EVALUATION OF ROOFTOP RAINWATER HARVESTING POTENTIAL IN JORDAN

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ANAS JARADAT

Thesis Advisor
Assist. Prof. Dr. ENES ÖZKÖK

EVALUATION OF ROOFTOP RAINWATER HARVESTING POTENTIAL IN JORDAN

Anas JARADAT

T.C.
Karabuk University
Institute of Graduate Programs
Department of Environmental Engineering
Prepared as
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Thesis Advisor

Assist. Prof. Dr. Enes ÖZKÖK

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I certify that in my opinion the thesis submitted by Anas JARADAT titled "EVALUATION OF ROOFTOP RAINWATER HARVESTING POTENTIAL IN JORDAN" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assist.Prof.Dr. Enes ÖZKÖK ....
Thesis Advisor, Department of Environmental Engineering

This thesis is accepted by the examining committee with a unanimous vote in the Department of Environmental Engineering as a Master of Science thesis. June 15, 2022

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Chairman	: Assist.Prof. Dr. Fatih SAKA (KBU)	....
Member	: Assist.Prof. Dr. Enes ÖZKÖK (KBU)	....
Member	: Assist.Prof. Dr. Selim DOĞAN (Konya Tech. Uni.)	Online

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ABSTRACT

M. Sc. Thesis

EVALUATION OF ROOFTOP RAINWATER HARVESTING POTENTIAL IN JORDAN

Anas JARADAT

Karabük University
Institute of Graduate Programs
Department of Environmental Engineering

Thesis Advisor:
Assist. Prof. Dr. Enes ÖZKÖK
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Rainwater harvesting is the collection and storage of rainwater during rainy days for use. This study aimed to evaluate the potential volume of rainwater that can be harvested from rooftops in 12 governorates of Jordan and to estimate the optimal tank sizes to store harvested rainwater. The population growth rate and the municipal water consumption growth rate values were found to be in close correlation. The projections made in this study demonstrate that total water supply per capita would decrease from 287 liters/day down to 178-226 liters/day by 2030 if no new sources were found after 2020.

Jordan's total potential for rooftop rainwater harvesting was estimated at 23.74 Mm^3/year, corresponding to 4.5% of the total water consumption. In the northern governorates of Irbid, Ajlun, and Jarash, 14.5%, 9.0%, and 7.8%, respectively, of the total demand could be met using rainwater harvested from rooftops. If the potential harvested rainwater was used only for toilet flushing, this type of consumption could be fully met by rainwater in the households in Ajlun and Irbid for any household with a rooftop area of over 50 m^2. The optimal tank sizes to store water for flushing in Ajlun and Irbid Governorates were 2.7 m^3 and 2 m^3 per household, respectively.

Key Word : Rooftop Rainwater Harvesting, Renewable Water Supply, Rainfall, Ripple Method, Water Balance Model, Jordan, Arid Region.
Science Code : 90318

ÖZET

Yüksek Lisans Tezi

ÜRDÜN’DE ÇATILARDAN YAĞMUR SUYU HASAT POTANSİYELİNİN DEĞERLENDİRİLMESİ

Anas JARADAT

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Çevre Mühendisliği Anabilim Dalı

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Yağmur suyu hasadı, yağışlı günlerde suyunun toplanması ve daha sonra kullanılmak üzere depolanmasıdır. Bu çalışmada, Ürdün'ün 12 ilinde çatılardan toplanabilecek potansiyel yağmur suyu hacminin değerlendirilmesi ve hasat edilen yağmur suyunu depolamak için gerekli tankın en uygun boyutlarının saptanması amaçlanmıştır. Nüfus artış hızı ve belediye su tüketimi artış hızı değerlerinin yakın korelasyon içinde olduğu tespit edilmiştir. Yapılan projeksiyonlar, 2020'den sonra yeni bir kaynak bulunamaması durumunda kişi başına toplam su miktarı arzının 287 litre/gün’den 2030 yılına kadar 178-226 litre/gün’e düşeceğini göstermektedir.

Ürdün'ün çatılardan yağmur suyu hasadı için toplam potansiyeli, toplam su tüketiminin %4,5'ine tekabül eden 23,74 Mm^3/yıl olarak tahmin edilmiştir. Kuzeydeki Irbid, Ajlun ve Jarash İllerinde, toplam talebin sırasıyla %14,5'i, %9,0'ı ve %7,8'i çatılardan toplanan yağmur suyu kullanılarak karşılanabileceği tahmin edilmiştir. Eğer potansiyel olarak toplanan yağmur suyu sadece tuvalet sifonu için kullanılsaydı, bu tür bir tüketimin hepsi Ajlun ve Irbid İllerindeki çatı alanı 50 m^2'nin üzerinde olan herhangi bir hane için yağmur suyu ile tamamen karşılanabildiği hesaplanmıştır. Ajlun ve Irbid İllerinde sifon için su depolamak için en uygun tank boyutları sırasıyla hane başına 2,7 m^3 ve 2 m^3 olarak tespit edilmiştir.

Anahtar Sözcükler : Çatıdan Yağmur Suyu Hasadı, Yenilenebilir Su Temini, Yağış, Ripple Yöntemi, Su Dengesi Modeli, Ürdün, Kurak Bölgeler.
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SYMBOLS AND ACRONYMS

SYMBOLS

∑(D-VR) : The cumulative values of monthly demand minus potential harvesting (m^3).
$: United States Dollars.
A : Roof Area (m^2).
C_i : The runoff coefficient.
CGR : Consumption Growth Rate.
Cpm : The cost per cubic meter (JOD/m^3).
D : The monthly water consumption by one family in a single household (m^3).
D_f : The flushing water consumption for a family (m^3).
i : single house.
j : multi-story house.
JOD : Jordanian Dinar.
k : villa.
Mm^3 : Million cubic meters.
N : Number of Roofs.
n : number of years.
N.A. : Not available.
ND : Number of Dwelling.
P : Average annual rainfall (mm/year).
$\overline{P}t$: Average monthly rainfall (mm).
PGR : Population Growth Rate.
PSP : The Potential Saving Percentage.
PSP_r : The reliability of the Potential Saving Percentage.
R_i : The monthly consumption (m^3/month).
S : The optimal tank size (m^3).
TAPG : Total Domestic Consumption for Every Governorate or Total Amount Per Governorate (m^3).

TRA : Total Roof Area for each governorate (m^2)

VR : Monthly potential volume of harvested rainwater (m^3).

VR_h : The monthly potential volume of rainwater harvested for a house by (m^3).

V_f : The maximum positive cumulative in the tank at the end of the month (m^3).

V_i : The volume of stored water at the beginning of the month (m^3).

ACRONYMS

CBOs : Community-based organizations
DOS : Department of Statistics
MWI : Ministry of Water and Irrigation
MoEnv : Ministry of Environment
RWH : Rainwater harvesting
WDM : Water Demand Management
WHO : World Health Organization

CHAPTER 1

INTRODUCTION

Water covers more than two-thirds of the planet; however, accessible freshwater accounts for less than 1% of the total amount of water on Earth, and hence, it must be considered a scarce resource (USGS, 2019). All creatures need water to survive, and water is a crucial resource that plays a role in all stages of human life. No community can properly develop without water security, benchmarked based on three main factors; water quality, demand, and supply (WaterAid, 2019). Water demand depends on factors like population, climate, water price, land use, and so forth. All these can change over time. In contrast, the water supply depends on natural water resources (Sun et al., 2008).

Globally, water security is one of the most critical issues, especially in the arid and semi-arid countries of the Middle-East Region (PRB, 2000), where Jordan is located. Jordan is a country that suffers the most from water scarcity since the total water demand in Jordan is higher than the natural renewable water sources of the country (UNICEF, 2020). Jordan has been suffering from a deficit in water resources since the 1960s (Abdulla and Al-Shareef, 2009). According to 2008 data, Jordan's available water volume per capita was 148 m^3/year, less than one-third of the globally agreed threshold of 500 m^3 per year per capita to be registered as a region with ‘absolute’ water scarcity (Assayed et al., 2013), and in 2020, it was less than 100 m^3/year per capita (UNICEF, 2020). The high population growth rate in Jordan and the significant migrations due to the recent conflicts in the region put a strain on the country's already limited water resources (GMDAC, 2022). Decision-makers make efforts to distribute available water fairly in Jordan, but these efforts do not succeed in supplying the required amount of water. Finding new water sources is required to achieve water security in Jordan. Rainwater harvesting can be the main source of water in remote areas (Abdulla and Al-Shareef, 2009). Accordingly, rainwater harvesting was listed as one of the potential water sources introduced in Jordan's water demand management policy that was implemented in 2015 (Al-Qawasmi, 2021).

Some studies on rainwater harvesting have found that rainwater harvesting can meaningfully contribute to the water supply in Jordan (Assayed et al., 2013; Saidan et al.,2015; Hadadin et al.,2014; Abu-Zreig et al.,2013; Awawdeh et al.,2012, Al-Houri et al., 2014). Saidan et al. (2015) found that rainwater harvesting could provide nearly five times cheaper water than conventional water systems. A study by Abdulla and Al-Shareef (2009) based on 2005 data found that 15.5 Mm^3/year of water could be harvested using rooftops, corresponding to 5.6% of Jordan's annual water demand in 2005; the potential water harvested varied from 0.023 Mm^3 in Aqaba to 6.45 Mm^3 in Amman. In another study assessing the utilization of rainwater harvesting in Jordan using DOS data from 2004, it was found that 14.7 Mm^3 of rainwater per year could be harvested using rooftops (Abu-Zreig et al., 2013); this amount was equivalent to 6% of the annual demand of 2004. These results suggest that 5-6% of the total demand can be met solely through the rainwater falling on rooftops. Other types of urban runoffs (e.g., runoff from city streets) can also be collected, but the authors consider that rooftop rainwater harvesting is the easiest to implement, building upon already existing rooftop drainage systems.

Another point to consider is the contamination level of collected rainwater. Contamination levels dictate the usage of collected rainwater for different purposes such as agriculture, raising livestock, toilet flushing, cooking, and drinking. Some studies have indicated that the quality of harvested water generally was compatible with ‘Jordanian Drinking Water Standards’ (Assayed et al., 2013). On the other hand, Radaideh (2009) concluded that harvested rainwater in Jordan was not suitable for drinking. The tests of rainwater samples showed that rainwater quality standards such as total dissolved solids, hardness, and turbidity were high for the first storms of the rainy season but then gradually decreased (Abu-Zreig et al., 2019). Abdulla and Al-Shareef (2009) reported that the harvested water must be treated before drinking and cooking, but it may be used for irrigation, cleaning, and flushing without prior treatment. Based on these conflicting results, it is safer to assume that rainwater collected from the roofs is contaminated and should not be used for drinking, cooking, and personal hygiene; hence it should be handled as a gray water source.

The most expansive component of a rainwater harvesting system is the installation of the storage tank. According to Abu-Zreig et al. (2019), the tank cost represents 95% of the total cost of installing the entire rainwater harvest system when steel and concrete are used to construct the tank, whereas Farreny et al. (2011) reported that the tank costs around 50% of the total cost of installation, operation, and maintenance. Therefore, depending on the optimal tank size, it can be assumed that the approximate cost of the rainwater harvesting system can be determined (Shadeed and Alawna, 2021; Imteaz and Shadeed, 2022). Two main factors determine the tank size required; (1) the monthly water consumption rate (2) and the amount of harvested rainwater (Abu-Zreig et al., 2019). The maximum optimal tank size depends on water consumption and the potential harvesting of rainwater.

This study was conducted to estimate the potential of harvesting rainwater using rooftops to enhance Jordan's accessible water sources and to estimate optimum storage tank sizes depending on the monthly rainfall rate and the water consumption. Data on daily rainfall rates over 32 years (from 1987 to 2018) were obtained for the 12 governorates of the Hashemite Kingdom of Jordan. Considering the census data from 1990 to 2020 and annual water demand data for 12 governorates, three scenarios were created based on different population growth rate estimations to depict the future water demand in 2025 and 2030. Total rooftop areas were estimated based on the number of buildings and building types in each governorate. The Ripple Method and Water Balance Model were both used to estimate the water volume of potential harvested rainwater. It has been assumed that rainwater harvested from rooftops can safely be used in flushing toilets and calculations were carried out accordingly to estimate if the demand for flushing could be met. The results were used to determine the effectiveness of rainwater harvesting via rooftops by calculating potential savings ratio compared to water demand and to estimate the optimal tank size with an approximate cost.

1.1. RAINWATER HARVESTING

Globally, the value and importance of access to water resources increase day after day. Freshwater has become an increasingly valuable resource. Some estimates indicate that there will be 3.4 billion people worldwide without access to freshwater by 2030 (UNICEF, 2021). Accelerated population growth, sprawling industries, increased demand for food, climate change, and decreased clean water resources are all factors that reduce the water quotas for individuals. Accordingly, these factors increase the costs of obtaining water. The cost of water bills is rising and becoming a significant expenditure at the household level, especially for low-income families (Ali, Zhang, and Yue, 2020).

Despite increases in water costs, there is a general lack of awareness of water-saving practices to reduce wasteful consumption. This matter requires experts and decision-makers to search for solutions that contribute to reducing the consumption rate and search for new sources of water.

Rainwater harvesting, which is defined as collecting rainwater using tanks, provides a new decentralized water source. It is the most basic self-supplying system to more efficiently benefit from natural resources in urban areas, instead of simply allowing the rainwater to become surface runoff or percolate into the ground (MWI, 2008). Ancient civilizations in various places resorted to collecting and using rainwater. For instance, rainwater collection systems in Thailand date back more than 2000 years; mud tanks were used to store water and they are still in use (Qiang et al., 2015). For more than 4000 years, the collection, storage, and use of rainwater through various methods have been a part of all civilizations (Larry W. Mays, 2001).

Rainwater harvesting using the rooftops for later use is an updated ancient method (Qiang et al., 2015). To ensure safe use, it is treated before sending it to storage in some cases (Campisano et al., 2017). Even though rainwater is relatively pure when it is first formed during the water cycle (Figure 1.1), harvested rainwater cannot necessarily be used directly as it may be contaminated by the pollutants present on collecting rooftops. Thus, the trick is to maintain the water quality within specific standards during the collection, storage, and consumption steps (Thomas H. Cahill, 2012; Nápoles-Rivera et al., 2015).

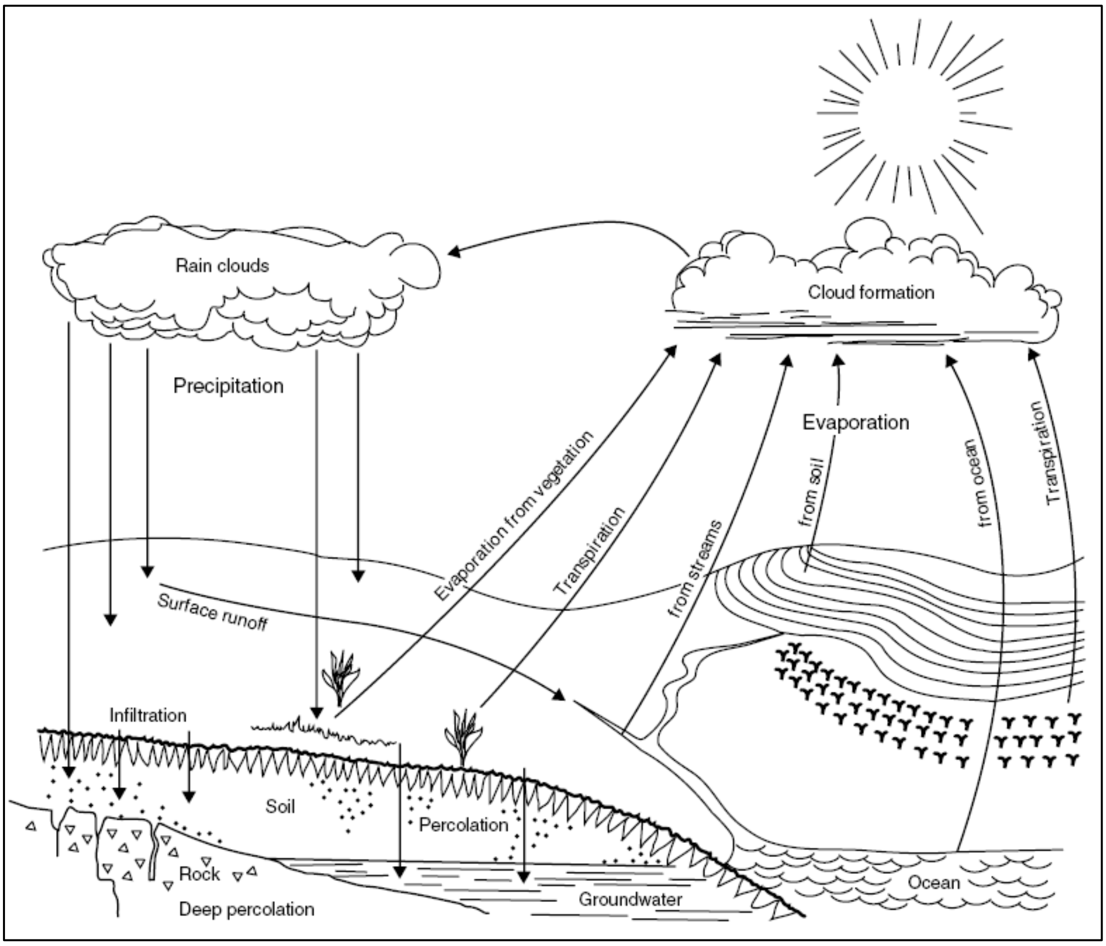

Figure 1.1. The hydrologic cycle (NRCS, 2019).

1.1.1. Rainwater Harvesting In The Worldwide

Technological development has helped facilitate users' access to water, which has led to high demand for freshwater. Unfortunately, any decentralized low-cost water source that is easy to obtain is usually neglected. When comparing modern rainwater harvesting techniques, we find that they share the basics with the old methods. The change mostly lies in the materials used to construct the rainwater harvesting system. Rainwater could be used where it was collected and stored; it is considered relatively uncontaminated. Some countries collect rainwater in dry seasons, especially semi-arid or arid ones (Sivanappan, 2006). Jordan is an arid and semi-arid country, and this requires studying the possibility of collecting rainwater and benefiting from it. The rooftops could be used as water catchment areas to collect rainwater on rainy days to use later, and this is one of the most easily applicable methods that can be used in urban areas (Thomas and Martinson, 2007). In many countries, the citizens collect rainwater using rooftops:

Bangladesh: In the late 1990s, in rural areas of Bangladesh, nearly 1000 rainwater harvesting systems were established at the cost of 150$/unit, with a tank capacity of 3.2 m^3 (Qiang et al., 2015).

Bermuda: In Bermuda, the average annual rainfall is 1458 mm/year, and underground tanks are used to harvest rainwater (Rowe, 2011).

Botswana: In Botswana, the dry season reaches up to six months within a year. Besides, the rainy season has low rainfall at around 53.6 mm/year, making rainwater collection vital (Batisani and Yarnal, 2010). the Botswana Government planned to install thousands of rainwater harvesting systems in schools, health institutions, government institutions, and houses using painted plastic tanks ranging from 1 to 20 m^3 (Qiang et al., 2015).

Kenya: Rainwater harvesting is a practical and feasible method that is well-established in Kenya due to necessity, encouraging farmers to rely on rainwater for agriculture (Odhiambo, Iro Ong'Or, and Kanda, 2021).

Taiwan: On the island of Taiwan, rainwater harvesting using tanks is recognized as an effective and economical technique because of water shortages (Islam et al., 2010). Currently, the Taiwanese Government continues to adopt the necessary policies to establish and develop rainwater collection tanks (Qiang et al., 2015).

Turkey: Harvested rainwater using rooftops can save up to 30% of domestic water consumption; the harvested rainwater meets the toilet flushing consumption (Dogan and Himat, 2019).

Palestine: According to 2017 data from the Palestinian Water Authority (PWA), there is a gap between supply and demand in the West Bank of 32 Mm^3. On the West Bank, roof rainwater harvesting is a strategic option to fill this gap due to the fragile water supply. The estimated amount of rainwater that may be collected by the roofs of the West Bank is 37 Mm^3 (Shadeed and Alawna, 2021).

1.1.2. Ancient Water Harvesting In Jordan

Based on the anthropological evidence, it is now believed that previous civilizations had designed unique systems for collecting and distributing water, especially in the Middle East, including Jordan, where water bodies or rivers are scarce (Wahlin, 1997).

Jawa: In Jawa, circa 3000 BC, the population relied on rainwater and designed an integrated water harvesting system (Helms, 1981). Around 3000 BC, the precipitation distribution was studied in the area, and the water demand rate was used to create water tanks to harvest rainwater by the population (Beckers et al., 2013).

Umm El-Jimal: In Umm el-Jimal in the late Roman period, storage systems (dams and tanks) and canals for water distribution were designed and built (de Vries, 1981, 1993). People monitored the rainy seasons between December and March and used the data to harvest the largest amount of rainwater and benefit from it (de Vries, 1993). After a while, the inhabitant of the city noticed a decrease in precipitation rates, which prompted them to construct canals to transfer harvested water to remote areas (de Vries, 1981).

Nabataeans: In southern Jordan, the Nabateans developed rainwater harvesting systems, which helped them increase their spread (Friedrich Pfeil, 2018). Forder (1923) wrote that the Nabateans placed tanks at the heights to isolate them from pollutants and to ease the pumping of water. These collection tanks were carved in the rock and connected so that the overflow would move from one tank to the next, creating a system of linked tanks that could accommodate millions of gallons of water.

The historical evidence demonstrates that rainwater was the primary water source of ancient civilizations in Jordan. The ancient civilizations knew a lot about water harvesting systems. The awareness of the importance of water among these civilizations is greater than many modern communities' awareness about the management of water resources; the successes that ancient civilizations achieved can be studied and used as a guide for managing water resources in the modern era, especially for gaining insight about construction techniques of water harvesting systems. It is possible to create a modern harvesting system that combines traditional rainwater harvesting techniques, modern materials and distribution methods, and more accurate measurement of rainfall and demand rates.

1.2. WATER SITUATION IN JORDAN

Currently, Jordan suffers a severe shortage in terms of water resources. This problem is mainly related to Jordan's arid climate and its growing population. It is a substantial obstacle to many activities (Postel, 2009). Water's quantitative and qualitative adequacy is an important issue of concern in Jordan, threatening the country's agriculture, manufacturing, and public health.

Before proposing any solution, the current water situation must be well understood and how water scarcity affects different communities must be investigated (UNICEF, 2021). Thus, Jordan's current water resources situation is explained in detail in this section.

Water sources are divided into two primary categories: (1) traditional (renewable) sources (surface water, groundwater, and rainwater) and (2) non-traditional sources, such as desalination of seawater or reusing of treated wastewater. For example; within the framework of the new 'The National Water Carrier Project', a new source of water is planned to be created in Jordan using the desalination process (Ghaith, 2022). The National Carrier Project will be implemented to increase water security in Jordan by transporting 300 million cubic meters of desalinated water annually from the Gulf of Aqaba to Amman without affecting the environment.

The factors affecting the availability of water in Jordan can be summarized under four main categories as follows:

Economic factors: Water supply costs in dry regions are increasing due to water scarcity. Therefore, Jordan has resorted to water harvesting, such as constructing dams

(Al Rousan, Ibrahim and Ali, 2005). The cost in Jordanian Dinar (JOD) of seawater desalination has been estimated at 1.0 JOD/m^3 (1.4 \$/m^3) in Jordan, which is very high compared to the cost of extracting groundwater at less 0.25 JOD/m^3 (0.35 \$/m^3) (Qtaishat et al., 2017).

Demographic factors: The increasing water demand is directly related to the growing population (Al Rousan et al., 2005; UNICEF, 2020).

Political factors: Jordan is the neighbor of Palestine, and Jordan's and Palestine's water securities are linked. Both countries share the Jordan River and use it as their main fresh water source (Al Rousan et al., 2005). In addition, the water security of Jordan and Palestine is correlated to the water security of Syria and Lebanon and thus, this is an international issue (Allan, 2002).

Climate characteristics: Jordan's rainfall rates range from less than 100 mm/year in desert regions to 500 mm/year in mountain highlands (Tarawneh and Kadioğlu, 2003). Over 88% of Jordan's area is dry. The northern regions of Jordan have a higher rainfall rate than the southern regions. (Al Rousan et al., 2005).

Jordan’s geography and arid climate dictate the availability of water. Jordan is roughly located between 35 and 39 degrees east longitudes and 29 and 33 degrees north latitudes on the northwestern edge of the Arabian Desert in the Arabian Peninsula, making it vulnerable to dry and cold-dry winds. There are two types of climates prevailing in Jordan: the Mediterranean and desert climates (Al Rousan et al., 2005; Khalifa, 2007). The Red Sea has a limited impact on the air masses blowing over Jordan since Jordan’s coastline to the Red Sea is relatively small (only 27 km-long) (Tarawneh and Kadioğlu, 2003; Khalifa, 2007).

Jordan characterizes the Mediterranean climate with mild, wet winters and dry summers affected by the desert climate (Khalifa, 2007). The rainy season begins in October and ends in May; December and February are the months with the highest rainfall during the winter seasons. Snow usually falls on mountain ridges at an altitude of 800 m above sea level. Summer begins in June, while the highest average temperatures are recorded in July. Summer temperatures are about 28°C in Amman and 51°C in the Jordan Valley, which means that the evaporation rate is high (MoEnv,2020).

1.3. THE PRECIPITATION IN JORDAN

Jordan is classified as a semi-dry zone, except for the mountainous region that extends from north to south. This mountainous region is 30 km wide and 300 km long and is classified to be in the Mediterranean climate zone (Khalifa, 2007). The precipitation in Jordan is mainly in the rain form. Snowfalls occur only once or twice per year, except in rare cases (MWI, 2020).

Only 1.3% of Jordan’s surface area receives an annual rainfall exceeding 400 mm; 1.8% receives between 300-400 mm; 3.8% receives between 200-300 mm; 12.5% receives between 100-200 mm; and the annual rainfall rate in the rest of the country (80.6%) is less than 100 mm (McEachern, 1991).

Jordan is among the top 10 countries with water scarcity (Abdulla and Al-Shareef, 2009, Assayed et al., 2013). Jordan's annual rainfall rate map clearly shows the low rain rate, along with the locations of the precipitation monitoring stations (Figure 1.2). Over 80% of Jordan's area is water deficient (Badia and desert areas) and has an annual rainfall rate of only 100 mm (World Bank, 2020). Due to drought and rainfall fluctuations, soil fertility and production gradually decline, and hence, Jordan is under a growing desertification threat (Tarawneh and Kadioğlu, 2003). Desertification results in the destruction of pastures and plantations, the loss of livestock, and increased soil and groundwater salinity (MoEnv,2020).

1.4. RIVERS AND DAMS IN JORDAN

1.4.1. Overview Of The Rivers In Jordan

The Jordan River is situated in the Dead Sea and Jordan Valley region, and the Jordan River is the most important river in the Levant region (Addustour, 2019); its basin encompasses four countries: Jordan, Palestine, Lebanon, and Syria. It starts at 522 m above sea level, while its estuary is 400 m below sea level, and its length is 192 km

(Al-Adaileh, 2005), and the basin is divided into three main parts: upper stream, middle course, and downstream (Le Moigne et al., 1992; FAO, 2009).

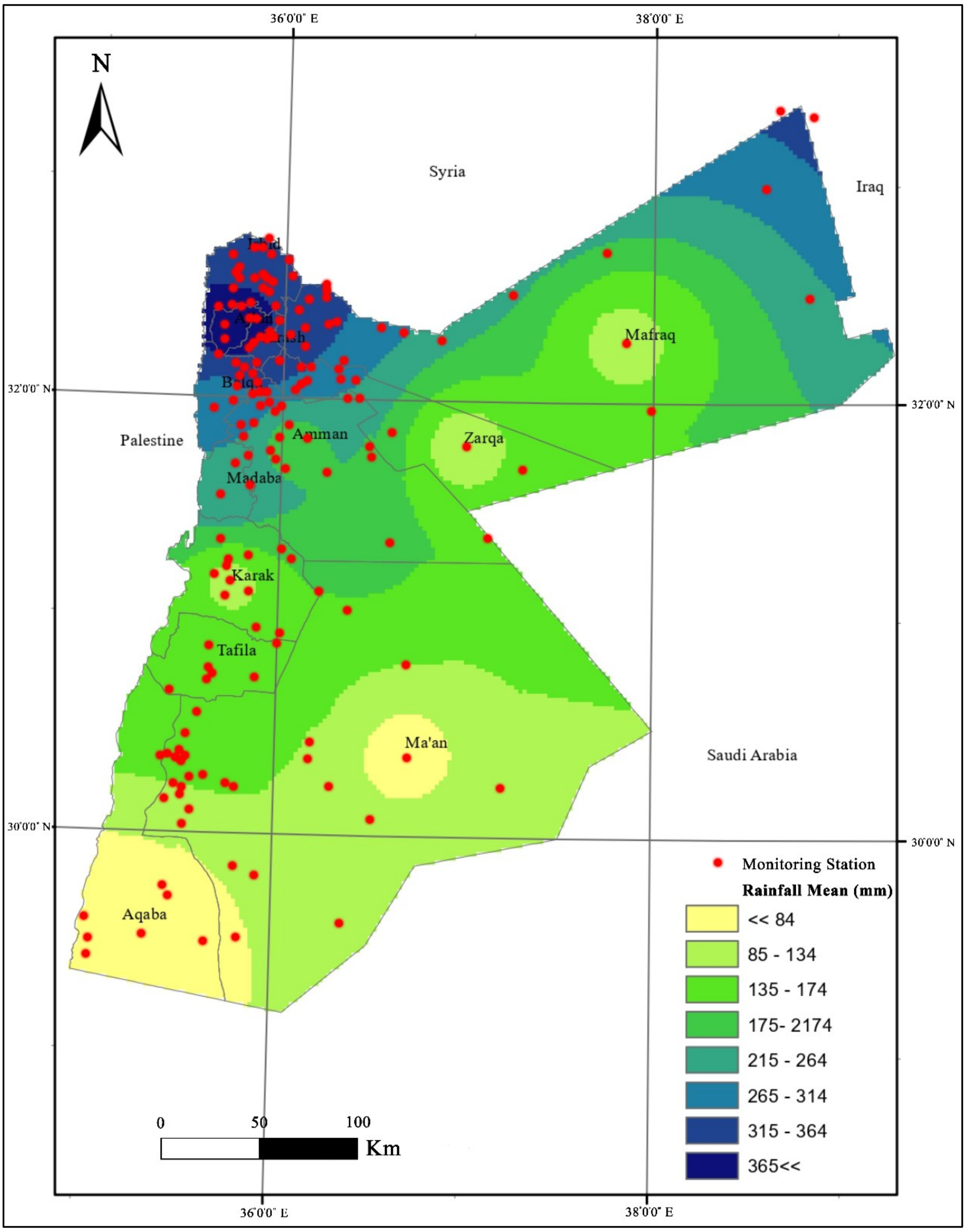

Figure 1.2. Distribution of Annual Mean Rainfall in Jordan (1987-2018). Red dots represent the precipitation monitoring stations.

The Yarmouk River is Jordan's essential surface water source; MWI tried to exploit its floodwater by storing it in a river-based dam in the summer (MWI, 2019). The river's water originates in the nearby foothills of Jebel al-Arab in the Golan Heights at an altitude of 400 m above sea level and meets the Jordan River 6 km away from Lake Tiberias at 225 m below sea level (Al-beshri, 1998).

The Zarqa River runs in the middle of Jordan, starting in downtown Amman and then meets the Jordan River halfway before entering the Dead Sea, with an annual discharge rate of 83 Mm^3 in the Deir Ala District. It is 70 km long and 7 to 10 m wide, with a basin area of about 3,400 km^2 (Al-Omari et al., 2019). The Zarqa River originates in the Jordanian capital, Amman, to the east, reaching the city of Zarqa. From Zarqa, it begins to run towards the Jordan Valley. In the past three decades, some factories have heavily polluted the Zarqa River (Le Moigne et al., 1992; Al-Omari et al., 2019). There are many sewage outlets that successive Jordanian Governments had not seriously controlled. Over the past year, the Ministry of Environment has taken responsibility for restoring the Zarqa River (Mohsen, 2007).

1.4.2. Overview Of The Dams In Jordan

Surface water bodies formed naturally and by dams are the largest water source in Jordan. Surface water basins have an estimated annual renewable amount of 690 Mm^3 divided into 16 basins. The Jordanian Government had built 14 dams with a total capacity of 339 Mm^3 (*see* Figure 1.3), which helps maximize the use of rainwater and increase water storage capacity (MWI, 2020).

There are eighteen small dams with a total capacity of about 32 Mm^3 located in the desert, and the stored water in these desert dams is used primarily for livestock and artificial groundwater recharge (Hadadin, 2015; MWI, 2019). In addition, many water harvesting projects store rainwater in large and small reservoirs. Besides, the Ministry of Agriculture built 14 small dams with a total storage capacity of 0.50 Mm^3 in Karak and Tafielah bringing the total number of desert dams to 32 with a total surface area of 10,313 km^2. Also, there are 44 lakes and 74 pools throughout Jordan with a total storage capacity of 31.25 Mm^3 (Salman et al., 2016; MWI, 2020).

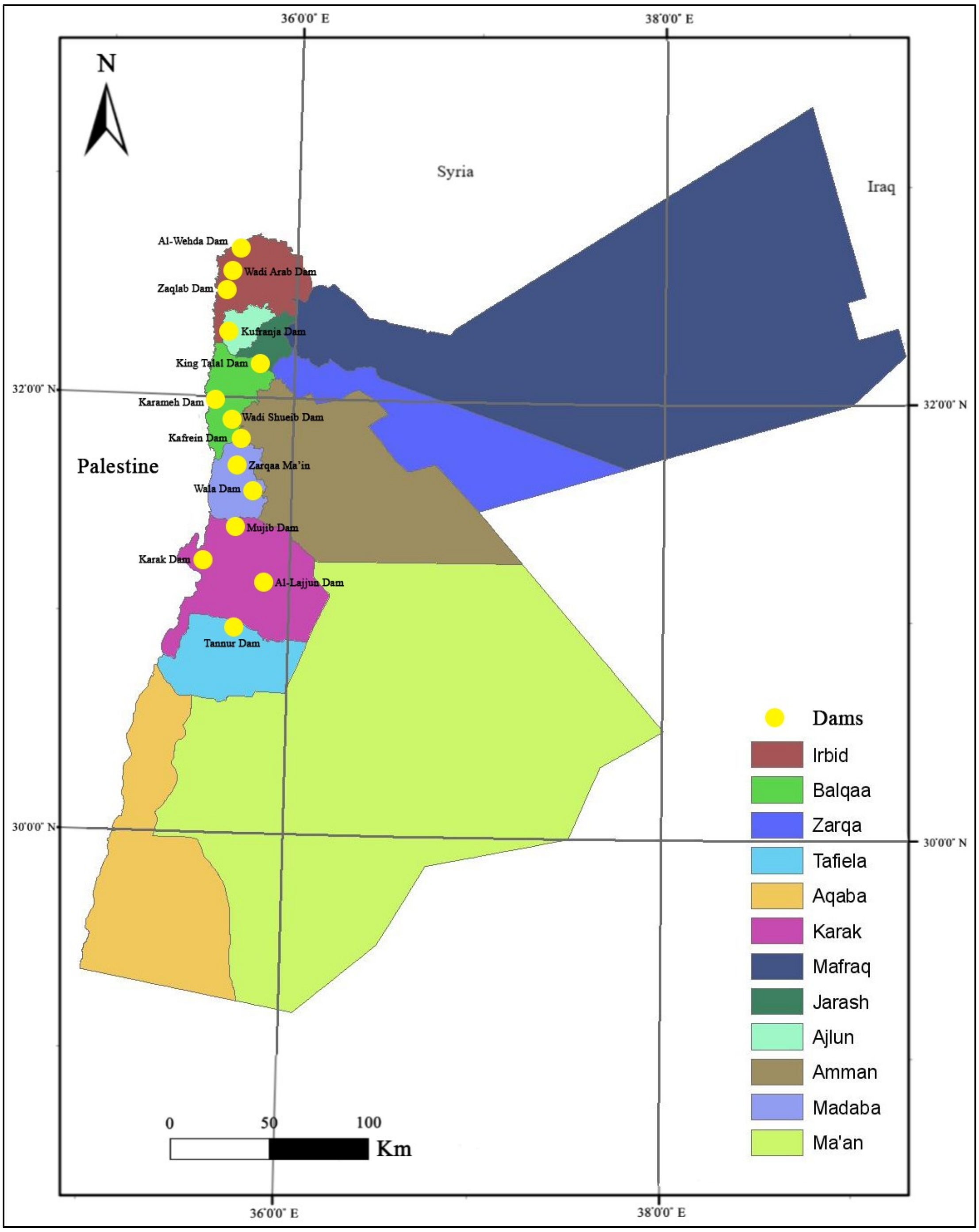

Figure 1.3. The distribution of dams in the Jordan Valley, adapted from Hadadin (2015).

1.5. SURFACE AND GROUNDWATER BASINS IN JORDAN

1.5.1. The Surface Basins In Jordan

Surface water sources were defined as the water of permanent runoff in valleys and rivers, the discharge of springs and floodwaters, which continue throughout the year (Wagner and Lanoix, 2015). However, the amount of this discharge resulting from precipitation varies. Surface water is distributed in different Jordanian governorates in varying proportions, divided into 12 basins (MWI, 2019; 2020). In Table 1.1, Jordan's primary surface water basins and their long-term discharge rates are listed (MWI, 2020).

Table 1.1. Surface water basins with yearly productivity (Mm^3/year).

Surface Water Basin	**Discharge** (Mm^3/year)
Yarmouk Basin	40
The side valleys of the Jordan River	15
Jordan Valley	21
Zarqa Basin	87.5
Dead Sea Basin	57
Disi and Mudawra Basin	125
The northern Wadi Araba basin	3.5
Southern Wadi Araba Basin	5.5
Jafr Basin	27
Azraq basin	24
Sirhan basin	5
Hammad Basin	8
Wadi Al-Hasa Basin	34
Wadi Mujib Basin	25 - 83

1.5.2. The Groundwater Basins In Jordan

Groundwater is the water found in rock layers, which is extracted from the aquifers by drilling wells into them (the Groundwater Foundation, 2013) and divided into two categories: (1) renewable and (2) stored groundwater.

Renewable groundwater is the rainwater that percolates into the ground and fills the pore space between granules and openings under the ground. The annual infiltrated water rate depends on the rainfall that feeds these layered areas (MWI, 2019).

Stored groundwater is the water that is accumulated in layers below the renewable groundwater level over long periods of time. Each aquifer has a thickness-dependent amount of water, constituting more than 93% of the total groundwater (MWI, 2019).

Table 1.2. Groundwater Basins with yearly productivity (Mm^3/year) (MWI, 2020).

Basin	**Mm^3 in 2018**	**Mm^3 in 2019**
Yarmouk	13.8	15.2
Amman Zarqa	90.2	86.6
Jordan River Side Wadis	39.8	40.9
Jordan Valley	11.1	10.1
Dead Sea	44.8	N.A.
Azraq basin	21.2	22.3
Hammad basin	1.3	1.3
Wadi Araba North	1.3	1.2
Wadi Araba south	0	0
Sirhan	0	N.A.
Jafer non-renewable	12.1	14.8
Disi, non-renewable	115.4	116.2
Total:	**351**	**308.6**

The Jordanian groundwater basins are shown in Table 1.2. (MWI, 2020). The capacity of these reservoirs varies. However, their total equilibrium capacity is 203 Mm^3, with reservoirs being consumed at a rate that exceeds their replenishment capacity by 153%

(MWI, 2019). The sandstone formation has large non-renewable reservoirs in Jordan. However, the quality of the reservoirs varies, including freshwater reservoirs such as the Desi Reservoir and other reservoirs with relatively high salinity.

1.6. CHALLENGES AND THREATS FACING JORDAN

Water security has become a global issue and a threat to many communities. This issue includes the Middle East, including Jordan. The issue is mainly related to several factors. However, the main challenge is the sudden population increase, mainly due to the increasing birthrate and influx of refugees. Water shortages in Jordan have significant impacts, particularly in areas with high population densities and urban growth. Economic security is essentially linked to water security; studying water is a basis for addressing the country's food and financial problems.

The last conflicts in the Middle East have led to three major migration waves to Jordan, a significant cause affecting the accurate predictability of population growth (Sweidan, 2018). The region's overall trend of relative calmness compared to the period between 2010-2015 may result in more accurate population projections when those projections are carried out based on the data from the last five years, translating into better planning to manage resources, including water resources.

The Jordanian census in 1946 was 350,000 (DOS, 2016) and a Jordanian citizen's share of water was up to 3000 m^3/year per capita, whereas it was approximately 100 m^3/year per capita in 2020 (UNICEF, 2020). Therefore, it can be said that the water problem is predominantly caused by the population explosion in combination with the inability to create new water sources and geographical limitations (MWI, 2008, 2020; Jordan’s Water Strategy, 2009).

1.7. IMPORTANCE OF STUDY

The deep connection between the economy and accessible water resources puts a clear limit on the economic development of Jordan. Resources are managed from two main aspects: supply and demand. Supply is the available quantity of specific resources, and demand is the quantity required to meet the population's needs. Unfortunately, the water resources in Jordan are minimal. On the other hand, the water demand rates are increasing, especially with the population growth during the last decade (2010-2020).

The first step in managing the available water supply is undoubtedly reducing the current loss of water in the distribution systems. The next step is to avoid wasting water during use. These are the fundamental methods for sustainability. In parallel to these efforts, the Jordanian government must realize new projects to tap into new water sources. The proliferation of rooftop rainwater harvesting can form one of these new water sources. The rainy days in Jordan are few compared to the dry days of the year, and therefore the climate necessitates taking advantage of the rainy days as much as possible. In this context, investing in rainwater harvesting is crucial in a water-poor country with an arid/semi-arid climate, like Jordan.

Rainwater can be easily captured on-site at a minimal cost (Assayed et al., 2013; Saidan et al., 2015; Hadadin et al., 2014; Abu-Zreig et al., 2013; Awawdeh et al., 2012, Al-Houri et al., 2014). Simply, a catchment area to collect rainwater and a means of storage for later use are needed. Rainwater harvesting systems had used in Jordan since 3000 B.C. by the migrants in Jawa (Helms, 1981). Collected rainwater can used for flushing and irrigation purposes without any treatment (Appan, 1999), and people in Jordan traditionally continue collecting rainwater despite the availability of water distribution systems due to water scarcity. Most studies agreed that rainwater harvesting (RWH) is a sustainable method of saving water in Jordan (Assayed et al., 2013; Saidan et al., 2015; Hadadin et al., 2014; Abu-Zreig et al., 2013; Awawdeh et al., 2012; Al-Houri et al., 2014; Al-Qawasmi, 2021). Also, it can be considered a secondary water supply, expanding the primary supply from the municipal water distribution system in urban areas.

As a result of the increase in urbanization and the easier access to water via modern infrastructure among the urban populations, awareness of the importance of rainwater harvesting systems has declined, so new policies to promote water harvesting systems in residential and governmental facilities are required (MWI, 2020). Rainwater can be harvested on small scales, such as utilizing the rooftops of schools, health institutions, and other buildings, or on large scales, such as dams and ponds (MWI, 2020). The performance of rooftop water harvesting systems depends on these factors: the monthly consumption of water, the monthly water supply rate, the annual precipitation rate, and the rooftop area.

Rainwater harvesting has many advantages that can encourage installing it in Jordan but with some limitations since the rainfall rate in Jordan is lower compared to other countries. The main advantages are: low investment and operating cost (Al-Qawasmi, 2021); construction and operation are easy (Hadadin et al.,2014; Abu-Zreig et al., 2013); the system provides a self-reliant water source since the maintenance is the responsibility of the domestic user (Abu-Zreig et al., 2019); collected water can be integrated into the existing water supply system (Abu-Zreig et al., 2013); and there are less adverse environmental effects (Abdulla, 2019). Once the system is installed, the collected raw rainwater is suitable for flushing and irrigation without prior treatment. Sha'ban et al. (2011) reported that up to 17.7% of domestic water demand in Jordan is spent on flushing toilets. So if enough rainwater can be harvested, all the household consumption due to flushing can be saved. Any amount of rainwater collected in urban areas will be able to preserve existing water sources, and also storing it will create an easy-to-use emergency supply. Lastly, rainwater harvesting can potentially reduce the amount of urban run-off, which will help decrease the pollution load in receiving environments (Qiang et al., 2015).

This study mainly aimed to estimate the optimal tank size for total demand per household using the 'Ripple Method' and the optimal tank size for flushing consumption using the 'Water Balance Model'. Additionally, the study estimated the total cost of the optimal tanks for each governorate. Also, evaluate Jordan's water security level by analyzing current water demand and water supply in 2020. The study also predicted three main scenarios based on the population growth rate in three main periods (n=1 year, n=5 years, n= 10 years). The total water supply was assumed to remain constant, and its value was fixed to the value reported in 2020 for estimating the amount of water supply per capita in those different scenarios.

To achieve the study's objectives, different kinds of data were gathered and analyzed. These data include the following (*see* Figure 1.4.):

- The daily rainfall data from 1987 to 2018 were obtained from the Ministry of Water and Irrigation in Jordan through a personal visit in 2020.
- The population census data for Jordan (1990-2020) were obtained from the website of the Hashemite Kingdom of Jordan Department of Statistics (DOS). Also, the distribution of the population in 2020 for each governorate.
- The most recent data set on the number of dwellings, rooftop area (8 categories), and dwelling types (apartment, single house, and villa) were from 2015 and was obtained from the General Department of Statistics in 2020.
- The daily water consumption per capita for each governorate in 2020 data were obtained from the Water and Irrigation Ministry via e-mail.
- The cost per a cubic meter (JOD/m^3) was adapted from Abu-Zreiq et al. (2013).

The obtained data were used to estimate the following (*see* Figure 1.4.):

- Monthly water consumption rate (D).
- Total water demand for each governorate (TAPG).
- Monthly potential harvested rainwater volume (VR).
- Annual potential harvested rainwater volume.
- Potential saving percentage (PSP).
- Water Consumption Projections, based on different population growth rates.
- The optimal tank size estimations for total demand and flushing consumption.
- The total cost of the optimal tank sizes.
- Expected economic saving rate.

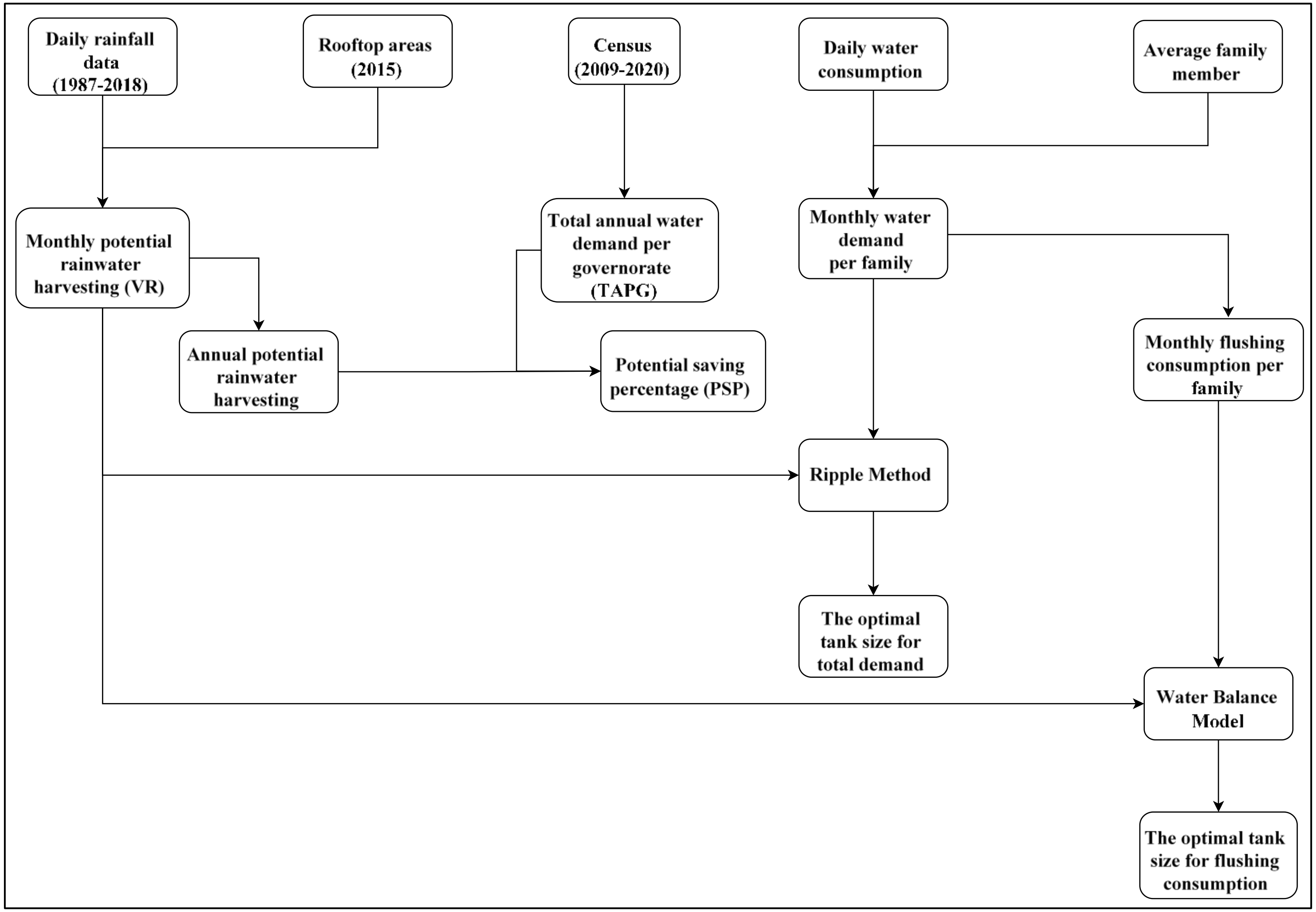

Figure 1.4. The flow chart of the research methodology.

CHAPTER 2

MATERIALS AND METHOD

2.1. RAINFALL DATA

Rainfall data were obtained from the Ministry of Water and Irrigation in Jordan through a personal visit in 2020. Rainfall data were obtained for 157 rainfall monitoring stations distributed over 12 governorates in Jordan. The monitoring stations recorded daily rainfall rates from 1987 to 2018; the data request was submitted to obtain the most recent information on rainfall in Jordan for the past 32 years. Verbal permission was obtained from the officials to use this data for the study and scientific research purposes, and then the data was received through an e-mail.

The steps of the calculations to estimate monthly rainfall rates for each governorate from 1987 to 2018 were summarized below and an extended explanation of the calculations for one governorate (e.g., Ajlun) was given in Annex A1 as an example.

1. Pick a governorate (G).

2. Select one monitoring station (S) is located in the selected governorate. For example, the number of monitoring stations in Ajlun Governorate was 6 (Annex A1).
3. Select a month (M) (for example; January). Calculate the cumulative precipitation amount for one month by summing daily measurement values of that month for the station. Then repeat this calculation for the same month of each year (January 1987, January 1988, January 1989, … , January 2018) (2.1).

$$\text{Monthly Rainfall}\,(\mathrm{G},\mathrm{S},\mathrm{M},\mathrm{Y}) = \sum_{\mathrm{D}=1}^{\mathrm{D}} \text{daily amount (mm)} \qquad (2.1)$$

4. Determine the average of the results that were calculated using Equation 2.1 to find the overall monthly average for the period of 1987-2018 (for example: Governorate (G): Ajlun, Station (S): AB 0004, Month (M): January) (2.2).

$$\text{Average Monthly Rainfall (G, S, M)} = \frac{\sum_{1987}^{2018} \text{Total Monthly Rainfall (G,S,M,Y)}}{\text{Number of Years}} \qquad (2.2)$$

5. Repeat the steps 2 to 4 for all stations in the same governorate. Then move on to the next month until the average values for all 12 months in each year between 1987-2018 were estimated.

6. The average monthly rainfall rate of a governorate is calculated using Equation 2.3.

$$\text{Average Monthly Rainfall for one Governorate} = \frac{\sum_{S=1}^{S} \text{Average Monthly Rainfall (G,S,M)}}{\text{Number of Stations in the Governorate}} \qquad (2.3)$$

7. The total annual rainfall rate of a single station (mm/year) is calculated using Equation 2.4; the output is rounded to the nearest integer.

$$\text{Average Annual Rainfall for one Station} = \sum_{\text{Jan}}^{\text{Dec}} \text{Avg. Monthly Rainfall (G. S. M)} \qquad (2.4)$$

8. The annual rainfall rate of a governorate was calculated using Equation 2.5; the output is rounded to the nearest integer:

$$\text{Average Annual Rainfall for one Governorate} = \frac{\sum_{S=1}^{S} \text{Avg.Yearly Rainfall for Every Station}}{\text{Number of Stations in the Governorate}} \qquad (2.5)$$

The steps listed above were repeated for all 12 governorates of Jordan to estimate average cumulative monthly and annual precipitatipon data between the period of 1987-2018.

2.2. POPULATION

The population census data for Jordan (1990-2020) were obtained from the website of Hashemite Kingdom of Jordan Department of Statistics (DOS). The distribution of the population in 2020 is shown in Figure 2.1. To calculate the population growth rate

(PGR), a standard equation that is used to estimate the population (Equation 2.6) is modified as shown in Parker (2002) (Equation 2.7).

$$\text{Estimated Future Population} = \text{Present Population} \left[\frac{\text{PGR}}{100} + 1\right]^{n} \tag{2.6}$$

$$\text{Population Growth Rate (PGR)} = \left[\frac{\text{final value}}{\text{initial value}}\right]^{\frac{1}{n}} - 1 \tag{2.7}$$

Where ‘PGR’ is the population growth rate; ‘n’ is the number of years in a period of time for which PGR will be calculated; ‘initial value’ is the population in the start of the period, and the ‘final value’ is the population at the end of the same period. PGR depends on a specific period of a known number of years, the current population, and the population in the past.

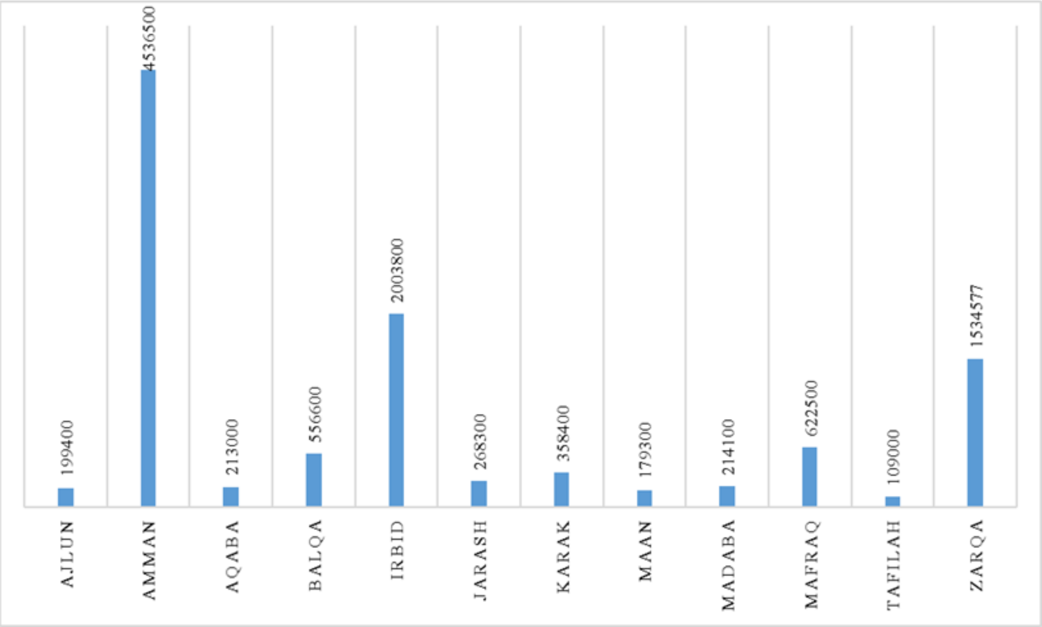

Figure 2.1. The Distribution of the Population by Governorates 2020 (DOS, 2021).

There population growth rates were calculated for three periods as described below, using the population numbers between 2010 and 2020 that are shown in Figure 2.2:

- Case 1 (n=1): The population growth rate was calculated using the available census data for 2019 and 2020; the 2019 census result was 10,554,000 and the total population had reached 10,806,000 according to the 2020 census result.

- Case 2 (n=5): The population growth rate was calculated using the available census data for 2015 and 2020; the population was 9,559,000 in 2015 and it was 10,806,000 in 2020.

- Case 3 (n=10): The population growth rate was calculated using the available census data for 2010 and 2020; the population was 6,698,000 in 2010, and it reached 10,806,000 in 2020.

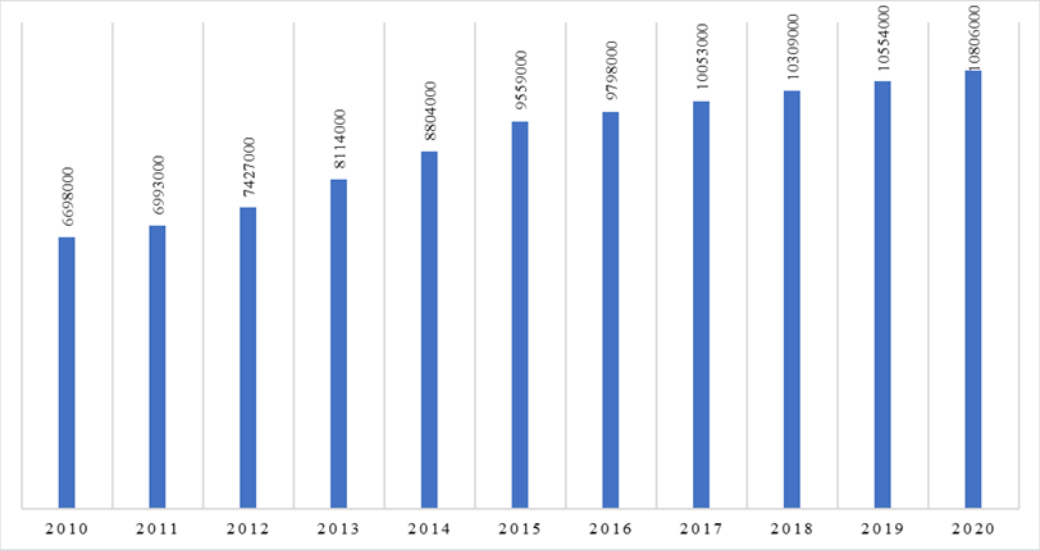

Figure 2.2. Census data for Jordan, 2010-2020 (DOS, 2020).

According to these three PGR estimations, three scenarios were created by which Jordan's population numbers in 2025 and 2030 were predicted.

2.3. DAILY WATER CONSUMPTION RATES

In a visit to the Ministry of Water and Irrigation (MWI) in Jordan, a request was submitted to obtain daily consumption rates per capita for each governorate in 2020. After getting official permission to use this data for scientific research purposes, the General Secretary of the Water and Irrigation Ministry supplied the requested data from the Environmental Studies Department of the General Department of Statistics via an e-mail.

Table 2.1 shows daily water consumption rates (MWI, 2020). The consumption rates ranged from 80 liters/capita/day in Irbid to 274 liters/capita/day in Ma'an.

Table 2.1. Daily water consumption in liters/day per capita (MWI, 2020).

Governorate	**Daily consumption rate (Liters/day/capita)**
Ajlun	106
Amman	132
Aqaba	191
Balqa	239
Irbid	80
Jarash	110
Karak	192
Ma’an	274
Madaba	160
Mafraq	140
Tafilah	244
Zarqa	120

The total water demand per year, here referred to as the ‘total amount per governorate’ (TAPG), was calculated using Equation 2.8.

$$\mathrm{TAPG} = 365 \times \left(\frac{\text{Daily Consumption}}{\text{Capita}}\right) \times \text{Population} \tag{2.8}$$

2.4. ROOF AREA

The data on the number of dwellings and dwelling types are released once every ten years in Jordan, and the rooftop areas are estimations based on average values (Al-Momani, 2020). Therefore, it should be noted that there is a large margin of error in total rooftop area estimates.

The most recent data set on the number of dwellings and dwelling types were from 2015 and was obtained from the General Department of Statistics in 2020. This data from 2015 was used to determine the total rooftop areas in the Jordanian governorates. It should be noted that the rooftop area values estimated in this study based on 2015 data must be lower than the current value since urban development since 2015 was missing in the data.

In the data set, the housing units were divided into three main categories according to their type: houses, villas, and single apartments in multi-story buildings; these dwelling types were also divided into eight sub-categories according to the housing unit's living area (from '<50 m^2' to '>500 m^2') (DOS, 2015). Equation 2.9 was used by the Department of Statistics to estimate the total rooftop area in each governorate.

$$\mathrm{TRA} = \sum_{x=1}^{N} \mathrm{ND}_x \times \mathrm{A}_x + \sum_{y=1}^{N} \mathrm{ND}_y \times \mathrm{A}_y + \sum_{z=1}^{N} \mathrm{ND}_z \times \mathrm{A}_z \qquad (2.9)$$

'X', 'Y', and 'Z' denote single houses, multi-story buildings, and villas, respectively, ND is the number of dwellings, and 'A' is the average rooftop area (m^2). Multi-story buildings were assumed to have four housing units (apartments) per floor (Al-Asad, 2004). Equation 2.10 was used to calculate the total areas of the roof (Abu-Zreig et al., 2019).

$$\mathrm{TRA} = \sum_{x=1}^{N} \mathrm{ND}_x \times \mathrm{A}_x + \sum_{y=1}^{N} \mathrm{ND}_y \times \mathrm{A}_y \times \frac{1}{4} + \sum_{z=1}^{N} \mathrm{ND}_z \times \mathrm{A}_z \qquad (2.10)$$

Table 2.2 shows the distribution of traditional houses in Jordan. The distribution of traditional inhabited houses is presented in 'Annex A2' according to housing area (m^2) and housing type (single houses, multi-story buildings, and villas).

Table 2.2. The Distribution of dwellings throughout Jordan by type and roof area (DOS, 2020).

Type of Housing Unit		**Apartment**	**House**	**Villa**	**Total**
		Number of Dwellings (ND)			
Area (m^2)	**<50**	54515	5493	0	60008
	50-99	353067	34986	0	388053
	100-149	576567	89012	1	665580
	150-199	350574	63287	0	413861
	200-299	135307	27651	3726	166684
	300-399	19423	3753	2295	25471
	400-499	4526	1317	1269	7112
	500+	5131	2538	2999	10668
	Total	1499110	228037	10290	1737437

2.5. THE POTENTIAL WATER HARVESTING (VR)

The potential water harvest volume was calculated using Equation 2.11.

$$\mathrm{VR} = P \times A \times C/1000 \qquad (2.11)$$

‘VR’ is the monthly potential volume of harvested rainwater by (m^3), ‘P’ is the monthly average rainfall (mm/month), ‘A’ is the rooftop area by (m^2), and ‘C’ is the runoff coefficient. The runoff coefficient value was always taken as 0.8 in the calculations (C=0.8). The summation of monthly VR values for 12 months was reported as the annual VR value.

2.6. POTENTIAL SAVING PERCENTAGE (PSP)

TAPG, the total amount per governorate (*see* Equation 2.8), and VR, the annual potential (*see* Equation 2.11), were used to find the ‘potential saving percentage’ values for twelve governorates. The potential saving percentage (PSP) was calculated using Equation 2.12.

$$\text{PSP} = \frac{\text{VR}}{\text{TAPC}} \times 100\% \qquad (2.12)$$

2.7. WATER CONSUMPTION PROJECTIONS

The expected water consumption scenarios were shown at the end of this study according to water supply, population growth rates, and the potential harvesting of rainwater. These scenarios were estimated as follows:

- The first scenario was created based on the population growth rate calculated based on census data for 2019-2020 (Case 1; *see* Section 2.2).

- The second scenario was created based on the population growth rate from 2015 to 2020 (Case 2).

- The third scenario was created based on the population growth rate from 2010 to 2020 (Case 3).

In all three scenarios, the total amount of water supply in Jordan was fixed at the total consumption rate measured in 2020; this value was accepted as the total amount of available water supply also in 2025 and 2030 (no new sources of water were assumed to be added to the system in the near future). Next, the future populations were estimated based on different scenarios (different PGR values). Finally, water consumption per capita was calculated by dividing the total water supply by the population size predicted for 2025 and 2030. The water consumption per capita was calculated again, but that time, the total amount of potential harvested rainwater volume was added to the total water supply.

2.8. THE OPTIMAL TANK SIZE

Based on the existing rainfall data and the Ripple Method as used in Shadeed and Alawna (2021), the tank size values for different governorates were estimated. For Ajlun, as an example in Annex A.1, calculations for cumulative values of monthly demand minus potential harvest (denoted as '∑(D-VR)'), and optimal tank sizes (S) for the different rooftop areas in the governorates are presented in Figures (3.3 – 3.14).

The optimal tank size (S) values for each governorate were calculated based on either VR or ∑(D-VR) values; whichever has the smaller value for a specific roof area.

The mathematical formulation of the monthly water balance was expressed in Equation 2.13.

$$\sum(D - VR) = \sum_{oct}^{sep}(D - VR_h) \qquad (2.13)$$

VR_h is the monthly potential volume of harvested rainwater for a single building by (m^3); and D is the monthly water consumption by one family in a single household (m^3). The average size of a Jordanian family is 4.8 people per household (CEIC, 2020).

$$D = daily\ water\ demand\ per\ capita \times 30 \times 4.8 \qquad (2.14)$$

The Ripple Method was used in many studies (Himat and Dogan, 2019; Shadeed and Alawna, 2021), also used in this study to estimate the optimal tank size based on the family's monthly water demand rate (for all types of uses). Total consumption per family was calculated using Equation 2.14; the value of 4.8 is the average number of family members per household (CEIC, 2020), and daily consumption per capita varies between governorates (*see* Table 2.1).

The ‘Water Balance Model’ was used in the study, it is a common method to estimate the optimal tank size and was used in Himat and Dogan, (2019) and Imteaz and Shadeed (2022). In the Water Balance Model, the water consumption for a family was accepted to be equal to the consumption solely due to flushing toilets. Rainwater was most likely to be contaminated during harvesting, so it was assumed that harvested rainwater could be safely used only for flushing without any treatment.

In a report issued by the Ministry of Water and Irrigation (Sha’ban et al., 2011), the amount of water spent for flushing was accounted for 17.7% of the total consumption. Accordingly, the flushing consumption (D_f) for each family in each governorate was calculated using Equation (2.15).

$$D_f = \frac{\mathrm{D}\times 17.7}{100} \tag{2.15}$$

By applying the water balance model, the monthly use of rainwater and the monthly volume of water stored in the tank can be calculated. Table 2.3 lists the data required to estimate the size of the reservoir.

Table 2.3. Water Balance Model and the data to estimate the optimal tank size.

Column (1)	**Column (2)**	**Column (3)**	**Column (4)**	**Column (5)**	**Column (6)**	**Column (7)**	**Column (8)**
Months	Average monthly rainfall (mm /month)	Monthly flushing consumption (m^3 /month)	Rooftop area (m^2)	VR (m^3)	V_i (m^3)	(Column 5– Column 3) (m^3)	V_f (m^3)
Oct … Sep				S (m^3) = (The biggest value in Column 8)			

Where:

Column (1): Months from October to September.

Column (2): Average monthly rainfall (mm/month) during the period (1987-2018), *See Equation 2.3*.

Column (3): Flushing consumption per family (m^3/month), calculated using Equation 2.15.

Column (4): Rooftop areas (m^2), depending on the mentioned administrative division in the chapter (Section 2.4).

Column (5): The rainwater harvesting potential (m^3) using Equation 2.11.

Column (6): The amount of water in the tank (m^3) at the beginning of each month, at the first mon th (October) was assumed the tank was empty, V_i value for October was zero.

Column (7): The difference between the volume of harvested water in column (5) and the amount of flushing consumption in column (3).

Column (8): The positive maximum cumulative difference corresponds to the optimal tank size (m^3) using Equation 2.16.

The following equation and are applied in the water balance model to determine the optimal tank size:

$V_f = V_i + (VR - D_f)$ (2.16)

If $V_f < 0$, then V_f and tank size were both assumed to be equal to 0. (2.17)

If $V_f > D_f$, then $S = D_f$ (2.18)

If $V_f < D_f$, then $S = V_f$ (2.19)

where, V_f is the maximum positive cumulative water volume in the tank at the end of the month (m^3); V_i is the volume of stored water at the beginning of the month (m^3); VR is the harvested rainwater volume within the month (m^3); D_f is the water consumption per family solely due to flushing within the month (m^3); and S is the optimal tank size to sustain flushing consumption (m^3).

For Ajlun, as an example, calculations of the maximum positive cumulative V_f value, and the optimal tank size for flush use (S) for the rooftop area of 250 m^2 are presented in Table A.1.6 for Ajlun Governorate; the figures for all 12 governorates are given in Figures 3.16 – 3.18.

2.9. CALCULATION OF EXPECTED ECONOMIC SAVING RATES

According to Al Rousan et al. (2005), the cost of seawater desalination was reported as 1.4 $\$/m^{3,}$ and the cost of extracting groundwater was ≤ 0.35 $\$/m^3$. In this study, the highest possible price for acquiring freshwater in Jordan was appraised at 1.4 $\$/m^3$ (the cost of desalinated seawater); hence, this value was assumed to be the maximum saving rate for harvesting rainwater per cubic meter. Similarly, the lowest possible price for freshwater and the lowest possible savings rate for rainwater harvesting were assumed to equal 0.35 $\$/m^3$ (the cost of groundwater). Based on these assumptions, the maximum and minimum expected economic saving rates were calculated using Equation 2.20.

$$\text{Expected Economic Saving Rate} = \text{VR} \times \text{C} \qquad (2.20)$$

C represents the cost of a cubic meter of water, which was taken as either 0.35 or 1.4 \$, based on the exchange rates of 2022 to calculate the minimum and maximum saving rates per cubic meter of harvested rainwater.

2.10. CALCULATION OF TANK COST

The majority of the cost of a rainwater harvesting system comes from the cost of the collection tank (Abu-Zreig et al., 2015; Abdulla and Al-Shareef, 2009). The optimal tank size was determined for every household based on three main factors: the rainfall rate of the governorate, the family's water consumption (m^3/month), and the rooftop area (m^2) as explained in Section 2.8. The curve plotted in Figure 2.3, which was adapted from a study by Abu-Zreig et al. (2013), was used to determine the approximate tank cost based on the optimal tank size (Equation 2.21). The cost varies depending on the total tank size (m^3); the cost per cubic meter starts at 100 JOD (\$141) and decreases to 60 JOD (\$85) as the volume of the tank gets larger.

$$\text{Tank Cost (JOD)} = \text{S} \times \text{Ccm} \tag{2.21}$$

‘S’ is the optimal tank size (m^3), and ‘Ccm’ is the cost per cubic meter (JOD/m^3) that was found utilizing the curve depicted in Figure 2.3.

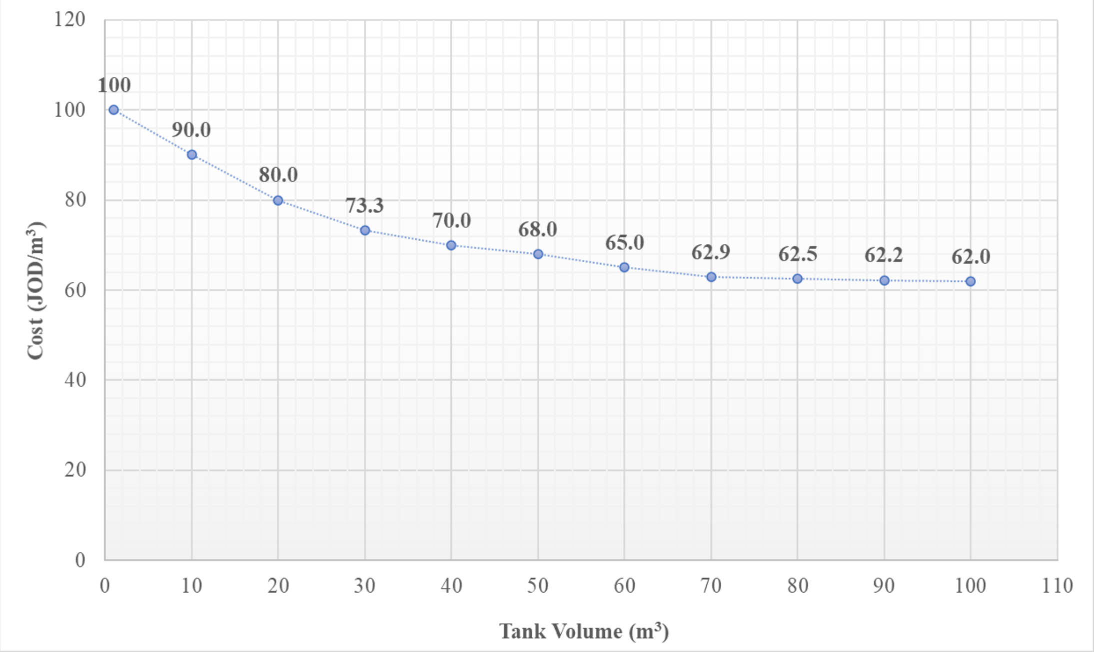

Figure 2.3. The average cost of installing a tank per cubic meter of stored rainwater (JOD/m^3); adopted from Abu-Zreig et al. (2013).

2.11. PAYBACK PERIOD ESTIMATIONS

The payback period is the time required to recoup the initial investment spent on a project and is expressed in years (Equation 2.22). In Figure 2.3, different methods for calculating the payback period for installing a rainwater harvesting system were presented.

$$\text{Payback} = \frac{\text{Rainwater harvesting system cost}}{\text{Annual flushing consumption per household} \times \text{worth of } m^3 \text{ of water}} \tag{2.22}$$

The maximum and minimum costs of the rainwater harvesting system were predicted by multiplying the estimated tank cost (Equation 2.21) and different factors that were reported in Abu-Zreig et al. (2019) and Farreny et al. (2011). Farreny et al. (2011) reported that the tank cost represents 50% of the total cost of the entire rainwater harvest system, and accordingly, the tank cost was multiplied by 2 (1/0.5) to calculate the maximum value for the system cost. Based on the value suggested in the study by Abu-Zreig et al. (2019) where the tank cost was reported to constitute 95% of the total system cost, the tank cost was multiplied by 1.05 (1/0.95) to calculate the minimum value for the system cost.

Then, the values calculated for system cost were divided by a modified version of a household's expected economic savings value for meeting only flushing needs through RWH (*see* Section 2.9). The upper and lower limit for the monetary worth of water collected through RWH were estimated by referencing the cost of desalination of seawater and of extracted groundwater, respectively (Equation 2.20). Annual water demand per family was regularized for the rainy periods and accepted as the total water consumption for only flushing within eight months (from October to May) for the payback period calculations.

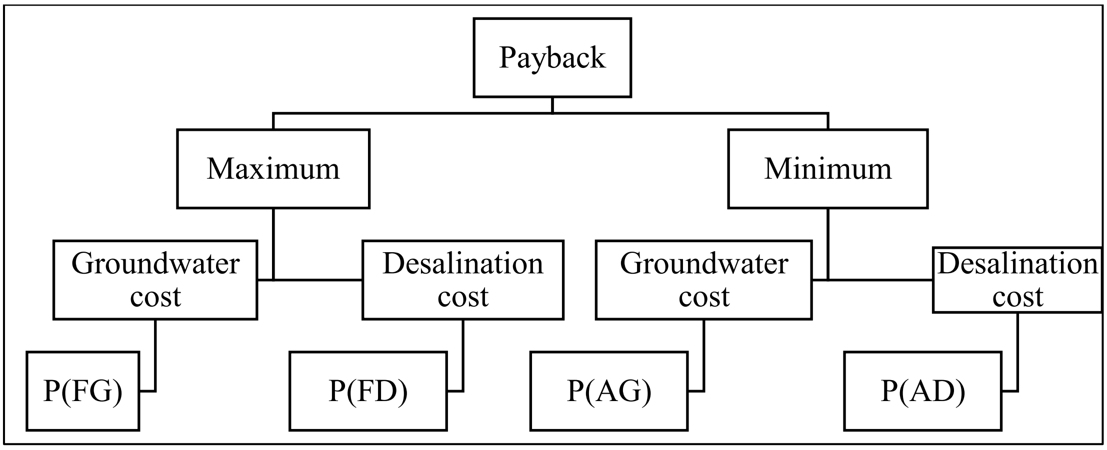

Figure 2.4. Flow chart for payback period calculation methods.

The regularization and payback calculations described in this section were applied to a hypothetical case. This case was a single house with 300 m^2 a rooftop area, accommodating a family of six members (the average Jordanian family size is 4.8 people per household) and located in the Swielih District (District No. 16) of Amman Governorate. Swielih District was chosen since it was considered a location with favorable characteristics for rooftop RWH applications. Swielih District is one of Jordan's most densely populated areas and receives a high annual rainfall (455 mm/year).

PSP_r (‘r’ subscript for ‘regularization’) is calculated as shown in Equation 2.12, but only for 8 months of the year (October–May) for the hypothetical single house in . If the $PSP_r > 100\%$, the potential rainwater harvesting volume could meet the flushing consumption in the rainy season (October–May), and installation of a rainwater harvesting system is recommended; whereas, if the $PSP_r < 100\%$, the potential rainwater harvesting volume could not meet the flushing consumption, and installation is not recommended.

CHAPTER 3

RESULTS AND DISCUSSION

After obtaining the data on rainfall, population change, rooftop areas, and water consumption rates, these data were analyzed, and the results were presented in this chapter.

3.1. THE RAINFALL DISTRIBUTION

Daily rainfall data from 157 rain monitoring stations were acquired from the Ministry of Water and Irrigation for the period between 1987-2018. The data from these stations were compiled into 12 groups based on their locations to represent rainfall distribution in twelve Jordanian governorates. The values of average monthly rainfall distribution in the study area are shown in Figure 3.1. The rainy season in Jordan runs from October to April, with peak rainfall during January and February, except in the Aqaba Governorate, where the rainy season is between April and July. The highest rainfall rates per year are over the heights of Ajlun, Jarash, Balqa, and Amman, which receive precipitation at 471, 386, 396, and 283 mm, respectively. These data indicate a considerable potential to harvest rainwater in these four governorates.

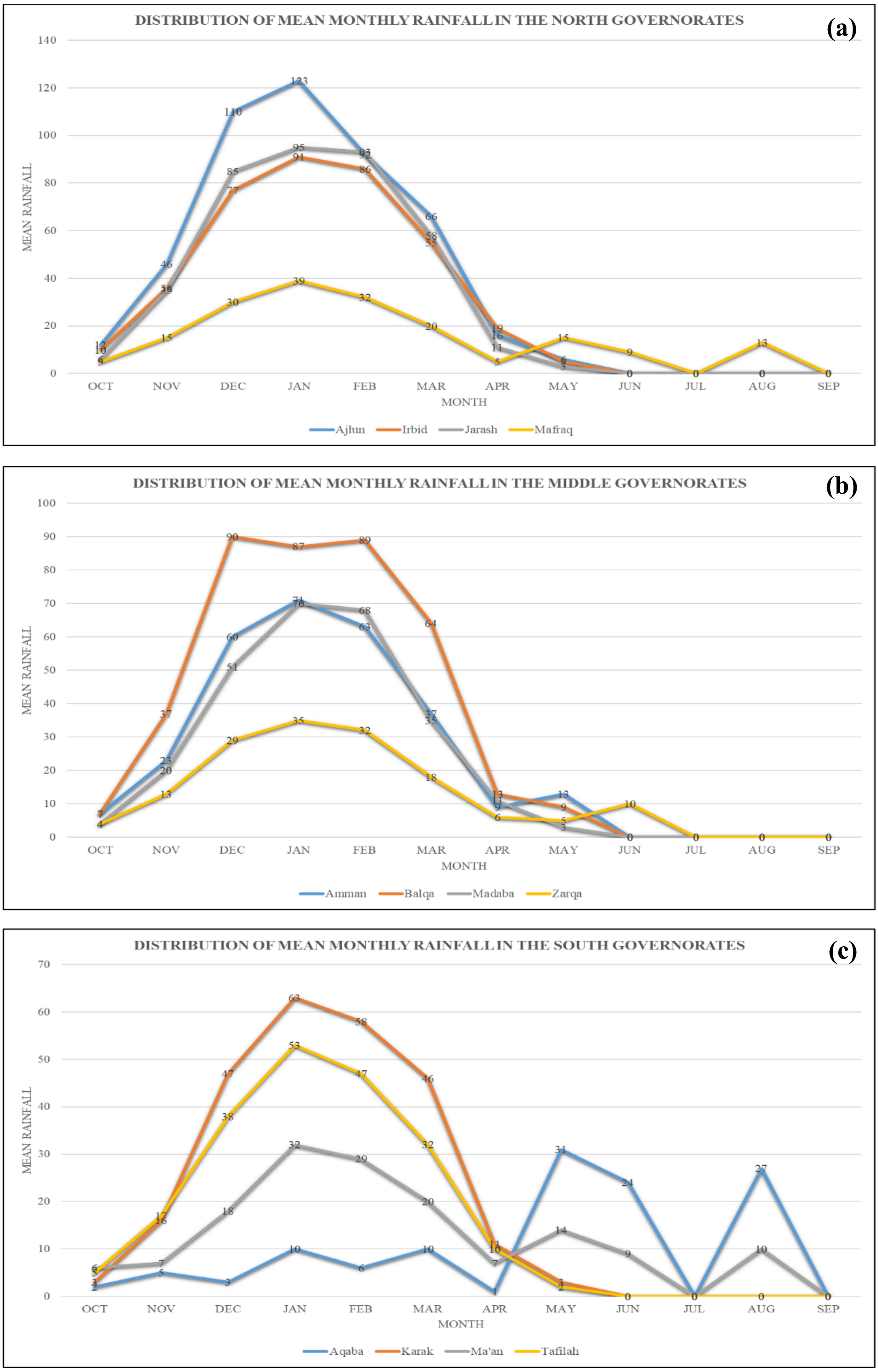

Figure 3.1. Temporal distribution of mean monthly rainfall in Northern (a), Middle (b), and Southern (c) Governorates.

3.2. POPULATION GROWTH AND WATER CONSUMPTION

The population distribution data and analysis of the population growth rate in Jordan helped to understand the current situation and anticipate future trends. According to the 2020 census conducted by the Jordanian Department of Statistics, Jordan's total population was 10.8 million (DOS, 2020). Table 3.1 shows the population for each governorate in 2020. Approximately 63.4% of the total population lives in the Central Region (Amman, Al-Zarqa, Madaba, Al-Balqa), 28.7% live in the Northern Region (Irbid, Mafraq, Jarash, Ajlun), and 7.9% live in the Southern Region (Ma'an, Kark, Al Tafeila and Aqaba). The availability of water strongly influences the settlement pattern in Jordan. The majority of the population was clustered in the relatively more water-rich Central Region.

Table 3.1. The population by governorate in 2020.

Governorate	**Population**	**% of the total**
Amman	4,547,023	42.1
Balqa	556,600	5.2
Zarqa	1,534,577	14.2
Madaba	214,100	2.0
Irbid	2,003,800	18.5
Mafraq	622,500	5.8
Jarash	268,300	2.5
Ajlun	199,400	1.8
Karak	358,400	3.3
Tafiela	109,000	1.0
Ma'an	179,300	1.7
Aqaba	213,000	2.0
Total:	**10,806,000**	**100.0**

The growing population of Jordan, the continuing improvement in living standards associated with higher incomes, and the current agricultural policy and traditional irrigation methods have increased the demand for freshwater. The increase in the total amount of consumed water was approximately proportional to Jordan's population growth rate (Figure 3.2). In general, urban dwellers' water consumption rates differ from those in villages and agricultural areas; the total water consumption in 2020 was about 1130.1 Mm^3 (Table 3.2). It was increased by 2.30% compared to 2019; similarly, the census in 2020 was 10,806,000, which increased by approximately 2.38%

compared to 2019 figures. Table 3.2 shows the water consumption by sectors between 2019-2020. In 2020, municipal usage was 514.27 Mm^3 (45.5% of the total annual consumption of Jordan), while the agricultural sector's water consumption reached 570.26 Mm^3 (50.5% of the total annual consumption). The industrial sector consumed 35.64 Mm^3 (3.15% of the total annual consumption), while the livestock sector is 9.93 Mm^3 at 0.9%. These consumption figures indicate a clear, steadily ascending trend in municipal consumption. The consumption rates in other sectors fluctuated by year without a steady upward trend. Therefore, the overall increase in total consumption was concluded to be mainly driven by municipal consumption.

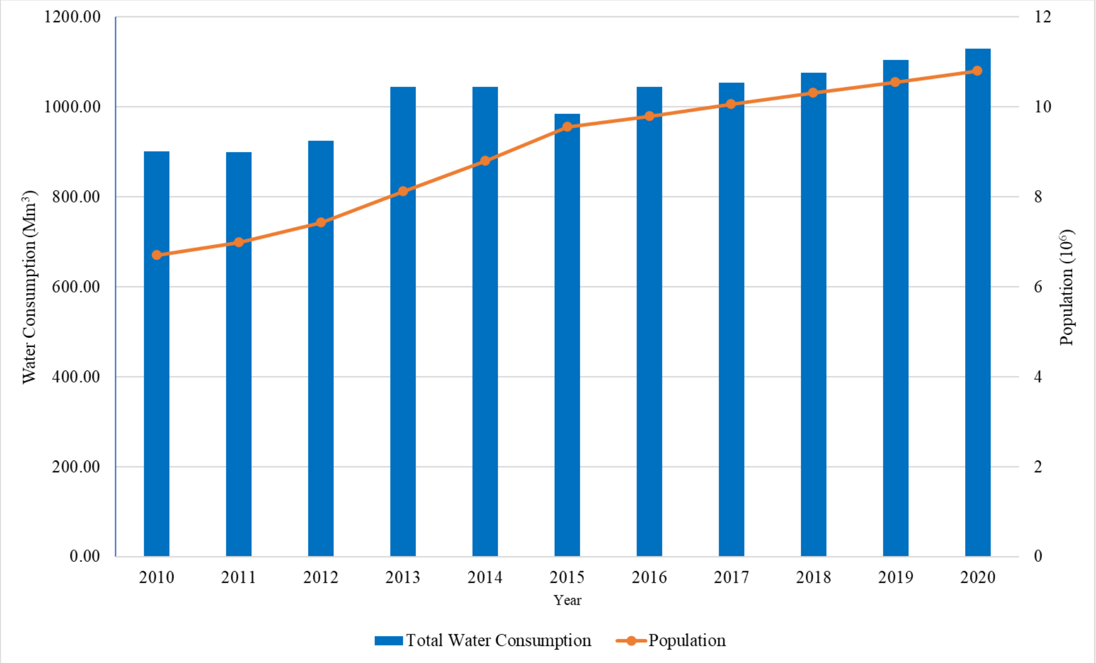

Figure 3.2. Census data and total water consumption for the period of 2009-2020.

Municipal consumption in 2009 was 308.7 Mm^3. It was 514.27 Mm^3 in 2020; this means an increase of 18.7 Mm^3/year on average, whereas the population growth rate, PGR (calculated using Equation 2.7), was 4.74% over the same period. Similar to the calculation of population growth rate (PGR), 'consumption growth rate' (CGR) was calculated using a modified version of Equation 2.7 as shown in Equation 3.1.

$$\text{Consumption Growth Rate (CGR)} = \left[\frac{\text{final value}}{\text{initial value}}\right]^{\frac{1}{n}} - 1 \qquad 3.1$$

When the values were plugged into the equation above (final value =the municipal consumption in 2020 =514.27 Mm^3; initial value = the municipal consumption in 2009 =308.70 Mm^3; n =2020–2009 =11), CGR value for 2009-2020 was calculated as 4.75%. These similar PGR and CGR values for the same period (4.74% PGR vis-à-vis 4.75% CGR) suggest a close correlation between population growth and an increase in municipal consumption.

Table 3.2. Distribution of water consumption (Mm^3) in Jordan by sectors (MWI, 2020).

Year	Livestock	Irrigation	Industrial	Municipal	Total
2009	7.90	458.40	37.30	308.70	938.30
2010	7.30	501.30	40.40	351.70	900.70
2011	7.10	504.80	40.20	346.80	898.80
2012	7.10	448.80	40.20	388.30	924.30
2013	7.10	541.70	51.70	443.40	1044.00
2014	7.10	539.50	51.70	424.00	1044.00
2015	7.20	483.90	37.40	456.50	985.00
2016	7.63	547.04	32.47	456.90	1044.00
2017	7.10	544.70	32.10	469.70	1053.60
2018	7.10	555.30	34.50	479.50	1076.40
2019	10.70	560.54	36.88	497.37	1104.86
2020	9.93	570.26	35.64	514.27	1130.10

3.3. THE TOTAL OF ROOFTOP AREAS

Table 3.3 lists the total roof area of each governorate. Amman Governorate has the highest roof area (34.2 $\times 10^6$ m^2); the lowest roof area (1.42 $\times 10^6$ m^2) is in Tafeila Governorate. The calculated total roof area values were used to estimate the volume of rainwater that could be harvested in each governorate.

Table 3.3. The Total Roof Area in Each Governorate (DOS,2020).

The Governorates	**Total Roof Area (m^2)**
Ajlun	1,838,920
Amman	34,248,500
Aqaba	1,606,400
Balqa	6,028,300
Irbid	27,879,500
Jarash	2,716,900
Karak	4,646,500
Ma’an	1,506,600
Madaba	2,638,600
Mafraq	7,036,400
Tafilah	1,417,200
Zarqa	9,792,900

3.4. WATER CONSUMPTION RATE

The average water consumption per capita (liter/capita/day) for the 12 governorates was given in Table 3.4, along with the average annual rainfall rate, total roof area, and population according to the 2020 census. The average consumption rates per capita ranged from 80 L in Irbid to 274 L in Ma'an, indicating a significant variation in water consumption rates per capita in different governorates.

Table 3.4. The results of TRA calculations for each governorate.

Governorate	**Annual rainfall averages (mm)**	**Total roof area (TRA) (m^2)**	**Population in 2020**	**Per capita water use (L/d/capita)**
Ajlun	471	1,838,920	199,400	106
Amman	283	34,248,500	4,536,500	132
Aqaba	80	1,606,400	213,000	191
Balqa	396	6,028,300	556,600	239
Irbid	379	27,879,500	2,003,800	80
Jarash	386	2,716,900	268,300	110
Karak	230	4,646,500	358,400	192
Ma’an	110	1,506,600	179,300	274
Madaba	262	2,638,600	214,100	160
Mafraq	183	7,036,400	622,500	140
Tafilah	204	1,417,200	109,000	244
Zarqa	152	9,792,900	1,534,577	120

The total annual per capita use in a governorate or Total Amount per Governorate (TAPG) was calculated using Equation 2.8, and the results of these calculations are presented in Table 3.5. TAPG values were affected by two main factors: the population and water consumption per capita. Amman had the highest TAPG of 218 Mm^3 since its population was the highest (4,547,023), but it had low water consumption per capita compared to other governorates like Ma'an. Ma'an had a low TAPG (18 Mm^3) compared to Amman, but the water consumption per capita was relatively higher in Ma'an.

The same phenomena could be seen again when Ajlun and Irbid were compared. The water consumption per capita value was 106 L/day in Ajlun and it was 80 L/day in Irbid. Nevertheless, Irbid's TAPG was 7.5 times that of Ajlun; because the population density in Irbid was more than ten times greater compared to Ajlun.

Table 3.5. The total water consumption for each governorate.

Governorate	**Total water consumption (Mm^3/Year)**
Ajlun	7.7
Amman	218.0
Aqaba	14.8
Balqa	48.5
Irbid	58.4
Jarash	10.7
Karak	25.0
Ma'an	18.0
Madaba	12.4
Mafraq	31.8
Tafilah	9.7
Zarqa	67.7
Total:	***522.9***

Therefore, the size of the population in a governorate was the main factor affecting the TAPG value, compared to the water consumption per capita. However, a high TAPG value did not reflect a higher water consumption per capita.

3.5. THE POTENTIAL WATER HARVESTING

Table 3.6 shows estimated potential water harvesting volumes in Jordan's 12 governorates along with PSP values. The potential amount of rainwater harvesting (VR) is estimated based on the total surface area of the roofs, average annual rainfall rate, and runoff coefficient using Equation 2.11 (Abdullah and Sharif 2009). The potential saving percentage (PSP) was calculated by dividing the potential harvested rainfall volume by annual water demand using Equation 2.12.

The total potential for rooftop rainwater harvesting was estimated at 23.74 Mm^3 per year. Comparing the governorates, Irbid was ranked first with a harvesting potential of 8.453 Mm^3/year, followed by Amman, which had a water harvesting potential of 7.754 Mm^3/year. The VR values of the other ten governorates were markedly lower compared to these top two governorates. The total rooftop area to harvest rainwater in Irbid was high, and this governorate has a higher average rainfall rate compared to other governorates. The precipitation rates in Amman were not the greatest among 12 governorates, but it had the largest total rooftop area. The lowest possible water harvesting rate of 0.103 Mm^3/year was calculated for Aqaba, which had a low rooftop area and the lowest annual rainfall rate.

Table 3.6. Potential water harvesting and potential saving in the 12 Governorates.

Governorate	**Potential water harvesting, VR (Mm^3/Year)**	**Total water demand, TAPG (Mm^3/Year)**	**Percentage of water-saving, PSP (%)**
Ajlun	0.693	7.7	9.0
Amman	7.754	218	3.6
Aqaba	0.103	14.8	0.7
Balqa	1.910	48.5	3.9
Irbid	8.453	58.4	14.5
Jarash	0.839	10.7	7.8
Karak	0.855	25.0	3.4
Ma’an	0.133	18.0	0.7
Madaba	0.553	12.4	4.5
Mafraq	1.030	31.8	3.2
Tafilah	0.231	9.7	2.4
Zarqa	1.191	67.7	1.8
Total:	**23.74**	**522.9**	**4.5**

In Jordan, the percentage of the domestic annual water requirements that can be met by rooftop rainwater harvesting was presented as a percentage of water-saving (PSP). The highest PSP of 14.5% was calculated for Irbid, suggesting that 14,5% of the total consumption could be covered in Irbid. PSP for the whole of Jordan was 4,5%. Other studies have found similar results. In countries with low rainfall rates, it was reported that 3.4–8.5% of the domestic annual water requirements could be met through rainwater harvesting (Sahin and Manioğlu, 2019; Summerville and Sultana, 2019; Baby et al., 2019; Abu-Zreig et al., 2013).

Jordan's total rooftop rainwater harvesting potential of 23.74 Mm^3/year was equivalent to 4.5% of the total domestic water demand in 2020. The total potential volume calculated here was significantly higher than the results from other older studies conducted for Jordan. This potential volume increase was most likely due to Jordan's urban expansion throughout the last 15 years, reflecting the increase in the total rooftop area. Based on 2004 data, Abu-Zreig et al. (2013) reported that the national potential for rooftops was 14.7 Mm^3/year corresponding to 6% of the total domestic water demand. Abdulla and Al-Shareef (2009) found that the potential rooftop harvested rainwater was 15.5 Mm^3 based on 2005 data, equivalent to 5.6% of the total domestic water demand.

The potential of rooftop harvesting volume varies from country to country, depending on the rainfall rate and rooftop area. Shadeed and Alawna (2021) found that the potential rainwater harvesting in the West Bank of Palestine is 37 Mm^3/year. Traboulsi and Traboulsi (2015) found that the potential rainwater harvesting from rooftops was 23 Mm^3/year in Lebanon. Mourad and Berndtsson (2011) reported that the potential rainwater harvesting from urban areas in Syria was 35 Mm^3/year.

3.7. EXPECTED WATER CONSUMPTION SCENARIOS IN JORDAN

Based on the past population growth results and the available water consumption rates in 2020, three future scenarios for water consumption were predicted. The predictions were shown in Table 3.7.

The first scenario was constructed based on PGR calculated for the period of 2019-2020 (*see* Section 2.7). The population growth rate was estimated at 2.39% and the expected population in 2025 and 2030 has been calculated using Equation 2.6. According to this prediction, the population would reach 12,161,000 in 2025, and the available daily water supply per capita would be at around 255 L/day; in 2030, the population was expected to reach 13,685,000, and the available daily water supply per capita would fall to 226 L/day. For comparison, the average water supply per capita was 287 liter/day in Jordan, according to 2020 data.

The second scenario was constructed based on PGR calculated for 2015-2020, the population growth rate was estimated at 2.48%. In this scenario, the population would reach 12,214,000 in 2025, and the available daily water supply per capita would be about 253 L/day; in 2030, the expected population would reach 13,806,000, and the available water per capita falls to 224 liters/day. The results of the second scenario were very close to the first one.

Table 3.7. Water consumption predictions for Jordan, based on different PGR values.

PGR (%)	**Year**	**Population**	**Total water supply w/o rainwater harvesting (Mm^3/year)**	**Available water supply per capita (L/d/capita)**
2.39	2025	12161000	1130.10	255
	2030	13685000		226
2.48	2025	12214000		253
	2030	13805000		224
4.89	2025	13719000		226
	2030	17418000		178

The third scenario was constructed based on PGR calculated for 2010-2020, the population growth rate was 4.89%. In this scenario, the population would reach 13,719,000 in 2025, and the available daily water supply per capita would be 226 L/day; in 2030, the expected population would reach 17,418,000, and the available daily water supply per capita would fall to 178 litres/day.

Based on the three scenarios mentioned above, achieving water security in Jordan is challenging due to the high population growth rate. Therefore, serious executive action must be taken to make citizens aware of these risks and to adopt better water management strategies in Jordan by the government. The Jordanian Ministry of Water and Irrigation prepared a water strategy in 1997, representing Jordan's main water management criteria; additional criteria and strategies were developed in 2008. Unfortunately, these strategies have not been appropriately implemented due to a lack of resources and mismanagement. Nonetheless, these plans are still valid and can contribute significantly to the improvement and development of water resources in Jordan. Additionally, developing a rainwater harvesting infrastructure can help enrich the available water supply in Jordan, mitigating the risk of a water crisis.

Table 3.8. Expected per capita water supply (L/day) based on potential water harvesting and estimated population for 2025, 2030.

SCENARIO	**Year**	**Population**	**Total VR (Mm^3/year)**	**Harvested water per capita (Liter/day)**	**Expected amount per capita (Liter/day)**	**Total expected per capita (Liter/day)**
First	2025	12161000	23.74	5.35	254.60	259.95
	2030	13685000		4.75	226.25	231.00
Second	2025	12214000		5.33	253.49	258.82
	2030	13805000		4.71	224.28	228.99
Third	2025	13719000		4.74	225.68	230.43
	2030	17418000		3.73	177.76	181.49

Table 3.8 shows the rooftop harvested water volume per capita in three scenarios and relatively small improvement on Jordan’s water supply. These results emphasize the need to stabilize the population growth rate immediately, citizens need to be informed on water issues, and finally, new water strategies must be strictly applied. It should be noted that the amount of potential water harvesting volume was based on the roof area data from 2015, not accounting for seven years of new building construction up to 2022. It was also neglected in these future predictions, but the total roof area should be getting larger with the growing population in the future.

3.8. THE OPTIMAL TANK SIZE AND COST

Figures 3.3-3.14 that were created using the Ripple Method demonstrate the optimum tank sizes that could be built; this is due to the underlying factors (i.e., monthly water consumption, roof area, and monthly rainfall rate) in determining the size of the tank using Equation 2.13 (*see* Table A.1.5).

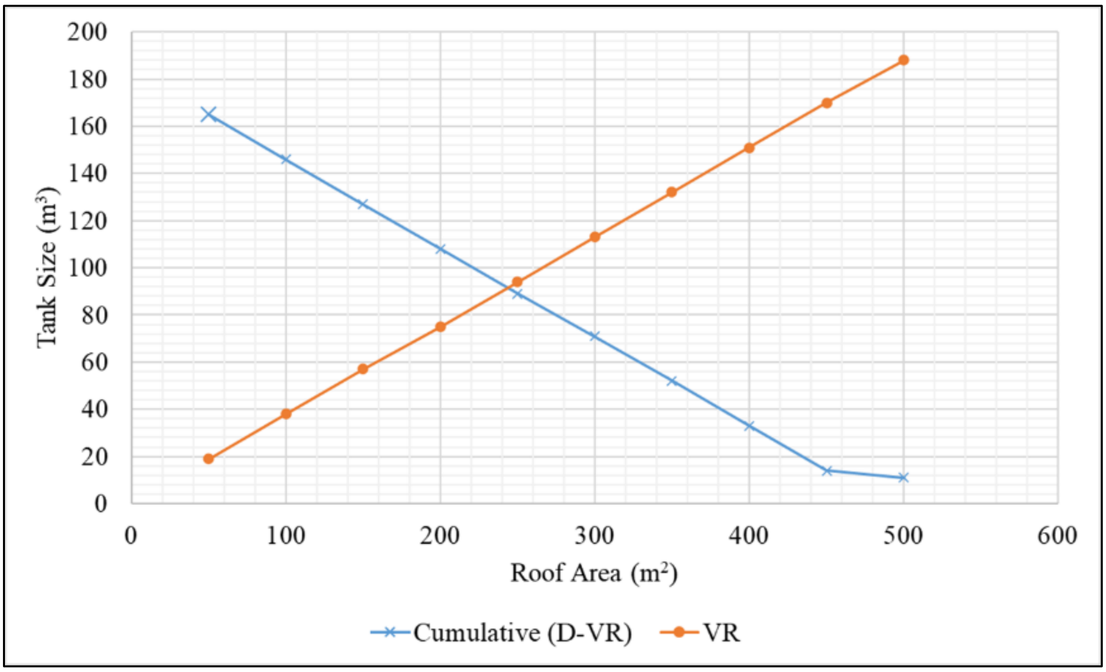

Figure 3.3. The optimal tank sizes by rooftop area in Ajlun Governorate.

In the Ajlun (Figure 3.3) and Irbid (Figure 3.4), for rooftop areas of 250 m^2 and less, the optimal tank size (S) was controlled by the VR_h value. Whereas, for rooftop areas of 300 m^2 and more, the optimal tank size (S) was being controlled by $\sum$(D-VR) values. In Jarash (Figure 3.5), for rooftop areas of 300 m^2 and less, the optimal tank size was controlled by the VR_h, whereas $\sum$(D-VR) values controlled S in case of 350 m^2 and more rooftop area.

Amman is a different case (Figure 3.6); the optimal tank size (S) was controlled by the VR_h for all rooftop areas (up to 500 m^2). For the rest of the governorates, the optimal tank size was also controlled by the VR_h for all rooftop areas up to 500 m^2 and it was not possible to fully meet the demand via rainwater harvesting in any case (Figures 3.7-3.14).

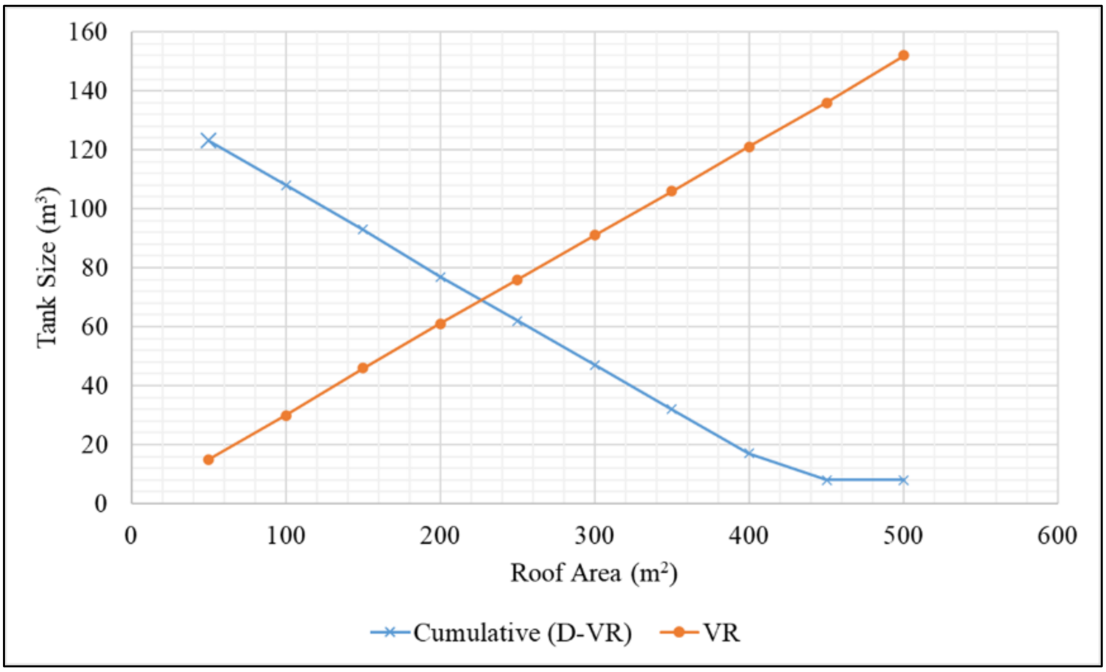

Figure 3.4. The optimal tank sizes by rooftop area in Irbid Governorate.

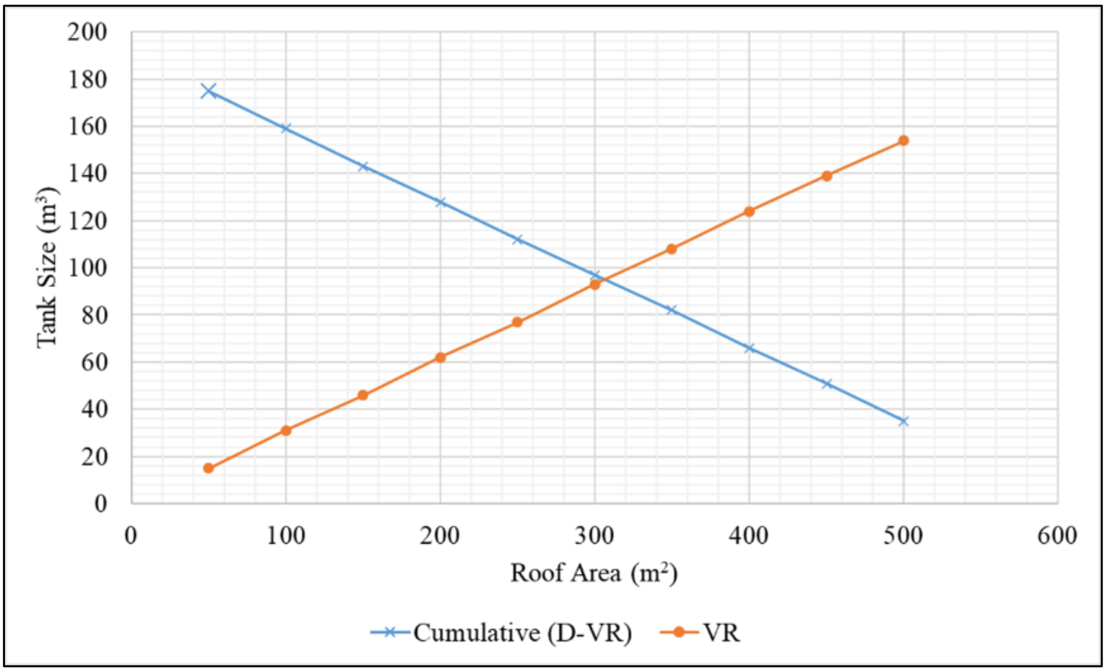

Figure 3.5. The optimal tank sizes by rooftop area in Jarash Governorate.

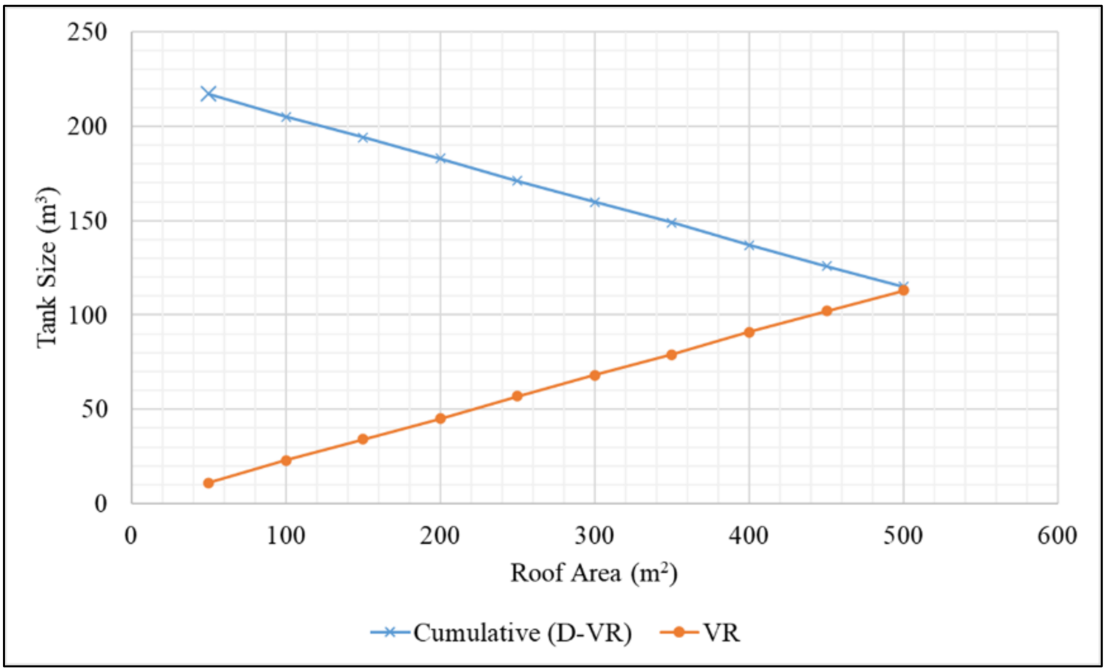

Figure 3.6. The optimal tank sizes by rooftop area in Amman Governorate.

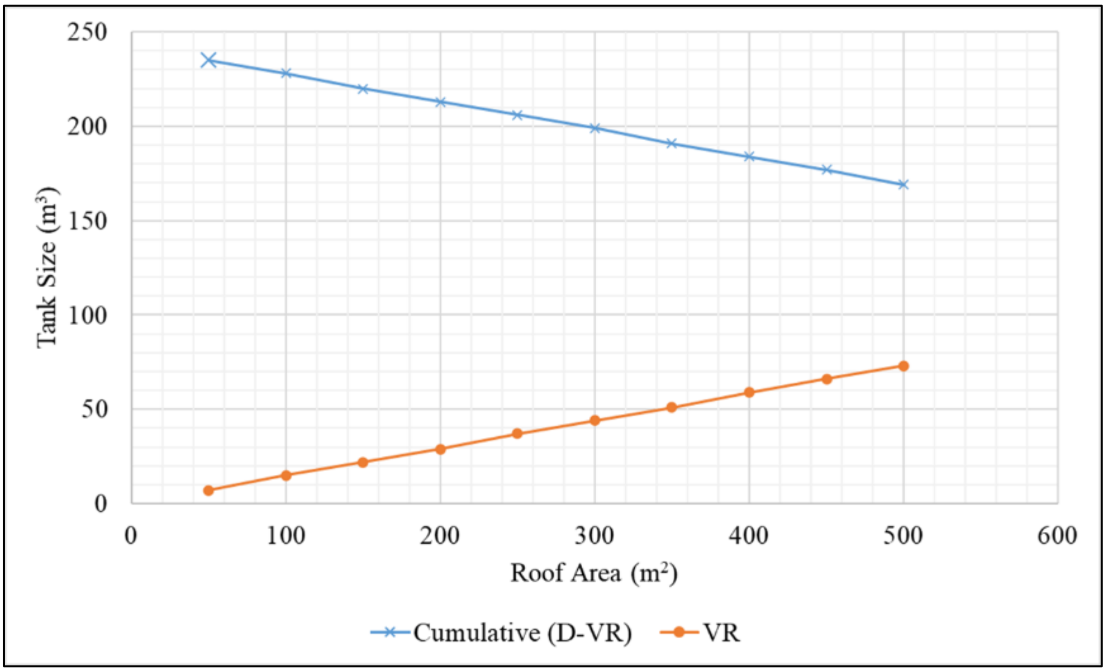

Figure 3.7. The optimal tank sizes by rooftop area in Mafraq Governorate.

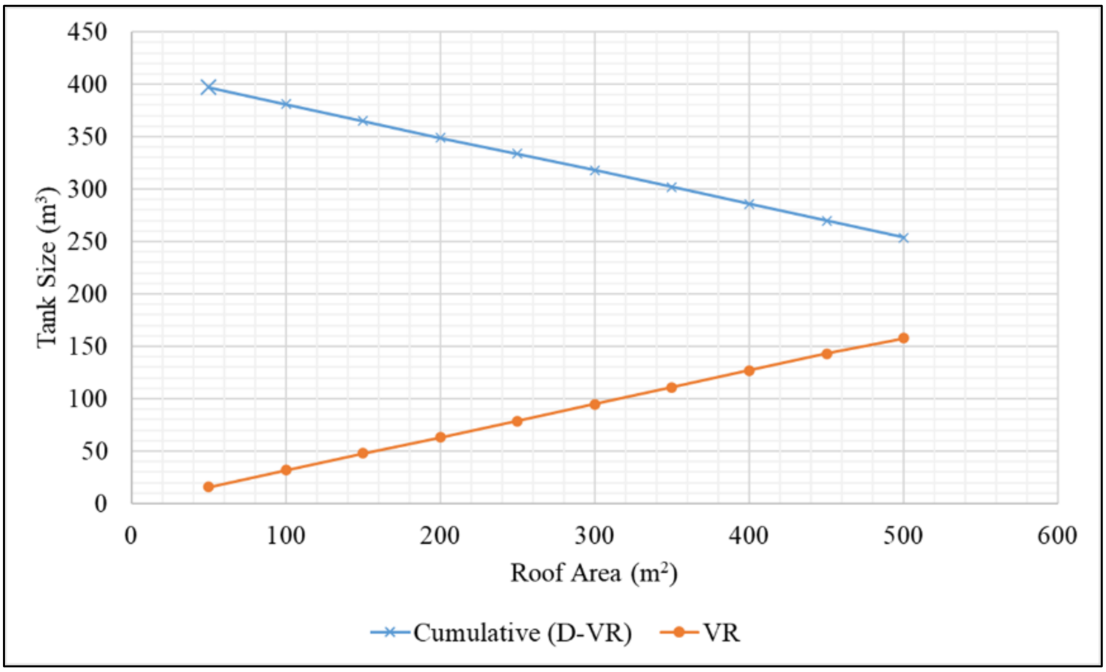

Figure 3.8. The optimal tank sizes by rooftop area in Balqa Governorate.

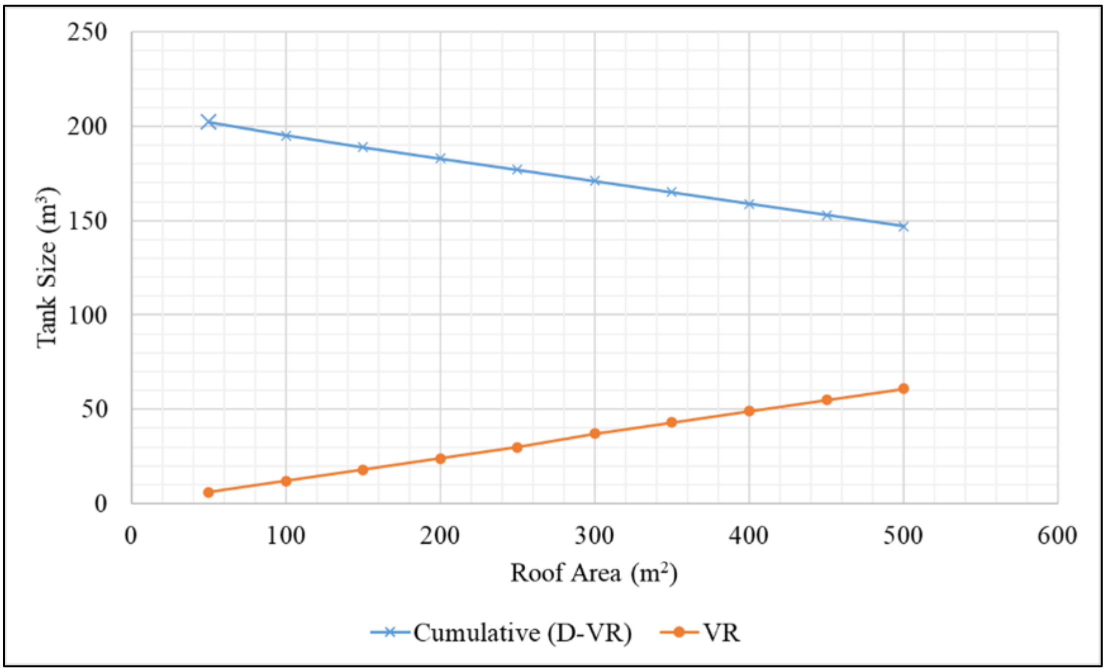

Figure 3.9. The optimal tank sizes by rooftop area in Zarqa Governorate.

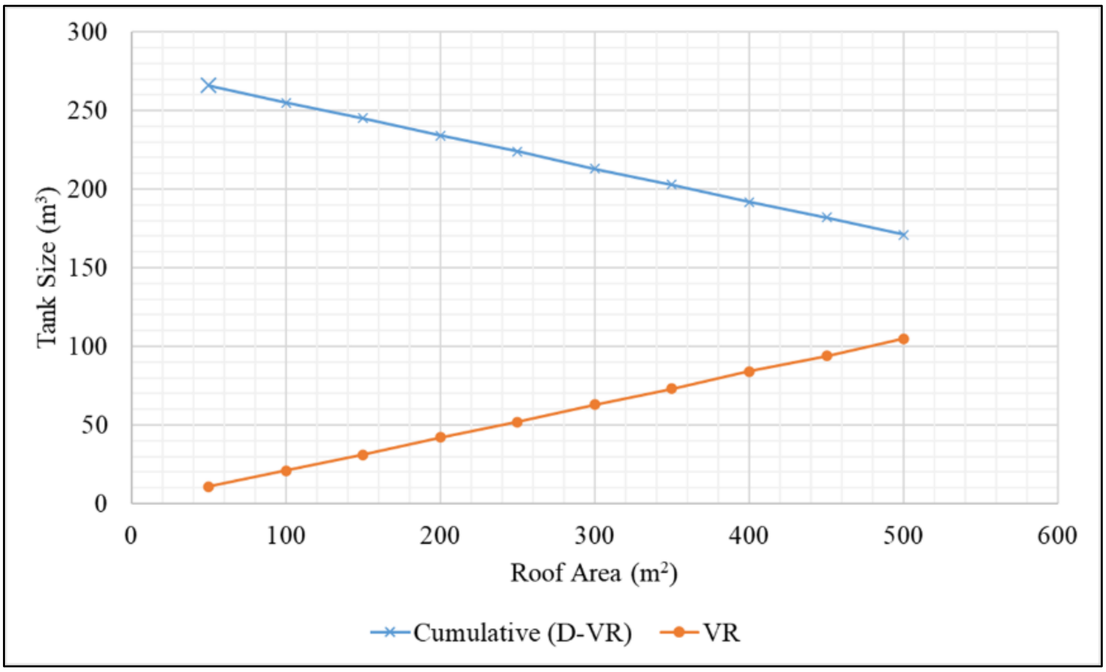

Figure 3.10. The optimal tank sizes by rooftop area in Madaba Governorate.

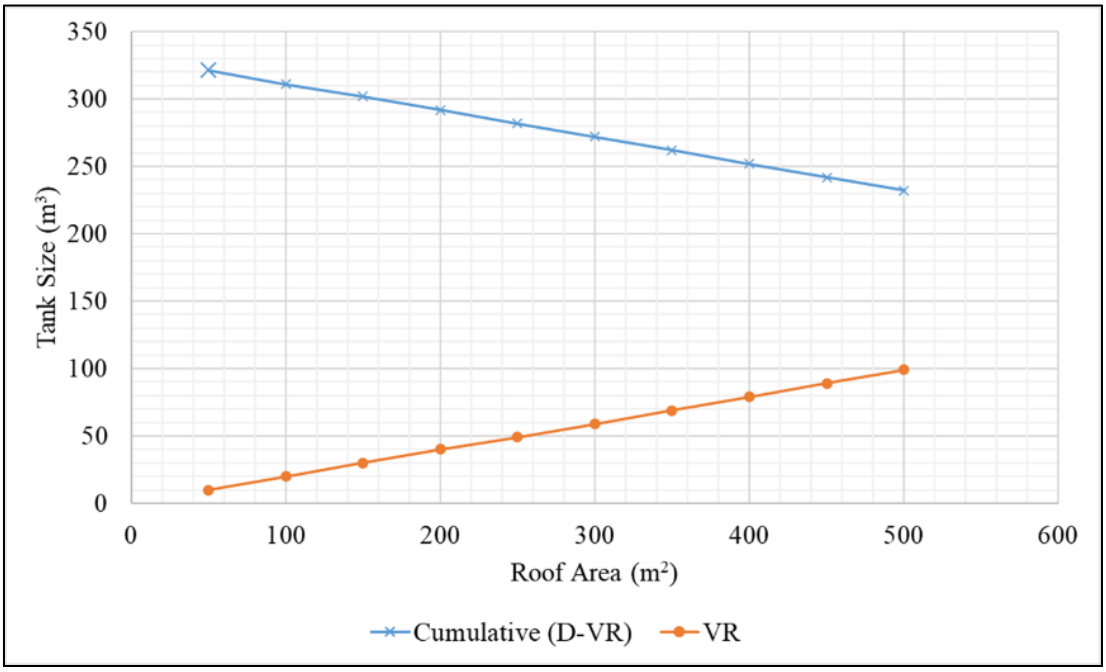

Figure 3.11. The optimal tank sizes by rooftop area in Karak Governorate.

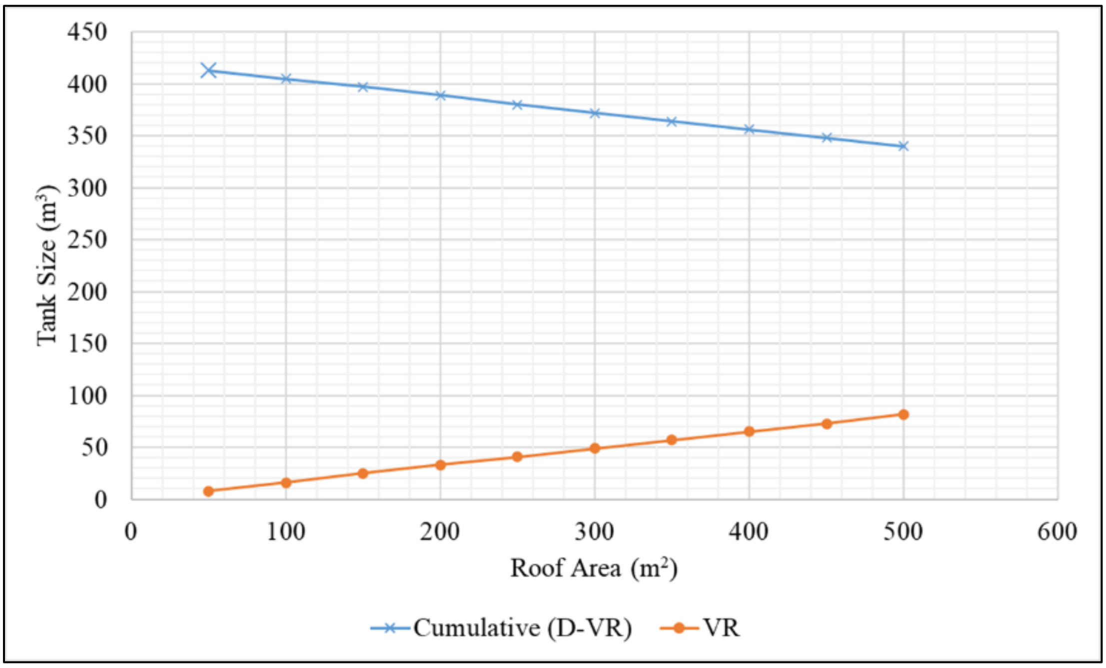

Figure 3.12. The optimal tank sizes by rooftop area in Tafiela Governorate.

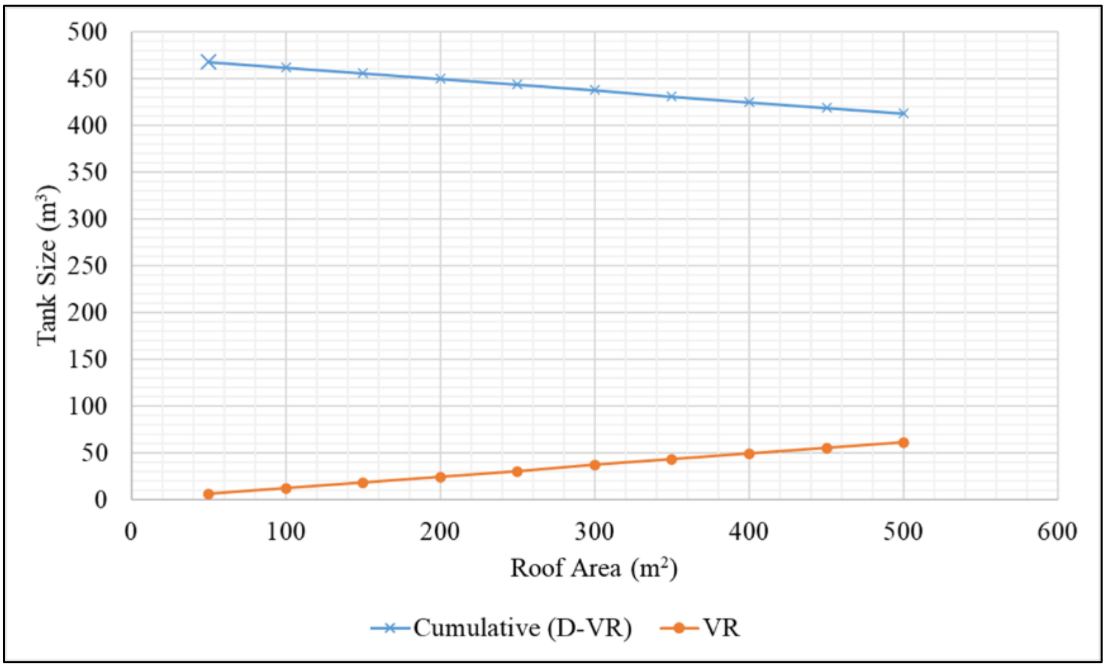

Figure 3.13. The optimal tank sizes by rooftop area in Ma'an Governorate.

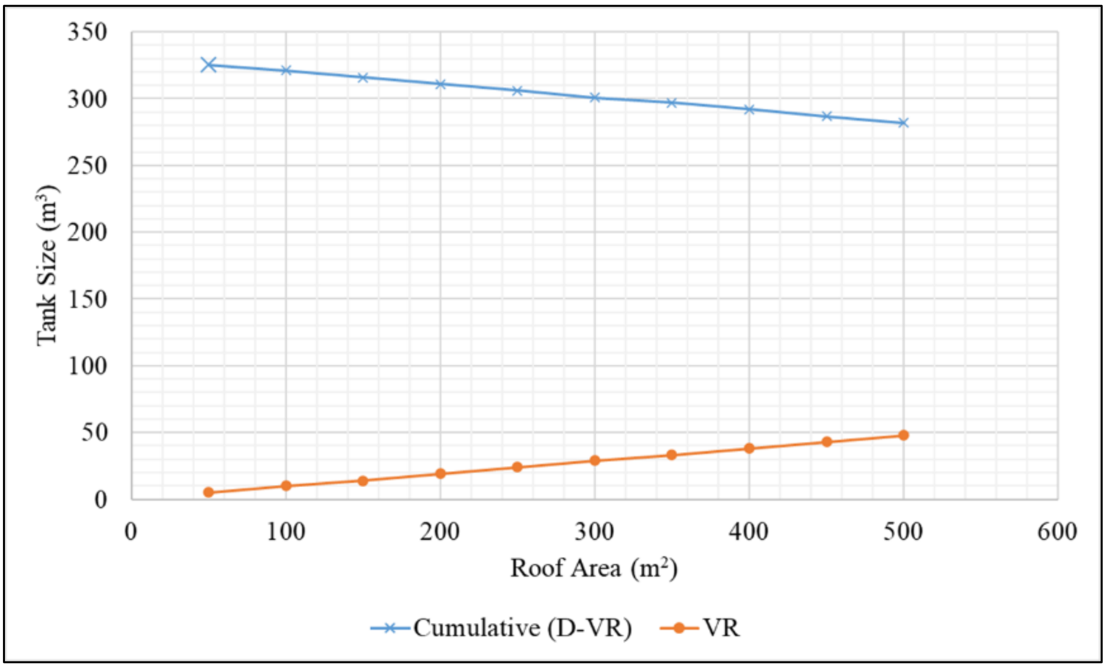

Figure 3.14. The optimal tank sizes by rooftop area in Aqaba Governorate.

Although a previous study found that harvested water was compatible with 'Jordanian Drinking Water Standards'. However, best management practices should ensure that harvested rainwater is free of pathogens (Assayed et al., 2013). The harvested rainwater must be treated for drinking and cooking; it can also be used in agriculture, cleaning and flushing without treatment (Abdulla and Al-Shareef, 2009). The harvested rainwater can be stored in tanks separate from existing tap water tanks and used in flushing.

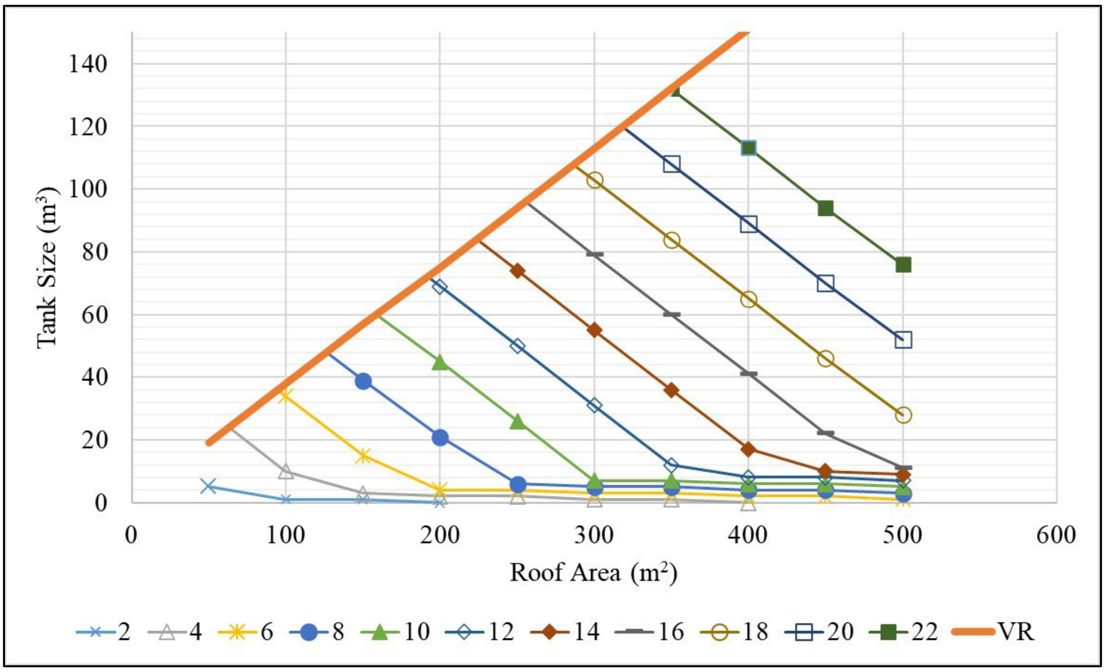

Figure 3.15. The optimal tank sizes for different water demand rates (2-22 m^3/month) and rooftop areas in Ajlun Governorate.

The Ripple method can be applied to all governorates. Figure 3.15 was created based on the Ripple method and shows the optimal tank sizes in Ajlun. The optimal tank size can be determined according to the rooftop areas (50-500 m^2) and monthly water consumption rate ranging from 2 to 22 m^3/month. The odds of consumption rates were selected as described in Abu-Zreig et al. (2019), which were within the range of 2-22 m^3/month for one family. Since the consumption rate of a single family can vary significantly, it was considered that it is better to plot for multiple possible consumption rates. The figure would be helpful in studying how rainwater can be used and treated to meet the monthly demand rate for future research.

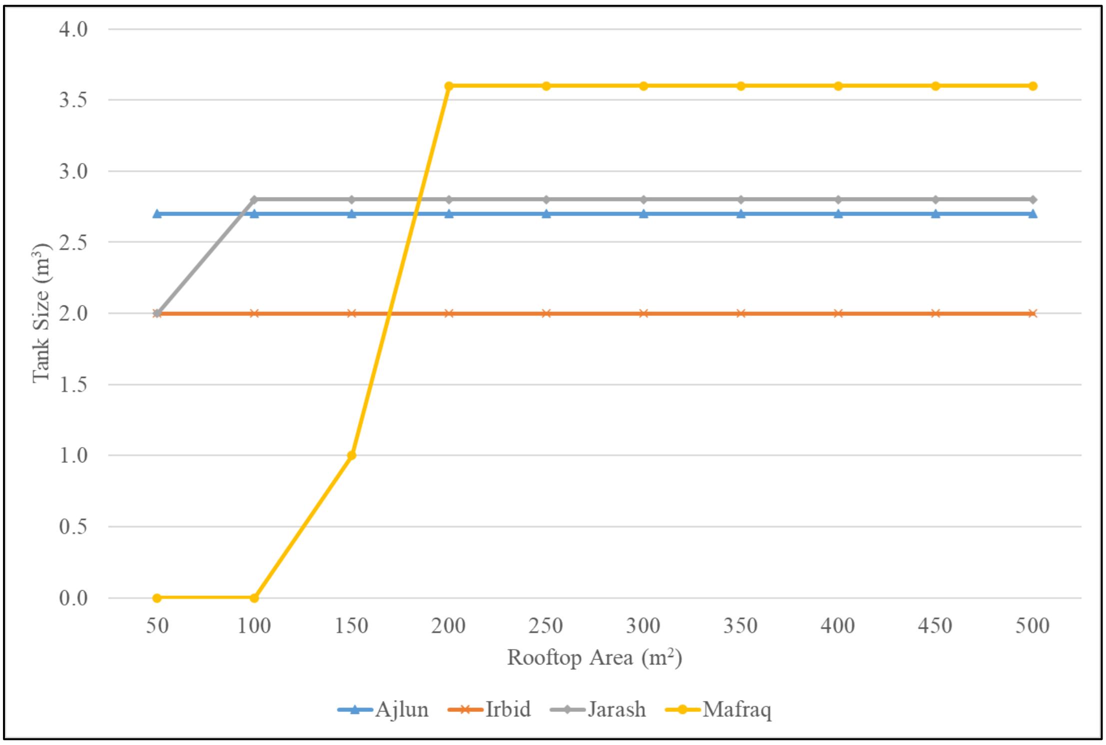

Figure 3.16. The optimal tank sizes (m^3) for flushing consumption in the Northern region.

The harvested rainwater could be used directly for irrigation and flushing (Assayed et al., 2013; Awawdeh et al., 2011; Matos et al., 2014). Harvested rainwater can be allocated for garden irrigation and flushing without any prior treatment. The quality of the harvested rainwater is associated with the location of the rainfall and the rooftop's surface conditions. Harvested rainwater is likely to contain air-borne pollutants. Additionally, the residential building roofs can collect contaminants such as dust, foliage, and even dead birds. Using rainwater in flushing is preferable to reduce pressure on other water sources while avoiding health risks and treatment costs. Even if the harvested water is solely used for toilet flushing, a significant tap water saving can still be achieved when the rooftop area and rainfall rate are sufficient. The amount of water used for flushing comprises 17.7% of total use in Jordan, according to Sha'ban et al. (2011).

The Water Balance Model was used in this study to estimate the optimal tank size for meeting flushing consumption. Figures 3.16-3.18 were plotted using Water Balance Model to determine the optimal tank size for each governorate, and these can be used to determine the optimum tank size depending on the amount of water required for flushing and the rooftop area (50-500 m^2).

Figure 3.16 showed that the potential harvested rainwater meets the required amount of flushing in Irbid and Ajlun for all categories of rooftop areas (50-500 m^2). The flushing consumption in Ajlun and Irbid could be met by harvested rainwater, and the optimal thank sizes for flushing in Ajlun and Irbid were 2.7 m^3 and 2 m^3 per household, respectively. The results in Jarash showed that the potential harvested rainwater from a roof area of 100 m^2 could meet the required amount of flushing, but from a roof area of 50 m^2, only 2 m^3/month per household could be collected. In Mafraq Governorate, the flushing consumption could be partially met for households with a rooftop area equal to 150 m^2, and fully met from 200 m^2 or more.

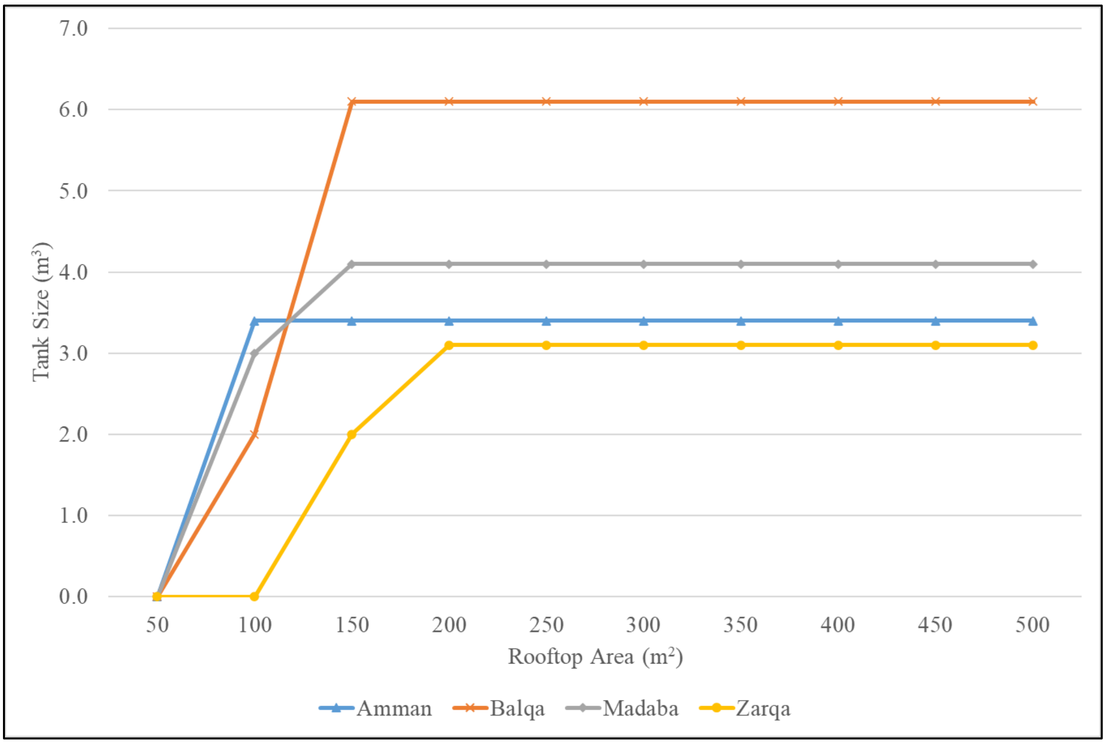

Figure 3.17. The Optimal Tank Sizes (m^3) for flushing consumption in the Middle region.

There was a significant difference in Irbid results in terms of PSP values (14.5% and 17.7%); because in the first case, a PSP of 14.5% was estimated using the actual population in Irbid, and in the second case, a PSP of 17.7% (fully met flushing consumption) was estimated based on Jordan's average family size per household (4.8

members), this difference indicates that the number of family members on average in Irbid was greater than the average of Jordan.

Amman, Balqa, and Madaba, the potential harvested rainwater could partially meet the flushing consumption for houses with a 100 m^2 rooftop area, while households with a roof area of 150 m^2 and more could meet the entire flushing consumption (Figure 3.17). In Zarqa, the water for the flushing was available only for households with a surface area of 200 m^2 and more. For households in the middle governorates with a roof area of 50 m^2, the flushing consumption amount could not be met by the potential harvested rainwater.

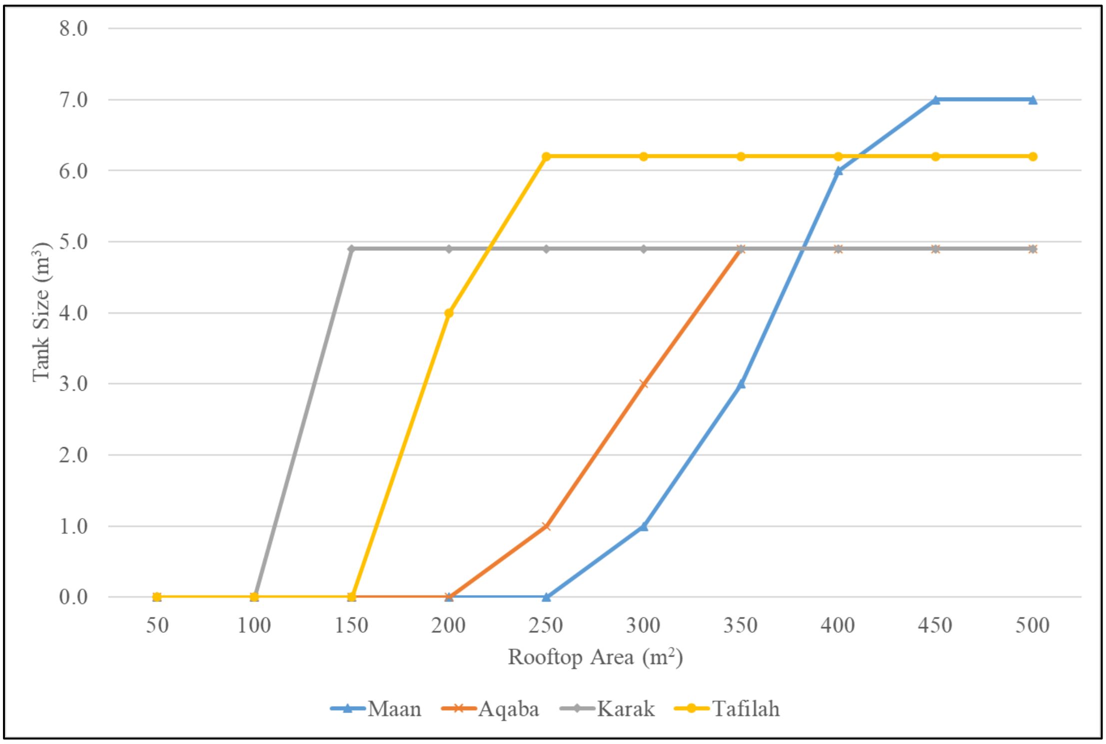

Figure 3.18. The Optimal Tank Sizes (m^3) for flushing consumption in the Southern region.

Figure 3.18 shows the situation in the Southern Governorates and households in these governorates performed the worst compared to the Middle and Northern Governorates. In the Ma'an governorate, flushing consumption could be supplied entirely only for households with rooftop areas of 450 m^2 and more. In Aqaba, the flushing consumption could be fully met by the potential rainwater harvesting for households with roof areas of 350 m^2 and more; in Tafiela, only for households with roof areas of 250 m^2 or more; in Karak, 150 m^2 and more.

Based on the cost of groundwater extraction (0.35 \$/m^3) and seawater desalination (1.4 \$/m^3), the monetary value of estimated water savings from rooftop rainwater harvesting were calculated using Equation 2.20. It was found to be within the range of 170×10^6 \$/year to 678×10^6 \$/year throughout Jordan.

3.9. REGULARIZATION STUDY FOR A HYPOTHETICAL BUILDING IN SWIELEH DISTRICT OF AMMAN GOVERNORATE

Al-Qawasmi (2021) recommended that the optimal tank size should be estimated for single houses and villas since the installation of large storage tanks is usually not possible for multi-story buildings in densely packed urban areas due to lack of space between buildings. Even if required land for a large storage tank is available, installing a harvesting system in those apartment buildings is usually not practical due to the low rooftop area per person.

In order to present results for more accurate calculations, a hypothetical case was regularized. Rainfall data from a single station was used instead of an average calculated for an entire governorate area using multiple stations. A family of six living in the Swieleh District of Amman Governorate (there is a precipitation measuring station in Swieleh) in a single house with 300 m^2 of rooftop area was selected as the case. The cost of this family's optimal tank has been estimated to meet the consumption only for flushing toilets in the rainy season from October to May using Equation 2.11. The toilet flushing consumption was accepted to be equal to 17.7% of the total average consumption per family. The total monthly demand, in this case, was calculated using Equation 2.14 and the family size was taken as 6 instead of 4.8. The consumption due to toilet flushing was estimated using Equation 2.15. Based on the calculations, the total water demand was estimated at 23.76 m^3/month per family, and the flushing consumption was estimated at 4.2 m^3/month. The optimal tank size was estimated using the Water Balance Model. The results of the method are presented in Table 3.9.

Table 3.9. Flushing consumption of a house in Sweilih District with a 300 m^2 rooftop area and a family of six members.

Column (1)	**Column (2)**	**Column (3)**	**Column (4)**	**Column (5)**	**Column (6)**	**Column (7)**	**Column (8)**
Months	Average monthly rainfall (mm)	Monthly flushing consumption (m^3)	Rooftop area (m^2)	VR (m^3)	V_i (m^3)	(Column 5– Column 3)	V_f (m^3)
Oct	12	4.2	300	2.88	0	-1.32	-1.32
Nov	44	4.2	300	10.56	-1.32	6.36	5.04
Dec	93	4.2	300	22.32	6.36	18.12	24.48
Jan	117	4.2	300	28.08	18.12	23.88	42
Feb	106	4.2	300	25.44	23.88	21.24	45.12
Mar	60	4.2	300	14.4	21.24	10.2	31.44
Apr	14	4.2	300	3.36	10.2	-0.84	9.36
May	4	4.2	300	0.96	-0.84	-3.24	-4.08

V_i value in October was assumed zero; the tank at the beginning of October was assumed empty. The maximum value of V_f in column (8) was 45.12 m^3, and the flushing consumption (D_f) in Ajlun was 4.2 m^3. According to Equation 2.18 ($V_f > D_f$), the optimal tank size for flushing use (S) was determined to be 4.2 m^3 per month.

The cost of the tank was estimated using Figure 3.3 and Equation 2.21 (Tank Cost = 4.2 m^3 * 95 JOD/m^3 = 399 JOD). The cost of the rainwater harvesting system was 419 JOD assumed to be the minimum cost. Moreover, the maximum cost of the rainwater harvesting system was 798 JOD.

Payback period of the rainwater harvesting system was predicted using Equation 2.22 and repeated to calculate P(FG), P(FD), P(AG), and P(AD) (Table 3.10). The payback period for the selected case in Sweilih ranged between 12.5-90 years based on groundwater extraction cost and 50-95 years based on seawater desalination cost.

For this regularized case, PSP_r was the ratio of the total flushing consumption over the potential harvested rainwater in the rainy season between October and May (*see* Section 2.10). The PSP_r for this case was estimated at 321%, indicating that installing a rainwater harvesting system to meet the flushing consumption was highly recommended.

Table 3.10. The payback results of flushing water consumption in Sweilih District for a 300 m^2 rooftop area with a family of six members.

Rainwater harvesting system cost (JOD)		Cost (JOD/m^3)	Annual flushing consumption (m^3)	Payback Period (Years)	
Maximum	798	1.00	33.6	P (FD)=	24
		0.25	33.6	P (FG)=	95
Minimum	419	1.00	33.6	P (AD)=	12.5
		0.25	33.6	P (AG)=	50

CHAPTER 4

CONCLUSION

4.1. CONCLUSION

Despite harnessing the current water sources to their full potential during the past years, Jordan has been suffering from an increasing deficit in the water supply due to its arid climate. Throughout the past three decades, the highest rainfall rate was measured at 471 mm/year in the Governorate of Ajlun, and the lowest was recorded as 80 mm/year for the Governorate of Aqaba. Between 2009 and 2020, municipal water consumption has been increased at a rate of 4.75% annually. According to 2020 data, the amount of water supply per capita was 287 liter/day and the average municipal metered water use (not including irrigation, water from wells, and similar unmetered uses) was 133 liter/day in Jordan. The projections made in this study demonstrated that total water supply per capita would decrease down to 178-226 liters/day by 2030, if only the existing water resources are relied upon without adding new sources.

Jordan's total potential for rooftop rainwater harvesting was estimated at 23.74 Mm^3/year. The potential rainwater harvesting volume for the governorates ranged from 0.103 Mm^3/year (in Aqaba) up to 7.754 Mm^3/year (in Amman). To put these numbers in perspective, the percentage of the domestic annual water requirements that can be met by rooftop rainwater harvesting was presented as a percentage of water-saving (PSP). Average PSP for the whole of Jordan was 4,5%, suggesting that 4,5% of the total consumption could be met via rooftop rainwater harvesting. On a governorate basis, the potential savings rates were the highest in the northern governorates of Irbid, Ajlun, and Jarash; PSP values were 14.5%, 9.0%, and 7.8%, respectively. These governorates have the highest annual rainfall rates. However, the southern governorates had the lowest saving rates due to their low rainfall and high demand. The lowest PSP values were calculated for Aqaba and Ma'an (0,7%).

The necessary roof areas for meeting water demand via rooftop rainwater harvesting were calculated using Ripple Method. In Ajlun and Irbid Governorates, a roof area over 250 m^2 per household could be used to collect enough to meet water demand; over 300 m^2 in Jarash Governorate. For other governorates, a rooftop area that was significantly higher than 500 m^2 was determined to be needed.

However, it is not realistic to assume covering the total water demand via rainwater unless vigorous roof maintenance and extensive water treatment can be applied to the collected volume. Thus, it was assumed that harvested rainwater would only be used to meet toilet flushing needs and that the consumption due to flushing was 17.7% of the total consumption. The calculations on meeting flushing consumptions were carried out using the Water Balance Method.

In the Northern Governorates, the results were again the most favorable. The rainwater harvesting met all flushing consumption for all rooftop areas (50-500 m^2) in Ajlun and Irbid governorates, but in Jarash, the rainwater harvesting from a rooftop area of 100 m^2 and more per household met the flushing consumption. In Mafraq Governorate, the rainwater harvesting from a rooftop area of 200 m^2 and more met the flushing consumption.

In the Middle-Region Governorates, the results were also good. The rainwater harvesting met the flushing consumption in Amman for 100 m^2 and more; it was the best in the Middle Region. Balqa and Madaba had good results; rainwater harvesting from rooftop areas of 150 m^2 and more met the flushing consumption. In Zarqa, rooftop areas of 200 m^2 and more were needed.

Among the Southern Governorates, the first best result was for Karak; the rainwater harvesting from a rooftop area of 150 m^2 and more met the flushing consumption. The second best one was Tafiela; the rainwater harvesting from a rooftop area of 250 m^2 and more met the flushing consumption. Then, in Aqaba, a rooftop with an area of 350

m^2 and more was necessary to meet the flushing consumption. In Ma’an Governorate, at least an area of 450 m^2 and more was necessary.

The Water Balance Model was also used to estimate the optimal tank size for covering flushing consumption; the flushing consumption in Ajlun and Irbid could be fully met by harvested rainwater, and the optimal thank sizes for flushing in Ajlun and Irbid were 2.7 m^3 and 2 m^3 per household, respectively.

The amount of rooftop harvested rainwater could generate monetary savings reaching 170 million US Dollars annually if the cost of groundwater is taken as the reference point; or 678 million US Dollars annually if the cost of seawater desalination is taken as the reference point.

For the hypothetical case in Sweilih District (300 m^2 rooftop area and six family members), which was regularized for eight months, the PSP value was estimated at 321%, indicating that installing a rainwater harvesting system to meet the flushing consumption was highly recommended. Based on tank size, the total cost of installing a rainwater harvesting system was approximated for the regularized hypothetical case to calculate the payback period of the project. The payback period for the same case in Sweilih ranged between 12.5-90 years based on groundwater extraction cost and 50-95 years based on seawater desalination cost.

4.2. RECOMMENDATIONS

The author's proposals that were made based on the water situation in Jordan and the results of this study are listed below. The proposals were classified as: (1) managing and regulating water demand and (2) managing and regulating water supply.

I. Managing and Regulating Water Demand

Raising awareness among residents: Government agencies must incentivize residents to use tools to rationalize water consumption by reducing the taxes on these tools and implementing strict legislation on immoderate consumers.

Agriculture: Competent authorities and decision-makers must monitor farms and implement strict legislation to enforce growing products with low water consumption and high yield. Experts and decision-makers must determine these in the Ministry of Agriculture.

Dams: Using modern techniques that reduce the amount of water lost to evaporation and carry out periodic maintenance of dams to reduce losses as much as possible.

Industry: Recommending reusing treated wastewater from factories and promoting industries with low water consumption.

II. Managing and Regulating Water Supply

Raising awareness among residents: The government must encourage the use of rainwater through domestic water harvesting systems. It must also provide subsidies for the materials used in these systems and not impose any taxes on setting up water harvesting systems on houses that do not have any.

Legislations and Laws: Implementing periodic monitoring in all regions to fine violators who steal water and setting a new tariff for bills to prompt citizens to reduce their monthly consumption.

The Political Aspect: The Jordanian government can sign water agreements with the neighboring countries with which Jordan shares surface and underground water basins. The National Carrier for the Desalination of the Red Sea Water project must be commenced as soon as possible, which will desalinate the Red-Sea water.

Cloud Seeding: Cloud seeding can be considered and studied to increase the annual rainfall rates and, therefore, the amount of water harvested. Additionally, rainwater harvesting systems using household roofs, school roofs, health and government facilities, and dams must be commenced. The possibility of designing rainwater harvesting ponds must be studied.

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ANNEX A.1

EXAMPLE CALCULATIONS: AJLUN GOVERNORATE

This Annex is an illustration using the equations, where the data for Ajlun was used.

Table A.1.1. The rainfall (mm) in Ajlun Governorate, AB0004 Station, in January 1987-2018.

The amount of monthly rainfall (mm) in Ajlun Governorate/ AB0004 Station/ in the Month of January for 1987-2018 years	Year	Total Monthly Rainfall (G, S, M, Y) (mm)	Year	Total Monthly Rainfall (G, S, M, Y) (mm)
	1987	52.6	2003	41
	1988	91	2004	156
	1989	41.3	2005	88.5
	1990	113.8	2006	112
	1991	127.1	2007	45
	1992	152.6	2008	74
	1993	0	2009	27
	1994	89.2	2010	57
	1995	19	2011	84
	1996	80.4	2012	117
	1997	102.8	2013	237
	1998	105.1	2014	0
	1999	70.9	2015	90.7
	2000	260.6	2016	56.2
	2001	72.5	2017	77.7
	2002	0	2018	154.9
Average Total Monthly Rainfall (G.S.M)				87.4

The following steps were followed to calculate rainfall rates in each governorate in the period 1987-2018, as in the study:

1. Pick a governorate (G): the governorate in this example is Ajlun.
2. Select one monitoring station (S) is located in the selected governorate. For example, the number of monitoring stations in Ajlun Governorate was 6..
3. Select a month (M) (for example; January). Calculate the cummulative precipitation amount for one month by summing daily measurement values of that month for the station. Then repeat this calculation for the same month of

each year (January 1987, January 1988, January 1989, …, January 2018) (2.1). The following Table presents station AB 0004 in Ajlun.

4. Determine the average of the results that were calculated using Equaion 2.1 to find the overall monthly average for the period of 1987-2018 (for example: Governorate (G): Ajlun, Station (S): AB 0004, Month (M): January) (2.2). Basic data are available on request). Table A.1.1.

5. Repeat the steps 2 to 4 for all stations in the same governorate. Then move on to the next month until the average values for all 12 months in each year between 1987-2018 were estimated.

6. The average monthly rainfall rate of a governorate is calculated using Equation 2.3 (see Table A.1.2).

Table A.1.2. Average Total Monthly Rainfall (G,S,M) (mm).

Governorate		**AJLUN**					
Station		AB0004	AD0018	AH0001	AH0004	AJ0001	AJ0002
Avg. Total Monthly Rainfall (G.S.M) (mm)	JAN	87.4	137	129	72	160	155
	FEB	82	111	113	0	132	116
	MAR	52	80	85	0	95	83
	APR	12	18	20	0	21	22
	MAY	5	6	6	0	7	10
	JUN	0	0	0	0	0	0
	JUL	0	0	0	0	0	0
	AUG	0	0	0	0	0	0
	SEP	0	0	0	0	0	0
	OCT	12	13	17	0	15	16
	NOV	39	54	53	23	55	53
	DEC	76	105	123	92	133	132

7. The total annual rainfall rate of a single station (mm/year) is calculated using Equation 2.4; the output is rounded to the nearest integer

Table A.1.3. Avg.Monthly Rainfall for Governorate (1987-2018) (mm).

Avg.Monthly Rainfall for Governorate (1987-2018) (mm)											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
123.3	92.3	65.8	15.5	5.7	0.0	0.0	0.0	0.0	12.2	46.2	110.2

8. The annual precipitation rate of a governorate was calculated using Equation 2.5; the output is rounded to the nearest integer (see Table A.1.4).

By using the same steps for every station for all months of all years in Ajlun governorate, the following table (Table A.1.4) shows the mean monthly rainfall rate of the governorate.

Table A.1.4. Conclusion of every station record in Ajlun.

Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
AB0004	87	82	52	12	5	0	0	0	0	12	39	76	365
AD0018	137	111	80	18	6	0	0	0	0	13	54	105	524
AH0001	129	113	85	20	6	0	0	0	0	17	53	123	546
AH0004	72	0	0	0	0	0	0	0	0	0	23	92	187
AJ0001	160	132	95	21	7	0	0	0	0	15	55	133	618
AJ0002	155	116	83	22	10	0	0	0	0	16	53	132	587
Avg (mm)	123	92	66	16	6	0	0	0	0	12	46	110	471

The average monthly rainfall is represented in Figure (3.1). The diagram helps to understand the general raining situation in the government. However, the average annual rainfall in Ajlun is 471 mm; upon this result and the total roof area obtained from the department of statistics in Jordan, The potential water harvesting was calculated by the Equation (2.11).

VR (Ajlun) = 0.471 m/year ×1,838,920 (m^2) ×0.8 = 0.693 Mm^3/year

Water consumption in Ajlun was calculated by Equation (2.8)

The daily consumption per capita in Ajlun is 106 L/capita, and the population is 199,400, so the TAPG was:

$$\text{TAPG (Ajlun)} = 365 \times [106\ \text{L} \times \frac{1\ \text{m}^3}{1000\ \text{L}}] \times 199{,}400 = 7.8\ \text{Mm}^3$$

By obtaining previous results, the extent to which rainwater benefits was determined by applying Equation 2.12.

$$\text{PSP (Ajlun)} = \frac{0.693}{7.8} \times 100\%$$

PSP (Ajlun) = 8.9%

Equation 2.20 was used to determine the estimated saving rate in Ajlun:

The minimum economic saving rate supposes the cost equals the cost of extracting groundwater for one cubic meter:

$$\text{The minimum Economic Saving Rate in Ajlun} = 0.693 \times 10\text{^}6 \times 0.35 = 242{,}550\ \$$$

The maximum economic saving rate supposes the cost equals the cost of desalination for one cubic meter:

$$\text{The maximum Economic Saving Rate in Ajlun} = 0.693 \times 10^6 \times 1.4 = 970{,}200\ \$$$

The Ripple Method:

Table A.1.5. The results of Ripple Method optimal tank size for roof area (500 m^2) in Ajlun.

(1)	(2)	(3)	(4)	(5)	(6)
Oct	12	2.4	15.3	12.9	12.9
Nov	46	9.2	15.3	6.1	19
Dec	110	22	15.3	-6.7	12.3
Jan	123	24.6	15.3	-9.3	3
Feb	92	18.4	15.3	-3.1	-0.1
Mar	66	13.2	15.3	2.1	2
Apr	16	3.2	15.3	12.1	14.1
May	6	1.2	15.3	14.1	28.2
Jun	0	0	15.3	15.3	43.5
Jul	0	0	15.3	15.3	58.8
Aug	0	0	15.3	15.3	74.1
Sep	0	0	15.3	15.3	**89.4**

VR_h:	**94**			

(1): Month

(2): Monthly average rainfall (mm)

(3): Rainfall harvested (VR) (m^3/month)

(4): Monthly water demand per family (m^3/month) (see The Equation 2.14)

(5): [Colunm (4)- Colunm (3)]

(6): Cumulative summation (5)

Tank Size (m^3) equal the minimum value eathir max of Colunm (6) and VR_h

The maximum value of Colunm (6)= 89.4 m^3, and VR_h=94 m^3, comparing VR_h to the maximum value of Colunm (6); the minimum value presents the optimal tank size.

The optimal tank size ≅89 m^3

The Water Balance Model:

Table A.1.6. Shows the result of using the Water Balance Model to estimate the optimal tank size for flushing water consumption for 250 m^2 rooftop area; the flushing water consumption in Ajlun was calculated using Equation 2.15. It was 2.7 m^3/month per family.

Table A.1.6. The result of using the "Water Balance Model" flushing water consumption in Ajlun for 250 m^2 rooftop area.

Column (1)	**Column (2)**	**Column (3)**	**Column (4)**	**Column (5)**	**Column (6)**	**Column (7)**	**Column (8)**
Months	Average monthly rainfall (mm)	Monthly flushing consumption (m^3)	Rooftop area (m^2)	VR (m^3)	V_i (m^3)	(Column 5– Column 3)	V_f (m^3)
Oct	12.0	2.7	250.0	2.4	0.0	-0.3	-0.3
Nov	46.0	2.7	250.0	9.2	-0.3	6.5	6.2
Dec	110.0	2.7	250.0	22.0	6.5	19.3	25.8
Jan	123.0	2.7	250.0	24.6	19.3	21.9	41.2
Feb	92.0	2.7	250.0	18.4	21.9	15.7	37.6
Mar	66.0	2.7	250.0	13.2	15.7	10.5	26.2
Apr	16.0	2.7	250.0	3.2	10.5	0.5	11.0
May	6.0	2.7	250.0	1.2	0.5	-1.5	-1.0
Jun	0.0	2.7	250.0	0.0	-1.5	-2.7	-4.2
Jul	0.0	2.7	250.0	0.0	-2.7	-2.7	-5.4
Aug	0.0	2.7	250.0	0.0	-2.7	-2.7	-5.4
Sep	0.0	2.7	250.0	0.0	-2.7	-2.7	-5.4

The maximum value of V_f in column (8) was 41.2 m^3.

The flushing consumption (D_f) in Ajlun was 2.7 m^3.

According to Equation 2.18, $V_f > D_f$; that is mean the optimal tank size for flushing use (S) =2.7 m^3.

The cost of tank was estimated using Figure 5.3 and Equation 2.21.

Tank Cost = 2.7*100 =270 JOD

ANNEX A.2

DISTRIBUTION OF ROOFTOP AREAS AND NUMBER OF DWELLINGS BY GOVERNORATES

Table A.2.1. Rooftop Areas and Dwellings Number in Amman.

Governorate: Amman	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	32116	614	0	34248500
	50-99	160702	4157	0	
	100-149	247172	8857	0	
	150-199	169385	7977	0	
	200-299	73627	5552	2141	
	300-399	13655	1525	1512	
	400-499	3094	727	921	
	500<	3355	1789	2485	

Table A.2.2. Rooftop Areas and Dwellings Number in Balqa.

Governorate: Balqa	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	3616	1317	0	6028300
	50-99	17241	5774	0	
	100-149	24343	8232	0	
	150-199	15808	5164	0	
	200-299	7220	2536	335	
	300-399	858	347	184	
	400-499	238	102	104	
	500<	186	149	200	

Table A.2.3. Rooftop Areas and Dwellings Number in Zarqa.

Governorate: Zarqa	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	5490	369	0	9792900
	50-99	73484	4912	0	
	100-149	97916	8220	0	
	150-199	35438	3929	0	
	200-299	11574	1677	179	
	300-399	1331	209	66	
	400-499	323	63	25	
	500<	595	112	32	

Table A.2.4. Rooftop Areas and Dwellings Number in Madaba.

Governorate: Madaba	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	615	126	0	2638600
	50-99	4767	1017	0	
	100-149	10488	3728	1	
	150-199	7955	3636	0	
	200-299	2816	1293	130	
	300-399	200	120	45	
	400-499	32	31	21	
	500<	27	40	35	

Table A.2.5. Rooftop Areas and Dwellings Number in Irbid.

Governorate: Irbid	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	6848	728	0	27879500
	50-99	52878	5799	0	
	100-149	109405	18093	0	
	150-199	74794	14609	0	
	200-299	24976	6415	607	
	300-399	2279	722	335	
	400-499	539	199	149	
	500<	573	194	163	

Table A.2.6. Rooftop Areas and Dwellings Number in Mafraq.

Governorate: Mafraq	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
Area (m^2)		**ND**			
	<50	1634	863	0	7036400
	50-99	9742	5162	0	
	100-149	16578	17311	0	
	150-199	8600	11377	0	
	200-299	2937	3937	174	
	300-399	245	317	75	
	400-499	67	66	17	
	500<	45	60	32	

Table A.2.7. Rooftop Areas and Dwellings Number in Jarash.

Governorate: Jarash	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	943	336	0	2716900
	50-99	7159	1834	0	
	100-149	14231	5426	0	
	150-199	6553	3211	0	
	200-299	2370	1134	42	
	300-399	235	130	18	
	400-499	60	34	10	
	500<	108	50	20	

Table A.2. 8. Rooftop Areas and Dwellings Number in Ajlun.

Governorate: Ajlun	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	579	157	0	1838920
	50-99	5453	1221	0	
	100-149	11368	4067	0	
	150-199	5800	2496	0	
	200-299	2018	916	31	
	300-399	128	73	18	
	400-499	28	12	4	
	500<	30	13	7	

Table A.2. 9. Rooftop Areas and Dwellings Number in Karak.

Governorate: Karak	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	1036	592	0	4646500
	50-99	4534	1928	0	
	100-149	15570	6692	0	
	150-199	14249	6874	0	
	200-299	4632	2922	41	
	300-399	262	217	25	
	400-499	53	56	7	
	500<	72	70	14	

Table A.2.10. Rooftop Areas and Dwellings Number in Tafiela.

Governorate: Tafiela	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	216	88	0	1417200
	50-99	1542	883	0	
	100-149	7014	3418	0	
	150-199	3042	1762	0	
	200-299	595	426	14	
	300-399	27	20	2	
	400-499	5	5	0	
	500<	2	1	0	

Table A.2.11. Rooftop Areas and Dwellings Number in Ma'an.

Governorate: Ma'an	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	288	47	0	1506600
	50-99	2798	451	0	
	100-149	11005	2382	0	
	150-199	6214	1266	0	
	200-299	1820	467	14	
	300-399	136	21	4	
	400-499	38	1	1	
	500<	94	9	2	

Table A.2.12. Rooftop Areas and Dwellings Number in Aqaba.

Governorate: Aqaba	**Type of Housing Unit**	**Apartment**	**House**	**Villa**	**TRA (m^2)**
		ND			
Area (m^2)	**<50**	1134	256	0	1606400
	50-99	12767	1848	0	
	100-149	11477	2586	0	
	150-199	2714	986	0	
	200-299	722	376	18	
	300-399	67	52	11	
	400-499	49	21	10	
	500<	44	51	9	

RESUME

Anas Jaradat graduated first and elementary education in Amman. He completed high school education in Sweilih Secondary School, after that, he started the undergraduate program at Tafila Technical University Department of Natural Resources and Chemical Engineering – Geological Engineering in 2011 - 2015. Then in 2015, he completed the internship training program for three months as a Geotechnical engineer at “Arab Bridge Center for engineering consulting, Jordan”. Then from 2016 to 2017, he worked as a Geotechnical engineer in “The Ministry of Public Works and Housing, Jordan”. Then he worked as a Sales Manager in Jaradat Store, Jordan until 2018. After that, he worked as a science teacher in “Thouqan Hindawi School, Jordan”. Then in 2019, to complete a Master of Science in Environmental Engineering education, he moved to Karabük University, Turkey.