



**AgEcon** SEARCH  
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

**This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.**

**Help ensure our sustainability.**

Give to AgEcon Search

AgEcon Search  
<http://ageconsearch.umn.edu>  
[aesearch@umn.edu](mailto:aesearch@umn.edu)

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

# Water harvesting options in the drylands at different spatial scales

Akhtar Ali<sup>1</sup>, Theib Oweis<sup>1</sup>, Mohammad Rashid<sup>2</sup>, Sobhi El-Naggar<sup>3</sup> and Atef Abdul Aal<sup>4</sup>

<sup>1</sup>International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria

<sup>2</sup>Soil and Water Conservation Research Institute (SAWCRI), Chakwal, Pakistan

<sup>3</sup>Matrouh Resource Management Project (MRMP) (1999-2003), Matrouh Egypt

<sup>4</sup>General Commission for Scientific Agricultural Research (GCSAR), Damascus, Syria

---

## Abstract

The effect of spatial-scale variations on water harvesting has been evaluated at micro-catchment, hillside/farm, and watershed (= catchment) scales in three relatively dry environments in Syria, Pakistan and Egypt. Micro-catchment water harvesting captures localised runoff only through independent micro-catchment systems and is not influenced by hill slope runoff and stream flows. In Syria, it was found that only a fraction of total runoff from a catchment is collected, with no significant effect on water supply downstream. Therefore, it is less sensitive to spatial-scale variations (rainfall, topography, soils) and it is less likely to create upstream–downstream water-use conflicts. Micro-catchment water harvesting established fodder shrubs, with 3–7 fold growth improvement and 27 to 90% survival rate. In contrast, spatial rainfall and geo-hydrological variations greatly influenced the potential of water harvesting at the watershed scale in north-west Egypt. The study revealed the importance of scientific data and appropriate assessment methods. Due to potential socio-economic disputes, the institutional arrangements for water allocation and conflict resolution are critical at this scale. At the farm scale, the low-cost farm runoff structures (US\$ 48 per structure), effectively regulated the runoff, reduced terrace damage and improved field soil moisture, and were shown to be suitable for water harvesting on terraces in Barani, Pakistan. The study infers that water harvesting in the drylands is a viable option to improve productivity and conserve natural resources, if it is appropriately implemented. Nevertheless, the size of the water harvesting system and the spatial scale at which it is to be implemented determine the options for water harvesting.

---

## Introduction

Drylands represent about 40% of the global area, spread over 110 nations, and their importance in food security contribution is well-acknowledged (FAO, 1978; Parr *et al.*, 1990). These are ecologically diverse and economically important areas (Behailu, 2001). Rainfed farming and livestock husbandry are the main sources of livelihood of majority of the rural population. Land degradation is common and productivity is low, and these are generally

linked to erratic rainfall, fragile soils and poor management of the available water resources. Rainfall is the main source of freshwater and people harvest rainwater for domestic and agricultural uses.

Water harvesting is a process of inducing, capturing and storing rainwater or stream flow to improve soil moisture or for subsequent uses (Boers, 1994; Boers and Ben-Asher, 1982; Critchley and Siegert, 1991; Oweis *et al.*, 1999). The benefits of water harvesting include domestic water supply,

the speeding up of tree establishment and deep root development (Boers, 1994), increase in crop productivity and diversity (Gatot *et al.*, 1999), and stabilising crop yields in poorly distributed rainfall areas (Oweis *et al.*, 2001). Other rarely evaluated benefits of water harvesting may include: reduced soil erosion and downstream flood peaks, and rehabilitation of degraded land. Some unsuccessful examples of water harvesting from Sudan (FAO, 1994) and the Ethiopian highlands (Shiferaw and Holden, 1998) are also reported in the literature. Batchelor *et al.* (2002) indicated that water harvesting, if used inappropriately, can lead to inequitable access to water resources and, in the extreme, to unreliable drinking water supplies. Tikue (2002) emphasised the need to integrate geophysical, agro-hydrological and socio-economic factors in water harvesting planning.

Water harvesting depends on rainfall amount and pattern (Reij *et al.*, 1988), topography and water storage capacities of the soils (Huibers, 1985), which are spatially variable. The variability in these governing factors plays an important role in determining the options for water harvesting. At the small scale, this variability can be less significant, may be easily understandable and its implications can be determined with moderate efforts. As the spatial scale increases, for example to the hillside, the spatial variability becomes important and other factors come into play (Gupta and Waymire, 1998). Beyond the hillside, for example at the watershed that may include many hill-channel networks, the complexity of the hydrological mass balance becomes more pronounced. Also, the runoff efficiency can decrease significantly with the increase in catchment area. Stern (1979) inferred that under the same hydrological conditions, a runoff equal to 50% of incident rainfall may be expected from a small area as compared with a complete river basin, for example, where it hardly reaches 5% of the rainfall. Shanan and Tadmor (1979) found that under given climate and soil conditions, the runoff per unit area increased from 10 to 30 times when the catchment area was reduced from 500 to 0.02 ha. Related to this is a trade-off between upstream and downstream water uses: spatial-scale variation can greatly influence water harvesting in drier environments. This paper presents case studies from three diversified drier environments in Egypt, Pakistan and Syria and provides some insight into potential options for water harvesting at different spatial scales.

## The study sites

### North-west Egypt

Over 200 watersheds in north-west Egypt (between latitudes of 25° 10' and 29° 50') serve more than 200 000 people to maintain their livelihoods. The people harvest rainwater for domestic and agricultural uses, to raise orchards and other crops. The World Bank financed the Matrouh Resource Management Project (MRMP, 1997–2003), aimed at the management of natural resources in watersheds over 21 000 km<sup>2</sup> area from Daba to Solume in north-west Egypt (Fig. 1). This study investigated the water harvesting potential in five watersheds whose area varies between 1 and 37 km<sup>2</sup>. A Mediterranean climate with mild winters and hot summers largely prevails. The climatic data (Table 1) for Matrouh in north-west Egypt (1945–92), shows an

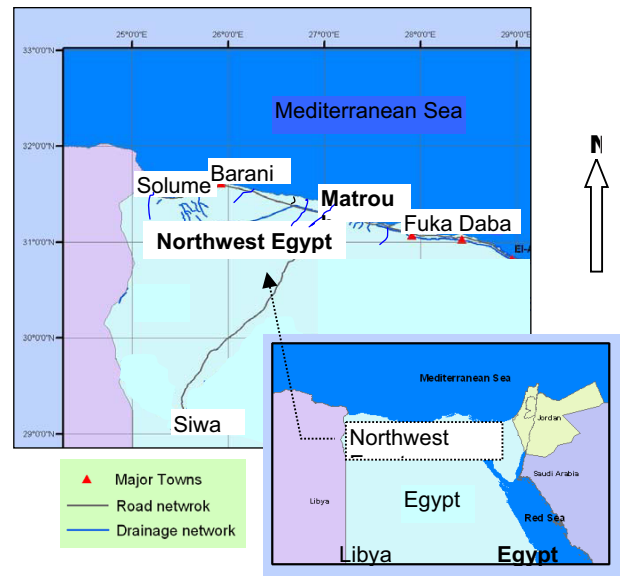


Figure 1. Location map of northwest Egypt

average annual rainfall of 155 mm, with coefficient of variation of 0.42 as compared to temperate climates where this coefficient varies between 0.1 and 0.2 (Thames, 1989). The annual evaporation is 1578 mm. The ratios of maximum and average annual rainfall to annual minimum rainfall are 8.1 and 4.56, respectively. Based on FAO (1981) criteria\*, dry, average and wet years occur for 38, 30 and 32% of the time, which indicates a frequency of occurrence of dry spells of 4 out of 10. According to UNESCO (1977) criteria for characterisation of semi-arid, arid and hyper-arid, the rainfall–evaporation ratio ( $P/E=0.09$ ) determines the study site as being an arid environment ( $P/E=0.03–0.2$ ).

Shallow soils underlain by soft to hard rock and hillsides cover the dominant part of the watersheds' drainage areas. Deep soils, mostly transported, are found in depressions, upstream of wadi dikes and in coastal plain. The soil texture varies from sandy loam to loamy sand. MRMP (2001) describes the soils as poor in organic matter (less than 0.25%) and deficit in macro- (nitrogen and phosphorus) and micro-nutrients (copper, zinc and manganese). The pH varies between 7 and 8. On all public land (according to government decree: Law: 124 of 1958, 17 of 1969 and 100 of 1969), the Bedouins have legal rights of using water and land. Visible investment in land and water also allows land selling rights.

Coastline–inland variations in topography and rainfall divide the watersheds into five agro-ecological zones (El-Naggar *et al.*, 1988). Zone 1 extends 5–7 km inland, comprises the coastal plain and receives rainfall between 150 and 160 mm. Orchards and urban area are the main land uses. Zone 2 extends from 7 to 20 km inland at 100 to 200 m above sea level. It consists of main wadis and escarpment

\*According to FAO (1981) criteria, dry conditions if annual rainfall below 75% of average annual rainfall, average conditions if annual rainfall between 75 and 125% of average annual rainfall and wet conditions prevail if annual rainfall above 125% of average annual rainfall.

**Table 1.** Main climatic data at Matrouh in northwest Egypt

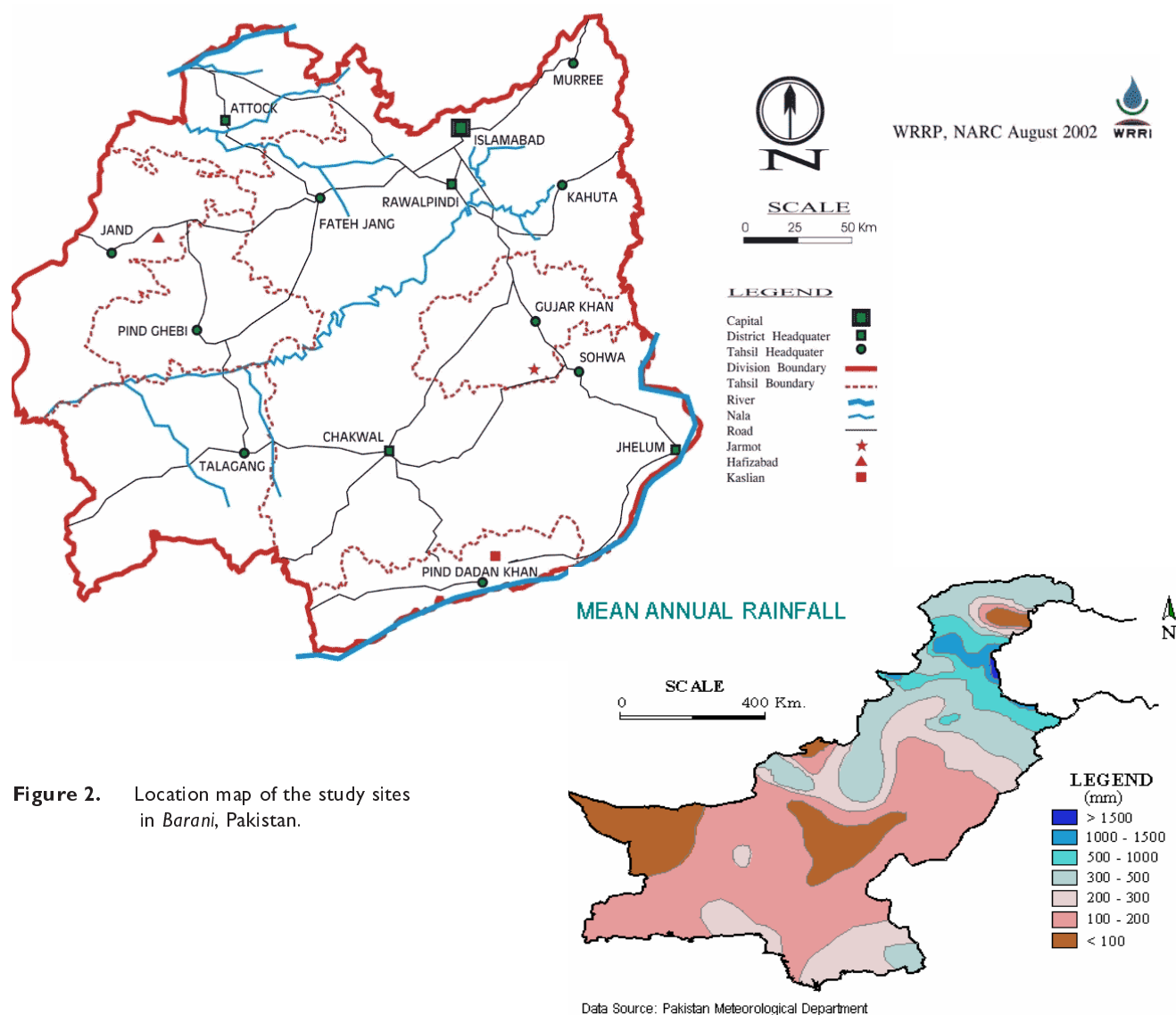
Climatic parameters	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall (mm)	36.8	21.3	12.0	3.8	2.7	1.1	0.0	0.5	1.5	16.1	23.6	36.0	<u>155.4</u>
Temp. (max) C°	18.0	18.8	20.2	22.6	25.5	27.7	29.1	29.8	28.6	27.0	23.3	19.6	24.4
Temp. (min) C°	8.0	8.3	9.6	11.7	14.5	18.1	20.1	21.0	19.6	16.7	13.2	10.0	14.2
ETo (mm)	90	85	115	145	160	158	180	175	150	130	100	90	<u>1578</u>
Radiation (cal.cm <sup>-2</sup> d <sup>-1</sup> )	233	319	429	538	574	590	594	553	462	343	243	232	426
Wind speed (m sec <sup>-1</sup> )	8.8	6.5	6.3	6.3	5.6	5.4	5.9	5.2	4.9	4.5	4.8	6.1	-

*The underlined values show annual total; ETo was estimated by the Penmann-Montieth method*

zones and receives rainfall between 100 and 140 mm. Barley on slope margins and orchards in wadi beds are the main land uses. Zone 3 extends from 20 to 50 km inland and receives from 60 to 100 mm annual rainfall. It largely consists of flat topography and numerous depressions. Barley and grazing are the main land uses. Most of the watersheds along the north-west coast of Egypt are located in zones 1, 2 and 3. Zones 4 and 5 extend from 50 to 100 km and 100 to 200 km, respectively, having insignificant rainfall and no inhabitants and are not relevant to this study.

#### **The Barani (rainfed) area in Punjab, Pakistan**

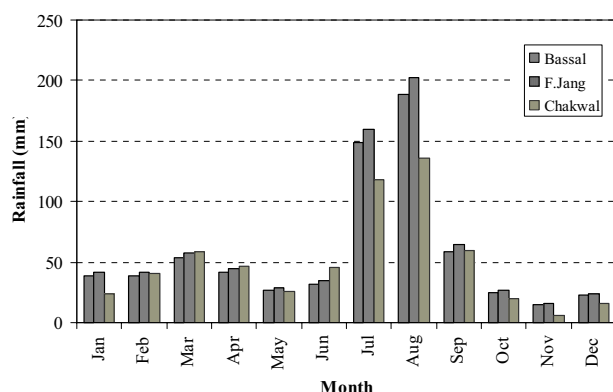
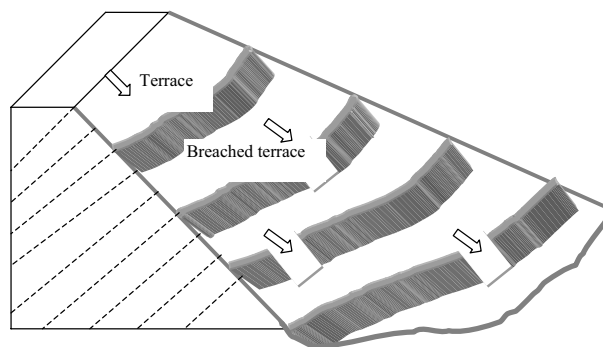
The *Barani* area is located in the Punjab Province of Pakistan between the rivers Indus and Jhelum (Fig. 2). It covers about one million ha and serves a population of over two million. It has hot summers and moderately cool winters. Average annual rainfall in *Barani* varies between 350 mm in the south to 800 mm in the north. Rainfall data for Chakwal (Table 2) show an average annual rainfall of 597 mm, with coefficient of variation of 0.36. Based on FAO (1981) criteria, dry, average and wet years occur for



**Figure 2.** Location map of the study sites in *Barani*, Pakistan.

**Table 2.** Monthly rainfall and temperature at Chakwal (1977-2000) in Barani area, Pakistan

Climatic parameters	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall (mm)	24	41	59	47	26	45	118	135	60	20	6	16	597
Max temp (°C)	20	21.9	27.4	34.6	45.5	45.5	35.7	36.7	34.7	33.8	27.2	21.9	45.5
Mini temp (°C)	0.2	3.9	7	13.8	16	16.5	24.2	22.3	20.0	14.7	5.62	2.6	0.2

**Figure 3.** Mean-monthly rainfall at three locations in Barani, Pakistan**Figure 4.** Schematic diagram of terrace fields and breaches in Barani, Pakistan

29, 46 and 25% of the time. Fig. 3 shows the monthly rainfall pattern at three locations in the *Barani* area. A large part of the hilly and semi-hilly areas in *Barani* have been bulldozer-levelled into terraced fields (0.5–1.0 m elevation) during the last 3–4 decades and that has modified the drainage pattern. Over 70% of the rural population depend on rainfed-agriculture on the terraces. The soils are deep and consist of loam and silt-loam. Table 3 shows some of the main soil parameters in the *Barani* area. The major crops include groundnut, lentil, wheat, chickpea, mash-bean and cowpea.

High intensity monsoon rains generate high runoff, which damages the terraces and existing crops, resulting in low soil moisture and causing high soil erosion. Runoff from the upper catchment (hillside) and from the neighbouring terraces causes chain breaching of the lower terraces (Fig. 4) and gully expansion downstream. Other downstream consequences include damage to infrastructure, high levels of sediment deposition in the reservoirs and deterioration of the water quality. Once a terraced field is damaged, it may take many seasons to repair and thus

several crops are lost. The *Barani* Area Development Agency constructs masonry structures for soil conservation at the outlets of sub-catchments. One such traditional structure costs US\$ 1000–2500. These structures help to control gully erosion and peak runoff rate at the catchment scale. However, they do not contribute to terraced field protection. This study evaluated farm-scale water harvesting to improve soil moisture and to conserve terraced fields.

Three study sites at Fateh Jang, Chakwal and Sohawa sub-districts were selected in the framework of the Barani Village Development Project (BVDP) (Fig. 2). Participatory planning resulted in testing low-cost farm runoff structures (FRS) using locally available stone. The topographic survey of each farm estimated the drainage area, fields' slopes, and determined elevations and natural drainage. The design of the structures considered a rainfall recurrence interval of 10 years, water harvesting requirements and safe disposal of surplus runoff from the upper fields. The discharging capacity of an FRS was fixed by considering 100% of surplus runoff from a field under consideration and 50% of the surplus flows from the upper fields. This assumption is reasonable due to different time-to-peak and the routing effect of terraces on the attenuation of the peak runoff rate. The crests were fixed on the basis of water harvesting requirements. The design parameters of the FRS were standardised for different field sizes. Figure 5 shows a schematic plan of such a structure. Twenty-six structures were constructed at three sites during 2002–03 (Table 4). Rain gauges were installed to measure rainfall events. The impacts of the major storms on the performance of the structures were noted; these performance indicators included the stability of the structures to withstand high rainfall, the wetting depth in the fields and cost effectiveness. The total cost of the structures included the capital and the maintenance cost for the study period.

**Table 3.** Main soil parameters in Barani Pakistan (BVDP-ARC, 2004)

Soil parameters	Ground surface	At a depth of 1.5 m
Organic matter	0.97%	0.13%
pH	7.4	7.9
ECe	0.48 dS m <sup>-1</sup>	0.05 dS m <sup>-1</sup>
Available phosphorus	10 mg kg <sup>-1</sup>	2 mg kg <sup>-1</sup>
Available potassium	150 mg kg <sup>-1</sup>	76 mg kg <sup>-1</sup>

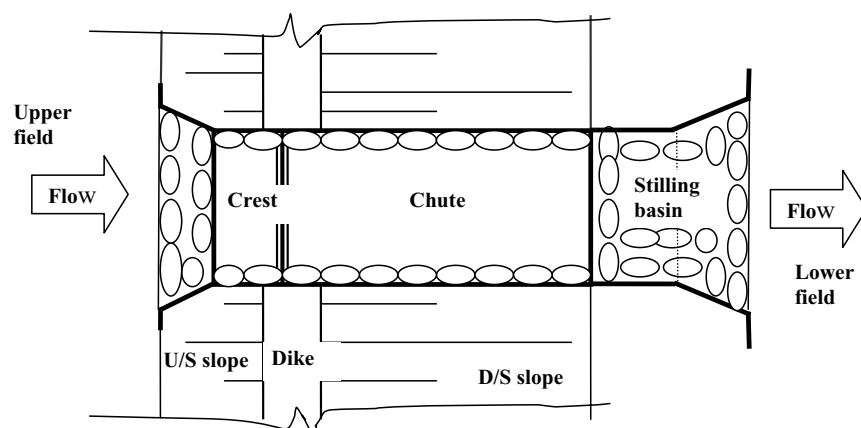


Figure 5. Schematic layout plan of a terrace structure

Table 4. Main design parameters of the farm runoff control structures in Barani, Pakistan

IRS/ Location	Drainage area (ha)	Total drop* (m)	Infiltration rate (cm/hr)	No of structures	Area served by one structure** (ha)	Estimated discharge ( $m^3 sec^{-1}$ )	Width of structures (m)	Crest height above average field level (m)
Khabal (Sohawa)	7.2	17.6	-	12	0.25–3.0	0.06–0.5	0.9–2.1	0.3–0.6
Jarmot (Chakwal)	6.4	16.0	2.2–6	7	0.4–5.0	0.05–0.6	0.3–1.5	0.3–0.5
Dhamal (F. Jang)	16.2	13.5	6–18	7	0.5–6.5	0.1–0.7	0.3–1.5	0.2–0.9

\*Total drop between most upstream and downstream fields  
 \*\*including upper area/fields

### The Syrian Badia

The Syrian steppe (*Badia*) covers about 8.3 million hectares (55% of the total area of Syria) and is used as rangeland (Syrian Ministry of Environment and UNDP, 1997). It is a largely communal land and, with a few exceptions, it is open access. The average annual rainfall over the *Badia* varies from 50 mm in the south to less than 200 mm in the north. The topography is flat to moderately steep, with low to medium range hills. Numerous gullies originate in the hills and disappear into flat plains down below. No perennial streams exist. A few ephemeral streams bring runoff once in 2–3 years. The study site is located in the hilly watersheds in the Meheseh area (37.25° E and 34.08° N; altitude, 350–900 m above mean sea level), i.e. almost in the middle of the Syrian *Badia* (Fig. 6). The winter is cool and the temperature drops below zero on average for 22 days during December, January and February. The summer is hot and remains dry. Table 5 shows the main climatic parameters at Qaryatein (about 15 km from the study site). Analysing annual rainfall data at Qaryatein (1958–93) shows average annual rainfall as 117 mm with coefficient of variation of 0.35. The annual minimum rainfall was 26% of the annual maximum and about 50% of the average annual rainfall. Annual rainfall varied between 45 and 160% of the average annual rainfall. Based on FAO (1981) criteria, dry, average and wet conditions occur for about 30, 59 and 11% of the time, respectively. The annual rainfall was just 8% of the reference evapotranspiration. Monthly rainfall shows May to September as a rainless period. The rainfall–evaporation

ratio: December to March 25–38%, April and November 12–15% and May to October almost zero, indicates periods of soil moisture stress. UNESCO (1977) climatic zoning, on the basis of the rainfall–evaporation ratio, places the research environment closer to the margin of an arid to hyper-arid zone.

Topographic maps and field survey shows steep hillsides with shallow soils (soil depth <30 cm), downhill surface (slope 2–9% and soil depth 50–80 cm) and small to medium size gullies. Range-land is the current and potential land use. Hillsides generate a major chunk of runoff that flows down into gullies almost once a year. The runoff disappears into discontinuous streams, where it drops its maximum sediment load and spreads over fan-out areas and in shallow depressions. Baseline information shows minimal use of this runoff downstream. Because of deep groundwater (100–130 m), the probability of its contribution to recharge is low. Harvesting this runoff into gullies is possible; however, due to unclear uses and the low probability of occurrence of runoff, the option of water harvesting on this scale was not explored further. Downhill surfaces cover a large area and due to reasonable soil depth they can support short-rooted vegetation. Nevertheless, surface crusting during rainfall reduces infiltration and encourages localised runoff about 3–4 times a year. Harvesting this runoff at plot or micro-catchment scale to establish fodder shrubs on downhill surfaces was further investigated.

Under the framework of the On-farm Water Husbandry Project (OFWH), a water harvesting site was selected along

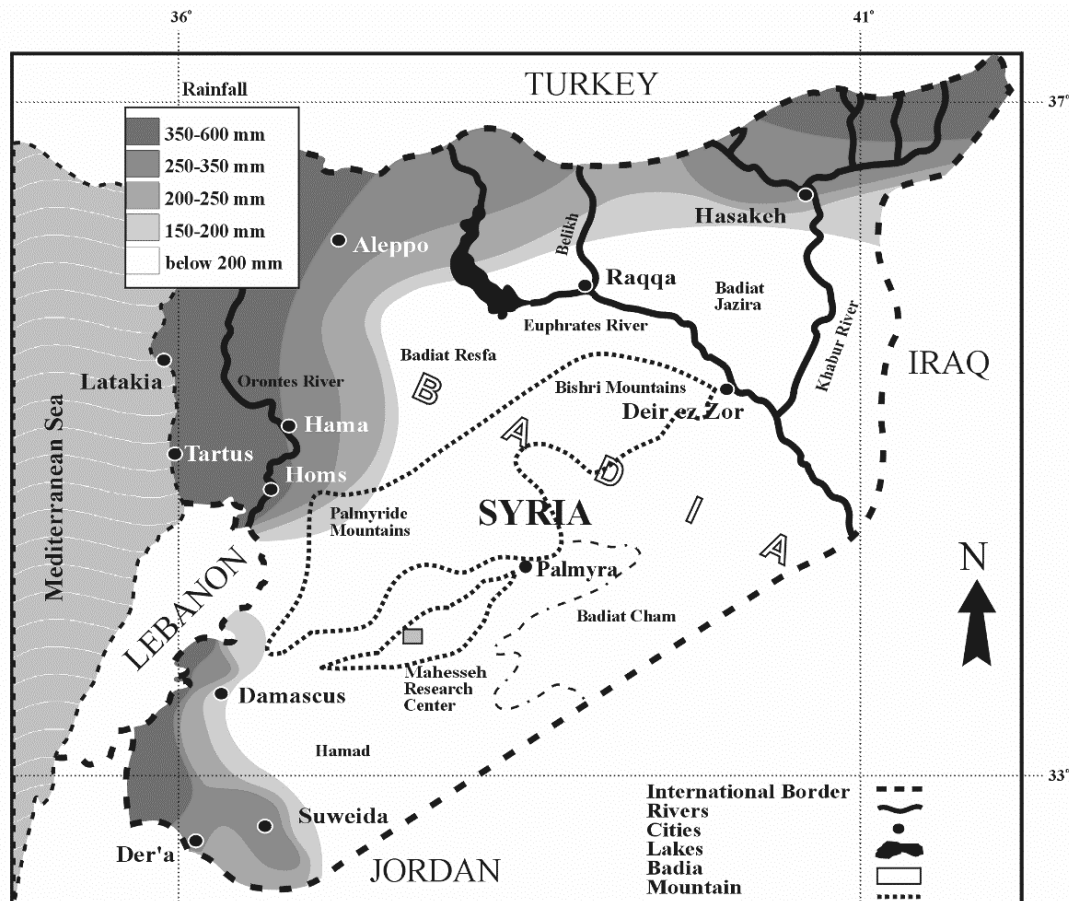


Figure 6. Location map of MCWH site in the Syrian Badia

Table 5. Mean-monthly climatic parameters at Qaryatein, in Syrian Badia

Climatic parameters	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall <sup>1</sup> (mm)	13.6	14.6	23.7	13.7	17.4	0.1	0.0	0.0	0.2	8.7	12.6	12.6	<u>117.2</u>
Mean temp. °C	6.4	6.5	8.84	13.8	21.3	23.7	26.6	25.7	22.8	17.7	11.8	7.0	16.0
Mean max. temp °C	10.5	12.3	14.5	22	29.1	32.8	34.3	34.0	30.5	25.2	18.6	12.8	23.0
Mean mini. Temp. °C	0.7	-0.2	2.0	6.2	11.7	14.8	17.5	16.3	13.1	8.2	5.9	1.6	8.1
Mean relative humidity (%)	73.9	64	58.2	51.7	34.7	43.9	45.2	48.7	48.2	50.6	61.7	73.1	54.5
Mean wind speed <sup>2</sup> (m/s)	3.40	373	3.7	4.1	4.2	4.6	5.9	4.3	3.8	3.2	3.6	4.1	4.0
ETo <sup>3</sup> (mm)	40	60	87	136	222	222	218	223	194	147	79	43	<u>1671</u>

<sup>1</sup>Based on data from 1958 to 1993

<sup>2</sup>Based on data from 1967 to 1983

ETo estimated by Penmann-Montieth method by using climatic data from 1958 to 1988

Underlined figures represents annual total

the foothills on 2 and 5% slopes and 50–80 cm soil depth. The soils are coarse-textured and organic matter is less than 1%. The natural vegetation was sparse. Runoff potential at micro-catchment scale was investigated by developing 24 runoff plots on land with a slope of 5–7%. Each plot is 5 m wide, with variable lengths of 5, 10, 15 and 20 m, resulting in plot catchment areas of 25, 50, 75 and 100 m<sup>2</sup>. The rainfall amount and intensity were measured by tipping-bucket type rain gauge. Runoff from the plots was collected in a steel tank at the outlet of each plot. The runoff coefficient

(C) is defined as the ratio of runoff to rainfall, and was computed by dividing the runoff in the tank by the rainfall, using similar units. Due to very low rainfall and potential range-land use, drought-tolerant fodder shrubs (*Atriplex halimus* and *Salsola vermiculata* with annual water requirements of ~250 mm) were tested by using a micro-catchment water harvesting (MCWH) technique. Five hundred and forty semi-circular bunds were constructed along the contours on land slopes of 2 and 5%. The topographic map and design were developed and field

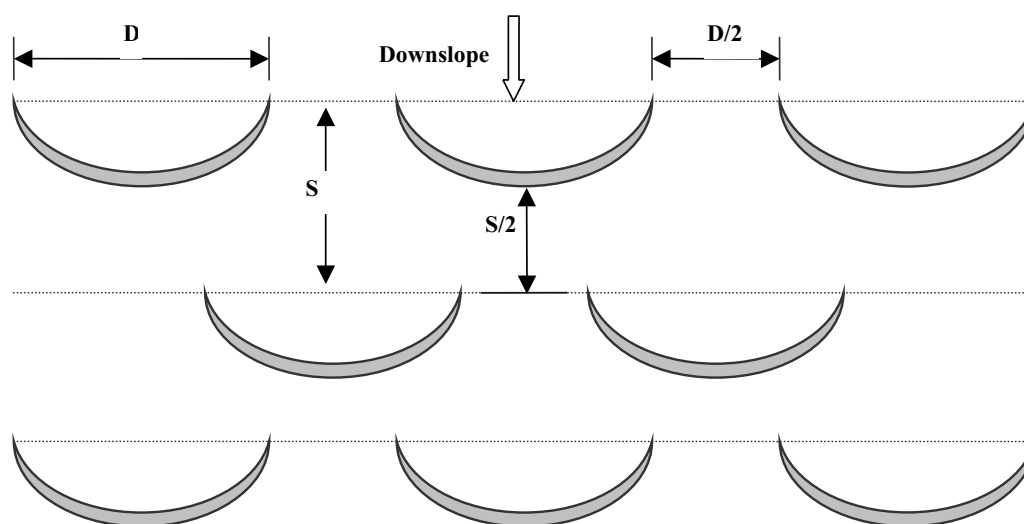


Figure 7. Layout of semi-circular bunds

layout was marked. The layout arrangement (Fig. 7) estimated the catchment areas of 6, 24 and 54 m<sup>2</sup> for 2, 4 and 6 m diameters, respectively, by using the relationship

$$A = \frac{3}{2} S \times D$$

where  $A$  is catchment area (m<sup>2</sup>),  $D$  is diameter of semi-circle in metres and  $S$  is the spacing between the two lines in metres. Manual development of semi-circles and digging pits facilitated the planting of seedling *Atriplex halimus* and *Salsola vermiculata* shrubs at a rate of one shrub per micro-catchment. Irrigation at a rate of 10 litres per shrub was applied at the time of planting.

## Water harvesting potential

### North-west Egypt—watershed scale

Field studies, discussions with focus groups and information extracted from topographical, soil and land use maps revealed that three hydrological systems largely prevail in the watersheds. *System I* consists of the upper catchment which, due to the flat terrain, low rainfall and frequent depressions, contributes hardly any runoff to wadi flows during average and dry years. This behaves as an independent system with potential for grazing and sporadic crops in the depressions. *System II* is where wadi flows are generated mainly on steep slopes and in escarpment areas, and is a main source of water for orchards in the wadi bed and in the coastal plains. *System III* consists of the margins of wadi sides and downhill surfaces, which have flat slopes dominated by rocky soils. In this system, sheetflow occurs, which may be harvested in cisterns (i.e. dug reservoirs of 200–300 m<sup>3</sup> capacity) for domestic and animal uses. Baseline information show a reduction in annual rainfall of 155 mm at the coast to 50 mm some 50 km inland. To explore the water harvesting potential, it was necessary to make appropriate water yield assessments and water balance studies at the watershed scale, including defining similar hydrological response units within the area.

The coastline-inland rainfall distribution was

approximated from rainfall data (Regner, 1995) along one transect in north-west Egypt that fit to a polynomial equation of  $y = 0.0278x^2 - 3.6347x + 156.4$  with  $r^2 = 0.99$ , where  $x$  represents the inland distance from the coast and  $y$  annual rainfall in mm. This equation is valid within the lower and upper bounds of annual rainfall of 50 and 156 mm, respectively. The rainfall near the coast ( $x = 0$ ) was considered to be the upper bound of the annual rainfall. Although FAO (1970) work on rainfall distribution in Egypt showed similar trends (variations of 20–30% at 25 to 50 km inland), due to difference in scale, the predictive capacity for north-west Egypt cannot be very reliable. Gathering more data on rainfall spatial variability may validate the above relationship. A runoff coefficient approach based on ORSTOM data for the Sudano-Sahelian zone of West Africa, published by Dubrevil (1972) and reported by Davy *et al.* (1976) was used to estimate runoff from each sub-watershed/ response unit. This approach is relevant because:

- (i) It is based on annual rainfall (curve  $a$ : 50–200 mm and curve  $b$ : 50–400 mm), which was available for the study area.
- (ii) It gives two separate relations for the steppe area with bare rock (30% minimum) and steppe and thorny steppe with less than 50% crop fields—these two environments largely prevail in north-west Egypt. The runoff coefficient in the former case varies between 5 and 25% with annual rainfall between 50 and 150 mm. For the same rainfall range, the runoff coefficient for the later case varies between 2.5 and 8%.
- (iii) It allows the incorporation of the effect of land slope on runoff coefficient (Rodier and Robstein, 1988), which is also relevant as most of the runoff is generated on the side slopes of wadis. The runoff coefficient with the slope effect ( $C_i$ ) is estimated by multiplying  $C$  with correction factor

$$C_i = C \times \left( \frac{C_n}{C_{0.5}} \right)$$

where  $C_n$  and  $C_{0.5}$  are the coefficients for the prevailing

and 0.5% slopes as determined from the curves (Rodier and Robstein, 1988),  $C$  is runoff coefficient estimated from Davy *et al.* (1976) and  $C_i$  is the adjusted runoff coefficient for the existing slope. The correction factor varies between 1 and 1.8 for slopes between 0.5 and 6%. Wakil *et al.* (2000) found comparable results by using this approach with a locally developed model based on limited data,  $[R = 0.75(P - 8)]$ , where  $R$  is runoff and  $P$  is event rainfall in mm, for the Hurega and Rateem watersheds in the area. They have recommended this approach for north-west Egypt, when only annual rainfall data is available.

The water balance study of the five watersheds considered runoff from average annual rainfall, the current water demand of the developed agriculture areas in the wadis and coastal plain, and the potential for further development upstream within the wadis. It is to be noted that the coastal plain and flat wadi beds downstream have already been developed for some decades due to their deep soils, better access and relatively large area. For the current land-use scenario (orchards), it is less likely to increase the agricultural water demand of this area. Urbanization of the coastal belt, i.e. potential future land use, may decrease agricultural water demand. An assessment was made of how much water is lost into the Mediterranean Sea under the current land use for average annual rainfall conditions and is called 'surplus runoff'. This surplus runoff set the limit for the maximum water that could be harvested for agriculture in the middle and upper reaches with minimum downstream consequences. Nevertheless, water harvesting in drylands works between two extremes—too little or too much—and has always been challenging and involves a certain degree of risk.

To cover risks during low rainfall, the farmers downstream use cistern-water for supplemental irrigation to fruit trees during water stress periods. Cistern-water, because it is a secure source of water and has great flexibility of use, is important for the people. The assessment based on these considerations (Table 6) illustrates that water availability in the three watersheds was more than the current water demands. These watersheds have the potential for further water harvesting up to a level where it does not create water shortage risks at the current level of agricultural water use. However, the water balance in the other two watersheds indicated that the potential water demand, based on the community plan, will create water shortages. Options for further water harvesting upstream in these watersheds were dependent on modification of the plan to match it with

water availability. A modified plan reduced the water deficit from 123 544 m<sup>3</sup> to about 23 500 m<sup>3</sup> in Shaiba watershed and from about 16 000 m<sup>3</sup> to zero in Abu-shanab watershed and was considered to be the preferred water harvesting option for these watersheds. Nevertheless, agreement among the main stakeholders was instrumental to implementing the plan.

The agreement became possible due to (i) social pressure from the traditional Bedouin system, (ii) compensation with cisterns at potential locations and (iii) risk of losing external investment (project support) in case of disagreement. In the study watersheds, availability of suitable land governs the agricultural water demand and, due to agricultural land limitation in the upper wadi reaches, substantial increase in agricultural water demand was not anticipated. The study revealed that System III generates little runoff and its harvesting in cisterns is viable because the small quantity does not create overall water imbalances. Further, cistern-water serves the high priority demands (domestic and animal uses) and is accessible for use to every community member; its harvesting is largely accepted.

#### Barani, Pakistan—hillside/farm scale

Fourteen major rainfall events at the Sohawa sites and 17 at the Dhamal sites were observed in 2002–03 (Fig. 8). The observations after every event showed that the structures harvested the entire runoff from small to medium size events and disposed of surplus runoff from high rainfall events without significant damages. The structures' stability to withstand very high rainfall events can be attributed to the ability of stones to readjust during overflow and development of grass around the structures, which provided reinforcement to the stones. However, an 85 mm rainfall event at Dhamal on 26 August 2002 damaged the most

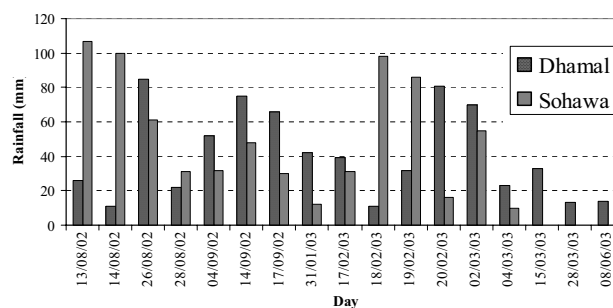


Figure 8. Major rainfall events at two research sites during 2002–03

Table 6. Water balance at watershed-scale in north-west Egypt (based on average annual rainfall)

Watershed	Catchment area (km <sup>2</sup> )	No. of units	Annual rainfall (mm)	Runoff coefficient (%)	Estimated runoff (m <sup>3</sup> )	Annual water demand* (m <sup>3</sup> )	Water balance (m <sup>3</sup> )
Shaiba	3.1	5	66–73	4–21	56 456	180 000	–123 544
Abu-Marzuk	13.4	12	120–147	7–50	584 101	260 000	324 101
Abu-Shanab	0.9	5	137–142	9–34	23 719	39 789	–16 070
Grawla-Glalib	37.4	18	93–137	4–34	764 687	692 000	72 687
Sidra	1.2	4	143–149	9–24	29 866	28 262	1604

\*Include domestic, livestock and agricultural water requirements as per community plan

**Table 7.** Cost of structures at three sites in Barani, Pakistan

Location	Number of structures	Construction year	Capital cost (US \$)	Maintenance cost (US \$)	Total cost (US \$)	Cost per structure (US \$)
Khabal	12	2002	296	75	371	30
Jarmot	7	2003	286	50	336	48
Dhamal	7	2002	119	13	132	20

Source: BVDP-ARC, Annual report 2005-06

downstream structure. The damages were repaired and maintenance cost was incorporated. The main reasons for the damage could be (i) a drop of more than 2 m, (ii) high rainfall immediately after construction when the grass was not fully developed and (iii) high flow concentration at the most downstream end. Table 7 shows the cost of structures at the three sites. The wetting depth—an indicator of water harvesting—varied between 60 and 120 cm across the fields. The two highest rainfall events resulted in a wetting depth of more than 120 cm, which was not measured, and deep percolation was assumed in those cases. Poor land levelling is considered to be the main reason for non-uniform water spreading in the fields.

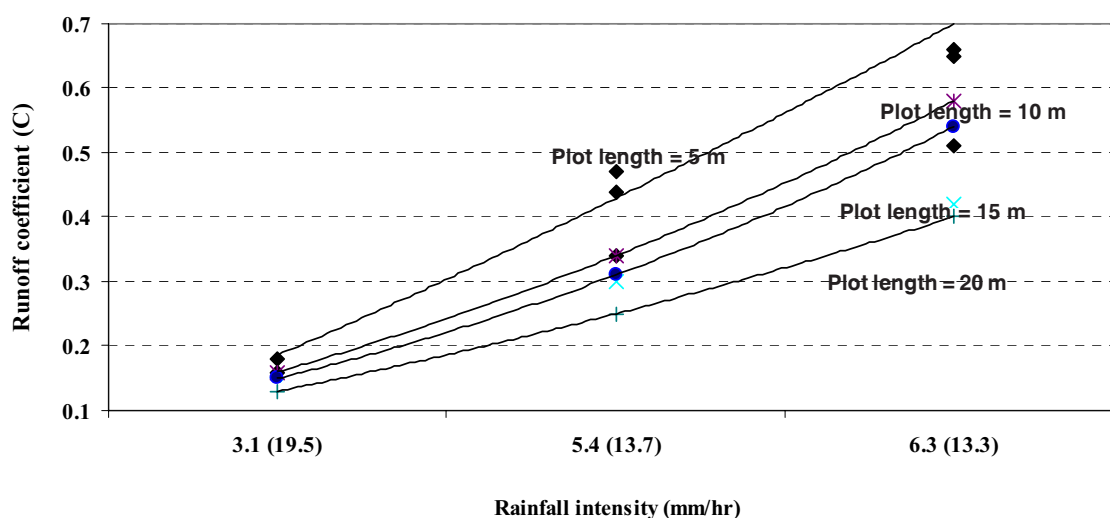
#### Syrian Badia—micro-catchment scale

Plotting the runoff from the plots (Fig. 9) shows that the runoff coefficient ( $C$ ) was lowest for 3.1 mm hr<sup>-1</sup> rainfall intensity (event rainfall = 19.5 mm) and highest for 6.3 mm hr<sup>-1</sup> rainfall intensity (event rainfall = 13.3 mm). For low rainfall intensity (3.1 mm hr<sup>-1</sup>),  $C$  was 0.13 for 100 m<sup>2</sup> and 0.18 for 25 m<sup>2</sup> areas. For high rainfall intensity (6.3 mm hr<sup>-1</sup>),  $C$  was 0.4 for 100 m<sup>2</sup> and 0.65 for 25 m<sup>2</sup> areas. The results indicate that  $C$  increased with rainfall intensity and decreased with increase in catchment size.

Table 8 shows the results of shrub survival and growth without and with M<sub>1</sub>CWH on 2 and 5% land slopes. Shrub survival rate by the end of the first year with good rainfall was about 20% for the control and 73 to 97% for M<sub>1</sub>CWH

on 2 and 5% slopes, which shows 3–5 times improvements. In extreme dry conditions during the following years (annual rainfall was below 50 mm for two consecutive years), the shrub survival rate of about 30 and 93% was achieved with M<sub>1</sub>CWH on 2 and 5% slopes respectively, as compared with insignificant survival (2–5%) under control conditions. Shrub growth with M<sub>1</sub>CWH was improved 3–4 times as compared with the control on the 2% slope (Table 8). Due to negligible survival rate on the 5% slope, the shrub growth data were not available for control. With M<sub>1</sub>CWH, the shrub growth was 1.5–2 times higher on 5% as compared with the 2% slope. For micro-catchment areas, the shrub growth was more than twice on 24 m<sup>2</sup> as compared with that on the 6 m<sup>2</sup> area. However, there was not much difference in shrub growth on 24 m<sup>2</sup> and 54 m<sup>2</sup>.

The results revealed that the maximum potential for shrub survival with favourable rainfall (3<sup>rd</sup> highest in 35 years) does not exceed 23% in control conditions. With the probability of occurrence of this rainfall being less than 11%, it shows the importance of water harvesting in rangeland rehabilitation. With M<sub>1</sub>CWH, higher shrub survival (93%) and higher growth on 5% slopes as compared with 30% shrub survival and slower growth on 2% slopes, shows the importance of land slope in water harvesting. Within the trial domain, 24 and 50 m<sup>2</sup> micro-catchment areas performed better; however, with almost double the number of shrubs per ha, the 24 m<sup>2</sup> micro-catchment is found to be more suitable for M<sub>1</sub>CWH for shrub establishment.



**Figure 9.** Runoff coefficient in relation to micro-catchment area and rainfall intensity. The values in parenthesis on x-axis shows rainfall amount in millimetres (adapted from Somme et al. 2004)

**Table 8.** Shrub survival and growth with M.CWH for different micro-catchment areas and under control conditions in the Syrian Badia (Source: Some *et al.*, 2004)

Year	Rainfall (mm)	Slope 2%				Slope 5%			
		Control	6 m <sup>2</sup>	24 m <sup>2</sup>	54 m <sup>2</sup>	Control	6 m <sup>2</sup>	24 m <sup>2</sup>	50 m <sup>2</sup>
Shrubs survival rate (% of total plants)									
97–98	174.4	23	74	75	70	20	96	98	97
98–99	36.0	12	52	54	51	7	92	95	93
99–2000	42.2	5	28	30	22	2	92	93	89
Shrubs growth ( 1000 cm <sup>3</sup> )									
97–98	174.4	15	30	60	50	na	40	120	150
98–99	36.0	15	66	135	62	na	55	164	177
99–2000	42.2	23	70	156	68	na	77	167	178

### **Implications of spatial-scale geo-hydrological variations and socio-economic factors for water harvesting**

The role of water harvesting to improve productivity in dry areas has been appraised by many during the last two decades (e.g. Boers, 1994, Gatot, 1999, Oweis *et al.*, 2001). Nevertheless, understanding how geo-hydrological constraints shape the options for water harvesting is a recent consideration. The influence of ‘scale factor’ in water harvesting has been emphasised very recently (Kumar *et al.*, 2006). This study provided a one-time snapshot of how geo-hydro-climatic and socio-economic factors influence the options of sustainable water harvesting at three different spatial scales.

In north-west Egypt, the variations in topography, soil and rainfall within the watersheds is critical for water harvesting. In larger inland catchments where low inland rainfall contributes to wadi runoff only during bigger events (2–3 in every 10 years) water harvesting is not dependable. Escarpments and hillsides in the middle reaches generate most of the wadi runoff but because of shallow soils these areas are not suitable for orchards. The lower wadi reaches and the coastal belt are suitable for orchards because of deep soils, but depend on wadi runoff from upstream. Secondly, farmers in the upper, narrow and steep reaches construct high bunds across the wadi beds to build up the soil profile and reclaim land. These bunds are not well-designed and often lack proper spillways. They impound runoff and causes water shortages downstream in proportion to their retention capacities during low rainfall events. During high rainfall events, breaking of these bunds causes chain breaching and heavy soil erosion downstream, damaging existing orchards. However, sediment deposition levels off after 3–4 years and reduces the impoundment effects. There is a long term requirement to build up the soil profile and establish plants on the limited land and marginal soils since water harvesting in the middle and upper reaches does not generate balanced benefits. Kumar (2000a) also indicated that incremental structures do not result in a proportionate increase in hydrological benefits, particularly due to upstream–downstream hydrological linkages. But limited livelihood opportunities in the region force people to work on marginal areas. These geo-hydrological realities and socio-economic factors determine the potential for water harvesting in the watersheds.

The project played a key role in achieving agreement on water harvesting through water resource assessment and planning, and by offering incentives in the upstream–downstream context. The traditional Bedouin system alone has not been effective in the past and is less likely to be effective in the future in resolving potential disputes over water harvesting. The effectiveness of the project-developed adaptive research centre and community organisations in the region will depend on the availability of a legal framework based on technical and socio-economic drivers. The absence of such arrangements could be the main constraint on sustainable water harvesting at the watershed scale.

Farm-scale water harvesting proved advantageous over traditional practices as it harvests runoff for each field to improve soil moisture and thus crop yield, and protects terraces by regulating runoff and disposing surplus flows safely downstream. Contrary to the traditional approach, FRS capture runoff from each field before it becomes destructive. Further, their low cost (US\$ 20–48) makes them an attractive option for the farmers. Structural stability, low cost and simple construction demonstrated that FRS are a viable option for water harvesting at field and farm scales in the targeted environment. Nevertheless, as these structures operate between two extremes—low and high flows—the runoff regulation at farms shared by more than one farmer sometimes raises conflict among shareholders. For low rainfall, FRS can harvest maximum runoff from each terrace and during average rainfall the small surplus flow from upper terraces can be beneficial for crops in lower fields. These two conditions do not usually provoke water harvesting disputes but they may occur through disposal of surplus runoff downstream during high rainfall. High rainfall generates destructive flood peaks which can damage the lower terraces. Farmers are more critical of the threat of damage to the terraces compared with any marginal increase in benefit from water harvesting.

The community plan was implemented successfully on farms shared by one family or close relatives. However, it could not be successfully implemented on farms shared by different people where the main concern of the farmers of the lower fields was that construction of these structures would legalise flood disposal through their fields. An alternative proposal was to modify the plan to restrict it to the farms with independent disposal outlets. Runoff regulation on farms with shared disposal points requires

stakeholders' agreement. Lacking any proper institutional mechanism, getting such agreement is not always possible. Presently, the State regulates stream flows and does not interfere at farm level. A formal runoff disposal mechanism at farm-scale could be helpful in water harvesting and terrace conservation.

In Syrian *Badia*, due to low rainfall, the probability of occurrence of runoff at the watershed scale is 11% (only during wet years). Steep hill slopes may also generate weak runoff during average years (probability 59%), but because of transmission losses, it is restricted to deep gullies in the upper catchments and has a low manoeuvring potential at this scale. The geo-hydrological conditions of downslope areas (surface crusting, moderate land slope and soil depth) are favourable to generate and harvest localised runoff at the micro-catchment scale even in dry years. A small earth ridge (30–40 cm high) can harvest enough runoff from a micro-catchment area of about 25–50 m<sup>2</sup> to support one fodder shrub. Stern (1979) and Shanan and Tadmor (1979) also support the importance of small area in runoff generation. Furthermore, the runoff from these downslope surfaces contributes only a fraction of the total runoff that is largely generated in upper catchments—the out-scaling of these small water harvesting structures downhill would not significantly affect runoff downstream. Participatory assessment also did not report significant negative impacts or social conflicts of raising fodder shrubs by using M<sub>1</sub>CWH. Nevertheless, the use of the improved range-land may raise conflicts to do with grazing among communities and necessitates grazing management arrangements enforced by the communities.

The results from three case studies present the potential for and implications of water harvesting at three different spatial scales. At micro-catchment scale, subject to its suitability for M<sub>1</sub>CWH—slope, soil, rainfall and plant species, spatial variability of rainfall and geo-hydrological variations do not affect water harvesting significantly. Because of insignificant downstream consequences, the water harvesting at this scale does not require rigorous technical work and farmers can implement it with little external support. At the farm-scale, such as water harvesting on terrace-fields, spatial variability of rainfall does not much affect runoff; however, topography and hydrological variations can impact on water harvesting and runoff management at this scale. Further, social elements become important in the case where different farmers share one disposal outlet. Water harvesting at this scale may require institutional support on technical and social aspects. At the watershed scale, geo-hydrological and rainfall variabilities and upstream-downstream water linkages affect the water harvesting tremendously. To avoid negative consequences, a strong technical and institutional support is required for sustainable water harvesting. The water balance approach can be the entry point for water harvesting at this scale. Besides the importance of proper planning for water harvesting in relation to spatial-scale variations, the three cases are similar in demonstrating the need for water harvesting for sustained production but simply differ in strategies for water harvesting planning in relation to its potential and uses.

## Conclusions and recommendations

1. Variations in spatial scale affect significantly the options for water harvesting in drier environments. On a small scale, because of localized effect, the M<sub>1</sub>CWH is less sensitive to downstream implications and is suitable for use in the Syrian *Badia*. The larger the spatial scale, the bigger its effect, as can be seen with farm-scale water harvesting in Barani, Pakistan, and watershed-scale water harvesting in north-west Egypt.
2. Appropriate assessment of water availability and its user rights are crucial for water harvesting planning at the watershed scale. For higher reliability, it is necessary to refine the water resource assessment approach on the basis of adequate field measurements. Real-time rainfall and runoff measurement was initiated in Abu-Groof watershed in north-west Egypt, which is likely to generate useful information. Equally important is defining the water use rights along the watershed drainage in north-west Egypt.
3. Rainwater cisterns in north-west Egypt are an efficient means of water harvesting and storage for domestic uses and supplemental irrigation. Because of small catchment areas and limited suitable locations for their construction, they do not affect the overall water balance at the watershed scale.
4. Low-cost FRS effectively harvested and regulated the runoff among terraced fields. Because of their stability to withstand high rainfall events and the conservation of terraces at an affordable cost, it is an appropriate option to harvest runoff from terraces at the farm-scale in *Barani* Pakistan.

## Acknowledgements

The authors wish to acknowledge Drs. Adriana Bruggeman and Hamid Farhani for reviewing this manuscript. The projects MRMP, BVDP and OFWH hosted this research and their field staff helped in fieldwork and data collection. Their support is highly appreciated.

## References

- Batchelor, C.H., Singh, A., Rama Mohan Rao, M.S. and Butterworth, J., 2002. Mitigating the potential unintended impacts of water harvesting. Paper presented at *IWRA Int. Regional Symp. "Water for Human Survival"* 26–29<sup>th</sup> November 2002. Hotel Taj Palace, New Delhi India.
- Behailu, M., 2001. Keynote speech. Workshop on the experience of water harvesting in the drylands of Ethiopia: Principles and practices.
- Boers, Th.M. and Ben-Asher, J., 1982. A review of rainwater harvesting. *Agric. Water Manage.*, **5**, 145–158.
- Boers, Th.M., 1994. Rainwater harvesting in arid and semi-arid zones. PhD. Dissertation, Wageningen Agriculture University, the Netherlands.
- BVDP-ARC, 2004. Annual report 2004–05. Barani Village Development Project, Applied Research Component. ICARDA Implementation Unit, PARC, Islamabad, Pakistan.

- BVDP-ARC, 2005. Annual report 2005-06. Barani Village Development Project, Applied Research Component. ICARDA Implementation Unit, PARC, Islamabad, Pakistan.
- Critchley, W. and Siegert, K., 1991. *Water harvesting: A manual for the design and construction of water harvesting schemes for plant production*. FAO, Rome, Italy.
- Davy, E.G., Mattei, F. and Sollomon, S.I., 1976. An evaluation of climate and water resources for development of agriculture in the Sudano-Sahelian zone of West Africa. *Special Environmental Report no. 9*, World Meteorological Organization, Geneva, Switzerland.
- Dubrevil, 1972. Annual rainfall runoff relationships. Cited in: Davy, E.G., Mattei, F. and Sollomon S.I. 1976. An evaluation of climate and water resources for development of agriculture in the Sudano-Sahelian zone of West Africa. *Special Environmental Report no. 9*, World Meteorological Organization, Geneva, Switzerland.
- El-Naggar, S., Perrier, E.R. and Shykhoun, M., 1988. Evaluation of farm resource management in the northwest coast of Egypt. *Report no. ARS-SWRI/ICARDA-FRMP*, presented in Alexandria/ Mersa Matrouh, Egypt 4-7 April, 1988.
- FAO, 1994. Water harvesting for improved agricultural production. *Water Report no. 3*. Food and Agriculture Organization of the United Nation, Rome, Italy.
- FAO, 1981. Arid zone hydrology for agricultural development. *FAO irrigation and drainage paper no 37*. Food and Agriculture Organization of the United Nation, Rome, Italy.
- FAO, 1978. Reports of the agro-ecological zones projects. *World Soil Resources Report 48 vol. 14*, Food and Agriculture Organization of the United Nation, Rome, Italy.
- FAO, 1970. Technical Report 2. In: Ali, A., Ahmad, T. and El-Naggar, S. 2001. *Land and Water Resources Conservation and Development, Annex 5*, Project Preparation Report, MRMP, prepared for World Bank, Matrouh, Egypt.
- Gatot, I.S., Duchesne, J., Forest, F., Perez, P., Cudennec, C., Prasetyo, T., and Karama, S., 1999. Rainfall-runoff harvesting for controlling erosion and sustaining upland agriculture development. In: *Sustaining the Global Farm*, D.E. Stott, R.H. Mohtar and G.C. Steinhart (Eds.) Selected papers from 10<sup>th</sup> International Soil Conservation Organization Meeting May 24-29, Purdue University and USDA-ARS National Soil Erosion Research Laboratory.
- Huibers, F.P., 1985. Rainfed agriculture in a semi-arid tropical climate: aspects of land and water management for red soils in India. Doctoral thesis, Agriculture University Wageningen.
- Gupta, V.K. and Waymire, E.C., 1998. Spatial variability and scale invariance in hydrological regionalization. In: *Scale Dependence and Scale Invariance in Hydrology*, G. Sposito (Ed.), Cambridge University Press.
- Kumar, M.D., Gosh, S., Patel, A., Singh, O.P. and Ravindranath, R., 2006. Rainwater harvesting in India: some critical issues for basin planning and research. *Land Use and Water Resource Research*, **6**, 1.1–1.17. Web. <http://www.luwr.com>
- Kumar, M.D., 2000a. Dug-well recharging in Saurashtra: Are the impacts and benefits over-stretched? *J. Indian Water Resour. Soc.*, July Issue.
- MRMP, 2001. *Land and water resource conservation and development*. Project appraisal report prepared for World Bank Mission, Matrouh, Egypt.
- Oweis, T., Prinz, D. and Hachum, A., 2001. *Water harvesting: indigenous knowledge for the future of the drier environment*. International Center for Agricultural Research in the Dry Area, Syria.
- Oweis, T., Hachum, A. and Kijne, J., 1999. Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. *SWIM paper no. 7. System-wide Initiative on Water Management*. International Water Management Institute, PO Box 2075, Sri Lanka.
- Parr, J.F., Stewart, B.A., Hornick, S.B. and Singh, R.P. 1990. Improving the sustainability of dry land farming system: a global perspective. *Adv. Soil Sci.*, **13**, 1–8.
- Regner, H.J., 1995. *Rainfall distribution in the north-south extension*. Project report, Qasar Rural Development Project (QRDP) north-west coast of Egypt.
- Reij, C., Mulder, P. and Begemann, L., 1988. Water harvesting for plant production. *Technical Paper no. 91*, The World Bank, Washington, D.C.
- Rodier, J. and Ribstein, P. 1988. *Estimation des caracteristiques de la crue decennale pour les petits bassins versants du Sahel couvrant de 1 a 10 km<sup>2</sup>*. ORSTOM, Montpellier, France. 108pp + Annexes. Also reported in Tauer, W. and Humborg, G., 1992. *Runoff irrigation in the Sahel Zone*. Technical Centre for Agriculture and Rural Cooperation (CTA), The Netherlands, and distributed by verlag Josef Margrave, Scientific Books. P.O. Box 105, D-6992 Weikersheim, Germany. [http://www.bondy.ird.fr/pleins\\_textes/pleins\\_textes\\_6/b\\_fdi\\_35-36/39698.pdf#search=%22Rodier%20%2B%20runoff%20%2B1988%20%22](http://www.bondy.ird.fr/pleins_textes/pleins_textes_6/b_fdi_35-36/39698.pdf#search=%22Rodier%20%2B%20runoff%20%2B1988%20%22)
- Shanan, L. and Tadmor, N.H., 1979. *Micro-catchment system*, Second Edition. Hebrew University, Jerusalem. Cited in: *Rainfall collection for agriculture in arid and semiarid regions*, G.R. Dutt, C.F. Hutchinson and A. Garduno (Ed.), 1981. Proc. workshop, University of Arizona, USA.
- Shiferaw, B. and Holden, S., 1998. Resource degradation and adoption of land conservation technologies in the Ethiopian Highlands: a case study in Andit Tid, North Shewa. *Agric. Econ.*, **18**, 233–248.
- Somme, G., Oweis, Y.T., Abdulal, A., Bruggeman, A. and Ali, A., 2004. Micro-catchment water harvesting for improved vegetation cover in the Syrian Badia. *On-farm Water Husbandry Series No. 3*, International Center for Agricultural Research in the Dry Area, Aleppo, Syria.
- Stern P.H., 1979. *Small-scale irrigation*. Intermediate Technology Publications, London.
- Syrian Ministry of Environment and UNDP, 1997. *Biological diversity: biodiversity strategy and action plan project* (SYR/97/G31), Tolyani, P.O. Box 3773, Damascus, Syria.

- Thames, J.L., 1989. Watershed management in arid zones. In: *Role of forestry in combating desertification*, FAO Conservation Guide 21, Food and Agriculture Organization of the United Nation, Rome, Italy.
- Tikue, G.G., 2002. Water harvesting practices in Raya Valley Integrated Agriculture Development Program Observation areas. In: *Workshop on the experience of water harvesting in the drylands of Ethiopia: principles and practices* (December 2001), M. Hailu (Ed.), *Dryland coordination group report no 19*, Norway.
- UNESCO, 1977. Climatic zonation of the arid and semi-arid regions. In: Reij, C., Mulder, P. and Begemann, L. (1988). *Water harvesting for plant production. Technical Paper no. 91*, The World Bank, Washington, D.C.
- Wakil, M., Shaker, R., Mansur. A.A.M. and Abdel Kader, Kh., 2000. *Potential of runoff irrigation in Hurega and Rateem watersheds*. World Bank/MRMP, project document, Egypt