



Rainwater harvesting to alleviate water scarcity in dry conditions: A case study in Faria Catchment, Palestine

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Abstract: In arid and semi-arid regions, the availability of adequate water of appropriate quality has become a limiting factor for development. This paper aims to evaluate the potential for rainwater harvesting in the arid to semi-arid Faria Catchment, in the West Bank, Palestine. Under current conditions, the supply-demand gap is increasing due to the increasing water demands of a growing population with hydrologically limited and uncertain supplies. By 2015, the gap is estimated to reach $4.5 \times 10^6 \text{ m}^3$. This study used the process-oriented and physically-based TRAIN-ZIN model to evaluate two different rainwater harvesting techniques during two rainfall events. The analysis shows that there is a theoretical potential for harvesting an additional $4 \times 10^6 \text{ m}^3$ of surface water over the entire catchment. Thus, it is essential to manage the potential available surface water supplies in the catchment to save water for dry periods when the supply-demand gap is comparatively high. Then a valuable contribution to bridging the supply-demand gap can be made.

Key words: rainwater harvesting; surface water; management options; water resources; Faria Catchment; arid and semi-arid catchments; TRAIN-ZIN model

1 Introduction

It is broadly accepted that the most appropriate unit for water resources development and management is the catchment. Resources development in one part of a catchment will have impacts in other places within the catchment (Prinz and Singh 2000). In arid and semi-arid regions of the Middle East, fresh water resources are limited and most of the economically viable development of these resources has already taken place (Hamdy et al. 1995). There is a growing disparity between water supply and demand in arid and semi-arid regions. Management options need to be developed to close this increasing supply-demand gap. The problem of allocating scarce water to competing uses and users is the most serious issue that water resources management has to consider (Lee 1999). Worldwide, many arid and semi-arid catchments are experiencing population growth, increasing demand for water, deteriorating

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water quality, increasing environmental degradation, and impending climate change.

Rainwater harvesting is the practice of collecting and storing rainwater runoff for productive purposes (Siegert 1994). In arid and semi-arid regions, rainwater harvesting has been used for many years to provide water for agricultural and domestic uses (Boers et al. 1986; Bruins et al. 1986; Reij et al. 1988; Critchley et al. 1991; Abu-Awwad and Shatanawi 1997; van Wesemael et al. 1998; Oweis et al. 1999; Li et al. 2000; Li and Gong 2002; Ngigi et al. 2005). Rainwater harvesting is an ancient technology that is gaining popularity in a new way. Its history can be traced back to biblical times. Extensive rainwater harvesting apparatuses existed 4 000 years ago in Palestine and Greece (Evenari et al. 1971; Critchley et al. 1991). In India, simple stone rubble structures for impounding rainwater date back to the third millennium BC. This was also a common technique throughout the Mediterranean and Middle East. Water collected from roofs and other hard surfaces was stored in underground reservoirs (cisterns) with masonry domes (Agarwal and Narain 1997). On slopes, rural rainwater harvesting techniques have provided supplementary water for rain-fed agriculture in arid and semi-arid regions (Yair 1983; Giráldez et al. 1988; Tabor 1995; Lavee et al. 1997). This system is commonly used in Spain, northern Africa, and arid and semi-arid parts of India to meet the water needs of families and their livestock (Chapman 1978; Samra et al. 1996; Joshua et al. 2008). In arid and semi-arid regions, rainfall produces discontinuous runoff that in many cases never reaches the valley bottom. Therefore, suitable sites where runoff is produced are limited and relatively small (Lavee and Yair 1990; Brown and Dunkerley 1996). Lavee et al. (1997) have shown that rock outcrops produce runoff that tends to infiltrate further downslope in the colluvial mantle during the majority of events. These rock outcrops and thin, stony soils show a spatial distribution that depends on the topography and land use (Poesen et al. 1998).

In Western Europe, America, and Australia, rainwater has often been the primary water source for drinking water. In all three continents it continues to be an important water source for isolated homesteads and farms (Agarwal and Narain 1997; Khastagir and Jayasuriya 2010). Recently, growing scarcity and intersectoral competition for water between all users in arid and semi-arid regions, along with groundwater depletion and problems facing major surface water control systems, have raised interest in restoring water harvesting systems that capture rainwater wherever it falls (Kerr and Pangare 2001).

Rainwater harvesting has various constructive benefits. It is inexpensive and highly decentralized, empowering individuals and communities to manage their water. It is environmentally safe and can be reasonably utilized. It provides a reliable renewable resource with special management and little investment. The harvested water can be transported with little energy. In agriculture, comparing to the 10% increase in food production from irrigation, rainwater harvesting has demonstrated the potential of increasing food production by 100%. Generally, on 80% of the world's agricultural land area, rain-fed agriculture is practiced and it

generates 65%-70% of the world's staple foods. For instance, in Africa more than 95% of the farmland is rain-fed, and almost 90% is rain-fed in Latin America (UNEP 2009).

Gould and Nissen-Petersen (1999) categorized rainwater harvesting systems according to the type of catchment surface used. These types are roof catchment systems, rock catchment systems, ground catchment systems, and check or earth dams. In this study, urban (roof catchment systems) and hillslope (rock and ground catchment systems) rainwater harvesting systems were compared.

The overall objective of the rainwater harvesting option is to protect surface water and ensure sustainability of all beneficial uses. Sustainable use of surface water resources will also bridge the supply-demand gap in the Faria Catchment, which is an example of an area facing severe water scarcity.

2 Description of study area

The Faria Catchment is one of the major arteries draining into the Lower Jordan River. Geographically, it is located in the northeastern part of the West Bank, Palestine, and has a total area of about 320 km², accounting for 6% of the total area of the West Bank (Fig. 1). Ground surface elevations range from 350 m below sea level to 900 m above sea level. The native population of the catchment, primarily rural, is estimated to be about 21 000. The climate in the Faria Catchment is arid to semi-arid, characterized by mild rainy winters and moderately dry and hot summers. Climatic parameters are highly variable and influenced by topography and circulation of air masses.

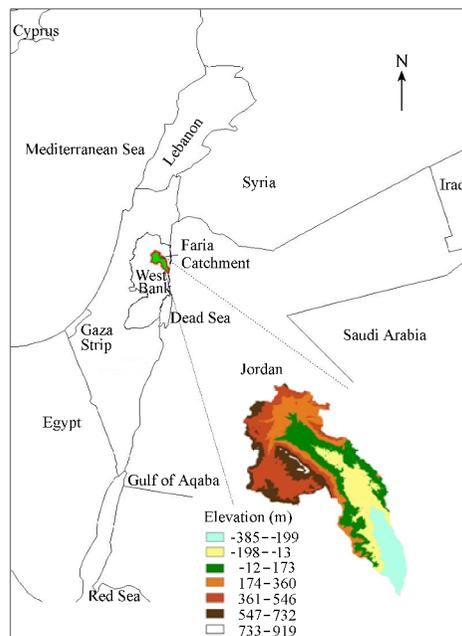


Fig. 1 Location of Faria Catchment

The catchment is characterized by high temperature variation over space and time. The

mean annual temperature is 18 °C on the western side of the catchment and 24 °C on the eastern side. Potential evaporation is particularly high in the summer due to high insolation. Evaporation greatly exceeds rainfall from April to October.

Rainfall events predominantly occur in autumn and winter, a period that accounts for 90% of the total annual precipitation. The Faria Catchment is gauged with six rainfall stations. The rainfall data for the years from 1965 to 2006 indicate that the average annual rainfall distribution in the catchment ranges from 640 mm at the headwaters to 150 mm in the vicinity of the Jordan River. Surface runoff generated in the upper part of the catchment is gauged with two Parshall flumes. One is located at the Al-Badan sub-catchment (with an area of 83 km²) outlet, and the other at the Al-Faria sub-catchment (with an area of 56 km²) outlet (Fig. 2).

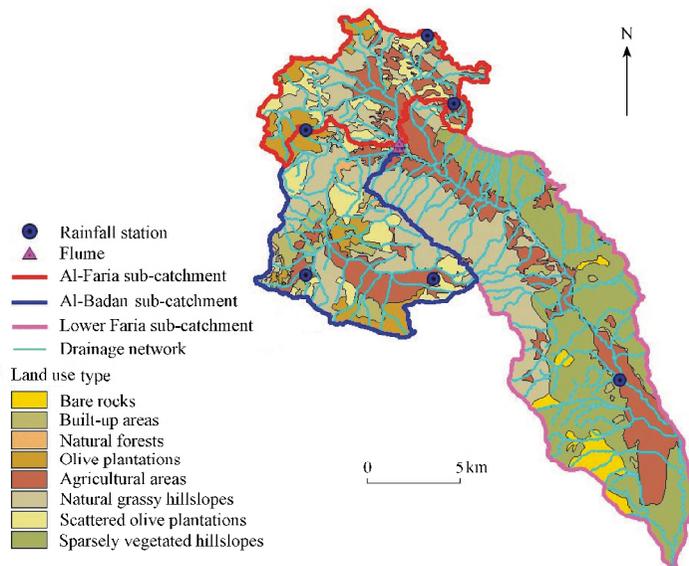


Fig. 2 Land use map of Faria Catchment

Land use in the Faria Catchment is classified into eight types (Fig. 2): bare rocks (2.8%), built-up areas (4.7%), natural forests (0.9%), olive plantations (6.4%), agricultural areas (22.1%), scattered olive plantations (8.2%), natural grassy hillslopes (28.3%), and sparsely vegetated hillslopes (26.6%).

Six main soil types are found in the Faria Catchment, with two types (Terra Rossa and Brown Rendzina) dominating: together they cover 65% of the total area. Geologically, the Faria Catchment is part of the larger Dead Sea Rift Valley, which has several horsts and grabens and directs drainage towards the Jordan River.

Water resources in the catchment are either surface water or groundwater. In the winter, the majority of generated surface runoff leaves the catchment, as there is no infrastructure to store excess water. Most springs are located in the upper and middle parts of the basin. In total, eleven springs provide baseflow for the upper main river, preventing it from drying up during hot summers. Spring discharge exhibits high variability. Annual totals of spring discharge vary

between $3.8 \times 10^6 \text{ m}^3$ and $3.83 \times 10^7 \text{ m}^3$, with an average of $1.44 \times 10^7 \text{ m}^3$. Accounting for more than 70% of the total runoff, baseflow in the Faria Catchment is the highest of all easterly draining catchments in the West Bank.

3 Methodology

During two recorded rainfall events, the available water for two different types of rainwater harvesting (urban and rural) was analyzed and compared using the TRAIN-ZIN model. ZIN is a spatially distributed, physically-based rainfall-runoff model that has been developed to simulate high-magnitude events in dry environments (Lange et al. 1999). Like all hydrological models, ZIN is a simplified representation of natural systems and can be used as a mathematical tool to simulate and interpret hydrological processes. The model is distributed in the sense that a catchment can be divided into smaller units in order to account for the variability of hydrological processes (Lange 1999). ZIN utilizes spatially distributed sub-catchments determined by geomorphological analysis with the help of aerial photography, topographic maps, and digital elevation models, supplemented by field studies. As outputs, the model yields hydrographs at any user-defined point along the watercourse.

TRAIN is a physically-based, spatially distributed model that has been designed to simulate the spatial pattern of actual evapotranspiration (Menzel 1999). The model includes information from comprehensive field studies of the water and energy balance. It has been designed to simulate the spatial pattern of the individual water budget components at different spatial and temporal resolutions. It has a special focus on processes at the soil-vegetation-atmosphere interfaces, with evapotranspiration as one of the principal mechanisms (Lange and Lucas 2005). For continuous modeling of rainfall over entire rainy seasons, TRAIN calculates evapotranspiration using the Penman-Monteith equation and meteorological inputs of temperature, rainfall, relative humidity, wind speed, and sunshine duration.

Gunkel (in preparation) coupled the TRAIN and ZIN models. TRAIN now simulates long-term vertical fluxes between soil, vegetation, and the atmosphere, whereas ZIN simulates short-term runoff generation processes. The TRAIN-ZIN model was developed for arid and semi-arid regions in order to correctly represent the dominant processes of runoff generation: Hortonian overland flow (HOF) and saturation excess overland flow (SOF). For this purpose, a wide distribution over space and time is used. As such, the TRAIN-ZIN model is superior to hydrologic models from more humid regions or simple engineering approaches.

Mathematically, TRAIN-ZIN first determines the fraction of rainfall that is transformed into direct runoff. HOF is parameterized with a concept of initial losses and an infiltration rate. The infiltrated amount fills a volume of soil storage that is emptied by evapotranspiration using the Penman-Monteith equation or deep percolation described by the Van-Genuchten method. Once the soil is saturated, SOF occurs. The channel network is divided into segments accepting

runoff from adjoining sub-catchments defined by topography. The transformation of runoff generated (through HOF and/or SOF) in each model element into lateral inflow to the adjacent channel segment is described by a mean response function. The routed channel network flow (Shadeed 2008) accounts for lateral inflow and transmission losses. The routing module uses the Muskingum-Cunge flow routing technique, which includes the Green-Ampt infiltration model, to simulate the channel transmission losses.

Shadeed (2008) applied the coupled TRAIN-ZIN model in the Faria Catchment. The model was calibrated and checked against single rainfall events, and then run continuously for three rainy seasons (from 2004 to 2007). Three years of monitoring rainfall and runoff combined with thorough field study allowed for thorough model parameterization. Accordingly, parameters of the coupled TRAIN-ZIN model were determined through physical measurements carried out directly in the field (to measure infiltration capacity) and from topographic maps (channel slopes), aerial photographs (channel geometry), and literature (published estimates of hydraulic conductivity, porosity, Manning coefficient n , etc.). Since the model was computationally costly (for one day the model required about three hours of computing time on an up-to-date PC), calibration was performed manually. Model parameters were adjusted one at a time and model performance was evaluated through visual comparison of observed and simulated hydrographs. In addition, different statistical goodness-of-fit measures were calculated. For model testing (validation), some rainstorm events (which were not used during the calibration process) were simulated successfully with the parameter set obtained from the calibration process. Only initial moisture was set according to preceding rainfall history.

4 Results

4.1 Rainfall events

To date, the Faria Catchment is the only catchment in the eastern drainage system of the West Bank with measured hydrological data. Due to the scarcity of rainfall, there are only two high-magnitude events from the period of data collection (from 2004 to 2007) that can be used for a basin-wide analysis of rainwater harvesting. These events occurred from February 4 to 6, 2005 (Event 1), and from February 8 to 9, 2006 (Event 2). Characteristics of these events are summarized in Table 1. More details about these events are provided in Shadeed (2008).

Table 1 Characteristics of two rainfall events

Event	Parameter			
	Amount of rainfall (mm)	Number of hours	Average rainfall intensity (mm/h)	Number of days since last event
1	118	55	2.5	2
2	88	22	4.2	5

4.2 Urban rainwater harvesting

The storage of rainwater on urban surfaces is a traditional technique. Structures used are cisterns, underground tanks, ponds, check dams and weirs. In Palestine, the family cistern is a traditional water harvesting technique that has been used for several decades to capture rooftop runoff for many purposes, including cooking, washing, and in some cases irrigation. In the upper Faria Catchment, where the eastern part of the city of Nablus is located, family cisterns are proposed for capturing water. They can provide domestic water for families, especially during breakdowns of the municipal water supply in the summer. The long-term annual average rainfall in the city of Nablus is estimated to be about 640 mm. This is relatively high compared to the average in the Faria Catchment. Thus, a relatively high potential for urban rainwater harvesting can be expected.

For both events, the TRAIN-ZIN model was used to assess generated surface runoff from the built-up areas of the eastern part of the city of Nablus which was estimated to be $5.7 \times 10^5 \text{ m}^3$ and $2.3 \times 10^5 \text{ m}^3$ for Event 1 and Event 2, respectively. In addition results show that the contribution of the built-up areas of the city of Nablus to the generated runoff from the Al-Badan sub-catchment is 57% for Event 1 and 62% for Event 2. For both events the generated runoff from the built-up areas was not separated according to source area (rooftops, paved roads, parking lots, etc.). However, on average, it is assumed that rooftop runoff makes up about 50% of generated urban runoff. This means that rooftop runoff totals $283\,486 \text{ m}^3$ for Event 1 and $113\,112 \text{ m}^3$ for Event 2. Assuming a water consumption rate of 70 liters per capita per day, rainwater harvesting from rooftops can theoretically supply the yearly demand of about 8000 inhabitants. The same amount can satisfy the domestic demands of nearly 24000 inhabitants for more than four months, from May to September, when the water resources are very limited. Hence, urban rainwater harvesting can largely help to bridge the supply-demand gap. To take advantage of this potential, it is proposed that family cisterns and other storage facilities be constructed wherever possible.

For urban runoff from streets and parking lots, which is assumed to account for 50% of the generated floods, it is proposed that underground reservoirs be constructed at selected locations. However, since water quality is expected to be poorer, utilization will be restricted.

4.3 Rural rainwater harvesting

A runoff generation map of the Faria Catchment was developed, in which areas of high potential for runoff generation were delineated (Shadeed 2008). For these areas, it is proposed that underground reservoirs (cisterns) be constructed to capture runoff for future use. Such cisterns may also contribute to isolated rain-fed agricultural farms. Topographically, these farms are elevated and suffer from a shortage of available water due to the difficulty of pumping water from distant agricultural wells. Cisterns in these areas may increase water availability, thus improving productivity in agriculture. In central and lower parts of the catchment, where Bedouins are living and mainly depending on livestock, hillslope rainwater harvesting systems can supply water for families and livestock.

Based on the developed runoff generation map and aerial photographs, an inventory of the best locations for generating runoff (rocky slopes, gentle slopes with crusted surfaces, and even headwater areas) was conducted. As a result, 19 locations for cisterns are proposed (Fig. 3).

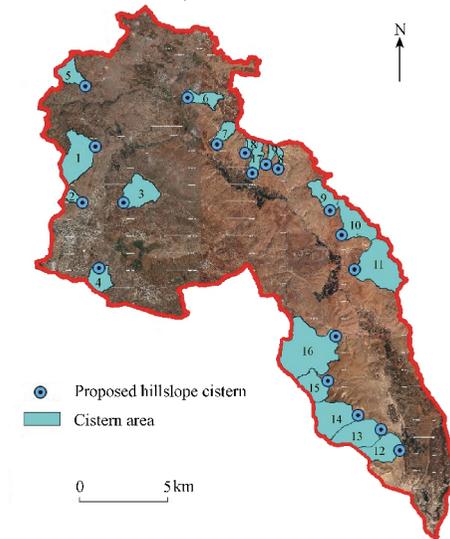


Fig. 3 Proposed locations for hillslope rainwater harvesting cisterns (background image source: Google Earth)

The most important characteristic of these hillslopes is their ability to produce runoff even during light rainfall. The TRAIN-ZIN model was used to assess the amount of runoff generation from these hillslopes for Event 1 and Event 2. This assessment is essential to determining the size of the proposed cisterns. Results are shown in Table 2.

Table 2 Simulated runoff volumes of proposed hillslope cisterns for Event 1 and Event 2

Cistern ID	Area of contributing catchment (km ²)	Event 1			Event 2		
		Rainfall (km ³)	Runoff (km ³)	Runoff coefficient (%)	Rainfall (km ³)	Runoff (km ³)	Runoff coefficient (%)
1	4.40	731	17	2.4	489	5	1.06
2	0.60	94	6	6.1	60	2	3.23
3	3.08	462	32	6.9	295	19	6.27
4	1.81	308	22	7.1	190	5	2.73
5	1.81	293	12	4.0	193	5	2.34
6	1.39	168	13	7.9	102	3	3.32
7	1.04	136	15	10.9	84	5	6.12
8	0.41	52	4	8.2	33	2	6.88
9	1.81	188	10	5.1	121	3	2.10
10	3.42	315	8	2.4	209	3	1.53
11	5.90	537	21	3.9	348	8	2.30
12	2.79	201	25	12.6	134	10	7.76
13	3.73	280	71	25.3	187	46	24.70
14	4.31	349	24	6.9	228	14	6.13
15	2.35	202	29	14.3	131	20	14.93
16	8.66	788	25	3.1	511	15	3.03
17	1.08	139	11	8.0	87	6	6.46
18	0.52	67	5	7.6	42	2	3.90

19	0.51	64	6	9.4	40	3	6.29
Average	2.61	283	19	8.0	183	9	5.85

Although the catchment areas of the proposed cisterns account for only 15% of the entire Faria Catchment, they generated 30% of the total catchment runoff in Event 1 and 62% in Event 2. During Event 1, rainfall had relatively moderate intensity but a higher volume than during Event 2. Hence, it is expected that SOF dominated the runoff generation process. With higher rainfall intensities, it is expected that HOF was the dominant runoff generation process during Event 2, which turned the cistern areas into the main runoff contributors in the basin.

The variability of collected runoff volume reflects, on the one hand, differences in rainfall characteristics from event to event and, on the other hand, differences in the locations of cisterns on the landscape.

5 Discussion and conclusions

The calculated amounts of generated runoff from urban surfaces suggest great potential for rainwater harvesting in urban areas of the Faria Catchment. Rural communities satisfy their domestic water needs either from direct household connections to nearby irrigation wells or by using tanker vehicles, which are filled at distant springs. Since these partly dry up, rainwater harvesting will help to supplement the water available to these communities and reduce competition between agricultural and household demands. Water resources are scarcest in the lower part of the Faria Catchment. Greenhouses are commonly used for growing vegetables. For these houses it is proposed that roof-rainwater be collected to contribute to their water needs.

From the hillslopes it is clear that the estimated runoff volumes are high and a series of cisterns may be more efficient than just one for each area. However, large cisterns may also be efficient, as shown in Nyabushozi, Southwestern Uganda. There, nine cisterns with an average capacity of about 10 000 m³ in total were built to save water for people and their livestock for the dry period that lasts more than three months yearly (Mawami 2005). In general, the present study should be seen as an attempt to quantify the maximum potential of the hillslope rainwater harvesting technique for a dry basin in water-scarce Palestine. To avoid large-scale adaptation problems (e.g., capital cost, location, and maintenance problems), measures should be implemented primarily on small scales. In this regard, it is worth mentioning that small-scale hillslope rainwater harvesting systems are well established techniques in Palestine. It is high time that scientifically-based feasibility studies examine the power of these management options from a catchment-scale perspective.

Hillslope water harvesting systems are viable provided that the runoff coefficients of the connected catchments are high and that the sizes of the cisterns are adapted to the size of the contributing catchments so that water losses via overflow are minimal. In addition, hillslope rainwater harvesting systems can catch more runoff by minimizing the considerable transmission losses that take place in the Faria Catchment.

It has always been believed that rainwater is quite pure and can be used without any treatment. While this belief is accurate in many areas that are unpolluted, the fact remains that rainwater collected in other locations has some impurities. Generally, the main source of contamination is the roof or the catchment. There are several techniques for minimizing water contamination by filtering or by diverting highly contaminated first-flush water. This is to avoid the very high pollution loads that are encountered during the initial phase of the storm. When pure water is stored in underground tanks that are covered, water quality normally does not deteriorate.

The annual water balance for the Faria Catchment indicates an actual supply-demand gap of about $2 \times 10^6 \text{ m}^3$. This situation will worsen due to inevitable growing water demands and hydrologically limited and uncertain supplies. By 2015, it is expected that the gap will increase to $4.5 \times 10^6 \text{ m}^3$. Consequently, water resources management in the catchment faces enormous challenges. As such, the establishment of a clear and well-defined local water policy is imperative. This study emphasizes the importance of quantifying naturally available surface water resources in Faria. It is recommended that surface water management options be utilized in trying to solve the ongoing water shortages. Rainwater harvesting systems in urban areas and on rural hillslopes are two options for bridging the supply-demand gap for both domestic and agricultural needs. However, managing surface water resources is difficult in absence of protection programs along with short-term monitoring. In particular, water quality issues have to be considered. The current political situation adds additional complexity to the management of the scarce water resources in the region. Consequently, intensive efforts are needed at national and even international levels to combat water scarcity. Managing surface water in the Faria Catchment should be seen as a valuable way to support the decision-making processes in future water resources development. Finally, for successful implementation of the proposed management options, concrete actions are required at national and local levels. It is necessary to go beyond basic research and undertake demonstration projects for possible application of the proposed rainwater harvesting options in the Faria Catchment.

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