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The Effectiveness of Continuous Contour Ridges and Intermittent Trenches Constructed Using the Vallerani in Water Harvesting in Arid Regions

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Abstract

Rainwater harvesting (RWH) is the most economic and sustainable management method utilized to overcome the problem of water penury in arid regions. Jordan is one of the countries in the Middle East most suffering from water deficit since more than 80% of the country's area receives 50-150 mm of annual rainfall. Different water harvesting techniques (WHT) have been used in many countries in arid and semi-arid regions. An evaluation experiment was conducted at two sites; one is at Al Mwaqar, southeast of Amman, and the other is at Al Grain, west of Al Azraq city. The objective of the current research is to evaluate and determine the effectiveness of two water harvesting techniques constructed by the common Vallerani system using continuous contour ridges and intermittent trenches (bunds) upon effective rainfall (runoff) affected by different land slopes, contour ridges spacing, and water harvesting structures. The results indicated that RWH increases water storage in planted area by two to three, fold depending on land slope and the contour ridges space, but with no significant differences between the applied WHT. Runoff amount increases with the increase of slope gradient (more than 5%), especially in small ridges space, which has shown the highest seasonal runoff range from 300 to 362 m^3ha^{-1} at Al Mwaqar site and from 192 to 243.5 m^3ha^{-1} at Al Grain site. Regression results indicated that there is high coloration between rainfall storms and runoff amount for all treatments. The best regression trend line was obtained from continuous contour ridges CT1 and CT2 with R^2 being 0.95 and 0.96, respectively, at Al Mwaqar site. At Al Grain site R^2 for continuous contour ranges between 0 .70 and 0.76 compared to R^2 which ranges from 0.80 to 0.93 for Vallerani intermittent trenches, due to the effect of rock fragments on the catchment surface in the continuous contour area.

Keywords: Water harvesting, Vallerani, Contour ridges, Intermittent trenches, Runoff, Arid regions.

1. Introduction

Jordan is a developing country located to the southeast of the Mediterranean Sea between 35° and 39° East and latitudes 29° and 33° North. Its area is about 90,000 km^2 and consists of various distinctive topographic units trending in a north-south direction. These units are the Rift Valley, heights and the arid-desert region called locally Badia (Alayyash et al., 2012). Historically, the term 'Badia' refers to the region where Bedouins live, with an annual rainfall of about about 50–150 mm. Jordanian Badia is subdivided into three geographical areas (Allison et al., 1998): Northern Badia with an area of 25,900 km^2 (about 35% of the total Badia area), Middle Badia with an area of 9,600 km^2 (about 13%), and Southern Badia with an area of 37,100 km^2 (about 51%). Jordan weather is severe and the variations in the hydrological parameters such as rainfall, runoff and evaporation are wide. They vary from day to day, from summer to winter, and from one year to another.

Water scarcity is one of the main challenges that Jordan has been consistently facing. The current per-capita annual share of water is estimated at 140 m^3 which is well below the 1000 m^3 threshold (Al-Adamat et al., 2012). The rising air temperatures, coupled with the change in precipitation patterns, are expected to increase water scarcity (Al-Bakri et al., 2013). By the year 2025, the per-capita water share is expected to fall below 91 m^3 per annum due to the limited water resources and the increase in population (Al-Bakri et al., 2013).

This severe water shortage has to be resolved by a comprehensive approach to manage both the water supply and water demand. While meeting domestic water needs has been given priority by the national government, the importance of the agricultural sector to rural employment requires an approach heedful of improving agricultural water security. The sustainable use of water can maintain a balance between the demands and supply (Rahman et al., 2014). Rainwater harvesting (RWH) is the most traditional and sustainable method which can be easily used in the Badia region to improve range lands (FAO, 2016).

Naseef and Thomas (2016) defined rainwater harvesting as a technique used to effectively trap the surface runoff. In technical terms, water harvesting is defined as the process of concentrating precipitation through runoff. Instead of causing erosion, the runoff will be harvested and utilized for beneficial uses (Critchley and Siegert, 1991). Rainwater harvesting has emerged as a vital means for improving water management and soil water conservation in scarce-water environments

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(Ziadatet et al., 2006). Wisseret et al., (2010) defined rainwater harvesting as a beneficial tool of used 'green water' which consists of consumptive water used in biomass production as a nutrition chain/cycle which begins with plants and ends with humans.

The objectives of RWH include improving water availability for plants, improving soil structure by increasing organic matter, decreasing soil erosion rates, reducing the impact of drought, reducing surface runoff, and improving the capacity of the soil to store water (Shawaheen et al., 2011). Therefore, RWH is a direct productive form of soil and water conservation. Yield and production reliability can be significantly improved through rainwater harvesting (Critchley and Siegert, 1991; Ziadat et al., 2006). Consequently, human intervention through using water harvesting can enhance the ecosystem functions in scarce-water areas.

Rainwater harvesting systems are typically classified into three categories based on the size of the runoff-producing area: on-farm systems, in situ, micro-catchment systems, and macro-catchment systems (Studer and Liniger, 2013). In situ systems capture rainfall where it falls and ensures that crops make the most effective use of scarce water. These include the use of deep tillage, dry seeding, mixed cropping, ridges and borders, terraces, and trash lines. Micro-catchment systems include pitting, strip catchment tillage, contour bunds, and semi-circular bunds that create a distinct division between a runoff-generating catchment area and a cultivated basin where the runoff is concentrated, stored, and productively used by the plants. Macro-catchment rainwater harvesting is characterized by large catchment areas, where the catchment area for this system is located outside the cropped area.

In Jordan, water-harvesting techniques can help re-establish the productive functioning of rangeland environments. These rangelands are fragile and subject to severe degradation due to drought and misuse, limited feed resources for livestock, and the desertification process. Since sheep are an integral part of the Bedouins' life, representing a source for food and clothing as well as a symbol of wealth and pride, grazing in the Badia used to be sustainable (Allison et al., 1998; Oweis et al., 2006). This lifestyle induced a set of values and laws and formed an environment-friendly system based on the principles of sustainability and self-sufficiency. It has been reported that water harvesting in these areas has resulted in improved fodder shrubs survival, productivity, and water-use efficiency (Abu-Zanat, 2004).

Micro catchment water harvesting is a method used for collecting surface runoff/sheet (and sometimes rill) flow from small catchments of short length, and water is concentrated in an adjacent application area, and is stored in the root zone for direct use by plants. Catchment and application areas alternate within the same field; thus, rainwater is concentrated within a confined area where plants are grown. Hence, the system is replicated many times in an identical pattern. Micro catchment water harvesting techniques are often combined with specific agronomic measures for annual shrubs (Hai, 1998).

The most important factors to be taken into account in the establishment of a water harvesting project include rainfall intensity and distribution, catchment runoff characteristics, soil depth, physical properties of the cultivated area, type of crops, and the social and economic conditions of the farmers (Shatanawi, 1995).

Generally speaking, a water harvesting project consists of an area divided into two sections: the catchment area (C) or the harvest area where runoff-rainwater is taken from and the cultivated area (CA) where the water is concentrated and stored. The ratio of catchment area to cultivated area (C: CA) can range from 1:1 up to 100:1 (FAO, 1991). Usually, trenches and contour ridges for water harvesting are constructed manually by laborers. The Vallerani System provides the possibility to establish micro catchments along contour lines in a fast and cheap manner (FAO, 2016).

Vallerani trenches are established using a tractor with adequate power (minimum 190 hp) in order to pull the special type of ploughs. The ploughs have been specifically designed by Venanzio Vallerani (1988) to be used under arid and semi-arid conditions for fast rehabilitation of large extensions of land at a low cost (Vallerani system web). It can be adapted to various needs, with different spacing between the contour ridges lines and adjusting the depth and length of work (GIZ, 2012).

The basic parameters needed to determine trenches spacing (Vallerani System) are: soil depth (at least 60 cm), land slope, and rainfall characteristics (FAO, 2016). The recommended number of Vallerani trenches (micro catchments) and the spacing between trenches according to Karrou,et al. (2011) are 250-400 trenches/hectare, five- seven meters apart for a gentle slope (4% to 9%) and 400-600 trenches/hectare, three to four meters apart for a steeper slope (more than 15%).

Youssef (1998) stated that the most efficient and applicable type of water harvesting technique is the contour ridges, with runoff catchment area to cultivated area ratio of 6:1. The highest amount of runoff yield was 6.7 mm for contour ridges compared with 4.1 mm for semi-circle technique at a 67% probability; about 24 mm rainfall.

This study is aimed at evaluating the effectiveness of the water harvesting techniques constructed by the common Vallerani system using continuous contour ridges and intermittent trenches (bunds) on runoff yield (effective rainfall) at two different sites.

2. Methodology

2.1 Investigated Area:

Two study sites were selected. The first site is at Al Mwaqar (N:31.76109 and E:36.27274), located southeast of Amman with an annual rainfall ranging between 120 mm and 150 mm and the land slope ranges between 0% and 15%. The second site is at Al Grain (N:31.9695 and E:36.68367) located to the west of Al Azraq with an annual rainfall between 70 and 100 mm and the land slope ranging between 0% and 10%. The two sites are located within the arid zone area of Jordan under the Badia Restoration Program (Figure 1). Most of the time, rainfall at both sites is characterized by rapid showers with poor distribution.

Contour ridges and intermitted bunds were constructed by the Vallerani plow according to land slope and land use by the National Center for Agriculture Research and Extension (NCARE).

2.2 Rainwater Harvesting Design

Area and the spacing between contour ridges were calculated using the following equations (FAO, 1991):

$$Spacing\ between\ Contours = \frac{WR - RFLT}{RFLT \times RC \times Eff} \quad \text{............ 1}$$

Equation (2) is a simplified form of equation (1):

$$\frac{C}{CA} = \frac{WR - DR}{DR \times RC \times Eff} \quad \text{.. 2}$$

Where:
C: catchment area (m^2)
CA: cultivated area (m^2)
WR: annual water requirement (mm)
RFLT: rainfall long term (mm)
DR: annual design rainfall (mm)
RC: runoff coefficient
Eff: efficiency factor, normally ranges between 0.5 and 0.7 (FAO, 1991).

The design rainfall represents the amount of rainfall that equals to or exceeds the seasonal rainfall, calculated at a certain probability of occurrence at which the system is designed to provide enough runoff to meet the crop water requirement. If rainfall is below the “design rainfall,” there will be a risk for crop failure due to moisture stress. On the other hand, if rainfall is above the “design rainfall”, runoff will be a surplus and may overtop the bunds (FAO, 1991).

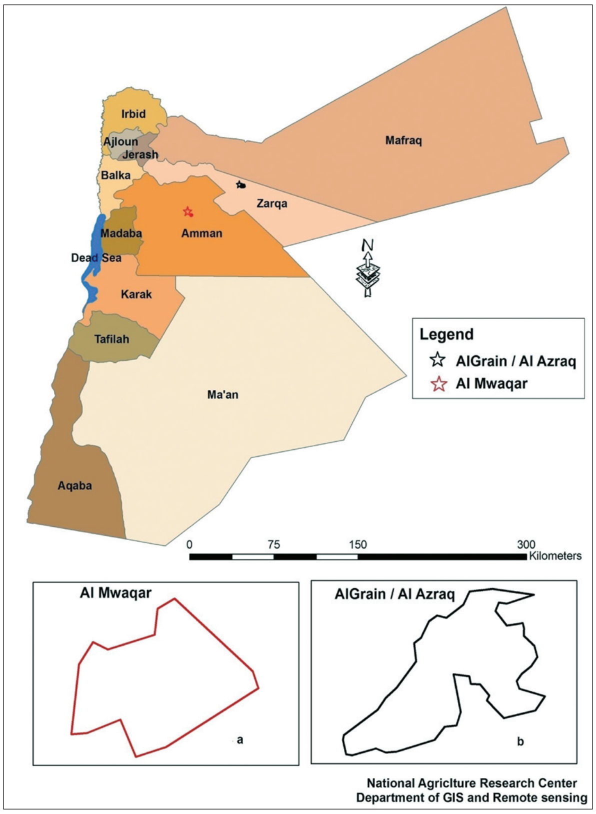

Figure 1. Research sites location; (a) for Al Mwaqar site map and (b) for Al Grain site map.

Increasing the C:CA ratio for high probability will decrease such risks. For example, if the probability of occurrence is set at 67%, this means that design rainfall will be met or exceeded (on average) in two years out of three years and the harvested rain will satisfy the crop water requirements also in two out of three years (FAO, 1991).

The runoff coefficient (RC) is a dimensionless coefficient relating the amount of surface runoff to the amount of rainfall received. It has a larger value for areas with low infiltration and high runoff (such as pavement and steep gradient), and a lower one for permeable, well-vegetated areas (such as forests or flat lands) and ranges between 0.2 and 0.35 for poorly-graded clay loamy, silty clay loamy soil and soil with a slope ranging between 2% and 10% (FAO, 1991).

The total worked areas at Al Mwaqar and Al Grain sites were 120.6 and 122 hectares, respectively. For both sites, spacing between continuous contour ridges and/or intermittent trenches ranges from 10 m for the land surface slope that exceeds 5% to 17 m for that below 5%. The width of the trench was 1 m.

In this research, eight treatments were investigated in an area that was not planted using two land surface slopes <5% and >5% and four spacing 10-12, 12-14 as small space, and 14-16, 16-18 m as large space (Table 1).

Table 1. Treatments: “V” represents intermittent trenches and “CR” represents continuous contour ridges

Technique	Slope (%)	Spacing (m)	Area (m^2)	Treatment symbol
Intermittent trenches (V)	< 5	17-18	35: (17.5x2)	V T1
	< 5	12-14	26:(13 x2)	V T2
	> 5	10-12	22: (11x2)	V T3
	> 5	15-16	31: (15.5x2)	V T4
Continues Contour (C)	< 5	17-18	35: (17.5x2)	C T1
	< 5	12-14	26: (13x2)	C T2
	> 5	10-12	22: (11x2)	C T3
	> 5	15-16	31: (15.5x2)	C T4

The effective rainfall (Runoff) volume stored was estimated by measuring the soil moisture at three depths (0-10 cm, 10-30 cm and 30-50 cm) in the cultivated area within 24-48 hours after each significant rainfall event. Effective rainfall stored in the crop root zone represents the difference in the soil moisture between the day before and the day after the rainfall event. Evaporation amounts were calculated based on weather data (Equation 3); then they were added to the effective rainfall equation (5).

$$Ev = (1 - kcb \times f(tw) \times Fw \times Etr \quad \text{.............. 3}$$

Where:
Ev: wet soil evaporation adjustment in mm/day
Kcb: basal crop coefficient for the day of wetting
f(tw): a time dependent decay function

$$f(tw) = 1 - \left(\left[\frac{tw}{td}\right]\right)^{\frac{1}{2}} \quad \text{.. 4}$$

where
Fw: proportion of gross land area which was wetted.
Etr: reference crop ET in mm/day
tw: time or days since wetting
td: time in days required for the soil surface to become dry

$$Effective\ rainfall\ (runoff) = SWCa - SWCb + Ev \quad \text{.. 5}$$

where
SWCa: soil water content after significant rainfall event (mm).
SWCa: soil water content before significant rainfall event (mm).
Ev: evaporation (mm)

2.3 Relationship between Effective Rainfall and Calculated Runoff Yield

Runoff was calculated using the direct relationship between rainfall and runoff using runoff coefficient (Boers, 1994):

$$Runoff\ Volume = Rainfall \times catchment\ Area \times Runoff coefficient \quad \text{. 6}$$

2.4 Rainwater Harvesting Design

• **Soil water content:** Gravimetric method was used to measure the soil moisture at three depths 0-10 cm, 10-30 cm and 30-50 cm (Black, 1965). Measurements were taken before and within 24 - 48 hours after any significant rainfall event along the trench. For each treatment, a composite of two soil samples were collected from the three depths in three replications, for both sites.

• **Soil Physical and Chemical Proprieties:** Infiltration rate, soil texture, bulk density, soil water holding capacity, soil acidity (pH), soil salinity (EC), $CaCO_3$ and total nitrogen were determined, spatially distributed, and depth-integrated (20 cm incremental depth) at four locations for each research site.

2.5 Statistical Analysis

Split plot design with three replicates was used as experimental design. Season runoff for all treatments was analyzed by using SAS program a Duncan's Multiple Range Test.

3. Results and Discussion

3.1. Soil Properties

Some soil physical and chemical properties, for both sites, are presented in Tables 2 and 3. The results showed that soil texture is the same for both sites being clay loam. Basic infiltration rate varies from 3.2 mm/hr at the catchment area to 4.0 mm/hr at the cultivated area; and from 2.6 mm/hr at the catchment area to 3.7 mm/hr at the cultivated area for Al Mwaqar and Al Grain sites, respectively. Soil texture, or the percentage of sand, silt, and clay in a soil, is the major inherent factor affecting infiltration. Water moves more quickly through the large pores in sandy soil than it does through the small pores in clayey soil, especially if the clay is compacted and has little or no structure or aggregation. Infiltration rate is most affected by the conditions near the soil surface, and can change drastically according to management. Indeed, infiltration capacity which was determined based on the final infiltration rate, is the most important factor controlling runoff generation in the hill slopes land (Roth, 2004).

The low infiltration rate for both sites could be attributed to the high silt percentage (40.6 – 43.0%) at the soil surface layer, causing surface crust and enhancing surface runoff at the catchment area. This result is consistent with Lal and Shukla (2004), who noted that soils that have surface sealing of pores and crusting consequently have less infiltration and high runoff.

Table 2. Soil physical properties at Al Mwaqar and Al Grain sites

Site	Soil depth (cm)	Texture			Bulk Density Kg/m³	Water Holding Capacity (mm/m)	Hydraulic Conductivity (mm/hr)	Basic Inflation Rate	
		Clay %	Silt %	Sand %				CA (mm/hr)	C (mm/hr)
Al Mwaqar	0-10	35.8	40.6	23.6	1.32	162	2.8	3.2	4
	10-30	33.7	37.3	29	1.23		2.4		
	30-50	36.6	42.2	21.1	1.16		2.6		
Al Grain	0-10	33.5	43	23.5	1.26	210	2.4	2.6	3.7
	10-30	32.9	41.7	25.4	1.17		2.37		
	30-50	33.6	39.1	27.3	1.23		2.28		

Table 3. Soil chemical properties at Al Mwaqar and Al Grain sites

Site	Soil depth (cm)	pH	ECe(dS/m)	Ca	Mg	Na	Total Cation	SAR	$CaCO_3$ %	N %
				Meq/L						
Al Mwaqar	0-10	8.3	1.05	1.7	2.4	8	12.1	6.1	18	0.036
	10-30	8.3	1.06	2.05	1.6	6.7	10.35	5	24.1	0.037
	30-50	8.2	0.82	1.5	1.4	4.8	7.7	4.4	23.8	0.031
Al Grain	0-10	8.2	1.18	2.5	2.4	6.5	11.4	4	22.7	0.057
	10-30	8.3	1.15	3	2.5	6.7	12.2	4.5	22.5	0.058
	30-50	8.1	1.69	3.5	3.6	10.4	17.4	5.8	36.5	0.040

3.2 Effective Rainfall (Runoff)

Seasonal rainfall (2016/2017) was 100 and 79 mm at Al Mwaqar and Al Grain sites, respectively. Table 4 shows the seasonal effective rainfall (runoff per unit area in m^3/ha) for the different treatments at the two sites (Al Grain and Al Mwaqar), for the most effective rainfall storms.

3.2.1 Water Harvesting Technique

Results showed that there were no significant differences (Table 5: P= 0.2879; and Table 6: P=0.4211) in the seasonal effective rainfall resulted from surface runoff between intermittent trenches (195 and 273 m^3/ha) and continuous contour techniques (188 and 277 m^3/ha),at Al Grain and Al Mwaqar sites, respectively.

Table 4. Seasonal effective rainfall (m³/ha) for all treatments at Al Grain and Al Mwaqar sites

Site	Al Grain				Al Mwaqar			
Replicates / Treatments	R1	R2	R3	Average	R1	R2	R3	Average
V T1	189.6	180.8	147.2	172.5	207.4	181.2	230.0	206.2
V T2	186.3	168.7	166.4	173.8	237.3	214.4	235.4	229.0
V T3	252.4	236.5	222.9	237.3	361.0	328.2	375.9	355.0
V T4	188.3	190.5	206.1	195.0	311.9	283.8	314.0	303.2
C T1	162.3	136.8	152.8	150.6	204.4	179.9	220.2	201.5
C T2	171.2	156.4	164.3	164.0	262.8	213.8	245.9	240.8
C T3	282.6	241.1	225.3	249.7	386.1	354.9	364.7	368.6
C T4	185.3	186.5	195.7	189.2	317.7	285.9	288.7	297.4

Table 5. ANOVA table seasonal effective rainfall (runoff), Al Grain site.

Source	df	SS	MS	F Value	P > F
Replicates	2	1402.96	701.48	3.61	0.0545
Technique	1	237.26	237.26	1.22	0.2879
Slope	1	16560.31	16560.31	85.17*	<.0001
Space	1	2911.16	2911.16	14.97*	0.0017
Technique x slope	1	550.79	550.79	2.83	0.1145
Technique x space	1	13.98	13.98	0.07	0.7925
Slope x Space	1	5165.83	5165.83	26.57*	0.0001
Technique x slope x space	1	342.98	342.98	1.76	0.2054

** Means significant at P <0.05.*

Table 6. ANOVA table seasonal effective rainfall (runoff), Al Mwaqar site.

Source	Df	SS	MS	F Value	P>F
Replicates	2	1702.96	401.48	4.2417	0.0678
Technique	1	82.14	82.14	0.69	0.4211
Slope	1	74812.02	74812.02	625.66*	<.0001
Space	1	1385.25	1385.25	11.58*	0.0043
Technique x slope	1	0.16	0.16	0.0	0.9711
Technique x space	1	2.90	2.90	0.02	0.8784
Slope*Space	1	12855.9	12855.89	107.51*	<.0001
Technique x slope x space	1	480.26	480.26	4.02	0.0648

** Means significant at P <0.05.*

3.2.2 Slope Effect

Results showed that slope gradient has significant impact on surface runoff, the greater the slope gradient is, the higher the potential for surface runoff (effective rainfall) will be. Using both water harvesting techniques (WHTs) on slope gradient more than 5% resulted in significantly higher amounts of effective rainfall (217.8 m³/ha) compared with 162.2 m³/ha using the same WHTs on slope gradient less than 5%; at P<0.0001 for Al Grain site. The same trend was obtained at Al Mwaqar site, where WHTs gave 331 and 219 m³/ha with slope more than 5% and less than 5%, respectively; at P<0.0001. Thus, as slope gradient increased soil infiltration will decrease and the surface runoff will increase. These results agree with Nasseef, et al. (2016), Sharma, et al. (1983) and Wenbin, et al.(2015).The big differences in the effective rainfall yield between the two study sites (Al Grain and Al Mwaqar) may be attributed to the condition of the site as explained by Agassi, et al. (1990). They measured the effect of the slope aspect with wind (wind ward vs. leeward) where on the leeward aspect runoff decreases as slope increases, but with no effect of the slope on the windward aspect. On the other hand, 50-60% of the catchment area in Al Grain site which is covered by rock and a high amount of rock fragments contributes to a delay in ponding resulting in delayed runoff flow and increased infiltration rates (Zavala, et al. 2010).

3.2.3 Space Effect

Results indicate that runoff and consequently effective rainfall significantly increased and inversely proportional with contour ridges spacing. In Al Grain site, effective rainfall was significantly higher (P=0.0017) with contour ridges 10-12 m and 12-14 m apart being 202.5 m³/ha compared to 180.5 m³/ha with contour ridges 15-16 m and 17-18 m apart. The same trend was obtained in Al Mwaqar site at which the effective rainfall was significantly higher (P=0.0043) with small spacing (10-12 m and 12-14 m) being 282.8 m³/ha as compared with 267m³/ha with large spacing (15-16 m and 17-18 m).

Ali, et al. (2007) conducted a study in the Syrian Badia and found out that the resulting runoff per unit area from

100 m^2 catchment area was significantly different from that obtained from an area of 25m^2. Also, Ali et al., (2010) found out that the harvested water amount was higher for the smaller catchments with 6 m spacing than for larger catchments with 12 m spacing because of the longer flow path and the higher abstraction losses in larger catchments compared with shorter flow path and lower abstractions in smaller catchments. Zougmore et al. (2000) concluded that the effect of stone lines on soil water content depends on the space between the stone lines, and that the efficiency of stone lines in checking runoff and in improving soil water storage increases with a reduced stone line spacing.

3.2.4 Interaction Effect:

In the two study sites (Al Grain and Al Mwaqar), there was a significant interaction between the effects of the contour ridges spacing and the slope gradient on the runoff yield ($P< 0.0001$), while, there was no significant interaction between the effects of the water harvesting techniques, slope gradient, and contour ridges spacing on the runoff yield ($P=0.2054$). Tables 7 and 8 present the interaction effect on the seasonal runoff and consequently the effective rainfall affected by slope gradient and distance between contour ridges, at Al Mwaqar and Al Grain sites, respectively.

The significantly highest seasonal runoff (effective rainfall) values were 362 and 243.5 m^3/ha, with land surface slope gradient being more than 5% and contour ridges spacing 10-14m, at Al Mwaqar and Al Grain sites, respectively. While the significantly lowest seasonal runoff (effective rainfall) values were obtained with land surface slope being less than 5% and contour ridges spacing 15-18m being 235 and 161.6 m^3/ha at Al Mwaqar and Al Grain sites, respectively. Fang et al., (2008) indicated that a shorter slope length gave the highest runoff coefficient which means a higher runoff or effective rainfall.

Table 7. Seasonal runoff (m^3/ha) as affected by land surface slope and contour ridges spacing at Al Mwaqar site ($P<0.0001$)*.

Slope	Space	
	15-18m	10-14m
> 5%	204 d	362 a
< 5%	235 c	300 b

**Means with the same letter are not significantly different.*

Table 8. Seasonal runoff (m^3/ha) as affected by land surface slope and contour ridges spacing at Al Grain site ($P=0.0001$)*.

Slope	Space	
	15-18m	10-14m
> 5%	169 c	243.5 a
< 5%	161.6 c	192 b

**Means with the same letter are not significantly different.*

3.3 Predicted Runoff versus Actual Runoff (Effective Rainfall)

The correlation between actual runoff (effective rainfall) estimated by using the gravimetric method by measuring soil water content before and after a significant rainfall event. Predicted runoff is represented in Figure 2. The correlation coefficient of 0.76 indicates a strong positive correlation between actual and predicted runoff. The lowest observed ratio between actual and predicted runoff was 0.45 which almost related to small rainfall storm, which was due to the threshold of runoff. Runoff began from 2-3 mm after the soil surface was saturated, and these amounts consisted (by 30-50%) of small storm. The highest ratio ranged from 1.2 to 1.7 for both sites and almost related to a large rainfall storm. NSE of 0.776 (Nash–Sutcliffe model efficiency coefficient) corresponds to a good match of predicted runoff to the observed data.

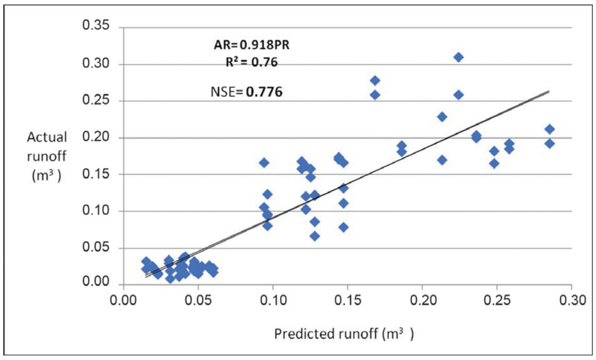

Figure 2. Regression analysis between actual and predicted runoff for both sites.

3.4 Runoff-Rainfall Relation

In general, regardless of the water harvesting technique, contour ridges spacing and slope gradient for both sites regression analysis indicate a good correlation between rainfall (mm) and runoff (effective rainfall) in cubic meter per unit area (m^3/ha), with a regression coefficient of $R^2 = 0.84$ (Figure 3). Details of regression correlation between runoff (m^3/ha) and rainfall (mm), for each treatment is presented in Table 9. The results indicate that there is a strong relation between effective rainfall and rainfall for all treatments. The best relations were obtained from continuous contour ridges which related to CT1 and CT2 with R^2 equal to 0.95 and 0.96 respectively, and R^2 range from 0.83 to 0.88 for small space (CT3, CT4). These results were consistent with previous results of Youssef (1998). Intermittent Vallerani trenches had given the same trend but were lower than continuous contour (Table 9). Al Grain site showed linear relation in continues contour (R^2 range from 0.72 to 0.77) lesser than Vallerani trenches (R^2 range from 0.79 to 0.93). These differences were due to the nature of land at Al Grain site which related to the slope aspect with wind and a rocky surface as previously mentioned. These results agree with Ali et al., (2010) who found out that runoff per unit area showed increase with rainfall amount following a linear trend. Linear regressions also indicated a rainfall of about 3-4 mm as rainfall-runoff threshold.

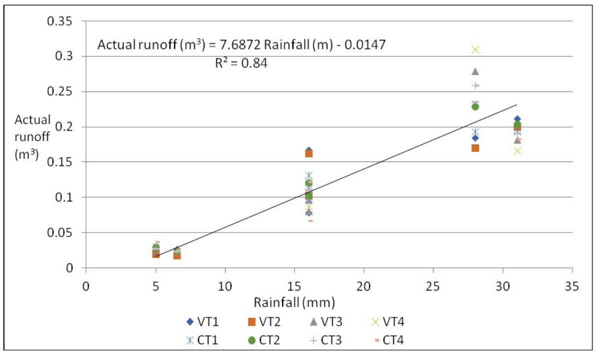

Figure 3. General regression correlation between average actual runoff (effective rainfall) and rainfall amount for all treatment at different rainfall amount.

Table 9. Detailed regression correlation between actual runoff (m^3/ha) and rainfall (mm).

Site	Treatment	Regression Equation	Regression Coefficient (R^2)
Al Mwaqar	VT1	Runoff = 2.1537 Rainfall - 3.1107	0.86
	VT2	Runoff = 2.2832 Rainfall - 1.607	0.86
	VT3	Runoff = 4.1229 Rainfall - 12.425	0.82
	VT4	Runoff = 3.5610 Rainfall - 9.6701	0.73
	CT1	Runoff = 2.0556 Rainfall - 2.0245	0.95
	CT2	Runoff = 2.6062 Rainfall - 4.9386	0.96
	CT3	Runoff = 3.9837 Rainfall - 7.4633	0.88
	CT4	Runoff = 3.2345 Rainfall - 7.0728	0.83
Al Grain	VT1	Runoff = 2.9438 Rainfall - 5.9642	0.93
	VT2	Runoff = 2.4367 Rainfall - 0.6682	0.85
	VT3	Runoff = 3.9098 Rainfall - 5.3416	0.81
	VT4	Runoff = 2.5496 Rainfall - 2.0319	0.79
	CT1	Runoff = 2.2605 Rainfall - 0.0233	0.72
	CT2	Runoff = 2.2605 Rainfall - 0.0233	0.72
	CT3	Runoff = 3.5997 Rainfall - 4.7331	0.77
	CT4	Runoff = 2.9211 Rainfall - 3.5611	0.77

4. Conclusions

Based on previous results, RWH increases water storage in the cropping area by two-three fold depending on land slope gradient and contour ridges spacing. The following conclusion and recommendations were extracted from the results:

Slope gradient plays a significant factor in site selection for RWH. Results indicate an increase in the runoff amount with the increasing of slope, especially in small contour ridges space.

The effective rainfall per unit area or runoff collected in soil profile varied from 5to 139 m^3 ha^{-1}. This variation is related to the variation in the rainfall amount, antecedent soil moisture conditions, micro catchment areas, and water harvesting techniques in the two sites area.

Although the relation between effective rainfall and rainfall amount showed a linear trend with strong relation for all treatments, it was the highest for continuous contour ridges (R^2 = 0.95).

A high percentage rock fragment cover on the catchment area surface contributes to a delay and decrease in the runoff flow as the results indicated, especially at Al Grain site.

Small and large ridges space was given an effective amount of runoff yield; however, small ridges space is recommended.

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