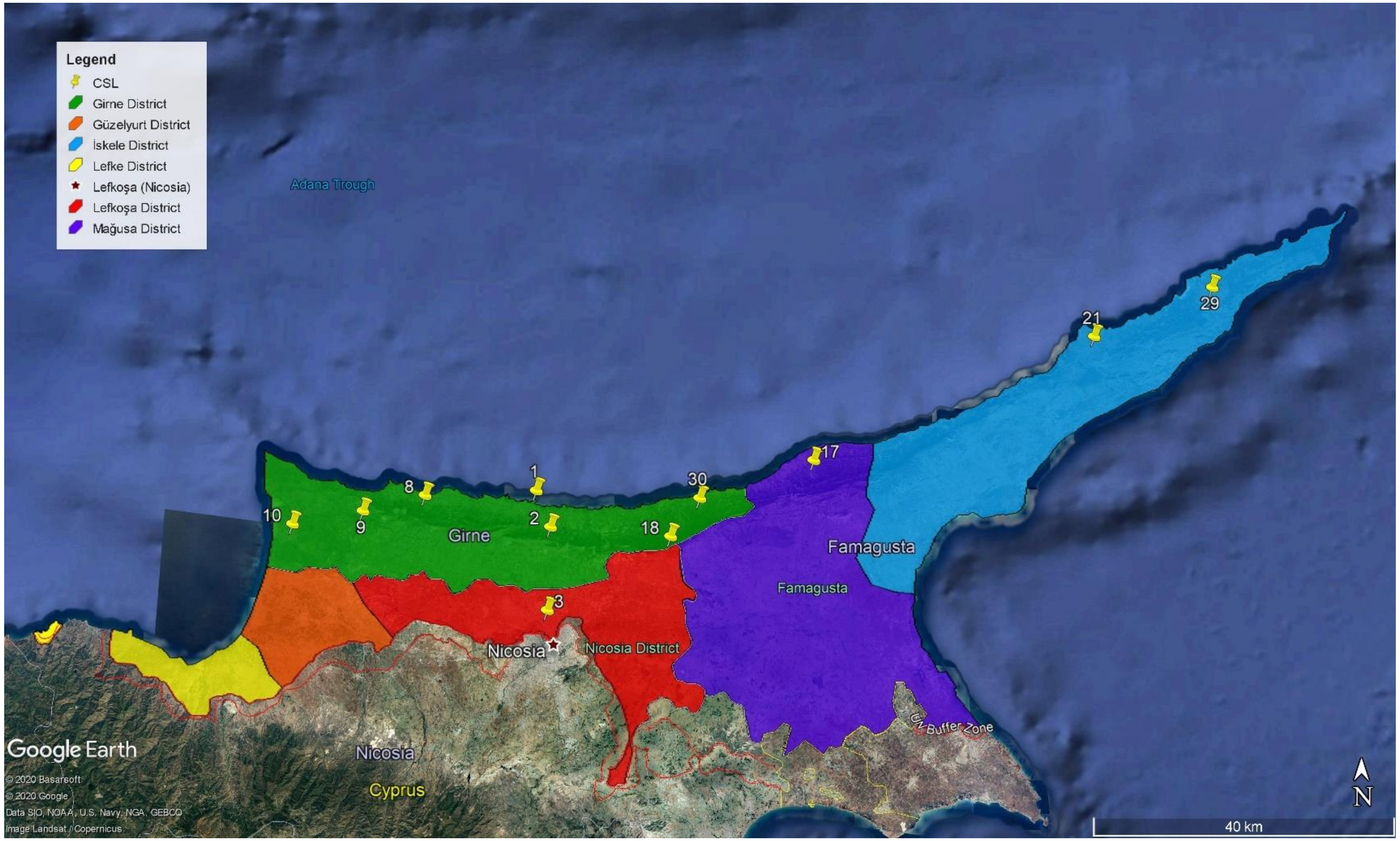


Figure 5.1. Feasible CSLs

As seen in Figure 5.1, except for Lefkoşa, the feasible CSLs are along the north and north-east shores of the country, where the daily average precipitation is relatively higher than at the other locations (see Table 3.1). Seven of eleven CSLs for which the RWHS is identified as feasible are found in the Girne district while the İskele district has two such CSLs, and Lefkoşa and Mağusa districts have one CSL each. Alevkaya, Esentepe, Beylerbeyi and Girne, which are in the Girne district, and Dipkarpaz, which is in the İskele district, are identified to be the ideal sites amongst the rest of the CSLs in terms of investing in RWHSs. Since the unit water costs and the daily average precipitation are high at these locations, NFBs greater than 800 TL are calculated for these locations (see highlighted results in the last column of Table 5.2). The discounted PPs of the feasible CSLs (i.e., CSLs with positive NFBs) are calculated and provided in Table 5.3.

As seen in Table 5.3, the discounted PPs are in the range of 13.2 years and 29.7 years. The discounted PP calculated for a CSL is related to its NFB. For example, for Beylerbeyi, which has the largest NFB value, the discounted PP is calculated as 13.2 years, which is the shortest discounted PP among all CSLs. The maximum discounted PP is 29.7 years for Akdeniz, and this indicates that the total cost of the RWHS investment is paid back at the end of the simulation period. For the CSLs that are not presented in Table 5.3 (i.e., CSLs with negative NFBs), the total cost of the RWHS cannot be compensated within the simulation period of 30 years.

Table 5.3. Discounted PPs of the Feasible CSLs

CSL Number	CSL	District	Discounted PP (year)
1	Girne	Girne	13.6
2	Beylerbeyi	Girne	13.2
3	Lefkoşa	Lefkoşa	21.9
8	Lapta	Girne	24.3
9	Çamlıbel	Girne	26.2
10	Akdeniz	Girne	29.7
17	Tatlısu	Mağusa	24.7
18	Alevkaya	Girne	17.9
21	Yeni Erenköy	İskele	24.6
29	Dipkarpaz	İskele	15.9
30	Esentepe	Girne	18.2
		Average	**20.9**

Although Ziyamet, Yenierenköy, Kantara, Lapta, Çamlıbel and Tatlısu have relatively high daily average precipitation compared to the overall daily average precipitation value, the NFBs are found to be low or negative. The reason is that the municipalities linked with those CSLs employ low water tariffs. Therefore, the daily water demands are mainly fulfilled by the UNs, and the installation of the RWHS is not justified at these CSLs. On the other hand, the NFB is found to be positive for Lefkoşa, whose daily average precipitation is one of the lowest among the other CSLs. But since the unit water cost at Lefkoşa is the highest among all CSLs, the LP model favors rainwater over water from the UN. Although low daily average precipitation is observed at Lefkoşa, the NFB is found to be positive due to the high unit water cost.

Investing in RWHSs is found to be infeasible at Dörtyol, Alayköy, Gönendere, Serdarlı, Vadili, Gaziveren, Lefke, Yeşilırmak, İskele, Geçitkale, Mağusa and Salamis because of the relatively cheap unit water cost and low daily average precipitation. Dörtyol, Alayköy, Gönendere, Serdarlı, Vadili, Gaziveren, and Lefke confirm Roebuck et al. (2010) conclusion that the financial loss which occurs at each CSL is almost equal to the RWHS installation cost. Also, the findings at all CSLs support Roebuck et al. (2010) conclusion that it is vital to consider maintenance costs in financial assessments of RWHSs since they strongly affect the NFB of RWHSs.

Ziyamet has higher daily average precipitation and employs a higher water tariff than Akdeniz. As a result, the optimum RWS tank size at Ziyamet is found to be larger than that of Akdeniz. However, more rainwater is harvested at Akdeniz than that of Ziyamet throughout the simulation period. This is because precipitation at Akdeniz is uniformly distributed through the simulation period when compared to the precipitation distribution at Ziyamet. Hence, the RWHS at Akdeniz is found to be more efficient than the RWHS at Ziyamet, which results in increased benefits at Akdeniz (i.e., $NFB_{Akdeniz} > NFB_{Ziyamet}$). Figure 5.2 shows the 30-year monthly average harvested rainwater in the ideal months at Akdeniz and Ziyamet.

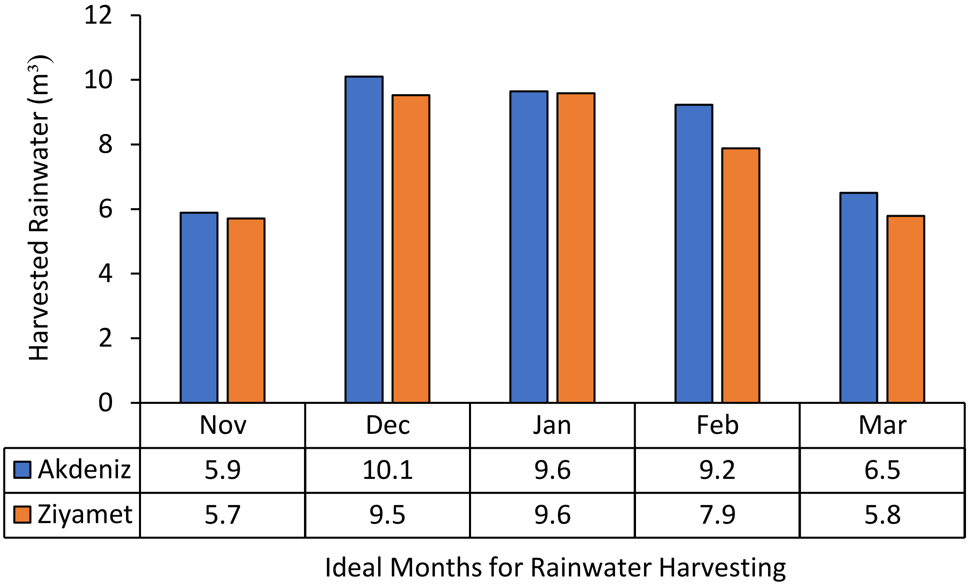


Figure 5.2. 30-year Monthly Average Harvested Rainwater in the Ideal Months at Akdeniz and Ziyamet

The ideal months for rainwater harvesting in NC are identified as November, December, January, February and March since the harvested rainwater in these months is relatively higher than the rest of the year. The concept of the ideal months for rainwater harvesting is explained in detail in Section 5.2.2. In Figures 5.3 and 5.4, deviations from the average daily precipitation of the ideal months for rainwater harvesting at Akdeniz and Ziyamet throughout the simulation period of 30 years are provided.

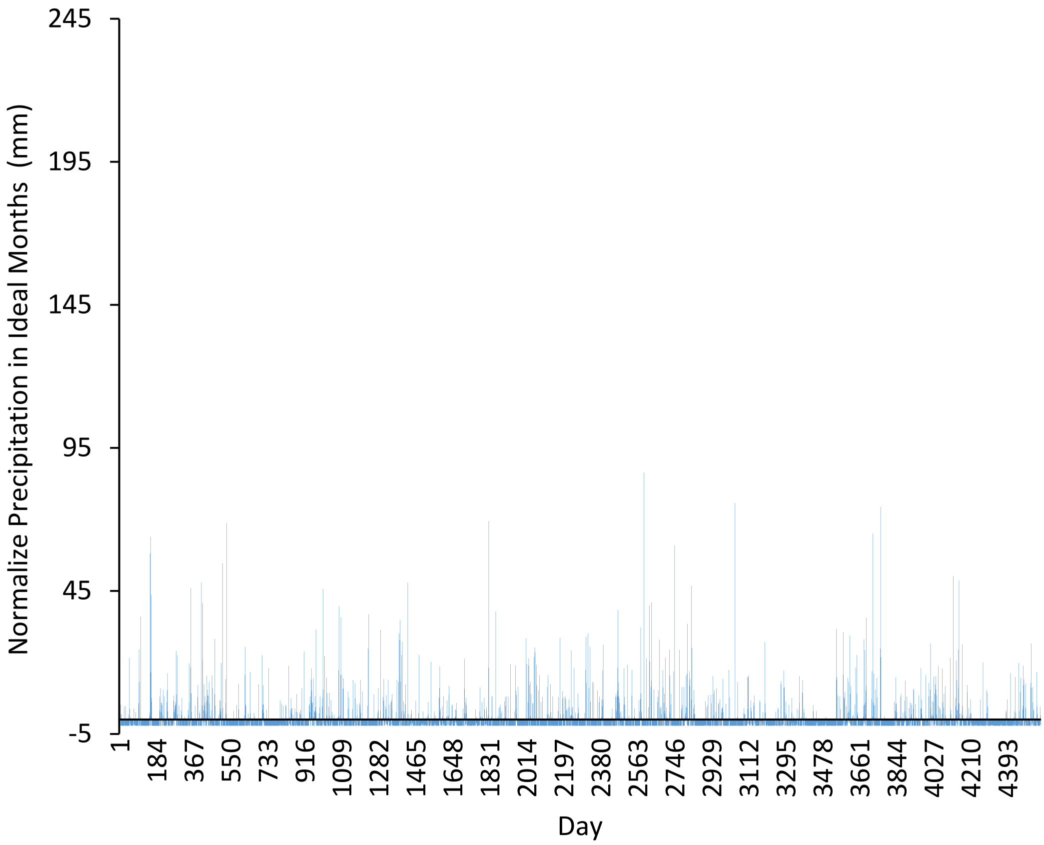


Figure 5.3. Deviations from the Average Daily Precipitation of the Ideal Months for Rainwater Harvesting at Akdeniz throughout the simulation period

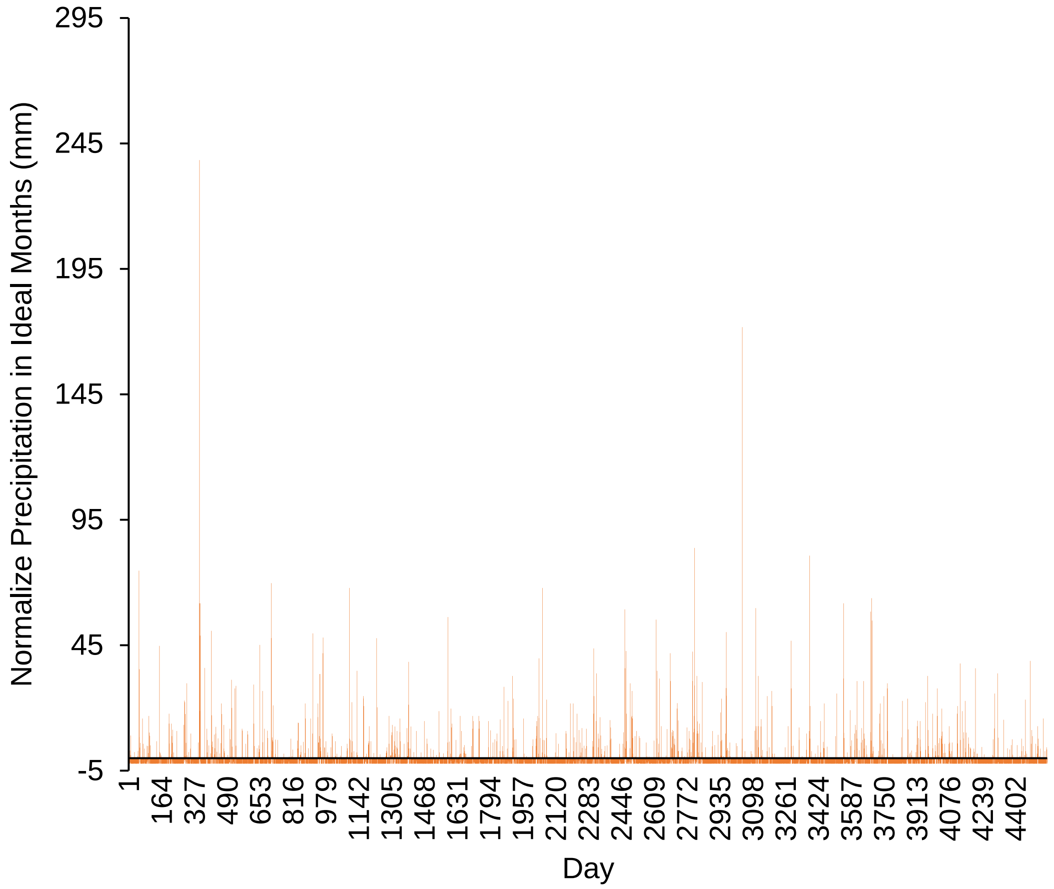


Figure 5.4. Deviations from the Average Daily Precipitation of the Ideal Months for Rainwater Harvesting at Ziyamet throughout the simulation period

Yeşilırmak and Lefke employ the same water tariff. Although Yeşilırmak gets more daily average precipitation than Lefke, the optimum RWS tank sizes at these two CSLs are found to be similar. The number of days for which the amount of daily precipitation exceeds the optimum RWS tank size at Yeşilırmak is greater than that of Lefke. In other words, at Yeşilırmak, the RWS tank overflows more than Lefke throughout the simulation period of 30 years (see Figure 5.5).

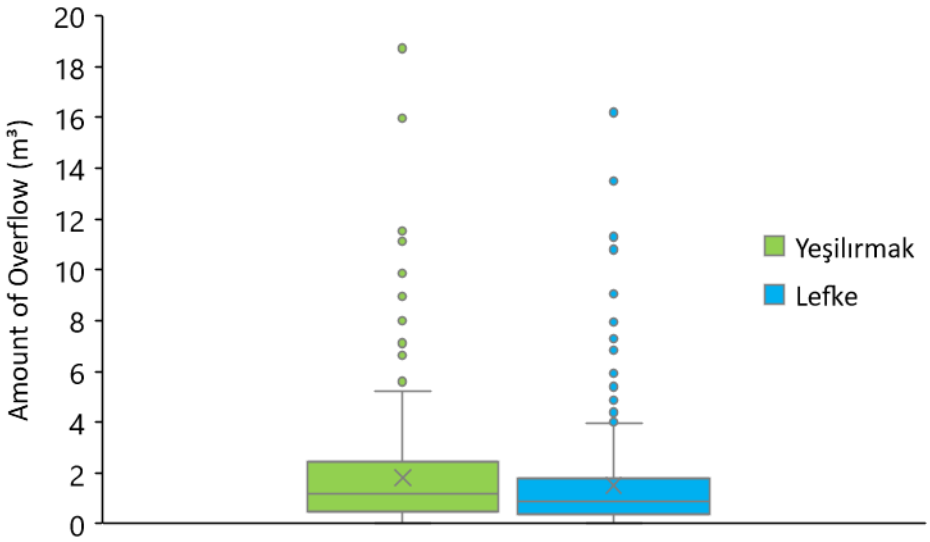


Figure 5.5. Amount of Overflow at Yeşilırmak and Lefke

The distribution of daily precipitation at Yeşilırmak leads to excess water (i.e., the amount of precipitation exceeds tank capacity) that cannot be harvested. Increasing the RWS tank size, of course, increases the amount of harvested rainwater, but this investment is not justified with the increase in the contribution of rainwater utilization in supplying the water demand. So, the RWS tank sizes are not further increased, and as a result, equal optimal RWS tank sizes are obtained for Lefke and Yeşilırmak.

Though the unit water costs used at Güzelyurt, Değirmenlik, Ercan, and Zümrütköy are above the average, the NFBs are found to be negative due to the low daily average precipitation. Similarly, because of the insufficient daily precipitation, the NFB is nearly found to be zero for Akdeniz even if its unit water cost is above the average. Mehmetçik, Boğaz, Beyarmudu and Çayırova are found to be infeasible due to the poor daily average precipitation and the moderate unit water cost.

5.2. Water Supply and Demand and Rainwater Harvesting Analyses at CSLs

In this section, water supply and demand patterns, and rainwater harvesting characteristics of the RWHSs that are obtained by solving the LP models are analyzed and discussed for the CSLs. First, the 30-year monthly average water supply and demand patterns at each CSL are presented. Second, the 30-year monthly harvested rainwater box plots and the figures which illustrate the 30-year monthly average harvested rainwater versus the 30-year monthly average maximum rainwater that could be harvested are given for all CSLs. As an example CSL, the 30-year daily average water supplies (i.e., from the RWHS and the UN) and demand pattern, the daily water supplies and demand relations for each day of the simulation period, and tank size-based overflow estimations are investigated for Lefkoşa. Finally, the LP model is used to carry out a sensitivity analysis for Lefkoşa RWHS to investigate the effects of a various number of residents, collector areas at the roof, discount rates, daily average domestic water consumptions per capita and RWS tank unit costs on the RWS tank size and the NFB.

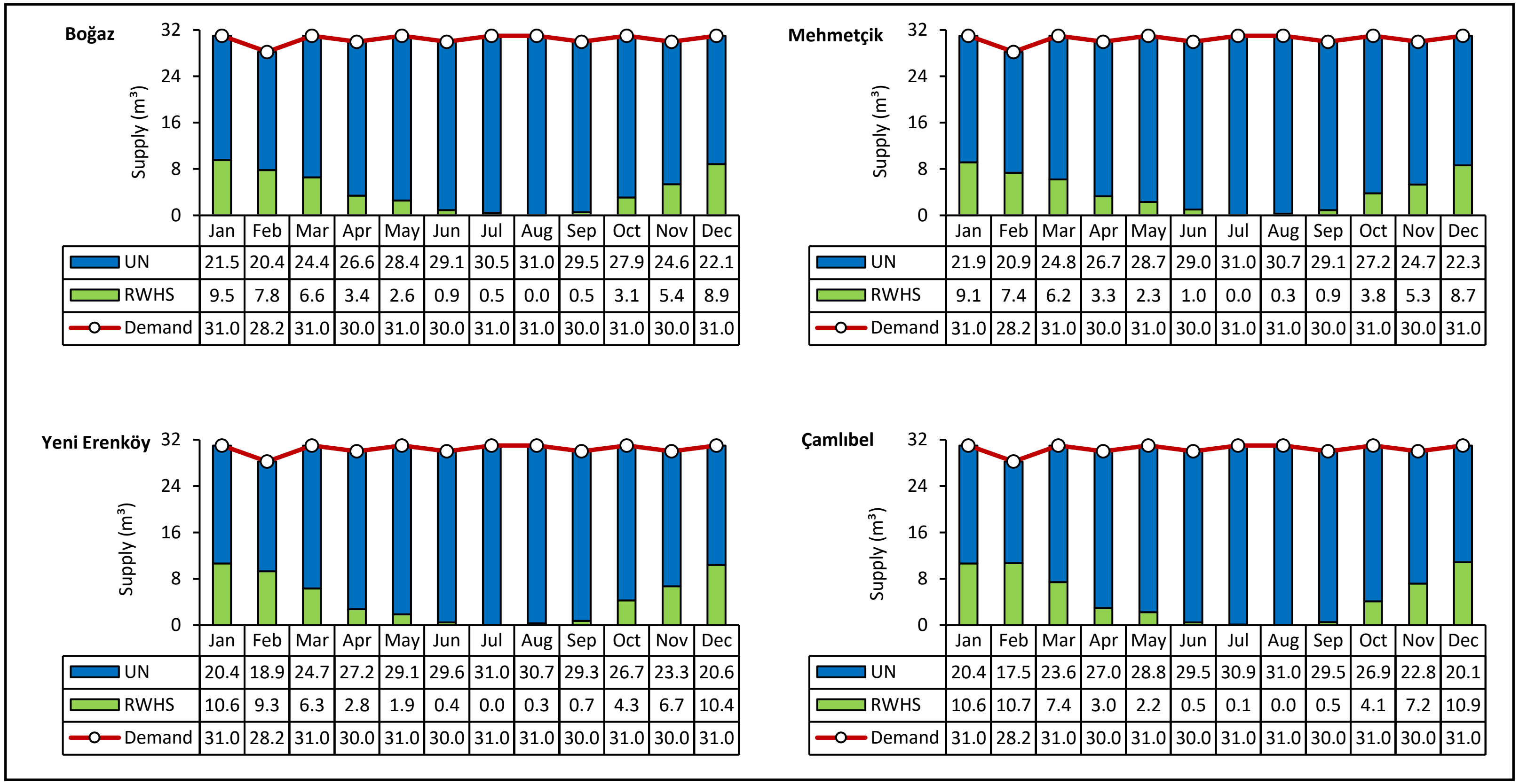
5.2.1. Monthly Water Supply and Demand at CSLs

The daily water demand is calculated for a family of four using Equation (4.15). The monthly water demand is calculated by summing the water demand of a family of four of each day of each month throughout the simulation. The total monthly water demand is calculated by summing the monthly water demand of a family of four throughout the simulation period. The total monthly water demand is divided by 30 to calculate the 30-year monthly average water demand of a family of four.

The 30-year monthly average water supply is calculated by dividing the total monthly water supply throughout the simulation period by 30. The 30-year monthly average water supplies (i.e., water supplied from the UN and rainwater supplied from the RWHS) and the 30-year monthly average demand relations are calculated for each CSL and given in Appendix B (see Figures B.1 to B.33).

As seen in Figures B.1 to B.33, the 30-year average water demand is not completely supplied from the RWHSs for any month at any CSL. It is observed that the large amounts of rainwater are used from the RWS tanks in winters while the minimum amounts are used in summers for all CSLs. The RWHSs support the UNs in January and December more than they do in other months in meeting the monthly water demand. It is revealed that rainwater supply is poor at all CSLs in June, July, August and September, particularly in July and August. Therefore, it is recommended to overhaul the RWHSs in the dry months, such as July and August, to minimize the loss in rainwater savings due to rainwater utilizations.

It is observed that the 30-year monthly average rainwater supply, which is approximately 40% of the monthly average domestic water demand of a family of four in NC, is attained at a maximum at Lapta in January (see Figure B.14). On the other hand, the 30-year monthly average rainwater supply is found to be zero for Mağusa in June (see Figure B.11), for Yeni Erenköy and Mehmetçik in July, and for Çamlıbel and Boğaz in August (see Figure 5.6).



Boğaz

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.5	20.4	24.4	26.6	28.4	29.1	30.5	31.0	29.5	27.9	24.6	22.1
RWHS	9.5	7.8	6.6	3.4	2.6	0.9	0.5	0.0	0.5	3.1	5.4	8.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Mehmetçik

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.9	20.9	24.8	26.7	28.7	29.0	31.0	30.7	29.1	27.2	24.7	22.3
RWHS	9.1	7.4	6.2	3.3	2.3	1.0	0.0	0.3	0.9	3.8	5.3	8.7
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Yeni Erenköy

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.4	18.9	24.7	27.2	29.1	29.6	31.0	30.7	29.3	26.7	23.3	20.6
RWHS	10.6	9.3	6.3	2.8	1.9	0.4	0.0	0.3	0.7	4.3	6.7	10.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Çamlıbel

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.4	17.5	23.6	27.0	28.8	29.5	30.9	31.0	29.5	26.9	22.8	20.1
RWHS	10.6	10.7	7.4	3.0	2.2	0.5	0.1	0.0	0.5	4.1	7.2	10.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure 5.6. 30-year Average Water Supply and Demand at Boğaz, Mehmetçik, Yeni Erenköy and Çamlıbel

It is detected that the 30-year monthly average rainwater supply exceeds the optimum RWS tank sizes in many months at the CSLs, which shows that the RWS tanks are filled with rainwater and emptied numerous times to supply the demands in months throughout the simulation period of 30 years.

Here only a single house that accommodates four people is considered. If similar optimization models are designed and solved for larger buildings or collections of individual houses, larger rainwater harvesting tanks may become optimum and more rainwater can be harvested and used in supplying the demand.

5.2.2. Rainwater Harvesting at CSLs

The 30-year monthly average harvested rainwater is calculated by dividing the total monthly harvested rainwater throughout the simulation period by 30. The 30-year monthly average harvested rainwater and the monthly harvested rainwater throughout the simulation period of 30 years are calculated for each CSL and demonstrated in Appendix C (see Figures C.1 to C.33).

As displayed in Figures C.1 to C.33, the harvested rainwater throughout the simulation period of 30 years is non-uniformly distributed through months at all CSLs. The highest amount of the harvested rainwater throughout the simulation period of 30 years is achieved in December at most of the CSLs. Low rainwater is harvested in July and August at all CSLs throughout the simulation period of 30 years.

June and September are the most unpredictable months (i.e., the variations are high) in terms of rainwater harvesting because of the various amounts of precipitation throughout the simulation period of 30 years. For example, the average harvested rainwater is calculated as approximately 1.40 m^3 for Alevkaya in June (see Figure C.27). Almost zero volume is calculated for many CLSs like Güzelyurt and Akdeniz in June (see Figure 5.7). Whereas roughly 1.55 m^3 of rainwater is harvested on a 30-year average in September at Tatlısu, nearly zero rainwater is harvested on a 30-year average in September at Gaziveren (see Figure 5.7).

The monthly average harvested rainwater is found to be 0.23 m^3 in July for Tatlısu (see Figure C.7). However, the monthly average rainwater supply is found to be 1.1 m^3 in July for Tatlısu (see Figure B.7). The monthly average rainwater supply is higher than the monthly average harvested rainwater in July for Tatlısu. This is because whenever the water which is supplied from the UN exceeds 30 m^3, the unit cost of water increases according to the Tatlısu municipality's increasing block rate tariff (see Table 3.2). Therefore, the LP model designed for Tatlısu ensures the municipal water supply is kept below 30 m^3 by using the harvested and stored rainwater in the previous month for July to purchase municipal water at the low level of the unit water cost in the increasing block rate tariff of Tatlısu municipality. Note that the harvested rainwater is not stored for the following months at the CSLs, where a fixed-unit rate water tariff is employed.

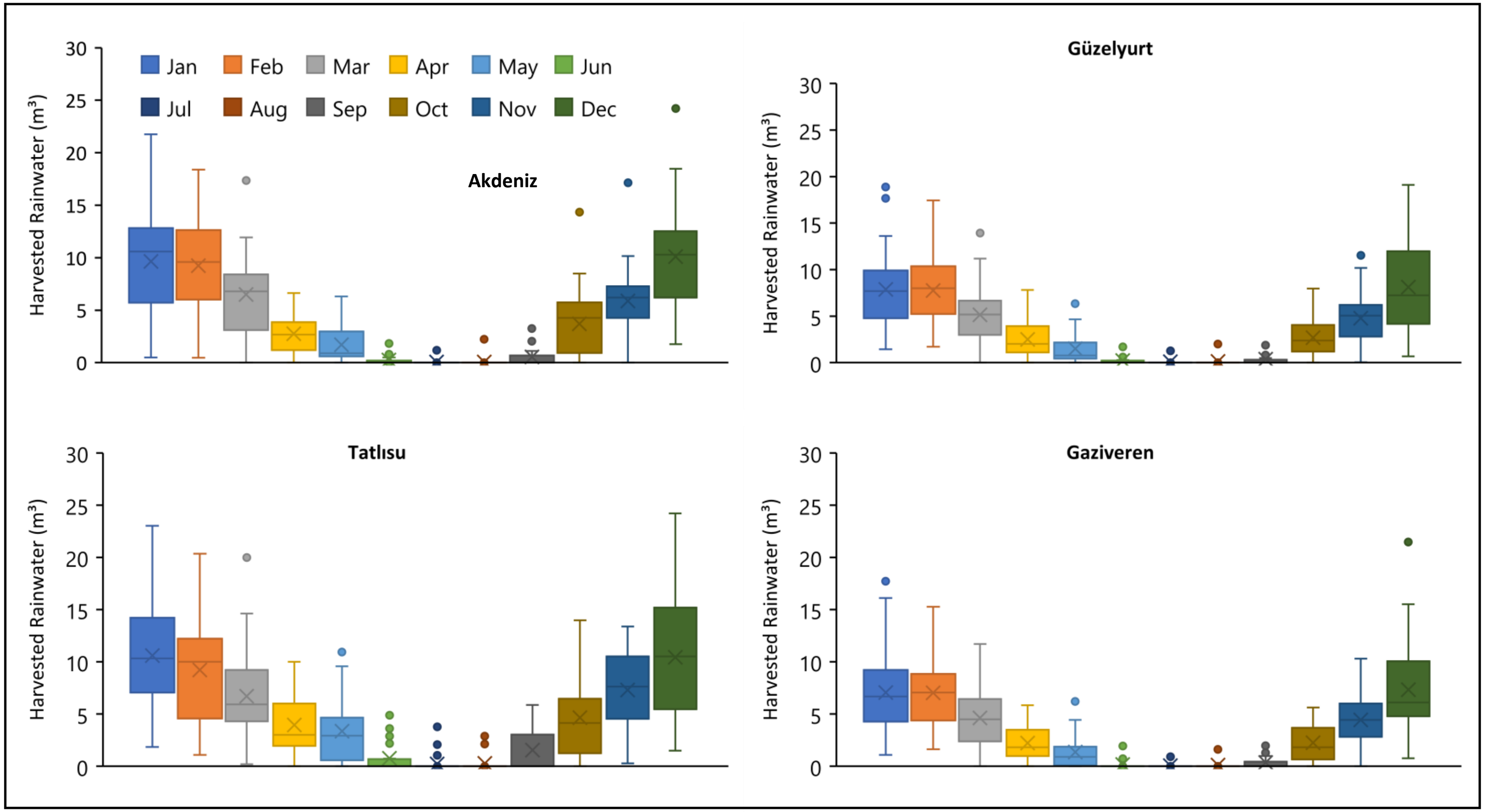


Figure 5.7. 30-year Harvested Rainwater at Akdeniz, Güzelyurt, Tatlısu and Gaziveren

The monthly average harvested rainwater of all CSLs is calculated as 3.88 m^3. The monthly average harvested rainwater among all CSLs is calculated as 5 m^3 at a maximum for Lapta while the minimum is calculated as 2.67 m^3 for Dörtyol. The monthly average harvested rainwater among all CSLs and months is calculated as 11.90 m^3 at a maximum for Dipkarpaz in December (see Figure C.22). The amount of 11.90 m^3 water can supply more than 40% of a monthly average domestic water demand of four people of 30 m^3 (i.e., 0.25 m^3/day/capita $\times$ 30 days/month $\times$ 4 people) and 158% of a monthly average domestic water demand per capita of 7.5 m^3 in NC.

As seen in Figures C.1 to C.33, rainwater harvesting at all CSLs is observed to be ideal in November, December, January, February, and March. This is because it is calculated that the monthly average rainwater of 7.20 m^3 is harvested in the ideal months at all CSLs, which is nearly two times higher than the 30-year monthly average harvested rainwater at all CSLs (i.e., 7.20 $m^3 >$ 3.88 m^3). The amount of 7.20 m^3 water can supply more than 95% of the monthly average domestic water demand per capita in NC. The 30-year monthly average harvested rainwater of the ideal months among all CSLs is calculated as 4.74 m^3 at a minimum for Dörtyol. Also, the 30-year monthly average harvested rainwater among all CSLs and the ideal months is calculated as 3.37 m^3 at a minimum for Dörtyol in November (see Figure C.33). This amount of water is almost equal to 45% of the monthly average domestic water demand per capita in NC.

The 30-year monthly average harvested rainwater of the ideal months among all CSLs is calculated as 9.81 m^3 at a maximum for Lapta. The amount of 9.81 m^3 water is more than 130% of the monthly average domestic water demand per capita in NC. It can supply approximately 33% of the monthly average domestic water demand of four people in NC.

When the ideal months are ignored, the 30-year monthly average harvested rainwater of all CSLs is calculated as 1.52 m^3 for the rest of the months. There is a huge difference between the 30-year monthly average harvested rainwater of the ideal months and the 30-year monthly average harvested rainwater of the rest of the months (i.e., $7.2\ m^3 > 1.52\ m^3$). Thus, the harvested rainwater in the ideal months can be stored in the RWS tanks in order to be used for the dry months or in case of an emergency like drought or a failure in the NC Water Supply System.

The daily maximum rainwater that can be harvested from the roof of the building through collectors is calculated for every day of the simulation period of 30 years using Equation (4.13). The monthly maximum rainwater that can be harvested is calculated by summing the daily maximum rainwater that can be harvested for all days of every month throughout the simulation period. The total monthly maximum rainwater that can be harvested is calculated by summing the monthly maximum rainwater that can be harvested of every month of the simulation period. The total monthly maximum rainwater that can be harvested is divided by 30 to calculate the 30-year monthly average maximum rainwater that can be harvested. That calculation is done for each CSL.

The 30-year monthly average precipitation is calculated for each CSL by dividing the total monthly precipitation throughout the simulation period by 30. The 30-year monthly average harvested rainwater, monthly average maximum rainwater that can be harvested and monthly average precipitation for each CSL are given in Appendix D (see Figures D.1 to D.33).

As seen in Figures D.1 to D.33, the 30-year monthly average harvested rainwater and the 30-year monthly average maximum rainwater that can be harvested are found to be almost equal in the summer months at all CSLs. The difference between the monthly average harvested rainwater and the monthly average maximum rainwater that can be harvested is significant at all CSLs in January, February, March, November and December throughout the simulation period of 30 years.

As seen in Figure 5.8, there is a significant difference between the monthly average harvested rainwater and the monthly average maximum rainwater that can be harvested at Kantara. It is calculated that about 59% of the annual average precipitation throughout the simulation period of 30 years (i.e., $p_{avg.total}^{1985-2015} = 562$ mm, $p_{avg.harvest}^{1985-2015} = 330$ mm), which is the least percentage among all CSLs, is harvested at Kantara. This percentage is calculated as 78% for Akdeniz, which is the highest percentage among all CSLs. At most of the CSLs, around 71% of the annual average precipitation throughout the simulation period of 30 years is harvested and used in supplying the water demand.

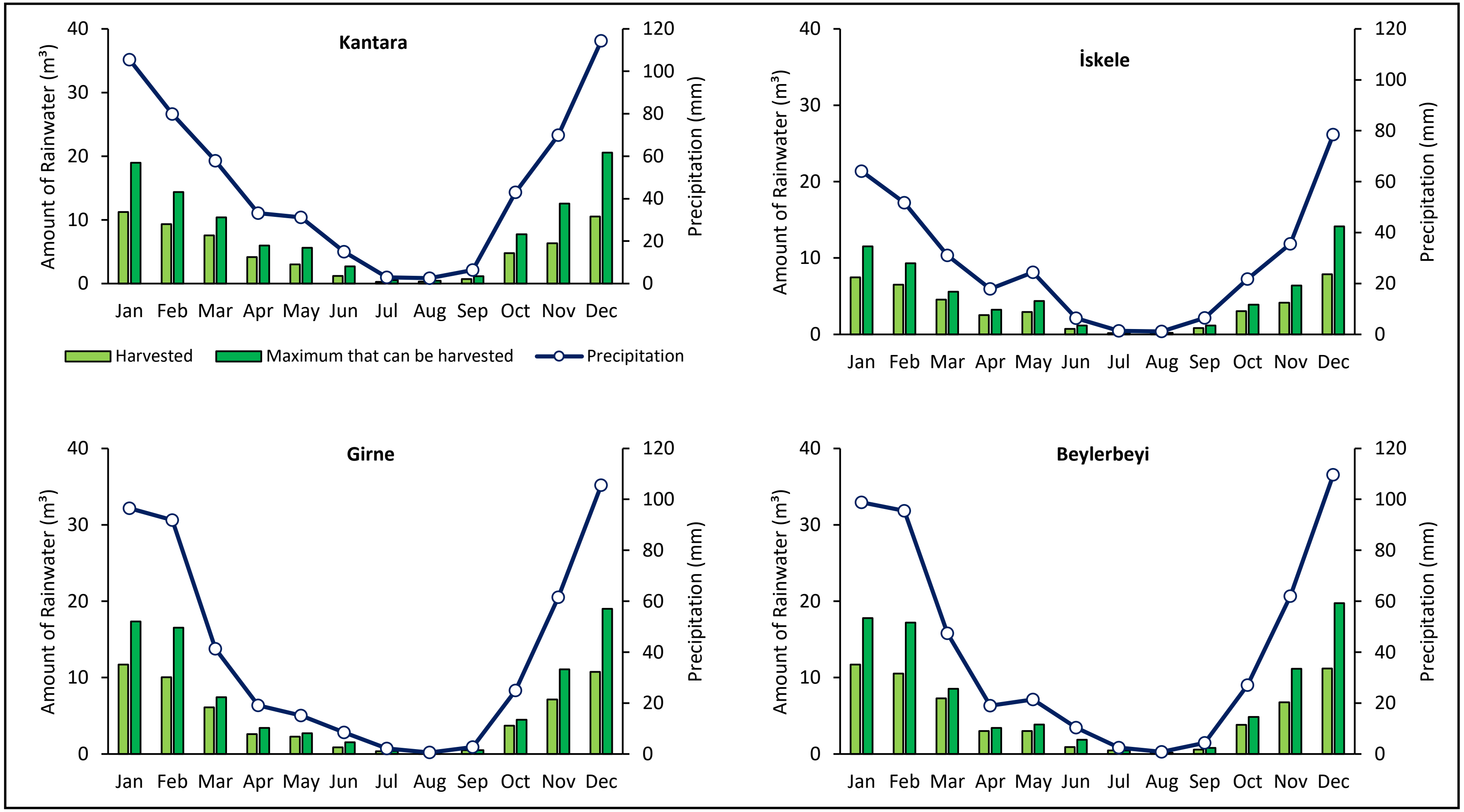


Figure 5.8. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Kantara, İskele, Girne, and Beylerbeyi

Water price is one of the most important parameters of the optimization models that affects the optimum RWS tank sizes. For example, in Figure 5.8, nearly 55% of the annual average precipitation in December (i.e., $p_{December}^{avg.\ 1985-2015} = 78.5$ mm) is harvested at İskele ($p_{avg.\ harvest}^{December\ avg.\ 1985-2015} = 44$ mm) throughout the simulation period of 30 years. The optimum RWS tank size at İskele is not further increased to harvest more rainwater in December because, in turn, it will increase the cost of the RWHS. Therefore, some portion of the water demand is supplied from the RWHS and the remaining water demand is supplied from the UN due to the relatively low unit water price at İskele.

As seen in Figures D.1 to D.33, the 30-year monthly average precipitation distribution at the CSLs considerably varies by months. This directly affects the optimum RWS tank sizes. As demonstrated in Figure 5.8, the 30-year monthly average precipitation is non-uniformly distributed through months at Girne and Beylerbeyi.

On the other hand, the monthly average precipitation is relatively high at Girne district, where Girne and Beylerbeyi are located. Even if the unit water cost is relatively high at Girne municipality compared to the rest of the municipalities (see Table 3.2), the optimum RWS tank sizes at Girne and Beylerbeyi are not found to be large enough. For example, the optimum RWHSs at Girne and Beylerbeyi harvest around 76% of the annual average precipitation throughout the simulation period of 30 years. Nearly 24% of the annual average precipitation throughout the simulation period of 30 years (i.e., equal to 20 m^3 and 23 m^3 of the annual average rainwater that can be harvested throughout the simulation period of 30 years) is not harvested at Girne and Beylerbeyi, respectively. These amounts of water can approximately meet the monthly average domestic water demand of a family of three in NC.

It is calculated that the optimum RWHSs at Girne and Beylerbeyi harvest almost 57% of the 30-year monthly average maximum rainwater that can be harvested in December. On the other hand, 100% of the 30-year monthly average maximum rainwater that can be harvested in July and August is harvested at Girne and Beylerbeyi. This is due to the non-uniform precipitation distribution in those months, and it leads to the loss of rainwater that could be harvested. Some amount of the loss in December would be harvested if the monthly precipitation distributions at Girne and Beylerbeyi were more uniform. These findings reveal that in addition to the water cost and precipitation, the precipitation distribution is an important factor that affects the optimum size of the RWS tank, and as a result, rainwater that can be harvested. As an example, the water supply and demand patterns and the rainwater harvesting characteristics are further investigated for Lefkoşa on a daily basis, and the results are presented in Section 5.2.3.

5.2.3. Daily Water Supply and Demand Analyses for Lefkoşa

In this section, the daily average water supplies (i.e., from the RWHS and the UN) and demand of Lefkoşa are analyzed. Lefkoşa is selected as the case site for this analysis. The daily average value for day i is calculated by summing up all the values for the i^{th} day of all the years of the simulation period (i.e., from 1985 to 2015) and dividing by the total number of years (i.e., 30 years). Daily average values for all days of a year are calculated (i.e., $i = 1,2, \ldots, 365$).

Lefkoşa, which is located in the center of NC, is the most crowded city in the country (SPO, 2011). Consequently, a relatively large amount of water needs to be transferred from the Geçitköy reservoir by a 67 km long pipeline to the city (see Figure 3.1). About 34% of the total municipal water consumed in NC was only used at Lefkoşa in 2002 (Elkiran and Ergil, 2006). As stated in Chapter 3, the average unit water price at Lefkoşa is higher than those of the other CSLs. Additionally, its daily average precipitation between 1985 and 2015 is one of the lowest among the other CSLs, which addresses the water scarcity problem at Lefkoşa. The daily average water supply values from the UN and the RWHS, the daily water demand values, and the daily average precipitations are plotted for each day of January and given in Figure 5.9.

Similar plots to Figure 5.9 are prepared for all months and provided in Appendix E (see Figures E1 to E12). The daily average water supply from the RWHS at Lefkoşa is almost zero throughout August (see Figure E.8). On the other hand, 24% of the daily average water demand is supplied by the RWHS in December (see Figure E.12). It is calculated that on average, 11% of the daily average water demand is supplied by the RWHS throughout the year. The daily average water supply from the RWHS exceeds 11% of the daily average water demand in January, February, March, November and December, which were previously identified as the ideal months for rainwater harvesting in NC (see Section 5.2.2).

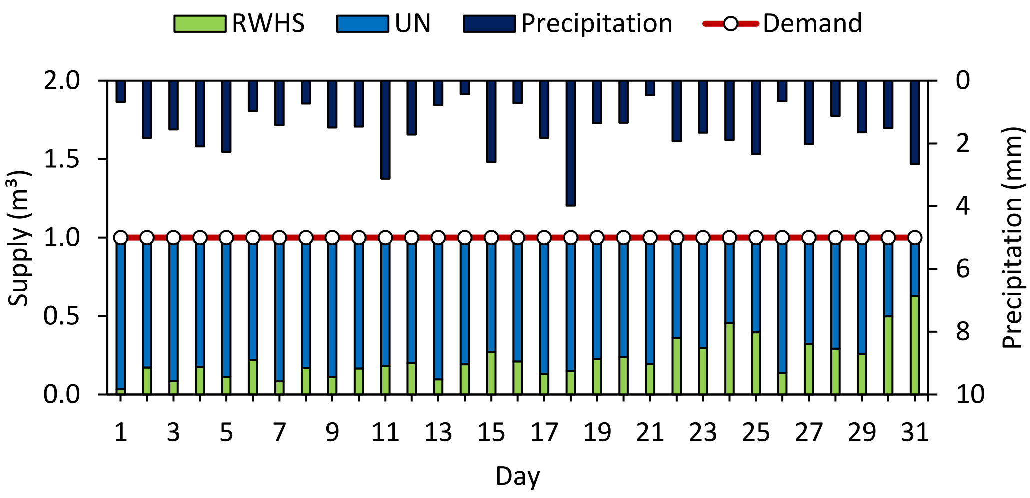


Figure 5.9. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in January

When Figures E.1 to E.12 are analyzed, it can be observed that the daily average water demand is never fully supplied from the RWHS. Moreover, the results of the LP model indicate that the optimum RWS tank overflows for 181 days of the simulation period of 30 years. Next, the simulation period of 30 years is investigated day by day and the number of days in which the daily water demand is supplied from the RWHS with different percents are calculated and given in Table 5.4.

Table 5.4. Daily Water Supply from the RWHS and Daily Water Demand Relations for Lefkoşa

Daily Water Supply from RWHS/Daily Water Demand (%)	Number of Days
0	9189
1-10	159
11-25	148
26-50	242
51-75	144
75-99	125
100	950
Total	**10957**

As seen in Table 5.4, the daily water demand is fully supplied by the RWHS on 950 days of the simulation period at Lefkoşa. The UN completely supplies the daily water demand for nearly 84% of the simulation period. The RWHS supplies more than half of the daily water demand for almost 11% of the simulation period. To better understand the operation details of the RWHS, the daily water balance for a selected month (i.e., February 1992) at Lefkoşa is investigated in more detail using the results of the LP model and provided in Table 5.5.

As seen in Table 5.5, sometimes the harvested rainwater is not used in the day it is collected, but kept in the RWS tank to be used in the following days. For example, the inventory level of the RWS tank for February 6th shows that the RWS tank was full at the end of the day, and it can supply 100% of the daily water demand (i.e., 1 m^3) on February 7th.

Table 5.5. Water Balance at Lefkoşa* in February 1992

Date	**Harvested Rainwater, rd_i^t (m³)**	**Rainwater used from the RWS Tank to Supply the Demand, Ud_i^t (m³)**	**Inventory Level of the RWS Tank at the End of the Day, Id_i^t (m³)**	**Max. Rainwater that could be Harvested, Rd_i^t (m³)**
1-Feb-92	0.00	0.00	0.00	0.00
2-Feb-92	0.16	0.00	0.16	0.16
3-Feb-92	2.32	1.00	1.48	3.40
4-Feb-92	0.16	1.00	0.65	0.16
5-Feb-92	2.32	0.65	2.32	2.65
6-Feb-92	0.58	0.58	2.32	0.58
7-Feb-92	0.00	0.56	1.76	0.00
8-Feb-92	0.56	0.00	2.32	0.56
9-Feb-92	0.00	0.00	2.32	0.00
10-Feb-92	0.00	0.00	2.32	0.00
11-Feb-92	0.02	0.02	2.32	0.02
12-Feb-92	0.16	0.48	2.00	0.16
13-Feb-92	0.00	0.00	2.00	0.00
14-Feb-92	0.00	0.00	2.00	0.00
15-Feb-92	0.00	0.00	2.00	0.00
16-Feb-92	0.00	0.00	2.00	0.00
17-Feb-92	0.00	1.00	1.00	0.00
18-Feb-92	0.00	0.00	1.00	0.00
19-Feb-92	0.00	1.00	0.00	0.00
20-Feb-92	0.00	0.00	0.00	0.00
21-Feb-92	0.92	0.00	0.92	0.92
22-Feb-92	0.40	0.00	1.31	0.40
23-Feb-92	0.25	1.00	0.57	0.25
24-Feb-92	0.00	0.00	0.57	0.00
25-Feb-92	0.00	0.00	0.57	0.00
26-Feb-92	0.09	0.00	0.66	0.09
27-Feb-92	0.00	0.00	0.66	0.00
28-Feb-92	0.00	0.00	0.66	0.00
29-Feb-92	0.00	0.66	0.00	0.00
Feb-92	**7.94**	**7.94**	**-**	**9.34**

* Optimum RWS tank size is 2.32 m³ for Lefkoşa (see Table 5.2).

However, on February 7th, rainwater is used from the RWS tank to supply 55% of the daily water demand. In other words, the amount of rainwater used from the RWS tank on February 7th is 0.56 m^3 (see Table 5.5). The same amount of rainwater harvested on February 8th is used from the RWS tank on February 7th (see Table 5.5). This is the maximum rainwater that could be harvested for February 8th. In other words, the LP model knows that 0.56 m^3 will be available as precipitation on February 8th, and used exactly that much from the RWS tank on February 7th. Till February 11th, since there is no precipitation, no rainwater is harvested. Then, on February 11th, 0.02 m^3 of precipitation falls, and it is harvested and used to supply the demand. Such scheduling is possible because the LP model sees daily precipitation amounts of the whole simulation period and adjusts the utilization of water from the RWHS or UN in the most economical way.

However, in practice, the future precipitation amounts are unknown, so it will not be possible to carry out such adjustments. Therefore, the assumption for this study is that past 30 years' precipitation pattern is representative of the coming years. If the identified optimum tank sizes are implemented, they will work effectively, at least in the near future.

As seen in Table 5.5, the maximum amount of rainwater that can be harvested on February 3rd is 3.40 m^3, and at the end of February 2nd, there are 0.16 m^3 of water in the RWS tank. On February 3rd, at first, 0.16 m^3 of water is used from the RWS tank to supply 0.16 m^3 of the daily demand (i.e., 1 m^3). Then, 2.32 m^3 RWS tank capacity is filled with the rainwater that falls on February 3rd (i.e., 3.40 m^3). Remaining 1.08 m^3

(i.e., $3.40\ m^3 - 2.32\ m^3$) of rainwater overflows on February 3rd. In other words, the RWS tank overflows in the days when the maximum rainwater that can be harvested together with the amount of water found in the RWS tank at the beginning of that day (i.e., after the demand of that day is supplied) exceeds the optimum RWS tank size. This effect can only be detected and used when the optimization model is run in daily time steps.

The use of the daily time steps in the optimization problems of RWS tank size ensures the effective utilization of the harvested rainwater. For example, a total of 7.94 m^3 of rainwater is harvested and used in February 1992 (see the last row of Table 5.5). This shows that the optimum rainwater RWS tank is filled and emptied multiple times in February. If monthly time steps are used in the optimization problems, the RWS tank is allowed to be filled and emptied only once a month, and the rest of the precipitation in that month is not harvested and utilized (see Ruso et al., 2019 results). Consequently, the NFBs calculated and the optimum RWS tank sizes identified using daily time steps are more efficient and realistic.

The number of days that the optimum RWS tank at Lefkoşa overflows throughout the simulation period is determined by identifying the days for which the maximum rainwater that could be harvested plus the amount of water found at the beginning of the day after the demand is supplied is higher than the RWS tank size. Additional analysis is carried out to determine the amount of overflow that can be prevented by increasing the RWS tank size above the optimum value identified through the LP model. The results are demonstrated in Table 5.6.

Table 5.6. Tank Size based Overflow Estimations at Lefkoşa

Increase in the RWS Tank Size (%)	RWS Tank Size (m³)	Number of Days that the RWS Tank Overflows	Amount of Overflow (m³)	Overflow that can be prevented (m³)
0	**2.3**	**181**	**383.3**	**0**
10	2.6	165	257.5	125.7
25	2.9	140	241.7	141.6
50	3.5	93	212.8	170.5
75	4.1	76	175.9	207.4
100	4.6	59	141.4	241.9
655	17.5	0	0	383.3

As seen in Table 5.6, it is observed that the optimum RWS tank at Lefkoşa overflows in 181 days of the 30-year simulation period. A total of 383 m^3 of rainwater (i.e., higher than the annual average domestic water demand of a family of four in NC) is wasted (see the bold row in Table 5.6). When the RWS tank size is increased by 10% to 75%, the amount of overflow decreases by 35% to 55% of the original overflow (i.e., 383 m^3). If the optimum tank size is increased by 100%, almost 65% of the original overflow can be harvested. All 383 m^3 of the overflow can be harvested if the optimum tank size is increased by 650%. Increasing the RWS tank size increases the RWS tank's cost and the total cost of the RWHS. If decision-makers provide incentives for the installation cost of the RWHS or the maintenance cost of the RWHS, investing in large RWS tanks may become financially feasible.

5.2.4 Sensitivity Analysis for Lefkoşa RWHS

The LP model is used to carry out a sensitivity analysis for Lefkoşa RWHS. In the sensitivity analysis, only one parameter is changed, while the rest of the parameters are assumed to be constant as specified originally. The sensitivity analysis aims to identify the effect of the various parameters on the financial feasibility of the RWHS and the optimum RWS tank size.

First, the number of residents is changed between one and eight. Its effect on the RWS tank size and the NFB is presented in Figure 5.10. The optimum RWS tank size is found to be in the range of 1.28 m^3 and 2.57 m^3 for the number of residents between one and eight. The optimum RWS tank size increases as the number of residents increases to seven. The optimum RWS tank size stabilizes at around 2.57 m^3 for higher than seven residents. The NFB is calculated to range from - 1248 TL to 432 TL when the number of residents is increased from one to eight. For one resident and two residents, the RWHS investment is found to be financially infeasible. The NFB is identified as positive, starting from three residents. The increase in the NFB is minimal (i.e., smaller than 0.05 TL) when the number of residents is increased above seven people. In other words, the NFB is not sensitive to the number of residents after seven people.

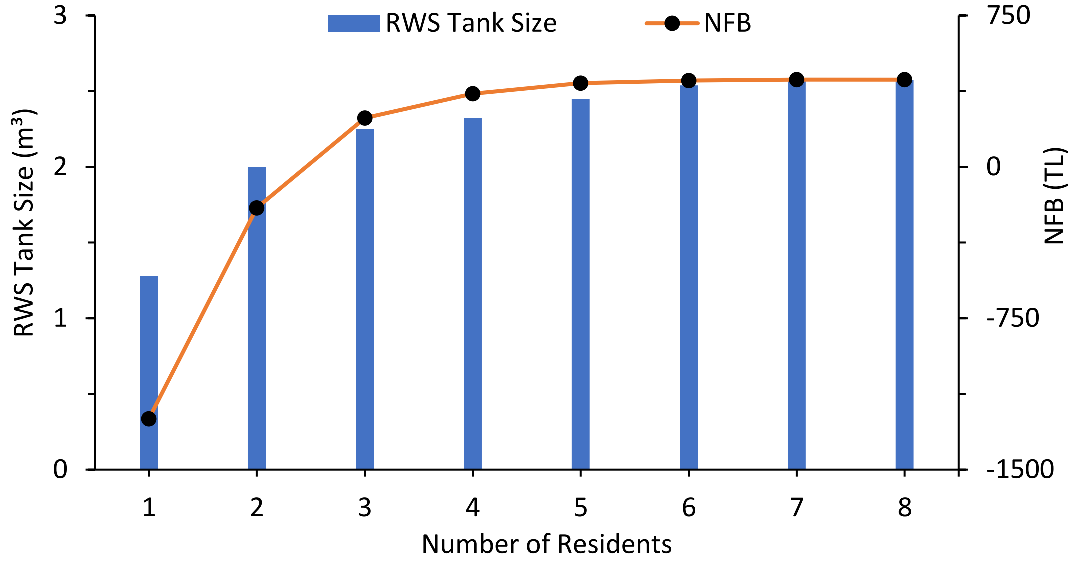


Figure 5.10. Effect of the Number of Residents on the RWS Tank Size and the NFB

Second, the collector area at the roof is changed between 50 m^2 and 300 m^2. The results are demonstrated in Figure 5.11. The optimum RWS tank size and the NFB are identified to be directly proportional to the collector area. The optimum RWS tank size is calculated between 0.64 m^3 and 3.35 m^3 when the collector area ranges from 50 m^2 to 300 m^2. The NFB is calculated as negative when the collector area is less than 200 m^2. For the collector area larger than 200 m^2, the RWHS investment becomes financially feasible. The NFB is calculated to range from 362 TL to 1746 TL when the collector area is increased from 200 m^2 to 300 m^2. Thus, the optimum RWS tank size and the NFB are identified to be highly sensitive to the change in the collector area.

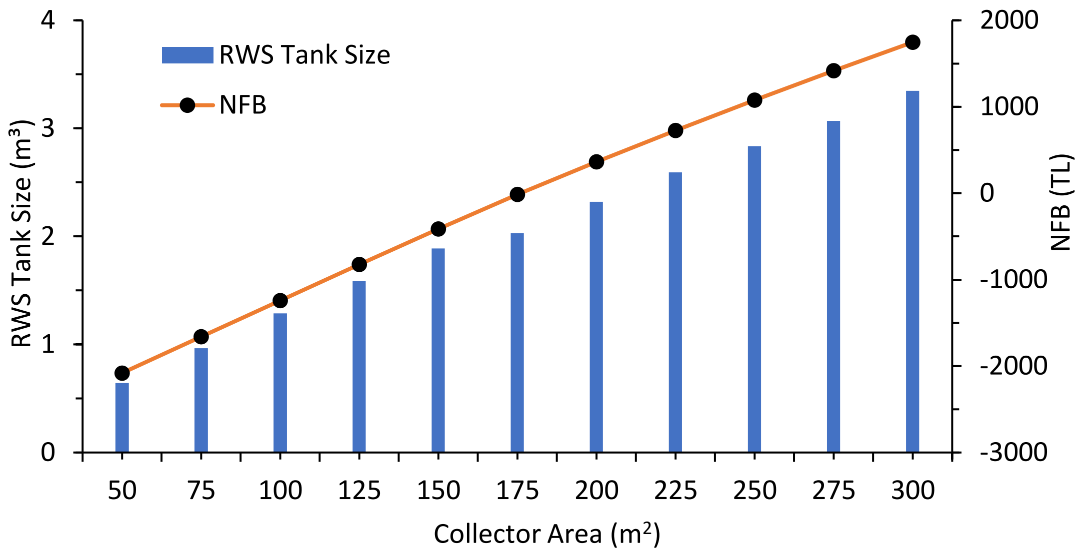


Figure 5.11. Effect of the Collector Area on the RWS Tank Size and the NFB

Third, the annual discount rate is varied between 2% and 10%. The change in the RWS tank size and the NFB is provided in Figure 5.12. As the discount rate increases, the optimum RWS tank size becomes smaller. The optimum RWS tank size is obtained in the range of 3.2 m^3 and 1.9 m^3 when the discount rate is varied between 2% and 10%. Positive NFBs ranging between 2585 TL and 362 TL are obtained when the discount rate is varied from 2% to 6%. The NFB is calculated as negative after a 6% discount rate, and the RWHS investment becomes financially infeasible.

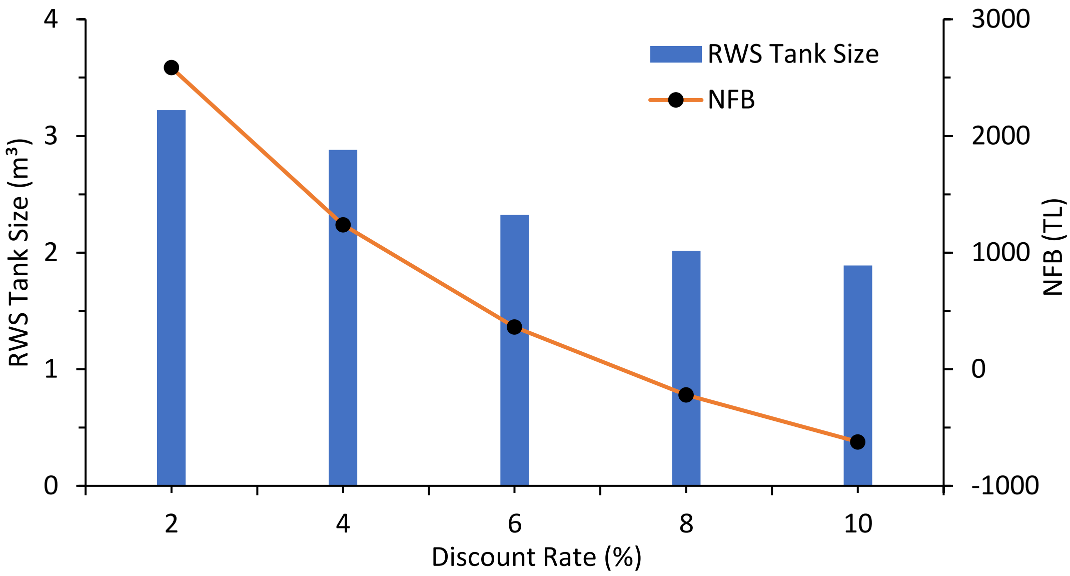


Figure 5.12. Effect of the Discount Rate on the RWS Tank Size and the NFB

Next, the LP model's sensitivity to the daily average domestic water consumption per capita is analyzed. The results are presented in Figure 5.13. The optimum RWS tank size is obtained between 1.2 m^3 and 2.6 m^3 when the daily average domestic water consumption per capita is changed from 0.05 m^3/day/cap to 0.55 m^3/day/cap. Up to 0.55 m^3 daily average domestic water consumption per capita, the NFB is identified as positive ranging from 64 TL to 432 TL for the consumption values ranging from 0.15 m^3/day/cap to 0.55 m^3/day/cap. The NFB keeps increasing until 0.45 m^3 daily average domestic water consumption per capita. The increase in the NFB levels off after the consumption value of 0.45 m^3/day/cap.

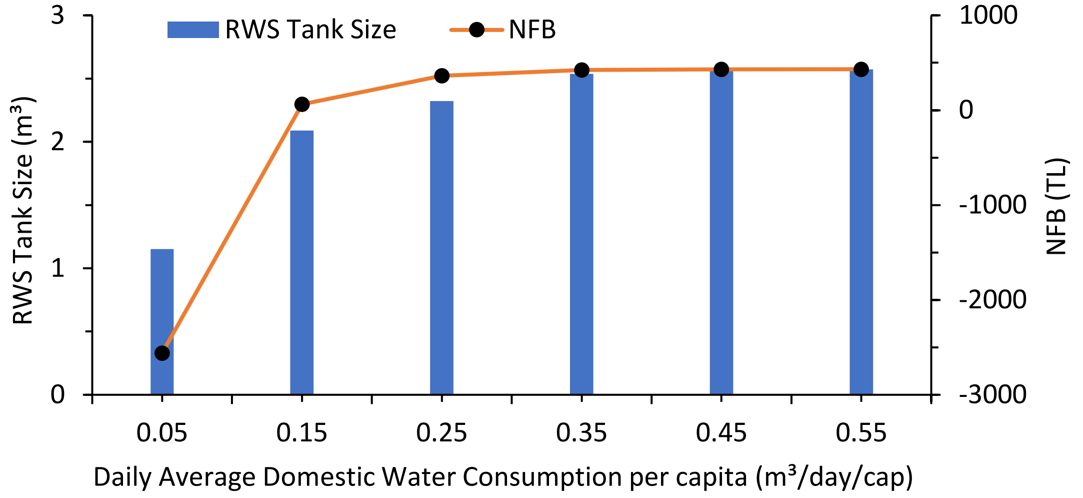


Figure 5.13. Effect of the Daily Average Domestic Water Consumption per capita on the RWS Tank Size and the NFB

Finally, the RWS tank unit cost is varied from 200 TL to 1000 TL. The effect of this change on the results is illustrated in Figure 5.14. The optimum RWS tank size changes from 4.6 m^3 to 1.6 m^3 when the RWS tank unit cost is varied from 200 TL/m^3 to 1000 TL/m^3. As expected, the NFB decreases with the increase in the RWS tank unit cost. The NFB is found to be positive between 1645 TL and 362 TL when the RWS tank unit cost ranges from 200 TL/m^3 to 600 TL/m^3. For higher than 600 TL/m^3 RWS tank unit cost, the RWHS investment is identified as financially infeasible.

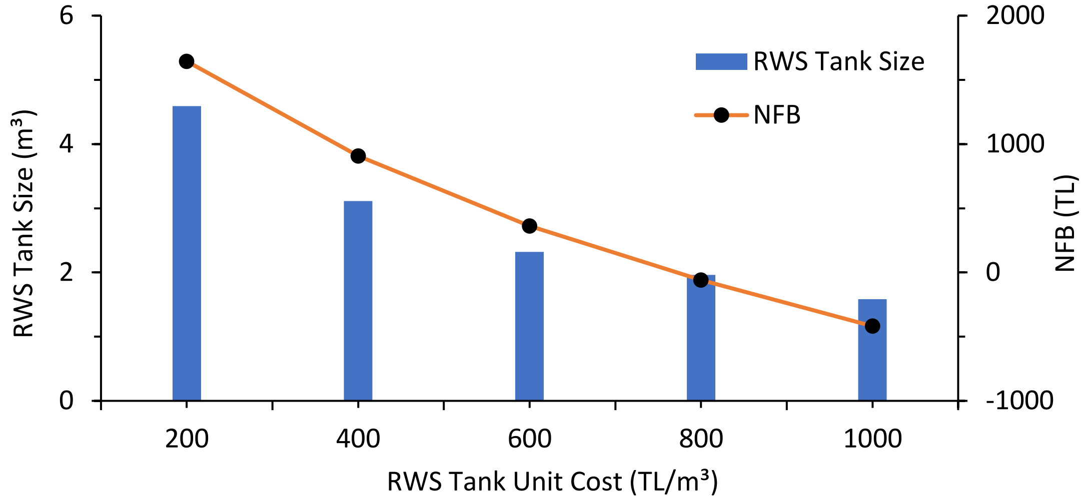


Figure 5.14. Effect of the RWS Tank Unit Cost on the RWS Tank Size and the NFB

5.3. Environmental Assessment of the RWHS at the Selected Cities

In this section, an economic evaluation of the environmental benefits of RWHSs due to the decrease they cause in electrical energy consumption is carried out. Owing to the lack of the number of single houses data at the cities, the environmental benefits of the RWHSs are calculated for demonstration purposes at the selected cities from NC; Girne, Mağusa, İskele and Lefke. The electrical energy consumption reduction at Güzelyalı and Geçitköy Pump Stations via rooftop RWHS applications at single houses are calculated. The total social carbon cost and the electrical energy generation cost are calculated throughout the environmental assessment of the RWHS. Additionally, the amount of avoided fuel oil no: 6 to generate electrical energy is estimated.

For Girne, using the results of the LP model of Girne CSL run for the simulation period of 30 years, the annual average water savings per single house through the RWHS is found to be about 56 m^3/year/house. This is calculated by summing up all the monthly average water savings per single house through the RWHS (see Figure B.18). The number of single houses in Girne is estimated as 8,562 (The TRNC Department of Urban Planning, Personal Communication in September 2020). Therefore, the total annual average water savings at Girne is calculated as approximately 479,500 m^3/year (i.e., $WS = 56 \times 8{,}562 = 479{,}500$ m^3/year). The number of single houses, the annual average water savings per single house, and the total annual average water savings for the selected cities (i.e., Girne, Mağusa, İskele and Lefke) are given in Table 5.7.

Table 5.7. The Number of Single Houses, the Annual Average Water Savings per Single House and the Total Annual Average Water Savings for the Selected Cities

City	Number of Single Houses	Annual Avg. Water Savings per Single House* (m^3/year/house)	Total Annual Avg. Water Savings, WS (m^3/year)
Girne	8,562	56	479,500
Mağusa	4,938	40	197,500
İskele	3,581	41	147,000
Lefke	3,538	42	148,500
Total	**20,619**	**179**	**972,500**

* Results of the LP model.

To transfer 479,500 m^3/year water using Güzelyalı and Geçitköy Pump Stations, approximately 321,000 kWh/year (i.e., $479{,}500$ m^3 $\times$ 0.67 kWh/m^3 – the unit electrical energy need for pumps is calculated as 0.67 kWh/m^3 in Chapter 3) of electrical energy is required. To generate 321,000 kWh/year of electrical energy, nearly 219 ton CO_2 eq/year (i.e., $321{,}000$ kWh/year $\times 0.68$ kg CO_2/kWh – the electricity generation – CO_2 emission intensity at Cyprus Island is presented in Chapter 3) is emitted into the atmosphere. This leads to a total annual social carbon cost of $9,200/year (i.e., 73,600 TL/year). For a carbon dioxide sequestration of 219 ton CO_2 eq, 3,650 urban trees (i.e., $T_s = 219\ /\ 0.06 = 3{,}650$ urban tree) are required - the weighted average carbon sequestered by a medium growth coniferous or deciduous tree, planted in an urban setting and allowed to grow for 10 years is 36.4 lbs of carbon per tree (i.e., $S_R = 0.06$ ton CO_2 per urban tree planted) (EPA, 2020).

Fuel oil no: 6, of which the net heating value is 124,000 Btu/gal (i.e., $LHV = 9600$ kWh/ton) (FPL, 2007), is used to generate electrical energy in the power plants in NC (CTEA, 2015). Consequently, nearly 34 ton/year fuel oil no: 6 (i.e., $321{,}000$ kWh/year $/\ 9600$ kWh/ton) is required for 321,000 kWh/year of electrical energy generation. Moreover, nearly 316,000 TL/year (i.e., $321{,}000$ kWh/year $\times$ 0.98 TL/kWh) - the unit cost of electrical energy generation, e_{el}, in NC is 0.98 TL/kWh (CTEA, 2019) - electrical energy generation cost incurs for 321,000 kWh of electrical energy generation.

To sum up, a total annual CO_2 equivalent emission of 219 ton/year (i.e., $E_{CO_2} =$ 219 ton CO_2 eq/year), a total annual social carbon cost of $9,200/year (i.e., $C_{carbon} =$

$73{,}600$ TL/year) and a total annual electrical energy generation cost of 316,000 TL/year (i.e., $E_{el} = 316{,}000$ TL/year) can be avoided when 479,500 m^3 of the domestic water demand of single houses at the city of Girne is supplied from the rooftop RWHSs. The same methodology applied to the city of Girne is employed for Mağusa, İskele and Lefke. The results of the environmental assessment of the RWHS for the selected cities are presented in Table 5.8.

A total annual social carbon cost of 149,600 TL/year and a total annual electrical energy generation cost of 640,000 TL/year can be avoided when RWHSs are implemented at the selected cities. Thus, if RWHSs can be implemented throughout NC, there will be significant environmental benefits. Furthermore, the environmental assessment of the RWHS is carried out considering the water transfer that occurs via the NC Water Supply Project, and the water transfer in the municipal water supply systems is not taken into account in this study. Hence, an additional analysis of electrical energy consumption due to the water transfer in the municipal water supply system will improve the environmental assessment results.

As seen in Table 5.8, the avoided costs through RWHSs calculated for Girne are highest among the rest of the cities due to the existence of larger number of single houses at Girne and the average water savings obtained from the LP model of Girne CSL. In the LP models of Mağusa, İskele and Lefke CSLs, it was presented that the RWHS investments were financially infeasibility (see Table 5.2) for the selected simulation period of 30 years. Nevertheless, RWHSs will reduce the total social carbon cost, carbon dioxide emissions and the total electrical energy generation cost in NC as demonstrated by the environmental assessment study. Therefore, if RWHS applications become widespread among the citizens of NC –such as by providing incentives by the government or through regulations, laws and policies to encourage sustainable water supply – in addition to the increase in the financial benefit of RWHS investments, benefits like the protection of public health, mitigating climate change impacts and the conservation of the environment can be achieved.

Table 5.8. Results of the Environmental Assessment for the Selected Cities

City	Avoided Total Annual ton CO_2 equivalent Emission, E_{CO_2} (ton CO_2 eq/year)	Avoided Total Annual Social Carbon Cost*, C_{carbon} ($/year)	Avoided Total Annual Electrical Energy Generation Cost, E_{el} (TL/year)	Amount of Avoided Annual Fuel Oil No: 6, F_o (ton/year)	Number of Urban Trees Required for CO_2 Sequestration, T_s (urban tree)
Girne	219	73,600 (9,200**)	316,000 (39,500**)	34	3,650
Mağusa	90	30,400 (3,800)	129,500 (16,187)	14	1,500
İskele	67	22,400 (2,800)	96,000 (12,000)	10	1,120
Lefke	68	23,200 (2,900)	98,500 (12,312)	10	1,140
Total	**444**	**149,600 (18,700)**	**640,000 (80,000)**	**68**	**7,410**

* $1 = 8 TL, as of November 12th, 2020 (The TRNC Central Bank, 2020a)

** Values in $/year are given in the parenthesis.

CHAPTER 6

CONCLUSION

An LP model is developed to determine the optimum RWS tank size of a rooftop domestic RWHS, and the maximum financial benefit is attained by minimizing the cost of water supplied from the UN, wastewater cost and the RWS tank cost. The developed LP model considers the daily precipitation data, the collector area at the roof of the building, the daily water consumption per capita, the number of residents, the unit water cost, the unit wastewater cost, the unit cost of the RWS tank, and the discount rate as inputs. The developed LP model is performed throughout the simulation period of 30 years for 33 CSLs. The CSLs, are selected from the semi-arid NC located in the Eastern Mediterranean. The 30-year daily average precipitation data of the CSLs between 1985-2015 ranges from 0.80 mm to 1.50 mm. The optimum RWS tank sizes at all CSLs are obtained between 1.6 m^3 and 3.2 m^3.

At all CSLs, the amount of harvested rainwater throughout the simulation period is identified to be relatively high in November, December, January, February, and March among all the months. During these months, harvested rainwater can be stored in the RWS tanks to be used for the dry months or in case of an emergency like drought or a failure in the NC Water Supply System.

The financial assessment of the RWHS is carried out for all CSLs. Results show that the RWHS investment is financially feasible for all CSLs without adding the installation and maintenance costs of the RWHS, and the NFBs are obtained between 1,241 and 4,729 TL. When the installation and maintenance costs are added to the financial assessment calculations, the RWHS investment becomes financially infeasible at nearly two-thirds of the CLSs. The NFBs are calculated to range from -1,677 to 1,811 TL. The majority of the feasible CSLs are identified along the north and north-east shores of the country, where the daily average precipitation is relatively higher than those of the other locations. The discounted PPs of the RWHSs are calculated between 13.2 years and 29.7 years at the CSLs where the RWHS investment is found to be financially feasible. With incentives for the installation and maintenance costs of the RWHS, the RWHS investment could become financially feasible at the CSLs. Furthermore, the possible increase in the water price due to the NC Water Supply Project may affect the financial feasibility of the RWHS in NC in an encouraging way.

Sensitivity analysis is carried out using the LP model of Lefkoşa by changing the parameters of the number of residents, the collector area, the discount rate, the daily average water consumption per capita, and the RWS tank unit cost. As the collector area at the roof increases from 50 m^2 to 300 m^2, the NFB and the optimum tank size continuously increase, which is observed through sensitivity analysis. It is identified that the NFB and the optimum tank size increase until a daily average domestic water consumption per capita of 0.45 m^3/day/cap. Sensitivity analysis shows that the NFB and the optimum tank size are not sensitive to higher than seven residents. For higher than 6% discount rate, the RWHS investment is found to be financially infeasible.

Additionally, for higher than a RWS tank unit cost of 600 TL/m^3, the NFB is calculated as negative. To summarize, sensitivity analysis results reveal that the use of precise parameters in the LP model is necessary since the change in the parameters affects the optimum RWS tank size and the NFB.

The environmental assessment is carried out for Girne, Mağusa, İskele and Lefke. The electrical energy consumption due to water transfer in the municipal water supply systems is ignored in the analysis. Only the electrical energy consumption required for water transfer through the NC Water Supply Project is considered in the environmental assessment study. A total annual CO_2 equivalent emission of 444 tons/year, a total annual social carbon cost of 150,000 TL/year and a total annual electrical energy generation cost of 640,000 TL/year can be saved via rainwater harvesting. These benefits are expected to increase when the environmental assessment is done for the rest of the cities of NC and the electrical energy consumption caused by water transfer in the municipal water supply systems is added to the environmental assessment calculations.

The effect of using different time steps in the LP model on the results of the optimum RWS tank size and the NFB is investigated. For this analysis, the results of the LP model developed in this study which uses daily time steps are compared to the results obtained using Ruso et al., 2019's LP model which uses monthly time steps. The analysis shows that rainwater harvesting and utilization are more realistically modeled by the LP model which uses daily time steps. Thus, the proposed LP model in this study leads to achieving accurate results in terms of the financial feasibility of the RWHS investment for decision-makers.

As a future study, the developed LP model could be used to identify optimum RWS tank sizes for different scenarios, like supplying potable water demand and adopting multiple residential units. The developed LP model's objective function can be modified by adding a new decision variable evaluating the environmental benefits of RWHS applications to internalize external costs. The rainwater loss due to the first flush implemented to prevent debris, leaves and particles that get into the RWS tank at the beginning of rain could be adopted in the water balance model for more conservative RWS tank sizing. Finally, it will be beneficial to investigate the effect of future daily precipitation data projections generated according to various climate change scenarios in the LP model.

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APPENDICES

APPENDIX A

A. LP Model using Monthly Time Steps

Objective Function (Ruso et al., 2019)

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

s.t.

$$I_t = I_{t-1} + r_t - U_t \qquad \forall t \qquad \text{(A.2)}$$

$$r_t \le min\{R_t, T_{cap}\} \qquad \forall t \qquad \text{(A.3)}$$

$$I_t \le T_{cap} \qquad \forall t \qquad \text{(A.4)}$$

$$T_{cap} \le S_{max} \qquad \text{(A.5)}$$

$$\sum_{j=1}^{J} P_{tJ} + U_t = D_t \qquad \forall t, \forall j \qquad \text{(A.6)}$$

$$P_{tj} \le V_j - V_{j-1} \qquad \forall t, \forall j \qquad \text{(A.7)}$$

$$I_0 = 0 \qquad \text{(A.8)}$$

$$T_{cap}, I_t, r_t, U_t, P_t, P_{tj} \ge 0 \qquad \forall t \qquad \text{(A.9)}$$

where t is the index for month, $t = 1,2,..,T$, T is the total number of months in the simulation period, j is the index for the price level at which water is purchased from the UN, $j = 1,2,..,J$, J is the total number of price levels used by the UN, a is the unit cost of the RWS tank (TL/m^3), b_j is the cost of water per unit volume purchased from the UN at the $j\ th$ price level (TL/m^3), R_t is the maximum amount of rainwater that can be harvested in month t (m^3), S_{max} is the maximum tank size (m^3), im is the monthly discount rate, c_w is the cost per unit volume of wastewater (TL/m^3), D_t is the demand in month t (m^3), T_{cap} is the volume of the RWS tank (m^3), I_t is the inventory level of the RWS tank at the end of month t (m^3), r_t is the amount of harvested rainwater in month t (m^3), U_t is the amount of rainwater used from the RWS tank in month t to satisfy the monthly demand (m^3), P_t is the amount of water purchased from the UN in month t to satisfy the demand (m^3), P_{tj} is the amount of water purchased from the UN in month t at the $j\ th$ price level (m^3), U_t is the amount of water used from the RWS tank in month t to satisfy the demand (m^3), Vj is the maximum volume of water that can be provided from the UN at the $j\ th$ price level (m^3). The sets are t and j, $a, b_j, R_t, S_{max}, im, c_w$, and D_t are the parameters, and T_{cap}, I_t, r_t, U_t, P_t and P_{tj} are the variables.

Equation (A.1) is the objective function that is the summation of the cost of the RWS tank, the present value of the total amount of water supplied from the UN, and the present value of the total wastewater cost. The monthly discount rate is used in Equation (A.1) to bring the costs occurring in the simulation period to the present.

Starting from period t = 1, the inventory level in the RWS tank at the end of period t is determined using the continuity equation as given in Equation (A.2). Constraint (A.3) guarantees that throughout the simulation period, the amount of harvested rainwater in each month does not exceed the maximum amount of rainwater that can be harvested in a month and the volume of the RWS tank. Constraints (A.4) ensures that the inventory level of the RWS tank does not exceed the volume of the RWS tank throughout the simulation period. Constraint (A.5) confirms that the volume of the RWS tank is smaller than the maximum tank size. Constraint (A.6) guarantees that water purchased from the UN or rainwater supplied from the RWS tank in a period should satisfy the demand in that period. Constraint (A.7) ensures that in any period, water purchased from the UN at the jth price level cannot exceed the permissible volume of water that can be purchased at that price level. Equation (A.8) states that the inventory balance level is zero at the beginning of the simulation period. Finally, Constraint (A.9) represents that all the decision variables are positive.

The maximum amount of rainwater that can be harvested in month t, R_t, is calculated as follows (Ghisi et al., 2006):

$$R_t = c_f \times A_{col} \times p_t \times 10^{-3} \qquad \text{(A.10)}$$

where c_f is the runoff coefficient for the roof, A_{col} is the collector area at the roof (m^2), p_t is the measured precipitation depth in month t (mm).

The demand in month t, D_t, is calculated as follows:

$$D_t = Wd \times n \times N_t \tag{A.11}$$

where Wd is the daily average water consumption per capita (m^3/day/cap), n is the number of residents, and N_t is the total number of days in month t.

The total cost of the RWHS, C_{total}, is calculated as follows:

$$C_{total} = Z + C_{fixed} \tag{A.12}$$

where Z is the optimum objective function value (TL), C_{fixed} is the summation of the fixed costs (TL) which is calculated as follows:

$$C_{fixed} = C_{inst} + C_{maint} \tag{A.13}$$

where C_{inst} is the RWHS installation cost (TL), C_{maint} is the total RWHS maintenance cost that occurs during the simulation period (TL), and it is calculated as follows:

$$C_{maint} = \sum_{t=1}^{T} \frac{c_m}{(1 + im)^t} \qquad \forall t \tag{A.14}$$

where c_m is the monthly fixed RWHS maintenance cost (TL).

The cost of supplying the whole water demand from the UN (i.e., the case where there is no RWHS), C_{un}, is calculated as follows:

$$C_{un} = \sum\nolimits_{t=1}^{T} \sum\nolimits_{j=1}^{J} \frac{b_j}{(1 + im)^t} P_{tj} + \sum_{t=1}^{T} \frac{c_w}{(1 + im)^t} D_t \qquad \forall t, j \le J \tag{A.15}$$

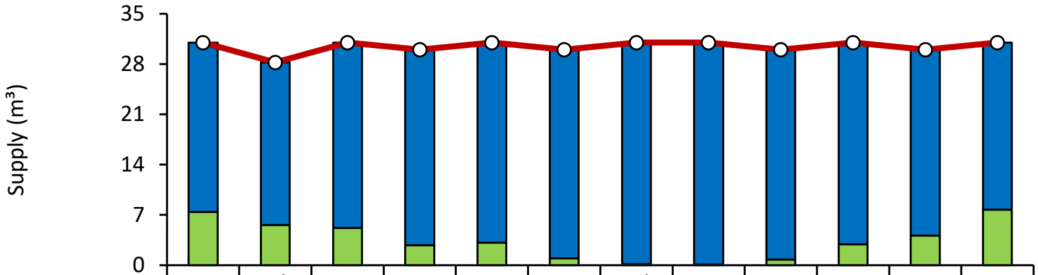
Finally, the NFB is calculated as follows:

$$NFB = C_{un} - C_{total} \tag{A.16}$$

If the NFB is positive, the RWHS investment is feasible; while if the NFB is negative, the RWHS investment results in economic losses.

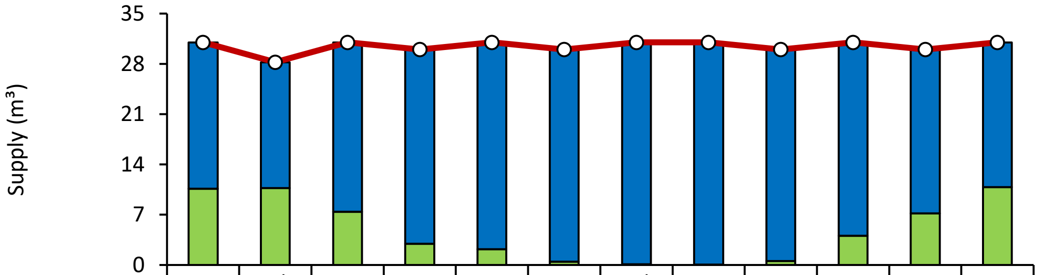
APPENDIX B

B. 30-year Average Water Supply and Demand at CSLs



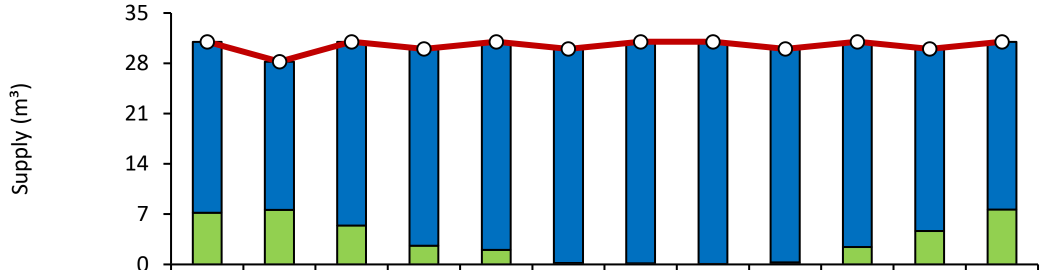
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.6	22.6	25.8	27.2	27.9	29.0	30.8	30.9	29.2	28.1	25.9	23.3
RWHS	7.4	5.6	5.2	2.8	3.1	1.0	0.2	0.1	0.8	2.9	4.1	7.7
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.1. 30-year Average Water Supply and Demand at İskele



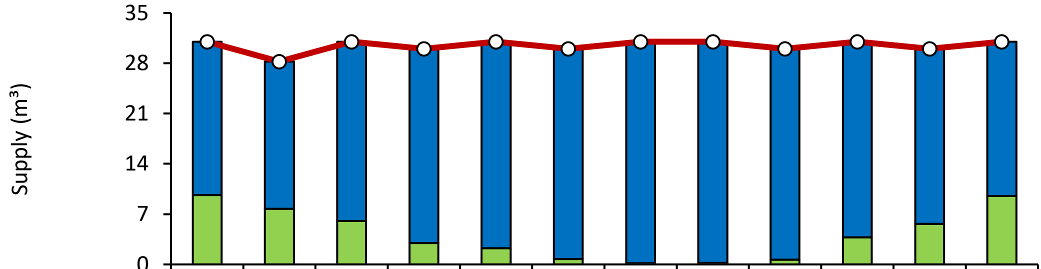
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.4	17.5	23.6	27.0	28.8	29.5	30.9	31.0	29.5	26.9	22.8	20.1
RWHS	10.6	10.7	7.4	3.0	2.2	0.5	0.1	0.0	0.5	4.1	7.2	10.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.2. 30-year Average Water Supply and Demand at Çamlıbel



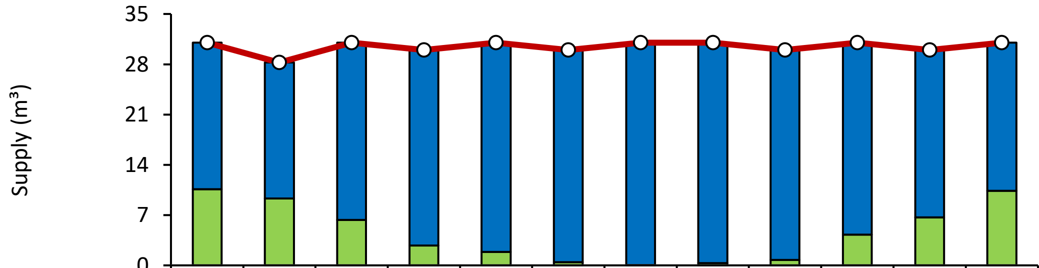
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.8	20.7	25.6	27.4	29.0	29.8	30.9	30.9	29.7	28.6	25.3	23.4
RWHS	7.2	7.6	5.4	2.6	2.0	0.2	0.1	0.1	0.3	2.4	4.7	7.6
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.3. 30-year Average Water Supply and Demand at Zümrütköy



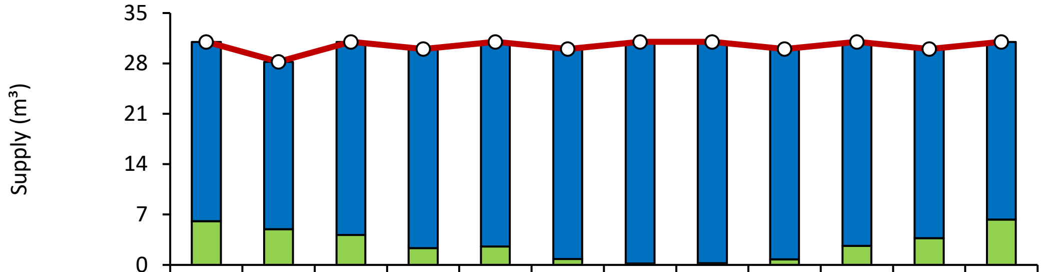
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.3	20.5	25.0	27.0	28.7	29.3	30.8	30.8	29.3	27.2	24.4	21.5
RWHS	9.7	7.7	6.0	3.0	2.3	0.7	0.2	0.2	0.7	3.8	5.6	9.5
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.4. 30-year Average Water Supply and Demand at Ziyamet



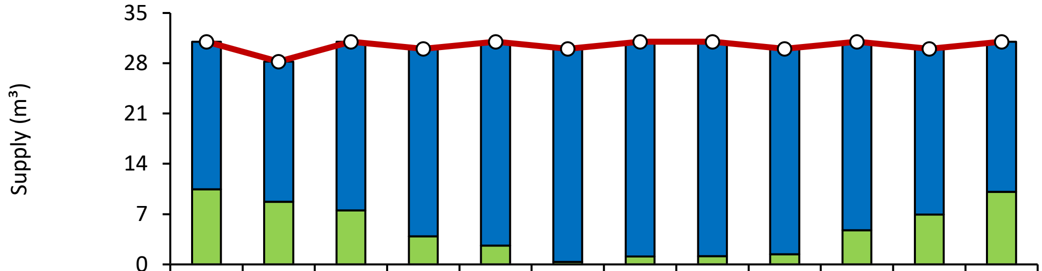
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.4	18.9	24.7	27.2	29.1	29.6	31.0	30.7	29.3	26.7	23.3	20.6
RWHS	10.6	9.3	6.3	2.8	1.9	0.4	0.0	0.3	0.7	4.3	6.7	10.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.5. 30-year Average Water Supply and Demand at Yeni Erenköy



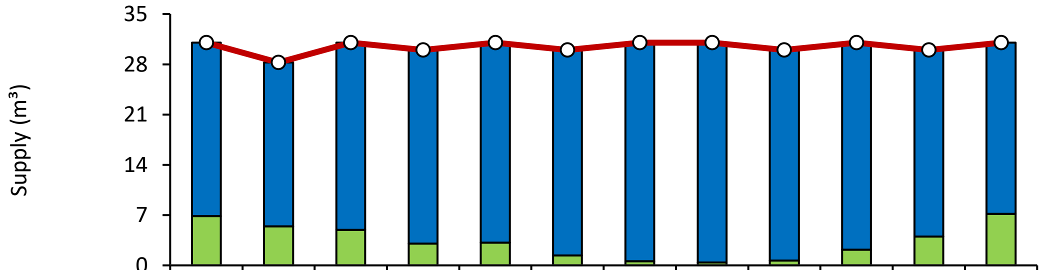
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	24.9	23.3	26.8	27.7	28.5	29.2	30.8	30.8	29.2	28.3	26.3	24.7
RWHS	6.1	5.0	4.2	2.3	2.5	0.8	0.2	0.2	0.8	2.7	3.7	6.3
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.6. 30-year Average Water Supply and Demand at Vadili



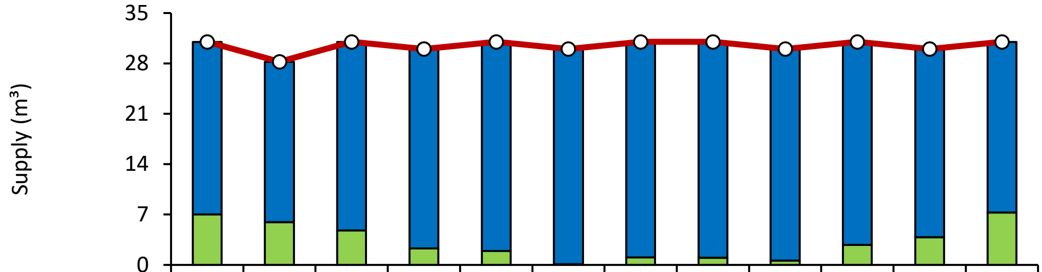
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.5	19.5	23.5	26.1	28.4	29.6	29.9	29.9	28.6	26.2	23.1	20.9
RWHS	10.5	8.7	7.5	3.9	2.6	0.4	1.1	1.1	1.4	4.8	6.9	10.1
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.7. 30-year Average Water Supply and Demand at Tatlısu



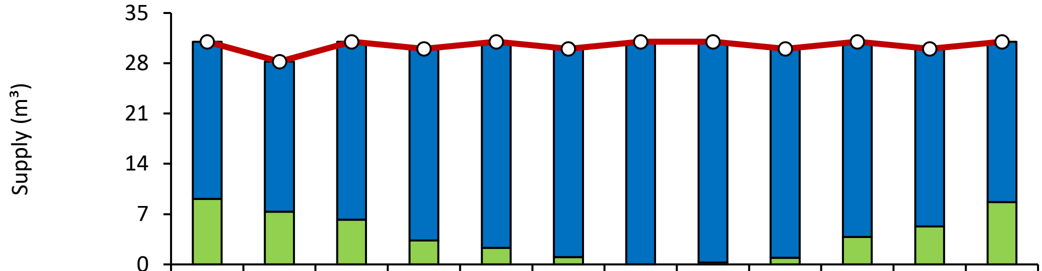
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	24.1	22.8	26.1	27.0	27.8	28.6	30.4	30.6	29.3	28.8	26.0	23.8
RWHS	6.9	5.4	4.9	3.0	3.2	1.4	0.6	0.4	0.7	2.2	4.0	7.2
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.8. 30-year Average Water Supply and Demand at Serdarlı



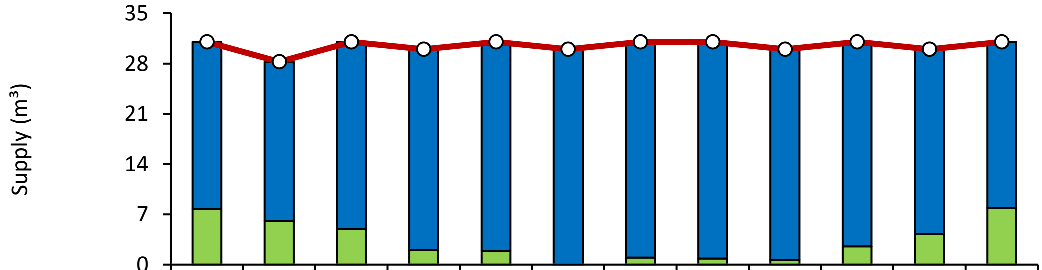
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	24.0	22.3	26.2	27.7	29.1	29.9	30.0	30.0	29.4	28.2	26.2	23.7
RWHS	7.0	5.9	4.8	2.3	1.9	0.1	1.0	1.0	0.6	2.8	3.8	7.3
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.9. 30-year Average Water Supply and Demand at Salamis



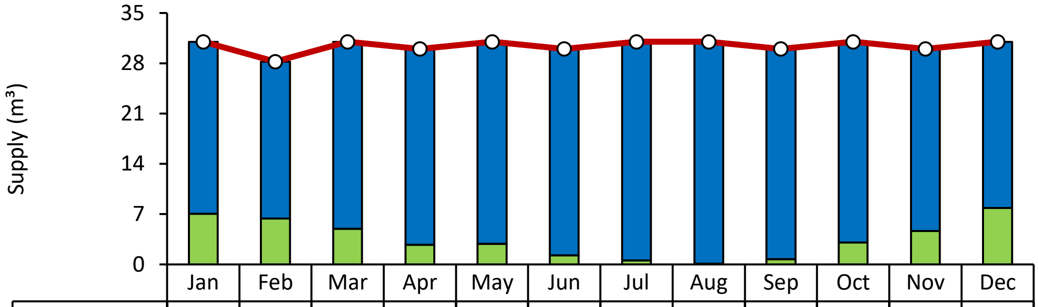
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.9	20.9	24.8	26.7	28.7	29.0	31.0	30.7	29.1	27.2	24.7	22.3
RWHS	9.1	7.4	6.2	3.3	2.3	1.0	0.0	0.3	0.9	3.8	5.3	8.7
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.10. 30-year Average Water Supply and Demand at Mehmetçik



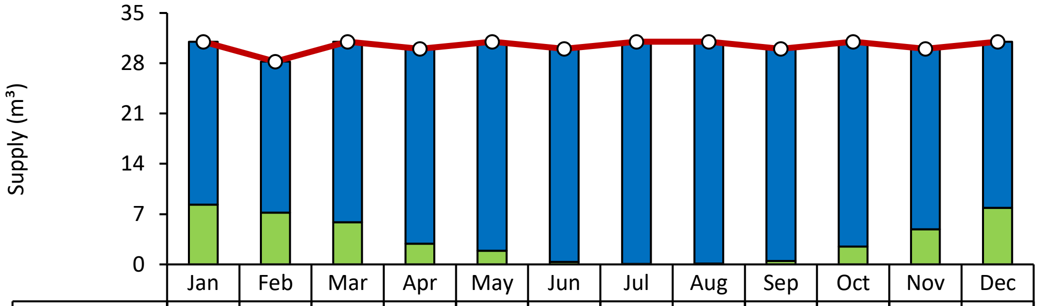
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.2	22.1	26.1	27.9	29.1	30.0	30.0	30.1	29.4	28.5	25.8	23.1
RWHS	7.8	6.1	4.9	2.1	1.9	0.0	1.0	0.9	0.6	2.5	4.2	7.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.11. 30-year Average Water Supply and Demand at Mağusa



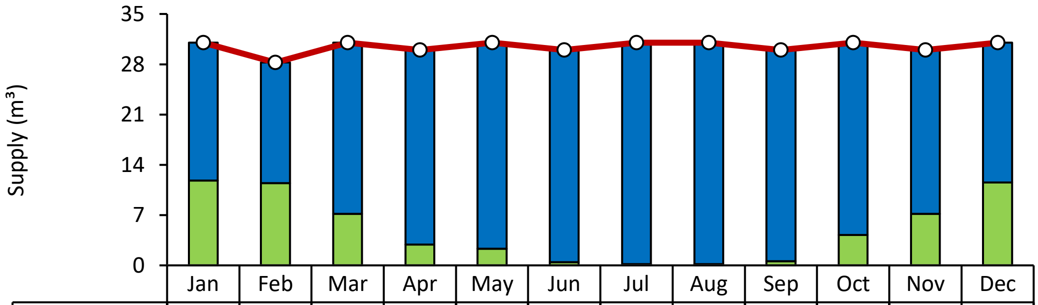
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.9	21.8	26.0	27.2	28.1	28.8	30.5	30.9	29.3	28.0	25.4	23.2
RWHS	7.1	6.4	5.0	2.8	2.9	1.2	0.5	0.1	0.7	3.0	4.6	7.8
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.12. 30-year Average Water Supply and Demand at Lefkoşa



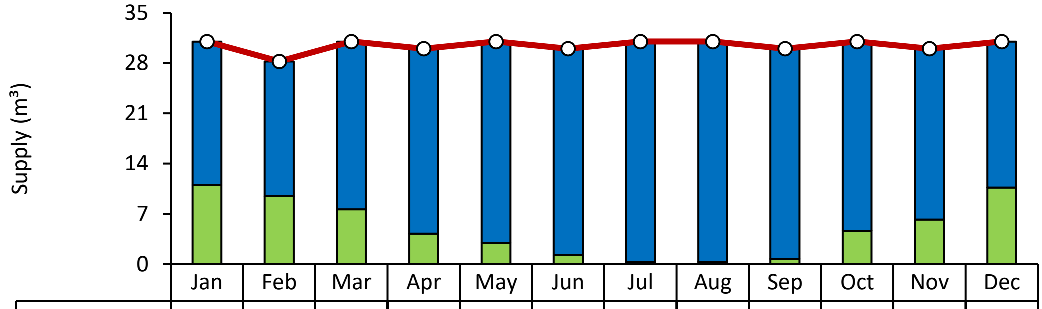
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	22.7	21.0	25.1	27.1	29.1	29.7	30.9	30.9	29.5	28.5	25.1	23.1
RWHS	8.3	7.2	5.9	2.9	1.9	0.3	0.1	0.1	0.5	2.5	4.9	7.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.13. 30-year Average Water Supply and Demand at Lefke



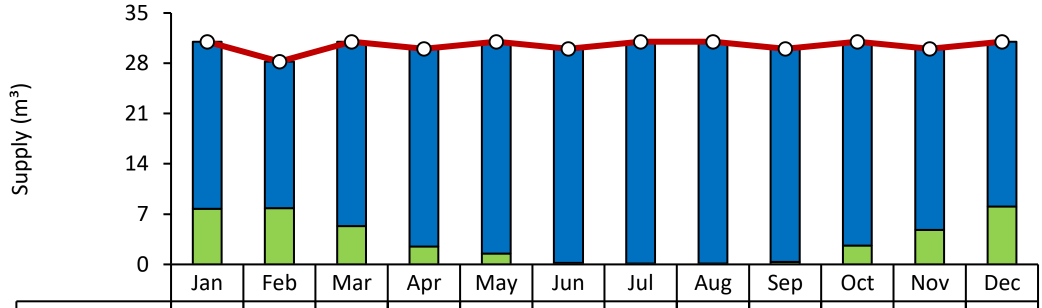
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	19.2	16.8	23.8	27.1	28.7	29.5	30.8	30.8	29.4	26.8	22.8	19.5
RWHS	11.8	11.4	7.2	2.9	2.3	0.5	0.2	0.2	0.6	4.2	7.2	11.5
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.14. 30-year Average Water Supply and Demand at Lapta



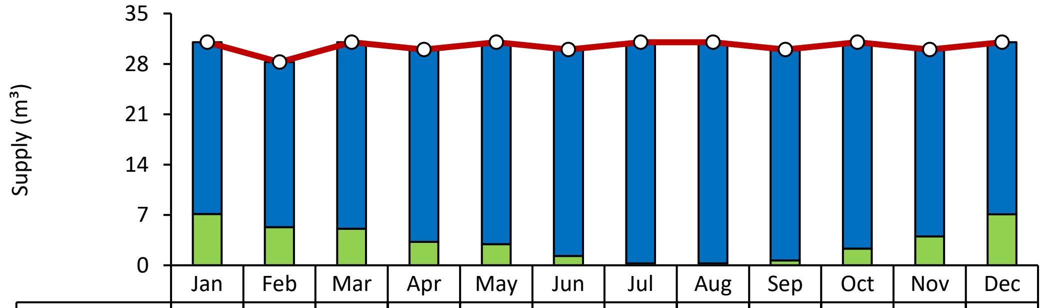
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.0	18.8	23.4	25.7	28.0	28.7	30.7	30.7	29.3	26.3	23.8	20.3
RWHS	11.0	9.5	7.6	4.3	3.0	1.3	0.3	0.3	0.7	4.7	6.2	10.7
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.15. 30-year Average Water Supply and Demand at Kantara



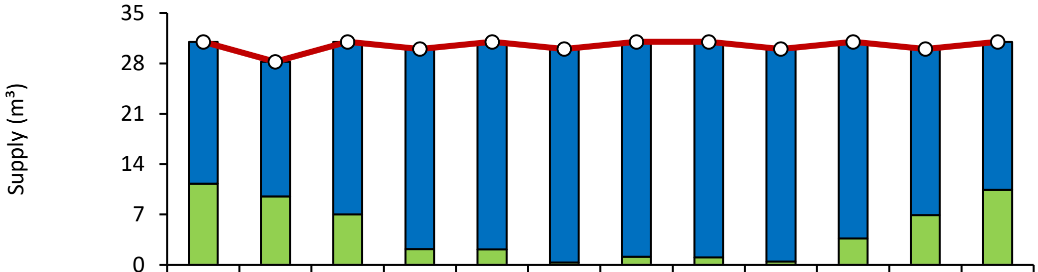
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.3	20.4	25.7	27.5	29.5	29.8	30.9	30.9	29.6	28.4	25.2	23.0
RWHS	7.7	7.8	5.3	2.5	1.5	0.2	0.1	0.1	0.4	2.6	4.8	8.0
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.16. 30-year Average Water Supply and Demand at Güzelyurt



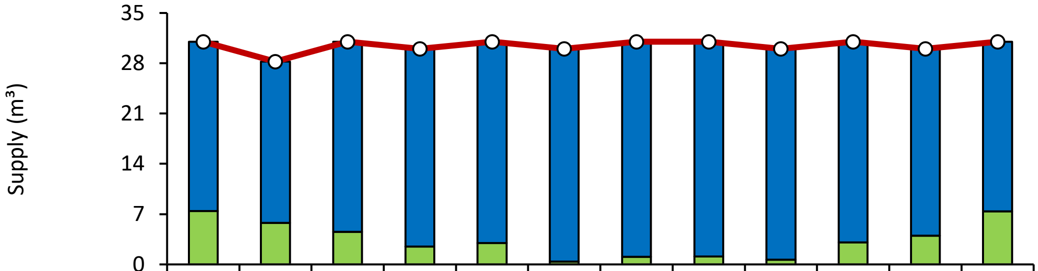
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.9	22.9	25.9	26.8	28.1	28.7	30.7	30.7	29.3	28.7	26.0	23.9
RWHS	7.1	5.3	5.1	3.2	2.9	1.3	0.3	0.3	0.7	2.3	4.0	7.1
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.17. 30-year Average Water Supply and Demand at Gönendere



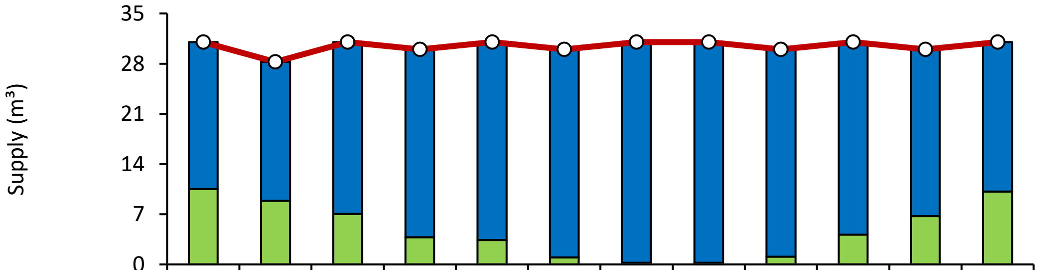
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	19.7	18.7	24.0	27.8	28.8	29.6	29.9	30.0	29.5	27.3	23.1	20.6
RWHS	11.3	9.5	7.0	2.2	2.2	0.4	1.1	1.0	0.5	3.7	6.9	10.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.18. 30-year Average Water Supply and Demand at Girne



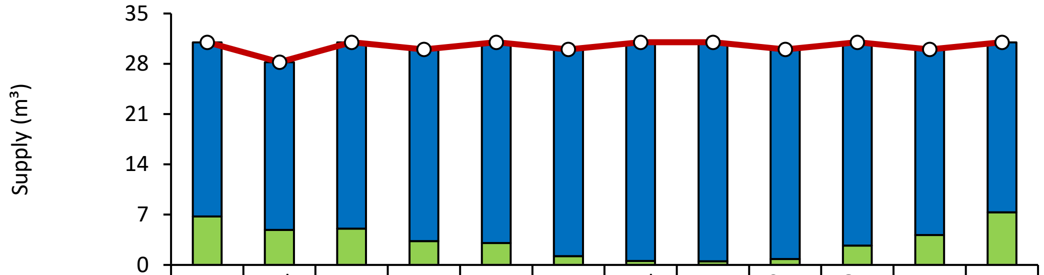
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.6	22.5	26.5	27.5	28.0	29.6	29.9	29.9	29.3	27.9	26.0	23.6
RWHS	7.4	5.8	4.5	2.5	3.0	0.4	1.1	1.1	0.7	3.1	4.0	7.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.19. 30-year Average Water Supply and Demand at Geçitkale



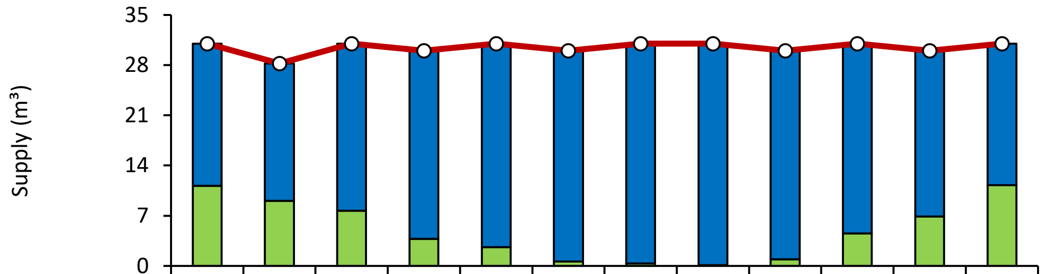
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.5	19.4	23.9	26.2	27.6	29.0	30.8	30.8	28.9	26.8	23.3	20.8
RWHS	10.5	8.9	7.1	3.8	3.4	1.0	0.2	0.2	1.1	4.2	6.7	10.2
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.20. 30-year Average Water Supply and Demand at Esentepe



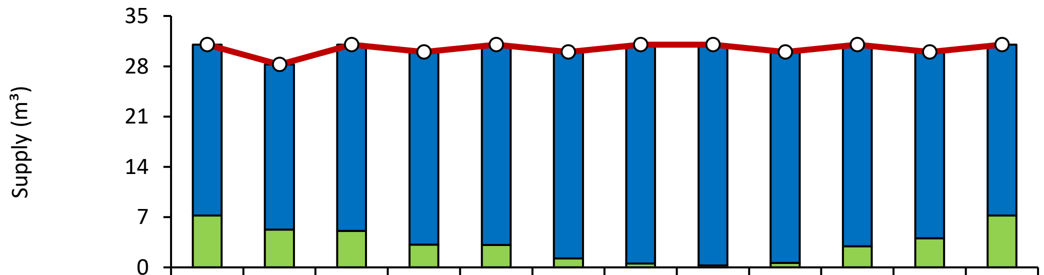
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	24.3	23.4	26.0	26.7	28.0	28.8	30.5	30.5	29.2	28.3	25.8	23.7
RWHS	6.7	4.9	5.0	3.3	3.0	1.2	0.5	0.5	0.8	2.7	4.2	7.3
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.21. 30-year Average Water Supply and Demand at Ercan



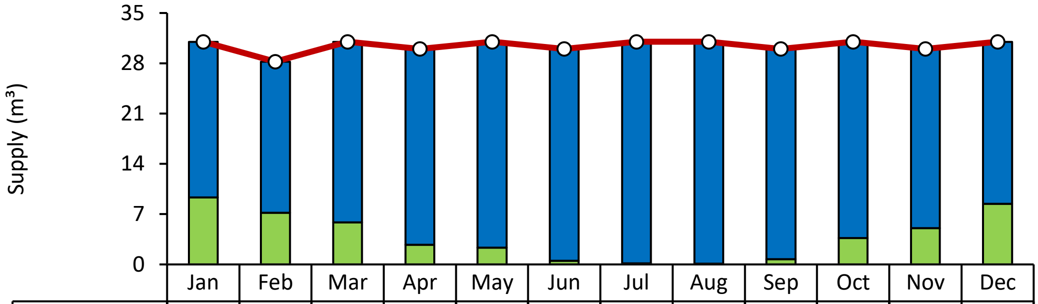
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	19.8	19.2	23.3	26.2	28.4	29.4	30.7	30.9	29.1	26.5	23.1	19.7
RWHS	11.2	9.1	7.7	3.8	2.6	0.6	0.3	0.1	0.9	4.5	6.9	11.3
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.22. 30-year Average Water Supply and Demand at Dipkarpaz



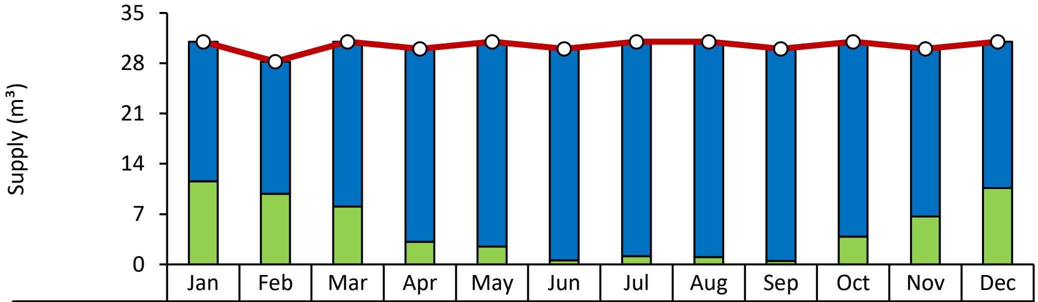
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.8	23.0	25.9	26.8	27.9	28.7	30.5	30.7	29.4	28.0	25.9	23.8
RWHS	7.2	5.2	5.1	3.2	3.1	1.3	0.5	0.3	0.6	3.0	4.1	7.2
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.23. 30-year Average Water Supply and Demand at Değirmenlik



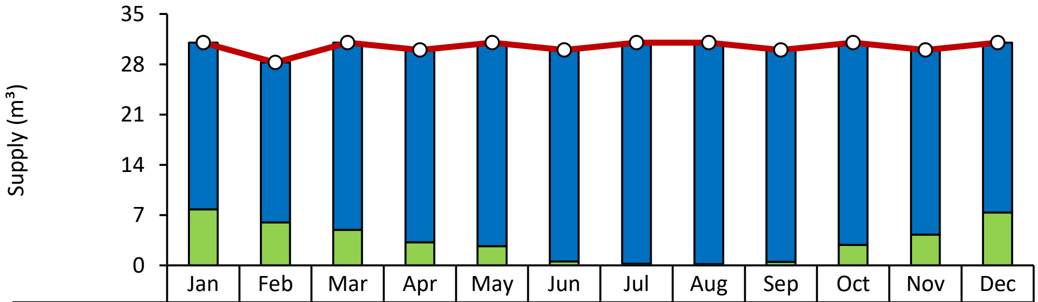
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.7	21.0	25.1	27.3	28.6	29.5	30.9	30.9	29.3	27.3	24.9	22.6
RWHS	9.3	7.2	5.9	2.7	2.4	0.5	0.1	0.1	0.7	3.7	5.1	8.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.24. 30-year Average Water Supply and Demand at Çayırova



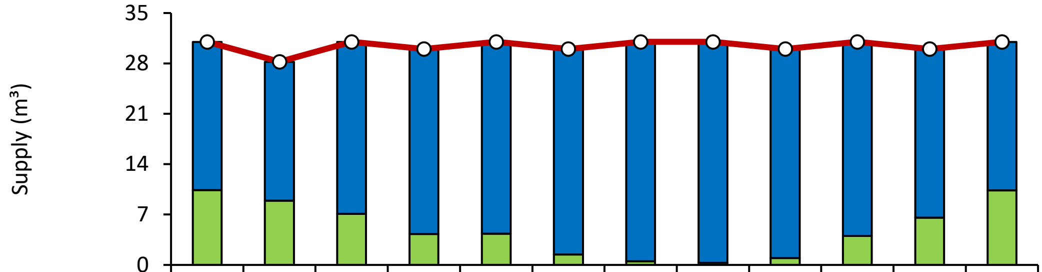
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	19.4	18.4	23.0	26.9	28.5	29.4	29.9	30.0	29.5	27.1	23.3	20.4
RWHS	11.6	9.8	8.0	3.1	2.5	0.6	1.1	1.0	0.5	3.9	6.7	10.6
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.25. 30-year Average Water Supply and Demand at Beylerbeyi



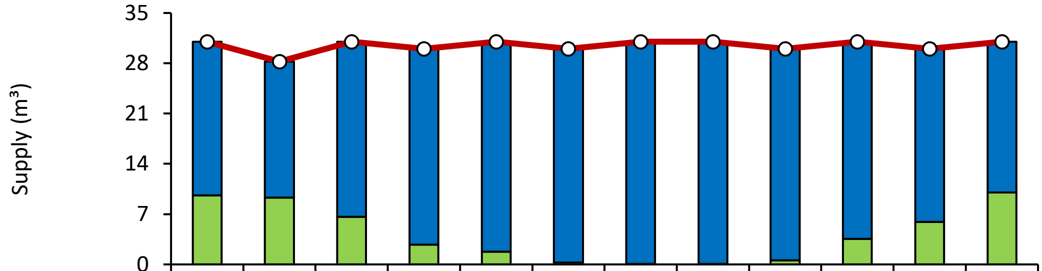
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.2	22.3	26.0	26.8	28.3	29.5	30.8	30.8	29.5	28.2	25.7	23.6
RWHS	7.8	6.0	5.0	3.2	2.7	0.5	0.2	0.2	0.5	2.8	4.3	7.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.26. 30-year Average Water Supply and Demand at Beyarmudu



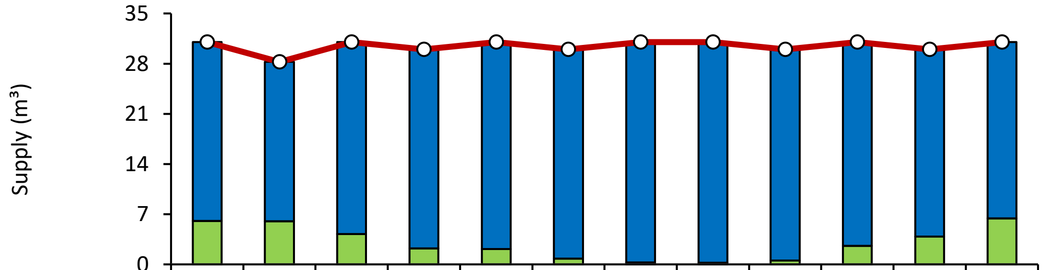
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	20.6	19.3	23.9	25.7	26.7	28.6	30.5	30.7	29.1	27.0	23.5	20.6
RWHS	10.4	8.9	7.1	4.3	4.3	1.4	0.5	0.3	0.9	4.0	6.5	10.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.27. 30-year Average Water Supply and Demand at Alevkaya



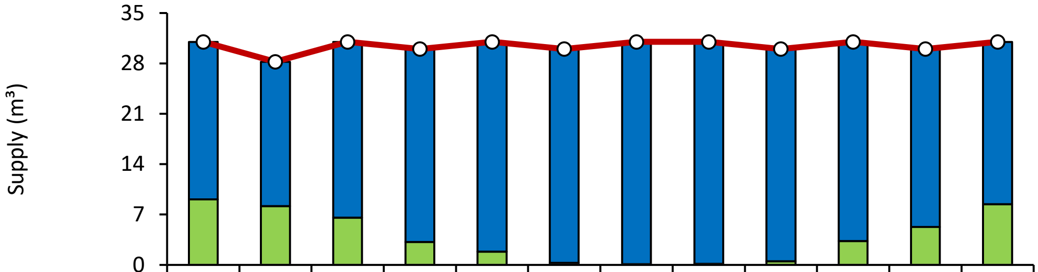
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.4	18.9	24.4	27.3	29.2	29.8	30.9	30.9	29.5	27.4	24.1	21.0
RWHS	9.6	9.3	6.6	2.7	1.8	0.2	0.1	0.1	0.5	3.6	5.9	10.0
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.28. 30-year Average Water Supply and Demand at Akdeniz



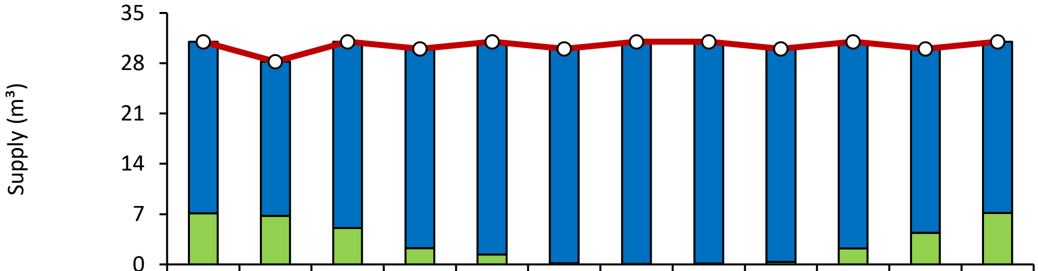
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	24.9	22.2	26.8	27.8	28.8	29.2	30.7	30.8	29.5	28.4	26.1	24.6
RWHS	6.1	6.0	4.2	2.2	2.2	0.8	0.3	0.2	0.5	2.6	3.9	6.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.29. 30-year Average Water Supply and Demand at Alayköy



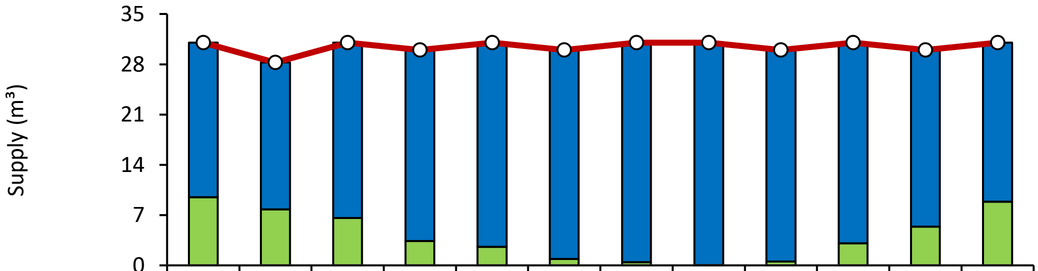
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.9	20.0	24.4	26.8	29.1	29.7	30.9	30.9	29.5	27.7	24.7	22.6
RWHS	9.1	8.2	6.6	3.2	1.9	0.3	0.1	0.1	0.5	3.3	5.3	8.4
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.30. 30-year Average Water Supply and Demand at Yeşilırmak



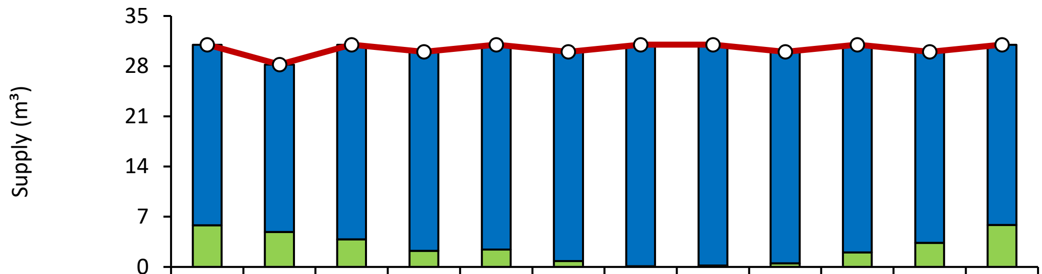
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	23.9	21.5	25.9	27.8	29.6	29.8	30.9	30.9	29.6	28.8	25.6	23.8
RWHS	7.1	6.8	5.1	2.2	1.4	0.2	0.1	0.1	0.4	2.2	4.4	7.2
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.31. 30-year Average Water Supply and Demand at Gaziveren



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	21.5	20.4	24.4	26.6	28.4	29.1	30.5	31.0	29.5	27.9	24.6	22.1
RWHS	9.5	7.8	6.6	3.4	2.6	0.9	0.5	0.0	0.5	3.1	5.4	8.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.32. 30-year Average Water Supply and Demand at Boğaz



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UN	25.2	23.3	27.2	27.8	28.6	29.2	30.9	30.8	29.5	29.0	26.7	25.1
RWHS	5.8	4.9	3.8	2.2	2.4	0.8	0.1	0.2	0.5	2.0	3.3	5.9
Demand	31.0	28.2	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0

Figure B.33. 30-year Average Water Supply and Demand at Dörtyol

APPENDIX C

C. Distribution of 30-year Harvested Rainwater at CSLs

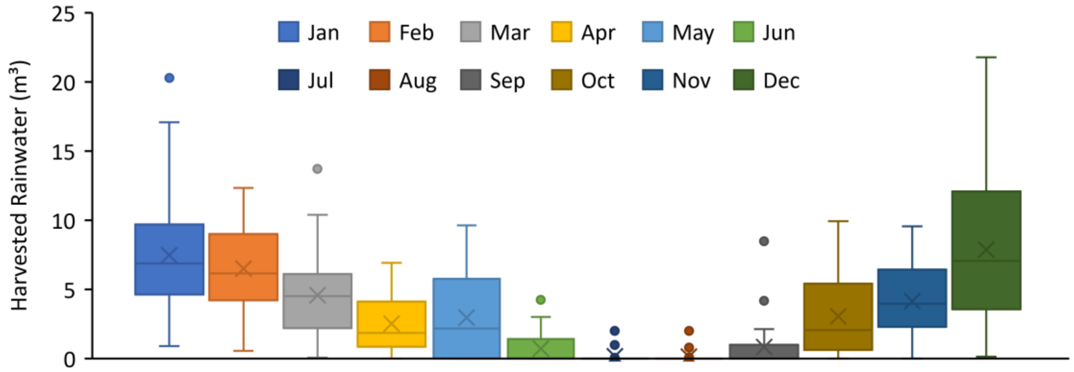


Figure C.1. 30-year Harvested Rainwater at İskele

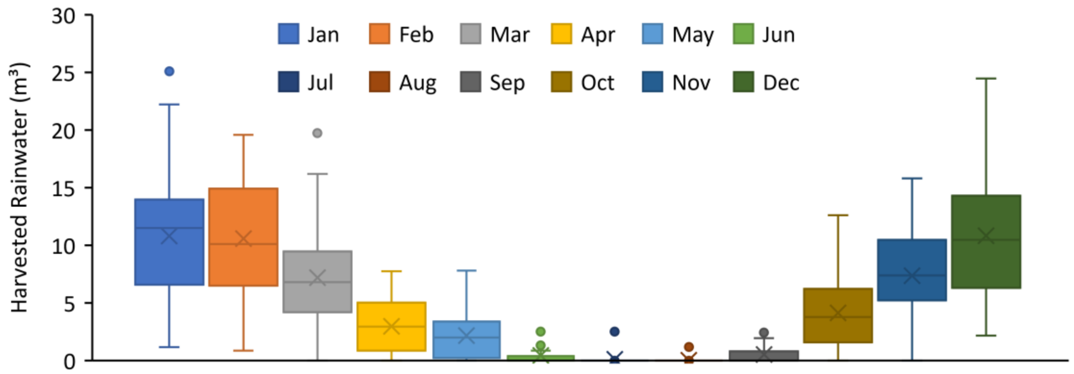


Figure C.2. 30-year Harvested Rainwater at Çamlıbel

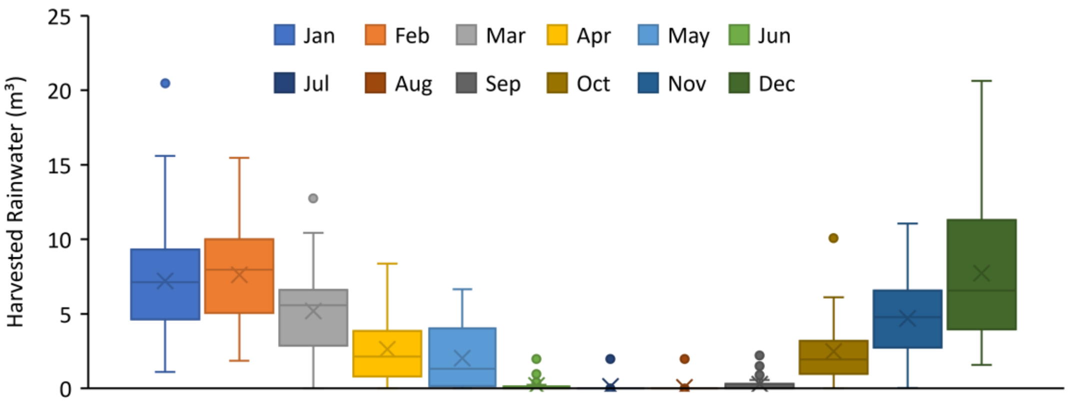


Figure C.3. 30-year Harvested Rainwater at Zümrütköy

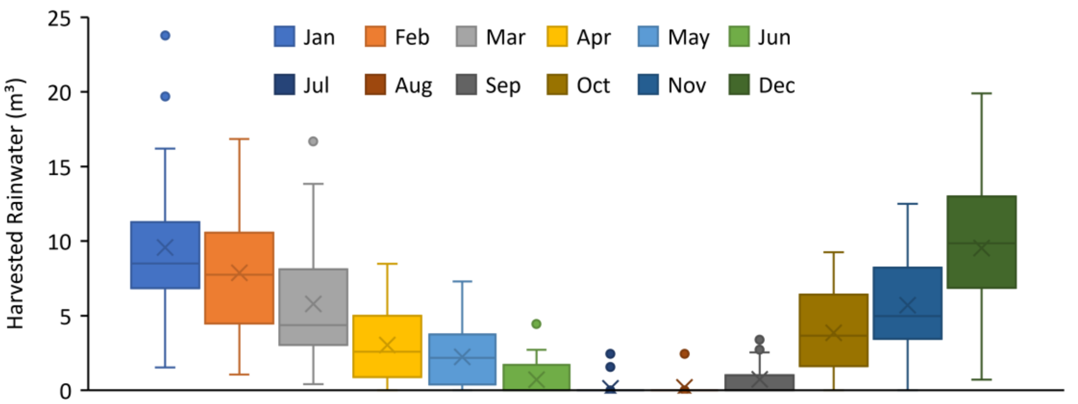


Figure C.4. 30-year Harvested Rainwater at Ziyamet

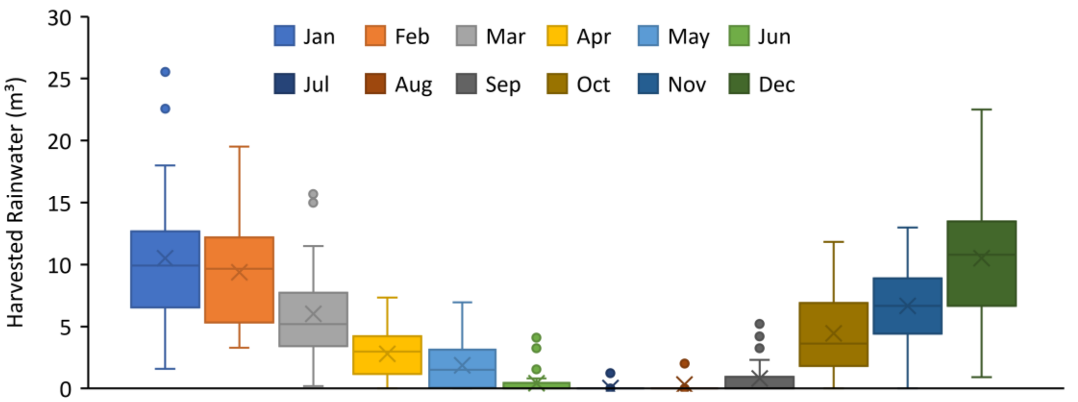


Figure C.5. 30-year Harvested Rainwater at Yeni Erenköy

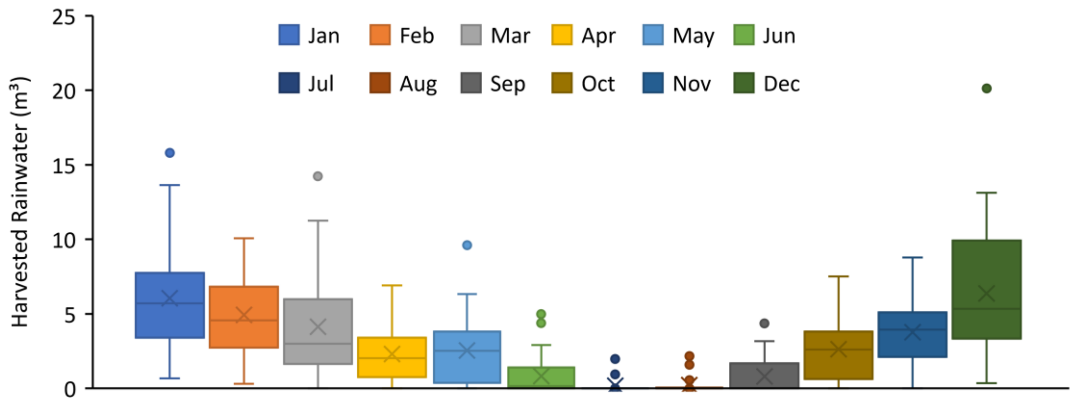


Figure C.6. 30-year Harvested Rainwater at Vadili

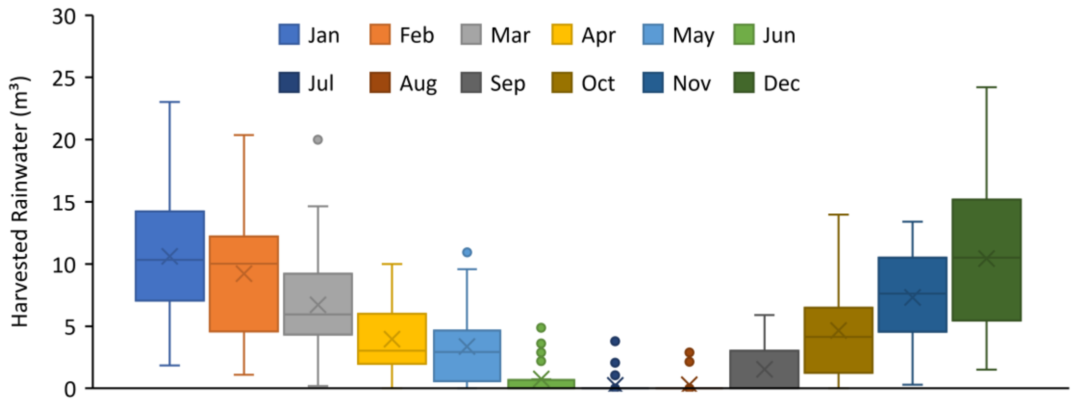


Figure C.7. 30-year Harvested Rainwater at Tatlısu

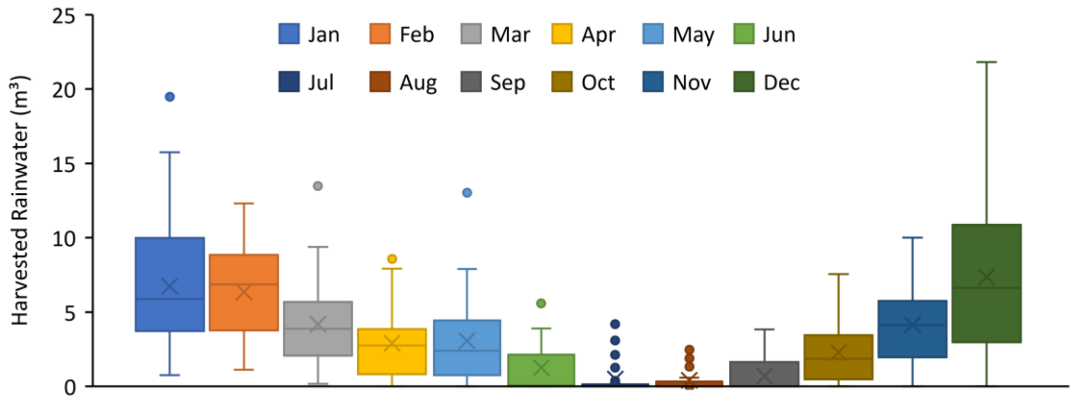


Figure C.8. 30-year Harvested Rainwater at Serdarlı

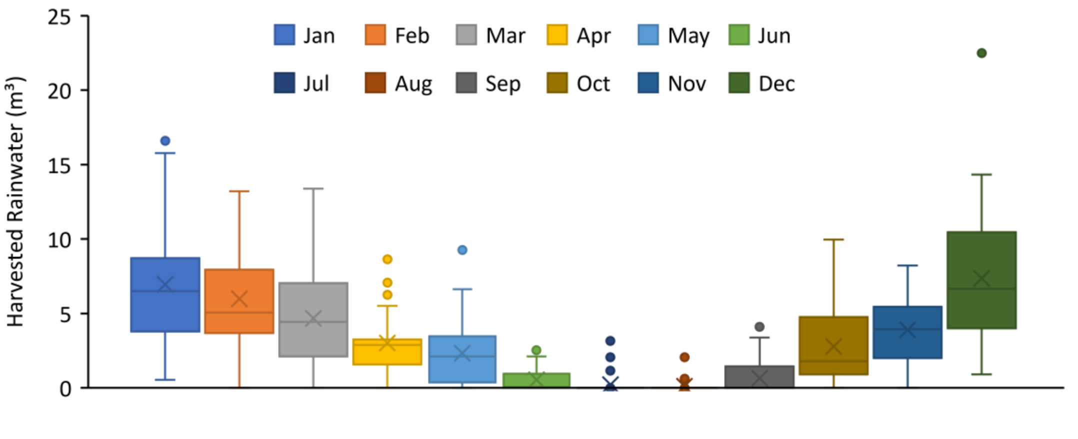


Figure C.9. 30-year Harvested Rainwater at Salamis

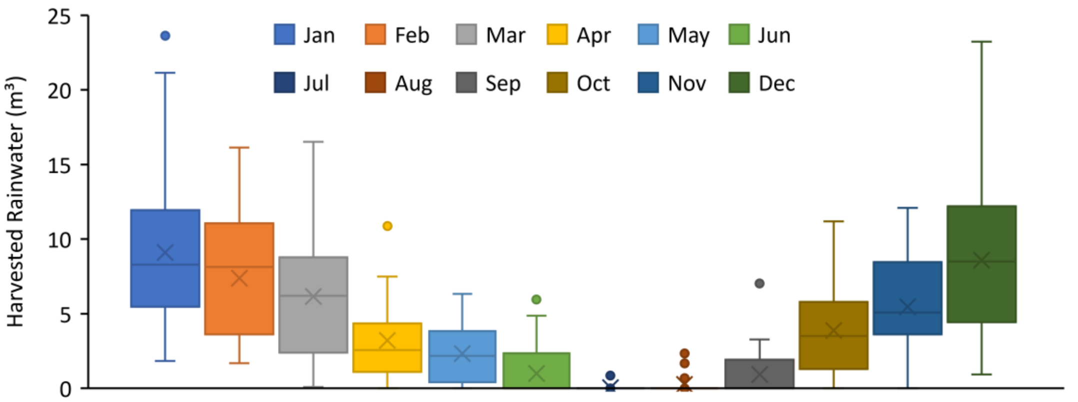


Figure C.10. 30-year Harvested Rainwater at Mehmetçik

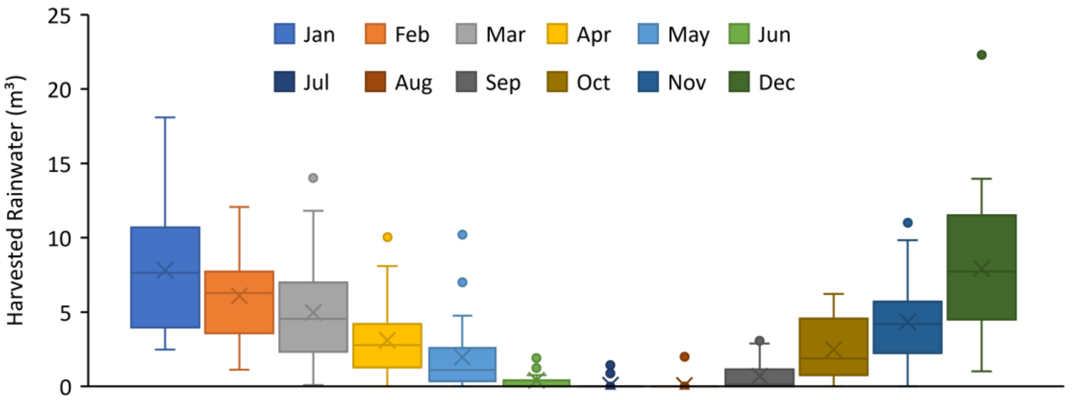


Figure C.11. 30-year Harvested Rainwater at Mağusa

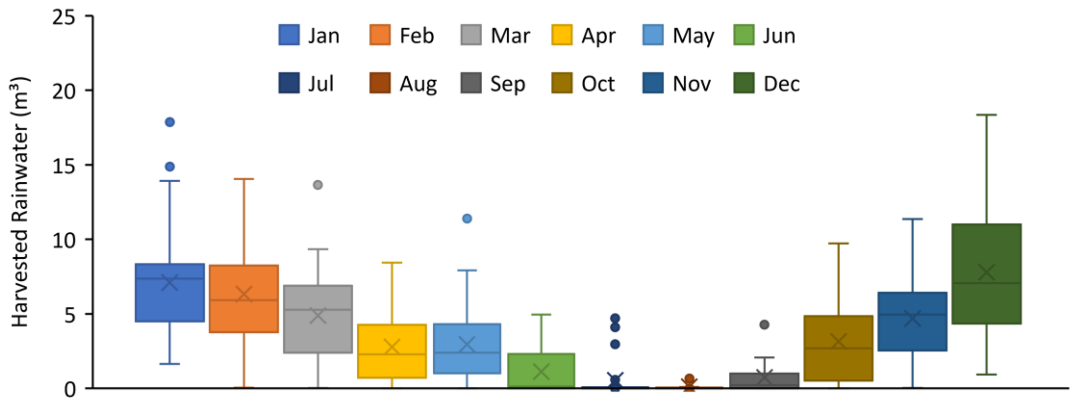


Figure C.12. 30-year Harvested Rainwater at Lefkoşa

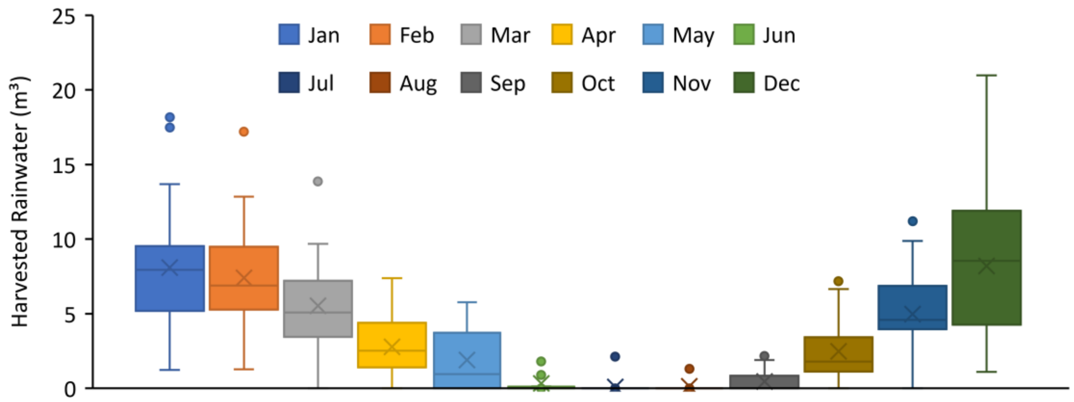


Figure C.13. 30-year Harvested Rainwater at Lefke

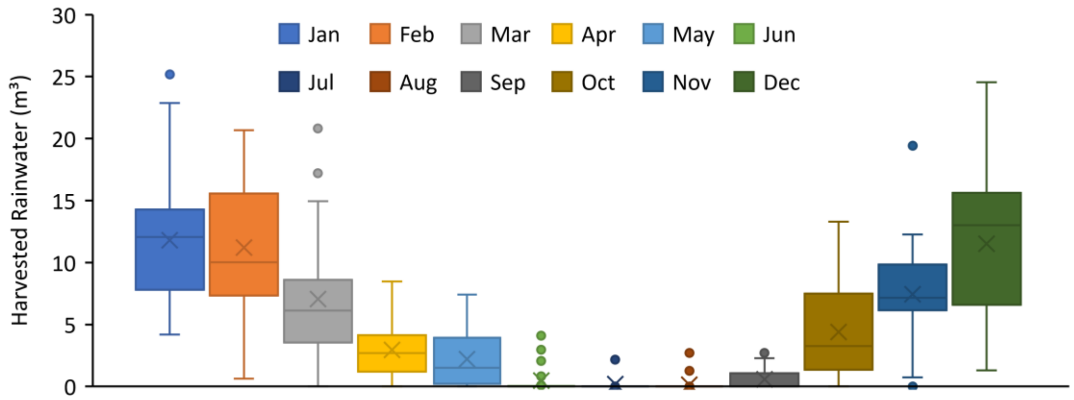


Figure C.14. 30-year Harvested Rainwater at Lapta

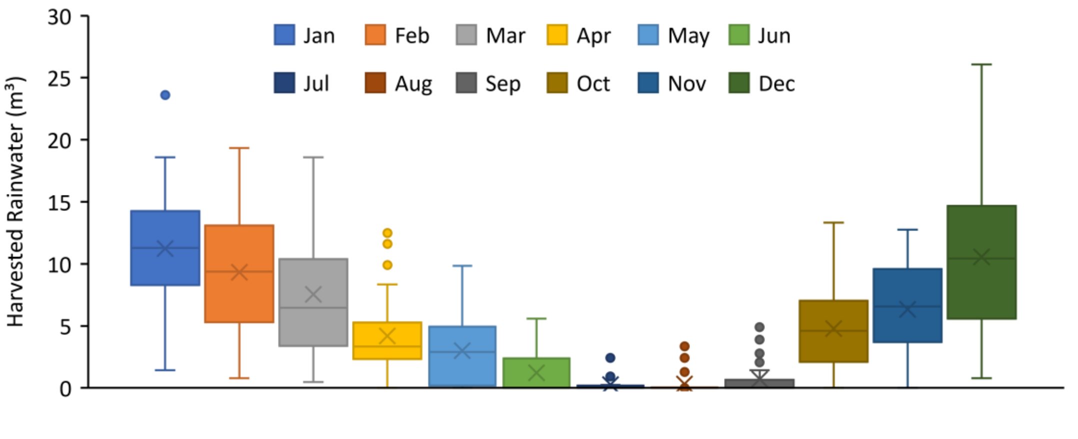


Figure C.15. 30-year Harvested Rainwater at Kantara

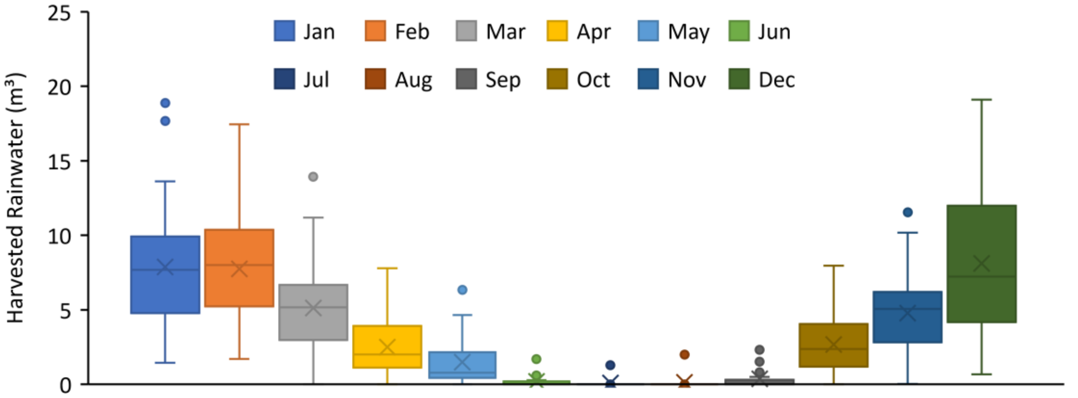


Figure C.16. 30-year Harvested Rainwater at Güzelyurt

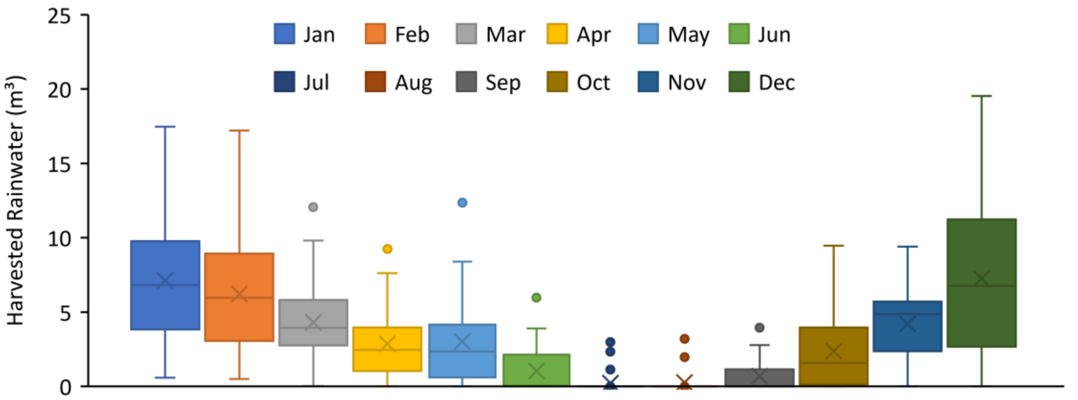


Figure C.17. 30-year Harvested Rainwater at Gönendere

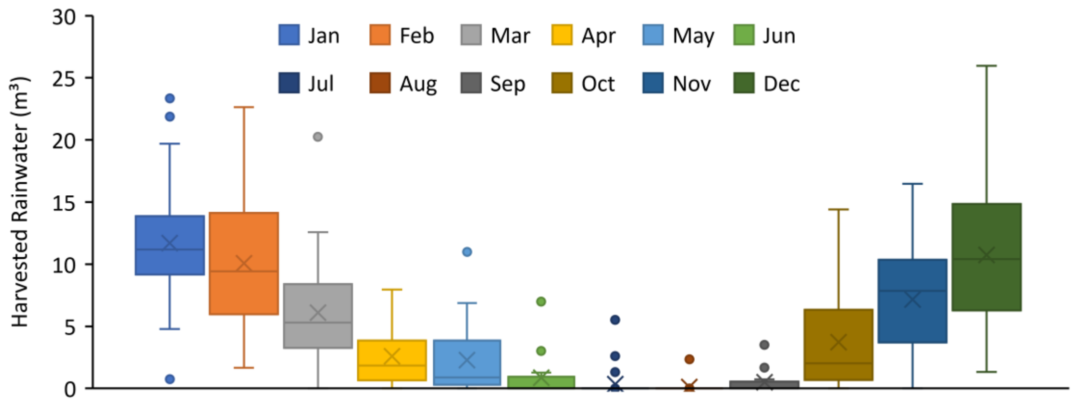


Figure C.18. 30-year Harvested Rainwater at Girne

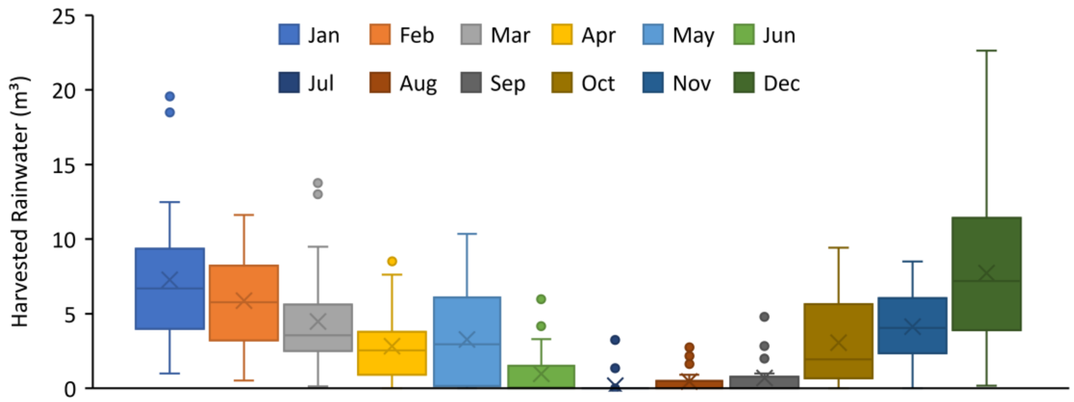


Figure C.19. 30-year Harvested Rainwater at Geçitkale

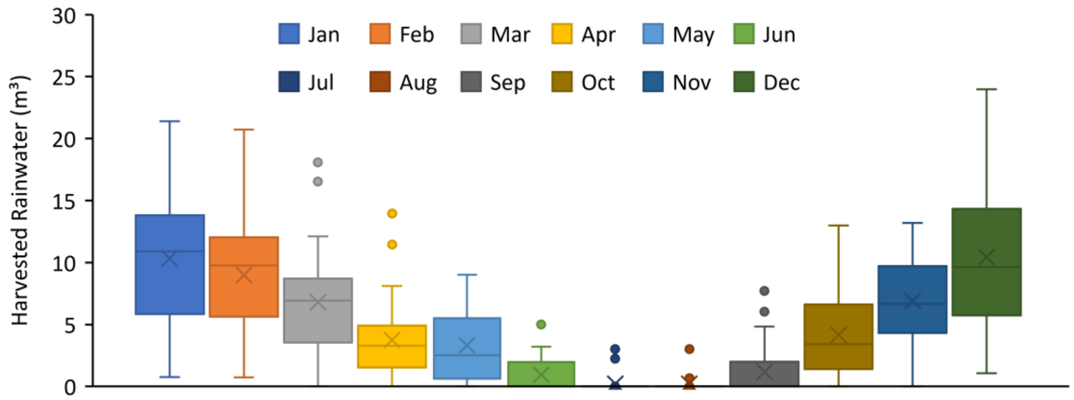


Figure C.20. 30-year Harvested Rainwater at Esentepe

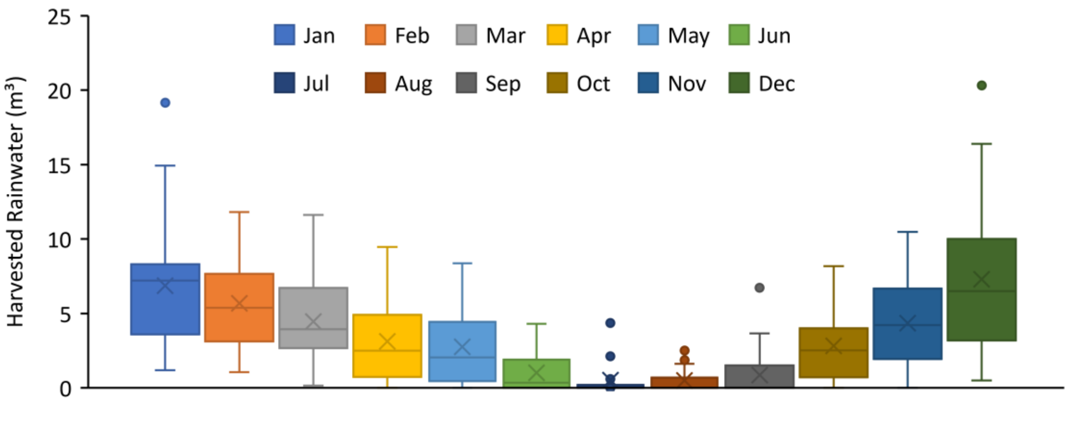


Figure C.21. 30-year Harvested Rainwater at Ercan

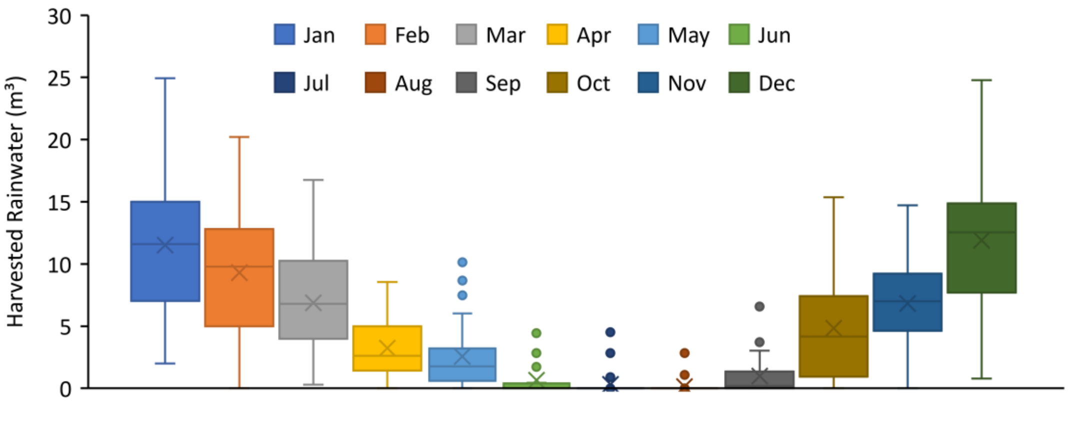


Figure C.22. 30-year Harvested Rainwater at Dipkarpaz

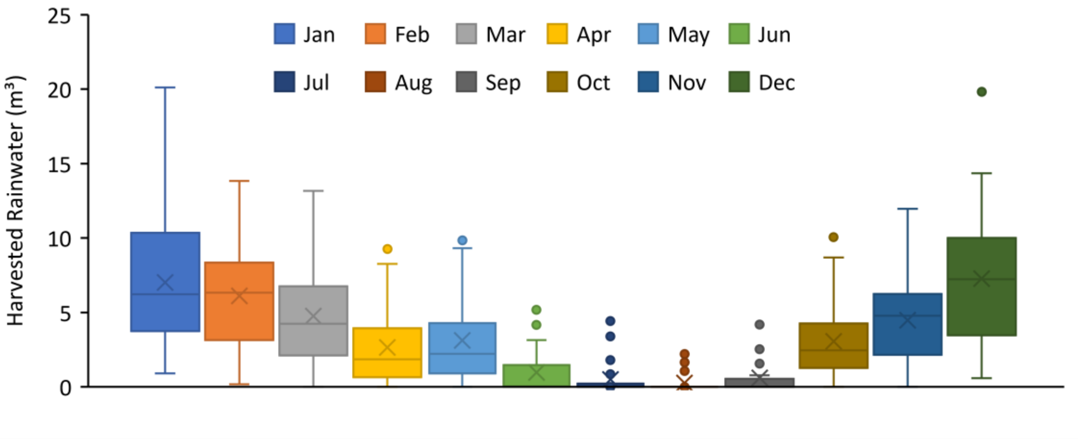


Figure C.23. 30-year Harvested Rainwater at Değirmenlik

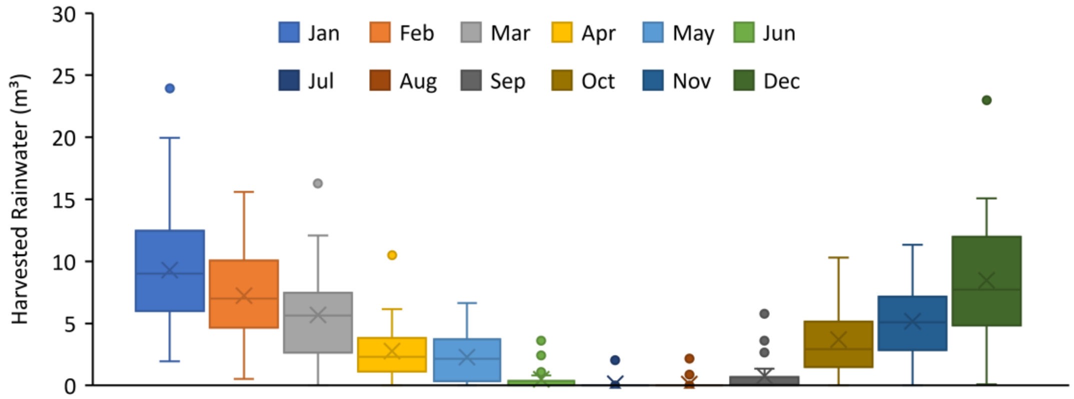


Figure C.24. 30-year Harvested Rainwater at Çayırova

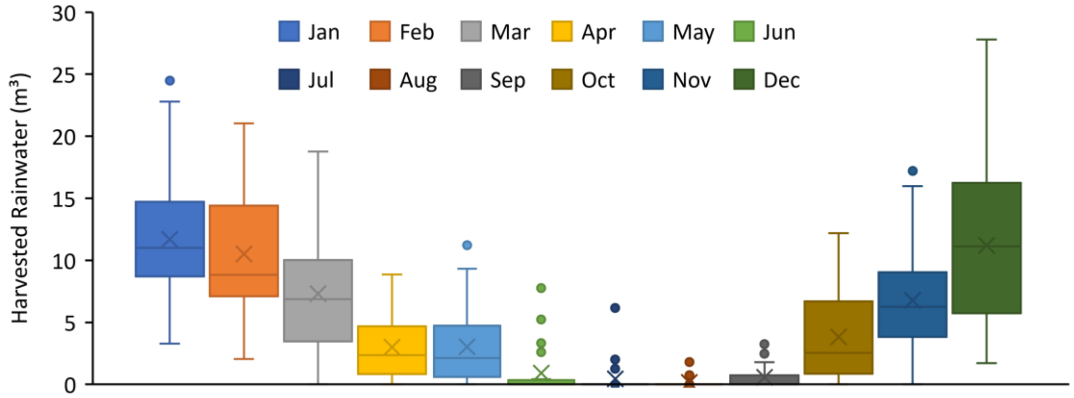


Figure C.25. 30-year Harvested Rainwater at Beylerbeyi

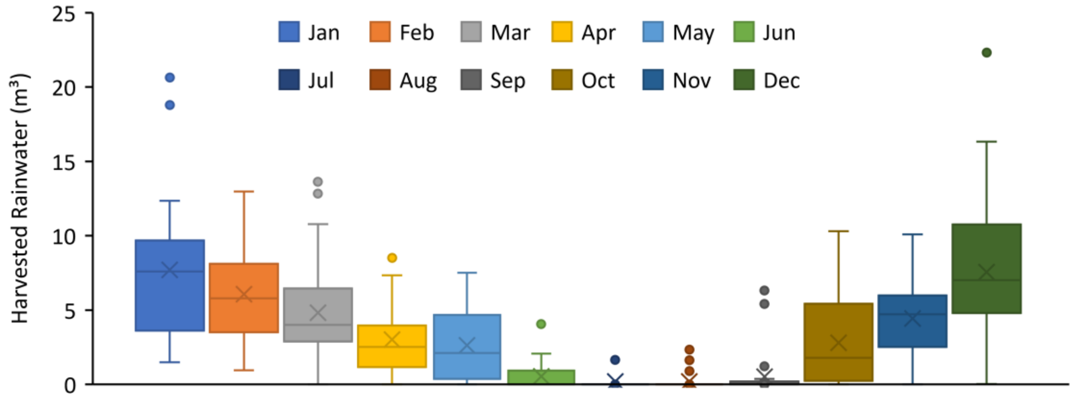


Figure C.26. 30-year Harvested Rainwater at Beyarmudu

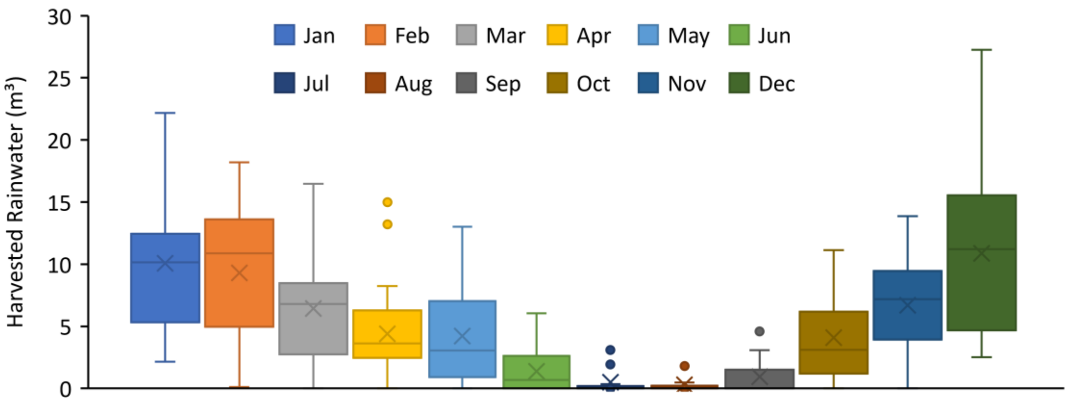


Figure C.27. 30-year Harvested Rainwater at Alevkaya

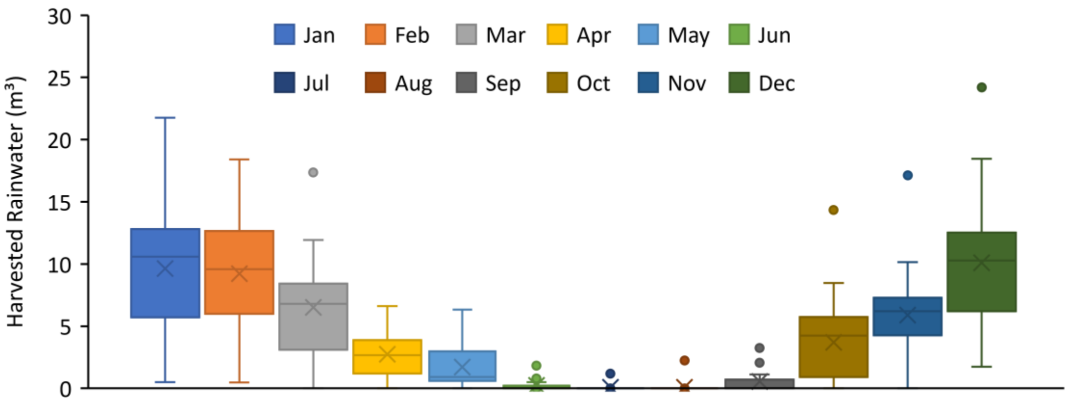


Figure C.28. 30-year Harvested Rainwater at Akdeniz

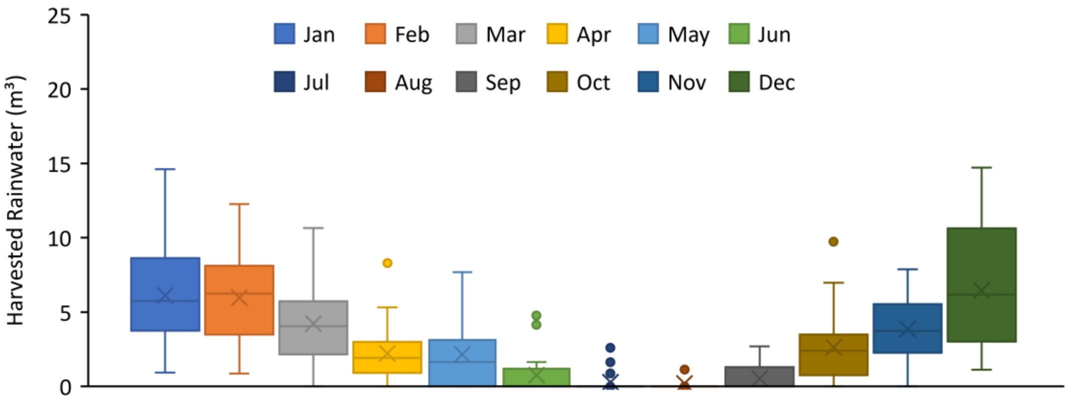


Figure C.29. 30-year Harvested Rainwater at Alayköy

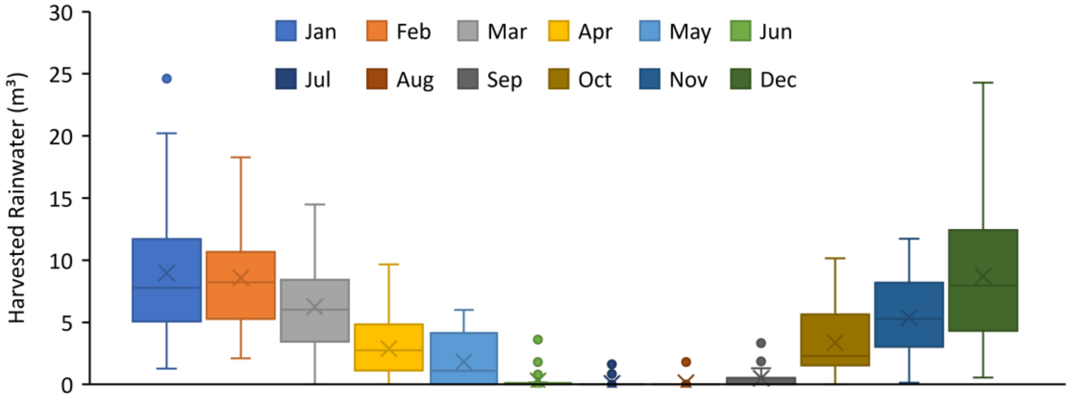


Figure C.30. 30-year Harvested Rainwater at Yeşilırmak

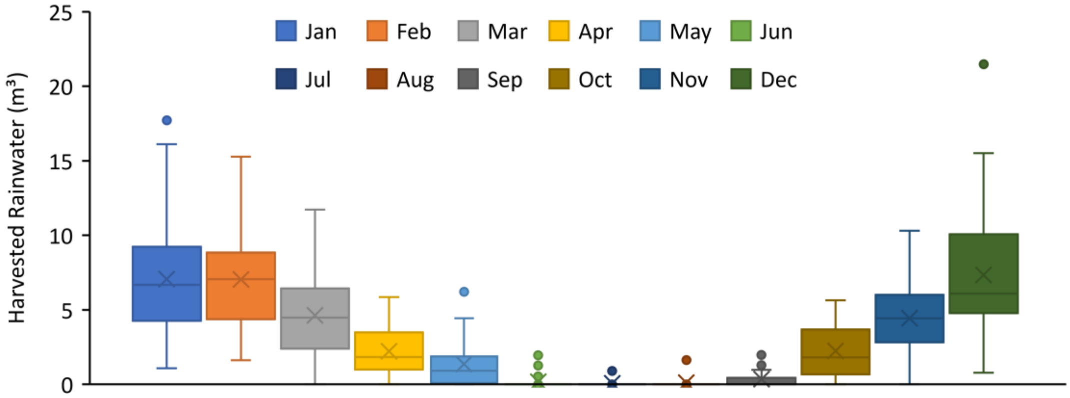


Figure C.31. 30-year Harvested Rainwater at Gaziveren

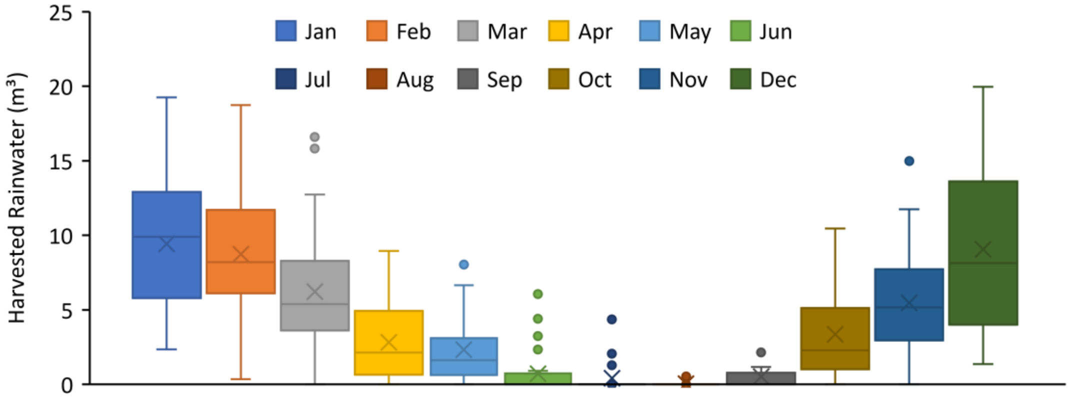


Figure C.32. 30-year Harvested Rainwater at Boğaz

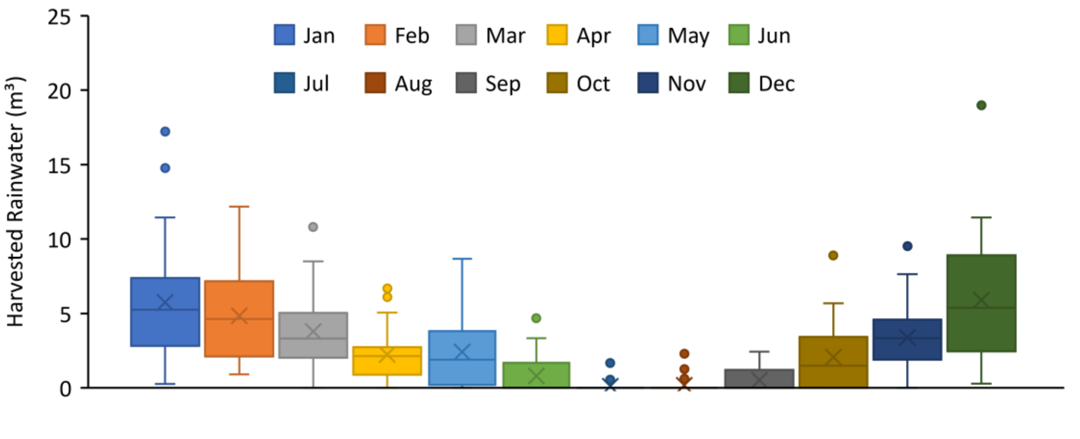


Figure C.33. 30-year Harvested Rainwater at Dörtyol

APPENDIX D

D. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at CSLs

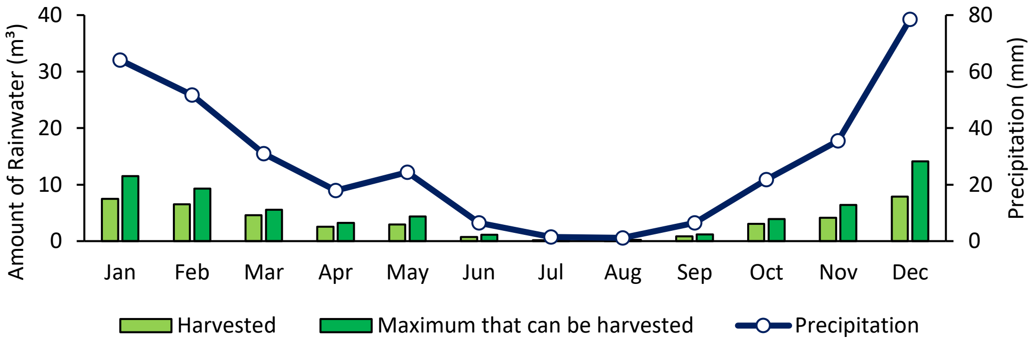


Figure D.1. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at İskele

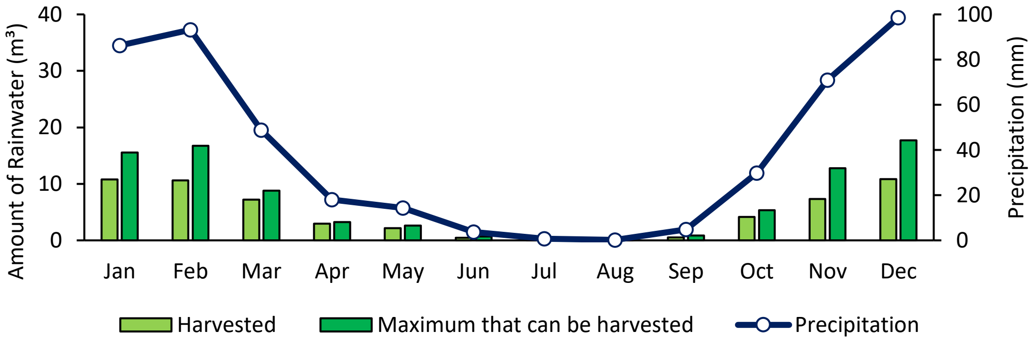


Figure D.2. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Çamlıbel

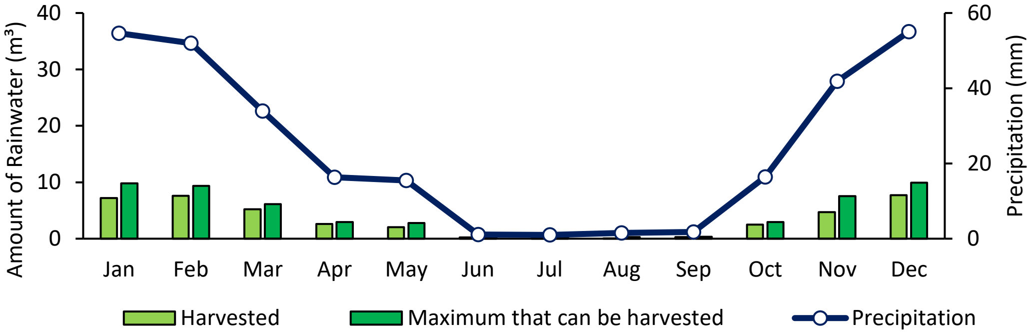


Figure D.3. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Zümrütköy

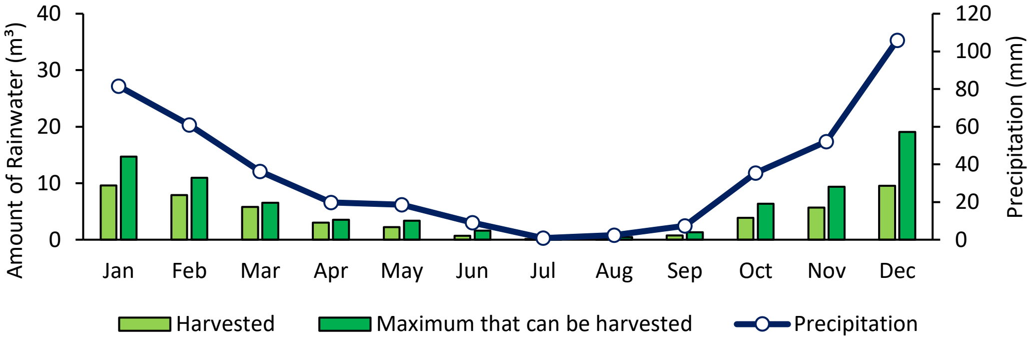


Figure D.4. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Ziyamet

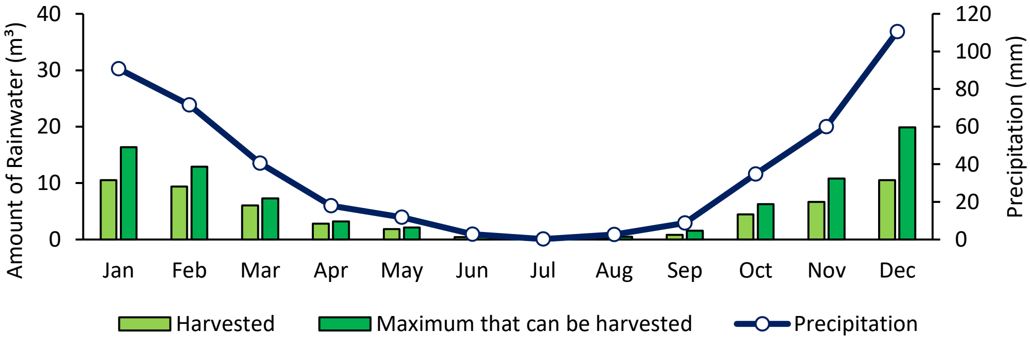


Figure D.5. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Yeni Erenköy

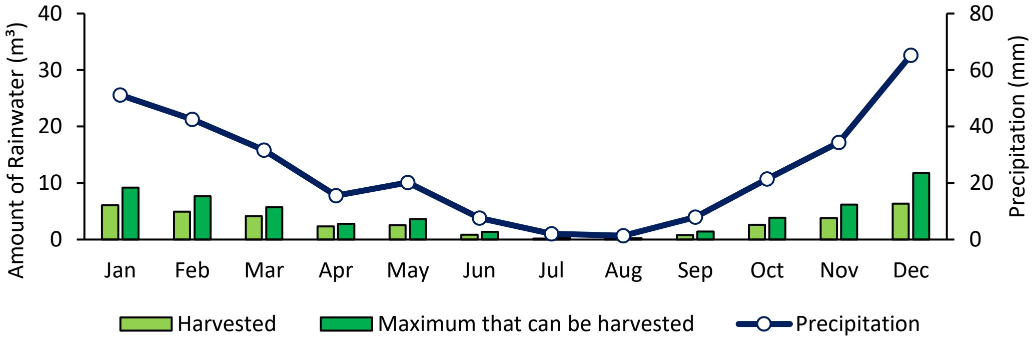


Figure D.6. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Vadili

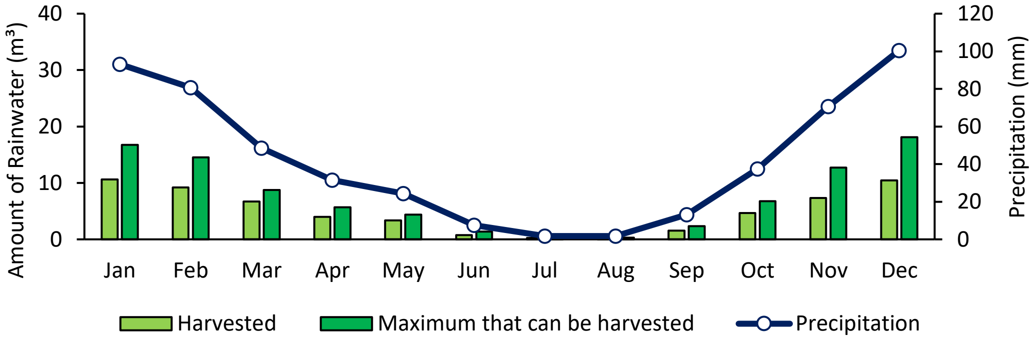


Figure D.7. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Tatlısu

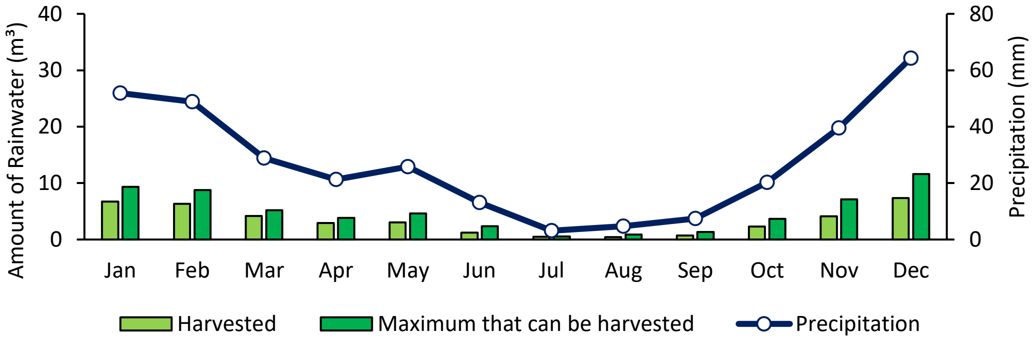


Figure D.8. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Serdarlı

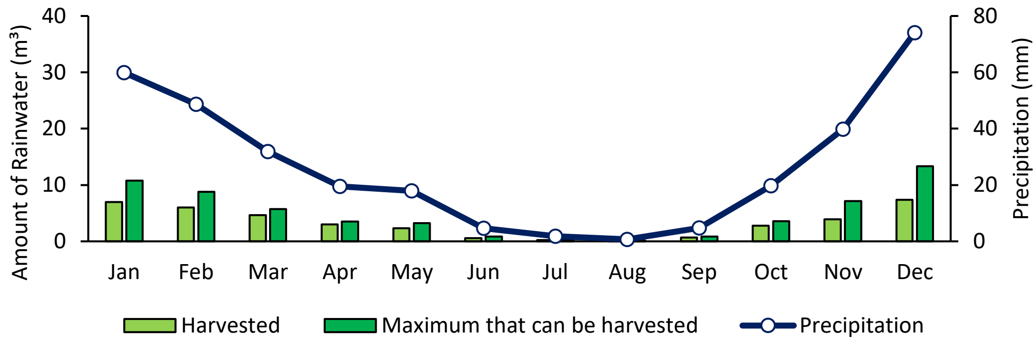


Figure D.9. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Salamis

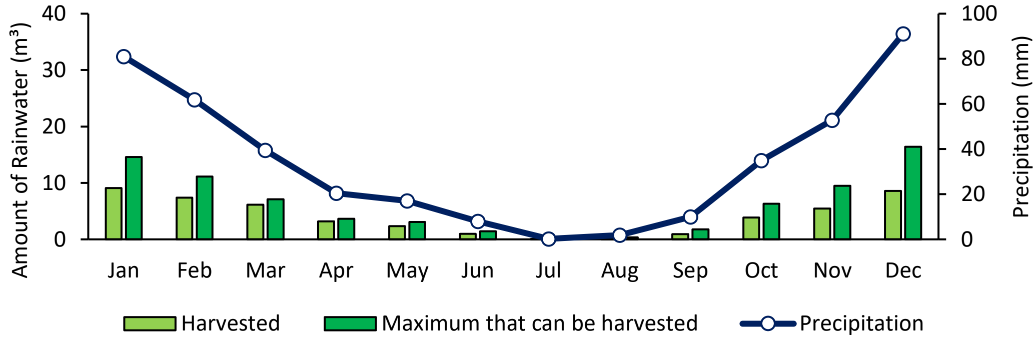


Figure D.10. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Mehmetçik

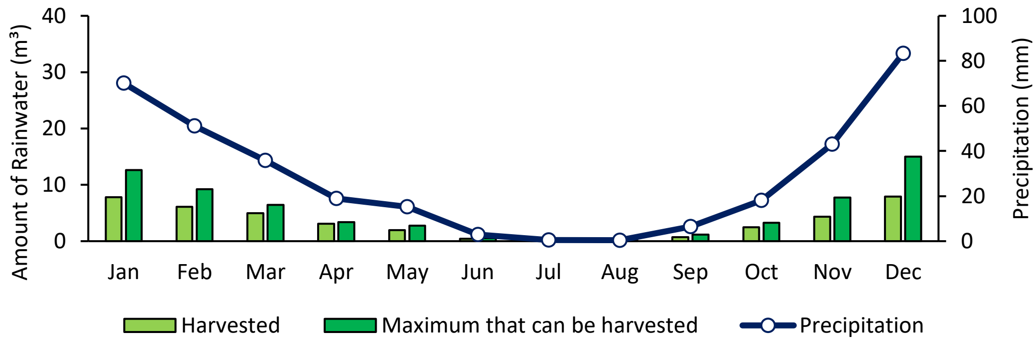


Figure D.11. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Mağusa

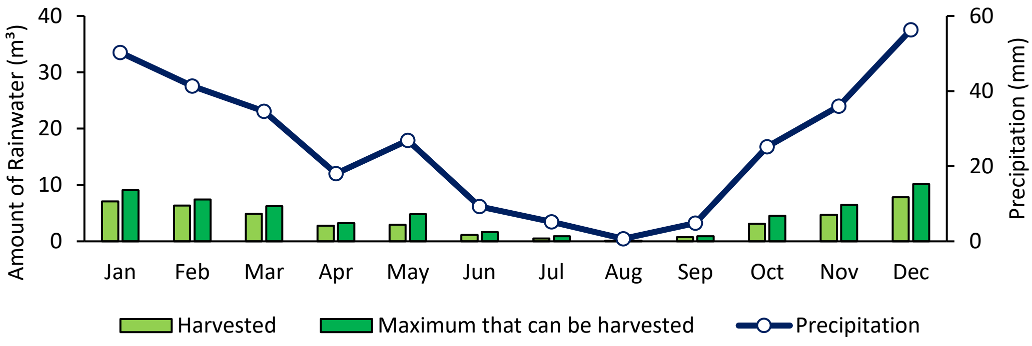


Figure D.12. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Lefkoşa

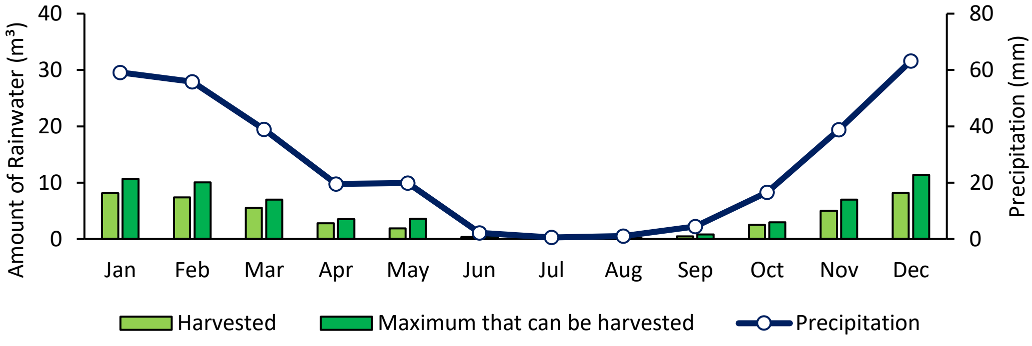
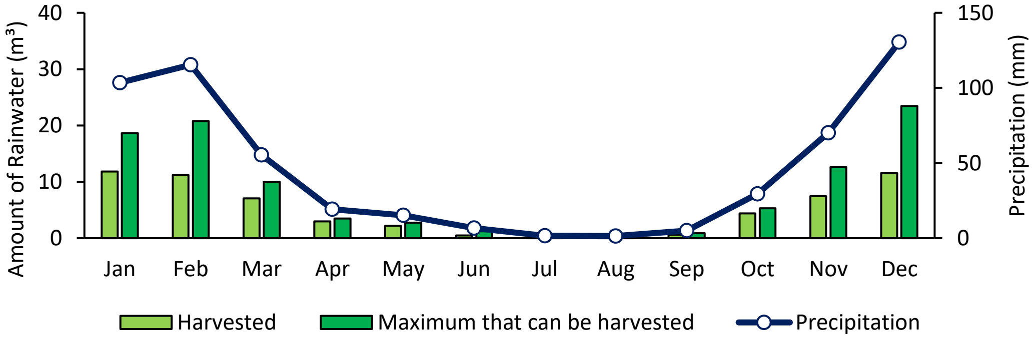


Figure D.13. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Lefke



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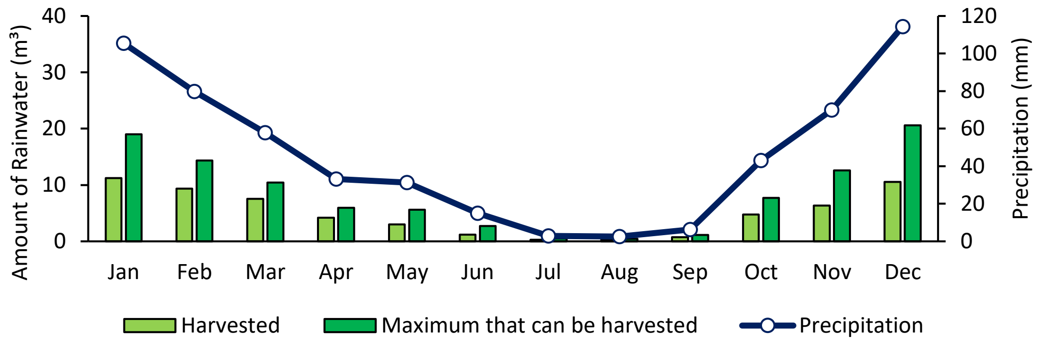

Figure D.15. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Kantara

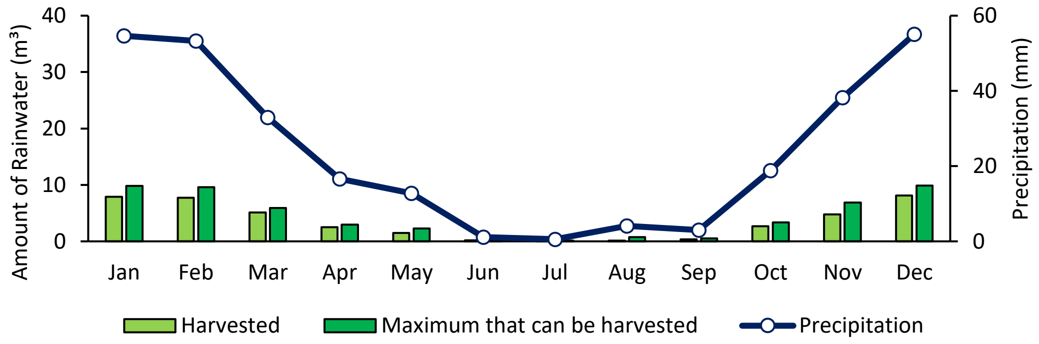

Figure D.16. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Güzelyurt

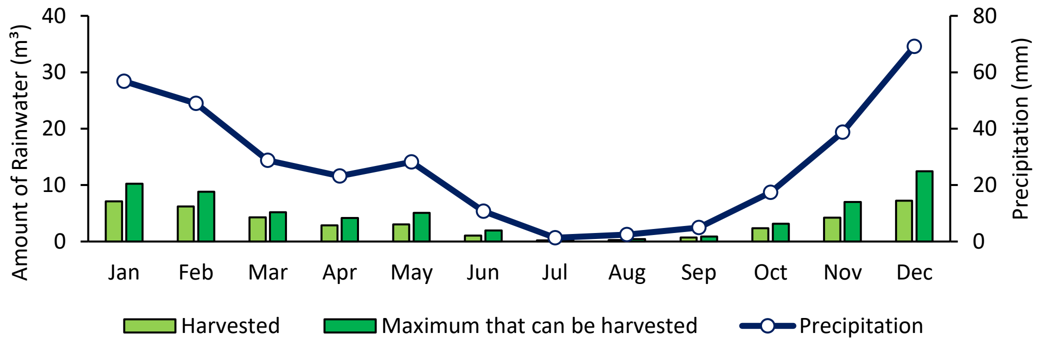

Figure D.17. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Gönendere

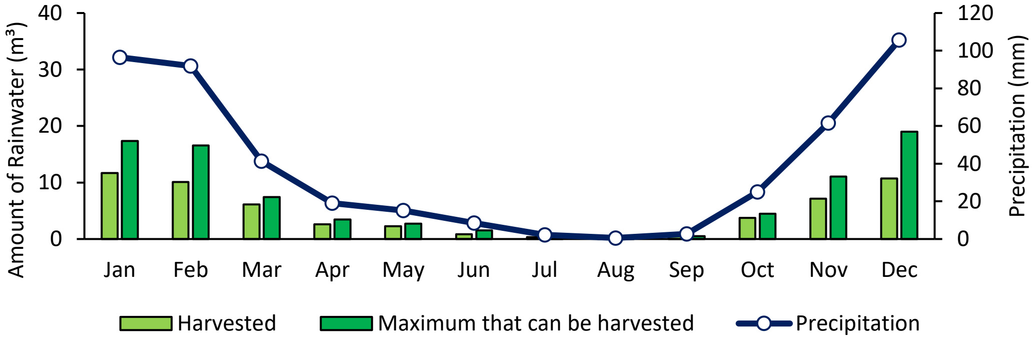

Figure D.18. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Girne

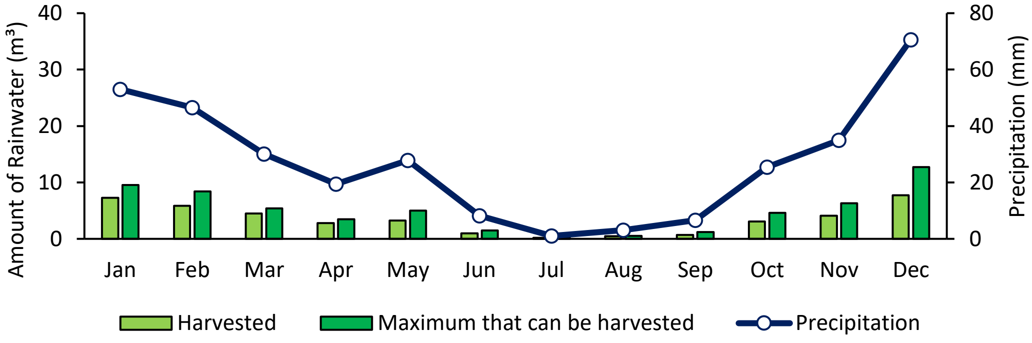

Figure D.19. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Geçitkale

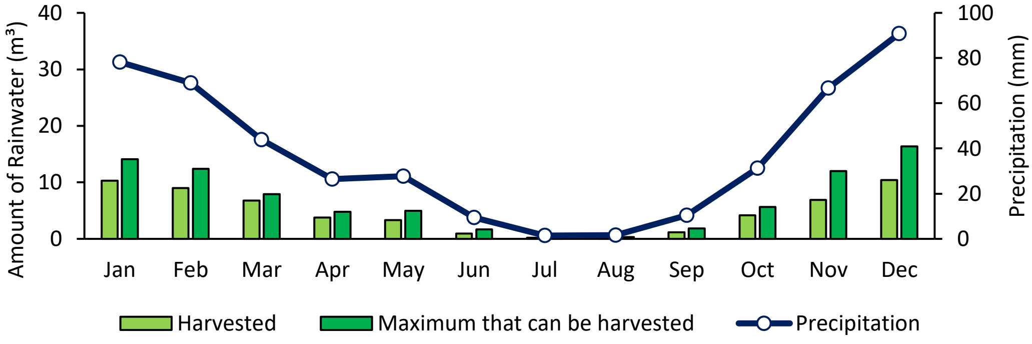

Figure D.20. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Esentepe

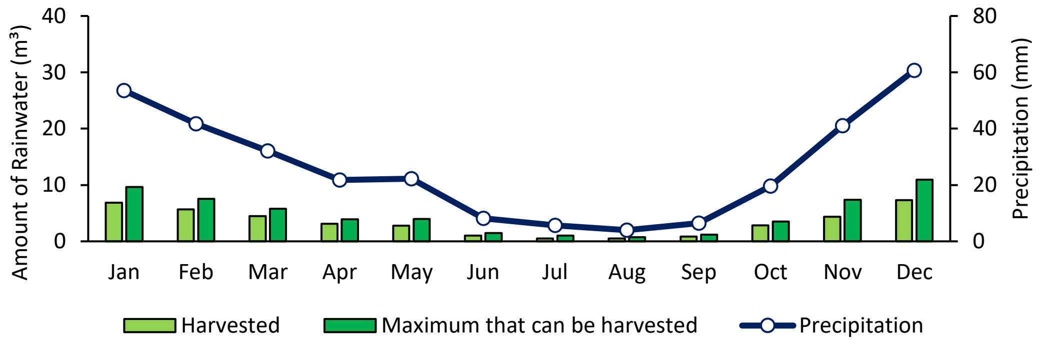

Figure D.21. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Ercan

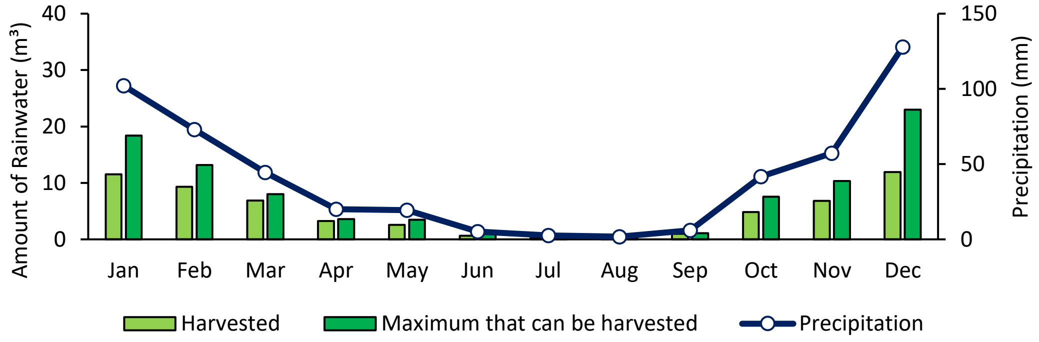

Figure D.22. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Dipkarpaz

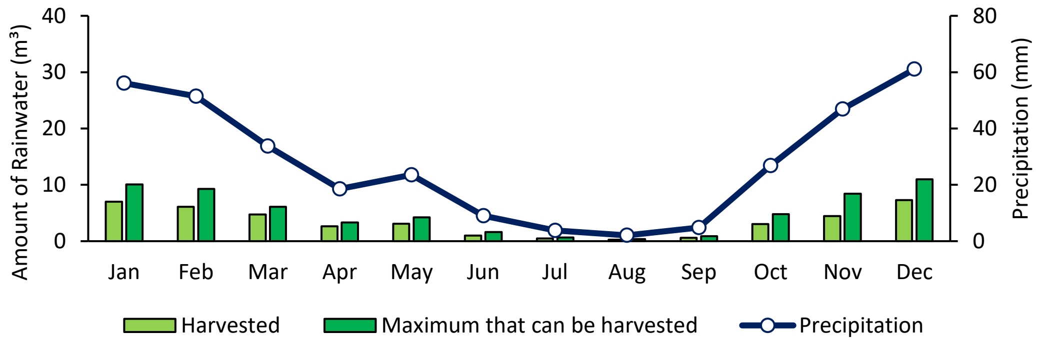

Figure D.23. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Değirmenlik

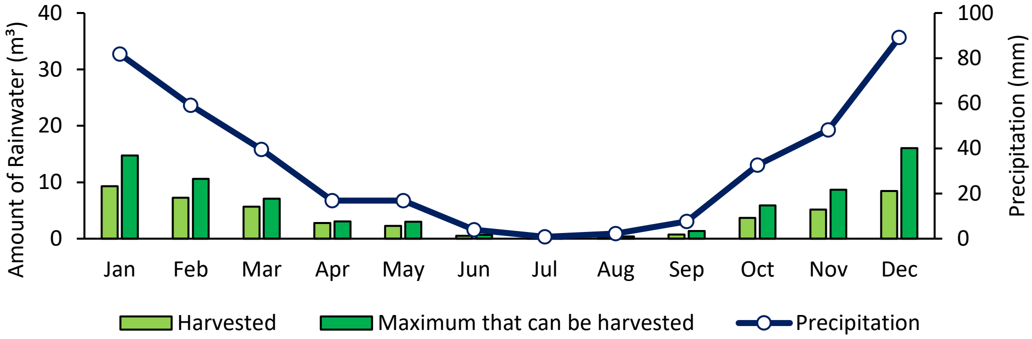

Figure D.24. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Çayırova

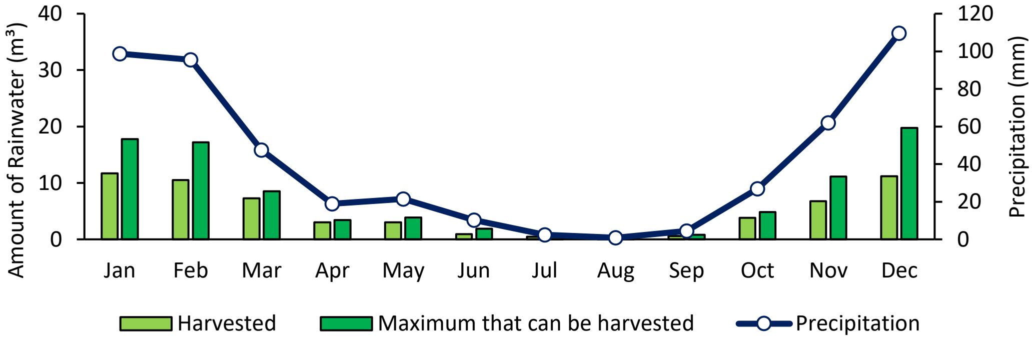

Figure D.25. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Beylerbeyi

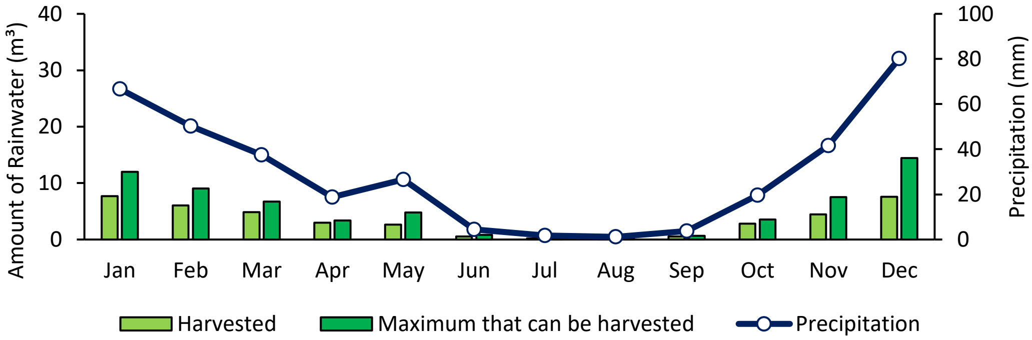

Figure D.26. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Beyarmudu

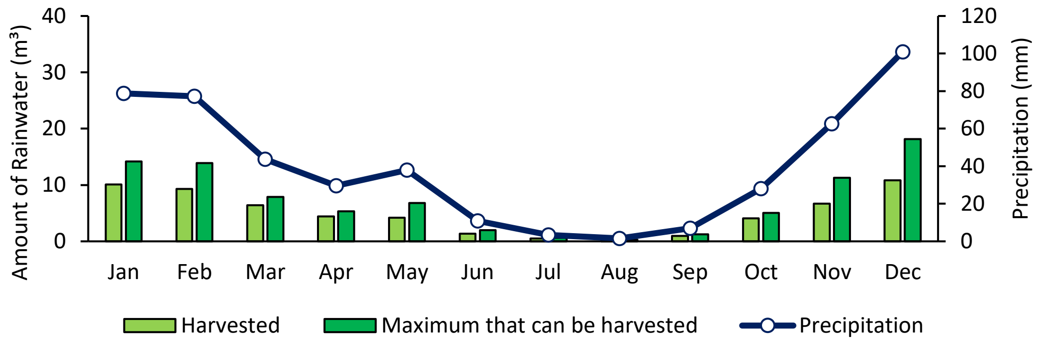

Figure D.27. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Alevkaya

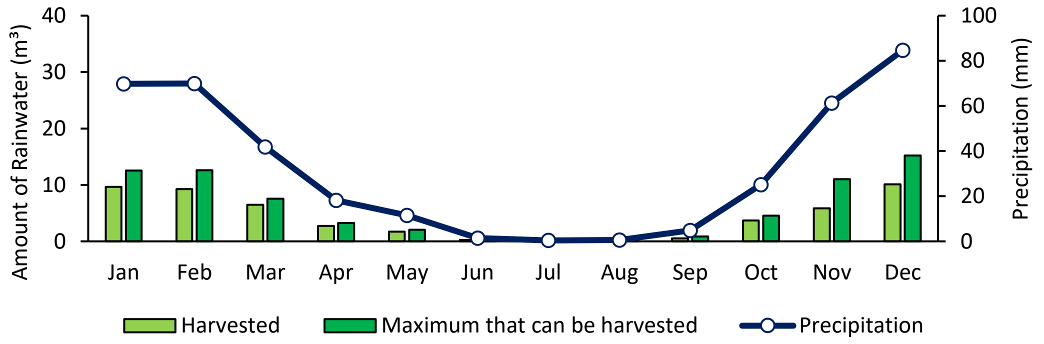

Figure D.28. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Akdeniz

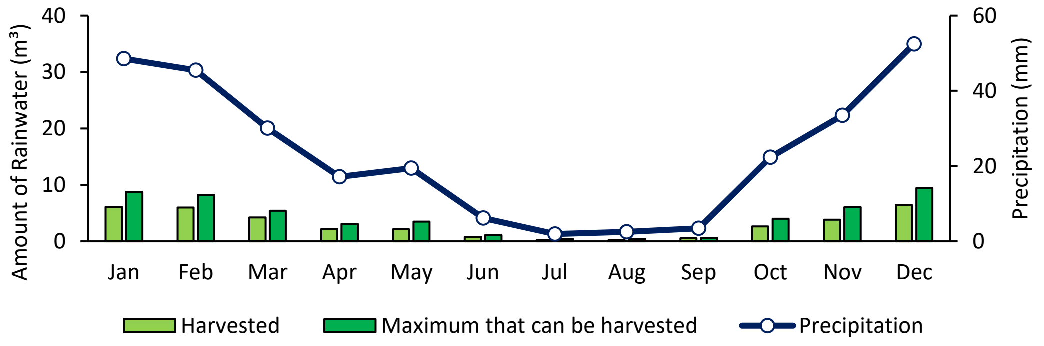

Figure D.29. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Alayköy

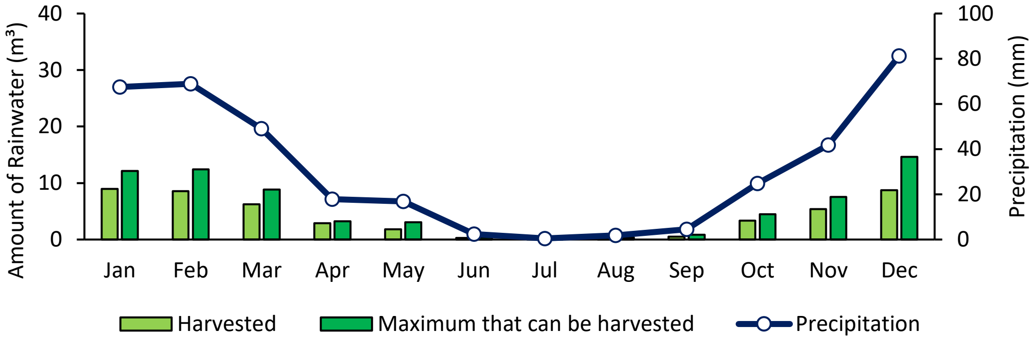

Figure D.30. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Yeşilırmak

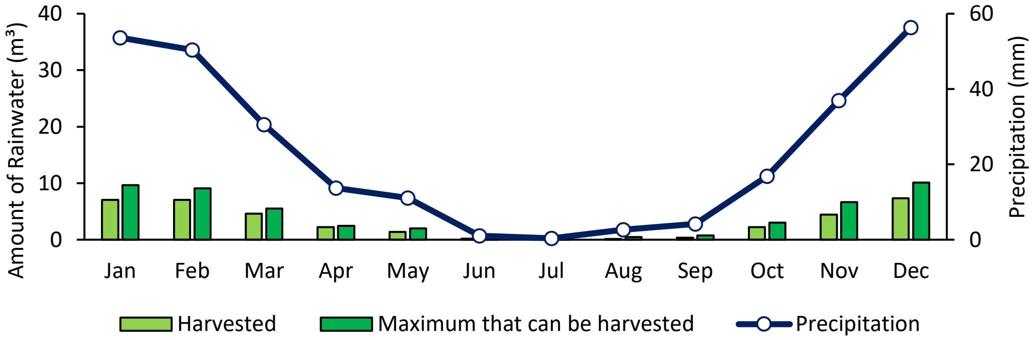

Figure D.31. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Gaziveren

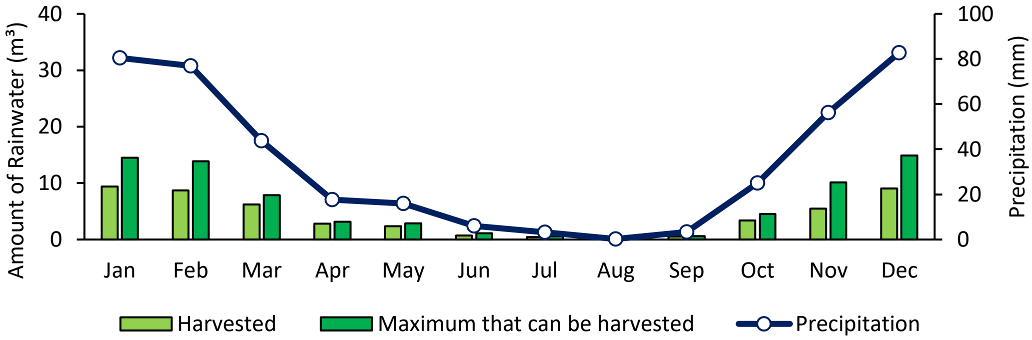

Figure D.32. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Boğaz

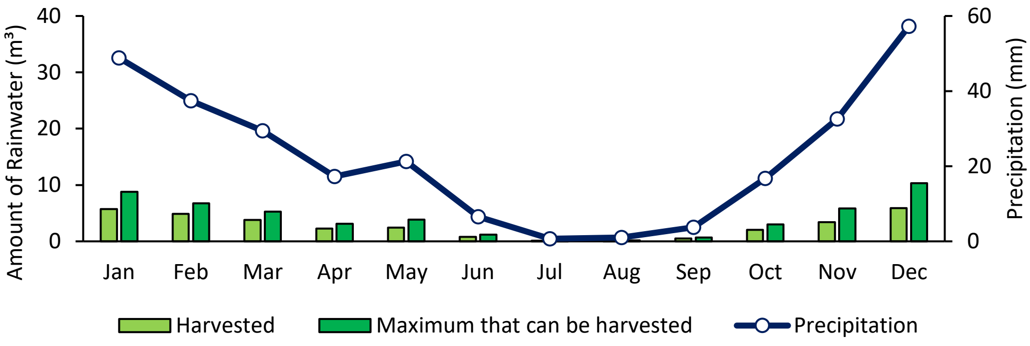

Figure D.33. 30-year Monthly Average Harvested Rainwater, Maximum Rainwater that can be Harvested and Precipitation at Dörtyol

APPENDIX E

E. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in Months

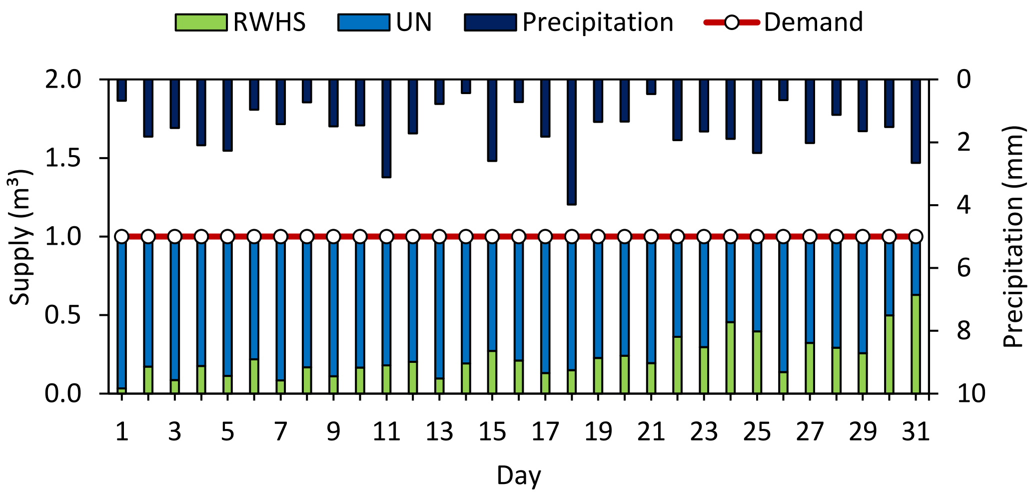

Figure E.1. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in January

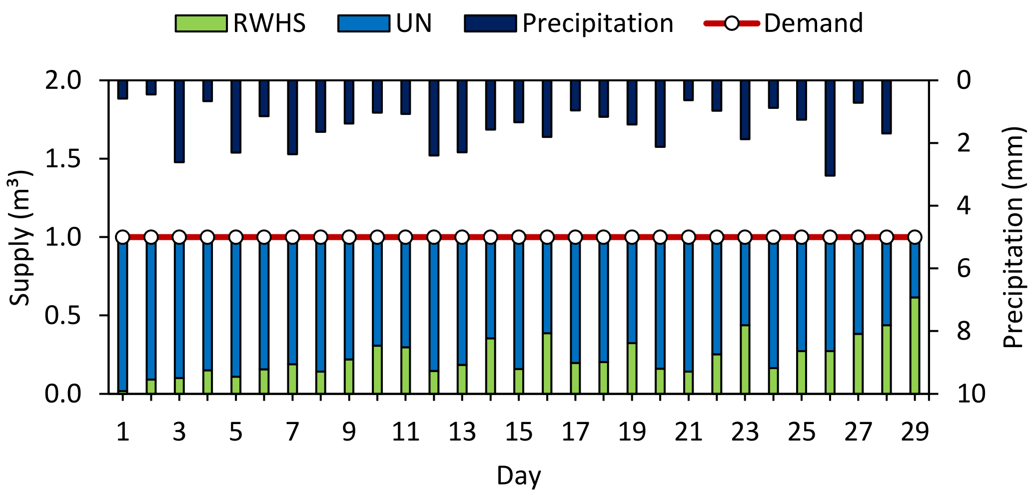

Figure E.2. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in February

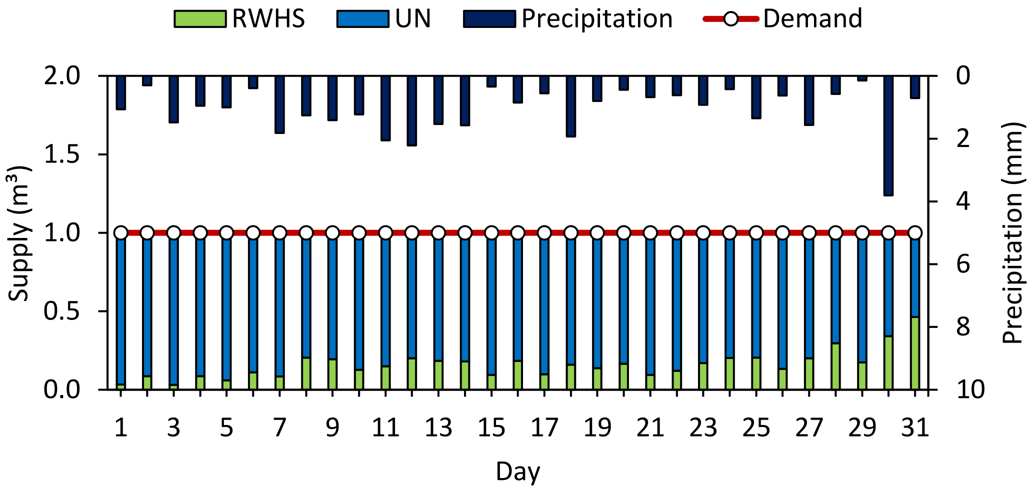

Figure E.3. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in March

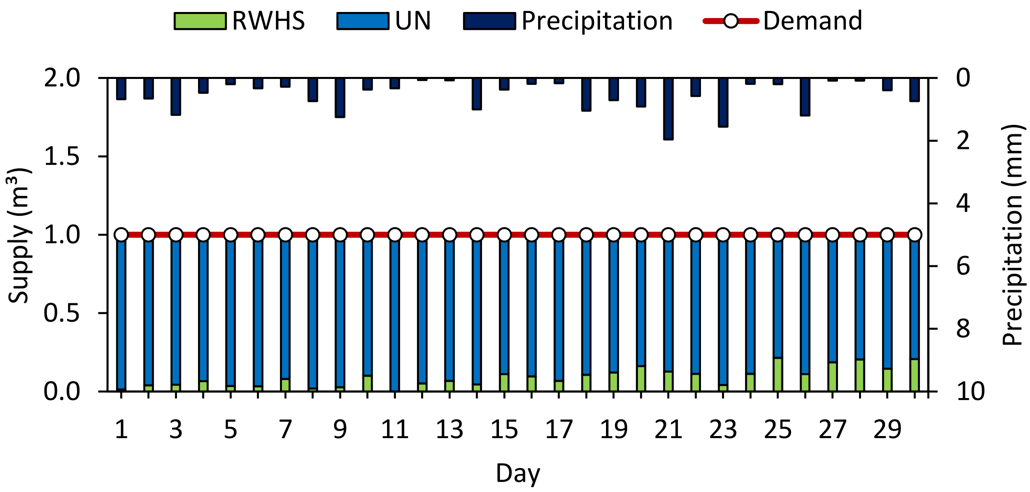

Figure E.4. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in April

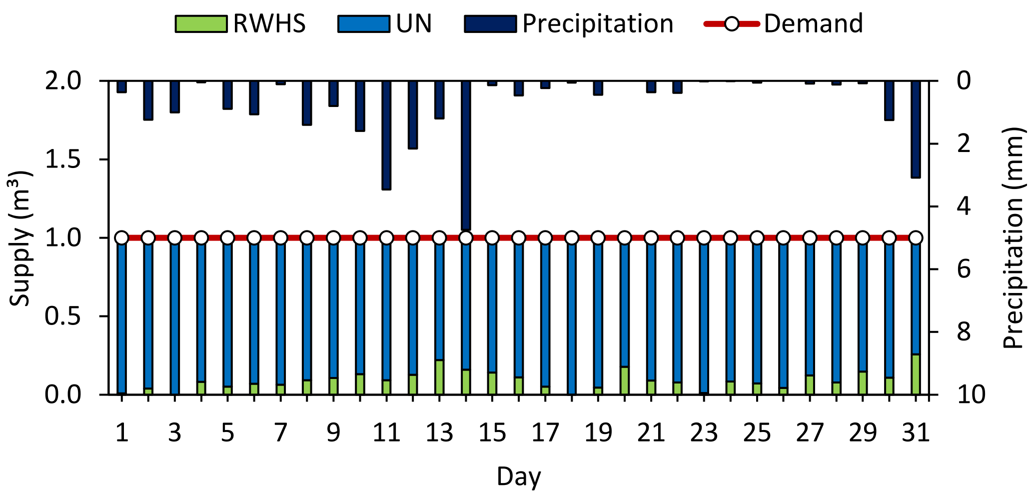

Figure E.5. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in May

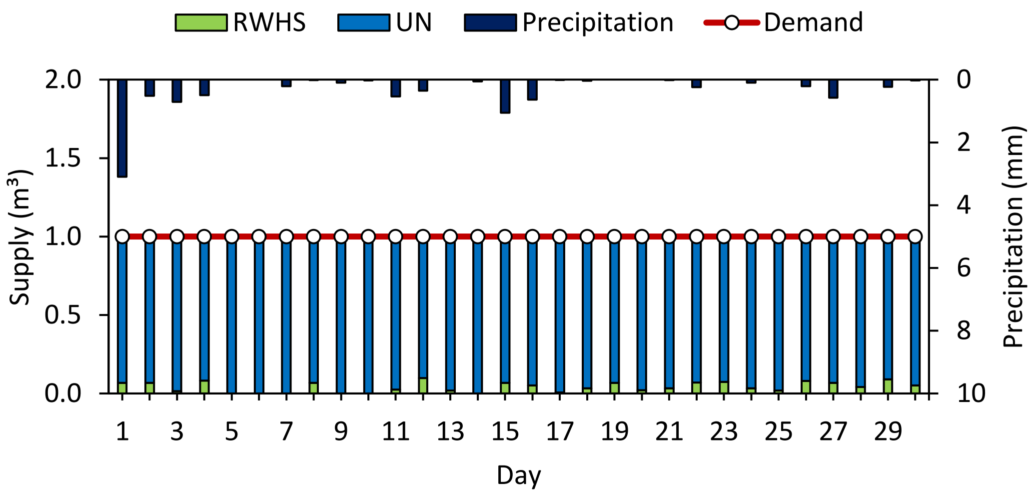

Figure E.6. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in June

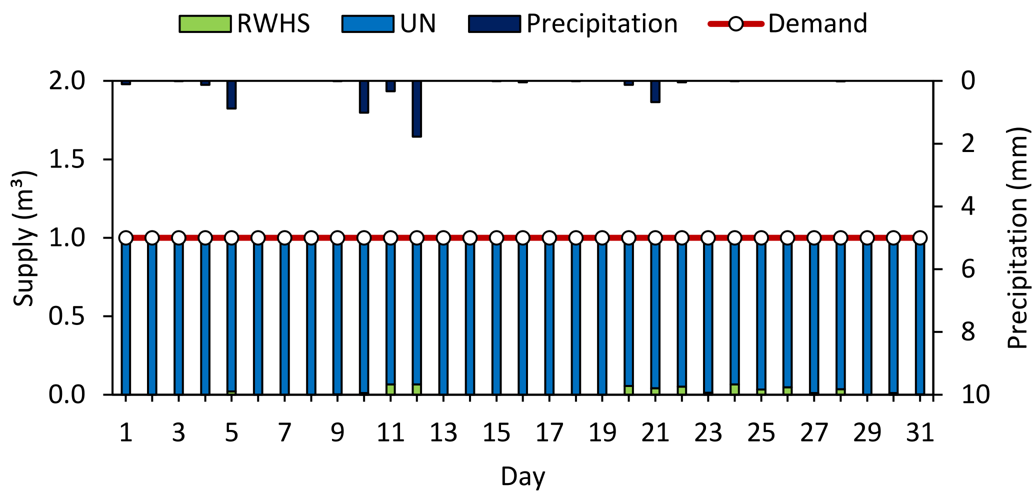

Figure E.7. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in July

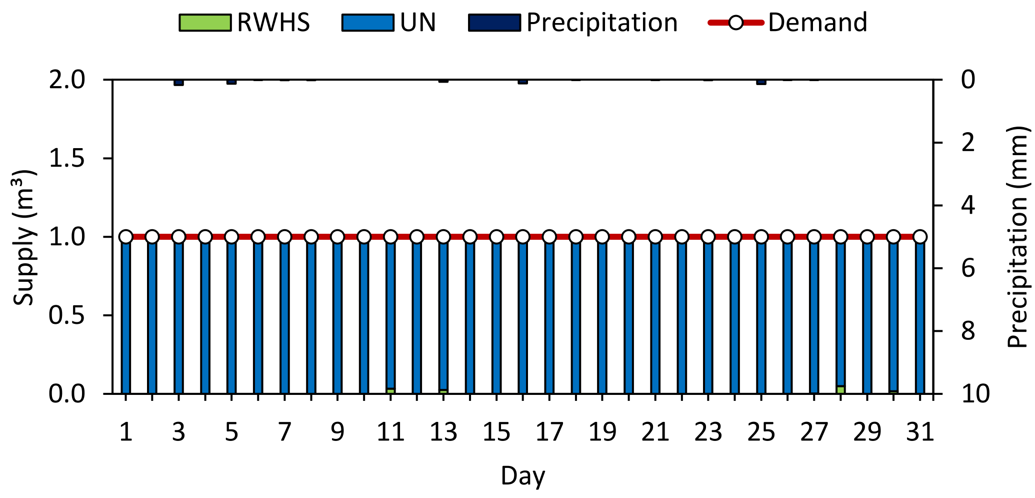

Figure E.8. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in August

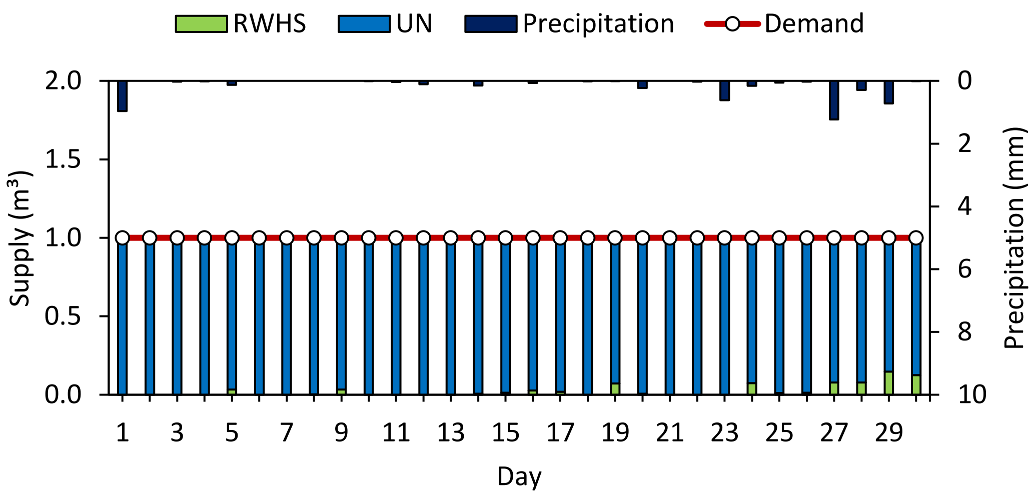

Figure E.9. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in September

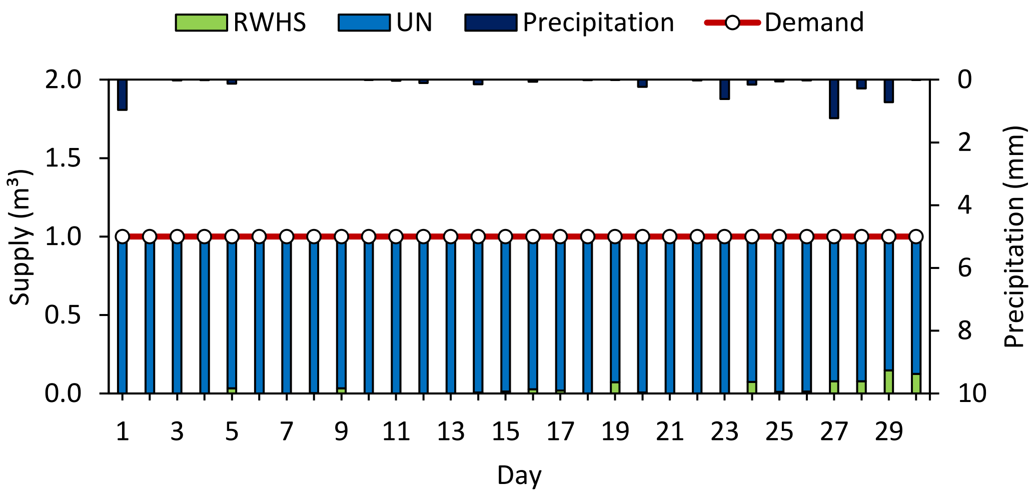

Figure E.10. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in October

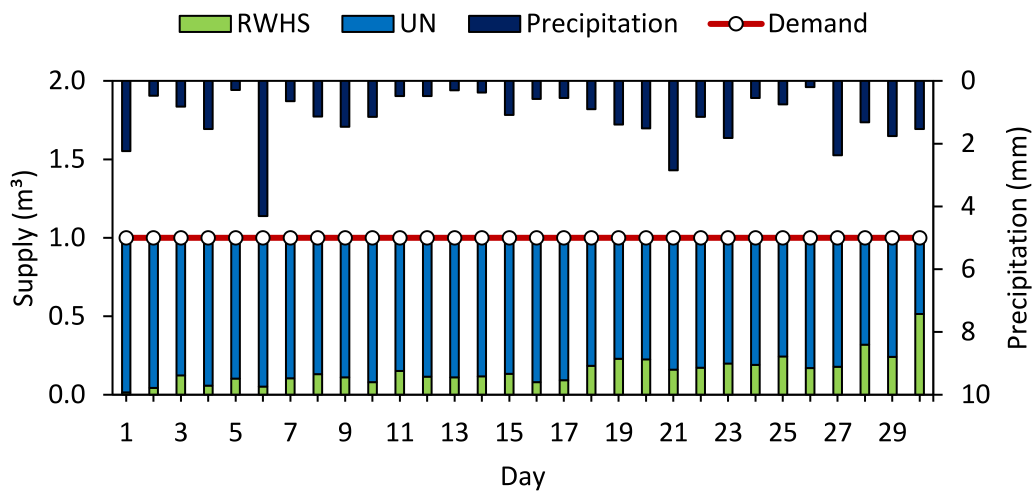

Figure E.11. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in November

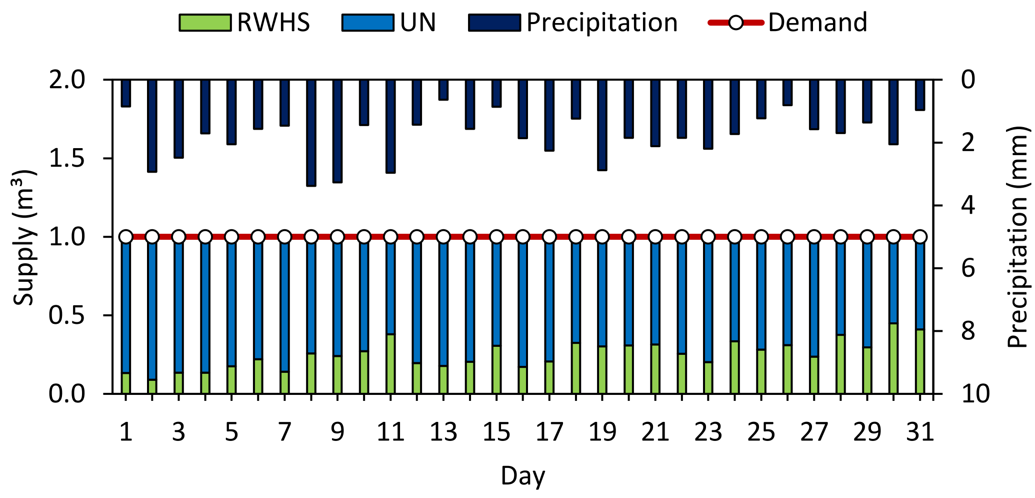

Figure E.12. Daily Average Precipitation, Water Supplies from the RWHS and the UN, and Demand at Lefkoşa in December

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