

Abstract

In the Middle East, water is scarce and population growth causes a rapid rise of urban centers. Since many towns of the Palestinian Authority (PA) suffer from water shortage, the use of rainwater harvesting (RWH) as an alternative to conventional water supply has gained increasing interest among water resources planners. This study quantifies actual volumes of urban RWH to be expected from highly variable Mediterranean rainfall. A one-parameter model uses measured potential evaporation and high resolution rainfall data as input to calculate RWH volumes from rooftops inside Ramallah, a traditional Arab town. While during average seasons a 87 % runoff harvest (480 from 550 mm of rainfall) can be expected, this value decreases to about 75 % (190 from 250 mm of rainfall) during drought seasons. A survey comprising more than 500 questionnaires suggests that approximately 40 % of the houses are equipped with RWH systems from which one third are out of use. Although water quality is perceived to be favourable, only 3 % of the active RWH systems are actually used for drinking and only 18 % for domestic purposes. All active RWH systems investigated may harvest approximately $16 \times 10^3 \text{ m}^3$ of rooftop runoff during an average season and $6 \times 10^3 \text{ m}^3$ during droughts. When these numbers are extrapolated to all houses in Ramallah, theoretical maximum potentials increase to approximately $298 \times 10^3 \text{ m}^3$ during average seasons and $118 \times 10^3 \text{ m}^3$ during droughts. A part of this potential can easily be exhausted by rehabilitation of installed RWH systems. Also, the use of collected water for drinking should be advocated. This should go along with regular checks of water quality and regulations concerning adequate water storage and treatment/disinfection procedures where necessary. Regional estimates for the entire Lower Jordan River Basin yielded RWH potentials of $20 \times 10^6 \text{ m}^3$ during the average season 2002/2003 but only $3 \times 10^6 \text{ m}^3$ during the drought season 1998/1999. Thus, urban RWH is a relatively small contribution to overcome water scarcity in the region and decreases significantly during droughts. Yet it is a sustainable water resource, which is available on spot for everybody. Due to population growth and ongoing urbanization it will be more important in future.

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1 Introduction

Water is a scarce resource in the Middle East and disputed between national entities, e.g. between Israel and a future State of Palestine (Brooks and Trottier, 2010). At the same time, like in many regions of the world, a tremendous population growth causes a rapid rise of urban centers. Many towns of the Palestinian Authority (PA) suffer from water shortage, which is revealed by regular failures of the water supply systems during summer months. Under these circumstances, the use of rainwater harvesting (RWH) in addition to water from supply networks has gained renewed and increasing interest among water resources planners. RWH has been used in the region since more than two-thousand years by the Nabateans, both for drinking water and for agriculture, making their prehistoric desert civilization flourish (Evenari et al., 1982).

Especially for developing regions, RWH is seen as a valuable water resource, both for agricultural and domestic use (Helmreich and Horn, 2009). In a world-wide overview, Rygaard et al. (2011) identified RWH as an important component to increase self-sufficiency of urban centres, among recycled wastewater and desalinated water. However, a recent case study in Mediterranean Spain showed that RWH may not always be cost-efficient, especially at a low pipe-water price (Farreny et al., 2011a). At conditions of water scarcity, the value of RWH is without controversy, as shown for the Indian megacity Chennai (Srinivasan et al. 2010), or for the Kingdom of Jordan (Abdulla and Al-Shareef, 2009).

The current regulatory framework is different in the national entities of the Middle East. According to health regulations, the Israeli Ministry of Health does not permit the use of RWH for drinking and any storage or purification system must be under its strict supervision. This comprehensive regulation prevents any legal use of harvested water for drinking. In the PA comparable limitations do not exist. Instead, the Palestinian Water Authority has given priority to RWH as a part of its water emergency plan (Kittani, 2006). Also the Jordanian Ministry of Water and Irrigation encourages RWH and new houses must be equipped with water storage facilities (Abdulla and Al-Shareef, 2009).

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3. Third, we extrapolate our findings to the entire Lower Jordan River Basin (LJRB). To account for climatic variability, we use rainfall radar data sets from a drought and an average season and apply variable runoff coefficients.

2 Study area

5 The 16 400 km² Lower Jordan River Basin (LJRB) is a multi-national water basin shared between Israel, Jordan, Syria and the Palestinian Authority (PA) (Fig. 1). Naturally, the Lower Jordan River exits Lake Tiberias (210 m b.s.l.) flowing south to the Dead Sea (410 m b.s.l.) through the Lower Jordan Rift Valley. To date, the exit of Lake Tiberias is blocked and dams are constructed in all major eastern tributaries. As a consequence, the Lower Jordan River is deprived of virtually all natural flow and mainly drains diverted saline spring water, sewage and excess water from irrigation (FOME, 2010). On both sides, the Lower Jordan Rift Valley is bordered by steep escarpments and mountain ranges reaching almost 1000 m a.s.l. in the PA and 1200 m a.s.l. in Jordan. This accentuated morphology creates sharp climatic gradients from a Mediterranean-type climate to fully arid. Precipitation is lowest in the Jordan Valley and in the eastern fringes of the LJRB (less than 100–200 mm yr⁻¹) and highest in mountainous areas (up to 600 mm yr⁻¹). There, also most urban centres are found with the Jordanian capital of Amman forming the biggest urban agglomeration. Ramallah is situated opposite to Amman on the crest of the western anticline at 750–850 m a.s.l. It receives 550 mm of mean annual precipitation with a range of 240–1200 mm (Morin et al., 1994). Most of the precipitation (80 %) occurs at low intensities (under 6 mm h⁻¹) and only 1 % falls with intensities exceeding 50 mm h⁻¹ (Sharon and Kutiel, 1986). A single rainstorm may last from a few hours up to several days, characterized by several separate rain spells (minutes to hours) interrupted by dry intervals, which can last for several hours.

25 As a traditional Arab town, Ramallah was built around an old quarter, which is the centre for daily life and small commercial businesses. Both modern and traditional houses are found around the city core. The periphery of the inner city also contains

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rural parts consisting of natural landscape and cultivated terraces. Typically for the Middle East, houses are covered by flat, concrete roofs. In historic times a small spring served as the main water supply. Today, most of the urban area is connected to the drinking water supply by a private water company (Jerusalem Water Undertaking, JWU). JWU owns the Ein Samia well field located 20 km NE of the city, where five wells tap groundwater at an altitude of 400 m a.s.l. However, this water is by far not enough to supply the growing demands of the city. Especially during summer, a major fraction must be purchased from external, i.e. Israeli, sources.

3 Methodology

3.1 Amount of harvested rainwater

A simple, one-parameter model calculated the amount of harvested rooftop rainwater (Fig. 2). In a one minute time step, the roof depression storage DS [mm] was filled with rainfall R [mm min^{-1}] and emptied by potential evaporation PE [mm min^{-1}]. Only when DS was reached, the exceeding water was treated as roof runoff RR [mm min^{-1}]. Daily CLASS-A-PAN measurements of four meteorological stations (Fig. 1) were averaged and divided by day length [min] for instantaneous potential evaporation. Evaporation was hypothesized to start at sunrise and terminate at sunset. Daily sun data was obtained from the Astronomical Applications Department of the US Naval Observatory (USNO). Finally, RR values were accumulated to seasonal amounts and divided by seasonal rainfall to arrive at seasonal roof runoff coefficients (RC, %).

During three winter seasons (1999/2000, 2000/2001 and 2001/2002) rainfall was measured at nine different locations inside Ramallah by rooftop tipping bucket rain-gauges (Fig. 3). The raw 0.1 mm tips of ULTIMETER TB Rain Gauges equipped with Hobo event data loggers were accumulated to 1 min time intervals. Due to instrument failures and limited accessibility following riots inside the town, not a single station measured continuously. Incomplete records were not excluded from the analysis but rather

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treated as independent data from low rainfall seasons. All obtained seasonal RC values were plotted against total rainfall. To assess model uncertainty, the single model parameter DS was varied according to reported values of roof detention storage. This sensitivity analysis also yielded statements about the impact of different roof types on the amount of harvested water.

3.2 Survey of local residents

Inside the city, all roofs were digitized from a 1:2000 orthophoto of the year 1997. By GIS analysis the total roof area was calculated and individual roofs were assigned to the respondents of the urban questionnaires. 541 of these questionnaires were distributed in a 1.3 km² district close to the city centre in the summer months of the year 2000 (Fig. 3). The questionnaire started with general questions about ownership structure, size of the building, type of roof and number of rooms, floors and apartments. Then questions were raised about water facilities including numbers of sanitary units, water taps, and eventually existing swimming pools. These were followed by questions about the type of water supply. In this part, a special focus was on the use of cisterns. The respondents were asked to answer questions about cistern capacity, about the designated use of the harvested water, and if their demands for harvested water were satisfied. Water quality from the cistern had to be rated from “excellent”, over “good”, “fair” to “not good”. Questions about the sanitation system and about garden irrigation completed the survey. Reported volumes of cisterns [m³] could be compared to connected rooftop catchment areas [m²].

3.3 Regional RWH potentials

For the entire LJRB, we created a contiguous GIS data layer of urban areas combining different data sources. For the Israeli part, a vector data set of 2002 delineated buildings as a distinct class. Urban areas of the PA were digitized from aerial photos with a

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spatial resolution of $1 \times 1 \text{ m}^2$. In Jordan, urban areas were extracted as a distinct pixel value class ($78 \times 78 \text{ m}^2$) from a 2002 land use map and converted to vector data.

A C-Band volume scanning rainfall radar system located at Ben-Gurion international airport, close to Tel Aviv, provided regional data sets of $1.4^\circ \times 1 \text{ km}$ (polar coordinates) rainfall during an average season (2002/2003) and during a drought (1998/1999). Five-minute radar data was obtained from E. Morin (Hebrew University of Jerusalem, Israel), after pre-correction by a multiple regression approach (Morin and Gabella 2007). This data was converted to a $1 \times 1 \text{ km}^2$ grid, regionalized to the LJRB and calibrated by station data (Gunkel and Lange, 2011). The Jordanian parts of the LJRB outside a 150 km range around the location of the rainfall radar had to be excluded due to uncertainties in rainfall estimates.

For both rainfall seasons, a GIS overlay of $1 \times 1 \text{ km}^2$ annual rainfall volumes and the urban vector data set yielded the annual rainfall that fell on urban areas. This data set was multiplied by factor 0.2 due to the fact that approximately 20 % of urban areas in the Middle East are covered by roof areas (Grodek et al., 2011). To obtain volumes of urban RWH, the data was multiplied by a variable roof runoff coefficient RC. RC was varied according to a linear regression found between annual rainfall amount and simulated RC of the rainfall stations in Ramallah. Thereby, we set the lower boundary for the RC values at 0.7 and the upper boundary at 0.9.

4 Results

4.1 Amount of harvested rainwater

Considering typical roof types in Ramallah, DS was set to 2.0 mm. Then the model was run in a one-minute step for all rainfall stations available. It included the basic dynamics of rainwater harvesting as seen during a large rainstorm (Fig. 4). The event of 20–21 January 2000 was the main storm of a two-storm high magnitude event, which was the largest on our measurement record and produced big floods in the urban drainage

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system (Grodek et al., 2011). According to the model, roofs were dry at the onset of rainfall. DS slowly filled by low intensity rainfall starting at around 12:30 until 14:00 LT. The main storm occurred during night. Due to zero evaporation, DS remained full and more than 40 mm of water could be harvested. After sunrise, DS was emptied by evaporation.

When the seasonal RC-values of all rainfall stations were plotted against recorded rainfall, an increase of RC with annual rainfall depth was noticed (Fig. 5). For low annual rainfall values, a large scatter of RC values was observed that decreased the significance of the correlation. This was mainly an effect of the short recording periods. When a single high intensity rainfall event occurred during the period of record (an example is shown in Fig. 4), RC values were relatively high, even at little total rainfall. Above 300 mm of annual rainfall, RC values were more alike, because they contained a relatively similar rainfall intensity spectrum.

For Ramallah this data suggests a lower boundary of about 75 % for a drought season (250 mm rainfall) resulting in 190 mm of rooftop runoff. For an average season (550 mm) a reasonable RC estimate was about 87 % which resulted in approximately 480 mm of rooftop water. The season 1999/2000 at four stations was selected to study the effect of a changing limit in DS on roof runoff coefficients (RCs) (Fig. 6). DS was changed according to literature values. It can be noticed that in the range of reported values for DS, annual RCs for single stations vary by about 5–10 %.

4.2 Survey of local residents

At the time of the survey, 577 separate buildings existed in the selected 1.3 km² district of Ramallah with a total roof area of about 154 000 m² (Fig. 3). 36 were uninhabited (under construction, functional buildings, etc.) and excluded from the questionnaire survey. From 541 distributed copies of the questionnaire, 513 were re-collected yielding a response rate of 95 %. 78 % of the buildings had flat concrete roofs, 97 % had access to the public water supply, but only 2 % had private swimming pools. 83 % were connected to the public sanitation network, the remaining buildings used cesspits for

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waste water disposal. Buildings were inhabited by 5.1 persons on average, which used 1.8 showers and 3.8 water taps.

Two-thirds of the buildings had surrounding private land. According to their owners, this land had an average size of about 700 m². From the collected questionnaires, a total area of 242 000 m² private land was calculated for investigated city district. About 67 % of this land was used as a cultivated garden and 60 % was irrigated, which added up to an irrigated area of approximately 144 000 m², 11 % of the investigated area. Asked about the source for irrigation water, 56 % of garden owners reported to use water from the public water supply, whereas 44 % relied on cisterns. In total, 40 % of the houses had cisterns installed that were filled by roof runoff. 94 % of these active cisterns supply enough water according to their owners. Rooftop runoff was used for different purposes, but overall had good quality (Fig. 7).

Information about storage capacity was available from 79 active cisterns. They were compared with connected rooftop area and grouped according to water quality (Fig. 8). Six cisterns plotted far above the 600 mm line of unit storage capacity and seem to be oversized. Even if water consumption is accounted for, 15 cisterns that fell below the 200 mm line seemed insufficiently dimensioned. Generally, perceived water quality did not depend on storage capacity. Finally, the expectancies of urban RWH during droughts and during average seasons (Fig. 5) were combined with questionnaire data and connected roof areas. The resulting volumes of rooftop water to be expected for Ramallah are summarized in Table 1.

4.3 Regional RWH potentials

Regional RWH potentials are summarized in Table 2. Results indicate considerable differences between the drought and the average season, especially for Jordan. Here, the drought season 1998/1999 was characterized by low precipitation especially in the eastern parts.

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5 Discussion

For a similar climate in Spain, Farreny et al. (2011b) measured a global 62 % RC value for a flat gravel roof. They explained this low value by the fact that in the gravel much water is initially abstracted due to a great interstitial pore space. Sloping roofs had much higher RC values reaching 84 % for clay tiles, 91 % for plastic and 92 % for metal roofs. When they plotted the amount of collected rooftop runoff per storm against rainfall, DS values could be quantified from the x-intercept of a linear regression model. This was successful for the clay tile (0.8 mm) and for the gravel roof (3.8 mm). In principle, our methodology was opposite. Assuming a representative value for DS, our one-parameter model calculated seasonal RC values from local measured rainfall and evaporation data. Using a 1–3 mm uncertainty range for DS, our seasonal RC values varied between 72 and 92 % (Fig. 6), which compared nicely to the Spanish study. However, most of this variation was caused by different rainfall magnitudes recorded by the four different rainfall stations, rather than by different values of DS. As reported by the questionnaire survey, almost 80 % of the buildings in Ramallah are covered by flat concrete roofs. Gravel roofs are totally absent. In an aerial picture, flat concrete roofs appear white to grey, while sloping clay tile roofs are characterized by a reddish colour (Fig. 9). Hence, a value of 2 mm, 0.5 mm below the textbook value for flat roofs, seems to be a reasonable estimate for a representative DS in Ramallah. Moreover, due to the dominance of two well defined roof types, the real uncertainty of this value seems well below our anticipated uncertainty range (1–3 mm).

Inside Ramallah, Grodek et al. (2011) classified the rainfall stations into two types (valley and ridge stations), averaged operating stations of each type on an event base, and used a mean of the two types to calculate catchment rainfall. In this study we decided not to fill gaps in the rainfall records but rather use the original recordings of each station as individual inputs for our analysis. Thus, the 19 points of Fig. 5 only represent measured rainfall data of three different seasons that were collected at more or less the same location but with different recording lengths. They are not

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equal to a 19 yr time series of independent seasons. Since operating periods of the individual stations were determined by coincidences – this is indicated by the large scatter obtained for low rainfall in Fig. 5 – we are confident, that incomplete data records may be used to represent low rainfall conditions. Although the obtained correlation was rather weak (mainly caused by the scatter described above), our data suggests that runoff coefficients for urban RWH generally decrease during drought periods. Hence, we used this correlation to account for variable rainfall in our regional estimates of RWH volumes in the LJRB.

In agreement to the world-wide consensus about the good chemical water quality of rooftop runoff (e.g. Lye, 2009), our data suggests that also in Ramallah there is no basic impediment to use harvested rooftop water for any purpose, including drinking. Almost three quarters of the cistern users reported good or excellent water quality (Fig. 6), which is in line with the local investigation of Hassan et al. (2010), who did not find problems in the chemical quality of water collected from an urban rooftop. However, these results should not be transferred to the general quality of urban storm runoff which might be poor due to urban pollution of roads or urban storm water sewers (Grodek et al., 2011). Hygienic problems were found to be the main obstacle for a widespread use of RWH in the region (Al-Saleymeh et al., 2011). To safeguard water quality, regulations for adequate storage and regular checks of water quality would be required. Nevertheless it seems surprising that in the year 2000 only 3 % of the active cisterns in Ramallah were actually used for drinking and that one-third of the installed systems were out of operation. Here, financial incentives could intensify the use of rooftop water. Relatively small investments are needed, because many systems exist and only have to be rehabilitated. Only for a small fraction (about 20 %) of existing systems, storage capacities need to be enlarged (Fig. 8). We are aware that our analysis is based on 10 yr old data. Today the exact numbers of urban water use in Ramallah might have changed in the light of the ongoing water scarcity. Nevertheless, one may expect large unutilized potentials for urban RWH still today.

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The reliability of our regional estimates for the LJRB mainly depends on the used input data. First, our data represents single seasons and should not be taken for long term averages. Second, the accuracy of the rainfall radar decreases with distance to the radar antenna which makes annual rainfall volumes more uncertain in Jordan. Third, a 20% coverage of roof areas for all cities should only be seen as a rough estimate. And fourth, the spatial resolution of the GIS input data for urban areas in Jordan is not as detailed as those for the PA or for Israel. Still, our results in Jordan ($13.2 \times 10^6 \text{ m}^3$ for our individual rainfall season 2002/2003, Table 2) compared nicely to the regional estimates of Abdulla and Al-Shareef 2009), who arrived at $15.5 \times 10^6 \text{ m}^3$ for entire Jordan. Population growth rates in the PA is among the world's highest (Tabutin and Schoumaker, 2005). Therefore, urban areas in the PA and in the neighbouring countries will constantly grow in the near future. Consequently, the importance of urban rainwater harvesting as a renewable alternative to conventional supply by water networks will increase as well.

6 Conclusions

Our analysis combined quantitative simulations of generated rooftop runoff with an extensive questionnaire survey of urban water use in the Mediterranean Arab town of Ramallah. Driven by one-minute rainfall data and measured potential evaporation, our one-parameter model facilitated realistic estimates of urban rainwater harvesting potentials for Eastern Mediterranean climate. Model simulations suggested that rooftop runoff coefficients strongly depend on seasonal rainfall amount. While during an average season a 87% runoff harvest (490 from 550 mm of rainfall) can be expected, this value decreases to about 75% (190 from 250 mm of rainfall) during drought seasons.

A questionnaire survey in the year 2000 suggested that inside a 1.3 km^2 urban district about 40% of the urban houses were equipped with a RWH system from which one third was out of use. Although the water quality was perceived to be favourable, only 3% of the active RWH systems were actually used for drinking and only 18% for

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domestic purposes. Most RWH systems served for irrigation of private gardens covering about 11 % of the investigated urban area. A comparison with connected rooftop areas indicated that cistern storage volumes were sufficient for the majority (80 %) of RWH systems. The active RWH systems may harvest approximately $16 \times 10^3 \text{ m}^3$ of rooftop runoff during an average season and $6 \times 10^3 \text{ m}^3$ during droughts. When these numbers are extrapolated to all houses in Ramallah, theoretical maximum potentials increase to approximately $298 \times 10^3 \text{ m}^3$ during average seasons and $118 \times 10^3 \text{ m}^3$ during droughts. Our data shows that a part of this potential can easily be exhausted by rehabilitation of installed RWH systems. To fully utilize RWH benefits the use of collected water for drinking should be advocated. This should go along with regular checks of water quality and regulations concerning adequate water storage and treatment/disinfection procedures where necessary. In our regional estimates for the entire LJRB the drought impact was even more significant. While during the average season 2002/03 almost $20 \times 10^6 \text{ m}^3$ could be harvested from all urban roofs inside the basin, this value decreased dramatically to approximately $3 \times 10^6 \text{ m}^3$ during the drought season 1998/1999. As already shown by Abdulla and Al-Shareef (2009), urban RWH is a relatively small contribution to overcome water scarcity in the region. Especially during droughts only small water volumes should be expected. However, urban RWH is a sustainable water resource, which is available on spot for everybody and will increase in importance in the future because of population growth and ongoing urbanization.

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Table 1. Potentials for rooftop water harvesting in Ramallah; calculations are based on an orthophoto of 1997 and a questionnaire survey of 2000.

	Number	Total rooftop area	Rooftop runoff expected for a drought season	Rooftop runoff collected during an average season
Rooftop runoff [mm]	–	–	190	480
Houses with active cisterns in the investigated city district	149	$33 \times 10^3 \text{ m}^2$	$6 \times 10^3 \text{ m}^3$	$16 \times 10^3 \text{ m}^3$
Houses with installed cisterns in the investigated city district	223	$53 \times 10^3 \text{ m}^2$	$10 \times 10^3 \text{ m}^3$	$26 \times 10^3 \text{ m}^3$
All houses in the investigated city district	558	$154 \times 10^3 \text{ m}^2$	$29 \times 10^3 \text{ m}^3$	$74 \times 10^3 \text{ m}^3$
Houses in entire Ramallah*	2777	$621 \times 10^3 \text{ m}^2$	$118 \times 10^3 \text{ m}^3$	$298 \times 10^3 \text{ m}^3$

* Only those that were included in the available orthophoto.

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Table 2. Potentials of urban RWH in different parts of the Lower Jordan River Basin for the average season 2002/2003 and the drought season 1998/1999.

Part of the LJRB	Total area [km ²]	Urban area [km ²]	RWH potential [10 ⁶ m ³]	RWH potential [10 ⁶ m ³]
–	–	–	Drought (1998/1999)	Average Season (2002/2003)
PA	1523	39	1.34	4.29
Israel	979	22	0.83	2.27
Jordan*	6877	233	0.87	13.21
Total*	9379	294	3.04	19.77

* Only parts inside the 150 km range from the rainfall radar.

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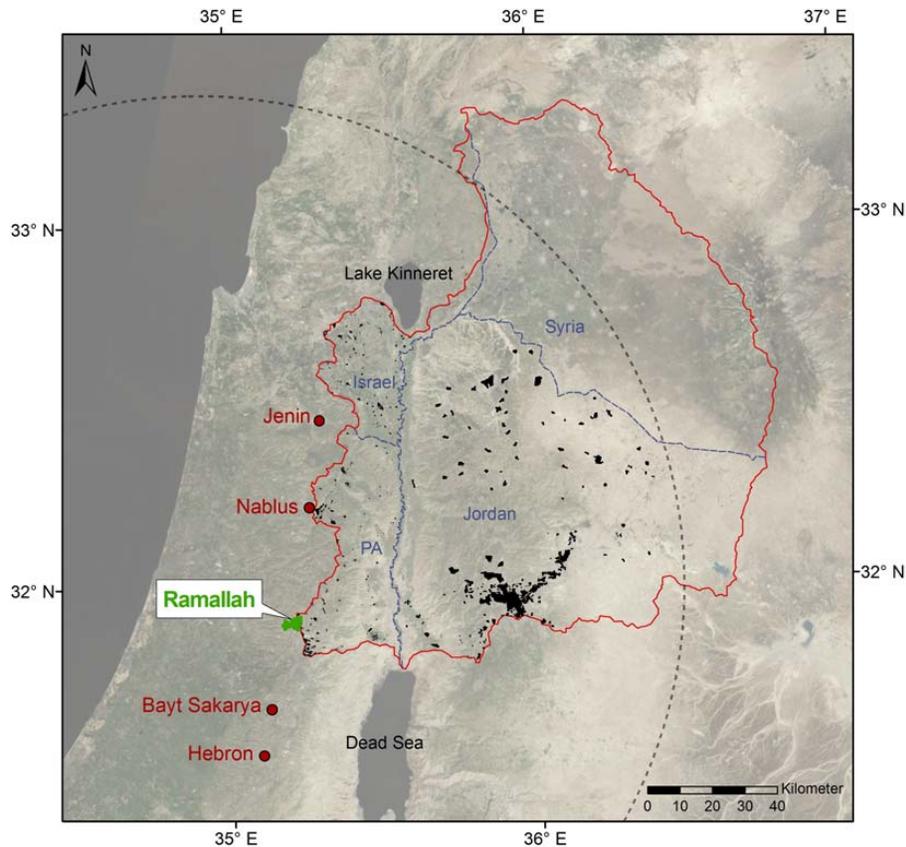


Fig. 1. Location Map: the multi-national Lower Jordan River Basin with its urban areas (black) and the city of Ramallah (green); in red: meteorological stations with available data for measured evaporation; circle indicates the 150 km range around the rainfall radar.

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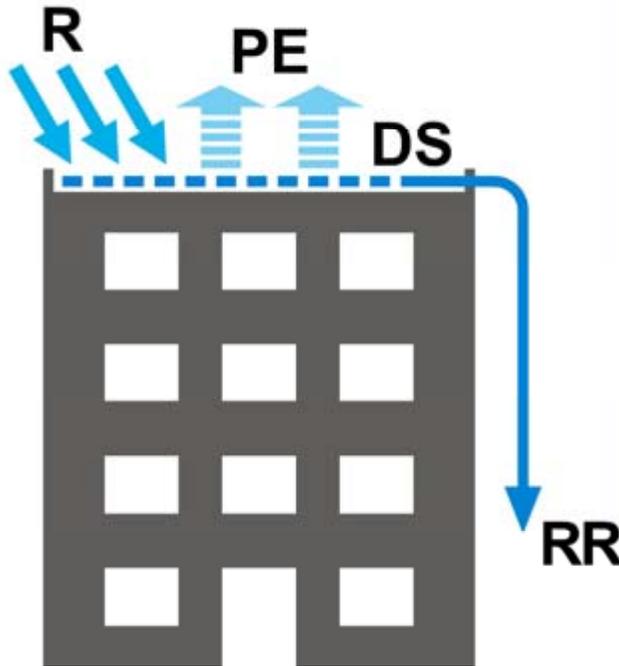


Fig. 2. Conceptual sketch of the rooftop harvesting model; R: rainfall, PE: potential evaporation, DS: depression storage, RR: roof runoff.

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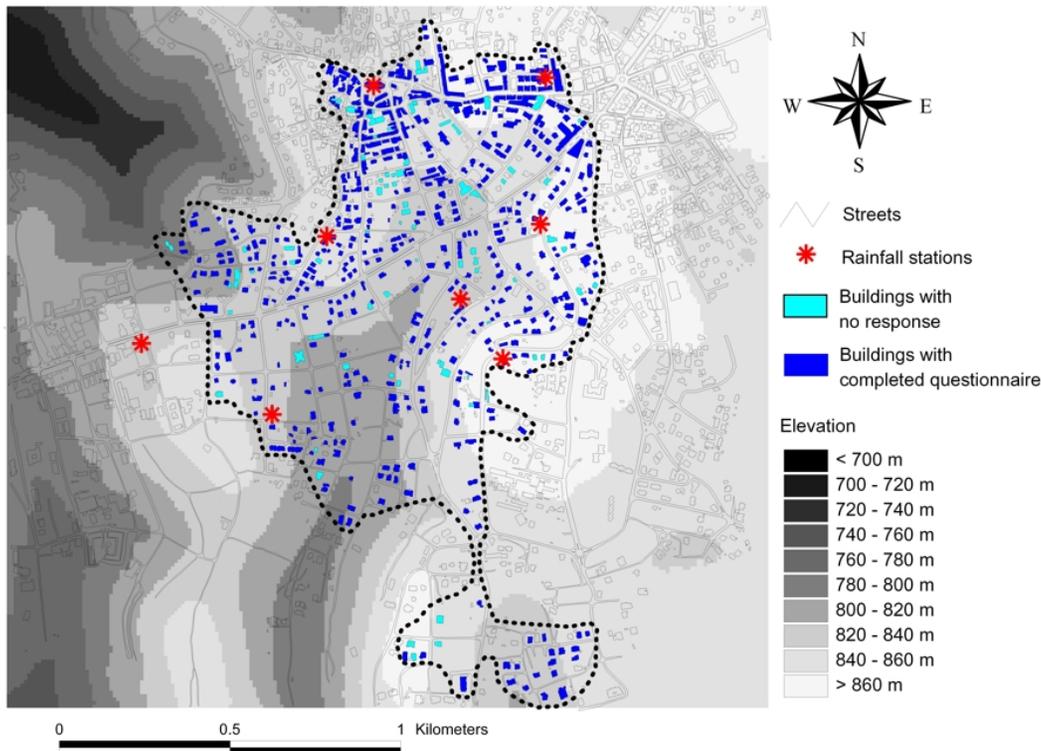


Fig. 3. Investigated city district inside Ramallah, buildings with residents surveyed and installed rainfall stations.

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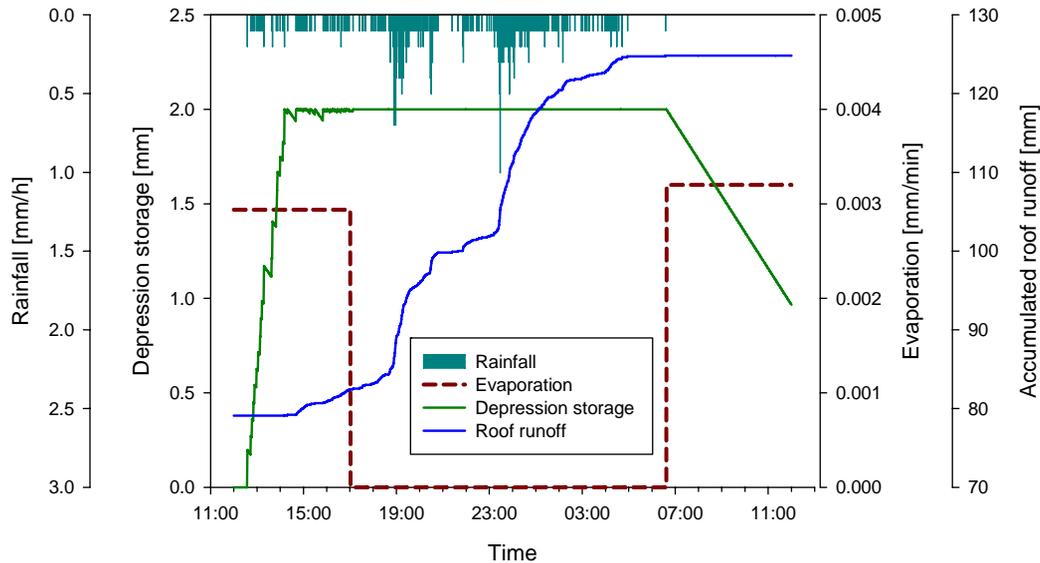


Fig. 4. Example of continuous one-minute modelling of rooftop harvesting; largest event on record, station Library, 20–21 January 2000.

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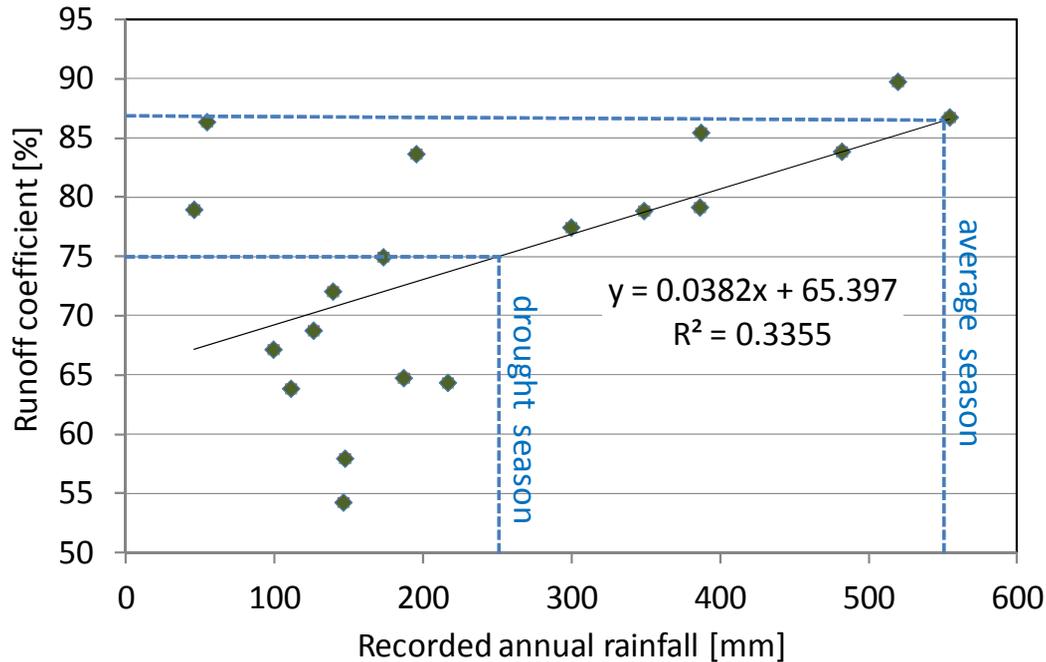


Fig. 5. Annual RC values calculated for all stations and plotted against annual rainfall. DS is set to 2 mm.

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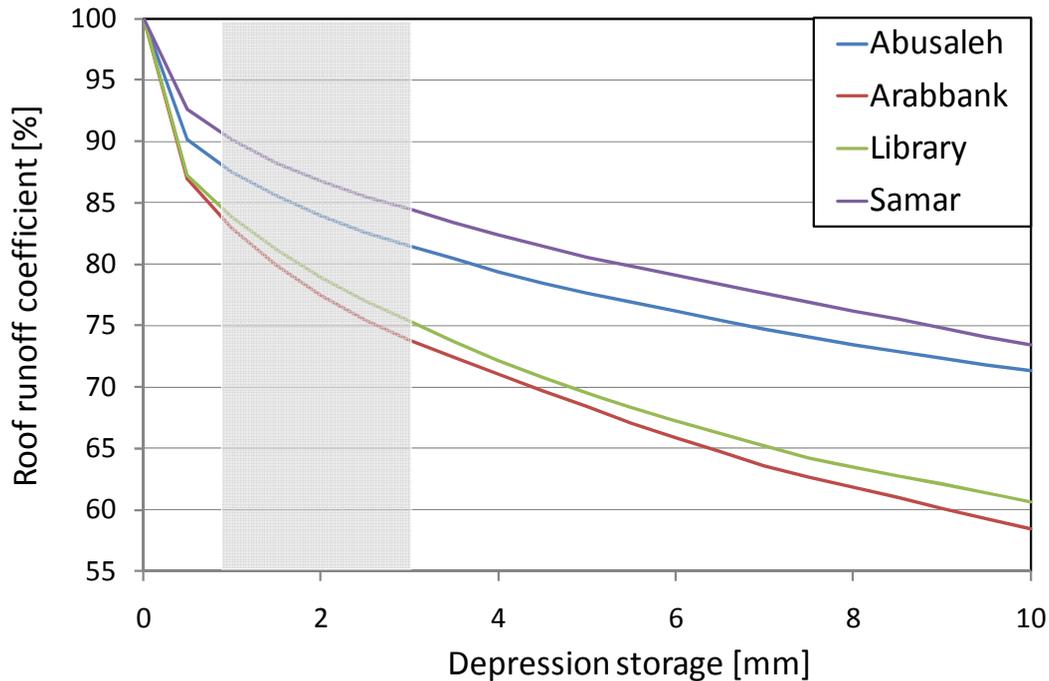


Fig. 6. Calculated RCs for different values of maximum roof depression storage DS; the shaded area (1–3 mm) represents the anticipated uncertainty range accounting for four rainfall stations and different roof types; rainfall of season 1999/2000 is used as input.

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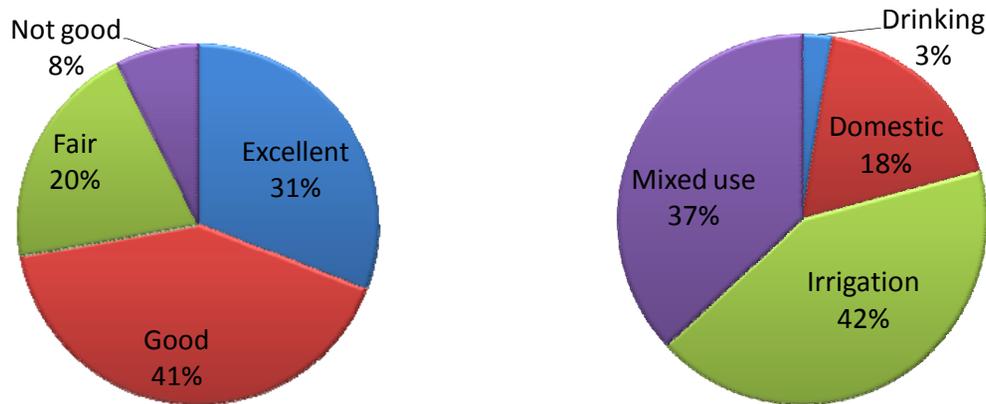


Fig. 7. Reported water quality and use of the 149 active cisterns in Ramallah.

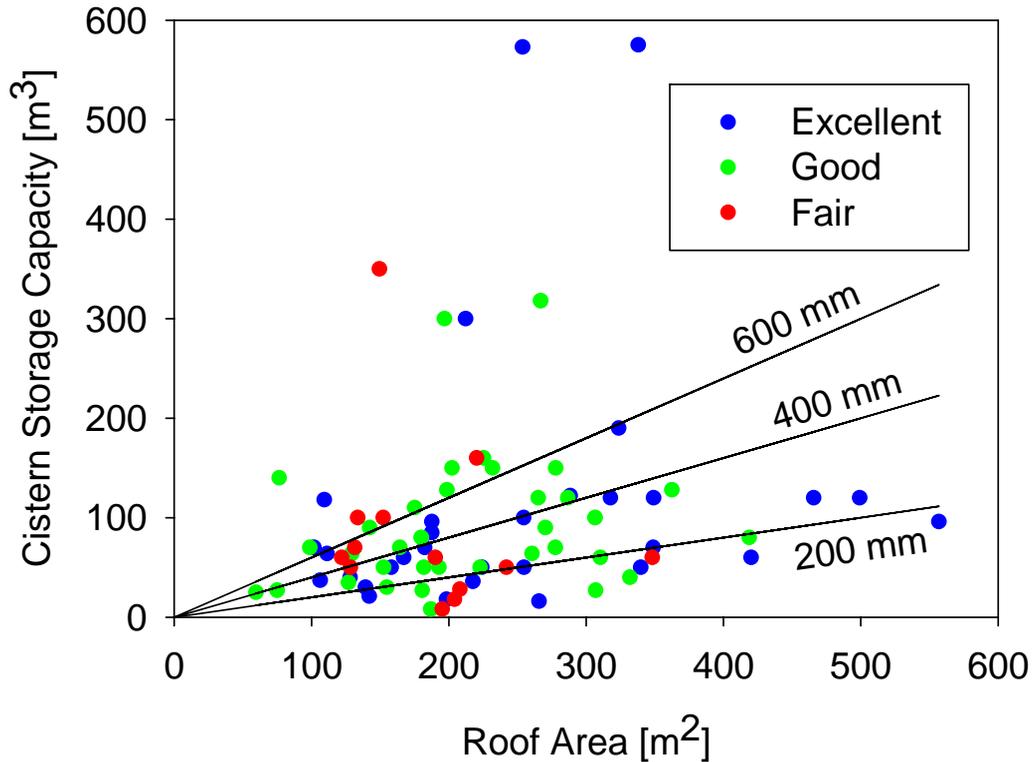


Fig. 8. Perceived water quality, storage capacity and connected rooftop area of active cisterns in Ramallah; lines indicate cistern capacity that is required to store 200, 400 and 600 mm of rooftop runoff.

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Fig. 9. Detail of the orthophoto used for GIS-analysis: the two dominant roof types in Ramallah can be identified: flat concrete roofs (grey) and sloping clay tile roofs (red).

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