Nari (calcrete) outcrop contribution to ancient agricultural terraces in the Southern Shephelah, Israel: insights from digital terrain analysis and a geoarchaeological field survey

Oren Ackermann a,*, Tal Svoray b, Mordechai Haiman a,c

a The Institute of Archaeology, The Martin (Szusz) Department of Land of Israel Studies and Archaeology, Bar Ilan University, 52900 Ramat Gan, Israel
b Department of Geography and Environmental Development, Ben-Gurion University of the Negev, P.O.B. 653, 84105 Beer-Sheva, Israel
c Israel Antiquities Authority, P.O.B. 586, 91004 Jerusalem, Israel

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Abstract

A field survey revealed that Byzantine and Early Arab (ca. 5th to 8th century C.E.) agricultural systems in the semi-arid region of the Shephelah (central Israel) were similar to runoff agricultural systems in the arid region of the Negev (southern Israel). This similarity led to the hypothesis that systems in the Shephelah also function as runoff farms. This hypothesis is not trivial since runoff values in semi-arid regions are generally low due to intensive but short rainfall events, and due to the presence of sink patches that absorb runoff on slope surface. The aim of the current research is to examine whether runoff potential in a representative agricultural system in the Shephelah is sufficient for sustaining runoff farming. A geoarchaeological field survey and digital terrain analysis show that large Nari (calcrete) outcrops on the footslopes generate high runoff values that improve water potential. Hydrological simulations and calculations show that 230 mm of direct rainfall generates a water potential equivalent to 300 mm of direct rainfall. In view of these results, it is reasonable to conclude that the presence of Nari enabled runoff agricultural farming in the Shephelah region, even in drought years.

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1. Introduction

Water harvesting systems such as runoff farming are an agro-technology that has been used, mostly in arid areas, since ancient times (Bruins, 1990; Bruins et al., 1986; Evenari et al., 1982; Kedar, 1967; Prinz and Malik, 2002). Such systems have been identified in several continents, including Asia, Africa, North America, and South America. Those systems vary in size, ranging from micro catchment systems, to terraced wadi systems, and large diversion systems. In general, micro catchment systems are located on slopes and receive runoff from those slopes. Terraced wadi systems are generally located at the bottom of small drainage basins; they receive runoff from two slopes. Diversion systems, often located on large floodplains, are irrigated through diversion of water from flood events (Bruins et al., 1986; Gale and Hunt, 1986; Nabhan, 1986; Prinz and Malik, 2002). Ancient farmers had hydro-technological knowledge which enabled them to build simple systems that enhanced overland flow generation efficiency and continuity along a single slope (Bruins et al., 1986; Yair, 1983). They were also capable of building complex structures to channel water for tens of kilometers. Evidence of this can be found at the Moche Valley in Peru (Farrington and Park, 1978).

In the Negev desert, an arid region in southern Israel (Fig. 1), archaeological research and field surveys conducted during the 1960s show remains of agricultural runoff farming systems that spanned an area of 40 km² (Kedar, 1967). Surveys
and excavations carried out during the 1980s dated these systems mostly to the late Byzantine and Early Arab periods (ca. 5th to 8th century C.E.), and estimated their area in the Negev Highlands alone to be 300 km² (Haiman, 1995a,b). Recent archaeological field surveys (Haiman, 2006; Haiman and Fabian, in press) in the Shephelah, a semi-arid region in central Israel, revealed agricultural systems similar to those observed in the Negev. This is the first time such systems have been documented in Israel’s semi-arid region. They may suggest that the population in the southern Shephelah used runoff water potential to support agricultural farming.

Though the remains of agricultural systems in the Negev and the Shephelah are similar, environmental conditions in the two regions differ. Surface properties and climatic conditions in semi-arid regions tend to result in lower runoff yields than in arid regions (Lavee et al., 1991, 1998); in general, water supply in runoff farming relies mostly upon harvested rainwater. This raises the question of whether runoff farming is possible in the Shephelah, a semi-arid environment.

According to Bruins et al. (1986), three basic landscape elements must exist to allow sufficient rainwater harvesting to support runoff farming. These elements are as follows: (1) surface conditions that produce runoff; (2) appropriate topography for transporting runoff to cultivated areas; (3) collection area with a deep soil horizon and suitable structure for storing runoff.

We conducted a field survey in the area surrounding Hurvat Benaya (Fig. 1), located in the Shephelah region. It showed the area is hilly and its surface is covered with Nari outcrops and pockets of shallow soil. Runoff was still observed 1 week after a heavy rain event of 72 mm as interflow on the soil/Nari interface (Fig. 2). This observation led to the hypothesis that Nari outcrops may act as a significant source of runoff in this environment, possibly enabling agricultural cultivation based upon this water source.

The aim of this research is to examine whether runoff farming may have been a viable agro-technology in Israel’s semi-arid region during ancient times. The research incorporated a simulation of upslope contributing area using digital terrain analysis (DTA), and a field survey to map surface conditions and measure soil depth. This spatially explicit approach allowed the assessment of runoff and water potential in the complete system, as well as in a single terrace.

2. Runoff characteristics in arid and semi-arid environments

Runoff caused by rainfall excess over infiltration is typical to arid environments. This type of runoff occurs mainly as a result of short rain events with high intensity. Due to the short duration of the rain events, the runoff is usually short-lived, and flows over a short distance (Lavee and Yair, 1990; Puigdefabregas et al., 1998). In most cases, runoff water is absorbed by colluvial units; this holds true for both arid and semi-arid footslopes (Lavee et al., 1998; Yair and Kossovsky, 2002). The length of the runoff contributing slope and runoff flow connectivity increase with increased storm duration (Yair, 1983).

The annual average runoff coefficient is generally higher in arid than in semi-arid environments (Lavee et al., 1991, 1998). The surface in semi-arid environments is often characterized for transporting runoff to cultivated areas; (3) collection area with a deep soil horizon and suitable structure for storing runoff.

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by a mosaic pattern of alternating source and sink patches. Source patches provide contributing runoff; they are composed of bare soil and rocky outcrops. Sink patches absorb rainfall and runoff; they are composed of soil pockets, small rock fragments that lie on the surface, vegetation, and biological crust (Lavee et al., 1998).

At the beginning of a rain event, after 1–3 mm depth of accumulated rainfall, rock outcrops generating overland flow reach the coefficient value of 50–100% (Yair, 1983; Yair and Kossovsky, 2002). The amount of runoff increases dramatically with an increase in the area of rock outcrop, and its connectivity (Poesen and Lavee, 1994; Yair and Lavee, 1976). Generated runoff is absorbed by adjacent sink patches along the slopes, and colluvium on the footslopes. Overall, runoff connectivity is generally low on slope surfaces in semi-arid environments; hence, runoff events in channels below those slopes are quite rare (Yair and Kossovsky, 2002).

However, in areas that include shallow soil pockets, saturation may occur and runoff may be generated downslope (Martínez-Mena et al., 1998). Ackermann (1995) reports that in rainfall simulation experiments, shallow soils (about 3 cm) covered by biological crusts are prone to saturation after 15 mm of accumulated rainfall. In a rainfall simulation experiment in the northern Judean mountains, in an area similar to the research area and composed of alternating rocky outcrops and soil pockets, Lange et al. (2003) found that saturation occurs after 53 mm of accumulated rainfall from two separate spells conducted over two consecutive days. The runoff coefficient was 80–90%, with high connectivity along the entire 18 m slope. The effect of sink patches was reduced dramatically.

3. Ancient runoff farms in southern and central Israel—archaeological background

The remains of ancient agricultural systems in the Negev desert are the dominant element among the well-preserved sites characterizing the area. Early research dated the remains of desert agriculture to the Nabatean period (ca. 2nd century B.C.E to 2nd century C.E.). However, after various studies including the Negev Emergency Surveys and excavations conducted from 1979 to 1990, it is quite clear that agricultural remains date to the late Byzantine and Early Arab periods (ca. 5th to 8th century C.E.) (Haiman, 1995a,b).

Terraced wadi systems located in small drainage basins situated in the bottom of valleys have been found. These systems functioned as runoff farms, and were characterized by Bruins (2003). These farms contained terraces that were bound by a check dam-like pattern of retaining walls that stretched across the width of the valleys, and were built directly onto the hard bedrock. In some instances, the terrace walls were extended progressively upwards as soil accumulated in the terraced field due to the transport of sediment by runoff flows (Bruins, 1986; Bruins and van der Plicht, 2004).

Recent archaeological studies show that the remains of desert agriculture span three distinct environmental regions:

1. The Negev Highlands—hyper-arid to arid
2. The Beer-Sheva Valley—arid to semi-arid
3. The Shephelah Region—semi-arid

In addition to the terraces, in all of these regions the systems consist of various installations including water cisterns, watch towers, winepresses, threshing floors, and enigmatic small stone mounds known as tuleilat el anab. It is widely believed that these mounds were constructed in order to improve the flow of runoff rainwater to the terraced wadis. The agricultural systems also include several farmhouses of various sizes, ranging from a single structure to scores of structures.

It seems that peripheral farming was not a local development, but marks a general trend during the Byzantine and Early Arab periods, perhaps with the aim of filling the area with agricultural farms in consideration of border policy (Haiman, 2006).

4. Water potential in ancient runoff farms in the Negev

Water harvesting efficiency was improved by ancient farmers in the Negev. They collected small rock fragments from the surface and place them in tuleilat el anab on the slope. Small rock fragments shield the surface from the impact of the falling rain thereby reducing runoff. By reducing the surface area covered by small rock fragments, runoff yield increases from 5% to 15–20% (Evenari et al., 1982). Low water conduits were built stretching from the top of the slopes to fields that were established at the footslopes to improve water connectivity (Yair, 1983). The annual water potential for the agricultural fields was equivalent to direct rainfall of 300–400 mm. This was calculated by adding the direct annual average rainfall and the average annual harvested runoff (Evenari et al., 1982).

The water that reached the field surface penetrated to the terrace fill, a loamy silty material that acted as a water container. Through soil micro-morphologic testing, Bruins (1986) revealed layers rich in iron concretions, attesting to localized saturation conditions. This led to high water retention and high soil moisture throughout the year, conditions which enabled fruitful agriculture.

5. Research area

The current research was conducted in a representative agricultural system situated in the area of Hurvat Benaya, 420 m above sea level, at the transition between the upper Judean Shephelah (Judean foothills), and the southern Judean ridge, southern Hebron monocline (Fig. 1). The area is characterized by low hills that are dissected by small dry valleys of the first to second drainage basin orders. The area is primarily composed of white chalk covered by thick calcere crust, known locally as Nari. The chalk is of the middle Eocene Age, being the “Maresha” member of the “Zor’a” formation (Hirsch, 1983).

The soil is Brown Rendzina, located in pockets on the Nari crust that covers the hillslopes. The valleys at the footslopes are composed of Brown Colluvial/Alluvial Rendzina soil.
The vegetation, part of the xeric Mediterranean phytogeographic region, is characterized by dwarf shrubs, mainly *Sarcopoterium spinosum*.

The climate is semi-arid, characterized by a hot, dry summer and a cool, rainy winter. The mean annual temperature is 17–19 °C. The mean temperature in January is 7 °C, and the mean temperature in August is 26 °C. According to Hole (2006), 200–250 mm annual average rainfall is the threshold for sustainable rain-fed agriculture in the Middle East. Hole also found that a wide range of interannual rain fluctuation may affect interannual agricultural yields. The mean annual rainfall in the study area is 250–300 mm (Department of Surveys, 1985), thus slightly wetter than the threshold identified by Hole. The rainy season generally lasts from October to May, and there is a wide range of interannual rain fluctuation.

6. Methodology

Our research is composed of two distinct components:

1. Archaeological and geoarchaeological field surveys. These were conducted to examine and characterize the small basin valley and the agricultural terraces within the valley.
2. Estimation of water potential in the terrace fields. This was done by calculating direct rainfall and conducting a hydrological assessment of additional runoff. These estimates were obtained in the following manner:
   - Rainfall calculations using data from nearby rainfall measurement stations
   - Calculation of runoff contributing areas using DTA
   - Runoff value assessment in saturated and non-saturated surface conditions

6.1. Archaeological and geoarchaeological field surveys

6.1.1. Terrace mapping

A single agricultural system, representative of the area in general, was chosen for these surveys (Fig. 3). Physical characteristics such as elevation, inclination, and surface cover were assessed for slopes and terraces. Terrace retaining walls were mapped using GPS; the lengths of the walls and the distances between them were confirmed through manual measurement using meter tape. This combined data provided the location of the retaining walls and allowed the compilation of a GIS layer of 13 terraces. Terrace borders delimited by the footslopes were marked manually on the airphoto (Fig. 4a).

6.1.2. Soil depth pockets

To determine soil depth along the slopes, four representative cross-sections, two on north-facing aspects and two on south-facing aspects, were selected. An iron pole was inserted into the center of 84 soil pockets until it was stopped by the hard bedrock. In each pocket, the penetration depth of the pole was measured and recorded as the maximum pocket depth. To verify that the pole was stopped by bedrock and not rock fragments in the soil, two pits were dug in each section using a hoe. When bedrock was reached the depth was measured; this depth was similar to the depth reached in most soil pockets.

6.2. Estimation of water potential in the terrace fields

6.2.1. Calculation of runoff contributing areas using DTA

The use of DEM for calculating runoff contributing area is widespread among scientists as well as practitioners. It has been found reliable for various purposes including flood simulation, building water reservoirs and dams, and bridges and roads planning and design (Wilson and Gallant, 2000). Potential contributing area is usually calculated based on the assumption that water accumulates downslope with increasing contributing area towards the channel. While using grid-based models, most methods assume that contributing area is estimated by applying three steps (Fig. 5a–c): (1) calculating the steepest slope for each cell in the DEM; (2) determining the flow direction based on the steepest slope; and then (3) calculating the flow accumulation matrix for each cell based on water flow simulation.

This paradigm, usually named D8 (O’Callaghan and Mark, 1984), was found useful for assessment of contributing drainage area in the nearest Beer-Sheva drainage basin (Svoray, 2004). In the study area, however, previous studies have shown that runoff flow has a more complex mechanism and the connectivity between slope units is often limited due to the existence of sinks along the slope. To better express the flow mechanism, in the study area, we have mapped explicitly the surface covers in the entire catchment and divided them into three categories: bare rock, vegetation, and soil. The maximum likelihood algorithm was used to classify an orthophoto taken in summer 2003.

The training sets where derived using data collected in the field. To validate image classification, an accuracy assessment was carried out using visual interpretation of the aerial photographs and field observations, on a sample of 100 pixels per class. As is common in remote sensing, accuracy was tabulated in a confusion matrix i.e., a table wherein each predicted class is plotted against the observed class and the number of

![Fig. 3. General view of agricultural terrace system in the research area. Note the large rock coverage in the footslope.](image-url)
items within each is compared. Manual interpretation was found reliable for accuracy assessments to the three land covers studied here in several similar landscapes (Svoray et al., 2007; Svoray and Carmel, 2005), and in our analysis of the study area.

For calculating contributing drainage area from elevation data, we used the eight flow direction matrix method (D8) that is embedded in the ARC/INFO workstation tool. The elevation data used is a contour-based DEM extracted from 5-m interval topographic maps of the Survey of Israel from the National GIS project. Extraction was done by creating a Triangulated Irregular Network (TIN) from the contour lines, then, the TIN was converted into a Raster DEM, all applied using the 3D Analyst toolbox in ArcGIS 9.1. Each cell in the output DEM is assigned with elevation in meters AMSL with 8 m spatial resolution and vertical RMSE of 2 m (Fig. 5a). After the DEM was available, pits (artificial low points in the DEM) were filled. Flow direction matrix was calculated and flow direction was assigned for each grid-cell, based on the steepest slope among its eight surrounding neighbors (Fig. 5b). In the next step, we calculated the runoff accumulation in each cell, in the catchment area, using a counter.
Flow accumulation calculations on the DEM are being weighted based on the surface covers (Fig. 5c). The entire database was adjusted to the Israel New Grid coordinate system. Both the DEM and the airphoto were geometrically corrected with less than 1 pixel RMS error, based on 48 ground control points, through a first order transformation. To facilitate data integration, the database was resampled to 1 m pixel size using the nearest neighbor algorithm.

6.2.2. Runoff coefficient

Runoff calculations were based on runoff coefficients obtained from studies of similar geomorphologic and climatic regions (Table 1). These studies include data from a rocky surface under arid conditions in the Negev (Yair, 1983); a small drainage basin under semi-arid conditions in the northern Negev near Lehamiv (Yair and Kossovsky, 2002); and a mosaic surface composed of alternating rocky outcrops and shallow soil pockets under sub-humid Mediterranean conditions in the Judean mountains (Lange et al., 2003).

Those studies show that runoff coefficient in rocky areas is 51% in a 63 m slope, and 100% in a 33 m slope. Accumulated rainfall of 1–3 mm is the threshold for runoff generation on the rocky surface. The runoff coefficient in a surface comprised of soil and sediment is 1.5% in a 20 m slope, 6–7% in an 8 m slope, and 37% in a 4 m slope. In general, runoff coefficient decreases as slope length increases. According to rainfall experiments conducted in an area with similar surface characterization by Lange et al. (2003), accumulated rainfall of 53 mm is considered the threshold value for saturation and connectivity runoff along the entire slope.

The estimations for runoff development were divided in the framework of this research into two phases: (1) runoff in unsaturated conditions; and (2) runoff during saturation. In the first phase, the runoff coefficient for rocky surfaces was valued at 51%; for soil pockets and vegetation, it was valued at 1.5%. During unsaturated conditions, runoff is generated primarily on rocky outcrops; most of it is likely absorbed in soil pockets. The primary runoff contribution in field terraces is from rocky outcrops situated at the bottom of the slopes. In the second phase, the runoff coefficient for rocky outcrops was valued at 90%; for soil pockets and vegetation, it was valued at 1.5%. During unsaturated conditions, runoff is generated primarily on rocky outcrops; most of it is likely absorbed in soil pockets.

Flow accumulation calculations on the DEM are being weighted based on the surface covers (Fig. 5c).

The entire database was adjusted to the Israel New Grid coordinate system. Both the DEM and the airphoto were geometrically corrected with less than 1 pixel RMS error, based on 48

6.2.3. Rainfall calculations using data from nearby rainfall measurement stations

Rainfall data was purchased from the Israeli Meteorological Service (IMS). Representative years ranging from years of extreme drought to those with very rainy seasons were selected to reflect interannual rainfall fluctuations in the research area. Annual daily rainfall data recorded at the following meteorological stations was collected: the Beit Govrin station, located 15 km north of the study area; the Lahav station, located 12 km south of the study area; and the Dvira station, located 11 km southwest of the study area. Daily rainfall depth data at Hurvat Benaya was calculated by compiling the average daily rain depth data recorded at these stations.

In the hydrological years 1995/6, 1996/7, and 1997/8, the annual rainfall was 328 mm, 332 mm, and 319 mm, respectively. The year 1998/9, with only 137 mm of rain, represents a severe drought year. The year 1999/2000, with 237 mm of
rain, represents a moderate drought. The year 2004/5, with 395 mm of rain, represents a relatively rainy year.

6.2.4. Runoff value assessment in saturated and non-saturated surface conditions

Annual water potential in each of the terraces was calculated as the sum of direct rainfall and additional contributing slope runoff, as presented by the following equation:

\[
\text{AWP} = \text{ADR} + \text{ACR}
\]

where AWP is Annual Water Potential (mm); ADR is Annual Direct Rainfall (mm); ACR is Annual Contributed Runoff (mm).

Annual Contributed Runoff (ACR) was calculated as the sum of contributing runoff from Phase 1, in unsaturated conditions (unsat), and Phase 2, in saturated conditions (sat).

\[
\text{ACR} = \left( \frac{\sum_{i=1}^{n} \text{DR}_i \times \frac{\text{CA}_i}{\text{TA}_i}}{\text{TA}_i} \right)_{\text{unsat}} + \left( \frac{\sum_{i=1}^{n} \text{DR}_i \times \frac{\text{CA}_i}{\text{TA}_i}}{\text{TA}_i} \right)_{\text{sat}}
\]

where \( n = \) Number of Rain Events; \( \text{DR}_i = \) Direct Rainfall (mm); \( \text{CA}_i = \) Runoff Contributing Area (m²); and \( \text{TA}_i = \) Terrace Area (m²).

\( \text{DR}_{\text{unsat}} \) was considered as the accumulative rain depth that was calculated in every rain event from 3–53 mm.

\( \text{DR}_{\text{sat}} \) was considered as the accumulative rain depth that was calculated in every rain event exceeding 53 mm. This quantity was calculated for rain depth over 53 mm.

\( \text{CA/TA} \) is the relation between the runoff contributing area and the terraced area. Multiplying \( \text{DR} \) by \( \text{CA/TA} \) provides the additional runoff in values equivalent to direct rainfall.

This calculation was based on the assumption that runoff is equally distributed across the terrace surface.

In the current research, a rainfall event may be any of the following situations: a single rainy day; consecutive rainy days; consecutive rainy days with an intermittent rain-free day. In the latter, it is assumed that soil moisture remains at a high level throughout the rainy period, despite the intermittent dry day.

The duration and intensity of rainfall events were not taken into account. In general, high vegetation cover creates interception in sink areas while rocky outcrops in source areas have low capacity for water infiltration. It is likely that these surface components will behave similarly under different duration and intensity conditions.

To increase caution, runoff assessments obtained in the current research are presented in minimal values. Minimal runoff coefficients for all landscape components were used. Areas covered by biological crusts were categorized as vegetation units, even though biological crusts generally increase runoff. Biological crusts are generally situated on shallow soil (10 cm or less) characterized by wide cracks. These cracks allow water to be conveyed at a relatively high speed, often resulting in interflow along the interface of soil and rock surfaces (Fig. 2). These interflows may last for several days after the rainfall event, thereby contributing water potential for a relatively long duration. Water potential from interflow was not counted in the calculations.

7. Results

7.1. Archaeological and geoarchaeological field surveys

In a field survey conducted in the winter of January 2005, one week after a rainfall event of 72 mm, interflow was observed running down the bedrock in the research area (Fig. 2). Such a flow is typical to areas under saturated conditions. The field survey revealed that the area is composed of small drainage basins of the first to second orders. The drainage basin selected for this research has a total area of 0.2 km². The bottom of the basin valley contains an agricultural terrace system composed of 16 walls. The height of the walls is 1–1.2 m, and they are characterized by a check dam-like pattern of retaining walls (Fig. 3). The wall bases do not reach bedrock, but are constructed on fine fill sediments. These “floating terraces” characterize stable conditions (Ackermann et al., 2005). The slopes that border the terraces are characterized by rocky outcrops and shallow soil pockets overlaying the Nari outcrops. Some of the soil pockets are covered by biological crust.

Depth measurement of the soil pockets reached a maximum depth of 42 cm on the north-facing aspect, and 26 cm on the south-facing aspect. The average depth is 20 cm on the north-facing aspect, and 15 cm on the south-facing aspect. Minimum soil depth measured in the patches is about 10 cm.

7.2. Estimation of water potential in the terrace fields

7.2.1. Contributing runoff area calculations

An overall accuracy of 95% was resulted from the analysis of confusion matrices. This level of accuracy is satisfactory.
and is similar to other achievements in airphoto classifications that were applied to the four land cover classes in adjacent study areas (Svoray and Carmel, 2005; Svoray et al., 2007). Table 2 shows the number of cells that contribute runoff to each terrace under both unsaturated and saturated conditions. The values in terraces 4 to 9 range between 0.44 and 0.87 cells in unsaturated conditions, and between 1 and 2 in saturated conditions. The values in terraces 10 to 16 range from 0.17 to 0.065 in unsaturated conditions, and from 0.4 to 0.04 in saturated conditions.

7.2.2. Annual water potential assessment

Annual water potential was quantified for terraces 4 to 16. In every terrace, annual water potential was expressed as the sum of direct rainfall and additional runoff. Table 3 shows that the average water potential for all terraces in the drainage basin in the years studied is 380 mm per year. Water potential ranges from 169 mm in a drought year to 532 mm in a very rainy year. Runoff absorbed by the terraces is equivalent to 24–32% of direct rainfall. Rainfall events with more than 53 mm accumulated rain generally occur only once or twice a year; in the drought year, such rainfalls do not occur at all.

Fig. 6 shows the water potential in each terrace through graphs A to D. In each graph, a thick dashed line marks 300 mm of rainfall, the threshold between the semi-arid and sub-humid Mediterranean environments (Goldreich, 2003). A thin dashed line marks annual direct rainfall.

Graph A, which presents the annual average water potential for the years studied, shows that water potential does not fall below 300 mm equivalent to direct rainfall per year. The water potential in terraces 4 to 9 is higher than 300 mm, and up to 500 mm per year. Graph B, which presents the water potential for 1999/2000, shows that 237 mm of direct rain fell, 84% of the average annual. In terraces 4 to 9, the water potential is higher than 300 mm; in the other terraces, it is lower than 300 mm. Graph C presents the water potential for 1998/9, a drought year. The graph shows that 137 mm of direct rain fell, about 40% lower than the annual average. Water potential in all terraces was lower than 300 mm. Runoff contribution was calculated at 60 mm for terraces 4 to 9, resulting in a total water potential of about 200 mm. There was minimal runoff contribution, if any, in terraces 10 to 16. Graph D presents the water potential for 2004/2005, a very rainy year. The graph shows that 395 mm of direct rain fell. The water potential was higher than 300 mm in all terraces.

These results show that the average water potential in the terraces is higher than 300 mm in most years. Even in a year with 237 mm of direct rain, the water potential in terraces 4 to 9 exceeded 300 mm per year. Indeed, it is only during extreme drought years that the water potential in these terraces is lower than 300 mm per year. It is important to note that terraces 4 to 9 are bounded on two sides by rocky outcrops (Figs. 2 and 4a). The direct contact of the agricultural

Table 2

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</tbody>
</table>

CA, runoff contributing area; TA, terrace area.

Table 3

<table>
<thead>
<tr>
<th>Terrace number</th>
<th>Annual Water Potential (AWP) in the terraces (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>567</td>
</tr>
<tr>
<td>5</td>
<td>599</td>
</tr>
<tr>
<td>6</td>
<td>512</td>
</tr>
<tr>
<td>7</td>
<td>468</td>
</tr>
<tr>
<td>8</td>
<td>465</td>
</tr>
<tr>
<td>9</td>
<td>550</td>
</tr>
<tr>
<td>10</td>
<td>381</td>
</tr>
<tr>
<td>11</td>
<td>336</td>
</tr>
<tr>
<td>12</td>
<td>351</td>
</tr>
<tr>
<td>13</td>
<td>332</td>
</tr>
<tr>
<td>14</td>
<td>348</td>
</tr>
<tr>
<td>15</td>
<td>361</td>
</tr>
<tr>
<td>16</td>
<td>360</td>
</tr>
<tr>
<td>Average water potential for all terraces</td>
<td>433</td>
</tr>
<tr>
<td>Total direct rainfall</td>
<td>328</td>
</tr>
<tr>
<td>% Runoff of total direct rainfall</td>
<td>32</td>
</tr>
<tr>
<td>No. of events with more than 53 mm rain</td>
<td>2</td>
</tr>
<tr>
<td>% Runoff in saturated conditions from annual runoff</td>
<td>21</td>
</tr>
</tbody>
</table>
field with the sealed surface of the outcrops supplies a high level of runoff to the field (Fig. 4b).

7.3. Relation between annual rainfall and annual water potential

Fig. 7 shows the annual relationship between direct rainfall and assessed water potential in all terraces. In general, the results show that surface conditions in the study area improve water availability by approximately 31%. The graph also shows that minimum direct rainfall of 230 mm per year is necessary for achieving an average annual water potential of 300 mm for all terraces. The results also show that in years with annual rainfall of less than 230 mm, water potential will not be improved beyond 300 mm.

8. Discussion

In this research, we ask whether the terraces in the Hurvat Benaya area could have functioned as runoff farms. More specifically, we ask whether water potential in this semi-arid region allowed for sustainable farming. To answer this query, the research examined whether the essential conditions for runoff farming described by Bruins et al. (1986) existed in the Hurvat Benaya terrace system.

8.1. Surface conditions

The field survey and airphoto classification revealed that rocky outcrops are a prominent feature on the surface of the slope. Previous studies have already shown that such surface conditions significantly enhance runoff generation (e.g., Martínez-Mena et al., 1998; Yair and Kossovsky, 2002). Avni (2005) even shows that agricultural farming can be based on runoff from this source.

In general, slope runoff in arid and semi-arid regions is absorbed by the colluvium (Lavee et al., 1998; Yair and Kossovsky, 2002). When rocky outcrops cover the footslope, a unique situation is created in which relatively small rain events, even ones that result in just 3 mm of direct rainfall, can generate
runoff that reaches the terraces (Yair, 1983; Yair and Kossovsky, 2002). In the research area, the presence of large rocky outcrops on the footslopes dramatically reduces runoff absorption in the slopes, allowing runoff to reach the agricultural terraces (Fig. 8a).

During heavy rain events with 53 mm or more of direct rain, we predict that the slopes in the research area are prone to saturation. Rocky outcrops function as source patches, generating high runoff yields. Soil pockets are saturated, permitting runoff connectivity along the entire slope (Fig. 8b). Clearly, connectivity between the rocky outcrops and the agricultural terraces allows large quantities of runoff water to reach the terraces (Fig. 8a,b).

The outcome in our study area is that runoff is generated in most rainfall events; the terraces are a primary site for runoff absorption due to the absence of colluvium on the footslopes. Therefore, there are improved runoff conditions in all terraces in the study area, particularly terraces 4 to 9 (Fig. 4b), as these terraces are bordered on two sides by rocky outcrops.

The interflow that results from saturated conditions on the slopes continues for several days after the rain event has ended, enhancing absorption efficiency in the terraces. This differs from arid areas, in which runoff generally ends shortly after the end of the rain event (Yair, 1983).

Hydrological calculations show that additional runoff potential of 30% over direct rainfall reaches the agricultural terraces. That is, annual water potential in the terraces is 130% annual direct rainfall. In most years, the amount of runoff received by the terraces results in total water conditions equivalent to 300 mm of direct rainfall or more. This quantity allows for successful agricultural farming in all terraces.

In 1999/2000, when direct rainfall was 237 mm, total water potential equivalent to 300 mm of direct rainfall or more was received by terraces 4 to 9, permitting successful agricultural farming in these terraces. It is important to emphasize that despite being considered a drought year; surface conditions in the study area enhanced water potential, thereby allowing successful agricultural farming in select areas. In 1998/9, when direct rainfall was just 137 mm, it is unlikely that successful agricultural farming on any of the terraces would have been possible.

Since it is likely that there were drought years here in the past, the question is raised of how ancient farmers survived such years. Research suggests that ancient farmers in the Middle East adapted to sustain interannual rain fluctuations, including droughts. These adaptations included fallow cycles, multi-crop subsistence farming, ability to shift between agriculture and livestock herding, and storage and trade of surplus yields and products (Hole, 2006).

8.2. Appropriate topography for transporting runoff and suitable structure for storing runoff

The slopes that bound the terraces have angles ranging from 21° to 31°, enabling runoff to be transported from the slopes to the terraces. The terrace fields are quite level, with angles ranging from 1° to 2°, allowing for runoff absorption. The height of the retaining walls is more than 1 m, indicating that the depth of the sediment in each terrace is more than 1 m. This depth is adequate for rainfall and runoff absorption by the fine fill material in the terrace body, and for moisture conservation during the hot dry summer.

8.3. The effect of evaporation on sustainable runoff farms

The study area is located in a semi-arid environment, and is subjected to a relatively high evaporation rate. This raises the question of whether evaporation would have inhibited sustainable runoff farming. Reference to runoff farming experiments conducted in the Negev (Evenari et al., 1982), an arid region with even higher evaporation conditions than the study area, shows that a high rate of evaporation need not inhibit successful runoff agricultural farming.

8.4. Ancient environmental conditions

One of the major questions that arises is whether environmental conditions in the past were similar to those that occur
today. Regarding surface characteristics, the slopes of the study area are currently covered by dwarf shrubs, mainly *Sarcopoterium spinosum*. It is likely that this vegetation was also dominant in the past (Lev-Yadun, 1997). It can be assumed that ancient local inhabitants practiced vegetation clearing on the slopes that would have resulted in greater bare soil thereby enhancing runoff yields (Abrahams et al., 1994, 1995; Butzer, 2005).

In terms of possible agricultural plots on the slopes, these could have existed in soil pockets along the slopes. Soil pockets are located along the upper area of the slopes while large rocky outcrops are located along the footslopes. As the outcrops contribute the majority of runoff to the terraces, their effectiveness would not have been reduced by the presence of agricultural plots in soil pockets.

Regarding the question of climatic conditions, studies show that although moderate fluctuations may have occurred in ancient times, there was likely no large difference in rainfall amounts from the present (Bar Matthews et al., 1998; Frumkin, 1997; Schilman et al., 2002).

9. Conclusions

According to the criteria set out by Bruins et al. (1986), our data support the hypothesis that the agricultural system examined here could have functioned as a runoff farm. Large parts of the surface area of the slopes are composed of large Nari outcrops; those situated at the bottom of the slope have a particularly significant contribution to runoff generation as they generate runoff even in short rain events. Since 3 mm accumulated rainfall is the threshold for runoff generation, the agricultural terraces receive runoff in almost every rain event.

Runoff calculation assessment was divided into two phases: (1) Runoff generated under unsaturated conditions; (2) Runoff generated during saturated conditions. We assumed that during unsaturated conditions, when rainfall depth is 3–53 mm, rocky outcrops adjacent to the terrace fields are the major contributor of runoff to the terraces. We assumed that under saturated conditions, when rainfall depth exceeded 53 mm, runoff connectivity exists along the slopes therefore the entire slope contributes runoff to the terraces.

DTA calculations, based on minimal values to ensure realistic results, show that annual direct rainfall of just 230 mm results in a total water potential of 300 mm, the threshold for successful farming in this area. According to these results, therefore, the presence of Nari played an important role in sustaining runoff agricultural farms in this semi-arid region. These natural structures generated runoff to the terraces, enabling them to receive sufficient water supply. Even in drought years, most of the terraces could have sustained agricultural farming.

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