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FLOODWATER HARVESTING FOR ARTIFICIAL RECHARGE AND SPATE IRRIGATION IN ARID AREA

Artificiell grundvattenbildning och översvämningsbevattning med flodvatten i ett aridt område

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Abstract

Utilizing passive floodwater harvesting for artificial recharge and spate irrigation in arid and semiarid areas is an opportunity to use marginal water to improve the livelihood of rural community. In the present study, groundwater modeling to estimate recharge, and field experiments for spate irrigation of barley, were carried out to investigate the performance and potential of water harvesting system to increase water availability and agricultural production in arid Iran. The estimated recharge for the years between 1993 and 2007 varied from a few hundred thousand m^3 per month during drought periods to about 4.5 million m^3 per month during rainy periods. The experimental results of spate irrigated barley showed 2.5-fold increase in yield for the cultivated barley inside the floodwater harvesting system in compare to the cultivated plot outside the system.

Key words – Groundwater modeling, water harvesting, artificial recharge, spate irrigation, arid area

Sammanfattning

Användning av passiv regnvatteninsamling för artificiell grundvattenåterbildning och konstbevattning i torra regioner är ett sätt att använda marginellt vatten och förbättra socioekonomiska förhållanden i rurala områden som baserar sin utkomst på jordbruk. Ett existerande regnvatteninsamlingssystem i södra Iran med ett fåtal regntillfällen per år utvärderades med hjälp av befintliga mätningar av regn och grundvattennivåer samt hydrologisk modellering. Beräknad artificiell grundvattenbildning under perioden 1993–2007 varierade mellan ett fåtal hundratusen till 4,5 miljoner m^3 per månad. Kompletterande experiment visar också att i områden bevattnade från regnvatteninsamlingen kan skörden öka med upp till 2,5 gånger.

1 Introduction

Per capita water resources availability has dwindled rapidly during the last four decades in the arid areas. Especially, in the arid Middle East short-term high-intensive rainfall with resulting flash flood runoff often constitutes the major part of potential water input to agriculture and water supply. In contrast, severe drought and over-grazing of rangelands have caused huge and destructive floods over the last half century which results in water and soil lost from this vulnerable environment.

A flash flood can be optimally harvested for spate irrigation and stored in the ground through artificial recharge and Flood Water Harvesting (FWH) techniques. FWH has traditionally been practiced in arid and semiarid regions (Bruins et al., 1986, Lavee et al., 1997, Li and Gong 2002, Prinz and Singh 2003, Nasri et al., 2004, Barghouth and Al-Sa`ed 2009). Extensive rainwater harvesting has been used for at least 4000 years in the Middle East and the Mediterranean region (Stiefel et al., 2009). The main objective of FWH techniques is to

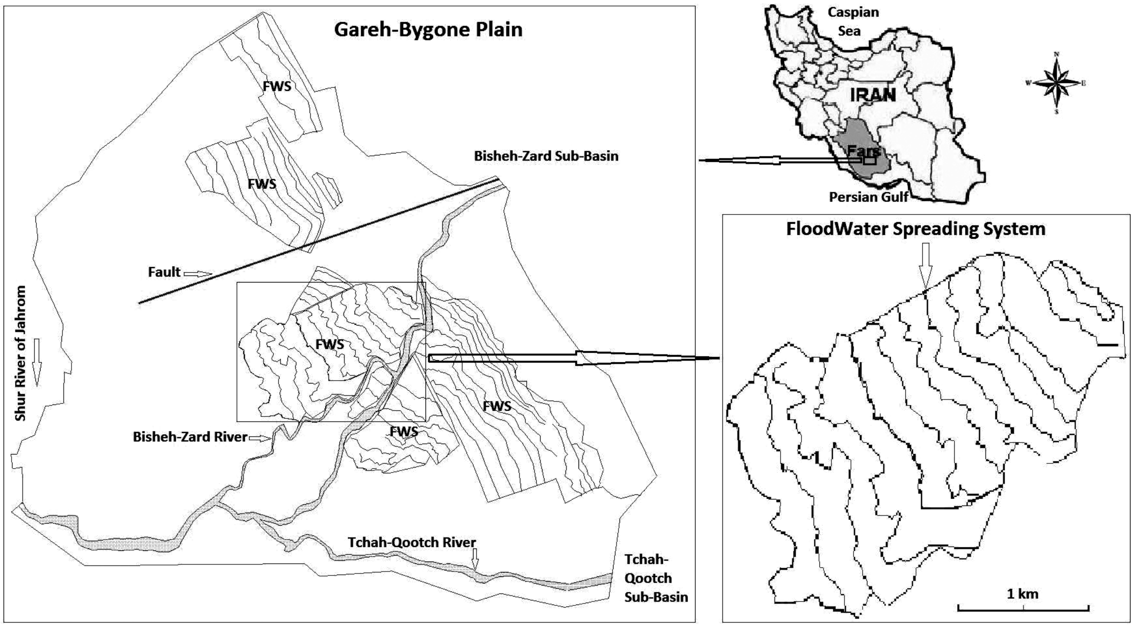

Figure 1. *Location of the study area in Iran and the floodwater spreading system in the Gareh-Bygone Plain (GBP).*

artificially recharge groundwater (Stiefel et al., 2009, Keller et al., 2000, Kumar et al., 2006, Oblinger et al., 2010) and to increase crop production and yield by increasing groundwater availability for farming (Glendenning and Vervoort 2010) and spate irrigation (Mehari et al., 2005, Kowsar 2009).

FWH is a parsimonious solution for water shortage problem in the Middle East, in which runoff from upland areas is collected and redistributed over a smaller area to increase the water availability in arid regions. Despite the long and successful history of these systems, little is still known about their function and effect on the hydrological processes and agricultural production in arid areas (Ouessar et al., 2009).

FWH for groundwater recharge and spate irrigation by water spreading have been practiced at 36 multipurpose Flood Water Spreading (FWS) sites in Iran since 1983. These sites represent an inexpensive but improved method of FWH that results in a large economic return for relatively small investment (Li and Gong 2002, Ghayoumian et al., 2005).

The main objective of the present work was to evaluate the overall efficiency of FWS to recharge groundwater resources in arid southern Iran. This was done by using an extensive groundwater model to estimate recharge. The partial objective was to investigate improved agricultural yield through spate irrigation. This was done by cultivation of rainfed barely (*tropy variety*) as an indicator for crop yield inside the FWS system.

2 Materials and methods

2.1 Study site

The study area is the Gareh-Bygone Plain (GBP), located 200 km southeast of Shiraz city, in southern Iran (28°34′N–28°41′N, 53°52′E–54°00′E) at an altitude of 1140 m above mean sea level (Fig. 1). According to the FAO climate classification, this region is extremely dry with a mean annual precipitation of 243 mm and a Class A Pan evaporation of about 2860 mm per year (Kowsar 2005). Moreover, the area is affected by the Mediterranean synoptic system with high temporal and spatial variation of precipitation. Typically, rain falls after long dry periods as sudden storms with heavy rainfall resulting in flash floods.

Due to scarce water resources in GBP, an improved method of FWS was established in the area between 1983 and 1987 including 1400 ha (increased to 2000 ha in 1996) to improve the groundwater quantity and spate irrigation of range land. Groundwater is the main source of fresh water in the GBP and inhabitants exploit groundwater by pumping from wells for drinking and irrigation purposes. The number of legal and illegal pumping wells in the area has increased to over 120, about 10 times the number in 1983 (Hashemi et al., 2013). Despite the artificial recharge by FWS over-exploitation of groundwater has led to a groundwater table drop of about 10 m during the last 10 years in the area (Hashemi et al., 2012).

There are two ephemeral rivers in the study area, namely Bisheh-Zard and Tchah-Qootch Rivers that discharge from two upper intermountain watersheds (Bisheh-Zard and Tchah-Qootch sub-basins) with areas of 192 and 171 km^2, respectively (Fig. 1). These join in the lower south-eastern part of the GBP. The two ephemeral rivers are the main source of incoming surface water to the GBP. These are, however, almost dry during the entire year except for a few annual occasions of flash floods.

Wheat, barley, and corn are dominant crops in the GBP. The cultivation period for wheat and barley start in late autumn (November–December) with harvesting in mid spring (April–May). The average irrigated and rainfed barley yield for the region is about 3500 and 1000 kg ha^{-1}, respectively.

2.2 Floodwater spreading system

In general, a FWS system serves as sedimentation basins and infiltration ponds for the artificial recharge of groundwater and also as spate irrigation of natural range land and rainfed farming. Flash floods in arid areas are characterized by high water velocity and turbidity through the ephemeral river channel that quickly crosses the catchment and then is lost from the area. In the FWS, the ephemeral river is diverted into a series of leveled terraces. Each of these terraces is slowing the water down and giving it a chance to infiltrate into the ground. Most of the suspended materials and coarse-grained particles settle in the first sedimentation basins. Thus, less turbid water enters the next basins through water gateways installed in the bank of the channels. Often, diverted water to the FWS system do not reach the last terrace as all water has infiltrated in the upstream basins. In any case, excess water is returned to the river at the outlet of the last terrace (Fig. 2).

2.3 Data collection

In the GBP, groundwater levels have been recorded monthly since 1993 by the Fasa District Water Organization. Monthly observations from four wells located within the GBP during 14 years between 1993 and 2007 were used in this study for calibration of a groundwater model. Monthly observations from two newer wells operated during the period 2007–2009 were used for verification of the model. To extend data records for the newly established Gareh-Bygone climatology station we used meteorological data from a neighboring station located in the same basin (Baba-Arab, 16 km from the studied area). The above mentioned data was used in groundwater modeling aiming to estimate recharge for the period between 1993 and 2007.

2.4 Groundwater modeling

Groundwater flow and recharge rates were simulated using MODFLOW-2000 (Harbaugh et al., 2000). In order to estimate recharge a 3-D conceptual model was built to represent the GBP. Geological, hydro-meteorological, and observed hydraulic head data for the period 1993–2007 were used to build the model domain. Four observation wells were used to build the conceptual model for the fourteen-year period. Subsequently, the model was calibrated over the study period based on observed monthly hydraulic head at the four observation wells and verified with two more recent observation wells data in steady-state condition. Groundwater flow was simulated and calibrated based on monthly observed data during both steady-state (Hashemi et al., 2012) and transient periods for a period between 1993 and 2007.

In the steady-state simulation, the model was calibrated for ten different time periods to achieve the best estimation of horizontal hydraulic conductivity (K_h) and boundary conditions. Then, the parameters for steady-

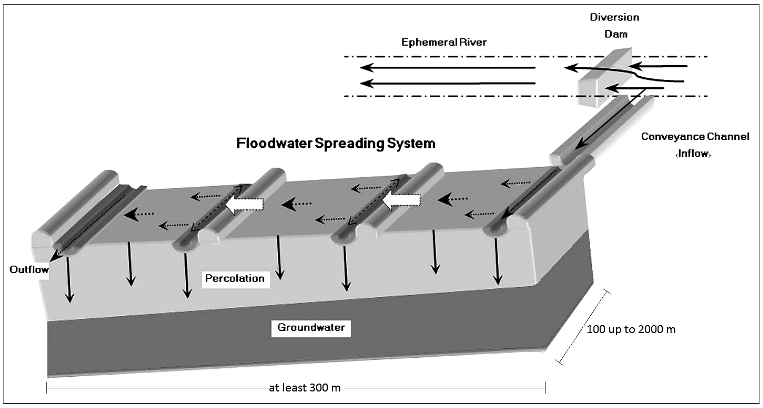

Figure 2. *Schematic representation of a three-basin floodwater spreading system.*

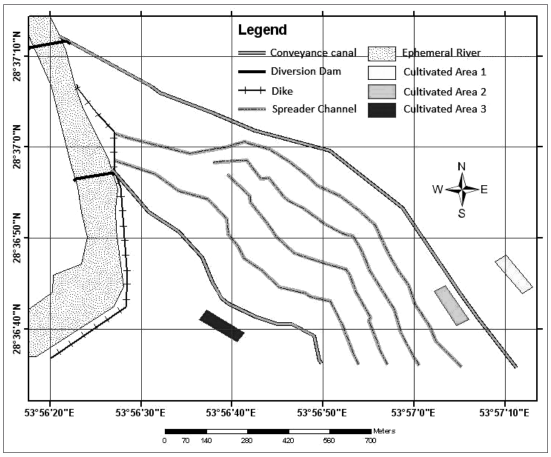

Figure 3. *The Tchah-Qootch floodwater spreading system and the location of three experimental plots (cultivated area 1 outside the system (control plot) and cultivated areas 2 and 3 inside the system (trial plots).*

state conditions were transferred to the transient model to estimate storativity, and recharge rate (*RCH*) using an inverse modeling approach (see further Hashemi et al., 2013). Due to unconfined aquifer characteristics, the transient model was constructed and calibrated against observed well data in order to estimate specific yield (S_y) for three different periods. However, since the drawdown of groundwater level in an unconfined aquifer depends on S_y (Al-Kharabsheh 2000) and to decrease the number of unknown parameters the model was calibrated for no recharge but with active pumping wells. The average estimated S_y was then transferred to the unsteady model to estimate recharge. In the unsteady model, the *RCH* was estimated for the different time intervals between the ten steady-state conditions.

2.5 Field experiment for spate irrigation of barley

Besides evaluating the system in terms of groundwater recharge, a field experiment was conducted to investigate improved agricultural yield using spate irrigation technique. For this purpose, barley (*tropy variety*) was tasted as an indicator for crop yield. Accordingly, the FWS system at Tchah-Qootch was used and two trial plots were prepared (Fig. 3). Also, an upstream area for control was selected. Thus, two one-hectare trial plots inside the FWS system (Cultivated Area 2 and 3, CA 2 and 3) and another one-hectare control plot outside the system (Cultivated Area 1, CA 1) were prepared for the experiments in December 2009 (Fig. 3).

After preparation of plots with low tillage method (e.g., Rathore et al., 1998, Ghuman and Sur 2001), 200 kg of barley seed (tropy variety) were prepared to be applied on each plot (total of 600 kg for all plots). On 5th December, 2009, barley seed were first cultivated in the CA 3 plot. The plot received rainfall on December 7 and spate irrigation on December 8. On 16 December, 2009, after the first floodwater spreading, barley seed were cultivated in the CA 1 and CA 2 plots. It should be noted that, during the growth period, spate was not available for the CA 2 plot. Therefore, planted barley in CA 1 and CA 2 only got moisture from rainfall. In principal, CA 1 and CA 2 only received 79 mm rainfall in the growth period whereas CA 3 received 169 mm rainfall in the growth period and by spate on December 8, 2009 (Table 1). Fertilizer was applied similarly to all plots with a rate of 100 kg ha^{-1} N on 27 February, 2010. In the beginning of the growth period, each plot was divided into 6 equal subplots, in direction of flood spreading with 40 m length and 20 m width. Plant sampling was consequently, done in each of the subplots. Subplots and sampling points in CA 1 and CA 2 as examples are shown in Figure 4.

In each sampling point (1x1 m^2) seed and straw yields/weight were recorded within the subplots. It is noted that the plants were cut from above the ground (roots were retained in the ground) and directly weighed using a digital scale.

Table 1. *Rainfall during the studied period.*

Year	Month	Day	Rainfall (mm)
2009	December	7	13
		8*	68.5
		9	5
		13	3.5
		18	13
		19	2
2010	January	1	20.5
		10	1
		21	1.5
		25	1
		26	7
2010	February	3	0.5
		4	1
		5	9
		27	10.5
2010	March	2	3
2010	April	18	7.5
		19	1.5

*flood event

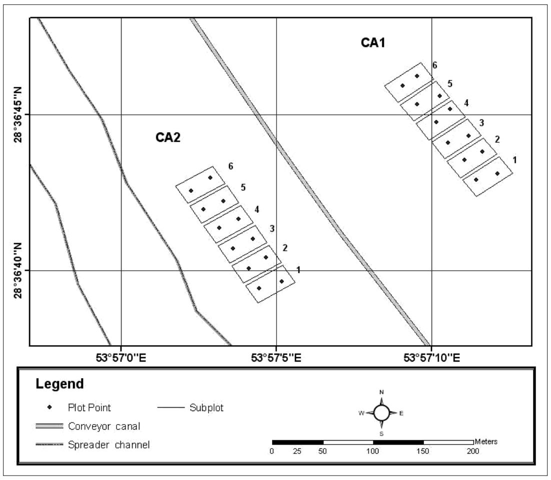

Figure 4. *Sub plots and plant sampling in CA 1 and CA 2.*

Table 2. *Barley yield (weight of grain and straw) in CA 1, CA 2, and CA 3.*

Plot number	Barley weight				
	Max (g)	Mean (g)	Min (g)	Total (g)	Average (kg ha^{-1})
CA 1	129	82	15	985	821
CA 2	266	162	93	1778	1616
CA 3	237	205	178	2462	2052

3 Results and discussion

3.1 Groundwater modeling and estimated recharge

Ten different steady-state simulation periods were modeled for which the hydraulic head difference between successive months was negligible. These ten steady-state simulations were calibrated, using the PEST module, regarding their K_h values. Then the model was verified using a new steady-state period in 2008 (Hashemi et al., 2012). The results show that the calibrated and verified K_h value are quite close, however, the residual and standard deviation are somewhat larger for the verified K_h. Thus, the average estimated K_h in the GBP was about 0.1 m/day, which is in the range of values of K_h (0.001 and 1 m/day) for typical alluvial fans (Freeze and Cherry 1979).

To estimate the S_y in each zone as a second step, the model was calibrated for three transient period intervals with no recharge but active pumping wells. The estimated S_y in each zone ranged from 0.008 to 0.10 with an average of 0.045. The average value of S_y was then transferred to the next transient interval to estimate the recharge rate. During these periods there was no recharge from the surface water and water was exploited through the pumping wells.

Simulations and recharge estimations were conducted for the entire model period (1993–2007). Accordingly, ten different transient models were assigned and calibrated starting from each steady-state and ending with the next one. Figure 5 shows the residual between simulated and observed GWL at the boreholes and the agreement between observed and simulated time series in one of the selected wells for estimating monthly recharge.

The recharge amount varied from a few hundred thousand m^3 per month during drought periods to about 4.5 million m^3 per month during rainy periods (Fig. 6). The results show that frequent floods resulted in larger recharge as compared to periods with the same magnitude in floods but with fewer events. Thus, the FWS has large influence on the groundwater balance.

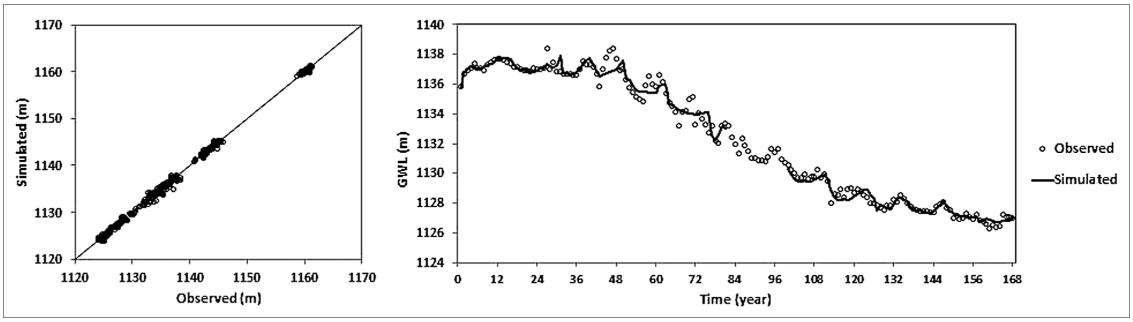

Figure 5. *Scatter plot of observed vs. simulated monthly GWL for all boreholes and time series of observed and simulated GWL in one of the selected observation wells between 1993 and 2007 (no simulation was done for 2000 and beginning of 2001 due to missing observations).*

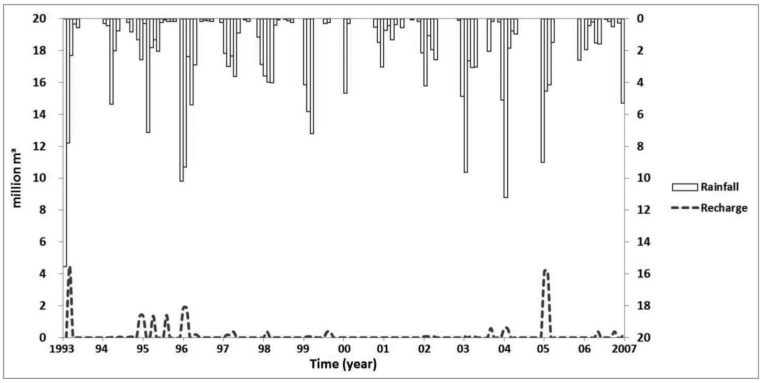

Figure 6. *Monthly rainfall and estimated recharge.*

3.2 Barley yield

Measured barley yield (weight of grain and straw) is presented in Table 2. As shown, barley yield in CA 2 is almost two-fold of that for CA 1. As mentioned before, barley seed was cultivated in both CA 1 and CA 2 on 16th December 2009, one week after a flood event and spreading inside the system. Thus, neither CA 1 (outside the system) nor CA 2 received spate irrigation during the cultivation period. However, due to the flood-spreading event before cultivation in CA 2 (on December 8), there must have been a significant effect in crop yield due to improved soil water content in CA 2. In addition, since fertilizer was applied with the same quantity for all plots, the physico-chemical characteristics of the soil in CA 2 are also the major parameter influencing the yield and perhaps the quality of the crop.

The barley yield in CA 3 was 2052 kg ha^{-1}, which is about 2.5-fold for that of CA 1 and 1.3-fold for that of CA 2 (Table 2). Barley seed in CA 3 was cultivated on December 5th and spate irrigated on December 8th. Otherwise all conditions such as seed rating, fertilizer, and rainfall were the same as in CA 1 and CA 2. Thus, larger yield for CA 3 as compared to CA 1 and CA 2 can only be explained by the influence from spate irrigation. However, no floodwater spreading occurred before cultivation in CA 3.

Kowsar (2011) stated that in the GBP barley production is ranging between 700 and 2000 kg ha^{-1} with only 145 mm of rainfall and two spate irrigation events. He also stated that the average yield of barley in a year with 330 mm of rainfall was about 2300 kg ha^{-1} with three flooding events. In addition, observed barley yield on December 1985 in a FWS system with one spate irrigation event on February 1986 produced about 1000 kg ha^{-1}. Assuming similar conditions for cultivation in 1985–86 and 2009–10, spate irrigation together with the appropriate crop variety appear to significantly increase the agricultural production as compared to traditional arid rainfed farming.

It is estimated that there are about 500 ha spate irrigated land in the studied FWS system. Bakhtiar et al., (1997) reported that 5.5 ha of irrigated fields on average could support a 6.7 member owner-manager family, and create 0.4 person extra occupation for farm labor. According to Bakhtiar et al., (1997) the average irrigated barley yield in the GBP is 3500 kg ha^{-1}. Based on this, the new spate irrigated farm fields with on average 2000 kg ha^{-1} barley production in a normal year on 500 ha land, would produce 1000 ton barley in a year that can support 348 persons or 52 households on average including 6.7 members per household. Moreover, the stubble of these fields is a valuable food reserve for the livestock. In addition, the 18-year monitoring of rangelands by Mesbah and Kowsar (2010) indicated that spate irrigation of a denuded rangeland in the GBP increases its productivity both in wet (>200 mm rainfall) and dry (<200 mm rainfall) years. Mean usable forage yield was 491 and 183 kg ha^{-1} year^{-1} for the spate irrigated and control, respectively. For wet and dry years, this was 331 and 116 kg ha^{-1} year^{-1}, respectively. These results verify the value of spate irrigation through FWS system in arid and semiarid areas.

4 Conclusions

Scarce and erratic rainfall is the most limiting constraint in arid land area. Therefore, it is essential for sustainable development of the rural communities to implement simple, inexpensive, and compatible methods that take into consideration the environment and the economic situation of arid countries. Taking into account the groundwater depletion in most arid areas due to the over-exploitation for irrigation purposes, artificial recharge and spate irrigation farming could be an efficient solution and alternative for water scarcity and agricultural practices. Hence, improved water harvesting systems for artificial recharge and spate irrigation play a significant role in improving the sustainable groundwater resources and agricultural production in such fragile environments to improve the livelihood of the rural community.

In this study we used available records of rainfall and groundwater observations together with groundwater modeling to quantify recharge rates over a 14-year period. In addition, field experiments were carried out in the period 2009–10 for cultivation of barley (*tropy variety*) inside and outside the FWS system in order to evaluate crop yield in spate irrigation systems.

The estimated recharge varied between about several hundred thousands to 4.5 million m^3 per month for the rainy season. The experimental results for spate irrigation of barley show a significant potential of spate irrigated farming in arid and semiarid areas using the FWS system to improve the livelihoods of the inhabitants. The results show that recharged water represents a valuable groundwater resource for the local farming community in terms of increased agricultural output.

In view of the increasing water scarcity, especially in the Middle East, alternative water management techniques such as rainwater harvesting and spate irrigation need to be investigated and further exploited. The scarcity of data in many of these regions poses special problems. However, studies and experiments like the one presented here can be used as representative for the present climatic and physiographical setting.

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