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Assessment of rooftop rainwater harvesting in Ajloun, Jordan

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ABSTRACT

In response to water scarcity in Ajloun governorate, Jordan, the effectiveness of implementing rooftop rainwater harvesting (RRWH) was investigated. In addition, a structured questionnaire was prepared and distributed to randomly selected residents to assess the status of the current RRWH practices in the governorate and the people's perceptions of this practice. It was found that between 0.39 million cubic meters (MCM) in a dry year (2017) and 0.96 MCM in a wet year (2018) can be harvested, which is equivalent to 7.6% and 16.8% of the domestic water supply for these years, respectively. The analysis of a total of 360 questionnaires revealed that only 14.2% of the households in Ajloun governorate own an RRWH system. However, the majority, 80.6%, of those who do not own an RRWH system showed interest in installing one. An overwhelming majority of the sample, 96.7%, believes that the government should provide incentives to subsidize the construction of RRWH systems, which is attributed to the high initial cost of these systems. The technical and social feasibilities of RRWH, in addition to the high cost of the alternatives, justifies providing incentives, such as cost sharing for the consumers in Ajloun to implement RRWH systems.

Key words: Ajloun, questionnaire, rainfall data, rooftop rainwater harvesting, RRWH

HIGHLIGHTS

- Rooftop rainwater harvesting is a technically and socially feasible option to address water shortage.
- Assessment of the status of the current RRWH practices in Ajloun governorate, and the residents' perceptions of these practices.
- People in Ajloun governorate who own a rainwater harvesting system are in the minority.
- The government of Jordan should provide financial assistance to encourage the installation of RRWH systems.

INTRODUCTION

Rainwater harvesting has been practiced since the dawn of history, as early as humans started to live in settlements, during the late Neolithic to the early Bronze ages. Inhabitants of Mesopotamia, today Iraq and Jordan, are among the very early civilizations who practiced water harvesting to satisfy their different daily needs (Yannopoulos *et al.* 2017). Water harvesting has also been known in Minoa, Crete, and in the Indus valley, South Asia, during the third millennium BC, where water supply networks and bathrooms have been discovered (Angelakis 2016). Water harvesting has also been practiced in India and China starting in the third millennium BC (Oweis *et al.* 2004). More recently, harvesting rainwater running over surfaces, i.e., rooftops and yards, has been widely practiced to provide water for potable use in urban areas of the developing world (Feki *et al.* 2015). Nowadays, rainwater rooftop water harvesting (RRWH) continues to be a promising option as a non-conventional water resource in rural and urban areas to reduce people's vulnerability to acute water shortages (Abdulla & Al-Shareef 2009; Balogun *et al.* 2016). Furthermore, RRWH is recognized as a low impact development (LID) practice for storm water management. In urban areas, rainwater harvesting reduces flooding risk caused by intense rainfall events (Ghisi & Schondermark 2013).

A literature review revealed that RRWH continues to receive increased attention worldwide, as a non-conventional resource, to enhance water supply in water-scarce regions (Meera & Ahammed 2006; Karim 2010). In their review article, Afrose *et al.* (2018) concluded that rainwater harvesting systems implement simple and cost-effective technologies; they further require the construction of suitable, yet simple, transport and storage facilities (Karim *et al.* 2015). In addition, rainwater harvesting reduces the demand for fresh water resources, ground and surface, reduces the risk of soil erosion, and surface water pollution by pesticides and fertilizers, as a consequence of reducing surface runoff. Furthermore, harvested rainwater is usually suitable for irrigation without further treatment. Besides quantifying the harvested rainwater and its impact on fresh water demand, several researchers have studied the quality of the harvested rainwater, its suitability for the intended use, and the necessary treatment (Amin *et al.* 2014; Sultana *et al.* 2016). The economic feasibility of rainwater harvesting has also been investigated by others (Mourad & Yimer 2017). The main drawbacks of RRWH systems are high initial cost, maintenance requirement, and the unpredictable rainfall; however, the initial high cost can be recovered in a few years (Afrose *et al.* 2018).

Adugna *et al.* (2017) investigated the potential contribution of RRWH from large public institutions in Addis Ababa, both at the city and individual levels, by comparing the RRWH potential to the water demand. They found that RRWH potential can provide up to 2.3% of the annual potable water demand. Their study showed that the ability of public institutions to take the role as frontrunners in RRWH is promising.

The volume of harvested rainwater depends mainly on precipitation intensity, duration, roof catchment area, and roof runoff coefficient (Woltersdorf *et al.* 2015). Rainwater harvesting is technically feasible in areas with average annual rainfall greater than 200 mm (Tobin 2014).

ROOFTOP RAINWATER HARVESTING IN JORDAN

In Jordan, water scarcity is a major problem that seriously threatens the socio-economic development of both urban and rural communities. The available annual per capita renewable water resources in Jordan is less than 100 m^3 (MWI 2017), which is far below the absolute water scarcity threshold of 150 m^3. Water demand in Jordan has increased dramatically over the past several decades, due to natural population growth and immigration from the neighboring countries as a consequence to the political instability in the region. It is further projected that water demand in Jordan is expected to continue rising, for all uses, due to the rapid socio-economic development, which will significantly widen the already existing gap between available resources and demands. Furthermore, due to the arid and semi-arid climate and the projected climate change impacts, the water crises in Jordan are expected to persist, and even worsen in the upcoming decades. In Jordan, rainwater harvesting is among the promising options that can help overcome water scarcity, relieve pressure on fresh water resources, and provide water for both domestic, other than drinking and cooking, and small-scale agricultural use, which is expected to reflect positively on the socio-economic development of the country.

Realizing the importance of RRWH in Jordan, several studies that address RRWH at different scales have been conducted. Abdulla & Al-Shareef (2009) evaluated the potential of potable water savings by implementing RRWH in residential areas of the 12 Jordanian governorates; they found that a maximum of 15.5 million cubic meters (MCM) of rainwater can be collected annually from the rooftops of residential buildings, 0.61 MCM of which is from the rooftops in Ajloun governorate, provided that all surfaces are used and all rain falling on these surfaces is collected. Saidan *et al.* (2015) investigated the potential for RRWH of nonresidential buildings in populated urban areas in Amman using a geographic information system (GIS); their study showed that 3.45 MCM/year can be harvested from rooftops of nonresidential buildings. They also found that the harvested water is five times less expensive than that provided by the water distribution system. Abdulla (2020) presented an integrated rainwater harvesting approach that investigated potential water savings, optimal tank sizing, and cost–benefit analysis, for different climatic zones in Jordan. It was found that a maximum of 30.5 MCM/year of rainwater can be harvested from rooftops of residential buildings in Jordan, 0.92 MCM/year of which is from the rooftops in Ajloun governorate. This is significantly higher than that estimated by Abdulla & Al Shareef (2009), and the increase is due to the increased urbanization in Jordan between 2004 and 2014, the two years for which rooftop areas were used in the two studies, respectively. Al-Houri *et al.* (2014) evaluated the potential of RRWH for Al-Jubiha and Shafa-Badran districts in Amman city; Google Earth and ArcGIS were used to estimate rooftop areas in both districts. The results indicated that 1.17 and 0.526 MCM/yr can be harvested in Al-Jubiha and Shafa-Badran districts, respectively.

This research is driven by the fact that Ajloun governorate faces severe water shortage that impedes its socio-economic development. It is further motivated by the fact that Ajloun governorate is one of the most precipitation-abundant governorates in Jordan; the long-term average annual precipitation in Ajloun is about 644 mm (Ghanem 2013), a considerable proportion of which runs off into the streets and eventually evaporates. The findings of this research will help establish a basis for the development of a water harvesting strategy in Ajloun governorate that aims at alleviating the impacts of water shortage, and its socio-economic consequences.

METHODS

Study area

Ajloun governorate is located in the northwest of Jordan. The governorate covers a total area of 420 km^2, and lies between latitude 32° 12′ and 32° 26′N and longitude 35° 36′ and 35° 49′E. Ajloun governorate is divided into two major administrative districts, Ajloun Qasbah and Kufranjah. Ajloun Qasbah includes three sub-districts which are Ajloun city, Sakhrah, and Orjan (Figure 1). The main land uses in Ajloun governorate are agricultural, forests, residential, and rural. The estimated population of Ajloun governorate, in 2019, was 194,700 and the population density 464 inhabitants/km^2 (DOS 2019). The population and the area of each district in Ajloun governorate are shown in Figure 1. The number of households in each district is given in Table 1.

Climate and rainfall in Ajloun

Ajloun climate is characterized by rainy cool winters and dry warm summers. The rainy season is between September and May. The annual average rainfall at Ajloun station is 644 mm (Ghanem 2013). The bulk of the rainfall occurs in December, January, and February. The long-term average maximum temperature lies at around 30 °C during summer and the long-term average minimum temperature ranges between 4 and 7 °C during winter.

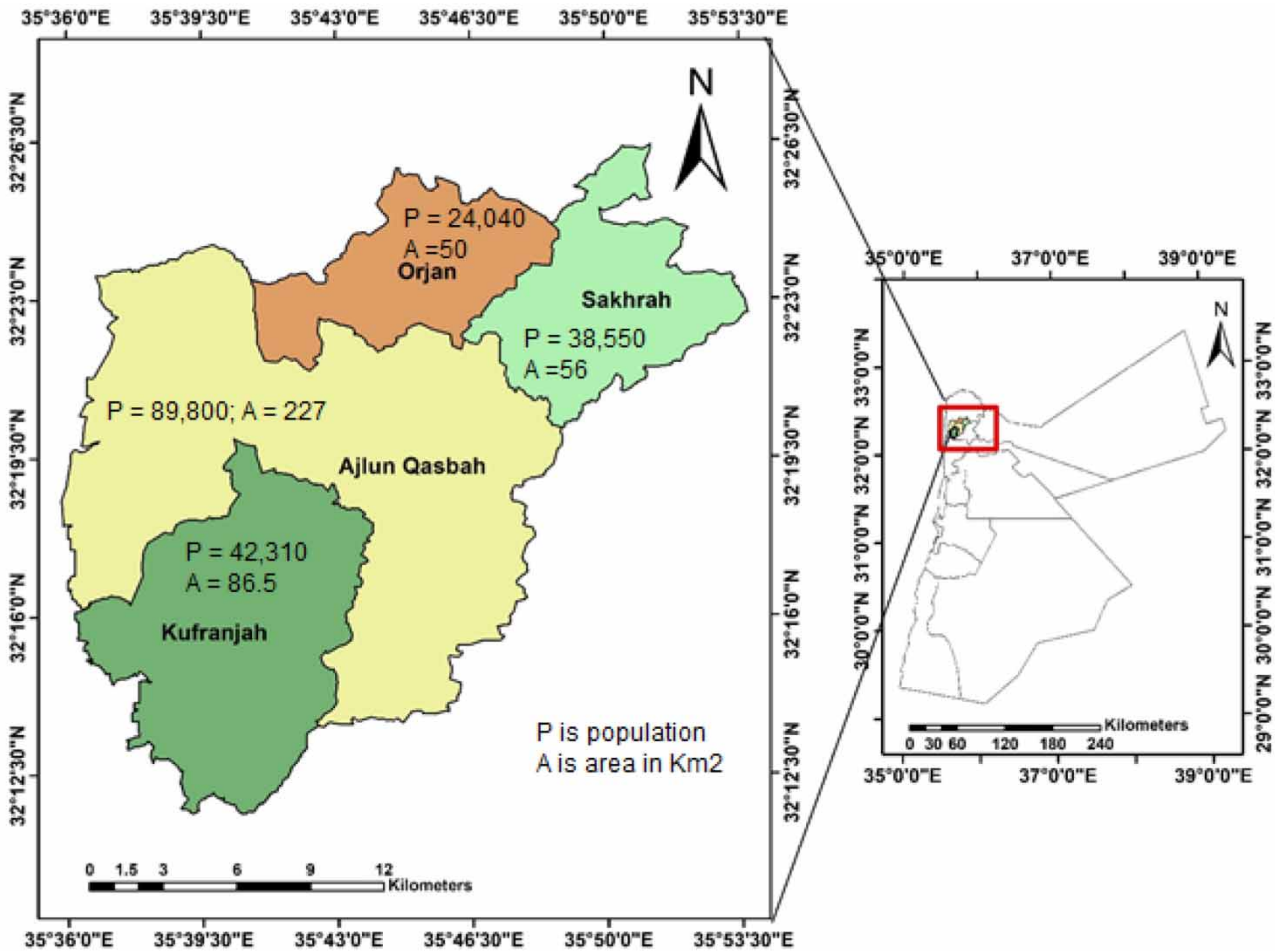

Figure 1 | Location of Ajloun governorate in Jordan and its administrative divisions.

Table 1 | Estimated population, number of households and questionnaire distribution among Ajloun districts

Administrative division	No. of households[a]	Rooftop area (m^2)	No. of questionnaires	% of total questionnaires
Ajloun sub-district	17,952	2,228,325	117	32.5
Sakhrah sub-district	7,572	941,615	116	32.2
Orjan sub-district	4,662	582,557	38	10.6
Kufranjah district	8,460	1,019,697	89	24.7
Total	38,646	4,772,194	360	100.0

[a]DOS (2019).

Water supply in Ajloun

The water supply to Ajloun governorate was 82.1 liters per capita per day (LPCD) for the year 2018. It is important to note that this includes non-revenue water, which is estimated at 42.2% for Ajloun governorate for the year 2014 (MWI 2016). The water supply for household and municipal purposes has increased from 3.9 MCM in 2010 to 5.7 MCM in 2018 (DOS 2018). The main sources of water for domestic use in Ajloun governorate are groundwater and springs. In addition, Kufranjah dam was constructed in 2016 with a 7.8 MCM capacity to enhance the supply to Ajloun city and Kufranjah (MWI 2017).

Volume of harvested rainwater

Unlike earlier studies that relied on rooftop areas from the Department of Statistics, rooftop areas, in this study, were estimated by digitizing a 2018 satellite image from Google Earth Pro, for each administrative region in Ajloun, which is expected to result in more accurate and recent rooftop areas. The total surface area of the digitized rooftops was estimated using the Earth Point tool of the Google Earth Pro. The estimated area of the rooftops in each administrative division is given in Table 1. Rooftop areas for the years 2004 and 2014 were obtained from the Department of Statistics annual reports (DOS 2004, 2014), and for the years in between, rooftop areas were interpolated. Potential harvested rainwater volumes in each administrative division in Ajloun were evaluated according to Mahmudul Haque *et al.* (2016):

$$HWV = \frac{C \times A \times R}{1{,}000} \tag{1}$$

where, HWV is the monthly volume of harvested rainwater in (m^3), A is catchment area, represented by roof area of house/building (m^2), R is monthly rainfall depth (mm), C is the runoff coefficient (dimensionless), and 1,000 is a unit conversion factor. The estimated harvested rainwater is sensitive to the runoff coefficient value. Most buildings in Ajloun are constructed using reinforced concrete; a runoff coefficient of 0.85 is a commonly used value for concrete roofs in Jordan (Al-Houri *et al.* 2014), which accounts for water losses due to evaporation, possible first flush diversion, losses in gutters and spouts, and surface material texture.

The efficiency of a water harvesting system can be assessed by calculating the percentage annual potential water saving in domestic water demand, which can be calculated by Equation (2) (Liaw & Tsai 2004; Balogun *et al.* 2016):

$$Efficiency = \frac{HWV}{WD} \times 100 \tag{2}$$

where, HWV is volume of harvested water in m^3 and WD is the domestic water demand in m^3.

Field survey/questionnaire

Among all the studies that have addressed water harvesting in Jordan, only one study addressed the public perceptions about water harvesting in Irbid governorate, which is that of Abu Zreig *et al.* (2019). However, the scope of the public perceptions survey was narrow, as all the questionnaires were distributed to third- and fourth-year level college students. In this study, a structured field survey/questionnaire that targets the local communities, in Ajloun governorate's four districts, was designed and distributed to the residents, to explore the current rainwater harvesting practices and the awareness and acceptance levels of the residents, to rainwater harvesting. RRWH attributes that have been addressed by the questionnaire are given in Table 2.

Table 2 | Main attributes targeted by the questionnaire and range of responses

Attribute	Required response
House area	Rooftop area
Does the house have a water harvesting system?	Yes/No
Are you willing to install a water harvesting system?	Yes/No
Do you believe that the government should subsidize water harvesting systems?	Yes/No
The intended use of the harvested water	Domestic/irrigation/cleaning and car washing
Constraints (if any)	Constraints related to the implementation of a RRWH

A total of 360 responses were collected, by personal visits to randomly selected residents, within the four administrative districts in Ajloun governorate. Table 1 shows the number and the percentage of questionnaires distributed in each administrative district in Ajloun governorate.

RESULTS AND DISCUSSION

Potential rainwater harvesting volumes

The volumes of rainwater that could have been harvested from the rooftops in each administrative district in Ajloun were estimated for the years between 2009 and 2018 using Equation (2). Figure 2 shows that the estimated annual harvested water volume, for the last ten years, ranged from 0.39 MCM for the year 2017, to 0.96 MCM for the year 2018, with an average of about 0.73 MCM, and a standard deviation of 0.20 MCM. The annual variation in the volume of rainwater that could have been harvested is attributed to the temporal variation in rainfall, and to the increase in rooftop areas over time, due to urbanization. The variations among the different administrative regions within Ajloun governorate, for a certain year, are attributed to the differences in rooftop areas.

Figure 3 shows that the bulk of the harvested water occurred between December and February, acceptable water volumes can still be harvested in November and March, and lower volumes can still be harvested in October and April. Figure 4 shows that harvested water could have covered between 7.6% for the year 2017, which was a dry year, to about 22.4% for the year 2009, which was a wet year, of the domestic water supplied to Ajloun governorate for these years, with an average efficiency of 16.2% for the period between 2009 and 2018. These numbers should draw attention to the efficiency of rooftop water harvesting, which should motivate both the decision-makers, and the people as well, to take serious steps towards implementing rooftop rainwater harvesting in Ajloun.

Questionnaire analysis

Table 3 shows that the average rooftop area in Kufranja is higher than that in the other three districts. In addition, the maximum rooftop area in Kufranja and Ajloun city is significantly higher than that of Sakhra and Orjan; however, the minimum rooftop

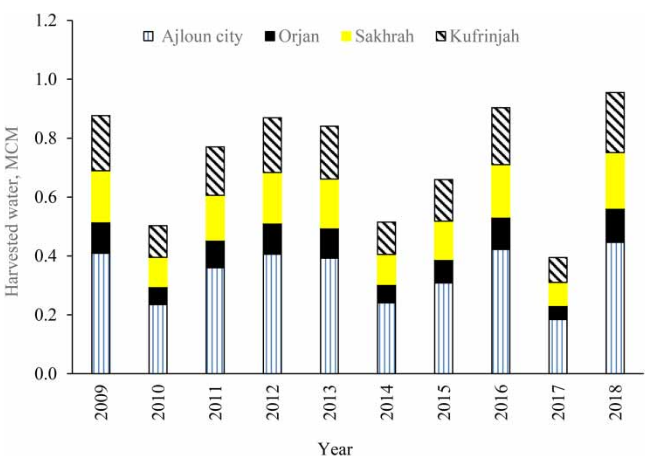

Figure 2 | Potential rainwater that can be harvested from rooftops at the four districts in Ajloun between 2009 and 2018.

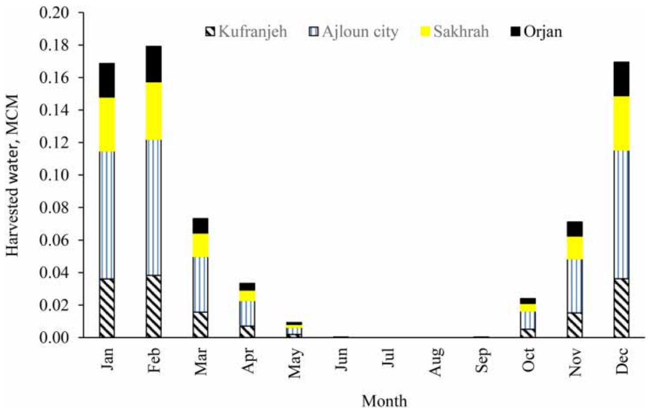

Figure 3 | Average monthly water that can be harvested from rooftops in Ajloun's four districts between 2009 and 2018.

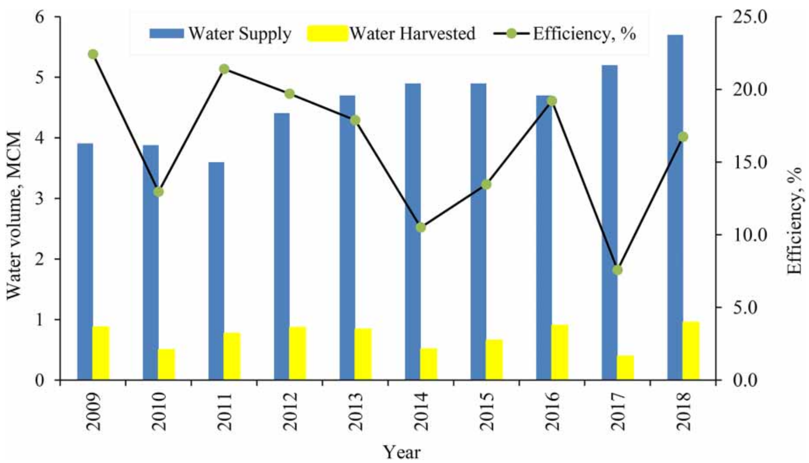

Figure 4 | Water supply, harvested water, and efficiency for Ajloun governorate between 2009 and 2018.

Table 3 | Statistical characteristics of roof areas in the four districts in Ajloun governorate

Roof area	Kufranja	Ajloun city	Sakhra	Orjan
Sample size	89	117	116	38
Respondents	85	117	115	38
No response	4	0	1	0
Average	210	161	161	163
Max.	700	700	300	230
Min.	100	60	100	100
STDEV	77	72	36	30

area for Ajloun city is lower than that of the other three districts. The standard deviation in the rooftop areas for Kuranja and Ajloun city is higher than that for Sakhra and Orjan. These differences in the rooftop areas reflect some minor socio-economic differences among the four administrative districts in Ajloun governorate and among the people within each district.

Existence of a water harvesting system

Figure 5 shows that the majority of people in the four Ajloun governorate districts do not have a water harvesting system; minor differences among these districts exist. Figure 5 shows that Kufranja has the highest percentage of people who have already installed a water harvesting system (19.1%), while Ajloun city has the lowest percentage (10.3%). The average for Ajloun governorate is 14.2%. The fact that only a small percentage of the population have already installed water harvesting systems can be attributed to the relatively high initial cost of these systems, as will be evidenced in a subsequent section by the fact that the majority of the population think that the government should subsidize these water harvesting systems. In addition, in the next sections, it will be seen that the majority of the people who do not have a rooftop water harvesting system are willing to install one, which means that the majority of the people are aware of the role that RRWH plays in alleviating water shortage; however, they cannot afford it due to its high cost.

Willingness to have a water harvesting system

Figure 5 shows that an overwhelming majority of the population in the four districts in Ajloun governorate who do not already have a water harvesting system are willing to have a water harvesting system; minor differences among the four districts exist. The highest is in Ajloun city, where 97.1% of the respondents express their willingness to have a water harvesting system, while the lowest is in Orjan with 90.9%. The average for Ajloun governorate is 93%. No reasons for those who are not willing to install water harvesting systems were given but, probably, a minority of the people are concerned about the quality of the harvested water and/or the cost. This high percentage indicates the level of awareness of the population, in the four Ajloun districts, of the importance of water harvesting in bridging the gap between supply and demand, and the high level of acceptance among the people to use the harvested water. In addition, it certainly reflects the severity of the existing water crisis in Ajloun governorate.

Should the government subsidize the construction of water harvesting systems?

Figure 5 shows that 100% of the population in Orjan and Sakhra districts thinks that the government should subsidize water harvesting systems, and 97 and 91% of the population in Ajloun city and Kufranja, respectively, think so too. The average for Ajloun governorate is 96.7%. The reason behind this overwhelming majority who think that the government should subsidize water harvesting systems is the relatively high initial cost of these water harvesting systems as opposed to the income of Ajloun's population. The average per capita annual income in Ajloun is JD2,012.8 as compared to that of the kingdom of JD2,377.8 (DOS 2017). In an average year, rainwater that can be harvested from an average rooftop area of 160 m^2 is estimated at 79.18 m^3. Assuming two-thirds of the harvested rainwater will be stored and used during the dry season, while the other one-third will be used during the dry period within the rainy season, a tank volume of 52.79 m^3 is needed. Based on a tank cost of about \$70/m^3 (JD49.56/m^3) of harvested water (Abdulla 2020), the cost of the tanks is JD2,616.3, which is about 21.7% of the annual income of a family of six people in Ajloun governorate, is apparently too expensive.

Due to the high efficiency of RRWH, and to the fact that the government is actually responsible for providing water to the people, it may be wise and prudent for the government to find a certain formula to subsidize rainwater harvesting systems in

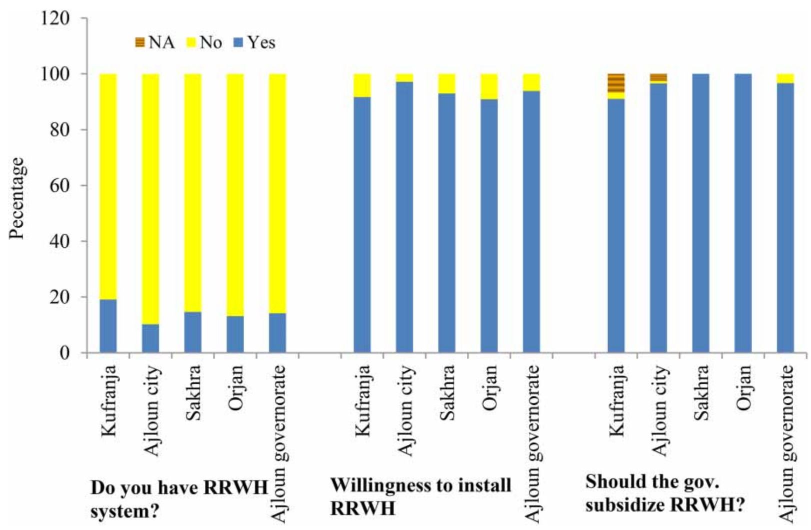

Figure 5 | Questionnaire results.

Ajloun governorate, which will reduce the government investment in high-cost large-scale projects and help the people implement RRWH.

Intended uses of harvested water

Figure 6 shows that a high percentage of the population in the four districts of Ajloun governorate are willing to use the harvested water for more than one single use (cleaning (CL), irrigation (IRR), and domestic (DO)), with some differences among the four districts. This, in the first place, assures the high level of water scarcity in Ajloun governorate, in addition to the high level of acceptance among the people to use the harvested water for all uses. The differences among Ajloun districts on how to use the harvested water reflect the level of confidence in, and awareness of, the quality of the harvested water, and the level of education among the people.

The high level of acceptance to use the harvested water for the different uses might have come from the people's previous experience with using harvested rainwater for different purposes, even for potable use. Fifty to sixty years ago, piped water supply was not available in rural areas in Jordan so people used to rely on harvested rainwater for all their uses, including drinking and cooking, with little and primitive treatment, such as sedimentation during storage and simple filtration using a cloth. Recently, Abu Zreig *et al.* (2019) found that 78% of the respondents in Irbid governorate used harvested rainwater for drinking; in addition, 50% of the respondents think that the quality of the harvested water is better than that supplied by the water distribution system. However, Radaideh *et al.* (2009), who analyzed 90 samples from collection cisterns in Jordan's northern governorates, including Ajloun, found that harvested water is not suitable for drinking without further treatment; however, it is readily suitable for other uses of cleaning and irrigation.

According to the field survey, about 14% of Ajloun residents have already installed rainwater harvesting systems. The harvested rainwater is stored in underground tanks for a few months and is used when needed, without treatment, for non-potable uses, such as home cleaning, toilet flushing, and car washing. Residents who live in houses with large open areas directly divert runoff from buildings' rooftops to irrigate plants, trees, lawns, and their gardens. In addition, according to the responses received, factors that impede the implementation of rainwater harvesting are lack of legislations that mandate or provide incentives for those who implement RRWH, in the buildings' codes.

Rainwater harvesting, a viable water resources management option in Ajloun and Jordan

The survey revealed that the overwhelming majority of the residents in Ajloun governorate are willing to install RRWH systems; however, they cannot afford to as it is too expensive. Knowing that all renewable fresh water resources, surface and ground, in Jordan, have already been exploited to their safe yield, or even overexploited, the government of Jordan does not have enough flexibility to deal with the severe water shortage Jordan faces. Long-term strategic projects face many complications and challenges; for example, the Red Sea Dead Sea Canal (RSDSC) project, which was projected to solve the water

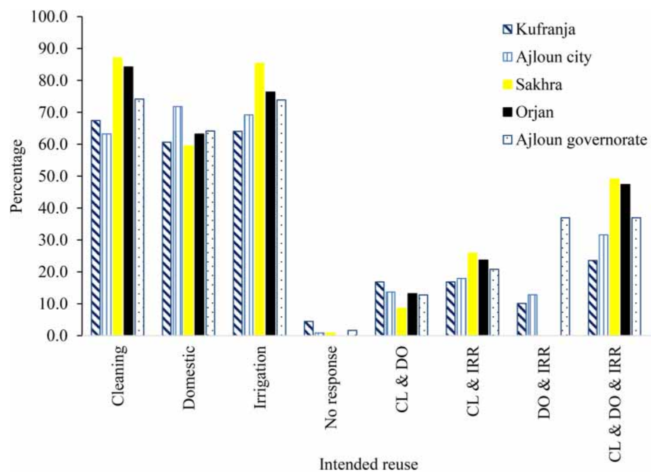

Figure 6 | Intended uses of harvested water for the different districts of Ajloun governorate. The technical and social feasibilities of RRWH, in addition to the high cost of the alternatives, is a motivation for the government to provide incentives to consumers in Ajloun to encourage them to implement water harvesting systems, such as cost sharing or funding in full.

crisis in Jordan (Al-Omari *et al.* 2014) has been abandoned by the Jordanian government, at least for now, because of the huge funding needed, in addition to the political challenges associated with it. As a consequence, the government of Jordan is now considering a new strategic project, which is the Amman-Aqaba Water Desalination and Conveyance National Project (AAWDC), which aims at desalinating 300 MCM, in Aqaba, and transporting it to the different Jordanian governorates, including Ajloun (Jordan News). However, this option also faces a funding challenge. Even if the government of Jordan found a solution to the funding challenge, water is not going be available for the people for several years. As a consequence, the government of Jordan must look into short-term, small-scale options to deal with the water shortage, such as greywater reuse and water harvesting. Greywater reuse is an option that can be implemented at the household level. However, there are several disadvantages attached to this option, among which is the fact that wastewater in Jordan is strong in terms of organic content; separating the dilute, large volume, greywater for irrigation use, for example, will cause the strength of the black water to increase by several orders of magnitude (Al Omari & Al Houri 2021), which will have other negative consequences on wastewater transport, via the collection system, and on its treatment as well. Furthermore, reusing greywater at a large scale is going to reduce the volume of the treated wastewater effluent, which is an important irrigation water source, especially in the Jordan Valley (Al-Omari *et al.* 2015). Thus, based on the fact that water harvesting is found to be technically feasible in Ajloun governorate, in addition to the people's acceptance to use the harvested rainwater for different purposes, it appears that RRWH, at the household level, is an opportunity at which the government and the people should take a closer look, to help respond to the severe water shortage in Ajloun and the other distant governorates in Jordan in a timely manner.

From a cost point of view, Saidan *et al.* (2015) found that rainwater harvesting is five times less expensive than piped water, via the water distribution system. Furthermore, it is projected that the cost of the finished water from the AAWDC is going be much higher than that of the harvested water, as the AAWDC requires the desalinated water to be transported about 400 km against an elevation difference of about 1,200 m, in addition to the high energy and carbon footprint for this.

CONCLUSION

Domestic rooftop rainwater harvesting has often been a neglected opportunity in water resources management in Ajloun governorate. This study showed that RRWH is a technically and socially feasible option to address water shortage in Ajloun, and can provide between 7.6% and 16.8% of the domestic water use in the governorate, in a dry and a wet year, respectively, and 16.2% in an average year.

The social survey revealed that a minority, 14.2%, of Ajloun governorate's population are currently practicing RRWH; however, the majority of the population, who have not implemented RRWH, 80.6%, are willing to do so, to satisfy part of their water needs. These numbers indicate that the population of Ajloun governorate is aware of the role that RRWH can play in alleviating the consequences of water scarcity in the governorate. The discrepancy between the actual practice and the willingness of the people is attributed to the high initial cost of the RRWH systems. This is supported by the fact that an overwhelming majority of the population in Ajloun governorate, 96.7%, think that the government should subsidize the construction of RRWH systems. Minor differences were observed among the different districts in Ajloun governorate, which reflect some minor socio-economic differences among these districts.

As per the intended use of the harvested water, the majority of the people indicated that they are willing to use the harvested water for domestic and/or cleaning, and/or irrigation, which reflects the confidence of the people in the quality of the harvested water, in addition to their awareness of the water scarcity in the governorate.

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DECLARATION OF INTEREST

The authors declare no conflict of interest. They certify that they are not affiliated with or involved with any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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