CGIAR Challenge Program on
WATER & FOOD

Improving Rainwater Productivity with Supplemental Irrigation in Upper Karkheh River Basin of Iran

A. R. Tavakoli, T. Oweis, H. Farahani, S. Ashrafi, H. Asadi,
H. Siadat and A. Liaghat

Improving On-farm Agricultural Water Productivity in the Karkheh River Basin Project (CPWF PN 8)

6

ICARDA
International Center for Agricultural Research in the Dry Areas

AEERO
Agricultural Extension, Education and Research Organization

CGIAR Challenge Program on
WATER & FOOD

CPWF project: Improving On-farm Agricultural Water Productivity in the Karkheh River Basin (PN8)

Research Report no. 6

Improving Rainwater Productivity with Supplemental Irrigation in Upper Karkheh River Basin of Iran

A. R. Tavakoli, T. Oweis, H. Farahani, S. Ashrafi, H. Asadi, H. Siadat and A. Liaghat

ICARDA
International Center for Agricultural Research in the Dry Areas

AREO
Agricultural Research and Education Organization

Citation: Ali Reza Tavakoli[1], Theib Oweis[2], Hamid Farahani[2], Shahram Ashrafi[3], Hormoz Asadi[4], Hamid Siadat[2], Abdolmajid Liaghat[5]. 2010. Improving Rainwater Productivity with Supplemental Irrigation in Upper Karkheh River Basin of Iran.
ICARDA, Aleppo, Syria. x + 102 pp.

ISBN: 92-9127-223-X

The authors are from: (1) Dryland Agricultural Research Institute, (DARI), Kermanshah, Iran, (2) International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, (3) Agricultural Engineering Research Institute, (AERI), Karaj, Iran. (4) Seed and Plant Improvement Institute, (SPII), Karaj, Iran. (5) University of Tehran, Irrigation and Reclamation Engineering Department, Karaj, Iran.

International Center for Agricultural Research in the Dry Areas (ICARDA)
P.O. Box 5466, Aleppo, Syria.
Tel: (963-21) 2213433
Fax: (963-21) 2213490
E-mail: ICARDA@cgiar.org
Website: www.icarda.org

Acknowledgments

This report presents findings from PN08 "Improving On-farm Agricultural Water Productivity in the Karkheh River Basin", a project of the CGIAR Challenge Program on Water and Food.

We gratefully acknowledge the contributions of the following individuals:
A. Javadi, F. Abbasi, Z. Shoaei, A. Amri, A. Hachum, A. Ghaffari, M. Roozitalab, S. S. Pourdad, A. Mirzaei, M. B. Moradjani, Z. Akbari, M. K. Arjomandi, S. Daei Chini, H. Azizi, M. Azizollahi, E. Amiri, F. Khodadost, A. Olfati, M. Kalhor, S. N. Mohammadi, T. Hoseinpour, M. Rafiea, R. Mohammadi and A. Abdullahi.

Authors would also like to thank the following institutions for their support:
Local extension service of Honam, Lorestan Meteorological Organization, local extension service of Merek, Seed and Plant Improvement Institute (SPII), Agricultural and Natural Resources Research Center, Khorram Abad. Jihad –e– Agriculture Directorate Office, Selseleh (Aleshtar), Lorestan. Jihad –e– Agriculture Provincial Organization, Kermanshah. Agricultural and Natural Resources Research Center, Kermanshah. Jihad –e– Agriculture Management Directorate Office, Kermanshah.

Partner Institutions

Institute	Address	Email
International Center for Agricultural Research in the Dry Areas	ICARDA, P.O. Box 5466, Aleppo, Syria	icarda@cgiar.org
International Water Management Institute (IWMI)	P.O. Box 2075 Colombo, Sri Lanka	IWMI@cgiar.org
Agricultural Research and Education Organization (AREEO)	P.O. Box 19835-111, Tabnak Ave. Tehran, Iran	areeo@dpimail.net
University of California, Davis (UCD)	UC Davis, Davis, CA 954616, USA	tchsiao@ucdavis.edu

Project Leader: Dr T. Oweis, Director, Integrated Water and Land Management Program (IWLM), ICARDA.
Project National Coordinator: Dr A. Javadi, Director General, Agricultural Engineering research Institute (AERI), Iran.
Basin Coordinator: Dr N. Heydari, AERI, Iran.

Project principal investigators:

Name	Professional Discipline	Institution	Title
Theib Oweis	Irrigation and water management	ICARDA	Director of the IWLM Program
Fariborz Abbasi	Irrigation engineer	AERI	DDG, AERI
Asad Qureshi	Water resources engineer	IWMI	IWMI-Iran program coordinator
Theodor Hsiao	Plant physiologist	UCD	Prof. of water science
Abbas Keshavarz	Irrigation and drainage engineer	AREEO	Former director of SPII
Ali Cheraghi	Soil scientist	AREEO	DG, Iran National Center for Salinity
Kamel Shideed	Agricultural economist	ICARDA	ADG-International Co-operation and Communication
Eddy De Pauw	Ecologist	ICARDA	Senior agroecologist

Project Team: Ali Reza Tavakoli, Theib Oweis, Hamid Farahani,, Shahram Ashrafi, Hormoz Asadi, Hamid Siadat, Majid Liaghat, Fariborz Abbasi, Abdolali Ghaffari, Seyed Saead Pourdad, Ali Mirzaei, Mohammad Bagher Moradjani, Zeinab Akbari, Masoumeh Khalili Arjomandi, Shirzad Daei Chini, Hamid Azizi, Morad Azizollahi, Einali Amiri, Farshid Khodadost, Adel Olfati, Manouchehr Kalhor, Saead Nour Mohammadi, Tahmasb Hoseinpour, Masoud Rafiea, Reza Mohammadi, abdolvahab abdullahi.

Contents

Abbreviations

AEERO	Agricultural Extension, Educational and Research Organization
AERI	Agricultural Engineering Research Institute
CGIAR	Consultative Group on International Agricultural Research
CPWF	Challenge Program of Water and Food
CRWP	Crop Rain Water Productivity
CWANA	Central and West Asia and North Africa
CWP	Crop Water Productivity
DARI	Dryland Agricultural Research Institute
GNP	Gross National Product
HI	Harvest Index
ICARDA	International Center for Agricultural Research in the Dry Areas
IRR	Internal Rate of Return
IWP	Irrigation Water Productivity
KRB	Karkheh River Basin
MBCR	Marginal Benefit Cost Ratio
NUE	Nitrogen Use Efficiency
PWP	Permanent Wilting Point
RAW	Readily Available Water
RWP	Rain Water Productivity
SI	Supplemental Irrigation / Single Irrigation
USDA	US Department of Agriculture
WP	Water Productivity
WUE	Water Use Efficiency

Preface

The Challenge Program on Water and Food (CPWF) contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase water productivity for agriculture—that is, to change the way water is managed and used to meet international food security and poverty eradication goals—in order to leave more water for other users and the environment.

As the overall goals, CPWF project PN08 “Improving On-Farm Agricultural Water Productivity in the Karkheh River Basin (KRB) Project” aimed at: Increasing water productivity in cereal rainfed production system in the upper catchment of KRB, stabilizing yield in rainfed areas by reducing or preventing crop losses in drought seasons, increasing food security in the rural areas, and increasing farmers’ income. The project was led by ICARDA in close partnership with the NARES under Agricultural Extension, Education and Research Organization (AEERO) of Iran.

At the start, the project embarked on selecting four benchmark sites representing the agro-ecological diversity of KRB. These were Honam and Merek catchments in the upper KRB and Sorkheh (also called Evan) Plain and Azadegan Plain in the lower KRB. Then, the project adopted a participatory research approach consisting of on-farm trials and field surveys fully managed by the national partners. Subsequently, local staff of AEERO, Provincial Jihad-e- Agriculture Organizations, Agricultural Research Centers, and extension agents mobilized farmers to engage with the national experts in conducting the research activities planned for the selected sites.

The project research programs included water productivity assessment in rainfed areas and improving (rain)water productivity with supplemental irrigation in the upper KRB, water productivity assessment and improvement under fresh and saline conditions, review of water policies and institutions in KRB, interaction between upper and lower KRB in response to the possible expansion of supplemental irrigation, and economical factors affecting water use efficiency(WUE).

Summary

The Karkheh River Basin (KRB) is located in the south-western parts of Iran. Most of the agricultural area in the upper KRB is rainfed and a large part of the region's agricultural livelihood is based on dryland farming systems. Current water productivity (WP) values for dryland crops range from 0.3 to 0.5 kg m^{-3}. This is in spite of the fact that the upper catchments in the KRB are among the most suitable rainfed zones of the country, with long-term annual precipitation of 300 to 600 mm. Low WP is mainly due to poor distribution of rainfall and poor agronomic management practices

To study the options for increasing water productivity in the basin, on-farm trials were conducted during the 2005-08 winter cropping seasons of wheat and barley at multiple farms across two benchmark watersheds of Merek (Kermanshah Province) and Honam (Lorestan Province) in the upper KRB. Under farmers practice at rainfed areas of Merek site, grain production for a local and an advanced barley variety (Sararood1), and a local and improved wheat variety (Azar2), were 1000-2100, 2100-2900, 800-2000, and 2000-2700 kg per ha, respectively. Early planting with the help of a single supplemental irrigation (SI) (about 75-50 mm), at Merek site, increased production to 3500-3700 for barley and 1800-3100 kg per ha for wheat. Similar results were obtained at the Honam site. Rain water productivity (RWP), for wheat, barley, and chickpea ranged from (0.3-0.5), (0.3-0.6), and (0.1-0.3) kg m^{-3}, respectively. The results of this study showed that a combination of advanced management with a single supplemental irrigation (SI) application at sowing or in the spring (heading to flowering stage) increased total water productivity (TWP), of wheat and barley from a range of 0.3-0.37 kg m^{-3} to a range of 0.45 -0.71 kg m^{-3}. The irrigation water productivity (IWP), of wheat and barley ranged from 0.55 to 3.62 kg m^{-3} by using single irrigation at sowing or in the spring. These preliminary results confirm the effective role of supplemental irrigation (SI) and improved agronomic management to enhance rainfed systems productivity.

Deficit irrigation (DI) studies showed that, crop water productivity for irrigated wheat in the two sites was higher than under full irrigation. Deficit irrigation not only increased water productivity, but also farmers' profits. Under pressurized irrigation, total water productivity achieved under a 25 percent water deficit was 1.2 times that achieved under normal irrigation.

Besides, a soil water and salt balance model (BUDGET) and a crop water productivity model (AquaCrop) were used to simulate grain and biomass yields, soil moisture content and evapotranspiration of winter wheat sown early with single irrigation scenarios. Experimental data from three growing seasons (2005–2008) were used. The experimental design incorporates Azar2 bread wheat cultivar tested under three treatments: no irrigation at sowing (rainfed), supplemental irrigation (SI) at sowing with 75 mm of water (SI sowing) and irrigation to replenish the total water requirement at 0–90 cm soil profile at spring (about 50 mm of water). Crop input parameters were selected from the model documentation and experimental data. The first crop season, field experimental data were used for model calibration and the other two crop season data were used for simulation. Results showed that BUDGET (2005) and AquaCrop (2009) were able to simulate well the grain yield reduction, the soil moisture content (SMC) and the evapotranspiration as observed in the field experiments.

Finally, economical analyses of different treatments for wheat and barley at Honam show that under current market condetions all treatments, except early planting with SI, were non-economical. Accordingly, at Honam, recommended management are in the following ranking: Advanced management (AM) + planting SI, AM + SI spring, and AM + rainfed treatments, respectively. Traditional management with SI or without SI is not recommended. Similar results with spring SI and early planting SI scenarios are recommended at Merek for both wheat and barley.

Chapter 1.

Background

1. Background

Rainfed agriculture in Iran covers large areas of land where wheat (*Tritium aestivum* L.) and barley (*Hordum vulgare* L.) are the major crops. Nearly 10% of the country's total agricultural products are derived from rainfed agriculture. Areas under rainfed wheat and barley were 3.95 and 1.11 million ha in 1997–98 and 4.032 and 0.87 million ha in 2003–04, respectively. According to the official documents published by the Ministry of Jihad-e-Agriculture, the total production of rainfed wheat and barley in 2003–04 season were 4.72 and 0.82 million ton, respectively. Low and variable rainfall, high evaporation rates, long dry periods, relatively low soil fertility, poor seed quality and inappropriate agronomic practices applied by farmers contribute to low yields in the rainfed areas. Presently, the national average yield of wheat and barley under rainfed condition are 832 and 934 kg ha^{-1}, respectively (Tavakoli *et al*., 2005).

Rainfall variability and unreliability of rainfall events prevent the farming community from larger investments into the production system. The prevailing high risk in rainfed agriculture needs to be addressed given the increase in food demand for a burgeoning population. New ways and methods of production are needed to increase and stabilize crop production in these areas. Optimized supplemental irrigation techniques have shown promising results to overcome low level and unstable yield levels.

The hypothesis of this project is that water productivity in the KRB could be substantially increased by improving on-farm management, introducing new crop varieties, optimizing SI and integrating appropriate agronomic practices in the crop production system. It is believed that the key to the realization of this hypothesis is the involvement and participation of farmers and local communities as well as the full cooperation of the official organizations and authorities responsible for water and agricultural development of the basin

1.1. Characteristics of Karkheh River Basin and the Selected Sites

The sites of water productivity studies carried out between 25° to 40° Northern Latitude and between 44° to 64° Eastern Longitude, and are bounded by the Caspian Sea, the Republic of Azarbaijan, the Republic of Armenia, and Turkmenistan in the north, the Persian Gulf in the south, Afghanistan and Pakistan in the east and Iraq and Turkey in the west. Karkheh River Basin (KRB) is located between 30˚ 57˚ to 34˚ 57˚ Northern Latitudes and 47˚ 30˚ to 50˚ 45˚ Eastern Longitudes in the western parts of Iran and represents semi-arid and arid areas of the region. Two major agricultural production systems prevail in the KRB: rainfed cropping in the upstream of the newly built Karkheh dam and the fully irrigated cropping in areas located mainly in the downstream of the dam.

Two research pilot sites and communities were selected for the project; one in Lorestan Province, and the other one is in Kermanshah Province. The pilot site in Lorestan, (Honam) is located at about 45 km north of Khorram Abad, the Provincial Capital of Kermanshah. The coordinates are 33º49' N; 48º15' E; and has an average elevation of 1567m a.s.l., with a long-term annual rainfall of 450 mm.

This site is drained by the Honam River. It is a sub-catchment of the KRB and covers an area of about 3400 km^2 (Fig. 1-1). According to the 2005 population census, Honam sub-catchment (HSC) and Aleshtar city have a population of about 10,000 and 67,000 inhabitants, respectively with an average annual growth rate of 1.9% .

Figure. 1-1 Karkheh River Basin location and the research sites

The pilot site in Kermanshah Province was Merek sub-catchment that is located at about 15 km south east of Kermanshah. Its coordinates are 34º 20' N; 48º19' E; with an average elevation of 1351m a.s.l and a long term average annual precipitation of 430 mm. This site is drained by the Merek River. It covers an area of about 4000 km^2 (Fig. 1-1). According to the 2005 population census, Merek sub-catchment (MSC) and Kermanshah city have a population of about 10,000 and 700,000 inhabitants, respectively with an average annual growth rate of 1.9% which is higher than the national average.

1.2. Literature Review

An extensive literature review on the subject of this report has been published by the project (Tavakoli, *et al*, 2008) and, therefore, only a summary containing the more important points are presented here.
While KRB is one of the more important rainfed areas of Iran, the first rainfall necessary for seed germination in most years occurs after October, resulting in poor crop establishment in colder highland areas where frost may occur in November, hindering plant growth. Therefore, rainfed yields are much lower compared to well established crops when crop growth takes off in early spring. Ensuring a good crop stand in Nov-December can be achieved by early sowing and applying a single irrigation in October.

In the highland rainfed regions of Iran, application of single irrigation at planting time or at heading-flowering growth stage for winter cereals (wheat and barley) increased yield from 500 to 2500 kg ha^{-1} and from 500 to 1000 kg ha^{-1}, respectively (Tavakoli, 2001; Tavakoli *et al*., 2000). Four-year trials, conducted at the central Anatolia plateau of Turkey, showed that applying 50 mm of SI to early sowing wheat increased grain yields by more than 60%, adding more than 2 t/ha to the average rainfed yield of 3.2 t/ha (ICARDA, 2003). Water productivity reached 5.25 kg grain/m^3 of consumed water, with an average of 4.4 kg m^{-3}. The study also revealed that SI applied later in the spring and early summer further increased yield, but resulted in lower water productivity. Similar results were obtained in the highlands of Iran at Maragheh (Tavakoli and Oweis, 2004).

Variation in rainfall amounts and distribution from one year to another causes substantial fluctuations in wheat grain production that can range from 0.3 to over 2.0 t/ha. This situation creates instability which negatively affects household incomes. Agricultural productions and livelihoods in dry areas can be sustained, only if priority is given to improving water productivity and enhancing the efficiency of water procurement. In other words, more food, feed and fiber must be produced using less water.

The foremost concern in arid and semiarid areas is availability and efficient use of water. In drylands of KRB, the major constraint to wheat production is low rainfall. Another yield determining constraint in drylands is the sowing date. In Iraq, during the 1997/98 season which was very dry, for every week delay in sowing, there was a resultant grain yield reduction of 220 kg ha^{-1} for rainfed crops, and 520 kg ha^{-1} for crops under SI (Adary *et al*., 2002). A multi-sowing date strategy reduced the peak farm water demand rate by more than 20%, thus potentially allowing a reduction in the irrigation system size and cost (Oweis and Hachum, 2001).

Among agronomic practices, application of nitrogen, SI and early sowing of appropriate cultivars are widely recognized as a means of increasing wheat yield in the dry areas (Cooper *et al*., 1987; Siddique *et al*., 1990; Anderson and Smith, 1990; Oweis *et al*., 1998). For the data obtained in Maragheh, the relation between ETa and crop yield was found to be as following (Tavakoli *et al*., 2005):

$$Y=0.0093\,ET_a - 1.384 \qquad R^2=0.74 \qquad (1\text{-}1)$$

where *Y* is wheat grain yield (t/ha) and *ETa* is actual crop seasonal evapotranspiration (mm). Timing of water application is also one of the most important factors to be determined when using SI. Supplemental water applications are especially important when water is scarce during critical growth periods. An experiment carried out during 1982–85 near Merek site showed that two irrigations applied at the heading and milk growth stages of wheat resulted in a 3 year average of about 2800 kg ha^{-1}, whereas average yield in the area was 1200 kg ha^{-1}. In Kermanshah province, the best single SI treatment for rainfed local wheat variety (Sardari cultivar) was found to be one time irrigation at heading to flowering stage (Sayadyan and Tallie, 2000). The increase of barley grain and straw yields by single irrigation were highly significance. In the same region, Tallie (2005) found that single irrigation of improved rainfed barley variety (Sararood1) during heading to flowering stage increased grain yield by 1204 kg ha^{-1} compared with rainfed condition. Irrigation water productivity was between 1.2 and 5.0 kg m^{-3}.

Research results in Maragheh (2000-2004) showed that RWP was between 0.31 to 0.43 kg m^{-3} while IWP was 0.72 - 2.39 kg m^{-3} and TWP was 0.36 - 0.85 kg m^{-3}. The average wheat grain yield of two seasons under single irrigation at planting and rainfed condition for Azar2 wheat variety were 2050- 3232 and 1404 kg ha^{-1}, respectively (Tavakoli, 2005).

Response of different wheat cultivars to various levels of SI and nitrogen application was studied at Maragheh, Sararood, and Haydarloo research stations in 1999–2002 (Tavakoli *et al*., 2003). Yields of rainfed conditions varied with seasonal rainfall and its distribution, with all main factors having significant effects. Results of path analysis for rainfed wheat showed that increase in grain yield was due to increased seed numbers per spike, height and straw yield, respectively. Optimum level of SI for Sabalan variety was 1/3 of full SI

with 60 kg N ha^{-1} resulted in maximum water productivity (3.1 kg m^{-3}). In spite of 20% reduction of yield in this treatment, a maximum net benefit was obtained along with possibility of 180% cropping area increase, which led to 74% increase in total grain yield. The limit of benefit ability for optimum level of SI was determined as 0.292 US$/$m^3$ water (1US$ = 9800 I.R-Rials). Results of path analysis for irrigated wheat showed that increase in grain yield was resulted from increase of spike/m^2, seed number per spike and straw yield, respectively (Tavakoli, 2003, 2004).
In another similar experiment at the same location, the rainwater productivity (RWP) varied between 0.277 and 0.304 kg m^{-3} while irrigation water productivity was 1.66–3.1 kg m^{-3} and total water productivity varied between 0.52–0.81 kg m^{-3}. The average grain yield of rainfed barley (Yesevi-93 barley advanced line) under SI planting, SI spring and rainfed treatments were 3007, 2273 and 1019 kg ha^{-1}, respectively.

Generally speaking, SI can be exercised in one of the following methods:

- Applying one or more irrigations at the specific stages of crop growth during soil-moisture stressed period.
- Application of deficit irrigation when the crop is experiencing moisture stress.
- Combination of single irrigation with recommended agronomic management
- Optimization of water use in irrigated wheat farming.

1.3. Objectives

The main objectives of the project are:

- Improve farm water productivity and sustainability
- Develop maps identifying suitable areas for supplemental irrigation.
- Assess and evaluate present RWP and sources of improvement for the major crops (wheat and barley) and farmers preferences in the region.
- Enhance RWP through supplemental irrigation (SI) (amount and time) in combination with improved water resource, land preparation, varieties, sowing date, fertility, rotation, weed and disease control and harvest practices.
- Using simulation models (Budget and AquaCrop) for analyzing grain yield and soil moisture content.
- Conduct economical analysis of the promising technologies for recommendation to the stakeholders
- Dissemination of proven technologies to extension and farmers through field days, farm demonstrations, and fact sheets.

Chapter 2.

Supplemental Irrigation of Rainfed Wheat and Barley

2. Supplemental Irrigation of Rainfed Wheat and Barley

2.1. Introduction

In the upper KRB, the first rainfall, necessary for seed germination, in most years occurs after October, resulting in poor crop establishment in colder highland areas where frost may occur in November, hindering plant growth. Therefore, rainfed yields are much lower compared to well established crops when crop growth takes off in early spring. Ensuring a good crop stand in Nov-December can be achieved by early sowing and applying a single irrigation in October. In the rainfed regions of Iran, application of single irrigation at planting time and heading-flowering growth stage for winter cereals (wheat and barley) increased yield from 500 to 2500 kg ha^{-1} and from 500 to 1000 kg ha^{-1}, respectively (Tavakoli, 2001; Tavakoli *et al*., 2000). An experiment carried out during 1982–85 near Merek site showed that two irrigations applied at the heading and milk growth stages of wheat resulted in a 3 year average of about 2800 kg ha^{-1}, whereas average yield in the area was 1200 kg ha^{-1}. In Kermanshah province, the best SI treatment for rainfed local wheat variety (Sardari cultivar) was found to be a one time (single) irrigation at heading to flowering stage (Sayadyan and Tallie, 2000). The increase of barley grain and straw yields by single irrigation were highly significance. In the same region, Tallie (2005) found that single irrigation of rainfed improved barley variety (Sararood1) during heading to flowering stage increased grain yield by 1204 kg ha^{-1} compared with rainfed condition. Irrigation water productivity was between 1.2 and 5.0 kg m^{-3}.
The existing status of water productivity in the region was assessed by a simple survey by questionnaire. The results are shown in Table 2-1 . Major crops grown under rainfed conditions are wheat, barley, chickpea and lentil. Usually chickpea and lentil are grown in rotation with wheat and barley.

Water losses in rainfed areas are mainly through surface runoff from lands with steep slopes and by surface evaporation. Effective rainwater productivity is about twice total rainwater productivity indicating that rainfall use efficiency is about 50%.

At Honam site, CRWP for wheat and barley is low, 0.17-0.43 and 0.22-0.63 kg m^{-3}, respectively. Crop rain water productivity for chickpea and lentil is also low 0.07-0.22 and 0.04-0.15 kg m^{-3}, respectively at rainfed farmer's areas in the upper KRB (Tavakoli *et al*., 2008).

At Merek site, CRWP for wheat and barley is low, 0.16-0.42 and 0.17-0.31 kg m^{-3} respectively. Crop rain water productivity

Table 2-1- Average grain yield and crop rain water productivity for different crops in the rainfed upper KRB and under traditional management at two sites (Honam and Merek), 2004-2007.

	Honam site		Merek site	
Crop	Yield (kg ha^{-1})	CRWP (kg m^{-3})	Yield (kg ha^{-1})	CRWP (kg m^{-3})
wheat	800-2000	0.17-0.43	900-2400	0.16-0.42
barley	1000-2900	0.22-0.63	1000-1800	0.17-0.31
chickpea	300-750	0.07-0.22	300-900	0.05-0.16
lentil	200-700	0.04-0.15	700-1100	0.12-0.19

for chickpea and lentil is also low 0.05-0.16 and 0.12-0.19 kg m^{-3}, respectively at rainfed farmer's areas in the upper KRB (Tavakoli *et al*., 2008).

Low RWP is mainly due to poor distribution of rainfall and poor agronomic management practices. Optimum program of single irrigation at planting time improved WP values to 1.3-2.1 kg m^{-3} (Tavakoli, 2007). In rainfed areas there are some agronomic factors which affect RWP such as land preparing machinery, seed rate, seed depth, sowing date, fertilizer management (amount, time and source), variety and harvesting.

It can be concluded that the single supplemental irrigation practice can increase yields, water productivity, water use efficiency and stability of crop production under different climatic conditions. However, these increases depend on factors such as seasonal precipitation, rainfall distribution especially at the two critical stages; and agronomic factors outlined earlier.

2.2. Materials and methods

On-farm trials on supplemental irrigation were carried out during three growing seasons over the period 2005-2008 in the two selected sites of the project. General characteristics of these sites are given in section (1-1) of this report. The general research approach used was community-based with full farmers participation. The direct interaction between the project's personnel and the beneficiaries produces the optimum results that will have the greatest chance of being adopted and adapted by farmers. Different farms were selected in the two sites during 2005-8: a total of 84 farmers in Honam and 74 in Merek. The farms filed information (rotation, sowing date, fertilizer management, preparation and planting machinery, weed and disease control, and harvest) at both sites are presented in Appendix I.

2.2.1. Soil properties

Soil samples were taken from the study sites for analysis. Average soil properties at the study sites are shown in Appendix II, Table II-1.

2.2.2. Climate

Daily meteorological data viz., rainfall, evaporation (Class A pan), relative humidity (maximum and minimum), maximum and minimum temperatures, wind speed, sunshine were recorded from nearest meteorological station (Aleshtar Station, for Honam, and Kermanshah Station (Sararood), for Merek). A summary of the behavior of meteorological parameters in the study sites are given below:

Precipitation

Total annual precipitation is directly influenced by the land topography and elevation, especially by the great mountain ranges. Merek site is considered sub-humid, with 12-year average annual precipitation of 430 mm, while Honam site is a semi-cold region having a 10-year average annual precipitation of 457mm, mostly falling as snow (Figs. VI-1 and VI-11).

Although total annual precipitation is highly effective in determining the success of dry-farming, distribution of the rainfall throughout the year is also of great importance.

At Merek, the annual rainfall amount was variable during the three growing seasons over the period 2005-2008 (Figs. VI-1, VI-7, and VI-9). In 2005/2006, rainfall was inadequate for full emergence after sowing in October. Total seasonal rainfall amount was 505 mm and first and last effective rainfall were 31 mm and 18.2 mm on 16-17 Nov. 2005 and 5-6 May 2006, respectively. In 2006/2007, adequate rainfall fell in October immediately after sowing with a total seasonal amount of 552 mm. The first and last effective rainfalls were 8.6 mm and 18.5 mm on 16-17 Oct. and 32.3 mm on 15-17 May 2007, respectively. In 2007/2008, again, insufficient rainfall limited full emergence after sowing in October. Total seasonal rainfall amount was 154 mm and first and last effective rainfall were 16.3 and 17 mm on 2-3 and 6-7 December and 25-26 February 2008, respectively. In 2005/2006 and 2007/2008 seasons, inadequate rainfall in October was later followed by limited rainfall during March to end of cropping season. The 2007/2008, season was extremely dry with a total amount of 154 mm with poor distribution, there were 86 rainy days in winter (mid Dec. 2007 – late February). For example, total rainfall amount during October 2007 – March 2008 was 127.8 mm and during March 2008– July 2008 (harvest time) rainfall amounted to only 26.2 mm, when the temperature dropped and negatively affected the crop development. In the third season, most rainfed wheat and barley farms were damaged by drought condition and were grazed by sheep and goats (Fig. 2-1). Thus, in the first and third seasons rainfall was not adequate for full crop emergence in October.

In Honam, similar variability in annual rainfall was experienced during the three growing seasons (Figs. VI-11 and VI-16). In 2005/2006 season, insufficient rainfall after sowing in October limited crop emergence. Total seasonal rainfall amount was 544 mm, the first effective rainfall amounts were 7.2 mm and 24.4 mm on 21 October and 6 November 2005, respectively and the last effective rainfall amounts were 37.7, 7.4 and 12.3 mm on 6-7 April, 17-18 April and 25-27 April of 2006, respectively. In the season of 2006/2007, adequate rainfall fell in October immediately after sowing with a total seasonal amount of 573 mm. The first and last effective rainfalls were 15.6 mm and 31.9 mm on 16 October 2006 and 16 May 2007, respectively. In 2007/2008 season, rainfall was inadequate for full emergence. Total seasonal rainfall amount was 505 mm and first and last effective rainfall were 45.4 mm and 32.5 mm on 21-23 November 2007 and 26 February 2008, respectively. In the seasons of 2005/2006 and 2007/2008, inadequate rainfall for emergence occurred after sowing in October and so inadequate rainfall during March to end cropping season. The 2007/2008 season was extremely dry with a total rainfall amount of 294 mm with poor distribution. For example, total rainfall amount during the interval October 2007 – March 2008 was 260 mm (88.3 percent of total annual precipitation) and during March – July 2008 (harvest time) was only 34.3 mm, when the temperature dropped and negatively affected the crop development. Most rainfed wheat and barley farms were damaged by drought condition and the crops were grazed by sheep and goats, (Fig. 2-1). Thus, in the first and third study seasons rainfall was not adequate for full crop emergence in October.

Air temperature

The average annual air temperature of the Merek and Honam sites ranges from 12 to 15° C. These sites represent most of the rainfed farm territory in the class of cold and cold-temperate climate regions, although there are some areas with very cold winter and warm summer temperature. The range of temperature from the highest in summer to the lowest in winter is considerable, but not widely different from other similar parts of the rainfed areas of Iran.
Mean temperatures (maximum, minimum and average) at Honam site (Fig. VI-14)


Fig. 2-1 drought condition and grazing by animals.

and during three years (2005/2006/2007) the annual average temperature were 12.5°C, 13°C and 12.9°C, the maximum temperature were 38.8°C, 39.8°C and 37.4°C, and the minimum temperature were -19.6°C, -17.4°C and -14.2°C, respectively.
At Merek site (Fig. VI-4) and during three years (2005/2006/2007) the annual average temperature were 14.9°C, 15°C and 14.8°C, the maximum temperature were 41.6°C, 41°C and 40°C, and the minimum temperature were -15°C, -11.6°C and -10°C, respectively.

Growing degree days (GDD)
Growing degree days (GDD) are defined as the integration of the ambient temperature curve between two temperatures Tc-max and Tc-min which define the range where crop growth occurs. Outside of this range the crop stops developing or dies. The majority of plants have a fixed value of cumulative GDD to reach each stage of phenological development and, ultimately, maturity. Consequently, the duration of a phenological stage for a crop can be estimated based on cumulative GDD. Estimation of GDD is commonly based on daily average air temperature using the following equations (Ojeda-Bustamante *et al*., 2004):

$$GDD = T_a - T_{c\text{-}min} \qquad T_a < T_{c\text{-}max} \qquad (2\text{–}1)$$

$$GDD = T_{c\text{-}max} - T_{c\text{-}min} \qquad T_a \geq T_{c\text{-}max} \qquad (2\text{–}2)$$

$$GDD = 0 \qquad T_a < T_{c\text{-}min} \qquad (2\text{–}3)$$

Where Ta is the daily average air temperature, Tc-min is the minimum air temperature for growth of the particular species and Tc-max is the maximum air temperature above which growth ceases for the particular species.
The GDD values in Honam site during the 2005/06, 2006/07 and 2007/08 seasons were 1677, 1496 and 1530, respectively. The same values for Merek site were (Oct. – June) 2100, 1856 and 2129, respectively.

Relative humidity
Mean relative humidity (maximum, minimum and average) at Honam site and during three years (2005/2006/2007) the annual average relative humidity is 55.2, 56.4 and 55.6% (Fig. VI-13). At Merek site and during the same period, annual average relative humidity was 44.7, 47.2 and 45.9% (Fig. VI-3). In both sites, July and August are the driest months of the year (Figs. VI-3 and VI-13).

Evaporation
Potential evaporation varies considerably within the KRB. There is a tendency for decreasing evaporation with increasing altitude. The pan evaporation during three years, April-November (2005/2006/2007) are 1682, 1432 and 1151 mm/year, respectively at Honam site (Figs. VI-12, VI-17 and VI-19) and 2432, 2313 and 2286 mm/year, respectively at Merek site (Figs. VI-2, VI-6, VI-8 and VI-10). The yearly variation is smaller and steady. The lowest evaporation is experienced in February (during the wet season) and increases during the dry season (from June to December), reaching a maximum in July/August. The rainfall deficits relative to evaporation are great in spring and summer, as can be see in Figs. VI-2 and VI-12. Significant rainfall deficits are evident in the months of May to October. At Honam site the annual total rainfall deficit for three years (2005, 2006 and 2007) was -1194, -837 and -896mm, respectively. At Merek site the annual total moisture deficit for the three years (2005, 2006 and 2007) was -2034, -1709 and -1893 mm, respectively (Figs. VI-2 and VI-12).

Potential evapotranspiration (ETo)
Climatic data of the nearest meteorological station (Aleshtar city) were used for estimation of potential evapotranspiration in Honam (Figs. VI-15 and VI-18) and climate data of Sararood station were used for Merek (Figs. VI-5 and VI-6). The potential evapotranspiration was computed using Penman Montheith method (FAO, 2009). Figs. VI-1 through VI-19 present climatic and potential evaporation from Aleshtar (Honam site) and Sararood Kermanshah (Merek site) meteorological stations, respectively. The results show that the potential evapotranspiration during three years, April - November (2005/2006/2007) were 1301, 1189 and 1018 mm/year, respectively at Honam site, and 1307, 1308 and 1304 mm/year, respectively at Merek site. The lowest potential evapotranspiration is experienced in February (during the wet season) and increases during the dry season (from May to October), reaching a maximum in the months of June/August. These results show that potential evaporation increases with decreasing altitude.

2.2.3. Supplemental irrigation trials

The field trials were conducted at farmers' fields for three crop seasons during 2005-2008 at the Honam and Merek sites. Crop cultivars were a local winter bread wheat cultivar (Sardari) and an advanced wheat cultivar (either Azar2 or Cross Alborz). In the case of barley, a local cultivar and an advanced genotype (Sararood1) were studied. Irrigation treatments were as follows:

1. 75 mm single irrigation at planting time
2. 50 mm single irrigation at spring time,
3. 75 mm single irrigation at planting time + 50 mm single irrigation at spring time
4. no irrigation (rainfed),

There were two main management treatments:

1. Traditional management (TM)
2. Advanced management (AM)

The trials were carried out in two replicates. We defined two farmers field for each replicate, and then the treatments were randomly assigned to each block and replicated two times (two farmer's field) (Fig. 2-2). Wheat and barley were sown for three seasons in October over the 3 years of the trial at 20 cm row spacing. The plot sizes varied from 1000 to 5000 m^2, of which 3 m^2 (3* $1m^2$) were used for grain yield and yield components measurements.
Early sowing date was usually 10–15 days before farmers' normal planting time.

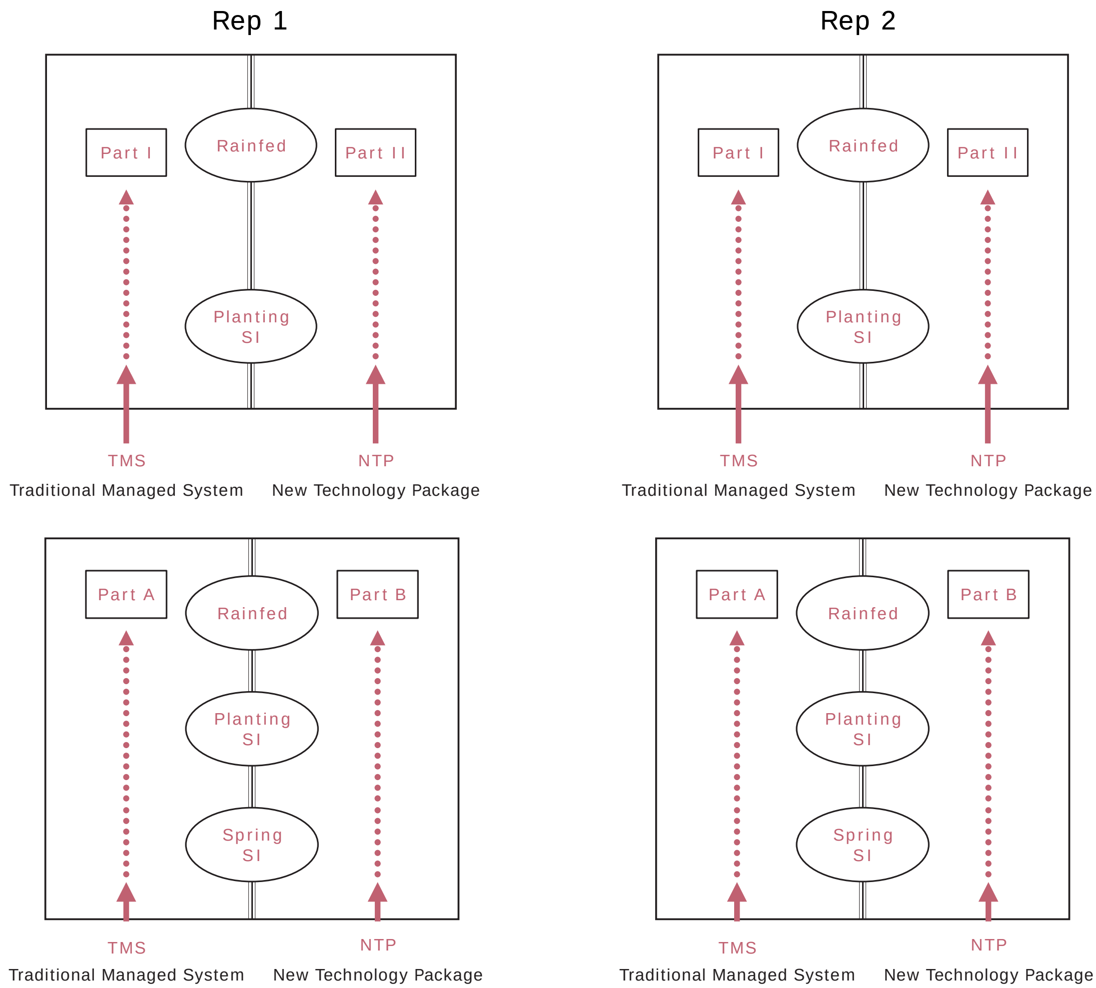

Fig. 2-2. Layout of the experiments for wheat and barley.

Water for irrigation was from different sources including: pumping of rivers, groundwater, springs, traditional canals and qanats. Spring irrigation was done based on crop stage during heading to flowering stage, when more than 50% of soil moisture content was depleted. This strategy allowed the crop to grow until maturity. Irrigation method was according to farmers practices: they were often border and basin surface irrigation.

Fertilizer requirements were splited into two doses, first dose was given at planting time and the second dose was applied at early spring time (early stem elongation stage). During the preparation of the land, ammonium sulfate and triple super phosphate of fertilizers were applied. Additional nitrogen was given as top dressing in March-April. During the season, growth stages, emergence, tillering, stem elongation, heading, flowering, maturity and harvest dates were observed and recorded.

2.2.4. Soil water monitoring

In order to measure soil moisture content in Honam, soil samples were taken at sowing date, before irrigation and after harvesting, respectively, from three successive layers, i.e. 0–0.2, 0.2–0.4 and 0.4–0.6 m, using an auger. At Merek experimental site, field access tubes were installed to a depth of 80 cm into some plots of middle replicate and soil water content was monitored every 15 days intervals, irrigation day (before irrigation) and harvesting day (after harvest), respectively, as well as after each rain by a TRIME device. The soil water depletion was measured gravimetrically once a week from 0 to 0.20, 0.20 to 0.40, 0.40 to 0.60 and 0.60 to 0.80 m soil layers. The actual water use (AWU) was estimated as per the equation:

$$AWU = R + SI + \Delta S + \int_{t}^{t_2} F_x dt \qquad (2-5)$$

Where, R = total rainfall received during crop season (mm), recorded from nearest meteorological station using, SI = single supplemental irrigation (mm), ΔS = change in soil moisture storage. Soil water upward flux (F_x) was negligible because of existence of deep water table (>3.0 m) in the study area. The runoff was also negligible because crops were grown in small boarded plots during winter/dry season and irrigation was applied at critical growth stages only. Some selected physical and chemical properties of the soil are presented in Appendix I.

2.2.5. Crop varieties and management

The winter wheat varieties used for the study were Local (Sardari) and advanced (Azar2) under two management treatments, traditional and advanced management. At early sowing data, the seeds were sown on 15th October 2005, 21st October 2006 and 20th October 2007, at a row spacing of 0.2 m, at normal sowing data, the seeds were sown about 10 -15 days after early sowing time. During the winter season, aboveground plant organs die and wheat plants are dormant. Under rainfed treatment the crop full germination revives in April, tillering stage in early May, stem elongation in May, flowering stage in June and is harvested in July. Under single irrigation at planting time treatment the crop full germination and tillering stage revives in autumn, stem elongation in May, flowering stage in June and is harvested in July.
Seedling density for TM and AM treatments were about 130-150 and 180-200 kg ha^{-1}, respectively.

At the end of the growing season, each plot was harvested for biomass (M) and grain yield. Yield components such as thousand-kernel weight (TKW) and number of grain (NG), were measured on one square meter and three replications. Other economic traits of wheat such as fertile spikelet number (FSN) and length of spike (LS) were also determined.
Soil moisture contents at sowing and harvesting in the whole soil profile were also used to calculate water consumption from soil stored water during the whole growing seasons. Harvest index (HI) was also determined.

2.3. Results and Discussions

Results are presented under different headings for each crop and site to facilitate reference and follow up of the materials.

2.3.1. Wheat

Merek site
The mean grain yield (GY), straw yield, total aboveground dry biomass (BY), harvest index (HI), thousand kernel weight (TKW) and plant height under rainfed and various SI treatments and for all cropping seasons were analyzed. Average rainfed grain yield under traditional management (TM) for the

2005/2006 and 2006/2007 seasons were 1983 and 1878 kg ha^{-1}, respectively (Fig. 2-3). Average rainfed grain yield under advanced management (AM) for 2005/2006, 2006/2007 and 2007/2008 seasons were 2294, 2273 and 665 kg ha^{-1}, respectively. The season of 2005/2006 had the higher rainfall (505 mm) compared with average long term (478 mm) with a good distribution during spring supporting such high yield. The 2006/2007 season had an average rainfall of 552 mm, inadequate rainfall for emergence in October. Emergence was late but favorable conditions later in the spring provided the second highest rainfed yield. The 2007/2008 season was the poorest for rainfed grain yield (613 kg ha^{-1}) under traditional management, because of lowest rainfall (154 mm) associated with late emergence. Lower rainfall amounts obtained in the spring of 2007/2008 associated with physical damages on crops by the unexpected rainfall from during March to maturity time (26.2 mm, 17% of total annual rainfall) caused the drop in yield (Figs. VI-1 and VI-7). Rainfed straw yield was affected similarly.

Average grain yield of SI at planting under traditional management (TM) were 2172 and 2157 kg ha^{-1} for 2005/2006 and 2006/2007 seasons, respectively. Average grain yield for the same SI treatment under advanced management (AM) for 2005/2006 and 2006/2007 seasons were 2836 and 2549 kg ha^{-1}, respectively. Average SI spring grain yield under traditional management (TM) for 2005/2006 and 2006/2007 seasons were with 2677 and 2592 kg ha^{-1}, respectively. Average SI spring grain yield under advanced management (AM) for 2005/2006, 2006/2007 and 2007/2008 seasons were with 3762, 3427 and 1912 kg ha^{-1}, respectively. End season control stress management by applying SI spring on crop production under AM, resulted in higher straw yields (8563, 6212 and 3468 kg ha^{-1}) in the three seasons, respectively. But, 2005/2006 season provided higher straw yield (9638 kg ha^{-1}) similar to grain yield with a good distribution of rainfall in spring that boosted the crop for better performance for both grain and straw yield under rainfed conditions (Fig. 2-3 and 2-4).

In the experiment, the average single irrigation amount applied at the planting time and the spring for the 3 years (2005/2006/2006/2007 and 2007/2008) was about 50 and 75mm, respectively. For the two times irrigation treatments (SI planting + spring), the irrigation amounts was 125 mm and given at the same time. By contrast, the 2007/2008 season was the worst in terms of drought and frost, which resulted in the lowest yields being obtained during this season. Some farmers at Merek site applied two or three irrigation at spring time during this season.

By applying 50 mm spring irrigation, wheat grain yield was increased by 1779, 1549 and 1247 kg ha^{-1} over purely rainfed plots in 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. Similarly straw yield was increased to 3286, 975 and 2222 kg ha^{-1}, respectively, usually local wheat variety had high producing straw yield (Fig. 2-3).

At Merek site, the ranks of recommended treatment options are: single irrigation at planting time (immediately after sowing), single irrigation at spring time (usually during heading – flowering stage) and rainfed, but all under advanced management compare to traditional systems. The highest mean grain yield (over all sowing dates) was 2284 kg ha^{-1} for the rainfed advanced management farming system.

The water productivity indices in producing grain yield (rainfall, irrigation and sum of rainfall and irrigation) was highly significantly ($P < 0.01$), influenced by sowing date, management type and SI time. There was a significant SI - sowing date - management interaction effect on both total water productivity (TWP) and irrigation water productivity (IWP). Effect of advanced management on increasing grain yield and rain water productivity (RWP) was significant.

For the rainfed treatment, the RWP were 0.39 and 0.34 kg m^{-3} for 2005/2006 and 2006/2007 seasons, respectively (observed at the traditional management of the all seasons), those were the lowest amounts which obtained from farmers local scales, while the RWP under combination of early sowing date and advanced management treatment were 0.45, 0.41 and 0.48 kg m^{-3}, respectively). The TWP under combination of sowing irrigation and traditional management treatment were 0.37 and 0.34 kg m^{-3} (Fig. 2-5) while the TWP under combination of sowing, irrigation and advanced management treatment were 0.49 and 0.41 and kg m^{-3} for 2005/2006 and 2006/2007 seasons, respectively. The TWP under combination of spring irrigation and traditional management treatment were 0.48 and 0.43 kg m^{-3} for 2005/2006, 2006/2007, while the TWP with combination of spring irrigation and advanced management treatment were 0.68, 0.57 and 0.71 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The IWP (Fig. 2-6 and 2-7) under combination of sowing, irrigation and traditional management treatment were 0.25 and 0.16 kg m^{-3}, while the IWP with combination of sowing irrigation and advanced management treatment were 0.72 and 2.31 kg m^{-3} for 2005/2006 and 2006/2007 seasons, respectively. The IWP under combination of spring irrigation and traditional management treatment were 1.39 and 1.12 kg m^{-3} for 2005/2006, 2006/2007, while the IWP with combination of spring irrigation and advanced management treatment were 2.94, 2.31 and 1.22 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively The overall mean RWP for the rainfed treatments of advanced management was 0.43 kg m^{-3} (Table III-1). The corresponding lowest and highest TWP values for the irrigated treatments were 0.34 kg m^{-3} (traditional management) and 0.47 kg m^{-3} (spring irrigation and advanced management), respectively. The lowest rainfed RWP was 0.34 kg m^{-3} (traditional management and independent of sowing date, 2006/2007 season), while the highest RWP value was 0.47 kg m^{-3}, observed at advanced management and independence of sowing date for the 2007/2008 season. The corresponding lowest and highest IWP values for the irrigated treatments were 0.25 kg m^{-3} (Normal sowing, planting irrigation and traditional management, 2005/2006) and 2.94 kg m^{-3} (normal sowing, spring irrigation and advanced management, 2005/2006). Figure 2-5 shows that IWP generally increases with SI treatment and decreases with rainfed treatment.

At Merek site, spring rainfall is usually insufficient to provide crop water requirement, therefore, spring irrigation (usually during heading – flowering stage) can greatly benefit grain yield and water productivity. Under rainfed conditions, early or normal sowing does not influence water productivity. Late sowing steadily resulted in the lowest WP under all situations of water availability (i.e., SI). Normal sowing under a combination of supplemental irrigation at spring time and advanced management consistently resulted in higher water productivity than normal sowing (around late October), but always the lowest WUE was with traditional management.

Therefore, the optimal date of sowing for wheat in this region is around mid to end of October, since later sowing dates decrease WP and earlier sowing date is not recommended, because the time interval between application of SI and the first effective rainfall (in November) can be 30 days to maximum 45 days.

Honam site:
The mean grain yield (GY), straw yield, total aboveground dry biomass (BY), harvest index (HI), thousand kernel weight (TKW) and plant height under rainfed and various SI treatments for all cropping seasons were analyzed. Average rainfed grain yield produced under traditional management (TM) for 2005/2006, 2006/2007 and 2007/2008 seasons were 2144, 1985 and 1050 kg ha-1, respectively (Fig. 2-8). Average rainfed grain yield under advanced management (AM) for 2005/2006, 2006/2007 and 2007/2008 seasons were 2456, 2670 and 1740 kg ha^{-1} (1680 for Azar2 and 1799 for Cross Alborz cultivars), respectively. The 2005/2006 season had higher rainfall (544 mm) compared to the long-term average (455 mm) with a good distribution over spring supporting such high yield. The 2006/2007 season had an average rainfall of 573 mm, inadequate for emergence in October. Emergence was delayed, but favorable conditions later in the spring provided the second highest rainfed yield. The 2007/2008 season was the poorest for rainfed grain yield because of lowest rainfall (294 mm) that resulted in delayed emergence: 1050 kg ha^{-1} under traditional management and 1740kg ha^{-1} (1680 for Azar2 and 1799 for Cross Alborz cultivars) under advanced management. Lower rainfall amounts obtained in the spring of 2007/2008 associated with physical damages to crops by the unexpected rainfall from March to maturity (34.3 mm, 11.7% of total annual rainfall) caused the drop in yield (Fig. VI-11 and VI-16). Rainfed straw yield was affected similarly.

Average SI planting resulted in an average grain yield under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons of 2484, 2303 and 1590 kg ha^{-1}, respectively. Under advanced management (AM), however, average SI planting grain yield for the 2005/2006, 2006/2007 and 2007/2008 seasons were 4108, 3359 and 2635 kg h^{a-1} (2543 for Azar2 and 2727 for Cross Alborz cultivars), respectively. SI spring gave an average grain yield under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 2458, 2314 and 1640 kg ha^{-1}, respectively. Average SI spring grain yield under advanced management (AM) for 2005/2006, 2006/2007 and 2007/2008 seasons were 3297, 3534 and 3325 kg ha^{-1} (3245 for Azar2 and 3405 for Cross Alborz cultivars), respectively. Early emergence of crop produced under AM higher straw yields 7083, 6028 and 5426 kg ha^{-1} in the three seasons, respectively. But, 2005/2006 season provided higher straw yield (7083 kg ha^{-1}) like grain yield due to good distribution of rainfall in spring that boosted both grain and straw yield under rainfed conditions (Figs. 2-8 and 2-9).

In the 3 years (2005 to 2008) experiment, the average single irrigation amount applied at the planting time and in the spring were about 50 and 75 mm, respectively. For the two times irrigation treatments (SI planting + spring), the total irrigation amounts was 125 mm and given at the same time. By contrast, the 2007/2008 season was the worst in terms of drought and frost, which resulted in the lowest yields. In this season, some farmers at Honam sites applied two or three irrigations at spring time.

Irrigation of 75 mm at sowing had increased wheat grain yield by 1964, 1374 and 1045 kg ha^{-1} over purely rainfed plots in 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. Similarly, straw yield was increased by 966, 192 and 795 kg ha^{-1}, respectively, because local wheat variety has high producing straw yield.

At Honam site, recommended treatment options are in the following order: single irrigation at planting time (immediately after sowing), single irrigation at spring time (usually during heading – flowering stage) and rainfed, but all under advanced management. For all seasons and sowing dates, the highest mean rainfed grain yield (2289 kg ha^{-1}) was under the advanced management treatment.

The water productivity indices in producing grain yield (rainfall, irrigation and sum of rainfall and irrigation) was highly significantly ($P< 0.01$), influenced by sowing date, management type and SI time. There was a significant SI - sowing date - management interaction effect on both total water productivity (TWP) and irrigation water productivity (IWP). Effect of advanced management on increasing grain yield and rain water productivity (RWP) was significance.

For the rainfed treatment, the RWP under farmers' traditional management for all seasons were 0.39, 0.35 and 0.31 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons respectively, while the RWP under combination of sowing date and advanced management treatment were 0.45, 0.47 and 0.46 kg m^{-3}, respectively) (Fig. 2-10). The TWP under combination of sowing irrigation and traditional management treatment were 0.40, 0.36 and 0.38 kg m^{-3}, while the TWP of combination of sowing irrigation and advanced management treatment were 0.66, 0.52 and 0.58 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The TWP under combination of spring irrigation and traditional management treatment were 0.41, 0.40 and 0.42 kg m^{-3}, while the TWP of combination of spring irrigation and advanced management treatment were 0.55, 0.52 and 0.77 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The IWP under combination of sowing irrigation and traditional management treatment were 0.45, 0.42 and 0.72 kg m^{-3}, while the IWP of combination of sowing irrigation and advanced management treatment were 2.62, 1.83 and 2.11 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively, The IWP (Figs. 2-11 and 2-12) under combination of spring irrigation and traditional management treatment were 0.63, 0.66 and 1.18 kg m^{-3}, while the IWP of combination of spring irrigation and advanced management treatment were 2.30, 3.10 and 4.55 kg m^{-3} for 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The overall mean RWP for the rainfed treatments of advanced management was 0.47 kg m^{-3} (Table III-2). The corresponding lowest and highest TWP values for the irrigated treatments were 0.36 kg m^{-3} (traditional management) and 0.77 kg m^{-3} (early sowing, advanced management), respectively. The lowest rainfed RWP was 0.31 kg m^{-3} (traditional management, 2007/2008 season), while the highest value was 0.47 kg m^{-3}, observed at advanced management for the 2006/2007 season. The corresponding lowest and highest IWP values for the irrigated treatments were 0.42 kg m^{-3} (Normal sowing, single irrigation at planting time and traditional management, 2006/2007) and 4.55 kg m^{-3} (early sowing, single irrigation at spring time and advanced management, 2007/2008). Figure 2-10 shows that TWP generally increases with SI treatment and decreases under rainfed treatment.

At Honam site, rainfall at sowing time is not adequate for supplying crop water requirements for germination therefore, early sowing irrigation (October) greatly benefits grain yield and water productivity. Under rainfed conditions, early or normal sowing does not influence water productivity. Late sowing steadily resulted in the lowest WP under all situations of water availability (i.e., SI). Early sowing under a combination of supplemental irrigation at sowing time and advanced management consistently resulted in higher water productivity than other sowing dates. Traditional management always results in lower WUE.

Therefore, the optimum date of sowing for wheat in this region is from mid until end of October, since later sowing dates decrease WP and earlier sowing date didn't recommend, because the time interval between application of SI and the first effective rainfall (in November) can be 30 days to maximum 45 days.

Statistical analysis of wheat results

Statistical analysis (t-Test) was performed for grain yield of wheat in the two sites and under different treatments of supplemental irrigation and agronomic management practices. At Honam site, results indicate that there are statistically significant differences between two agronomic managements on grain yield producing under rainfed, SI planting (50-75 mm) and SI spring (50 mm) at 5%, 1% and 1%, respectively (Table 2-2). At Merek site results indicate that there are statistically significant differences between two agronomic managements on grain yield produced under rainfed, SI planting (50-75 mm) and SI spring (50mm) at 5%, 1% and 1%, respectively (Table 2-3).

Results of year-by-year on grain yield and biomass showed that the effects of the three primary factors involved: sowing date and irrigation time and management type. For all years, the effect of irrigation time, management type and sowing date on grain yield and biomass were consistent and highly significant ($P < 0.01$). Combined statistical analysis was performed for grain and straw yields. Results indicate that there are statistically significant differences (at 1% level) on yields of the years, main plots and sub-plots. Depending on the amount of rainfall received at the sowing period of different seasons as explained above, irrigation at sowing had a significant effect (1% level) on grain and straw yields both, particularly in the seasons where late crop emergence occurred because of insufficient rainfall after sowing.

Irrigation in the spring has a significant effect (1% level) on both grain yield and

Table 2-2- Statistical analysis (t-Test) of wheat grain yield values under different SI and agronomic managements treatments, average three crop seasons at Honam site.

			Mean grain yield (kg ha^{-1})	Standard Deviation (kg)	F value	t or t′ value	SD of differences
Rainfed	TM¥	N=24	1928	374	1.5	-2.89*	109.1
	AM¥¥	N=45	2243	459			
SI planting	TM	N=22	2344	223	-12.6	-6.57**	136.8
	AM	N=38	3244	791			
SI spring	TM	N=21	2279	317	1.45	-15.04**	75.45
	AM	N=42	3414	264			

* and ** : significant at the 1 and 5% levels of probability respectively

¥: TM: Traditional management ¥¥: AM: Advanced management.

Table 2-3 - Statistical analysis (t-Test) of wheat grain yield values under different SI and agronomic management treatments, average of two crop seasons at Merek site.

			Mean grain yield	Standard Deviation (SD)	F value	t or t′ value	SD of differences
Rainfed	TM¥	N=12	1931	143	1.09	-6.8**	51.9
	AM¥¥	N=24	2283	149			
SI planting	TM	N=12	2164	197	4.44	-4.35**	102.2
	AM	N=24	2609	416			
SI spring	TM	N=12	2634	166	4.64	-9.31**	97.1
	AM	N=18	3538	358			

** significant at the 1% level of probability ¥: TM Traditional management ¥¥: AM Advanced management.

thousand kernel weight. The t- test was applied on the 3-year mean irrigation levels in order to determine the effect on the grain yield at Honam and Merek sites (Tables 2-2 and 2-3). Mean wheat straw yield over 3 years showed that the application of irrigation water in the spring do not differ from each other, increased grain yield, influenced thousand kernel weight and number kernel per spike. Mean wheat grain and straw yields over the 3 years showed that the application of irrigation water at the planting time, increased grain and straw yields and increased number of tiller, thousand kernel weight, number spike per square meter and early maturity. Straw yield under rainfed and SI spring treatments was similar under both agronomic management practices, but SI planting was superior to both rainfed plots and irrigation at spring. Most likely early sowing might be adversely affected by frost while late sowing is negatively affected by drought during spring. Generally, WP increases with water supply (irrigation) and earliness of sowing.

The coefficient of variation for grain yield decreased from 50-100% under rainfed conditions to 20-30% under supplemental irrigation. The study indicated that, when early rain is inadequate for crop germination, SI, given at sowing, substantially increases wheat and barley grain yield by about 1500 – 2500 kg ha^{-1} above the average rainfed yield (800 – 2000 kg ha^{-1}). Plants, which emerge earlier in the autumn, grow more vigorously and develop faster in the following spring than plants which emerge later, which is reflected in higher yields with higher water productivity. In most years, the first rainfall sufficient to germinate the seeds occurs later than November. This is not an optimal time for emergence in the highlands environment because the crop stand of non-irrigated wheat remains small when the first frost stops plant growth in mid November. Although in the second season (2006/2007) of the trial, adequate normal rain in October allowed emergence and enough crop establishments with optimum growth before the winter cold in November. In the first and third seasons (2005/2006 and 2007/2008) of the trials, inadequate early rain in October, didn't allow emergence and enough crop establishments with optimum growth before the winter cold in November. In this season, SI treatment at sowing had additional impact on crop growth and yield of the rainfed treatments, because crop went into tillering stage, which had maximum tolerance to cold. Therefore, high plant vigour combined with relatively higher rainfall during the growing season rendered 50 mm irrigation at planting was quite effective.

The third season (2007/2008) of the study, however, experienced different conditions in which rain came late in

November. Irrigation at sowing (50 mm) had a significant effect on the rainfed grain yield, but accession drought conditions adversely affected crop growth and damaged rainfed treatments.
The most dramatic implication from this study is the saving in irrigation water with little loss in yield. In most cases, applying single irrigation with new advanced varieties double yield as compared with rainfed conditions (Tavakoli 2004, 2005 & 2007). Such yield increase clearly supports the findings of Stewart and Musick (1982), Tavakoli and Oweis (2004) and Oweis *et al*. (1999) in favor of the potential for conjunctive use of irrigation and rainfall in semi-arid regions.

The strategy of applying restricted amounts of water at critical growth stages based on available soil moisture, as practiced in this experiment, is the essence of the concept of single irrigation. The high return for limited irrigation water is another advantage of single irrigation. Obtained WP values with SI of over 1.5 kg m^{-3} are not attainable in conventional rainfed wheat. Based on water availability, a relatively small amount of irrigation water applied at strategic times could achieve substantial increases in yield and WP of rainfed wheat and barley (Zhang and Oweis, 1999; Tavakoli, 2000, 2003 and 2004).

The management parameter, date of sowing, is more problematic under rainfed conditions. In this cold winter environment (such Honam condition), an adequate plant stand before the dormant frost period (end of November and March) is essential for a high crop yield. This may not be attained in the growing seasons when the first adequate rainfall occurs later than November. However, where irrigation water is available, early germination and emergence can be ensured by applying a small (30–40 mm) irrigation after sowing (Tavakoli and Oweis, 2004; Oweis and Hachum, 2001; Ilbeyi *et al*., 2006; Tavakoli, 2004, 2005 and 2007; Tavakoli *et al*., 2005). Oweis *et al*. (2001) reported substantial increases in wheat yield, in a similar highland environment in the Central Anatolian Plateau of Turkey, as a result of a 50 mm irrigation at early sowing time.

Optimum level of supplemental irrigation for Sabalan wheat cultivar was 33% of full supplemental irrigation with 60 kg-N/ha resulted to maximum water productivity (3.01 kg m^{-3}). In spite of 20% reduction of yield in this treatment, maximum net benefit was obtained along with probability of 180% cropping area increase which can result in an increase of 74% in total grain yield. Limit of benefitability for optimum level of supplemental irrigation was determined as 2857 Rial/m^3 water (Tavakoli, 2004).

Supplemental irrigation and single irrigation are a highly efficient practice with great potential for increasing agricultural production and improving livelihoods in the dry rainfed areas (Tavakoli and Oweis, 2004, 2006).
Average rainwater productivity of wheat grains in WANA is about 0.35 kg m^{-3} (Oweis and Hachum, 2003 and 2004). However, it may increase to as high as 1.0 kg m^{-3} with improved management and favorable rainfall distribution. It was found that one cubic meter of water applied as SI at the proper time might produce more than 2.0 kg of wheat grain over that of rainfed (Oweis and Hachum, 2003 and 2004).

Similar impact of early sowing with SI was also reported in the highland environment of northwest Iran (Tavakkoli and Oweis, 2004). Gains in yield and water productivity, however, were relatively lower. In Central Anatolia Plateau, the optimal sowing period extends from the last week of September to mid-October. The study also revealed that SI applied in the spring at Merek site or single irrigation applied in sowing time increased grain yield and higher water productivity. This confirms the result of Oweis *et al*. (1998, 1999 and 2001), Oweis and Hachum (2001) and Tavakkoli and Oweis (2004), which showed that deficit SI on wheat provides higher water productivity.

Summary of wheat results

At Honam site, the optimum program was a combination of advanced agronomic management with SI options (single irrigation at planting time) and the second option was single irrigation at spring time (during heading – flowering stage). At Merek site, the optimum program was a combination of advanced agronomic management with SI options [single irrigation at spring time (during heading – flowering stage)] and the second option was single irrigation at planting time. At rainfed farming (i.e., without SI), advanced agronomic management (AM) had preference to traditional management at two sites. At these preferential programs, maximum water productivity and net benefit were obtained. At rainfed condition, RWP under AM (0.41-0.47 kg m^{-3}) increased by about 15-33% as compared to TM (0.34-0.39 kg m^{-3}). The results of this study showed that a single irrigation application at sowing or spring time (during heading to flowering stage) increased total water productivity (TWP) of wheat to a range of 0.55 to 0.82 kg m^{-3} during three seasons. The irrigation water productivity (IWP) of wheat reached a range of 1.39-4.55 kg m^{-3} by using single irrigation at sowing or spring time. Low RWP (and yield) in farmers' practices were mainly due to suboptimal agronomic management practices. These preliminary results confirm the potential of single irrigation and early planting as an effective method to enhance productivity.

At Merek site and under rainfed conditions, wheat grain yield of AM (2284 kg ha^{-1}) increased by 18% as compared to TM (1931 kg ha^{-1}). Under SI planting scenarios, grain yield of AM (2693 kg ha^{-1}) increased by 20%, 24% and 39% as compared to rainfed-AM, SI spring-TM (2165 kg ha^{-1}) and rainfed-TM, respectively Under SI spring scenarios, grain yield of AM (3052 kg ha^{-1}) increased by 36%, 16% and 58% compared to rainfed-AM, SI planting/spring-TM (2126 kg ha^{-1}) and rainfed-TM, respectively (Table III-1, Fig. 2-13).

At Merek site and under rainfed condition, RWP of AM (0.43 kg m^{-3}) increased by about 16% compared to TM (0.37 kg m^{-3}). Under SI planting scenario, TWP of AM (0.45 kg m^{-3}) increased by about 5% and 22% compared to rainfed-AM and rainfed-TM, respectively. Under SI spring scenario, TWP of AM (0.53 kg m^{-3}) increased by about 23%, 15% and 43% compared to rainfed-AM, SI spring-TM (0.46 kg m^{-3}) and rainfed-TM, respectively (Table III-1).

At Honam site and under rainfed condition, wheat grain yield of AM (2289 kg ha^{-1}) increased by 33% compared to TM (1726 kg ha^{-1}). Under SI planting/spring scenarios, grain yield of AM increased by 47%, 57% and 94% compared to rainfed-AM, SI spring-TM (2635 kg ha^{-1}) and rainfed-TM, respectively (Table III-2, Fig. 2-14).

At Honam site and under rainfed condition, RWP of AM (0.45 kg m^{-3}) increased by about 29% compared to TM (0.35 kg m^{-3}). Under SI planting scenarios, TWP of AM (0.57 kg m^{-3}) increased by about 27%, 50% and 63% compared to rainfed-AM, SI planting/spring-TM (0.38 kg m^{-3}) and rainfed-TM, respectively. Under SI spring scenarios, TWP of AM (0.63 kg m^{-3}) increased by about 40%, 54% and 80% compared to

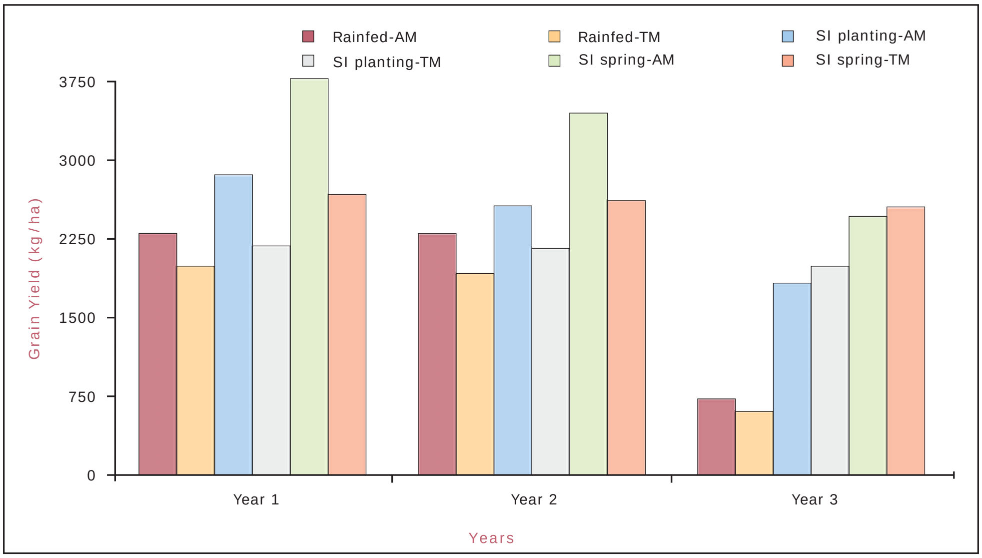

Fig. 2-3- Wheat grain yield under different irrigation treatments at Merek site, 2005/08.

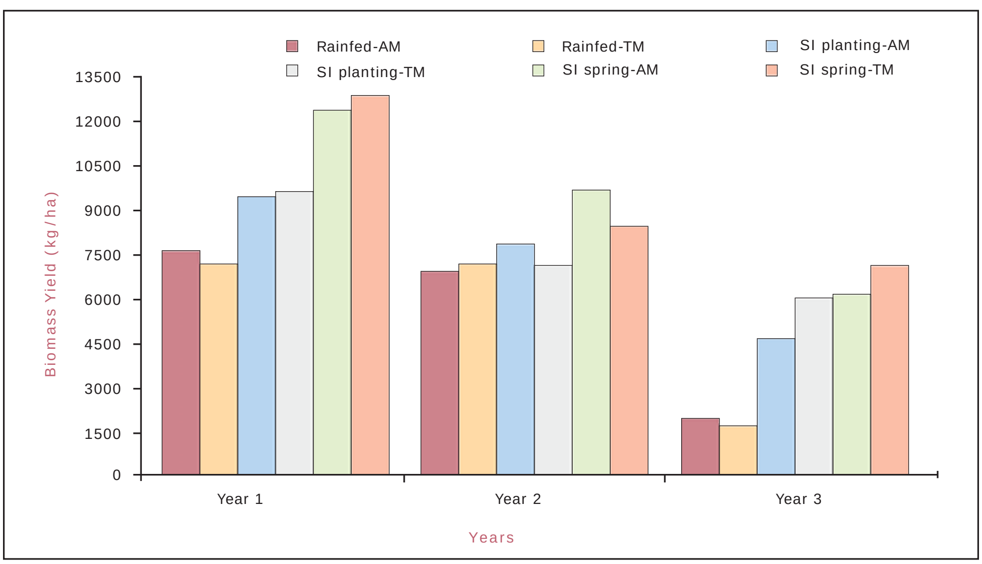

Fig. 2-4- Wheat biomass yield under different irrigation treatments at Merek site, 2005/08.

rainfed-AM, SI spring-TM (0.41 kg m^{-3}) and rainfed-TM, respectively (Table III-2).

2.3.2. Barley

Merek site

The mean grain yield (GY), straw yield, total aboveground dry biomass (BY), harvest index (HI), thousand kernel weight (TKW) and plant height under rainfed and various SI treatments and for all cropping seasons are analyzed. Average rainfed grain yield under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 1980, 2033 and 457 kg ha^{-1}, respectively (Fig. 2-15). Average

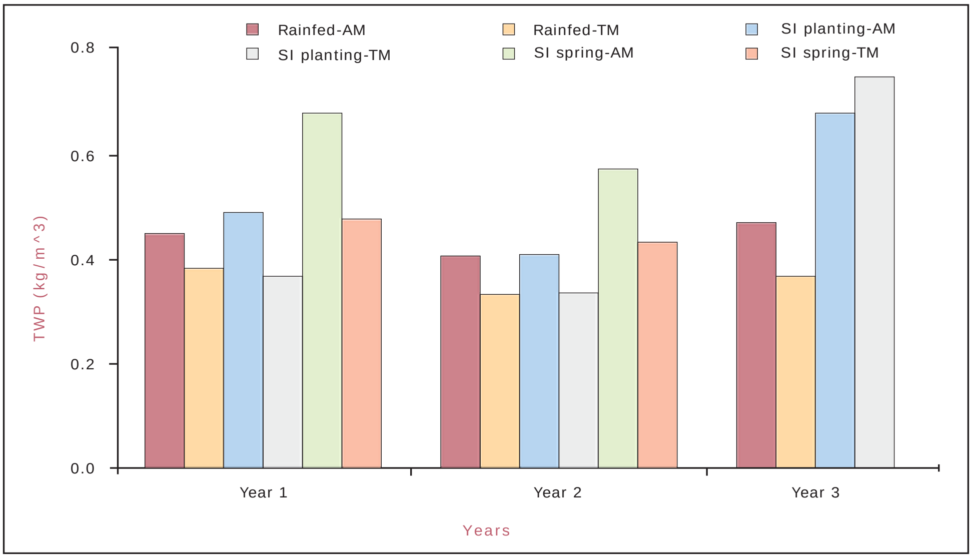

Fig. 2-5- TWP index under different irrigation treatments for wheat at Merek site, 2005/08.

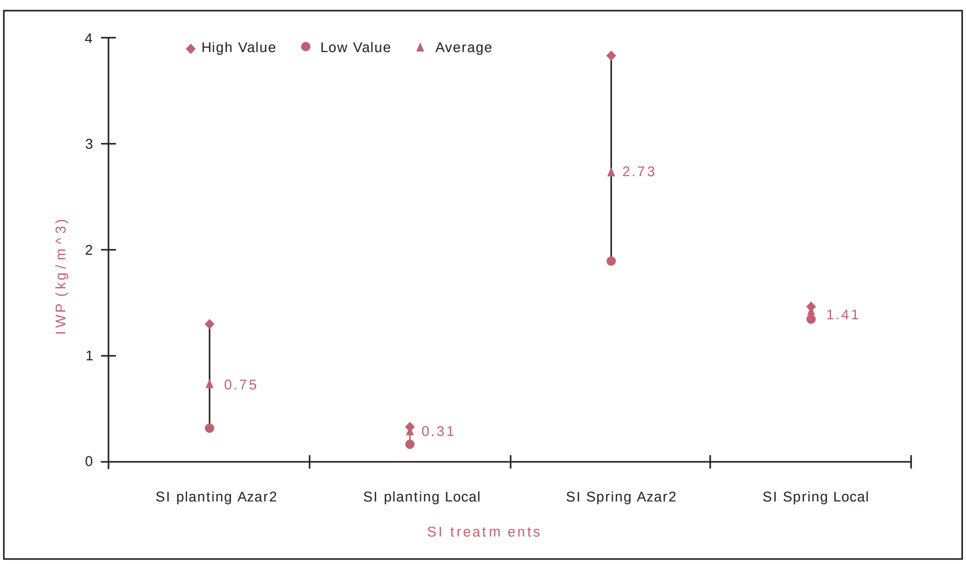

Fig. 2-6- Observed mean and ranges of IWP index under different irrigation treatments for wheat at Merek site, 2005/07.

rainfed grain yield under advanced management (AM) for 2005/2006, 2006/2007 and 2007/2008 seasons were 2666, 2625 and 670 kg ha^{-1}, respectively. The season of 2005/2006 had the higher rainfall (505 mm) compared to average long term (478 mm) with a good distribution over spring supporting such high yield. The 2006/2007 season had rainfall of 552 mm, but rainfall in October was inadequate for emergence. Emergence was late but favorable conditions later in the spring provided the second highest rainfed yield. The 2007/2008 season was the poorest for rainfed grain yield (457 and 670

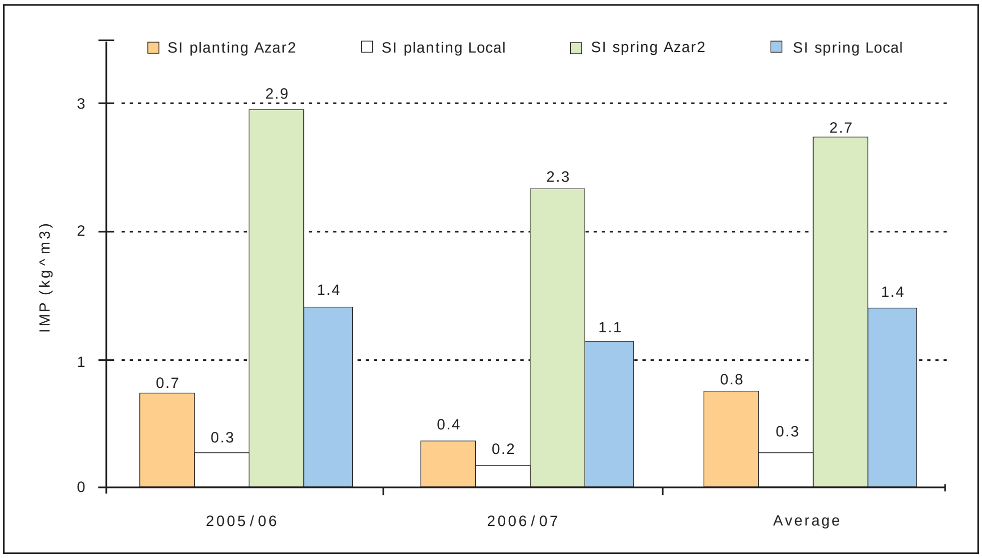

Fig. 2-7- IWP index under different irrigation treatments for wheat at Merek site, 2005/07.

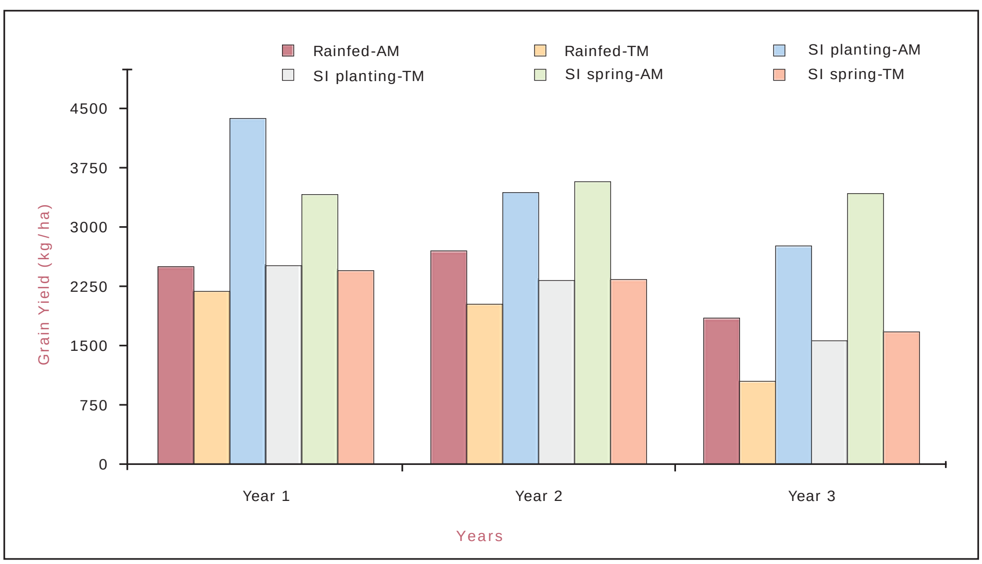

Fig. 2-8- Wheat grain yield under different irrigation treatments at Honam site, 2005/08.

kg ha^{-1} under traditional and advanced management, respectively, because of lowest rainfall (154 mm) associated with late emergence. Lower rainfall amounts during the spring of 2007/2008 associated with physical damages on crops by the unexpected rainfall from during March to maturity time (26.2 mm, 17% of total annual rainfall) caused the drop in yield (Figs. VI-1 and VI-7). Rainfed straw yield was similarly affected. Average grain yield for SI planting treatment under traditional management (TM) for the 2005/2006 and 2006/2007 seasons were 2016 and 2125 kg ha^{-1}, respectively. Average SI planting grain

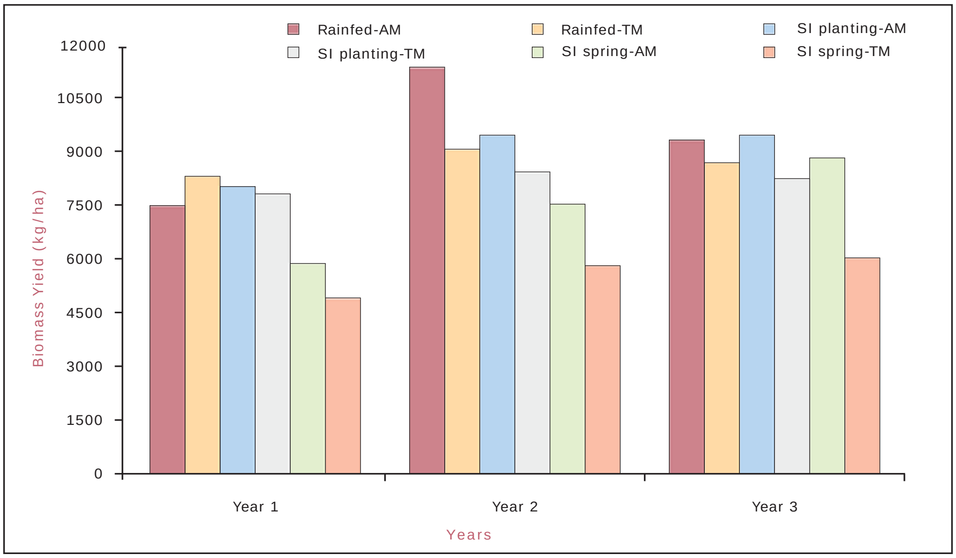

Fig. 2-9- Wheat biomass yield under different irrigation treatments at Honam site, 2005/08.

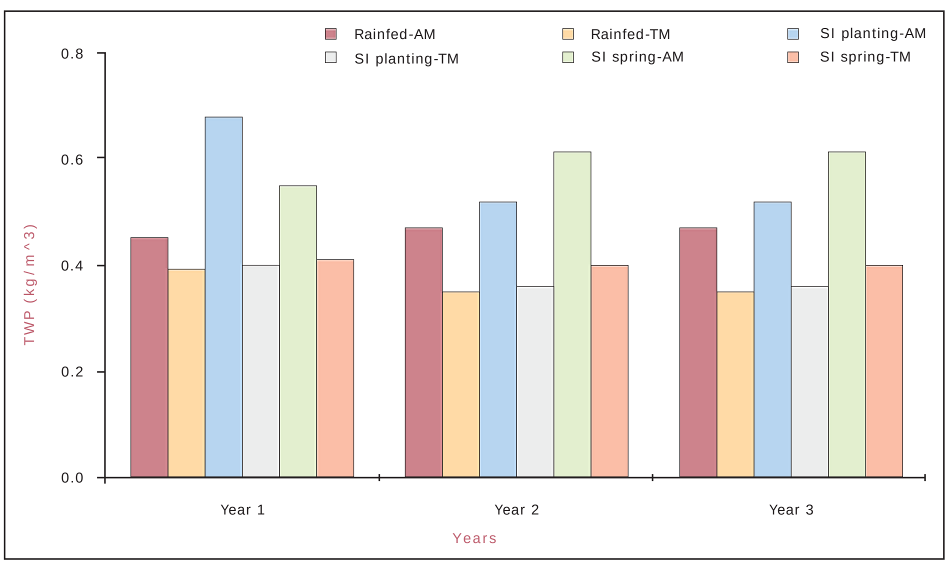

Fig. 2-10- TWP index under different irrigation treatments for wheat at Honam site, 2005/08.

yield under advanced management (AM) for the 2005/2006 and 2006/2007 seasons were 3383 and 2901 kg ha^{-1}, respectively. Average SI spring grain yield under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 2354, 2412 and 2325 kg ha^{-1}, respectively. Average grain yield for SI spring under advanced management (AM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 4043, 3768 and 2720 kg ha^{-1}, respectively. End season stress control management by applying SI spring under AM resulted in straw yields of 6103, 6358 and 6138 kg ha^{-1} in the three

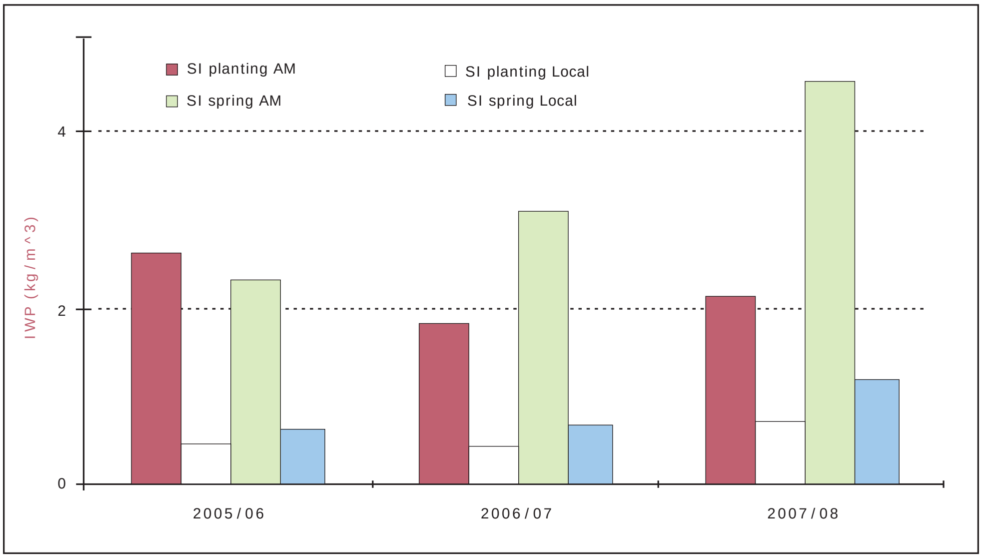

Fig. 2-11- IWP index under different irrigation treatments for wheat at Honam site, 2005/08.

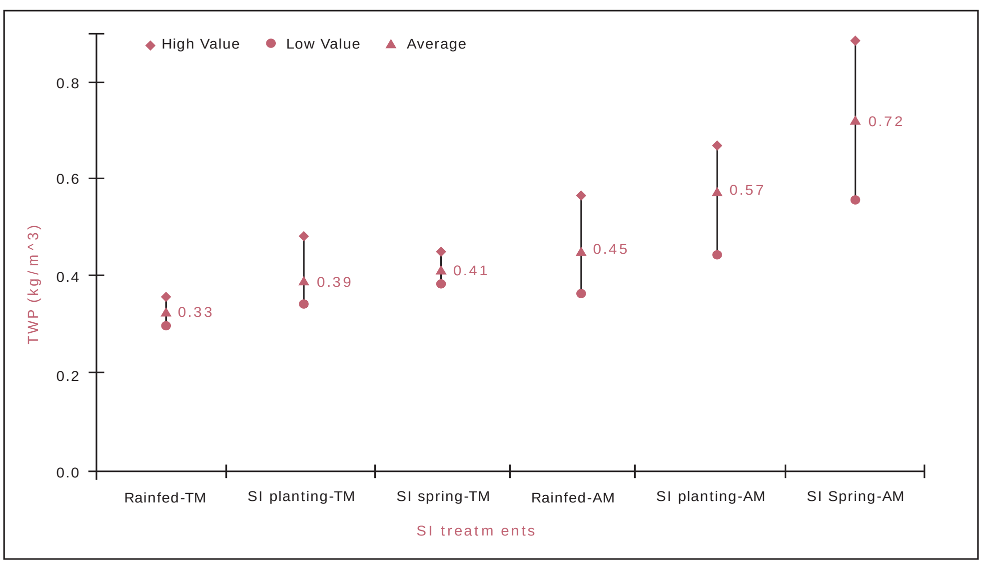

Fig. 2-12- Observed ranges of TWP index under different irrigation treatments for wheat at Honam site, 2005/08.

seasons, respectively. But the 2005/2006 season provided higher rainfed biomass yield (10147 kg ha^{-1}), like grain yield, due to good distribution of rainfall in spring which boosted the crop for better performance for both grain and straw yield, (Fig. 2-16).

The average single irrigation amount applied for the 3 years (2005/2006, 2006/2007 and 2007/2008) was about 50 at the planting time and 75 mm at spring, respectively. For the two times irrigation treatments (SI planting + spring), the irrigation amounts was 125 mm and given at the same time. By contrast, the

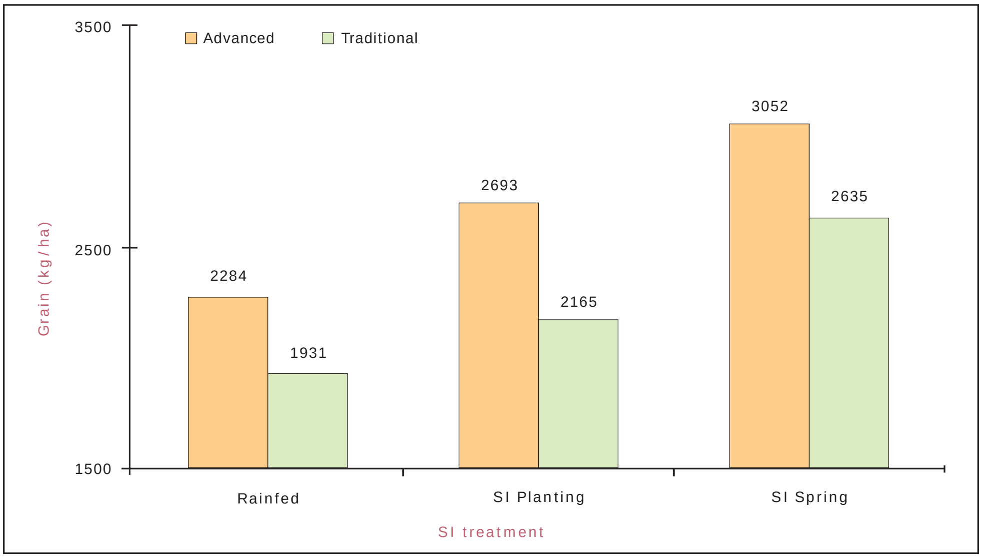

Fig. 2-13- Average wheat grain yield under different SI treatments at Merek site, 2005/07.

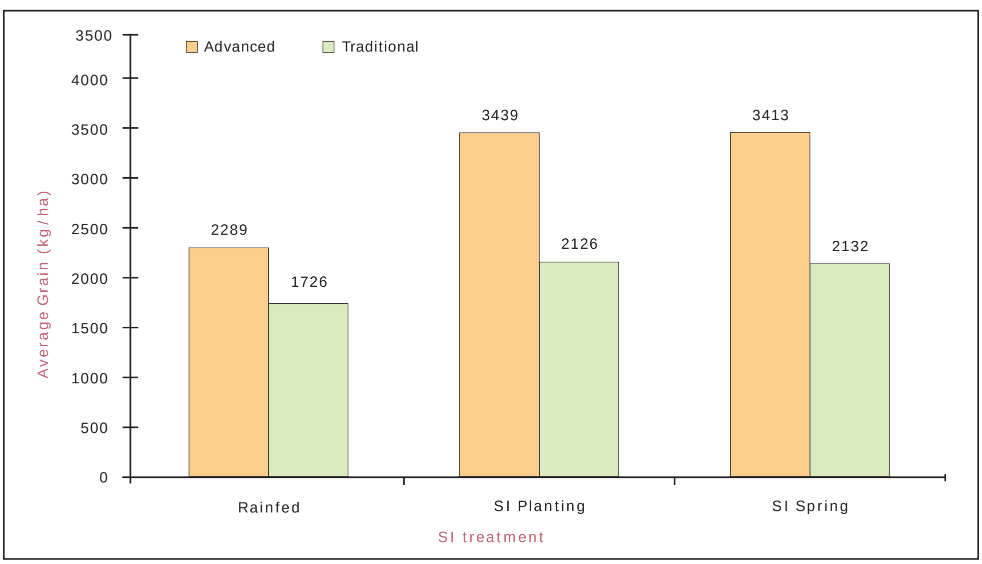

Fig. 2-14- Average wheat grain yield under different SI treatments at Honam site, 2005/08.

2007/2008 season was the worst in terms of drought and frost, which resulted in the lowest yields being obtained during this season. In this season some farmers, at Merek site, applied two or three irrigations at spring time.

A 50 mm single spring irrigation increased barley grain yield by 2063, 1735 and 2050 kg ha^{-1} over purely rainfed plots in 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. Similarly straw yield in 2005/2006 and 2007/2008 seasons were increased by 1846, and 1767 kg ha^{-1}, respectively,

but in the second season, straw yield decreased by 645 kg ha^{-1}, because local barley variety had high producing straw yield (Fig. 2-15, 2-16).
At Merek site, the recommended treatment options are in the following order: single irrigation at planting time (immediately after sowing), single irrigation at spring time (usually during heading – flowering stage) and rainfed, but all under advanced management compared to traditional systems. Rainfed advanced management treatment had higher mean grain yield (2157 kg ha^{-1}) compared to traditional rainfed farming system.

The water productivity indices in producing grain yield (RWP, IWP and TWP) was highly significantly ($P < 0.01$), influenced by sowing date, management type and SI time. There was a significant SI - sowing date - management option interaction effect on both total water productivity (TWP) and irrigation water productivity (IWP). Effect of advanced management on increasing grain yield and rain water productivity (RWP) was significant.

For the rainfed treatment, the RWP were 0.37 and 0.30 kg m^{-3} for the 2006/2007 and 2007/2008 seasons, respectively (observed at the traditional management of all seasons during the experiment), however, those were the lowest values obtained from farmers local scales.
The RWP under combination of early sowing date and advanced management treatment were 0.53, 0.48 and 0.44 kg m^{-3}, respectively (Fig. 2-17). The TWP under a combination of sowing irrigation and traditional management treatment was 0.34 kg m^{-3} for the 2006/2007, while the TWP under a combination of sowing irrigation and advanced management treatment were 0.61 and 0.46 kg m^{-3} for the 2005/2006 and 2006/2007 seasons, respectively. The TWP under a combination of spring irrigation and traditional management treatment were 0.40 and 0.65 kg m^{-3} for the 2006/2007 and 2007/2008 seasons, while the TWP under a combination of spring irrigation and advanced management treatment were 0.73, 0.63 and 0.76 kg m^{-3} for the 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The IWP (Fig. 2-18) under a combination of sowing irrigation and traditional management treatment was 0.12 kg m^{-3} for the 2006/2007, while the IWP under a combination of sowing irrigation and advanced management treatment were 1.43 and 1.16 kg m^{-3} for the 2005/2006 and 2006/2007 seasons, respectively. The IWP under a combination of spring irrigation and traditional management treatment were 0.76 and 0.90 kg m^{-3} for the 2006/2007 and 2007/2008 seasons, while the IWP with a combination of spring irrigation and advanced management treatment were 2.75, 3.47 and 1.12 kg m^{-3} for the 2005/2006, 2006/2007 and 2007/2008 seasons, respectively.

The overall mean RWP for the rainfed treatments under advanced management was 0.34 kg m^{-3} (Table IV-1). The corresponding lowest and highest TWP values for the irrigated treatments were 0.34 kg m^{-3} (traditional management) and 0.65 kg m^{-3} (spring irrigation and advanced management), respectively. The lowest rainfed RWP was 0.3 kg m^{-3} (traditional management and independent of sowing date, 2007/2008 season), while the highest rainfed RWP value was 0.53 kg m^{-3}, observed at advanced management and independent of sowing date for the 2005/2006 season. The corresponding lowest and highest IWP values for the irrigated treatments were 0.12 kg m^{-3} (normal sowing, sowing irrigation and traditional management, 2006/2007) and 3.47 kg m^{-3} (normal sowing, spring irrigation and advanced

management, 2006/2007). Figures 2-17 and 2-18 show that TWP and IWP are generally higher under SI treatments and low under rainfed treatment.
At Merek site, rainfall distribution during spring time does not satisfy crop water requirement, then spring irrigation (usually during heading – flowering stage) greatly increased grain yield and improved water productivity. Under rainfed conditions, early or normal sowing dates did not influence water productivity. Late sowing steadily resulted in the lowest WP under all situations of water availability (i.e., SI). Normal sowing under a combination of supplemental irrigation at spring time and advanced management consistently resulted in higher water productivity than normal sowing (around late October). The lowest WUE was always under traditional management.

Therefore, the optimal date of sowing for wheat in this region is around mid to end of October, since later sowing dates decrease WP and earlier sowing date is not recommended, because the time interval between application of SI and the first effective rainfall (in November) can be 30 days to maximum 45 days.

Honam site

The mean grain yield (GY), straw yield, total aboveground dry biomass (BY), harvest index (HI), thousand kernel weight (TKW) and plant height under rainfed and various SI treatments and for all cropping seasons were analyzed. Average rainfed grain yield under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 1613, 1490 and 1040 kg ha^{-1}, respectively (Fig. 2-19). Average rainfed grain yield under advanced management (AM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were at 2130, 2830 and 1243 kg ha^{-1}, respectively. The season of 2005/2006 had the highest rainfall (544 mm) compared to average long term (457 mm) with a good distribution over spring supporting such a high yield. The 2006/2007 season had an average rainfall of 573 mm, but inadequate rainfall for emergence in October. Emergence was late but favorable conditions later in the spring provided the second highest rainfed yield. The 2007/2008 season was the poorest for rainfed grain yield (1040 and 1243 kg ha^{-1}) under traditional and advanced management, respectively, because of low rainfall (294 mm) over the season resulting in late emergence. Lower rainfall amounts obtained during spring of 2007/2008 resulted in physical damages to crops. The unexpected low rainfall during March and maturity time (34.3 mm, 11.7% of total annual rainfall) caused a drastic drop in yield (Figs. VI-11 and VI-16). Rainfed straw yield was similarly affected.

Average grain yield for SI planting treatment under traditional management (TM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were respectively 2837, 1720 and 1260 kg ha^{-1}. Average grain yield for SI planting under advanced management (AM) for the 2005/2006, 2006/2007 and 2007/2008 seasons were 3799, 3237 and 2107 kg ha^{-1}, respectively. Average SI spring grain yield under traditional management (TM) for the 2005/2006 and 2007/2008 seasons were at 2670 and 1615 kg ha^{-1}, respectively. Average SI spring grain yield under advanced management (AM) for the 2005/2006 and 2007/2008 seasons were 3290 and 2763 kg ha^{-1}, respectively. Higher biomass yield was similar to grain yield due to good distribution of rainfall in spring that boosted the crop for better performance for both grain and straw yield under rainfed conditions (Fig. 2-20).

The average single irrigation amount applied during planting time and spring for the 3 years (2005/2006, 2006/2007 and 2007/2008) was about 50 and 75 mm, respectively. For the two times irrigation treatments (SI planting + spring), the irrigation amounts was 125 mm and given at the same time. By contrast, the 2007/2008 season was the worst in terms of drought and frost, which resulted in the lowest yields being obtained during this season. In the third season, some farmers at Honam sites applied two or three irrigations during spring time.

A 75 mm irrigation applied at sowing, barley grain yield was increased by 2186, 1747 and 1067 kg ha^{-1} over purely traditional rainfed plots in 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. Similarly straw yield in 2005/2006 and 2007/2008 seasons were increased by 915, and 565 kg ha^{-1}, respectively, but in the second season straw yield was decreased by 430 kg ha^{-1}, because local barley variety had high producing straw yield. Barley grain yield was increased by a 50 mm spring irrigation as 1887 and 1723 kg ha^{-1} over purely traditional rainfed plots in 2005/2006 and 2007/2008 seasons, respectively. Similarly straw yield was increased by 715 and 692 kg ha^{-1} in the 2005/2006 and 2007/2008 seasons, respectively, because local barley variety had high straw yield.

At Honam site ranks of recommended treatment options are: single irrigation at planting time (immediately after sowing), single irrigation at spring time (usually during heading – flowering stage) and rainfed. All of these options, however, are under advanced management. For all seasons the highest mean grain yield was 2070 kg ha^{-1} (over all sowing dates) for the rainfed advanced management treatment compared to the traditional rainfed farming system.
The three water productivity indices in producing grain yield (WP rainfall, WP irrigation, and WP for sum of rainfall and irrigation) were highly significant ($P < 0.01$), influenced by sowing date, management type and SI time. There was a significant SI - sowing date - management interaction effect on both total water productivity (TWP) and irrigation water productivity (IWP). Effect of advanced management on increasing grain yield and rain water productivity (RWP) was significant.

For the rainfed treatment, the RWP were 0.30, 0.26 and 0.35 kg m^{-3} for the 2005/2006, 2006/2007 and 2007/2008 seasons, respectively (observed at the traditional management of the all seasons), those were the lowest values obtained from farmers local scales, while the RWP under combination of early sowing date and advanced management treatment were 0.39, 0.49 and 0.42 kg m^{-3}, respectively (Fig. 2-21), The TWP under combination of sowing irrigation and traditional management treatment were 0.46, 0.27 and 0.34 kg m^{-3}, while the TWP of combination of sowing irrigation and advanced management treatment were 0.61, 0.50 and 0.57 kg m^{-3} for the 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The TWP under a combination of spring irrigation and traditional management treatment were 0.45 and 0.47 kg m^{-3} for the 2005/2006 and 2007/2008 seasons, while the TWP of combination of spring irrigation and advanced management treatment were 0.59 and 0.80 kg m^{-3} for the 2005/2006 and 2007/2008 seasons, respectively.

The IWP (Fig. 2-22) under a combination of sowing irrigation and traditional management treatment were 1.63, 0.31 and 0.29 kg m^{-3}, while the IWP under a combination of sowing irrigation and advanced management treatment were 2.91, 2.33 and 1.41 kg m^{-3} for the 2005/2006, 2006/2007 and 2007/2008 seasons, respectively. The IWP under a combination of spring irrigation and traditional management treatment were 2.11 and 1.15 kg m^{-3} for the 2005/2006 and 2007/2008 seasons, while the IWP under a combination of spring irrigation and advanced management treatment were 3.79 and 3.45 kg m^{-3} for the 2005/2006 and 2007/2008 seasons, respectively.

The overall mean RWP for the rainfed treatments of advanced management was 0.43 kg m^{-3} (Table IV-2). The corresponding lowest and highest TWP values for the irrigated treatments were 0.27 kg m^{-3} (traditional management) and 0.80 kg m^{-3} (early sowing, advanced management), respectively. The lowest rainfed RWP was 0.26 kg m^{-3} (traditional management and independent of sowing date, 2006/2007 season), while the highest value was 0.49 kg m^{-3}, observed at the advanced management and independence of sowing date for the 2005/2006 season. The corresponding lowest and highest IWP values for the irrigated treatments were 0.29 kg m^{-3} (Normal sowing, single irrigation at planting time and traditional management, 2007/2008) and 3.79 kg m^{-3} (early sowing, single irrigation at spring time and advanced management, 2005/2006). Figs. 2-21 and Fig. 2-22 show that TWP and IWP generally increases with both SI treatments and low under rainfed treatment.

At Honam site, rainfall at sowing time is not adequate for supplying crop water requirement for germination. Moreover, early sowing irrigation (October) greatly benefits grain yield and water productivity. Under rainfed conditions, early or normal sowing did not influence water productivity. Late sowing steadily resulted in the lowest WP under all situation of water availability (i.e., SI). Early sowing under a combination of supplemental irrigation at sowing time and advanced management consistently resulted in the highest water productivity than other sowing. Traditional management always results in lower WUE.
The optimal date of sowing for barley in this region is during mid to end of October, since later sowing dates decrease WP and earlier sowing date isn’t recommended, because the time interval between application of SI and the first effective rainfall (on November) can be 30 days to maximum 45 days.

Statistical analysis of barley’s results
Statistical analysis (t-Test) was performed for grain yield of barley in the two sites under different supplemental irrigation and agronomic management practices treatments. At Honam site, results indicate that there are statistically significant differences between the two agronomic managements on grain yield under rainfed, SI planting (50-75 mm) and SI spring (50mm) at 5%, 1% and 1% levels of significance, respectively (Table 2-4). At Merek site, results indicate that there are statistically significant differences between the two agronomic managements on grain yield under rainfed, SI planting (50-75 mm) and SI spring (50mm) at 5%, 1% and 1% levels of significance, respectively (Table 2-5). Results of year-by-year analysis of variance on grain yield and biomass showed the effects of the three primary factors involved: sowing date and irrigation time and management type. For all years, the effect of irrigation time, management type and sowing data on grain yield and biomass were consistent and highly significant ($P< 0.01$). Combined statistical analysis was performed for grain and straw yields. Results indicate that there are statistically significant differences (at 1% level) on yields of the years, main plots and sub-plots. Depending on the amount of rainfall received in the sowing period of different seasons as explained above, irrigation at sowing had a significant

Table 2-4- Statistical analysis (t-Test) of barley grain yield values under different SI and agronomic management treatments, average of two crop seasons at Honam site.

			Mean grain yield	Standard Deviation (SD)	F value	t or t′ value	SD of differences
Rainfed	TM¥	N=12	1327	328	2.46	-2.2^{*}	163.5
	AM¥¥	N=24	1686	514			
SI planting	TM	N=8	2442	763	1.31	-1.85^{ns}	367
	AM	N=15	3122	873			
SI spring	TM	N=9	1967	545	1.03	-4.74^{**}	220.6
	AM	N=18	3012	538			

ns , * and ** : non significant and significant at the 1and 5 levels of probability, respectively
¥: TM Traditional management ¥¥: AM Advanced management.

Table 2-5- Statistical analysis (t-Test) of barley grain yield values under different SI and agronomic management treatments, average of two crop seasons at Merek site.

			Mean grain yield	Standard Deviation (SD)	F value	t or t′ value	SD of differences
Rainfed	TM¥	N=6	2033	148	1.48	-7.2^{*}	85.5
	AM¥¥	N=12	2648	180			
SI planting	TM	N=6	2125	131	2.01	-10.1^{ns}	81.2
	AM	N=6	2945	185			
SI spring	TM	N=6	2412	98	33.8	-8.53^{**}	169.4
	AM	N=12	3857	570			

ns , * and ** : non significant and significant at the 1and 5 levels of probability respectively
¥: TM Traditional management ¥¥: AM Advanced management.

effect (1% level) on grain and straw yields both, particularly in the seasons where with late crop emergence (because of insufficient rainfall after sowing).

Irrigation in the spring has a significant effect (1% level) on both grain yield and thousand kernel weight. The t- test was applied on the 3-year mean irrigation levels in order to determine the effect on the grain yield at Honam and Merek sites (Tables 2-4 and 2-5). The application of irrigation water at the spring does not affect barley straw yield over the 3 years but increased grain yield and influenced the thousand kernel weight and number of kernels per spike. Mean barley grain and straw yields over 3 years showed that the application of irrigation water at the planting time, increased grain and straw yields as influenced by increasing number of tiller, thousand kernel weight, number spike per square meter and early maturity. Straw yield production for rainfed and SI spring treatments under the two group managements was similar, but SI planting was superior to both rainfed plots and irrigation at spring.

Most likely, early sowing might be adversely affected by frost while late sowing is negatively affected by drought during spring. Generally, WP increases with water supply (irrigation) and earliness of sowing. The highest WP value was obtained with the early (not with the normal) sowing. With early sowing, barley develops large green leaf area and rapid ground cover, which reduces soil evaporation losses, and absorbs a significant proportion of available solar radiation early in the season when vapor pressure deficits are low. As a result, early sowing of barley produced more biomass.
Yields of wheat and barley can be substantially increased and stabilized with minimal irrigation and agronomic

management practices, with higher yield potential. While many of the previous studies in the dryland Mediterranean zone have focused on individual components of cereal cropping, few have integrated these components into a technology package with potential for adoption. However, even when this technology package is applied, some year to year yield ceilings will occur due to factors such as cold and fungal disease, which are difficult to control (Tavakoli and Oweis, 2004).

The most dramatic implication of this study is the saving in irrigation water with little loss in yield. In most cases, applying single irrigation with new advanced varieties double yield compared with rainfed conditions (Tavakoli 2004, 2005 & 2007). Such yield increase clearly supports the findings of Stewart and Musick (1982), Tavakoli and Oweis (2004) and Oweis *et al*. (1999) in favor of the potential for conjunctive use of irrigation and rainfall in semi-arid regions.

Tavakoli (2007) showed RWP of rainfed barley varieties varied between 0.28 and 0.30 kg m^{-3}. In the drier environments, most of the rainwater is lost by evaporation; therefore the rainwater productivity is extremely low. Single irrigation water productivity (IWP) was between 1.66 – 3.1 kg m^{-3} and the total water productivity (TWP) was between 0.52 – 0.81 kg m^{-3}. The average grain yield of rainfed barley under SI planting, SI spring and rainfed treatments were 3007, 2273 and 1019 kg ha^{-1}, respectively.

The strategy of applying restricted amounts of water at critical growth stages based on available soil moisture, as practiced in this experiment, is the essence of the concept of single irrigation. The high return for limited irrigation water is another advantage of single irrigation. Obtained WP values with SI of over 2.75 kg m^{-3} are not attainable in conventional rainfed barley. Based on water availability, a relatively small amount of irrigation water applied at strategic times could achieve substantial increases in yield and WP of rainfed wheat and barley (Zhang and Oweis, 1999; Tavakoli, 2000, 2003 & 2004).

Date of sowing is one of the more problematic management parameter under rainfed conditions. In the cold winter environment of Honam, an adequate plant stand before the dormant frost period (end of November to March) is essential for a high crop yield. This may not be attained in the growing seasons when the first adequate (onset) rainfall occurs later than November. However, where irrigation water is available, early germination and emergence can be ensured by applying a small (30–40 mm) irrigation after sowing (Tavakoli and Oweis, 2004; Oweis and Hachum, 2001; Ilbeyi *et al*., 2006; Tavakoli, 2004, 2005 & 2007; Tavakoli *et al*., 2005). Oweis *et al*. (2001) reported substantial increases in wheat yield, in a similar highland environment in the Central Anatolian Plateau of Turkey, as a result of a 50 mm irrigation at early sowing date.

Supplemental irrigation and single irrigation practice are highly efficient practices with great potential for increasing agricultural production and improving livelihoods in the dry rainfed areas (Tavakoli and Oweis, 2004, 2006). Supplemental irrigation has the potential to improve and stabilize crop yield, therefore, reducing the risk of crop failure in dry years. With regard to the study, the coefficient of variation for grain yield decreased from 50-100% under rainfed conditions to 20-30% under supplemental irrigation. The study indicated that, when early rain was inadequate for crop germination, SI, given at sowing, substantially increased wheat and barley grain yield by about 1500 – 2000 kg ha^{-1} to the average rainfed yield (1000 – 2900 kg ha^{-1}). Earlier emerge in the autumn, grow more vigorously and develop faster in the following spring than plants which emerge later, which is reflected in higher yields with higher water productivity. Similar wheat trials, in the second season (2006/2007) of the trial, adequate normal rain in October allowed emergence and enough crop establishments with optimum growth before the winter cold in November. In the first and third seasons (2005/2006 and 2007/2008) of the wheat and barley trials, inadequate early rain in October, didn't allow emergence and enough crop establishments with optimum growth before the winter cold in November. In this season, SI treatment at sowing had additional impact on crop growth and yield of the rainfed treatments, because crop went into tillering stage, which had maximum tolerance to cold. Therefore, high plant vigor combined with relatively higher rainfall during growing season rendered 50 mm irrigation at planting quite effective.

The third season (2007/2008) of the study experienced different conditions in which rain was late in November. Irrigation at sowing (50 mm) could have a significant effect on the rainfed grain yield, but accession drought conditions drastically affected crop growth and damaged rainfed treatments.

Similar impact of early sowing with SI for barley varieties was also reported in the highland environment of northwest Iran (Tavakoli, 2007). Gains in yield and water productivity, however, were relatively lower. In Central Anatolia Plateau, the optimal sowing period extends from the last week of September to mid-October. The amount needed for germination depends on the effectiveness of the rain which is mainly related to the rain duration. An amount of 50 mm of rain may be enough for germination if it falls in a short duration (over one or two days). Rainfall analysis showed that at least in 3 out of 4 years the expected rainfall will not be early enough or sufficient enough to achieve optimal crop germination and yield. This also means that SI can be effective at sowing in most years. The impact of SI at sowing on yield and water productivity, however, depends on how early and how much rain falls in that year.

The study also revealed that SI applied in the spring at Merek site or single irrigation applied at sowing time increased both grain yield and water productivity. This confirms the result of Oweis *et al*. (1998, 1999 and 2001), Oweis and Hachum (2001) and Tavakkoli and Oweis (2004), which showed that deficit SI on wheat provides higher water productivity.

The timing of irrigations may not be in favorable synchronization with the temporal distribution of rainfall during the growing season and so not all the water applied in the last irrigation is used by the crop; part of it remains in the root zone as a carry-over stored moisture to first effective rainfall. In the present study, in response to supplemental irrigation, wheat produced an overall mean of about 10 kg grain per hectare per millimeter (or 1 kg grain per cubic meter of water consumed). This response to supplemental irrigation is twice of that obtained for legume crops in the same locality (Zhang and Oweis, 1999), which produced about 0.5 kg of chickpea grain per cubic meter of water. This result is due to the shorter crop stature and lower yield potential of chickpea, as compared with wheat.

Summary of barley results

At Honam site, the optimum program was a combination of advanced agronomic management with SI options (single irrigation at planting time) and the second option was a single irrigation at spring time (during heading – flowering stage). At Merek site, the optimum program was a combination of advanced agronomic management with SI options (a single irrigation at spring time (during heading – flowering stage)) and the second option was a single irrigation at planting time. At rainfed farming (without SI) advanced agronomic management had preference to traditional management at two sites. At these preferential programs, maximum water productivity and net benefit were obtained. At rainfed conditions RWP under AM (0.26-0.37 kg m^{-3}) increased by about 20-50% compared to TM. The results of this study showed that TWP of barley with a single irrigation application at sowing or spring time (during heading to flowering stage) ranged from 0.53 to 0.75 kg m^{-3} during the three seasons. The irrigation water productivity (IWP) of barley reached to 1.74-4.69 kg m^{-3} by using single irrigation at sowing or spring time. Low RWP (and yield) under farmers' practices were mainly due to suboptimal agronomic management practices. These preliminary results confirm the potential of single irrigation and early planting as an effective method to enhance productivity.

At Merek site and under rainfed conditions, barley grain yield of AM (2157 kg ha^{-1}) increased 73% compared to TM (1245). By applying SI planting scenarios, grain yield of AM (3142 kg ha^{-1}) increased by 46%, 48% and 152% compared to rainfed-AM, SI planting-TM (2125 kg ha^{-1}) and rainfed-TM, respectively. By applying SI spring scenario, grain yield of AM (3510 kg ha^{-1}) increased by 63%, 48% and 182% compared to rainfed-AM, SI spring-TM (2368 kg ha^{-1}) and rainfed-TM, respectively (Table IV-1, Fig. 2-23).

At Merek site and under rainfed condition, RWP of AM (0.49 kg m^{-3}) increased about 44% compared to TM (0.34 kg m^{-3}). By applying SI planting scenario, TWP of AM (0.54 kg m^{-3}) increased by about 10%, 59% and 59% compared to rainfed-AM, SI planting-TM (0.34 kg m^{-3}) and rainfed-TM, respectively. By applying SI spring scenario, TWP of AM (0.71 kg m^{-3}) increased by about 45%, 34% and 109% compared to rainfed-AM, SI spring-TM (0.53 kg m^{-3}) and rainfed-TM, respectively (Table IV-1).

At Honam site and under rainfed condition, barley grain yield of AM (2068 kg ha^{-1}) increased 50% compare to TM (1381). By applying SI planting scenario, grain yield of AM (3048 kg ha^{-1}) increased by 47%, 57 % and 121% compare to rainfed-AM, SI planting/spring-TM (1939 kg ha^{-1}) and rainfed-TM, respectively. By applying SI spring scenario, grain yield of AM (3137 kg ha^{-1}) increased by 52%, 46% and 127% compare to rainfed-AM, SI spring-TM (2143 kg ha^{-1}) and rainfed-TM, respectively (Table IV-2, Fig. 2-24).

At Honam site and under rainfed condition, RWP of AM (0.43 kg m^{-3}) increased by about 43% compared to TM (0.30 kg m^{-3}). By applying SI planting scenario, TWP of AM (0.56 kg m^{-3}) increased by about 30%, 56% and 87% compared to rainfed-AM, SI planting/spring-TM (0.36 kg m^{-3}) and rainfed-TM, respectively. By applying SI spring scenarios, TWP of AM (0.70 kg m^{-3}) increased by about 63%, 52% and 133% compared to rainfed-AM, SI spring-TM (0.46 kg m^{-3}) and rainfed-TM, respectively (Table IV-2).

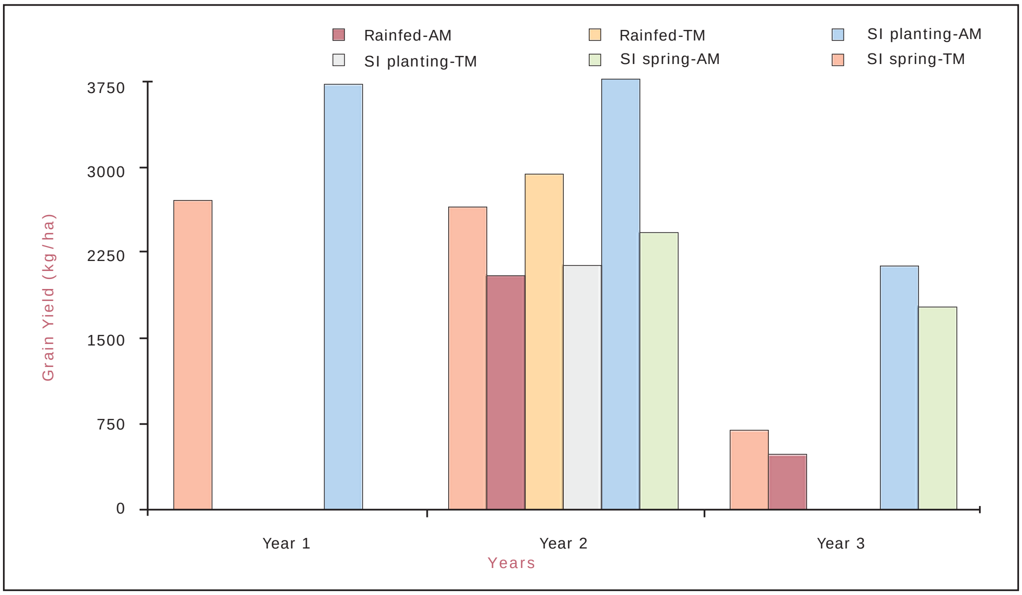

Fig. 2-15- Barley grain yield under different irrigation treatments at Merek site, 2005-08.

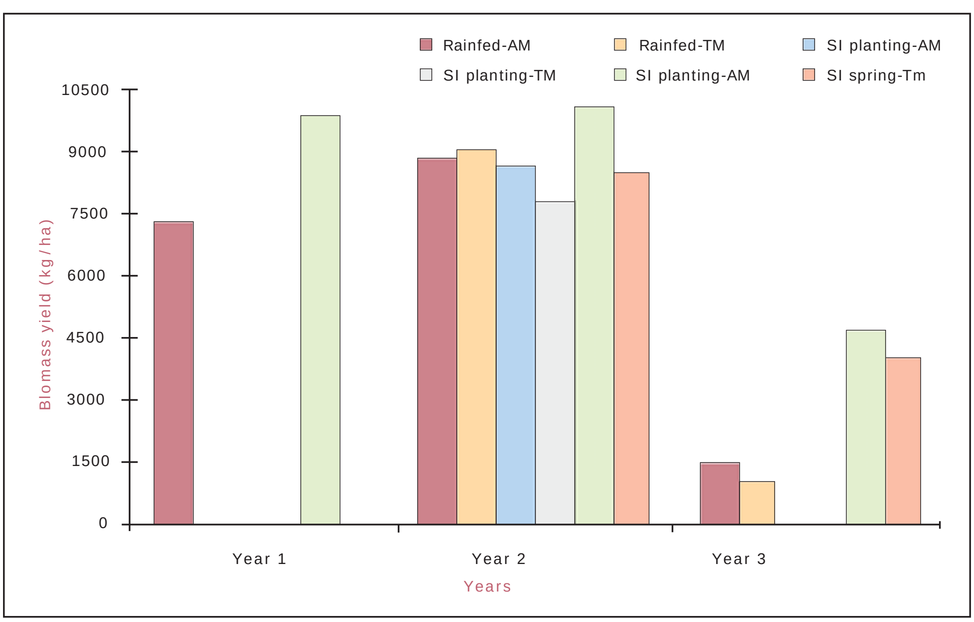

Fig. 2-16- Barley biomass yield under different irrigation treatments at Merek site, 2005-06.

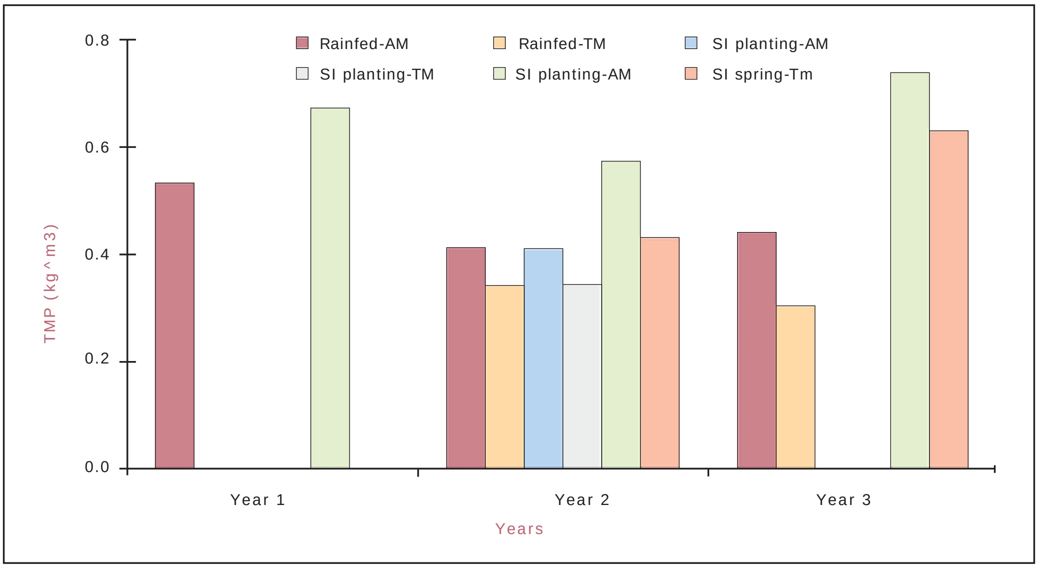

Fig. 2-17- TWP index under different irrigation treatments for barley at Merek site, 2005-08.

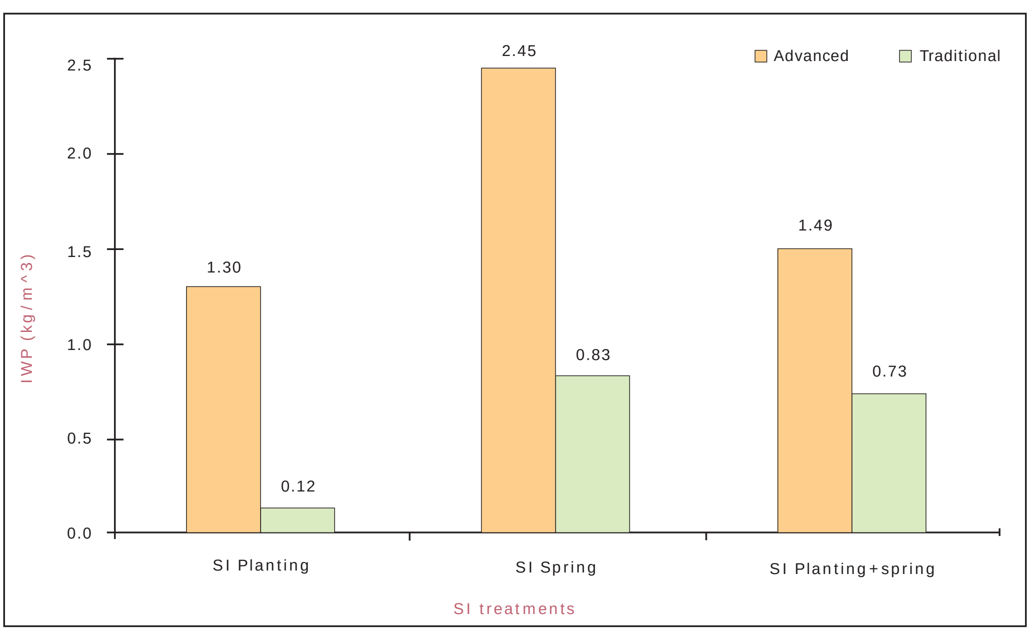

Fig. 2-18- IWP index under different irrigation treatments for barley at Merek site, 2005-08.

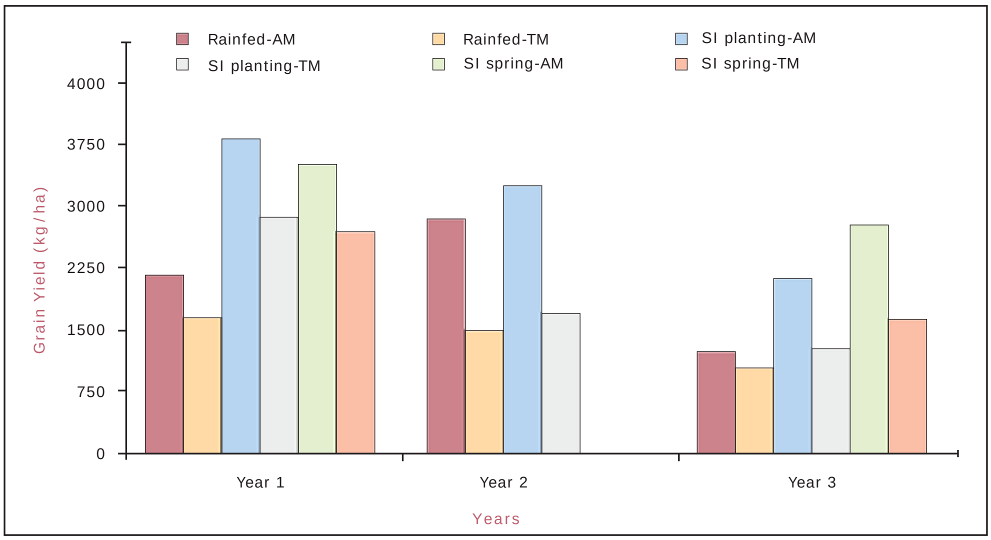

Fig. 2-19- Barley grain yield under different irrigation treatments at Honam site, 2005-08.

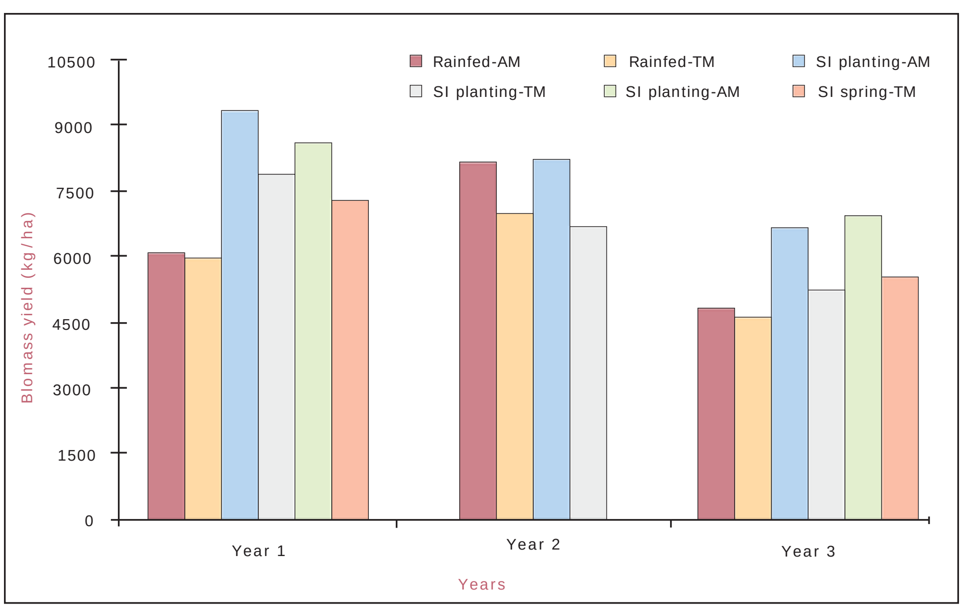

Fig. 2-20- Barley biomass yield under different irrigation treatments at Honam site, 2005-08.

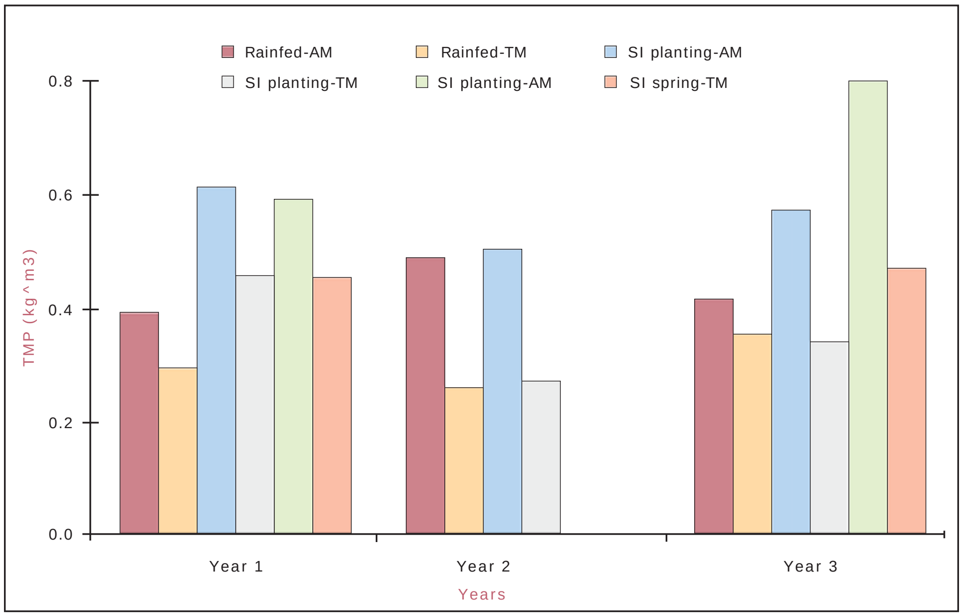

Fig. 2-21- TWP index under different irrigation treatments for barley at Honam site, 2005-08.

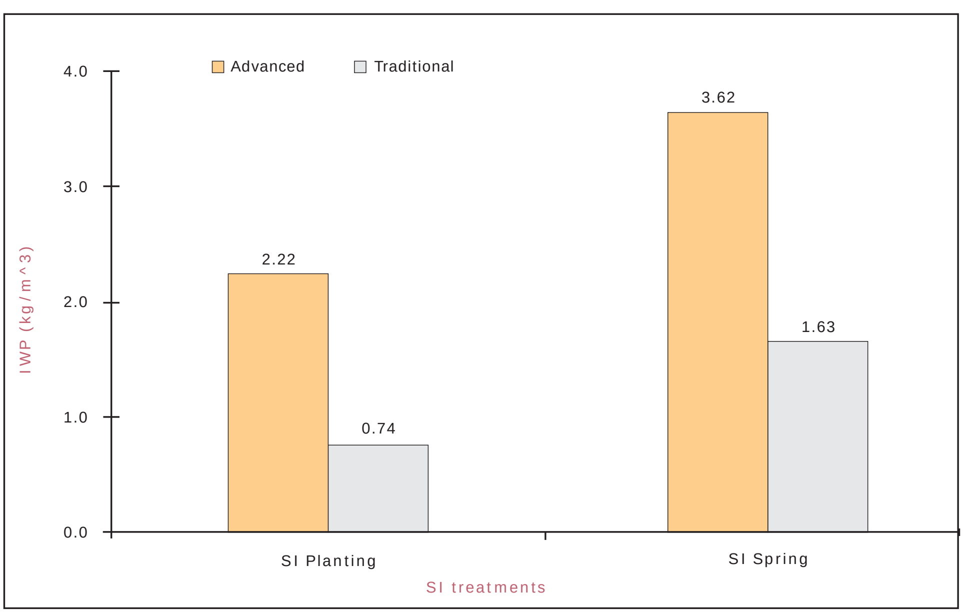

Fig. 2-22- IWP index under different irrigation treatments for barley at Honam site, 2005-08.

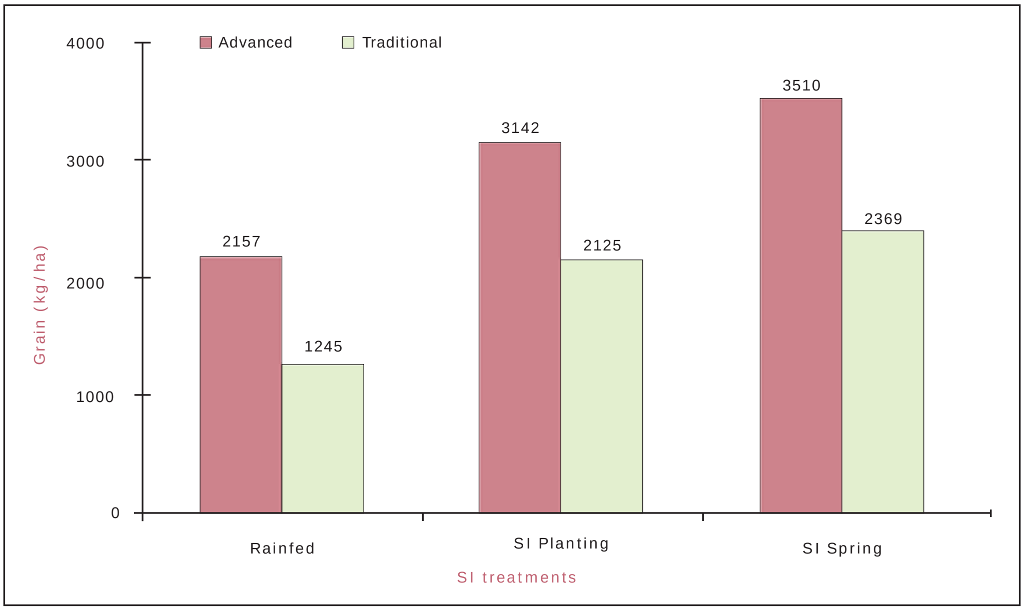

Fig. 2-23- Average barley grain yield under different SI treatments at Merek site, 2005-08.

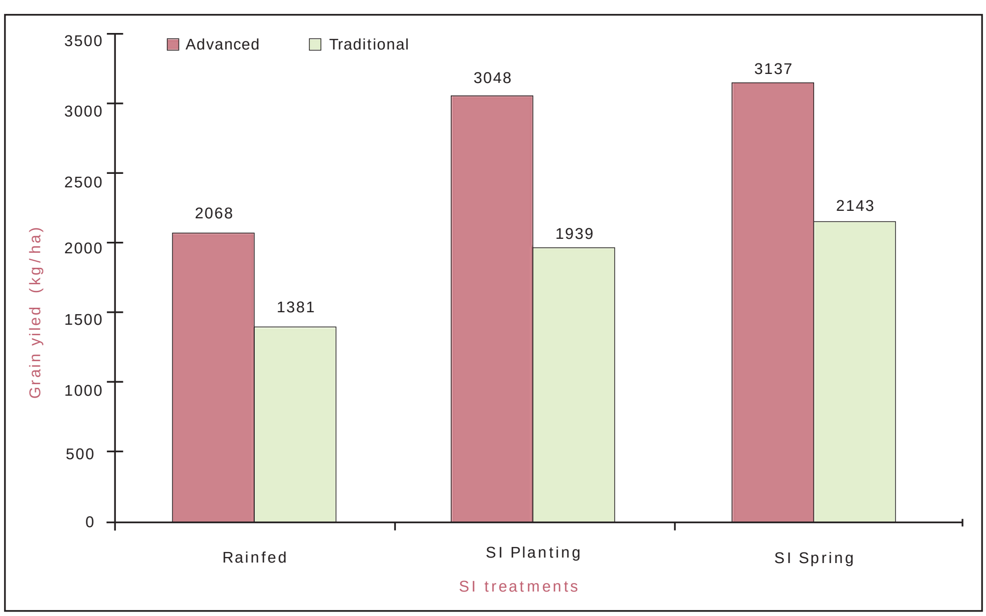

Fig. 2-24- Average barley grain yield under different SI treatments at Honam site, 2005-08.

Chapter 3.

Deficit Irrigation of Irrigated Wheat

3. Deficit Irrigation of Irrigated Wheat

3.1. Introduction

Fully irrigated fields of different crops in KRB are mostly in the southern and lower parts of the basin where the climate is much warmer with less rainfall. Nevertheless, irrigation of crops in upper KRB is also practiced by some farmers who have easy access to water, mostly from surface sources. However, relatively frequent droughts that occur in the basin cause water shortages that may reduce crops yield to different degrees.

When water supplies become limiting, farmers should aim at maximizing net income per unit volume of water rather than per unit land area. Recently, emphasis has been placed on the concept of water productivity, defined here either as the yield or net income per unit of water used in ET (Kijne *et al*., 2003). WP increases under deficit irrigation (DI), relative to its value under full irrigation, as shown experimentally for many crops (Zwart and Bastiaansen, 2004; Fan *et al*., 2005).

There are several reasons for the increase in WP under DI. Small irrigation amounts increase crop ET, more or less linearly up to a point where the relationship becomes curvilinear because part of the water applied is not used in ET but lost, mainly as deep percolation. At one point, yield reaches its maximum value and additional amounts of irrigation do not increase it any further. The location of that point is not easily defined and thus, when water is not limited or cheap, irrigation is applied in excess to avoid the risk of a yield penalty. The amount of water needed to ensure maximum yields depends on the uniformity of irrigation. Under low uniformity, irrigation efficiency decreases and water losses are high.

By contrast, in DI the level of water application is less than full irrigation (FI) and the losses by deep percolation are high. Thus the WP, of irrigation water under DI has to be higher than that under full irrigation.

Thus, deficit irrigation is one way of maximizing water use efficiency (WUE) and water productivity (WP) for higher yields per unit of irrigation water applied. Under DI the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops.
However, before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999; Sepaskhah *et al*., 2007). High-yielding varieties are more sensitive to water stress than low-yielding varieties; for example, deficit irrigation had a more adverse effect on the yields of new maize varieties than on those of traditional varieties (FAO, 1979). Crops or crop varieties that are most suitable for deficit irrigation are those with a short growing season and are tolerant of drought (Stewart and Musick, 1982, Kheirabi *et al*., 1996).

3.2. Materials and Methods

Four field experiments were conducted during the period 2005-07 on a loamy soil at the two selected sites in the Upper Karkheh River Basin i.e.,Honam and Merek. General description of these sites is given in Section (1-1) and climatic conditions are explained in Section (2-2-2) of the present report.

3.2.1. Soil characteristics

Soil texture at the experimental site was loamy and clay loam. The 0–1000 mm top layer was homogeneous, with an average bulk density of 1.4 $g.cm^{-3}$, and permanent wilting point and field capacity of 0.15 and 0.37 $cm^3.cm^{-3}$, respectively. The readily available water (RAW) for winter wheat in this region is 50% of the available water, which amounts to 11 $cm.m^{-1}$, i.e., an irrigation soil water content threshold of 0.22 $cm^3.cm^{-3}$, (Table I-2).
Chemical characteristics of the soil depth layer (0–1000 mm) were determined using standard procedures of the Soil and Water Research Institute (SWRI), (Table I-2). Results for the Honam and Merek experimental years were, respectively, 7.6-8.0 for pH, 0.3-0.7 dS/m for EC, 18.3-42.9 (%) for T.N.V, 0.5-0.7 (%) for O.C, 2.4-4.5 meq/l for $HCo3^{-2}$, 2-3.6 meq/l for Cl^{-1}, 1.7-2.1 meq/l for $So4^{-2}$, 3.6-5.5 meq/l for $Ca^{+2}+Mg^{+2}$, 3-4.4 meq/lfor Na^{+1}.

3.2.2. Crop management

Winter wheat cultivars (*Triticum aestivum*) ‘Pishtaz, Marvdashat and Shiraz’ were newly advanced irrigated wheat varieties were sown 5-7 cm deep in October with a density of 180 kg seeds/ha in rows spaced 20 cm. Weeds were removed effectively by chemical material during the growing seasons. Pests were also effectively controlled by pesticide in time. All plants were harvested at the end of July in both years.

3.2.3. Irrigation treatments

Two types of irrigation systems (surface and pressurized) were used to apply water to two regulated deficit irrigation treatments designed to subject the crops to various degrees of soil water deficit at different stages of crop development beside a full irrigation treatment (with no-soil-water deficit) as a control . Farmer’s information in Honam and Merek sites are summarized in Tables V-1 and V-2.

Under pressurized irrigation, single source sprinkler was used to apply different irrigation amounts. The points nearest to the sprinkler line receive the maximum amount of water, gradually decreasing as the distance from the sprinkler line increased. Perpendicular to the sprinkler line, each 2-m wide field strip was considered as an experimental plot having different irrigation treatment i.e. receiving different amount of water. During the growing season, irrigation water applied to each separated part was measured using a catch can (Table 3-1 and Fig. 3-1).

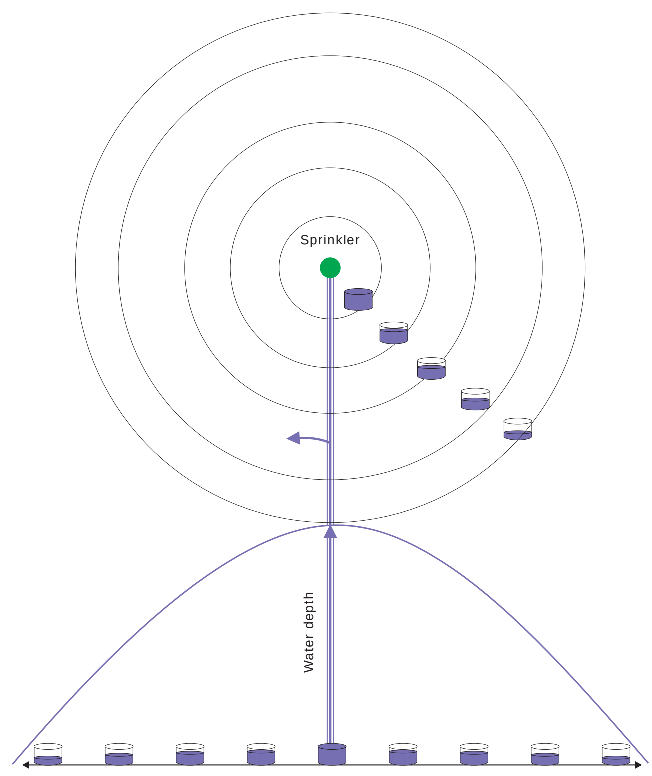

Fig. 3-1- Application pattern of a sprinkler irrigation lines once.

Under surface irrigation (border) system, three irrigation treatments were applied: full irrigation, omission of the first spring irrigation, and omission of first and third spring irrigation (Tables 3-2 and 3-3). In three locations, soil moisture was measured gravimetrically at depth of 0-20 cm, while, in one location, it was measured by TDR (time domain reflectrometry) in 20 cm increments down to a depth of 100 cm. Soil moisture content at sowing and harvesting in the whole soil profile was used to calculate water consumption from the soil profile during the whole growing season.

3.2.4. Agronomic data collection

At the end of the growing season (June 30), each plot was harvested for biomass (B) and grain yield. Yield components such as thousand-kernel weight (TKW) and number of grain (NG), were measured on one square meter with three replications. Other traits of wheat such as fertile spikelet number (FSN) and length of spike (LS) were also determined. Harvest index (HI) was calculated as grain yield divided by mature crop biomass (Table 3-2).

3.3. Results and Discussion

Under pressurized irrigation system, relationships between water use – total water productivity and water use – grain yield were developed and expressed in the following form (see Figs. 3-2 and 3-3):

$$TWP = -3\times10^{-5}WU^{2} + 0.0445WU - 15.075$$
$$Yield = -0.0002WU^{2} + 0.3003WU - 104.92$$

$$R^{2} = 0.8513 \qquad (3-1)$$
$$R^{2} = 0.9545 \qquad (3-2)$$

Where:
TWP= total water productivity, (kg m^{-3})
Yield= grain yield, (ton/ha)
WU= total water use (rainfall + irrigation), (mm)
The field crop TWP was 1.09 times higher than when no water use deficit occurred. This suggests that increasing the areas irrigated with the water saved would compensate for any yield loss. If the planned WU deficit is imposed throughout the season, it is possible to calculate the total irrigation water saved if one knows total crop water requirement. However, if the stress is imposed during a specific growth stage, one needs to know the total water requirement (i.e. crop water consumption) during that stage to quantify the water saved. As crop yield response factor (k_y) increases, field WP decreases, which in turn implies that benefit from deficit irrigation is unlikely.

With a 25 percent deficit, TWP was 1.2 times (increasing 20 percent) that achieved under normal irrigation practices. Irrigation scheduling based on deficit irrigation requires careful evaluation to ensure enhanced efficiency of use of increasingly scarce supplies of irrigation water.

Grain yield and TWP for different treatments under surface irrigation system, and according to farmer's irrigation managements, are shown in Fig. 3-2 through 3-6. Regardless of farmer's management, the pattern of response to deficit irrigation was similar. Deficit irrigation, management and their interaction affected water productivity. The TWP calculated for treatments averaged over the three replications. Table 3-3 showed that no significant differences between cut of first irrigation and full irrigation.

Today, irrigation is the largest single water consumer on the planet. Competition for water from other sectors will force irrigation to operate under water scarcity. Deficit irrigation, by reducing irrigation water use, can aid in coping with situations where supply is restricted. In field crops, a well-designed DI regime can optimize WP over an area when full irrigation is not possible. In many cropping areas, DI has been shown to improve not only WP but farmers' net income as well. It would be important to investigate the basis for the positive responses to water deficits observed in the cases where DI is beneficial. While DI can be used as a tactical measure to reduce irrigation water use when supplies are limited by droughts or other factors, it isn't known whether it can be used over long time periods. It is imperative to investigate the sustainability of DI via long-term experiments and modeling efforts to determine to what extent it can contribute to the permanent reduction of irrigation water use.

With increasing municipal and industrial demands for water, its allocation for agriculture is decreasing steadily. The major agricultural use of water is for irrigation, which, thus, is affected by decreased supply. Therefore, innovations are needed to increase the efficiency of use of the water that is available. There are several possible approaches. Irrigation technologies and irrigation scheduling may be adapted for more-effective and rational uses of limited supplies of water. Drip and sprinkler irrigation methods are preferable to less efficient traditional surface methods. It is necessary to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of allocated water.

Deficit irrigation practices differ from traditional water supplying practices. The manager needs to know the level of transpiration deficiency allowable without significant reduction in crop yields. The main objective of deficit irrigation is to increase the WUE and WP of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with

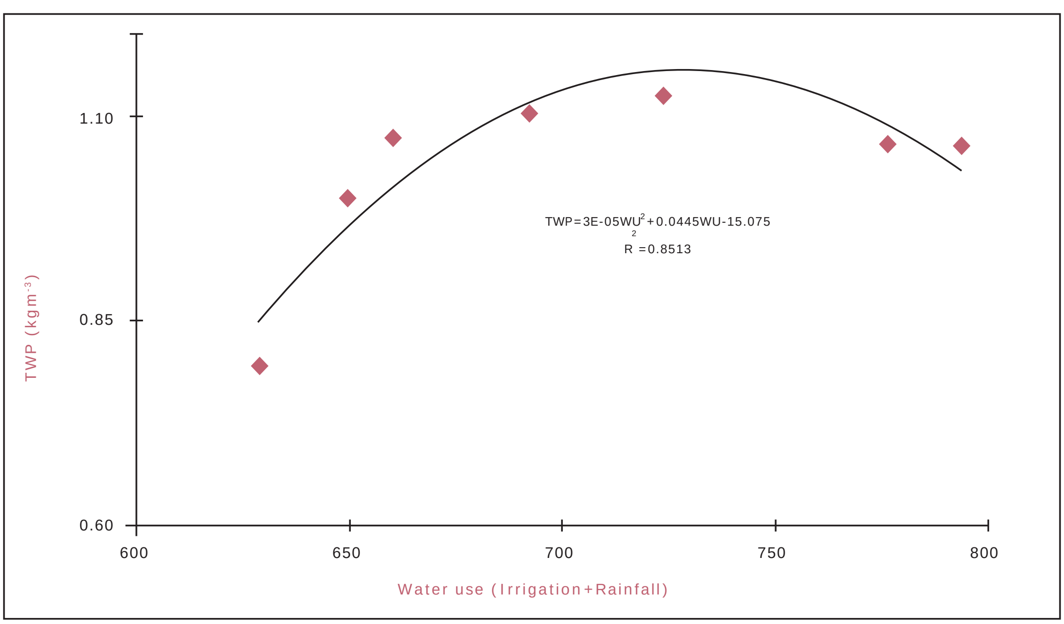

Fig. 3-2- Relationship between total water use (mm) and total water productivity.

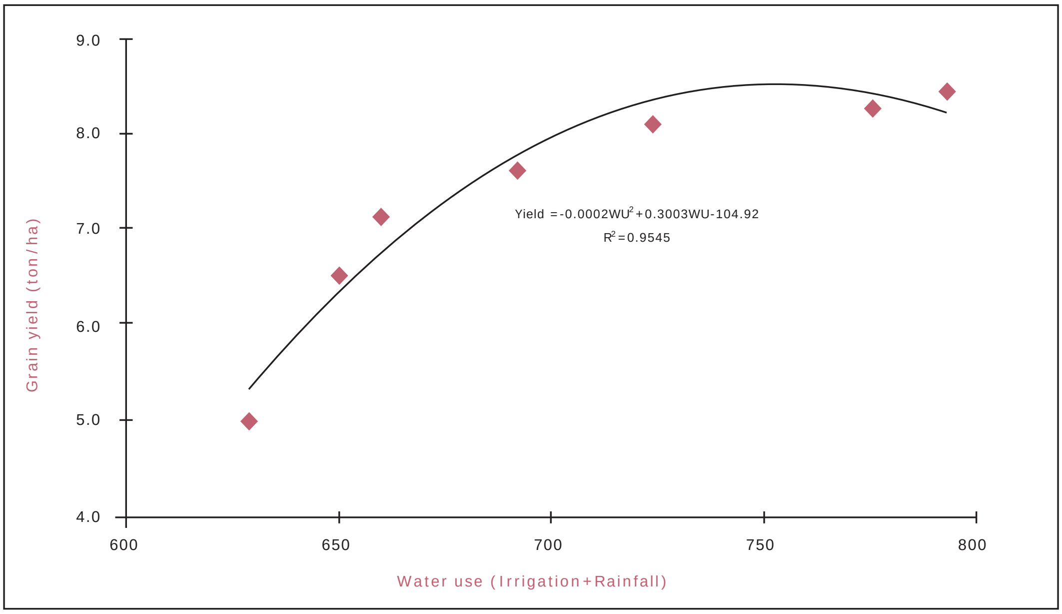

Fig. 3-3- Relationship between total water use (mm) and wheat grain yield.

the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil. In sandy soils plants may undergo water stress quickly under deficit irrigation,

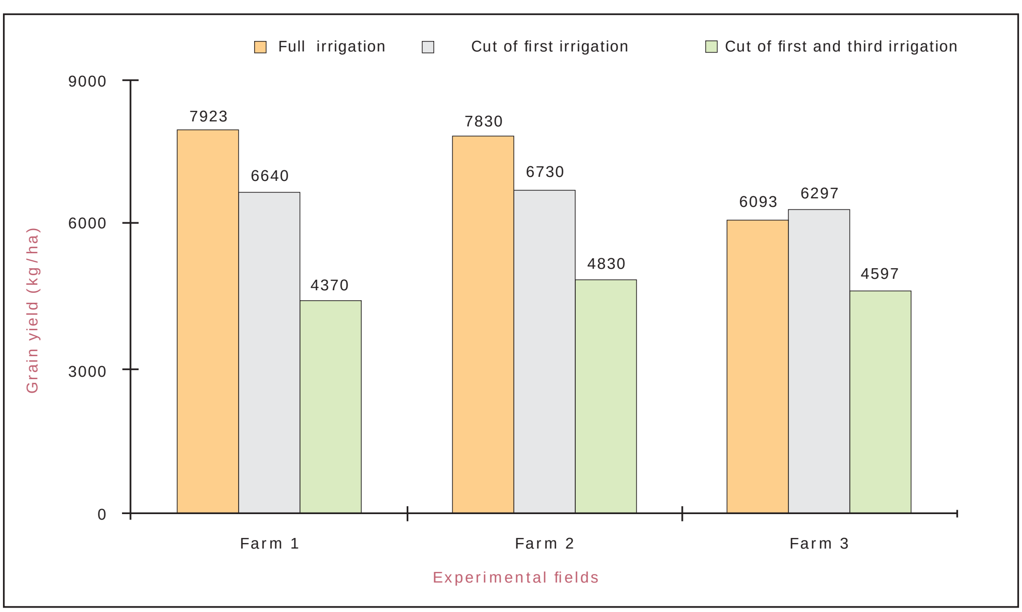

Fig. 3-4- Wheat grain yield under different deficit irrigation strategies.

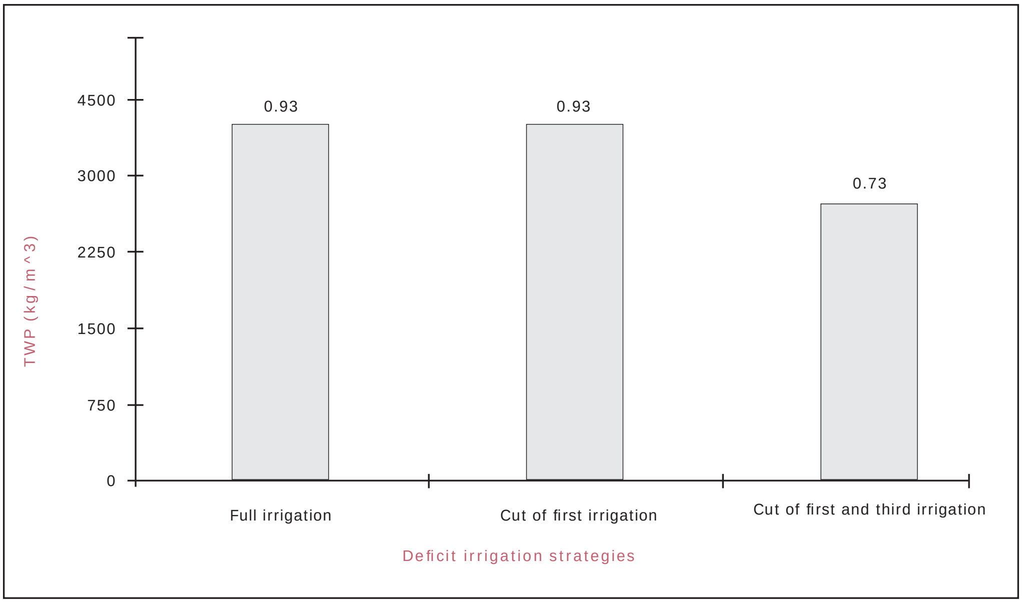

Fig. 3-5- TWP of irrigated wheat under different deficit irrigation strategies.

whereas plants in deep soils of fine texture may have ample time to adjust to low soil water matric pressure, and may remain unaffected by low soil water content. Therefore, success with deficit irrigation is more probable in finely textured soils (Sepaskhah *et al*., 2007).

Under deficit irrigation practices, agronomic practices may require modification, e.g. decrease plant population, apply less fertilizer, adopt flexible planting dates, and select shorter-season varieties (Sepaskhah *et al*., 2007, Kheirabi *et al*., 1986).

Table 3-1- Relationship between water use, wheat grain yield and TWP.

Irrigation (mm)	rainfall (mm)	Total water use (mm)	Yield (ton/ha)	TWP (kg m^{-3})
220.5	573	794	8.4	1.06
203	573	776	8.3	1.06
151	573	724	8.1	1.12
119	573	692	7.6	1.10
87.5	573	661	7.1	1.07
77	573	650	6.5	1.00
56	573	629	5.0	0.79

Table 3-2- Deficit irrigation strategies and agronomic field data under different on-farm trials.

Farmer name	Deficit irrigation strategy	Biomass (kg ha^{-1})	Grain (kg ha^{-1})	Straw (kg ha^{-1})	H.I (%)	NO grain	Plant height (cm)
H.R. Lotfi	full irrigation	16135	7923	8212	49.1	38.7	115
H.R. Lotfi	cut of first irrigation	13885	6640	7245	47.8	36.1	106.5
H.R. Lotfi	cut of first and third irrigation	12240	4370	7870	35.7	31.4	101.5
A. Rahmani	full irrigation	15107	7830	7277	51.8	29.0	93.3
A. Rahmani	cut of first irrigation	14675	6730	7945	45.9	27.6	84.0
A. Rahmani	cut of first and third irrigation	11035	4830	6205	43.8	26.0	78.5
Sh. Yousefvand	full irrigation	12385	6093	6291	49.2	31.1	86.1
Sh. Yousefvand	cut of first irrigation	14150	6297	7853	44.5	39.1	78.1
Sh. Yousefvand	cut of first and third irrigation	10944	4597	6348	42	27.8	70.6

Table 3-3- Deficit irrigation strategies and analytical results under different on-farm trials.

Farmer name	Deficit irrigation strategy	Rainfall (m^3/ha)	Irrigation (m^3/ha)	Total water use, WU (m^3/ha)	TWP (kg m^{-3})	Decreased WP (%), compare to F.I	Decreased yield (%), compare to F.I	Decreased WU (%), compare to F.I
H.R. Lotfi	full irrigation (F.I)	5520	2250	7770	1.02	-	-	-
H.R. Lotfi	cut of first irrigation	5520	1500	7020	0.95	7.2	16.2	9.7
H.R. Lotfi	cut of first and third irrigation	5520	750	6270	0.70	31.6	44.8	19.3
A. Rahmani	full irrigation (F.I)	5520	2250	7770	1.01	-	-	-
A. Rahmani	cut of first irrigation	5520	1500	7020	0.96	4.9	14.0	9.7
A. Rahmani	cut of first and third irrigation	5520	750	6270	0.77	23.6	38.3	19.3
Sh. Yousefvand	full irrigation (F.I)	5730	2250	7980	0.76	-	-	-
Sh. Yousefvand	cut of first irrigation	5730	1500	7230	0.87	-14.1	-3.3	9.4
Sh. Yousefvand	cut of first and third irrigation	5730	750	6480	0.71	7.1	24.6	18.8

Chapter 4.

Simulation of Winter Wheat Production Using "Budget" and "Aquacrop"

4. Simulation of Winter Wheat Production Using "Budget" and "Aquacrop"

4.1. Introduction

The most important question in supplemental irrigation management is when and how much water to apply. It is a laborious and expensive task to develop supplemental irrigation schedules solely by conventional field experimentation. Crop simulation models are effectively used for filling the gap and out scaling the results. Cropping system simulation models can be used to predict the effect of weather, soil properties, plant characteristics and management practices on the soil water balance, nutrient dynamics and growth of crops. Therefore, they can enhance our understanding of cropping systems performance under different water regimes. Models may also be used to assess the effects of management practices and plant characteristics on crop performance over a period that is long enough to characterize the climatic variability of a site (Van Keulen and Seligman, 1987), leading to improvements in the efficacy of decision-making for fertilizer and water management.

However, suitable field experiments are required for model validation, a necessary step before model applications can be developed for a given region (Cabelguenne *et al*., 1990; Kropff *et al*., 1994; Lengnick and Fox, 1994). A soil water and salt balance model (Budget) and a crop water productivity model (AquaCrop) represent an effort to simulate the growth of single crops or crop rotations in response to weather/soil/crop/irrigation scenarios and provide an estimate of environmental impact. Management options include cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations and residue management.

4.2. Materials and Methods

4.2.1. Models used

Two models were used in this study, namely, BUDGET (2005) and AquaCrop (2009). The BUDGET is composed of a series of summary sub-models describing the various processes involved in soil water movement, soil salinization and root water uptake. The described processes are infiltration of rain and/or irrigation water, surface runoff, internal drainage and deep percolation losses, evaporation, and transpiration. As a result of infiltration of saline water, salts enter the soil as solutes with the irrigation water and transport in the soil and distributed and stored in the soil profile.

AquaCrop is a water-driven simulation model that requires a minimum number of parameters and input data to simulate yield response to water of most of the major field and vegetable crops with sufficient balance between accuracy, simplicity and robustness. It is aimed to be used by a broad range of users, including rainfed and irrigation practitioners, extensions services and various agricultural and water-manager professionals. It is also useful for scenario simulations and planning investigations. AquaCrop will include also the crop response to saline water; it will accommodate for different input levels of fertilizers; it will consider different irrigations methods (e.g., surface, sprinkler and trickle) and types of managements (e.g., supplementary and deficit irrigation), as well as mixed field cropping.

During periods of crop water stress, the resulting yield depression is estimated by means of yield response factors. By selecting appropriate time and depth criteria, irrigation schedules can be generated.

The climatic input data consists of daily, mean 10-day or monthly ETo (reference crop evapotranspiration) and Rainfall observations. At run time, the 10-day and monthly data are processed to derive daily ETo and rain data. By specifying and selecting a few appropriate crop parameters in a Menu driven environment, the program creates a complete set of parameters that can be displayed and updated if additional information is available. The soil profile may be composed of several soil layers, each with their specific characteristics. BUDGET contains a complete set of default characteristics that can be selected and adjusted for various types of soil layers.

Budget and AquaCrop calculate the water storage and salt content in a cropped soil profile as affected by input and withdrawal of water for a given period. The soil profile may be composed of several soil layers, each with their specific characteristics. The soil water flow is only described in the vertical direction. The model runs with a constant time step of a day.

To obtain a general trend of differences in soil moisture regime between irrigation and rainfed, the BUDGET soil water and salt balance model (Raes, 2002) and a crop water productivity model (AquaCrop) (Raes *et al*., 2006; Steduto, 2008) were used to simulate the soil moisture content in the 0 to 5 and 5 to 20 cm layers during the growing season of corn under irrigated and dryland conditions. Data on the local climate, soil texture, crop characteristics, and irrigation scheduling were used as inputs.

4.2.2. Model calibration

Soil moisture content ($m^3.m^{-3}$) was periodically measured in the upper 0-0.60 m from April 1st to June 15th, 2006 and 2007 using the gravimetric method. To evaluate model performance and accuracy in prediction, statistical indicators were computed from observed and simulated variables (grain yield reduction and soil moisture content and evapotranspiration).

Trials of the models have been carried out using a number of field data, three SI scenarios of which two years have been selected for discussion. First year data were used for calibration of models and second year data used simulation.

4.3. Results and Discussions

The data input included daily weather data, crop, soil and irrigation management data. Soil moisture content (SMC), was part of the output of the models, which were compared with measured soil moisture data. These analyses applied for rainfed, SI planting and spring SI condition. The results for model calibration and evaluation showed that simulated growth and development of wheat were in good agreement with their corresponding observed values. Thus, the BUDGET and AquaCrop models can be successfully used for simulating growth, SMC, evapotranspiration, biomass and grain yield for major wheat growing region in KRB (Honam and Merek sites).

For the verification of the models, input data for the season (2005/2006) is used. Simulated output is compared with the measured soil moisture content at rainfed, planting SI and spring SI. The comparison is showed in Figs. 4-1, 4-2 and 4-3, respectively. Then these models were compared together and also with measured soil moisture data using second necessary input data for the season (2006/2007), as shown in Figs. 4-2, 4-4 and 4-6. The comparison indicated similar trend of SMC between measured and models simulated data, except for the measurements during the late stage of the crop growing season. The difference between the simulated (models) and measured data at the end of the season, showed that the errors are mostly with soil moisture sampling when soil is relatively dry.

Soil moisture content (SMC) for the two seasons was very different, reflecting the differences in rainfall amount and distribution. The soil moisture pattern during the 2005/2006 crop growing season (Figs. 4-1, 4-3 and 4-5) was characterized by an important profile recharge during winter. During cool months, rainfall and snow exceeded low evapotranspiration and water was stored in the profile. Soil moisture content had a reduction trend for the rainfed and sowing SI treatments, but in spring SI treatment after increasing SMC due to irrigation and then soil moisture depletion by evapotranspiration, the decrease in SMC follows similar pattern of other treatments. Spring SI supported crop growth, then increased crop period by about two weeks. At rainfed treatment, there wasn't enough moisture which negatively influenced grain yield. Sowing SI caused early crop establishment at autumn, and relatively early maturity which reduced crop's growing period. Sowing date SI affected number of tiller, plant height, straw and grain yields. Soil profile recharge under sowing SI and spring SI were very similar to that under rainfed, but rainfed SMC trend curve was between the other two curves, which indicates that sowing SI SMC trend is the lowest in amount.

At rainfed treatment, evapotranspiration was dominated by evaporation from soil surface. From spring on, when air temperature, radiation and canopy development increased, the evaporative demand exceeded rainfall (Figs. VI-2 and VI-12). As a result, soil profiles loss their water continuously up to crop maturity and harvest. The spring rains did not recharge the profile, because of the high evaporative demand during that period.

Calibration of crop input parameters for rainfed and SI treatments for the 2005/2006 season allowed BUDGET and AquaCrop to perform satisfactorily in wheat grain yield, soil moisture content, and ET during the three cold winter growing seasons in the highlands of KRB of Iran. In this area, crop emergence, before the severe winter starts, is important to ensure an adequate stand establishment. Thus, early sowing combined with sufficient amount of water as SI, since the probability of sufficient rainfall at this time is very low, would allow crop to get stronger stand before the cold winter starts by about 10 October to early November. Otherwise, wheat crop planted late would not emerge because of lower temperatures prevailing at late planting irrespective of higher rainfall obtained.

The other years' results were then confirmed through modeling. We could not conduct so many years of experiments to see the yield sustainability with reduced acceptable risk to be recommended to farmers. A water management strategy to shift the supplemental irrigation from Spring SI to Planting SI (during the period of 10 October to early November) is highly promising due to the relatively low air temperatures for optimum crop growth and improved water-productivity as well as higher biomass and grain yields.

Estimated grain and biomass yield (or yield reduction prediction) under rainfed, planting SI and spring SI are shown in

Figs. 4-7 and 4-8, for the two growing seasons of 2005/2006 and 2006/2007, respectively. In the first crop season, expected yield of rainfed, planting SI and spring SI were 31, 51 and 67 percent of potential yield (5-6 ton/ha) (Fig. 4-7). Single irrigation at planting positively affected crop establishment and improved expected grain yield. At the second crop season, better conditions of rainfall distribution (especially at planting and spring times) boosted yield of rainfed, planting SI and spring SI so the predicted yields were 58, 67 and 89 percent of potential yield (5-6 t/ha), respectively (Fig. 4-8). The average cumulative grain yield during the two crop seasons is shown in Fig. 4-9.

These year-specific results of these study sites should be extrapolated in time and out scaled to other regions in order to be more useful. Results from the study suggest that the use of BUDGET and AquaCrop after proper calibration and validation can be feasible for such extrapolations. Given the results reported here, it is expected that the application of the model in similar climates of the region will allow long-term extrapolations with less experimental results, thus reducing time and research cost. Different earlier sowing scenarios in longer period of time has proved that advancement of sowing date to 10 October compared with rainfed sowing around late October combined with sufficient water for crop emergence would increase the crop yield by about 30 to100% and eventually the water productivity as well.

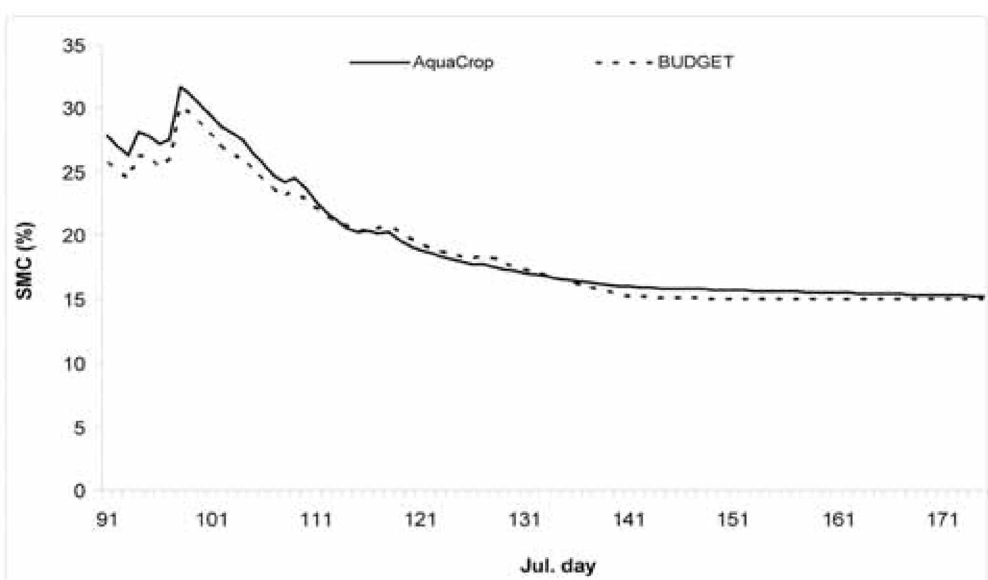

Fig. 4-1- Comparison of two models simulations to predict soil moisture content at rainfed treatment of Honam site, 2005/2006.

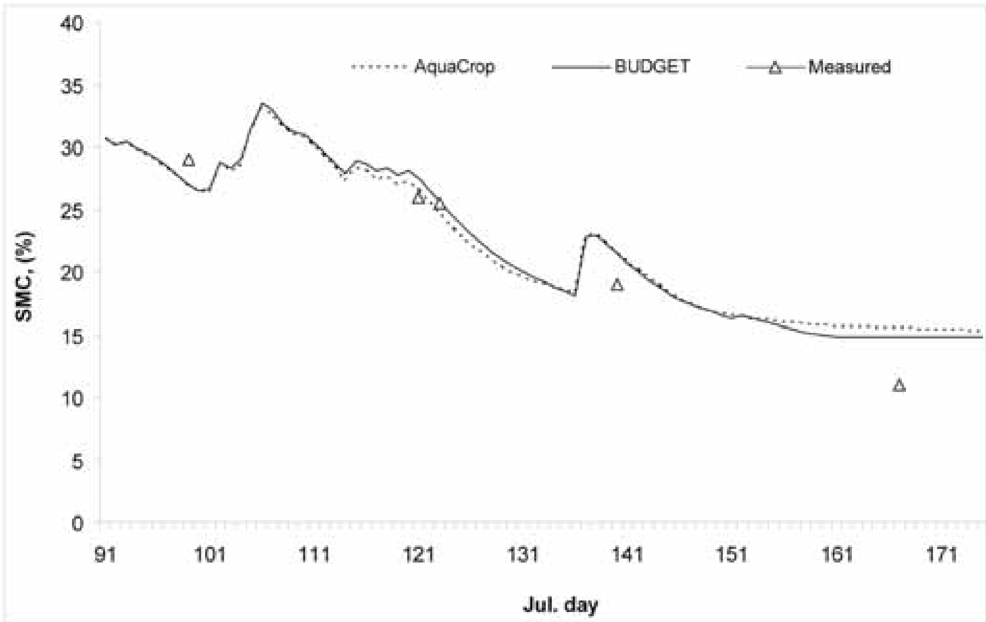

Fig. 4-2- Comparison of two models simulations to predict soil moisture content for the rainfed treatment at Honam site, 2006/2007.

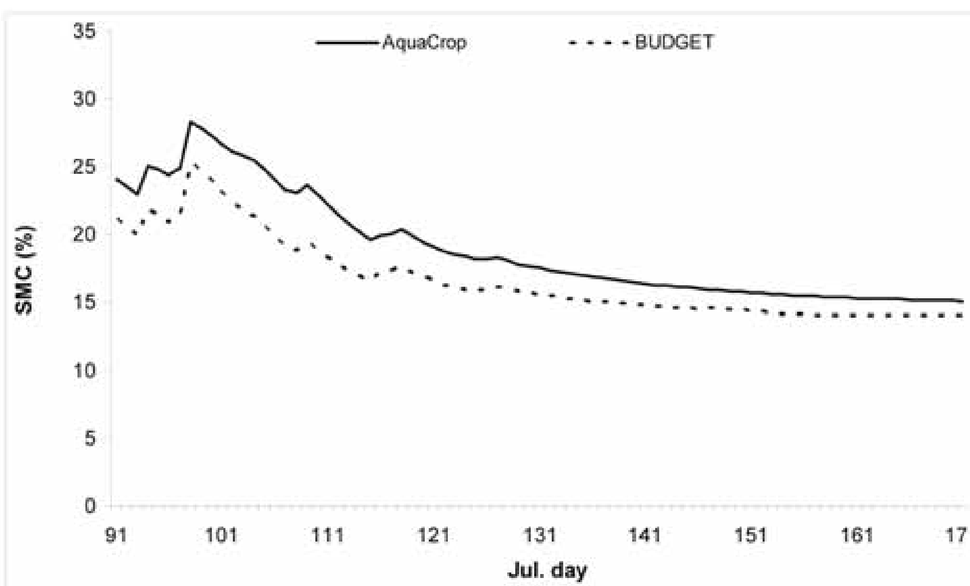

Fig. 4-3- Comparison of two models simulations to predict soil moisture content at SI planting treatment of Honam site, 2005/2006.

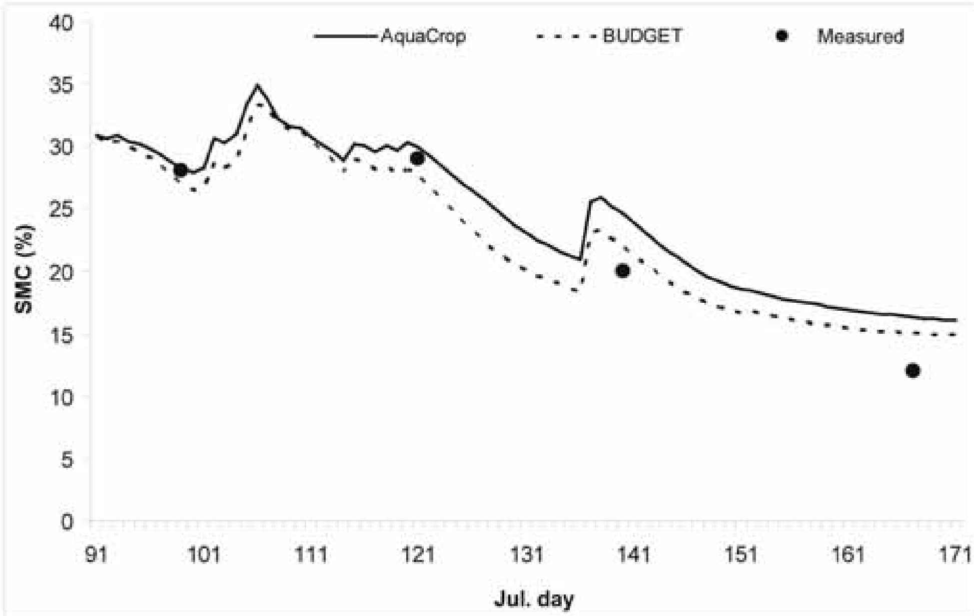

Fig. 4-4- Comparison of two models simulations to predict soil moisture content for the SI planting treatment at Honam site, 2006/2007.

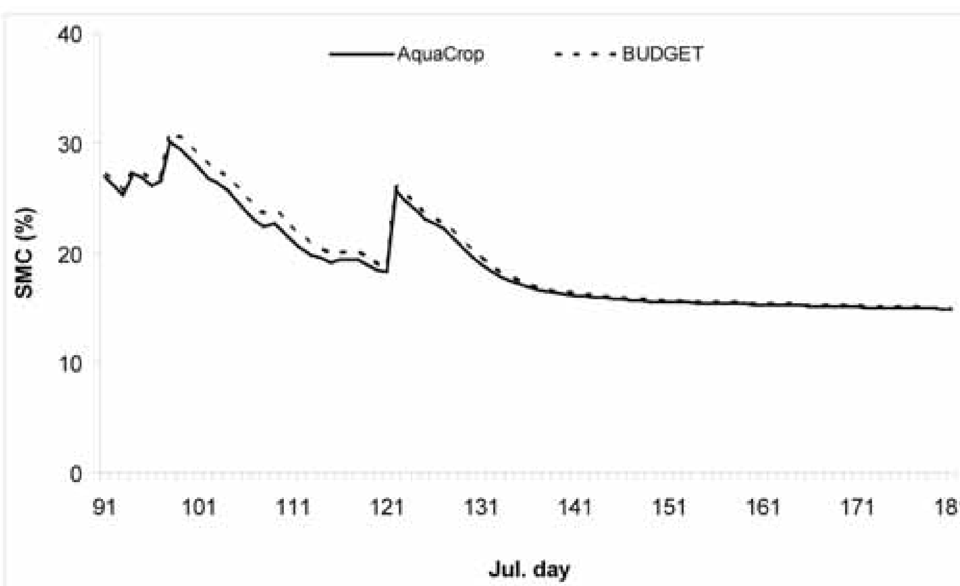

Fig. 4-5- Comparison of two models simulations to predict soil moisture content at SI spring treatment of Honam site, 2005/2006.

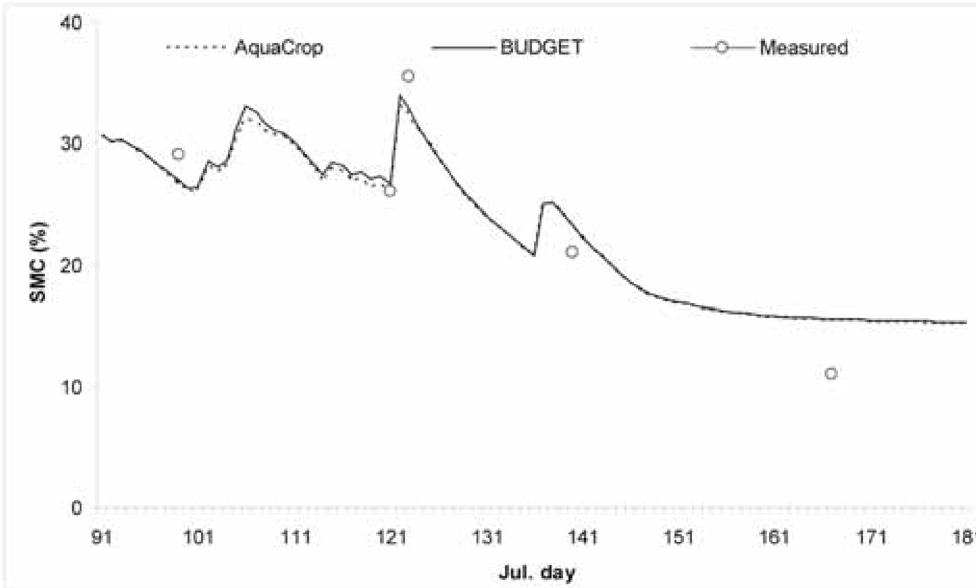

Fig. 4-6- Comparison of two models simulations to predict soil moisture content at SI spring treatment of Honam site, 2006/2007.

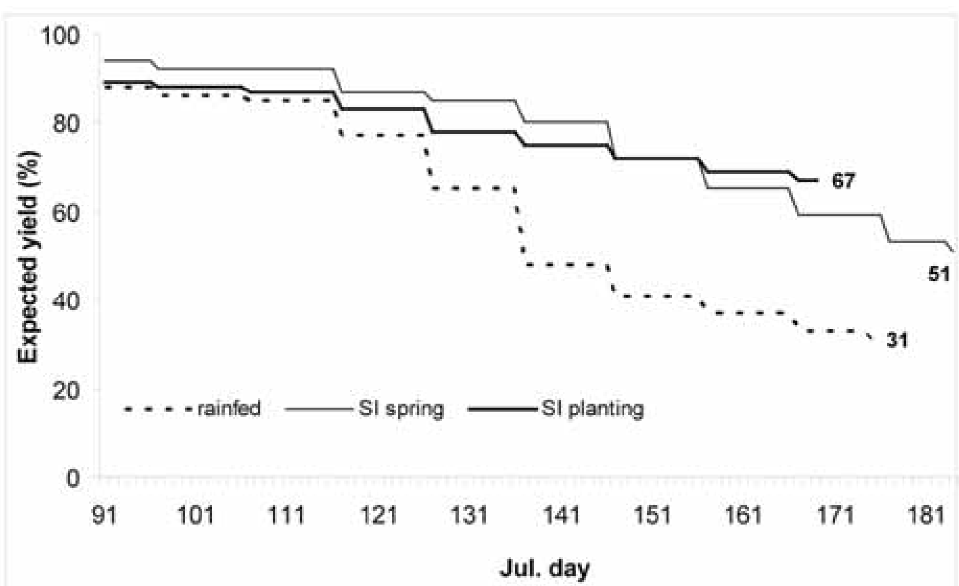

Fig. 4-7- Expected yield percentage using BUDGET under different treatments of Honam site, 2005/2006.

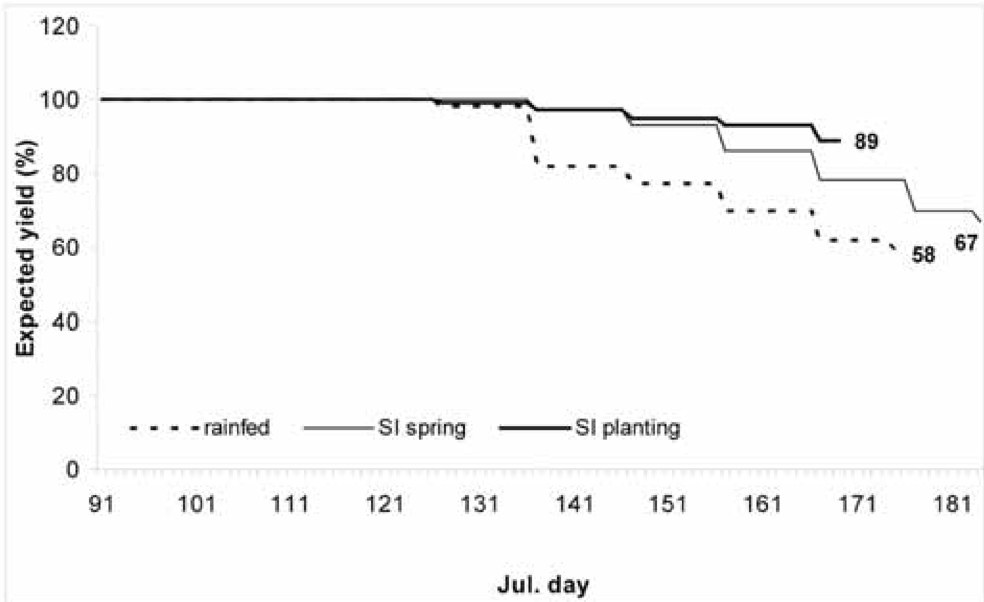

Fig. 4-8- Expected yield percentage using BUDGET under different treatments of Honam site, 2006/2007.

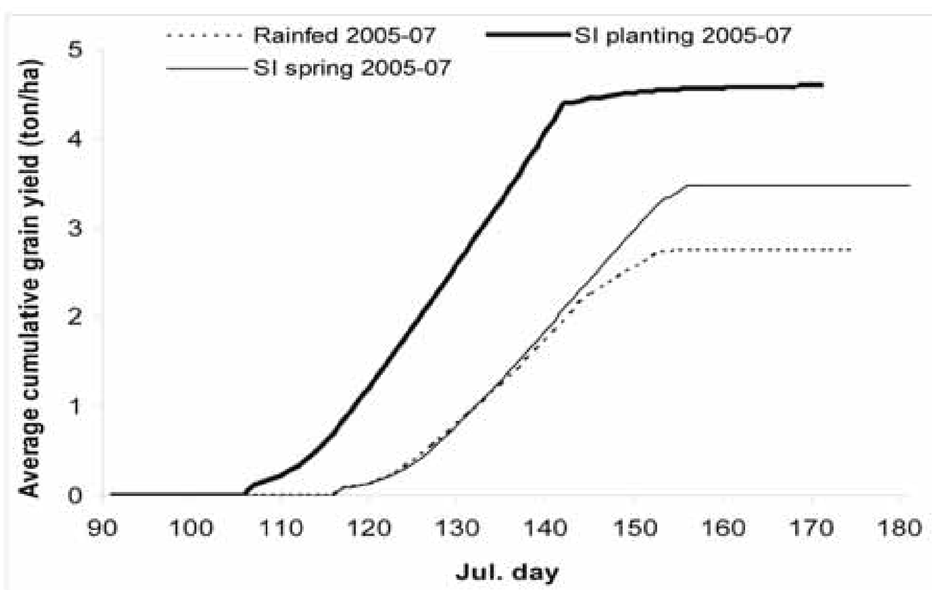

Fig. 4-9- Average cumulative grain yield for rainfed and SI treatments (2005/2007).

Chapter 5.

Economical Analysis of Supplemental Irrigation

5. Economical Analysis of Supplemental Irrigation

5.1. Introduction

The purpose of this part of the report is to evaluate the economic feasibility of agriculture with supplemental irrigation at two selected sites in Kermanshah and Lorestan provinces, of KRB located on west of Iran. Investigation on the efficient use of rainwater is critically important for developing optimum agricultural production systems for this region. In order to obtain the maximum benefit from wheat and barley production and optimize the available water resources, some supplemental irrigation field experiments scenarios were conducted at on-farm scales during 2005-2008 seasons at Honam and Merek sites of KRB rainfed areas. The treatments included two levels of agronomic management (traditional management and improved management) as main plot and three levels of supplemental irrigation (rainfed (without SI), 75 mm single irrigation at planting time, 50 mm single irrigation at spring time) as sub plot. The experiments were carried out on rainfed wheat and barley varieties. Data was analyzed by Partial Budgeting, Marginal Benefit–Cost Ratio (MBCR), different states of water and irrigation prices, income functions and scenario analysis of water productivities.

5.2. Material and methods

5.2.1. Crops and rainfall distribution

The main crops in the KRB are winter wheat and barley. The prevailing cropping pattern is winter cereals/legumes intercropping. The wheat and barley are sown in autumn with rows spacing of 17-20 cm.

In the study region, only 57% of annual rainfall occurs during the growth stage of spring wheat, therefore crops in the Honam and Merek regions depend, to a great extent, on the supplemental irrigation period. According to the field experiment, the water requirement of winter wheat is 300-500 mm. However, rainfall during the same period is not enough, leaving the crops with a total water deficit for all growth stages of 40-125 mm under limited irrigation strategy. The first critical stage of irrigation occurs in sowing time at autumn, when there is not enough effective precipitation and a large portion of the seasonal water deficit occurs at this time. Irrigation is also needed during the second critical stage when the crop is in the heading and flowering stages.

5.2.2. Economic evaluation

Two dynamic economic indices, financial net present value (NPV) and financial internal rate of return (IRR), are used to compare each scheme of supplemental irrigation. It is assumed that the pumping and irrigation systems have a useful life of 20-30 years. A discount rate of 15% and 25% based on the code of water economic calculation is used for NPV calculations. During the analysis period, profits and operational costs are constant. Therefore, the present value of gross benefits (GB) and total costs (TC) are, respectively,

$$GB = \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} \qquad (5-1)$$

$$TC = K_1 + \sum_{t=0}^{m} \frac{K_{2t}}{(1+i)^t} + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \qquad (5-2)$$

where B_t is the gross profit at the t^{th} year, C_t the cost at the t^{th} year, i the discount rate, K_1 the investment on constant cost, K_{2t} the investments on pumping equipment and irrigation system tools at the t^{th} year, m the replacement time of irrigation equipment, and n the calculation period.

Therefore, the net present value of profit is

$$NPV=GP-TC \qquad (5\text{-}3)$$

If NPV > 0, the scenario is accepted, if not, the scenario is infeasible. The duration of time when the net revenue compensates for the total investment is the capital recovery period.

In order to calculate the internal rate of return the solution of IRR in the equation must be found, that is

Where, IRR is the internal rate of return.

$$\sum_{t=1}^{n}\frac{B_t}{(1+IRR)^t}-\left[K_1+\sum_{t=0}^{m}\frac{K_{2t}}{(1+IRR)^t}+\sum_{t=1}^{n}\frac{C_t}{(1+IRR)^t}\right]=0 \qquad (5-4)$$

The IRR is acceptable if it is greater than minimum expected interest rate.

5.2.3. Partial Budgeting (PB) technique

A Partial Budgeting (PB) technique and Marginal Benefit Cost Ratio (MBCR) were used to assess the economics of supplemental irrigation and single irrigation application from groundwater on rainfed wheat. Basic data used for the assessment includes yield and revenue gains due to supplemental irrigation or single irrigation above that of rainfed system and the cost associated with the application of irrigation water. The partial budgeting of wheat production (with and without supplemental irrigation) showed that, economically, supplemental irrigation is very attractive investment. Net benefit is calculated using the following equation:

$$N.B = B(w) - C(w) = (Y_G \times P_G + Y_S \times P_S) - (C1 + P_W \times W) \qquad (5\text{-}5)$$

Where:

N.B = net benefit (Rial/ha)

B(w) = gross income (Rial/ha)

C(w) = total costs (Rial/ha)

YG = grain yield (kg ha^{-1})

PG = price of grain (Rial/kg)

YS = straw yield (kg ha^{-1})

PS = price of straw (Rial/kg)

C1 = total fixed costs without water and irrigation (Rial/ha)

PW = price of water and irrigation (Rial/m^3)

W = amount of irrigation water use (m^3/ha)

$$\Delta B = B(w)_j - B(w)_{j+1} \qquad (5\text{-}6)$$

$$\Delta C = C(w)_j - C(w)_{j+1} \qquad (5\text{-}7)$$

5.3. Results and Discussions

Maximum irrigation water productivity (IWP) related to rainfed condition was for combination of improved management and SI spring at Merek site and combination of improved management and SI planting at Honam site, respectively.

The mean field experimental costs of wheat and barley at Honam and Merek sites during 2005-07 were similar and they are shown in Tables 5-1 and 5-2 for each crops and management treatments. Price of water and irrigation at research region based on its components is shown in Table 5-9. The mean values of total cost at Honam site and under traditional management were 1635, 1265 thousand Rials per hectare for wheat and barley, respectively and under advanced management were 2045 thousand Rials per hectare for wheat and barley. The mean values of wheat grain yield for treatments TM-rainfed, TM-SI planting, TM-SI spring, ,AM-rainfed, ,AM-SI planting, AM-SI spring at Honam site were 2116, 2394, 2386, 2525, 3841 and 3456 kg ha^{-1}, respectively and The mean values of barley grain yield for the same treatments were 1572, 2487, 2670, 2270, 3444 and 2853 kg ha^{-1}, respectively.

The mean gross income, costs and net benefit of wheat and barley under different scenarios are shown in Tables 5.3, 5-4, 5-5 and 5-6 for each selected sites.

Economical and non economical tests of comparison treatments with planting supplemental single irrigation at Honam site are shown in Table 5-7. According to this test all other treatment compare to planting SI were non economical. Then at Honam recommended management are including: AM + planting SI, AM + SI spring and AM + rainfed treatments, respectively. Traditional management with SI or without SI is not recommended. Economical and non economical test of comparison treatments with spring supplemental single irrigation at Merek site are shown in Table 5-8. According to this test, all treatments , except planting time SI, were non economical.

For Merek, recommended management is: AM + spring SI, AM + SI planting and AM + rainfed treatments, respectively. Traditional management with SI or without SI is not recommended.
The mean values of total cost at Merek site and under traditional management were 1107.5, 1282.5 thousand Rials per hectare for wheat and barley, respectively and under advanced management were 1576.5 thousand Rials per hectare for wheat and barley. The mean values of wheat grain yield at Merek site for treatments TM-rainfed, TM-SI planting, TM-SI spring, AM-rainfed, AM-SI planting, AM-SI spring were 2039, 2263, 2826, 2334, 2705 and 3527 kg ha^{-1} respectively. The mean values of barley grain yield for the same treatments were 2033, 2125, 2412, 2625, 2901 and 3768 kg ha^{-1} respectively.

Table 5-1- Average field experimental costs (1000 Rials)* of wheat and barley at Honam site (Lorestan province), 2005-2007.

Source of costs	Wheat		Barley	
	Traditional management	Advanced management	Traditional management	Advanced management
Preparation land and tillage	200	345	200	345
Seed and planting	625	640	585	640
Maintenance (fertilizer, wee/ disease control, water, irrigation)	560	810	230	810
Harvest	250	250	250	250
Total	1635	2045	1265	2045

Source: research data. *: 1US$=9800 IR. Rials.

Table 5-2- Average field experimental costs (1000 Rials) of wheat and barley at Merek site (Kermanshah province), 2005-2007.

Source of costs	Wheat		Barley	
	Traditional management	Advanced management	Traditional management	Advanced management
Preparation land and tillage	97.5	157.5	97.5	157.5
Seed and planting	535	685	710	685
Maintenance (fertilizer, weed/ disease control, water, irrigation)	365	615	365	615
Harvest	110	110	110	110
Total	1107.5	1567.5	1282.5	1567.5

Source: research data.

Table 5-3- Average wheat and barley grain yield at Honam and Merek sites, 2005-2007.

Treatments	Honam		Merek	
	Wheat	Barley	Wheat	Barley
TM-rainfed	2116	1572	2039	2033
TM-SI planting	2394	2487	2263	2125
TM-SI spring	2386	2670	2826	2412
AM-rainfed	2525	2270	2334	2625
AM-SI planting	3841	3444	2705	2901
AM-SI spring	3456	2853	3527	3768

Source: research data.

Table 5-4- Gross income (1000 Rials) of different treatment of wheat and barley at Honam and Merek sites, 2005-2007.

Treatments	Honam		Merek	
	Wheat	Barley	Wheat	Barley
TM-rainfed	4337.8	2515.2	4179.9	3252.8
TM-SI planting	4906.6	3979.2	4638.1	3400
TM-SI spring	4891.3	4272	5793.3	3859.2
AM-rainfed	5176.2	3632	4783.7	4200
AM-SI planting	7873	5510.4	5545.2	4641.6
AM-SI spring	7085.8	4564.8	7231.4	7724.4

Source: research data.

Table 5-5- Gross income, costs and net benefit (1000 Rials) per hectare of different treatment of wheat and barley at Honam site, 2005-2007.

	Wheat			Barley		
	Gross incomes	Costs	Net benefit	Gross incomes	Costs	Net benefit
TM-rainfed	4337.8	1635	2702.8	2515.2	1265	1270.2
TM-SI planting	4906.6	2035	2871.6	3979.2	1665	2314.2
TM-SI spring	4891.3	2035	2856.3	4272	1665	2607
AM-rainfed	5176.2	1645	3531.2	3632	1645	1987
AM-SI planting	7873	2045	5828	5510.4	2045	3465.4
AM-SI spring	7085.8	2045	5040.8	4564.8	2045	2519.8

Table 5-6- Gross income, cost and net benefit (1000 Rials) of different treatment of wheat and barley at Honam site, 2005-2007.

	Wheat			Barley		
	Gross incomes	Costs	Net benefit	Gross incomes	Costs	Net benefit
TM-rainfed	4179.9	1107.5	3072.4	3252.8	1282.5	1970.3
TM-SI planting	4638.1	1507.5	3130.6	3400	1682.5	1717.5
TM-SI spring	5793.3	1507.5	4285.8	3859.2	1682.5	2176.7
AM-rainfed	4783.7	1167.5	3616.2	4200	1167.5	3032.5
AM-SI planting	5545.2	1567.5	3977.7	4641.6	1567.5	3074.1
AM-SI spring	7231.4	1567.5	5663.9	7724.4	1567.5	6156.9

Table 5-7- Economical and non economical test of comparison treatments with SI planting at Honam site (1000 Rials per hectare), 2005-2007.

Treatment	Wheat		Barley		comparison of treatments with SI planting
	Average difference cost ΔC	Average difference benefit ΔB	Average difference cost ΔC	Average difference benefit ΔB	
TM-rainfed	-410	-3535.2	-780	-2995.2	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
TM-SI planting	-10	-2966.4	-380	-1531.2	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
TM-SI spring	-10	-2981.7	-380	-1238.4	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
AM-rainfed	-400	-2696.8	-400	-1878.4	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
AM-SI spring	0	-787.2	0	-945.6	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$

Table 5-8- Economical and non economical test of comparison treatments with SI spring at Merek site (1000 Rials per hectare), 2005-2007.

Treatment	Wheat		Barley		comparison of treatments with SI spring
	Average difference cost ΔC	Average difference benefit ΔB	Average difference cost ΔC	Average difference benefit ΔB	
TM-rainfed	-460	-3051.5	-285	-4471.6	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
TM-SI planting	-60	-2593.3	+115	-4324.4	For wheat: Non economic $\Delta B <<< 0$ $\Delta C < 0$ For barley: Non economic $\Delta B <<< 0$ $\Delta C > 0$
TM-SI spring	-60	-1438.1	+115	-3865.2	For wheat: Non economic $\Delta B <<< 0$ $\Delta C < 0$ For barley: Non economic $\Delta B <<< 0$ $\Delta C > 0$
AM-rainfed	-400	-2447.7	-400	-3524.4	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$
AM-SI planting	0	-1686.2	0	-3082.8	For wheat and barley: Non economic $\Delta B <<< 0$ $\Delta C < 0$

Table 5-9- Price of water and irrigation calculated for a farm in the study area.

	List of water and irrigation costs	Primary cost (1000 Rials)	Annual present value (Rials)	
			interest rate 15%	interest rate 25%
1	Pump & electromotor	13300	2124828	3363782
2	Semi deep well	14000	2132203	3504338
3	Power instrument	71040	10819406	17782013
4	Maps, pipe transport and implementation network, etc.	128875.3	20589307	32594615
5	Other primary cost	36547	5838802	9243318
6	Total primary cost	263762.3	41504546	66488067
7	Current cost	1000	1000000	1000000
8	Total costs	264762.3	42504546	67488067
9	Price of water and irrigation (Rial/m^3)*	-	213	338.1

- Total annual water volume used by the farm in the area was199584 cubic meter

Chapter 6.

Summary and Recommendations

6. Summary and Recommendations

6.1. Rainfed barley

At Honam site, the optimum program was a combination of advanced agronomic management with SI options (single irrigation at planting time) and the second option was a single irrigation at spring time (during heading – flowering stage). At Merek site, the optimum program was a combination of advanced agronomic management with SI options (a single irrigation at spring time (during heading – flowering stage)) and the second option was a single irrigation at planting time. At rainfed farming (without SI) advanced agronomic management had preference to traditional management at two sites. At these preferential programs maximum water productivity and net benefit were obtained. At rainfed conditions RWP under AM (0.26-0.37 kg m-3) increased by about 20-50% compared to TM. The results of this study showed that a single irrigation application at sowing or spring time (during heading to flowering stage) increased total water productivity (TWP) of barley from 0.53-0.75 kg m^{-3} during three seasons. The irrigation water productivity (IWP) of barley reached to 1.74-4.69 kg m^{-3} by using single irrigation at sowing or spring time. Low RWP (and yield) in farmer practices were mainly due to suboptimal agronomic management practices. These preliminary results confirm the potential of single irrigation and early planting as an effective method to enhance productivity.

At Merek site and under rainfed condition, barley grain yield of AM (2157 kg ha^{-1}) increased 73% compare to TM (1245). By applying SI planting scenarios, grain yield of AM (3142 kg ha^{-1}) increased 46%, 48% and 152% compare to rainfed-AM, SI planting-TM (2125 kg ha^{-1}) and rainfed-TM, respectively By applying SI spring scenario, grain yield of AM (3510 kg ha^{-1}) increased by 63%, 48% and 182% compare to rainfed-AM, SI spring-TM (2368 kg ha^{-1}) and rainfed-TM, respectively (Table IV-1, Fig. 2-24).

At Merek site and under rainfed condition, RWP of AM (0.49 kg m^{-3}) increased about 44% compared to TM (0.34 kg m^{-3}). By applying SI planting scenario, TWP of AM (0.54 kg m^{-3}) increased by about 10%, 59% and 59% compare to rainfed-AM, SI planting-TM (0.34 kg m^{-3}) and rainfed-TM, respectively. By applying SI spring scenario, TWP of AM (0.71 kg m^{-3}) increased by about 45%, 34% and 109% compared to rainfed-AM, SI spring-TM (0.53 kg m^{-3}) and rainfed-TM, respectively (Table IV-1).

At Honam site and under rainfed condition, barley grain yield of AM (2068 kg ha^{-1}) increased 50% compared to TM (1381). By applying SI planting scenario, grain yield of AM (3048 kg ha^{-1}) increased by 47%, 57 % and 121% compared to rainfed-AM, SI planting/spring-TM (1939 kg ha^{-1}) and rainfed-TM, respectively. By applying SI spring scenario, grain yield of AM (3137 kg ha^{-1}) increased by 52%, 46% and 127% compared to rainfed-AM, SI spring-TM (2143 kg ha^{-1}) and rainfed-TM, respectively (Table IV-2, Fig. 2-25). At Honam site and under rainfed condition, RWP of AM (0.43 kg m^{-3}) increased by about 43% compared to TM (0.30 kg m^{-3}). By applying SI planting scenarios, TWP of AM (0.56 kg m^{-3}) increased by about 30%, 56% and 87% compared to rainfed-AM, SI planting/spring-TM (0.36 kg m^{-3}) and rainfed-TM, respectively. By applying SI spring scenarios, TWP of AM (0.70 kg m^{-3}) increased by about 63%, 52% and 133% compared to rainfed-AM, SI

Table 6-1- Avenues to improve rainfed agricultural crops through integrated agronomic and water management.

Strategy for upgrading	Type of Management	Methodology	Target parameter (s)
Rain water productivity	Agronomic management practices	Tillage and land preparation Crop rotation Fertilizer management Crop choice Crop rotation Timing of operations Pest management Weed control Harvest	Root length and density Crop development Soil moisture conservation Increasing quality and quantity yield Optimum cropping pattern Control of weed and diseases Decreasing lost Increasing income
Total water productivity	Agronomic management practices	Tillage and land preparation Crop rotation Fertilizer management Crop choice Crop rotation Timing of operations Pest management Weed control Harvest	Root length and density Crop development Soil moisture conservation Increasing quality and quantity yield Optimum cropping pattern Control of weed and diseases Decreasing lost Increasing income
	Water management	Single/Supplemental irrigation Amount and time of SI Irrigation system Soil and water conservation	Crop establishment Improving yield components Soil infiltrability Less unproductive competition Improving soil moisture content Control of weed and diseases Water holding capacity Stability and increasing yield

spring-TM (0.46 kg m^{-3}) and rainfed-TM, respectively (Table IV-2).

6.2. Rainfed wheat

At Honam site, the optimum program was a combination of advanced agronomic management with SI options (single irrigation at planting time) and the second option was single irrigation at spring time (during heading – flowering stage). At Merek site, the optimum program was a combination of advanced agronomic management with SI options (single irrigation at spring time (during heading – flowering stage) and the second option was single irrigation at planting time. At rainfed farming (without SI) advanced agronomic management had preference to traditional management at two sites. At these preferential programs, maximum water productivity and net benefit were obtained. At rainfed condition RWP under AM (0.41-0.47 kg m^{-3}) increased by about 15-33% as compared to TM (0.34-0.39 kg m^{-3}). The results of this study showed that with a single irrigation application at sowing or spring time (during heading to flowering stage), the total water productivity (TWP) of wheat reached a range of 0.55 to 0.82 kg m^{-3} during the three seasons. The irrigation water productivity (IWP) of wheat reached a range of 1.39 to 4.55 kg m^{-3} by using single irrigation at sowing or spring time. Low RWP (and yield) in farmer practices were mainly due to suboptimal agronomic management practices. These preliminary results confirm the potential of single irrigation and early planting as an effective method to enhance productivity.

At Merek site and under rainfed condition, wheat grain yield of AM (2284 kg ha^{-1}) increased by about 18% compared to TM (1931). By applying SI planting scenarios, grain yield of AM (2693 kg ha^{-1}) increased by about 20%, 24% and 39% compared to rainfed-AM, SI spring-TM (2165 kg ha^{-1}) and rainfed-TM, respectively. By applying SI spring scenarios, grain yield of AM (3052 kg ha^{-1}) increased by 36%, 16% and 58% compared to rainfed-AM, SI spring-TM (2126 kg ha^{-1}) and rainfed-TM, respectively (Table III-1, Fig. 2-14).

At Merek site and under rainfed condition, RWP of AM (0.43 kg m^{-3}) increased by about 16% compared to TM (0.37 kg m^{-3}). By applying SI planting scenario, TWP of AM (0.45 kg m^{-3}) increased by about 5% and 22% compared to rainfed-AM and rainfed-TM, respectively. By applying SI spring scenario, TWP of AM (0.53 kg m^{-3}) increased by about 23%, 15% and 43% compared to rainfed-AM, SI spring-TM (0.46 kg m^{-3}) and rainfed-TM, respectively (Table III-1).

At Honam site and under rainfed condition, wheat grain yield of AM (2289 kg ha^{-1}) increased by 33% compared to TM (1726). By applying SI planting/spring scenarios, grain yield of AM increased by 47%, 57% and 94% compared to rainfed-AM, SI planting/spring-TM (2126 kg ha^{-1}) and rainfed-TM, respectively (Table III-2, Fig. 2-14).

At Honam site and under rainfed condition, RWP of AM (0.45 kg m^{-3}) increased by about 29% compared to TM (0.35 kg m^{-3}). By applying SI planting scenarios, TWP of AM (0.57 kg m^{-3}) increased by about 27%, 50% and 63% compared to rainfed-AM, SI planting/spring-TM (0.38 kg m^{-3}) and rainfed-TM, respectively. By applying SI spring scenarios, TWP of AM (0.63 kg m^{-3}) increased by about 40%, 54% and 80% compared to rainfed-AM, SI spring-TM (0.41 kg m^{-3}) and rainfed-TM, respectively (Table III-2).

6.3. Irrigated wheat

Under pressurized irrigation system, the field crop TWP under deficit irrigation was 1.09 times higher than that with no water deficit (full irrigation). This suggests that increasing the areas irrigated with the water saved would compensate for any yield loss. With a 25 percent water use deficit, TWP was 1.2 times that achieved under normal irrigation practices.n Under surface irrigation system and according to farmer's irrigation managements, eliminating first irrigation at spring time did not affect grain yield and TWP for different treatments, thus it can be deleted.

6.4. Conclusions

Based on the results of their research, the following conclusions can be drawn:

1. During the dry season, the water resources in the KRB are inadequate in meeting the domestic, livestock and crop production requirements. However, the highlands receive fairly more rainfall (than the lowlands), which is adequate to meet crop water requirements under rainfed conditions, but may not be suitable.
2. The average households' size in

Honam and Merek villages is relatively higher than that of the national average. There is wide income disparity among households. The average net mean income was US$ 1500 per annum.

3. Livelihood strategies and coping mechanisms in the upper KRB are diverse and vary. Livelihood strategies relate to farming practices, business market, social and cultural relations.
4. The vulnerable groups in upper KRB are the poor who get an income of less than US$5-6 per day per person. They include poor women. They are at risk of food security and their households fall under the bottom income quintile for different family types.
5. The cropping calendars, patterns and sequences in the upper KRB are quite diverse. This is made possible by use of residual soil moisture and irrigation. Both wheat and barley are extensively grown in the upper KRB. Chickpea and lentil are mostly grown in the upper KRB in rotation with cereals.
6. Among the different water users (agriculture, livestock, domestic and industrial) in the upper KRB, agriculture is the leading consumer under both rainfed and irrigated production systems.
7. Generally, the crop water productivity under rainfed crop production was higher in the upper KRB for most cereals compared to the other rainfed areas of Iran.
8. Under deficit irrigation conditions, crop water productivity for irrigated wheat in the upper KRB was found to be higher than same crops when grown under full irrigation conditions.

From a water perspective, there are two main avenues for upgrading rainfed agriculture: (1) increase rain water productivity, and (2) increase irrigation and total water productivity (Table 6-1). Even though, these strategies focus on water, the approaches and practices to achieve them are not necessarily solely associated to field water management.

REFERENCES:

Adary, A., Hachum, A., Oweis, T., and Pala, M. 2002. Wheat productivity under supplemental irrigation in northern Iraq. On-Farm Water Husbandry Research Report Series, No.2. International Center for Agricultural Research in the Dry Areas (ICARDA). Aleppo, Syria. 38pp.

Anderson, W.K., and Smith, W.R. 1990. Yield advantage of two semi-dwarf compared to two tall wheat depends on sowing time. Aust. J. Agric. Res., 41: 811-826.

Cabelguenne, M., Jones, C.A., Marty, J.R., Dyke, P.T., and Williams, J.R., 1990. Calibration and validation of EPIC for crop rotations in southern France. Agric. Sys. 33, 153–171.

Cooper, P.J.M., and Gregory, P.J., Tully, D., and Harris, H. 1987. Improving water –use efficiency in the rainfed farming systems of West Asia and North Africa. Exp. Agric., 23: 113–158.

Fan, T, Stewart, B.A, Payne, W.A, Wang, Y, Song, S, Luo J, and Robinson, C.A. 2005. Supplemental irrigation and water: yield relationships for plasticulture crops in the loess plateau of China. Agronomy Journal, 97: 177–188.

FAO. 1979. Yield response to water by J. Doorenbos & A.H. Kassam. Irrigation and Drainage Paper No. 33. FAO, Rome.

FAO. 2009. AquaCrop-The FAO crop model to simulate yield response to water.

FAO. 2009. Eto calculator, Land and Water Digital Media Series, No 36. FAO, Rome, Italy. Website: http://www.fao.org. nr.water/ETo.html.

ICARDA, 2003. ICARDA Annual Report 2002. International Center for Agricultural Research in the Dry Areas (ICARDA). Aleppo, Syria

Ilbeyi, A., Ustun, H., Oweis, T., Pala, M., and Benli, B. 2006. Wheat water productivity and yield in a cool highland environment: Effect of early sowing with supplemental irrigation. Agric. Water Manage. 82, 399–410.

Kherabi, J., Tavakoli, A.R., Entesari, M.R., and Salamat, A.R. 1996. Manual of deficit

irrigation. Iranian National Committee on Irrigation and Drainage (IRNCID), 218pp. (in Persian).
Kijne, J.W, Barker, R., and Molden, D.J. 2003. Water productivity in agriculture: limits and opportunities for improvementWallingford, UK CABI, IWMI.
Kirda, C., and Kanber, R. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. In: C. Kirda, P. Moutonnet, C. Hera & Nielsen, D.R., (Eds.). Crop yield response to deficit irrigation, Dordrecht, The Netherlands, Kluwer Academic Publishers.
Kropff, M.J., Van Laar, H.H., and Matthews, R.B. 1994. ORYZA1, an eco-physiological model for irrigated rice production. In: SARP Research Proceedings, DLO-Research Institute for Agro biology and Soil Fertility, Wageningen, WAU Department of Theoretical Production Ecology, Wageningen. International Rice Research Institute, Los Banos, p. 110.
Lengnick, L.L., and Fox, R.H. 1994. Simulation by NCSWAP of seasonal nitrogen dynamics in corn: II. Corn growth and yield. Agron. J. 86, 176–182.
Ojeda-Bustamante, W., Sifuentes-Ibarra, E., nack, D., and Carrillo M. 2004. Generalization of irrigation scheduling parameters using the growing degree days concept: application to a potato crop. Irrigation and Drainage, 53: 251–261
Oweis, T. Pala, M., and Ryan, J. 1998. Stabilizing rain-fed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. Agronomy J. 90:672-681.
Oweis, T., and Hachum A. 2001. Reducing peak supplemental irrigation demand by extending sowing dates. Agric. Water Manag. 50: 109–123.
Oweis, T., and Hachum, A. 2003. Improving water productivity in the dry areas of West Asia and North Africa. In: Kijne, J.W., Barker, R., and Molden, D. (eds.) Water Productivity in Agriculture, limits and opportunities for improvement, International Water Management Institute (IWMI), Colombo, Sri Lanka. CABI Publishing, Wallingford, U.K. pp.179–198.
Oweis, T., and Hachum, A. 2004. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. 4th International Crop Science Congress, 26th Sep. to 1st Oct. 2004, Queensland, Australia.
Oweis, T., Hachum, A., and Kijne, J. 1999. Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. International Water Management Institute, Colombo, Sri Lanka, SWIM paper 7. 38pp.
Oweis, T., Salkini, A., Zhang, H., Ilbeyi, A. Hustun, H. Dernek, Z. and Erdem, G., 2001. Supplemental irrigation potential for wheat in the central Anatolian plateau of Turkey, ICARDA.
Raes, D. 2002. BUDGET: A soil water and salt balance model. Reference manual. Department of Land Management, Katholieke Univ. Leuven, Leuven, Belgium.
Raes, D., Steduto, P., Hsiao, T.C. and Fereres, E. 2006. Structure, algorithms and functionalities of the FAO crop-water productivity model AquaCrop. International Symposium on Water and Land Management for Sustainable Irrigated Agriculture, Adana (Turkey), 4 – 8 April, 2006.
Sayadyan, K., and Tallie, A.A. 2000. The effect of supplemental irrigation on rainfed wheat. Iranian J. Soil & Water Sci., 14(1): 57–68, (in Persian).
Sepaskhah, A.R., Tavakoli, A.R., and Mosavi, F. 2007. Principles and Applications of Deficit Irrigation. Iranian National Committee on Irrigation and Drainage (IRNCID), 288pp. (in Persian).
Siddique, K.H.M., Tennant, D., Perry, M.W., and Belford, R.K. 1990. Water use and water use efficiency of old and modern wheat cultivars in a Mediterranean type environment. Aust. J. Agric. Res., 41: 431–447.
Steduto, P. 2008. The FAO Crop-water productivity model AquaCrop. Land and Water Development Division, Agricultural Department. FAO, , Rome
Stewart, B.A., and Musick, J.T. 1982. Conjunctive use of irrigation and rainfall in semiarid regions. Advances in Agronomy 1: 1-23.
Tallie, A.A. 2005. Response of rainfed barley (Sararood 1) to supplemental irrigation and nitrogen (on-farm). Final report, Dryland Agricultural Research Institute (DARI), (in Persian).
Tavakkoli, A.R., and Oweis, T. 2004. The role

of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. Agric. Water Manag, 65:225-236.
Tavakoli, A.R. 2001. Optimal management of single irrigation on dryland wheat farming. Iranian J. Agri. Eng. Research, 2(7): 41–50. (in Persian).
Tavakoli, A.R. 2003. Effects of supplemental irrigation and nitrogen rates on yield and yield components of rainfed wheat. J. Crop and Seed, 19(3):367-381. (in Persian)
Tavakoli, A.R. 2004. An economic evaluation of supplemental irrigation at optimum rate of nitrogen on wheat in rainfed condition. J. Agric. Eng. Res., 5(20):86–97. (in Persian).
Tavakoli, A.R. 2005. Determining optimal single irrigation amount and planting date of five wheat varieties at rainfed condition. Final research Report, Dryland Agricultural Research Institute (DARI), Maragheh, Iran. (in Persian)
Tavakoli, A.R. 2007. Determining Optimal Planting Date and Single Irrigation Management for Barley Varieties at Rainfed Condition. Final Research Report, Dryland Agricultural Research Institute (DARI), Maragheh, Iran. (in Persian)
Tavakoli, A.R. Liaghat, A., Ashrafi Sh., and Abbasi, F. 2008. Chapter II – Supplemental Irrigation in Iran. In: Oweis, T. H., Farahani, M. Qadir, J. Anthofer, H. Siadat, F. Abbasi and A. Bruggeman (eds). Improving On-farm Agricultural Water Productivity in the Karkheh River Basin. Research Report no. 1: A Compendium of Review Papers. ICARDA, Aleppo, Syria. Iv+103 pp.
Tavakoli, A.R., and Oweis, T. 2006. Supplemental irrigation for improving water productivity of wheat production in northwest of Iran. Eighth International conference on Development of Dry Lands, Beijing, China, Feb 2006.
Tavakoli, A.R., Belson, V., Ferri. F., and Razavi, R. 2003. Response of rainfed wheat to supplemental irrigation and nitrogen rates. Final Research Report, Dryland Agricultural Research Institute (DARI), Maragheh, Iran. (in Persian)
Tavakoli, A.R., Belson, W., and Ferri, F. 2000. Impacts of supplemental irrigation on advanced lines of wheat. Final Research Report, Dryland Agricultural Research Institute (DARI), Maragheh, Iran. (in Persian)
Tavakoli, A.R., Oweis, T., Ferri, F., Haghighati, A., Belson, V., Pala, M., Siadat, H., and Ketata, H. 2005. Supplemental Irrigation in Iran: Increasing and stabilizing wheat yield in rainfed highlands. On-Farm Water Husbandry Research Report Series No.5. 46 pp, ICARDA.
Zhang, H., and Oweis T. 1999. Water – yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agricultural Water Management, 38: 195-211.
Zwart S.J., and Bastiaanssen, W.G.M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69 115–133.

Appendices

Appendix I

Farmers' names and Characteristics of the Farms Studied

Table I-1- 2005-06 Honam site, farmer's information.

Farmer (name)	Location (village)	Crop	Main Treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide	Planting time	Seed Rate (kg ha^{-1})	Rotation
M. Khosravi	Siyah Posh	Wheat	Traditional	2000	1400	Sardari	Karboxin Tiram	23/10/05	200	Chickpea
M. Khosravi	Siyah Posh	Wheat	Advanced	7000	6000	Azar2	Karboxin Tiram	23/10/05	160	Chickpea
P. Moradi	Char Takhteh	Wheat	Traditional	2500	1500	Sardari	Karboxin Tiram	12/10/05	200	Faba been
P. Moradi	Char Takhteh	Wheat	Advanced	2500	1500	Azar2	Karboxin Tiram	12/10/05	160	Faba been
M.A. Naderi	Char Takhteh	Wheat	Traditional	3000	2500	Sardari	Karboxin Tiram	21/10/05	180	Chickpea
M.A. Naderi	Char Takhteh	Wheat	Advanced	3000	2500	Azar2	Karboxin Tiram	21/10/05	160	Chickpea
A.M.SiyahPosh	Siyah Posh	Wheat	Advanced	4000	3500	Azar2	Karboxin Tiram	23/10/05	160	Chickpea
S.R. Belvasi	Norollahi	Wheat	Advanced	4500	4000	Azar2	Karboxin Tiram	12/10/05	160	Chickpea
P. Moradi	Char Takhteh	Barley	Traditional	3500	2000	Local	Karboxin Tiram	12/10/05	200	Chickpea
P. Moradi	Char Takhteh	Barley	Advanced	3500	2000	Sarood1	Karboxin Tiram	12/10/05	160	Chickpea
S. Moradi	Char Takhteh	Barley	Advanced	3000	1500	Sarood1	Karboxin Tiram	23/10/05	160	Chickpea
N.M. Nazari	Sarab Honam	Barley	Advanced	7000	3000	Sarood1	Karboxin Tiram	10/11/05	160	Chickpea
M.A. Naderi	Char Takhteh	Barley	Traditional	2000	1500	Local	Karboxin Tiram	22/10/05	180	Lentil
M.A. Naderi	Char Takhteh	Barley	Advanced	4500	3000	Sarood1	Karboxin Tiram	22/10/05	160	Lentil

Table continue

Farmer (name)	Land Preparation	Planting Machinery	Harvest	Weed control	Irrigation at planting	Irrigation at spring	Water Resource	Amount of SI	Fertilizer Formula
M. Khosravi	tillage - disk	hand - disk	21/07/06	2-4-D	23/10/05	16/05/06	River & pumping	50-75	$N_{60}P_{23}$
M. Khosravi	tillage - disk	hand - disk	21/07/06	2-4-D	23/10/05	16/05/06	River & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
P. Moradi	tillage - disk	hand - disk	21/07/06	2-4-D	14/10/05	14/05/06	Canal & pumping	50-75	$N_{60}P_{23}$
P. Moradi	tillage - disk	hand - disk	21/07/06	2-4-D	14/10/05	14/05/06	Canal & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
M.A. Naderi	tillage - disk	hand - disk	21/07/06	2-4-D	21/10/05	15/05/06	Canal & pumping	50-75	$N_{60}P_{23}$
M.A. Naderi	tillage - disk	hand - disk	21/07/06	2-4-D	21/10/05	15/05/06	Canal & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
A.M.SiyahPosh	tillage - disk	hand - disk	21/07/06	2-4-D		17/05/06	River & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
S.R. Belvasi	tillage - disk	hand - disk	21/07/06	2-4-D	14/10/05	09/05/06	Canal	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
P. Moradi	tillage - disk	hand - disk	11/07/06	2-4-D	14/10/05		Canal & pumping	50-75	$N_{60}P_{23}$
P. Moradi	tillage - disk	hand - disk	11/07/06	2-4-D	14/10/05		Canal & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
S. Moradi	tillage - disk	hand - disk	11/07/06	2-4-D		12/05/06	Canal & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
N.M. Nazari	tillage - disk	hand - disk	11/07/06	2-4-D	27/10/05		Well	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN
M.A. Naderi	tillage - disk	hand - disk	11/07/06	2-4-D	22/10/05	20/05/06	Canal & pumping	50-75	$N_{60}P_{23}$
M.A. Naderi	tillage - disk	hand - disk	11/07/06	2-4-D	22/10/05	20/05/06	Canal & pumping	50-75	$N_{60}P_{23}K_{25}$ + 1-2% ZN

Table I-2- 2006-07 Honam site, farmer's information.

Farmer (name)	Crop	Location (village)	Main treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide (25 gr)	Planting time	Seed rate (kg ha^{-1})	Rotation
G. Siyah Posh	wheat	Siyah Posh	Traditional	2500	1000	Sardari	Mankozeb	13/10/06	180	Chickpea
G. Siyah Posh	wheat	Siyah Posh	Advanced	2500	1000	Azar2	Mankozeb	13/10/06	160	Chickpea
R. Asadollahi	wheat	Yari Abad	Traditional	5000	3500	Sardari	Mankozeb	16/11/06	200	Chickpea
R. Asadollahi	wheat	Yari Abad	Advanced	6500	3500	Azar2	Mankozeb	16/11/06	160	Chickpea
M.H. Karamollahi	wheat	Siyah Posh	Traditional	5000	4000	Sardari	Mankozeb	12/10/06	200	Chickpea
M.H. Karamollahi	wheat	Siyah Posh	Advanced	6000	5000	Azar2	Mankozeb	12/10/06	160	Chickpea
A. Siyah Posh	wheat	Siyah Posh	Traditional	5000	3000	Sardari	Mankozeb	18/11/06	180	Chickpea
A. Siyah Posh	wheat	Siyah Posh	Advanced	7000	5000	Azar2	Mankozeb	18/11/06	160	Chickpea
M.R. Sabzevari	Barley	Yari Abad	Traditional	4500	1200	Local	Mankozeb	15/11/06	200	Chickpea
M.R. Sabzevari	barley	Yari Abad	Advanced	6000	4500	Sararood1	Mankozeb	15/11/06	160	Chickpea

Table continue

Farmer (name)	Preparation Land	Planting Machinery	Harvest	Weed control	Irrigation at planting	Irrigation at spring	water resource	Amount of SI	Fertilizer Formula
G. Siyah Posh	tillage - disk	hand-6 Plow*	11/07/07	2-4-D	14/10/06		canal & pumping	50-75	N60P23
G. Siyah Posh	tillage - disk	Row Planter	11/07/07	2-4-D	14/10/06		canal & pumping	50-75	N60P23K25 + 1-2% ZN
R. Asadollahi	tillage - disk	hand-6 Plow*	11/07/07	2-4-D	16/11/06	02/06/07	canal & pumping	50-75	N60P23
R. Asadollahi	tillage - disk	Row Planter	11/07/07	2-4-D	16/11/06	02/06/07	canal & pumping	50-75	N60P23K25 + 1-2% ZN
M.H. Karamollahi	tillage - disk	hand-6 Plow*	12/07/07	2-4-D	13/10/06	02/06/06	canal	50-75	N60P23
M.H. Karamollahi	tillage - disk	Row Planter	12/07/07	2-4-D	13/10/06	02/06/06	canal	50-75	N60P23K25 + 1-2% ZN
A. Siyah Posh	tillage - disk	hand-6 Plow*	12/07/07	2-4-D	18/11/06	01/06/07	canal & pumping	50-75	N60P23
A. Siyah Posh	tillage - disk	hand-6 Plow*	12/07/07	2-4-D	18/11/06	01/06/07	canal & pumping	50-75	N60P23K25 + 1-2% ZN
M.R. Sabzevari	tillage - disk	hand-6 Plow*	11/07/07	2-4-D	15/11/06		canal & pumping	50-75	N60P23
M.R. Sabzevari	tillage - disk	Row Planter	11/07/07	2-4-D	15/11/06		canal & pumping	50-75	N60P23K25 + 1-2% ZN

* Shesh Khish

Table I-3- 2007-08 Honam site, farmer's information.

Farmer (name)	Crop	Location (village)	Main treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide (25 gr)	Planting time	Seed rate (kg ha^{-1})	Rotation
M. Gholami	wheat	Siyah Posh	Traditional	2500	2000	Sardari	Mankozeb	9/10/07	200	Rapeseed
M. Gholami	wheat	Siyah Posh	Advanced	4000	3000	Azar2	Mankozeb	9/10/07	160	Rapeseed
M. Gholami	wheat	Siyah Posh	Advanced	5000	4000	Cross Alborz	Mankozeb	9/10/07	160	Rapeseed
A.M. Saremi zadeh	wheat	Peresk Sofla	Advanced	5000	4000	Azar2	Mankozeb	22/10/07	160	berseem
A.M. Saremi zadeh	wheat	Peresk Sofla	Advanced	5000	4000	Cross Alborz	Mankozeb	22/10/07	160	berseem
F. Sattar Vand	wheat	KhosroAbad	Advanced	2500	2000	Azar2	Mankozeb	22/10/07	160	Rapeseed
F. Sattar Vand	wheat	KhosroAbad	Advanced	2500	2000	Cross Alborz	Mankozeb	22/10/07	180	Rapeseed
K.Kh. Hasanvand	wheat	Ali Abad	Advanced	2000	1500	Azar2	Mankozeb	22/10/07	160	
K.Kh. Hasanvand	wheat	Ali Abad	Advanced	7000	5500	Cross Alborz	Mankozeb	22/10/07	200	
Y. Kheirollahi	barley	CharTakhteh	Advanced	8000	5500	Sararood1	Mankozeb	9/10/07	160	chickpea
Y. Kheirollahi	barley	CharTakhteh	Traditional	2000	1100	Local	Mankozeb	9/10/07	200	Chickpea
M.A. Naderi	barley	CharTakhteh	Advanced	1500	1000	Sararood1	Mankozeb	9/10/07	160	Chickpea
M.A. Naderi	barley	CharTakhteh	Traditional	1500	1000	Local	Mankozeb	9/10/07	200	Chickpea
H.A. Hosseini	barley	Sarab Honam	Advanced	10000	8500	Sararood1	Mankozeb	22/10/07	160	Lentil
H.A. Hosseini	barley	Sarab Honam	Traditional	600	450	Local	Mankozeb	22/10/07	200	Lentil
A. Kazemi	barley	Sarab Honam	Advanced	7000	5000	Sararood1	Mankozeb	29/10/07	180	

Table continue

Farmer (name)	Preparation Land	Planting Machinery	Harvest	Weed control	Irrigation at planting	Irrigation at spring	water resource	Amount of SI	Fertilizer Formula
M. Gholami	tillage - disk	hand-6 Plow*	3/07/08	2-4-D	11/10/07	4/05/08**	Conventional canal	50-75	N40P15
M. Gholami	tillage - disk	Row Planter	3/07/08	2-4-D	11/10/07	4/05/08**	Conventional canal	50-75	N60P30
M. Gholami	tillage - disk	Row Planter	3/07/08	2-4-D	11/10/07	4/05/08**	Conventional canal	50-75	N60P30
A.M. Saremi zadeh	tillage - disk	Row Planter	3/07/08	2-4-D	23/10/07	9/05/08***	Groundwater	50-75	N60P30
A.M. Saremi zadeh	tillage - disk	Row Planter	3/07/08	2-4-D	23/10/07	9/05/08***	Groundwater	50-75	N60P30
F. Sattar Vand	tillage - disk	Row Planter	3/07/08	2-4-D	23/10/07	7/05/08****	Groundwater	50-75	N60P30
F. Sattar Vand	tillage - disk	Row Planter	3/07/08	2-4-D	23/10/07	7/05/08****	Groundwater	50-75	N60P30
K.Kh. Hasanvand	tillage - disk	Row Planter	3/07/08	2-4-D	24/10/07	9/05/08*****	Canal	50-75	N60P30

K.Kh. Hasanvand	tillage - disk	Row Planter	3/07/08	2-4-D	24/10/07	9/05/08*****	Canal	50-75	N60P30
Y. Kheirollahi	tillage - disk	Row Planter	26/06/08	2-4-D	11/10/07	25/04/08	Canal & pumping	50-75	N60P30
Y. Kheirollahi	tillage - disk	hand-6 Plow*	26/06/08	2-4-D	11/10/07	25/04/08	Canal & pumping	50-75	N40P15
M.A. Naderi	tillage - disk	Row Planter	26/06/08	2-4-D	11/10/07	25/04/08	Canal & pumping	50-75	N60P30
M.A. Naderi	tillage - disk	hand-6 Plow*	26/06/08	2-4-D	11/10/07	25/04/08	Canal & pumping	50-75	N40P15
H.A. Hosseini	tillage - disk	Row Planter	26/06/08	2-4-D	25/10/07	13/04/08	Conventional canal	50-75	N60P30
H.A. Hosseini	tillage - disk	hand-6 Plow*	26/06/08	2-4-D	25/10/07	13/04/08	Conventional canal	50-75	N40P15
A. Kazemi	tillage - disk	hand-6 Plow*	26/06/08	2-4-D	30/10/07	13/04/08	Conventional canal	50-75	N60P30

* Shesh khish
** Uniform irrigation (50 mm) for all treatments, 20/04/08
*** Uniform irrigation (50 mm) for all treatments, 18/04/08 and 27/04/08
**** Uniform irrigation (50 mm) for all treatments, 20/04/08
***** Uniform irrigation (50 mm) for all treatments, 18/04/08 and 27/04/08

Table I-4- 2005-06 Merek site, farmer's information.

Farmer (name)	Location (village)	Crop	Main Treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide	Planting time	Seed Rate (kg ha^{-1})	Rotation
M. Azizi	Bagh-e-Karam bak	Wheat	Traditional	4000	400	Sardari	Karboxin Tiram	21/10/05	180	chickpea
M. Azizi	Bagh-e-Karam bak	Wheat	Advanced	4000	700	Azar2	Karboxin Tiram	21/10/05	160	chickpea
H.R. Lotfi	Koreh Khosravi	Wheat	Traditional	6500	2500	Sardari	Karboxin Tiram	06/11/05	180	chickpea
H.R. Lotfi	Koreh Khosravi	Wheat	Advanced	5800	4200	Azar2	Karboxin Tiram	06/11/05	160	chickpea
A.S. Mohamadi	Sekh-kher Olya	Wheat	Advanced	2000	1000	Azar2	Karboxin Tiram	11/11/05	160	chickpea
H. Karami	Kargan	Wheat	Traditional	8000	5000	Sardari	Karboxin Tiram	10/10/05	180	Fallow
H. Karami	Kargan	Wheat	Advanced	1500	500	Azar2	Karboxin Tiram	10/10/05	160	Fallow
H. Karami	Kargan	Barley	Advanced	3000	1600	Sararood1	Karboxin Tiram	10/10/05	160	chickpea
E. Mohammadi	Poshteh Rizeh	Barley	Advanced	4500	660	Sararood1	Karboxin Tiram	06/10/05	160	chickpea

Table continue

Farmer (name)	Land Preparation	Planting Machinery	Harvest	Weed control	Irrigation at planting	Irrigation at spring	Water Resource	Amount of SI	Fertilizer Formula
M. Azizi	tillage - disk	hand - disk	28/07/06	2-4-D		14/05/06	Groundwater	50-75	N60P23
M. Azizi	tillage - disk	hand - disk	28/07/06	2-4-D		14/05/06	Groundwater	50-75	N60P23K25 + 1-2% ZN
H.R. Lotfi	tillage - disk	hand - disk	28/07/06	2-4-D	08/11/05	16/05/06	Groundwater & qanuat	50-75	N60P23
H.R. Lotfi	tillage - disk	hand - disk	28/07/06	2-4-D	08/11/05	16/05/06	Groundwater & qanuat	50-75	N60P23K25 + 1-2% ZN
A.S. Mohamadi	tillage - disk	hand - disk	28/07/06	2-4-D		05/05/06	Groundwater	50-75	N60P23K25 + 1-2% ZN
H. Karami	tillage - disk	hand - disk	28/07/06	2-4-D		09/05/06	Groundwater	50-75	N60P23
H. Karami	tillage - disk	hand - disk	28/07/06	2-4-D		09/05/06	Groundwater	50-75	N60P23K25 + 1-2% ZN
H. Karami	tillage - disk	hand - disk	20/07/06	2-4-D		10/05/06	Groundwater	50-75	N60P23K25 + 1-2% ZN
E. Mohammadi	tillage - disk	hand - disk	20/07/06	2-4-D		05/05/06	Spring & qanuat	50-75	N60P23K25 + 1-2% ZN

Table I-5- 2006-07 Merek site, farmer's information.

Farmer (name)	Location (village)	Crop	Main Treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide (2/1000)	Planting time	Seed rate (kg ha^{-1})	Rotation
H.R. Lotfi	Koreh Khosravi	Wheat	Traditional	1500	1000	Sardari	Karboxin Tiram	06/11/06	180	Vegetables
H.R. Lotfi	Koreh Khosravi	Wheat	Advanced	1500	1000	Azar2	Karboxin Tiram	06/11/06	160	Vegetables
H.M. Mousavi	Pache-gha	Wheat	Traditional	1500	1000	Sardari	Karboxin Tiram	11/11/06	180	Chickpea
H.M. Mousavi	Pache-gha	Wheat	Advanced	1500	1000	Azar2	Karboxin Tiram	11/11/06	160	Chickpea
S.M. Hoseini	Najaf Abad	Wheat	Advanced	30000	10000	Azar2	Karboxin Tiram	20/10/06	170	Chickpea
S.M. Hoseini	Sar-ve-No	Wheat	Advanced	2500	2000	Azar2	Karboxin Tiram	22/10/06	160	Chickpea
H.R. Lotfi	Koreh Khosravi	Barley	Traditional	1500	1000	Local	Karboxin Tiram	10/11/06	180	Vegetables
H.R. Lotfi	Koreh Khosravi	Barley	Advanced	1500	1000	Sararood 1	Karboxin Tiram	10/11/06	160	Vegetables
H.M. Mousavi	Pache-gha	Barley	Traditional	1500	1000	Local	Karboxin Tiram	11/11/06	180	Chickpea
H.M. Mousavi	Pache-gha	Barley	Advanced	1500	1000	Sararood 1	Karboxin Tiram	11/11/06	150	Chickpea
S.M. Hoseini	Najaf Abad	Barley	Advanced	7000	6000	Sararood 1	Karboxin Tiram	21/10/06	160	Chickpea
H. Mahmoodi	Sar-ve-No	Barley	Advanced	4000	2000	Sararood 1	Karboxin Tiram	21/10/06	160	Chickpea

Table continue

Farmer (name)	Land Preparation	Planting Machinery	Harvest	Weed Control	Irrigation at planting	Irrigation at spring	Water Resource	Amount of SI	Fertilizer Formula
H.R. Lotfi	tillage - disk	hand - disk	01/08/07	2-4-D	08/11/06	15/05/07	Groundwater & qanuat	50-75	N60P23
H.R. Lotfi	tillage - disk	Row Planter	01/08/07	2-4-D	08/11/06	15/05/07	Groundwater & qanuat	50-75	N60P23K25 + 1-2% ZN
H.M. Mousavi	tillage - disk	hand - disk	02/08/07	2-4-D	11/11/06	16/05/07	Groundwater	50-75	N60P23
H.M. Mousavi	tillage - disk	Row Planter	02/08/07	2-4-D	11/11/06	16/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
S.M. Hoseini	tillage - disk	Row Planter	02/08/07	2-4-D	20/10/06	12/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
S.M. Hoseini	tillage - disk	Row Planter	01/08/07	2-4-D	24/10/06	19/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
H.R. Lotfi	tillage - disk	hand - disk	21/07/07	2-4-D	11/11/06	15/05/07	Groundwater & qanuat	50-75	N60P23
H.R. Lotfi	tillage - disk	Row Planter	21/07/07	2-4-D	11/11/06	15/05/07	Groundwater & qanuat	50-75	N60P23K25 + 1-2% ZN
H.M. Mousavi	tillage - disk	hand - disk	21/07/07	2-4-D	11/11/06	16/05/07	Groundwater	50-75	N60P23
H.M. Mousavi	tillage - disk	Row Planter	21/07/07	2-4-D	11/11/06	16/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
S.M. Hoseini	tillage - disk	Row Planter	21/07/07	2-4-D	21/10/06	13/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
H. Mahmoodi	tillage - disk	Row Planter	21/07/07	2-4-D	25/10/06	16/05/07	Groundwater	50-75	N60P23K25 + 1-2% ZN

Table I-6- 2007-08 Merek site, farmer's information.

Farmer (name)	Crop	Location (village)	Main treatment	Field size (m^2)	SI size (m^2)	Variety	Pesticide (25 gr)	Planting time	Seed rate (kg ha^{-1})	Rotation
Karimi	wheat	Sar-ve-No	Advanced	10000	7500	Cross Alborz	Mankozeb	10/10/07	160	Chickpea
Karimi	wheat	Sar-ve-No	Advanced	10000	7500	Azar2	Mankozeb	10/10/07	160	Chickpea
Karimi	barley	Sar-ve-No	Traditional	10000	7500	Local	Mankozeb	10/10/07	200	Chickpea
Karimi	barley	Sar-ve-No	Advanced	10000	7500	Sararood1	Mankozeb	22/10/07	160	Chickpea
S.M. Hosseini	wheat	Najaf Abad	Advanced	10000	7500	Cross Alborz	Mankozeb	22/10/07	160	Chickpea
S.M. Hosseini	wheat	Najaf Abad	Advanced	10000	7500	Azar2	Mankozeb	22/10/07	160	Chickpea
S.M. Hosseini	barley	Najaf Abad	Traditional	10000	7500	Local	Mankozeb	22/10/07	200	Chickpea
S.M. Hosseini	barley	Najaf Abad	Advanced	10000	7500	Sararood1	Mankozeb	22/10/07	160	Chickpea
S.S.B. Hosseini	barley	Najaf Abad	Traditional	5000	3500	Local	Mankozeb	22/10/07	200	Chickpea
S.S.B. Hosseini	barley	Najaf Abad	Advanced	5000	3500	Sararood1	Mankozeb	9/10/07	160	Chickpea
S.Sh. Hosseini	wheat	Najaf Abad	Advanced	7500	5500	Cross Alborz	Mankozeb	9/10/07	160	Chickpea
S.Sh. Hosseini	wheat	Najaf Abad	Advanced	7500	5500	Azar2	Mankozeb	9/10/07	160	Chickpea
A. Sharafi	wheat	Bagh-Tifon	Advanced	6000	4500	Cross Alborz	Mankozeb	9/10/07	160	Chickpea
A. Sharafi	wheat	Bagh-Tifon	Advanced	6000	4500	Azar2	Mankozeb	23/10/07	160	Chickpea
B. Abdoli	barley	Halashi	Traditional	5000	3500	Local	Mankozeb	23/10/07	200	Chickpea
B. Abdoli	barley	Halashi	Advanced	7500	5500	Sararood1	Mankozeb	29/10/07	160	Chickpea

Table continue

Farmer (name)	Preparation Land	Planting Machinery	Harvest	Weed control	Irrigation at planting	Irrigation at spring	water resource	Amount of SI	Fertilizer Formula
Karimi	tillage - disk	Row Planter	11/07/07	2-4-D	14/10/06		Conventional canal	50-75	N60P23
Karimi	tillage - disk	Row Planter	11/07/07	2-4-D	14/10/06		Conventional canal	50-75	N60P30K25 + 1-2% ZN
Karimi	tillage - disk	Row Planter	11/07/07	2-4-D	16/11/06	02/06/07	Conventional canal	50-75	N60P30K25 + 1-2% ZN
Karimi	tillage - disk	hand	11/07/07	2-4-D	16/11/06	02/06/07	Groundwater	50-75	N60P30K25 + 1-2% ZN
S.M. Hosseini	tillage - disk	Row Planter	12/07/07	2-4-D	13/10/06	02/06/06	Groundwater	50-75	N60P30K25 + 1-2% ZN
S.M. Hosseini	tillage - disk	Row Planter	12/07/07	2-4-D	13/10/06	02/06/06	Groundwater	50-75	N60P23K25 + 1-2% ZN
S.M. Hosseini	tillage - disk	Row Planter	12/07/07	2-4-D	18/11/06	01/06/07	Groundwater	50-75	N60P23K25 + 1-2% ZN
S.M. Hosseini	tillage - disk	hand	12/07/07	2-4-D	18/11/06	01/06/07	canal	50-75	N60P23K25 + 1-2% ZN
S.S.B. Hosseini	tillage - disk	Row Planter	11/07/07	2-4-D	15/11/06		canal	50-75	N60P23K25 + 1-2% ZN

S.S.B. Hosseini	tillage - disk	hand	11/07/07	2-4-D	15/11/06	canal & pumping	50-75	N60P23K25 + 1-2% ZN
S.Sh. Hosseini	tillage - disk	Row Planter	11/07/07	2-4-D	14/10/06	canal & pumping	50-75	N60P23
S.Sh. Hosseini	tillage - disk	Row Planter	11/07/07	2-4-D	15/11/06	canal & pumping	50-75	N60P23K25 + 1-2% ZN
Sharafi	tillage - disk	Row Planter	11/07/07	2-4-D	14/10/06	canal & pumping	50-75	N60P23
Sharafi	tillage - disk	Row Planter	11/07/07	2-4-D	15/11/06	Conventional canal	50-75	N60P23K25 + 1-2% ZN
B. Abdoli	tillage - disk	hand	11/07/07	2-4-D	14/10/06	Conventional canal	50-75	N60P23
B. Abdoli	tillage - disk	Row Planter	11/07/07	2-4-D	15/11/06	Conventional canal	50-75	N60P23K25 + 1-2% ZN

Appendix II

Tables of Soil Characteristics

Table I I-1- Summary of physical and chemical properties of the soil at two sites, SI field experiments, 2005/2007.

Site	Soil depth	Sand	Clay	Silt	W.P (-33)	F.C (-1500)	bulk density	Available water	Saturation hyd. cond.	Saturation
	cm	%	%	%	m^3/m^3	m^3/m^3	gr/cm^3	m^3/m^3	m/day	m^3/m^3
Honam	0-20	22.5	18.75	58.75	0.118	0.289	1.383	0.171	0.297	0.478
Honam	0-100	22.5	24	53.5	0.138	0.304	1.347	0.166	0.181	0.492
Merek	0-20	21.4	20.25	58.35	0.123	0.294	1.37	0.171	0.26	0.483
Merek	0-100	17.5	27.3	55.2	0.153	0.323	1.318	0.17	0.173	0.502

Table I I-2- physical and chemical properties of the soil at irrigated field experiments

	Depth	pH	EC	T.N.V	O.C	Anion (meq/lit)				Cation (meq/lit)			Clay	Silt	Sand	Soil Texture	S.P
	cm		dS/m	%	%	HCO_3^{-2}	CL^{-1}	SO_4^{-2}	SUM	$Ca^{+2} + MG^{+2}$	Na^{+}	SUM	%	%	%		%
Kolivand	0-100	8.0	0.3	35.1	0.5	2.4	2.0	1.7	6.1	3.6	3.0	6.6	23.5	52.2	24.4	SCL	43.5
Yousofvand	0-100	7.8	0.7	18.3	0.9	3.8	3.6	2.1	9.6	5.2	4.4	9.6	32.0	44.9	23.2	SCL	55.2
Lotfi	0-100	7.6	0.6	42.9	0.7	4.5	2.5	2.1	9.1	5.5	3.2	8.7	20.7	57.1	22.5	SL	59.3

Appendix III

Tables of Wheat Agronomic Results

Table III-1- Average field agronomic results, 2005-08, Merek site, and wheat on-farm experiments.

Wheat, Azar2 (Advanced management) - 2005-07 Merek						
Wheat, Azar2	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	2284	6168	6157	0.32	-	0.43
SI planting	2693	7343	7199	0.32	0.55	0.45
SI spring	3052	9506	9881	0.29	1.85	0.53
SI planting +spring	3074	5131	8205	0.38	1.07	0.63
Wheat, Cross Alborz (Advanced management) - 2007-08 Merek						
Wheat, Cross Alborz	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	613	1201	1814	0.37	-	0.37
SI spring	1991	4044	6035	0.34	1.3	0.74
SI planting +spring	2548	4572	7119	0.34	1.09	0.75
Wheat, Sardari (Traditional management) - 2005-07 Merek						
Wheat, Sardari	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	1931	6249	6196	0.27		0.37
SI planting	2165	7250	7232	0.27	0.21	0.36
SI spring	2635	9311	9268	0.26	1.26	0.46
SI planting +spring	2695	5437	8132	0.33	0.53	0.40

Table III-2- Average field agronomic results, 2005-08, Honam site, and wheat on-farm experiments.

Wheat, Azar2 (Advanced management) - 2005-08 Honam						
Wheat, Azar2	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	2289	4754	7023	0.32		0.45
SI planting	3439	6040	9376	0.36	2.15	0.57
SI spring	3413	5821	9180	0.37	3.26	0.63
SI planting +spring	4203	5599	9802	0.43	2.09	0.72
Wheat, Cross Alborz (Advanced management) - 2007-08 Honam						
Wheat, Cross Alborz	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	1799	4274	6073	0.30	0.00	0.49
SI planting	2727	4903	7630	0.36	2.24	0.61
SI spring	3405	5272	8677	0.39	4.71	0.82
SI planting +spring	4000	5600	9600	0.42	2.36	0.81
Wheat, Sardari (Traditional management) - 2005-08 Honam						
Wheat, Sardari	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	1726	5251	6977	0.25		0.35
SI planting	2126	5620	7745	0.28	0.53	0.38
SI spring	2132	5569	7707	0.28	0.82	0.41
SI planting +spring	2073	3960	6033	0.35	0.82	0.44

Appendix IV

Tables of Barley Agronomic Results

Table IV-1- Average field agronomic results, 2005-08, Merek site, and barley on-farm experiments.

	Barley, Sararood1 (Advanced management) - 2005-08 Merek					
Barley, Sararood1	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	2157	4286	6108	0.37		0.49
SI planting	3142	5912	9054	0.35	1.30	0.54
SI spring	3510	6200	7897	0.41	2.45	0.71
SI planting + spring	3124	5890	6917	0.41	1.49	0.68
	Barley, Local (Traditional management) - 2005-08 Merek					
Barley, Local	**Yield (kg ha^{-1})**			**Harvest index**	**IWP**	**RWP/TWP**
	Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Rainfed	1245	4052.5	4841	0.32		0.34
SI planting	2125	5662	7787	0.27	0.12	0.34
SI spring	2368.5	5490	5533	0.39	0.83	0.53
SI planting + spring	2135	4837	5234	0.38	0.73	0.50

Table IV-2- Average field agronomic results, 2005-08, Honam site, and barley on-farm experiments.

		Yield (kg ha^{-1})			**Harvest index**	**IWP**	**RWP/TWP**
		Grain	Straw	Biomass	%	kg m^{-3}	kg m^{-3}
Traditional	rainfed	1381	4502	5883	0.24		0.30
Traditional	SI planting	1939	4713	6652	0.28	0.74	0.36
Traditional	SI spring	2143	4254	6397	0.33	1.63	0.46
Advanced	rainfed	2068	4333	6400	0.32		0.43
Advanced	SI planting	3048	5094	8141	0.37	2.22	0.56
Advanced	SI spring	3137	4638	7774	0.41	3.62	0.70

Appendix V

Information on Irrigated Fields Studied

Table IV-1- Average field agronomic results, 2005-08, Merek site, and barley on-farm experiments.

Farmer (name)	Location (village)	Crop	Irrigation method	Field size (m^2)	Experimental size (m^2)	Variety	Pesticide	Planting time	Seed Rate (kg ha^{-1})	Rotation
A. Kolivand	Kahriz	Wheat	Sprinkler	60000	2500	Pishtaz	Karboxin Tiram	22/10/06	200	Bean
Sh. Yousofvand	Dehrahm	Wheat	Surface	10000	2000	Shiraz	Karboxin Tiram	28/10/06	220	Bean

Table continue

Farmer (name)	Land Preparation	Planting Machinery	Harvest	Weed control	Irrigation water saving strategy	Water Resource	Fertilizer Formula
A. Kolivand	tillage - disk	Row planter	21/07/07	2-4-D	Decreasing water use	groundwater	$N_{90}P_{43}K_{15}$ + 1-2% ZN
Sh. Yousofvand	tillage - disk	hand - disk	21/07/06	2-4-D	Cut one or two irrigation	River	$N_{90}P_{43}K_{15}$ + 1-2% ZN

Table IV-2- Average field agronomic results, 2005-08, Honam site, and barley on-farm experiments.

Farmer (name)	Location (village)	Crop	Irrigation method	Field size (m^2)	Experimental size (m^2)	Variety	Pesticide	Planting time	Seed Rate (kg ha^{-1})	Rotation
H.R. Lotfi	Koreh Khosravi	Wheat	Surface	30000	700	Marv-Dasht	Karboxin Tiram	23/10/06	250	Chickpea
A. Rahmani	Nou-job	Wheat	Surface	5000	2000	Shiraz	Karboxin Tiram	30/10/06	250	Chickpea

Table continue

Farmer (name)	Land Preparation	Planting Machinery	Harvest	Weed control	Irrigation water saving strategy	Water Resource	Fertilizer Formula
H.R. Lotfi	tillage - disk	Row planter	21/07/07	2-4-D	Cut one or two irrigation	groundwater and qanuat	$N_{90}P_{43}K_{15}$ + 1-2% ZN
A. Rahmani	tillage - disk	hand - disk	21/07/07	2-4-D	Cut one or two irrigation	groundwater	$N_{90}P_{43}K_{15}$ + 1-2% ZN

Appendix VI

Graphs of Meteorological Data

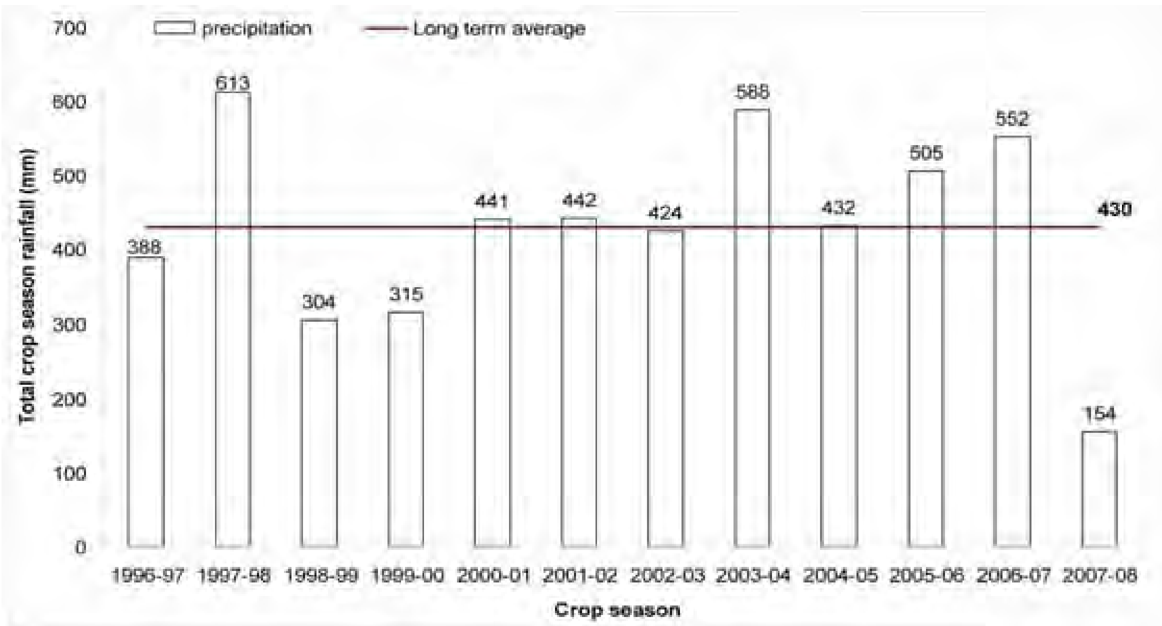

Fig. VI-1- Mean crop season rainfall for Merek site, 1996-2008.

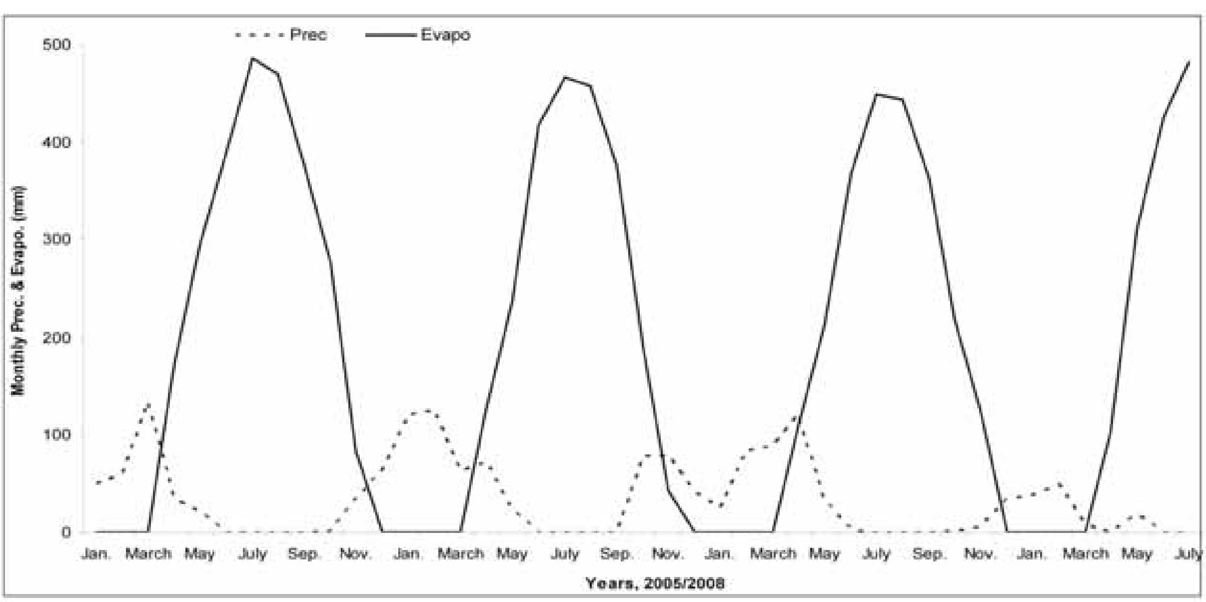

Fig. VI -2- Mean monthly rainfall and evaporation at Merek site 2005/2008.

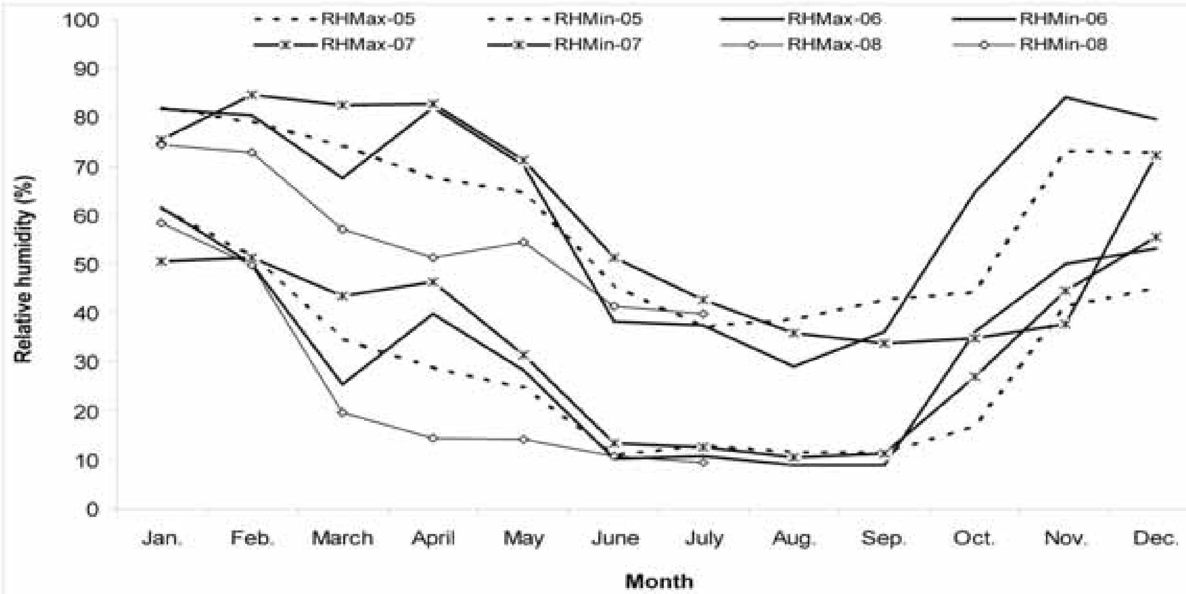

Fig. VI -3- Mean monthly relative humidity (RH), Merek site, 2005/08.

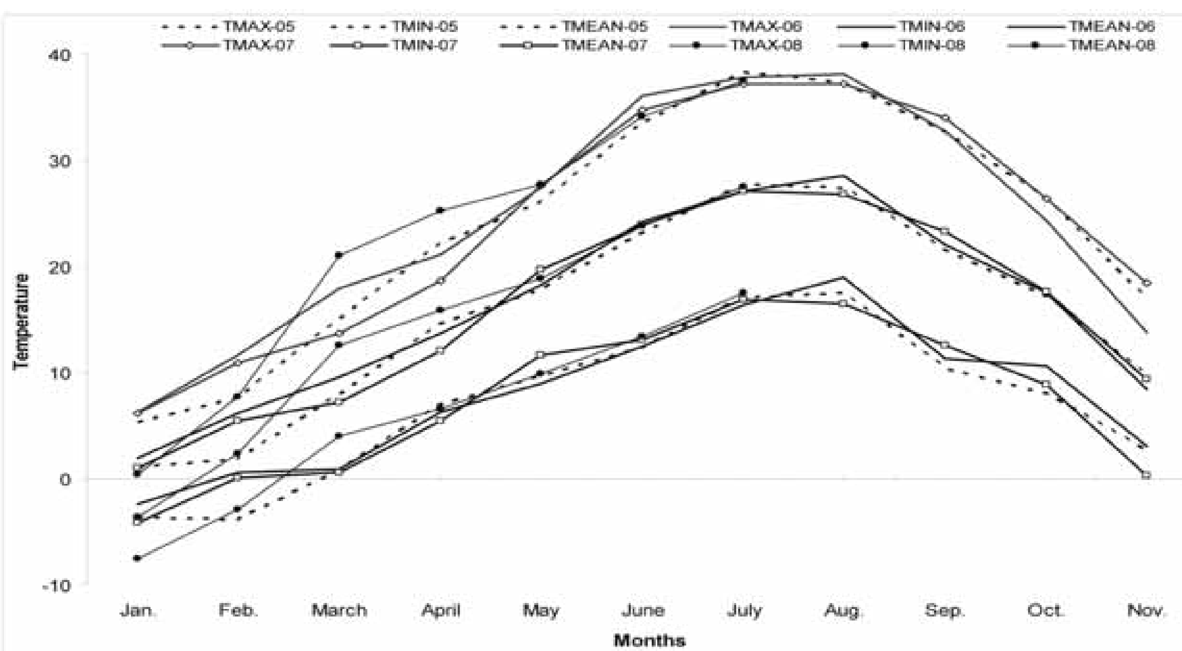

Fig. VI -4- Maximum, minimum and mean monthly air temperatures, Merek site, 2005/08.

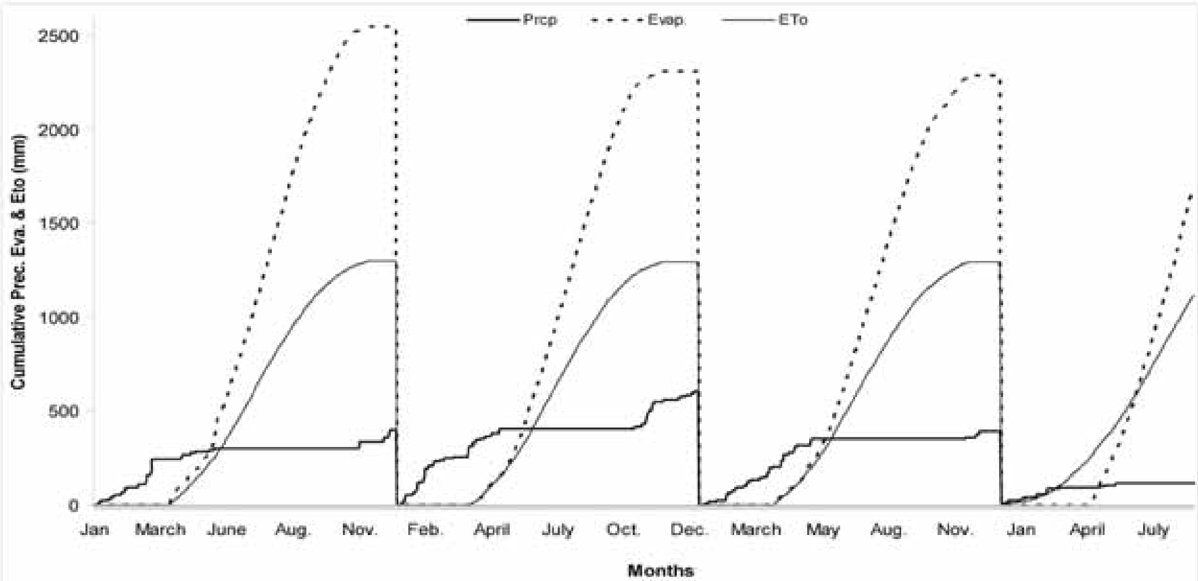

Fig. VI -5- Cumulative precipitation, evaporation and potential evapotranspiration, Merek site, 2005/08.

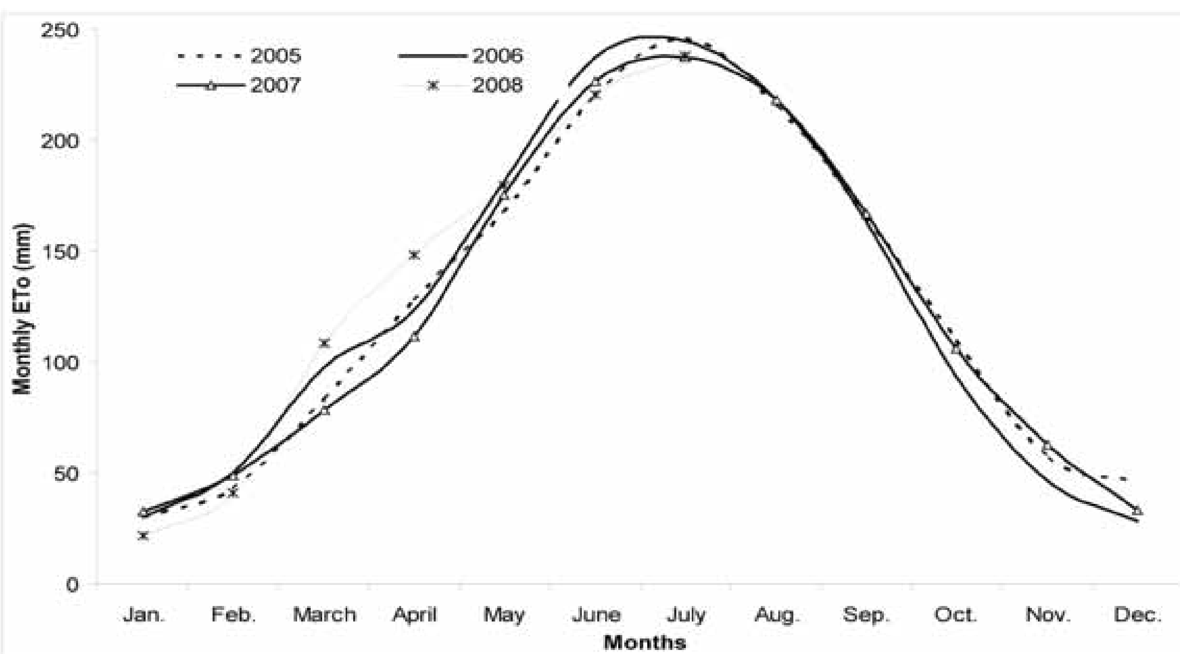

Fig. VI -6- Monthly potential evapotranspiration (ETo), Merek site, 2005/08.

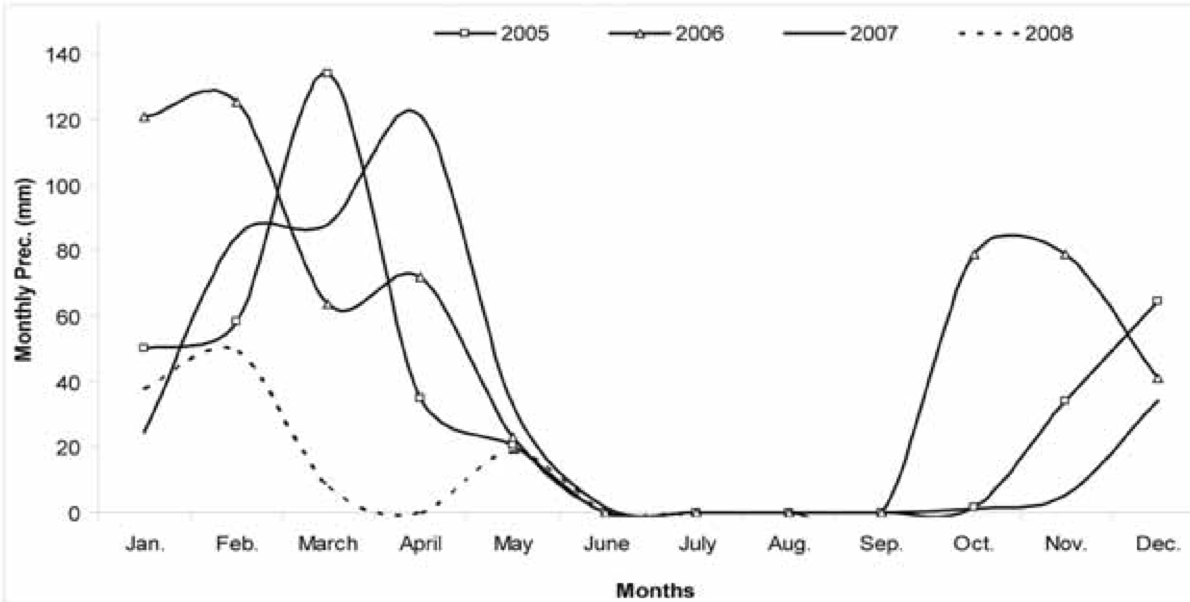

Fig. VI -7- Monthly precipitation distribution, Merek site, 2005/08.

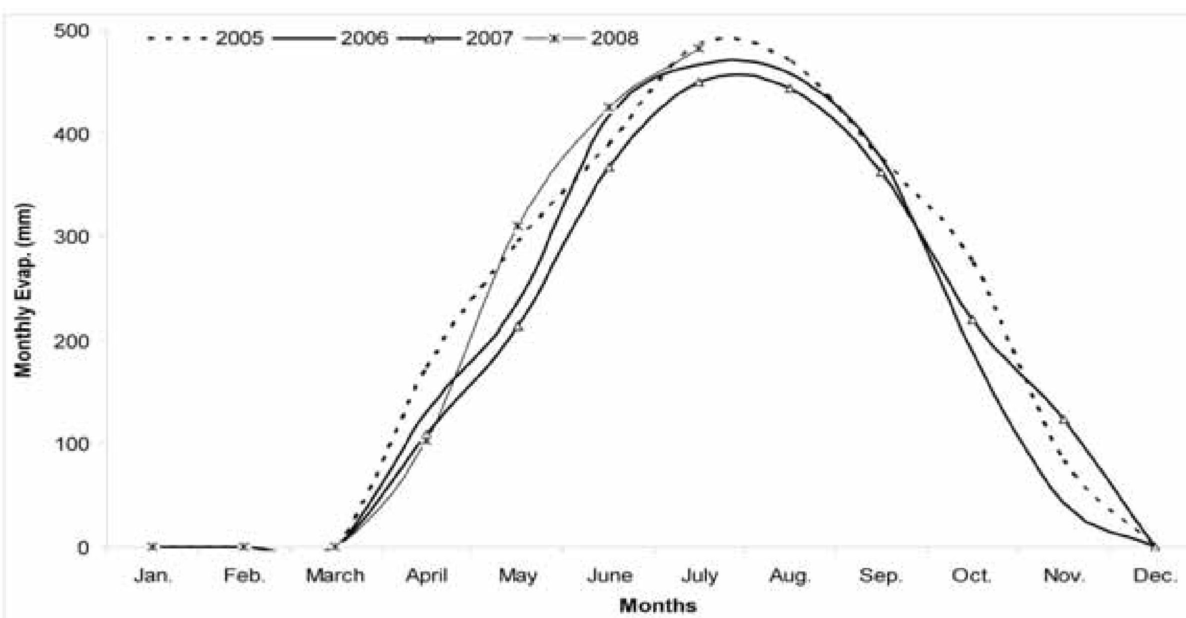

Fig. VI -8- Monthly pan evaporation pattern, Merek site, 2005/08.

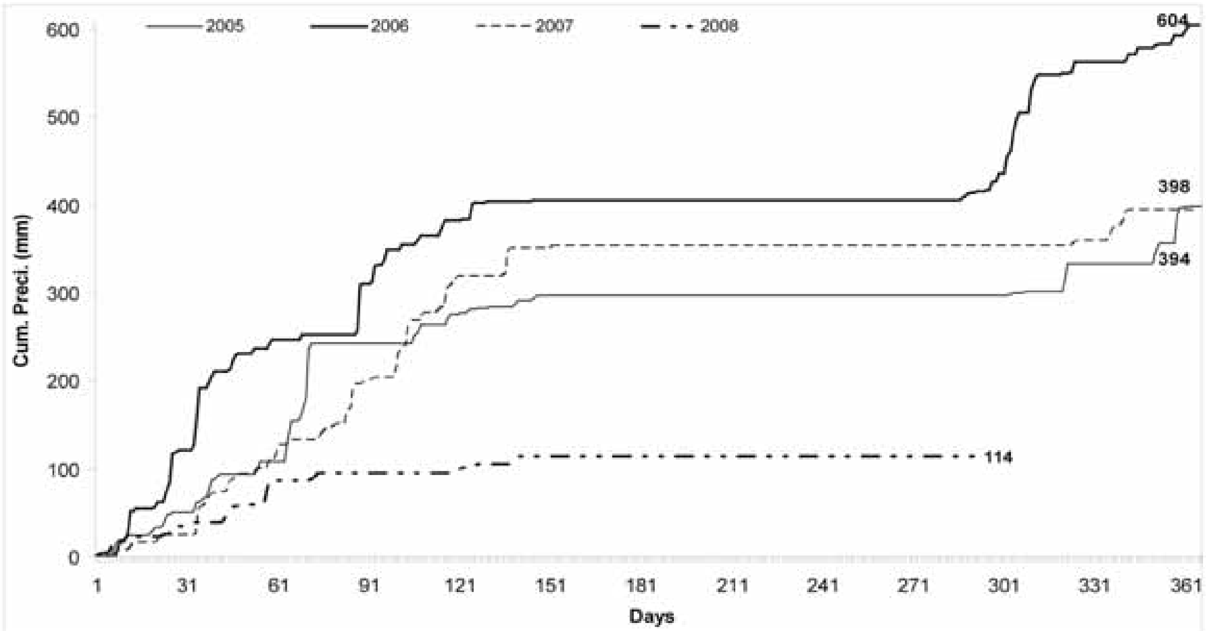

Fig. VI -9- Cumulative precipitation, Merek site, 2005/08.

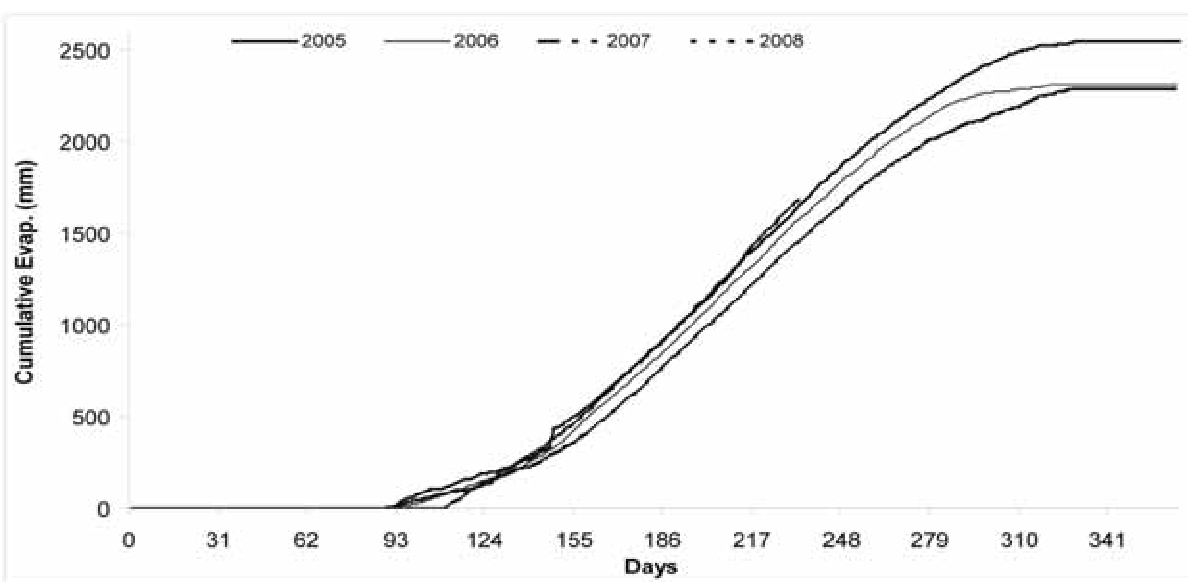

Fig. VI -10- Cumulative pan evaporation, Merek site, 2005/08.

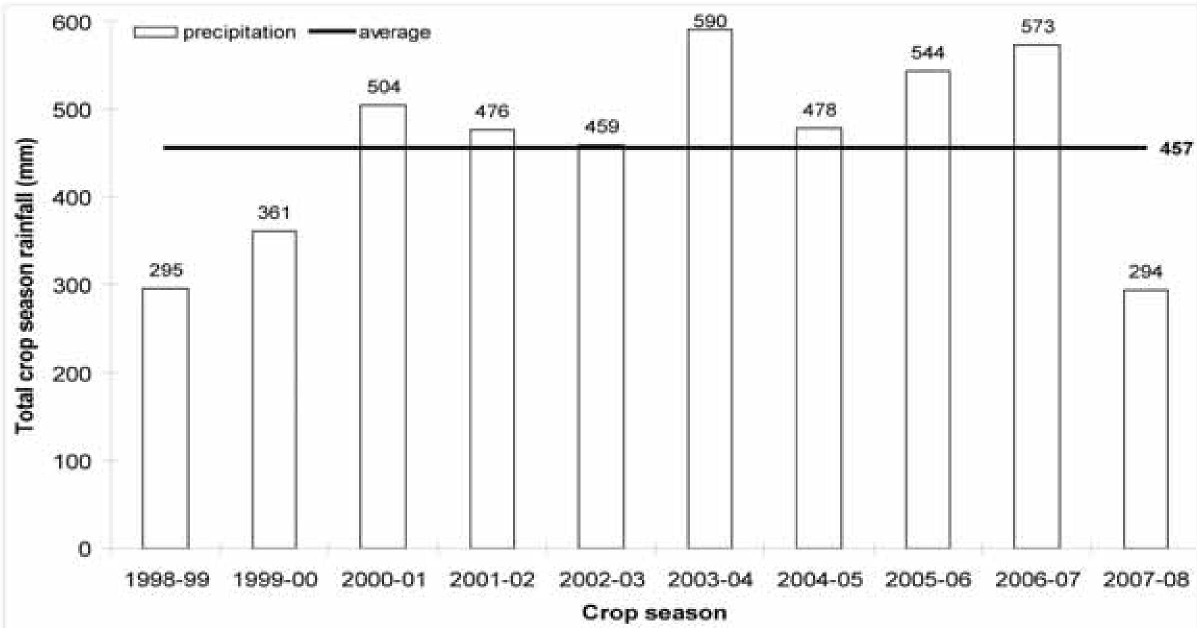

Fig. VI -11- Mean crop season rainfall for Honam site.

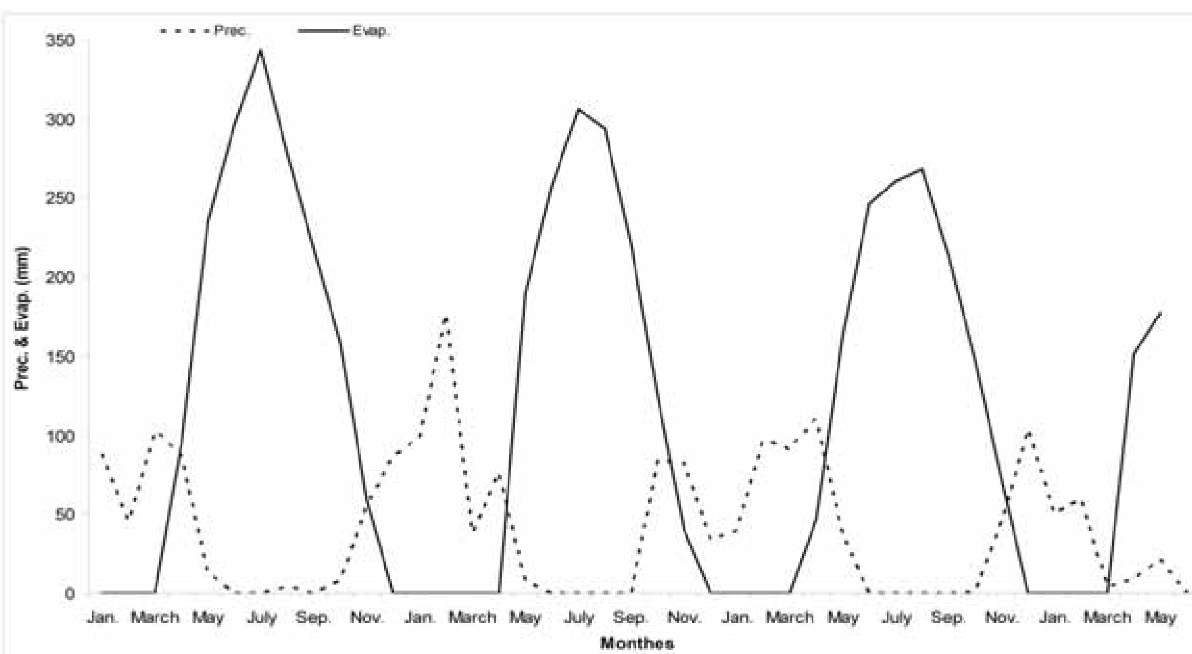

Fig. VI -12- Mean monthly rainfall and evaporation, Honam.

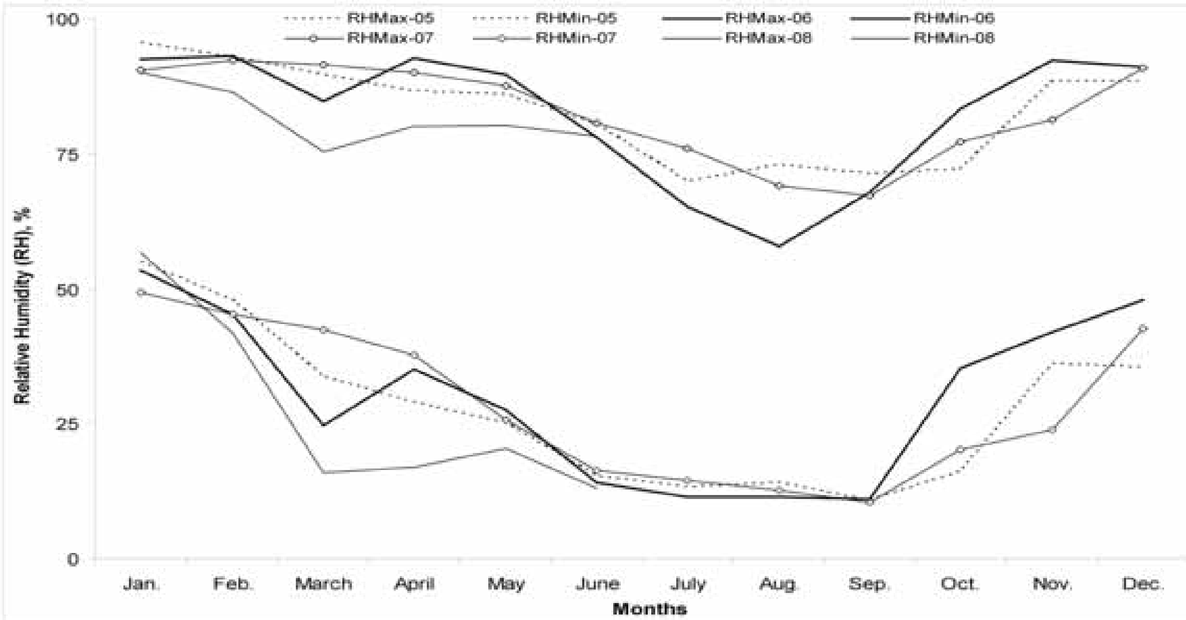

Fig. VI -13- Mean monthly relative humidity (RH), Honam, 2005/08.

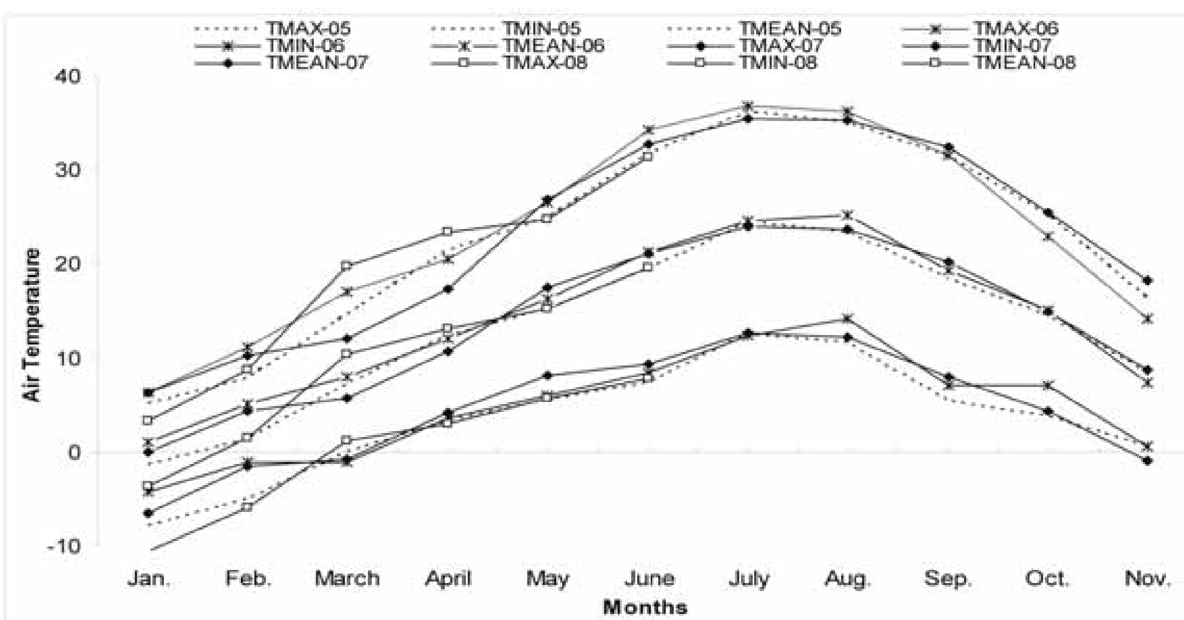

Fig. VI -14- Maximum, minimum and mean monthly air temperatures, Honam site, 2005/08.

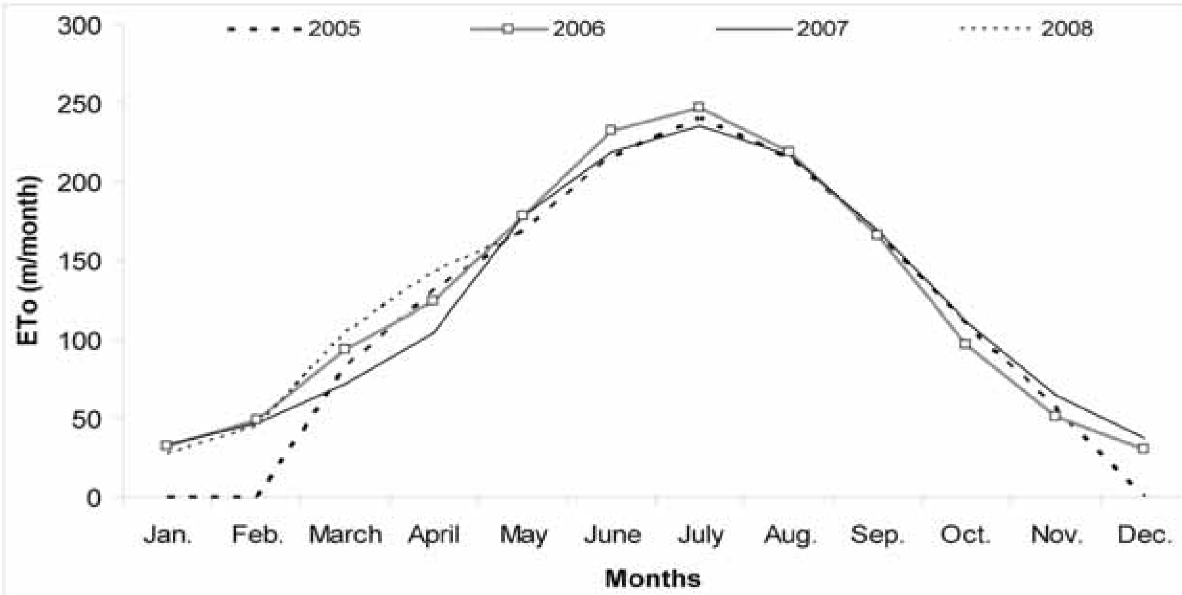

Fig. VI -15- Monthly potential evapotranspiration (ETo), Honam 2005/08.

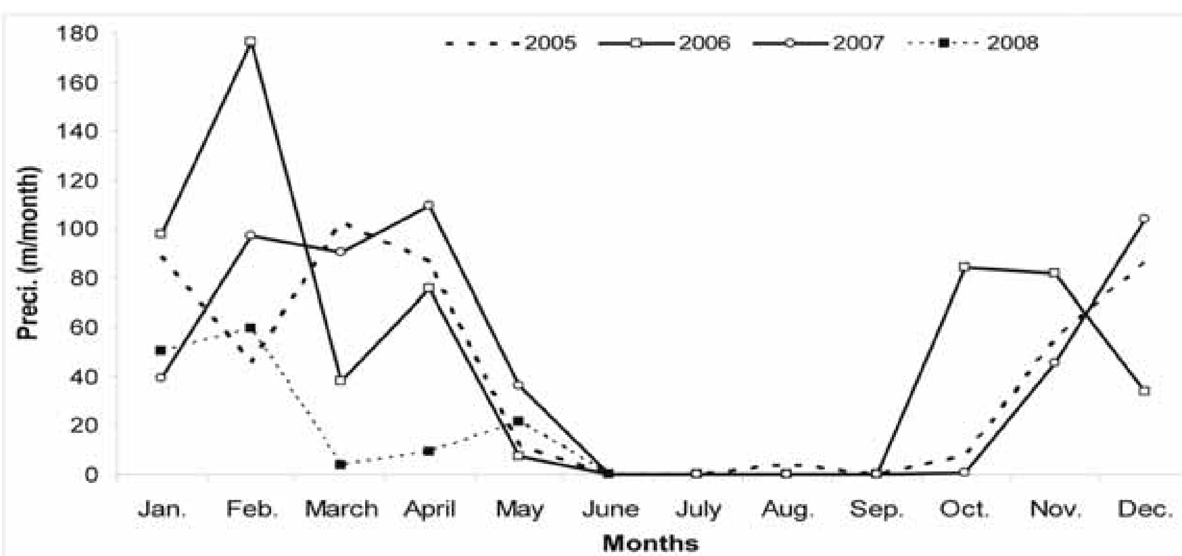

Fig. VI -16- Monthly precipitation, Honam 2005/08.

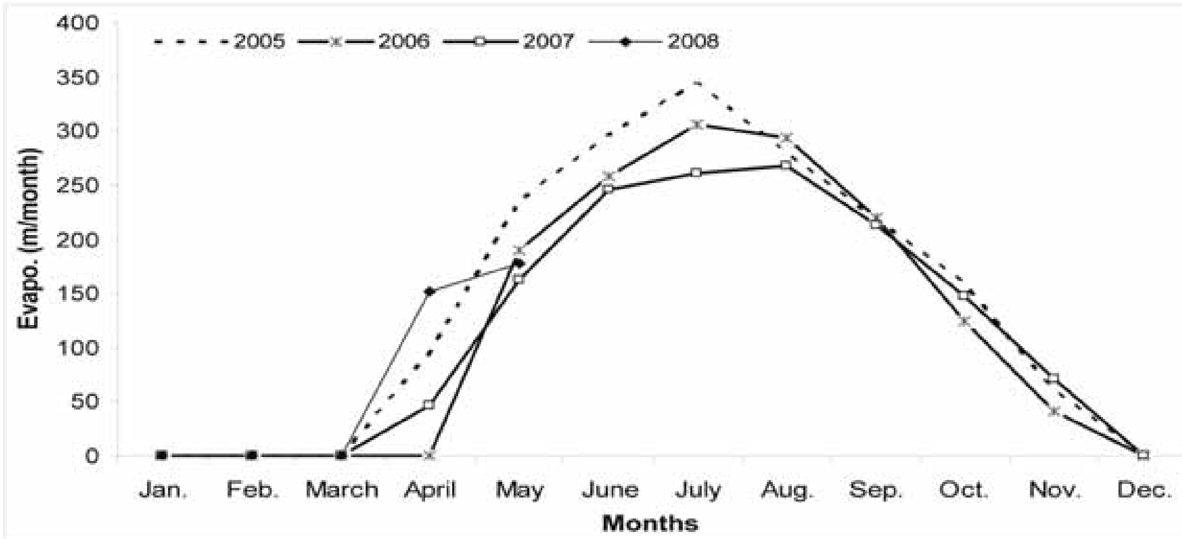

Fig. VI -17- Monthly pan evaporation, Honam 2005/08.

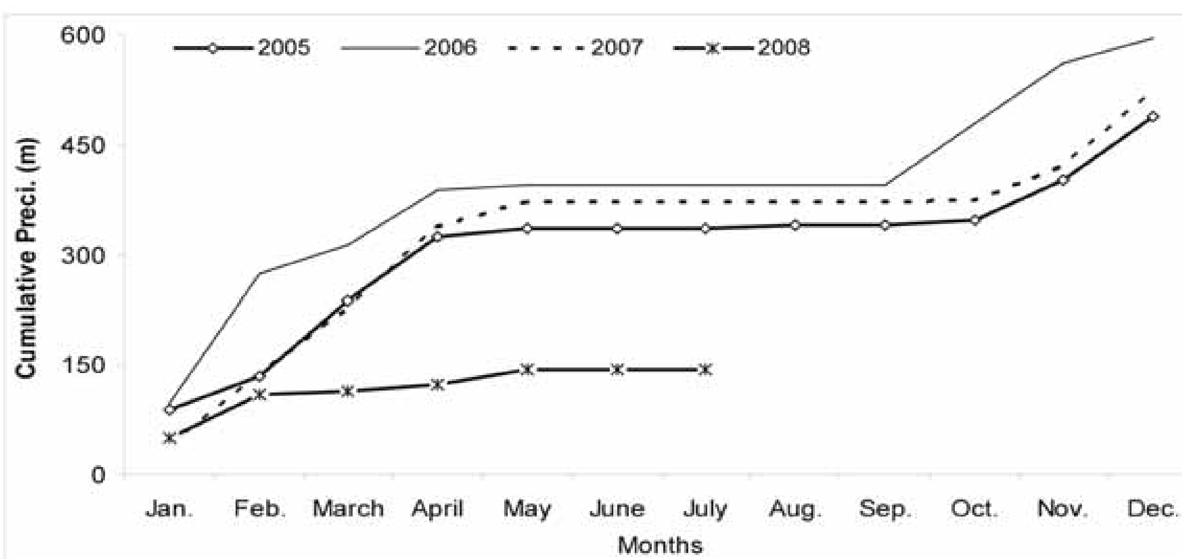

Fig. VI -18- Cumulative precipitation, Honam 2005/08.

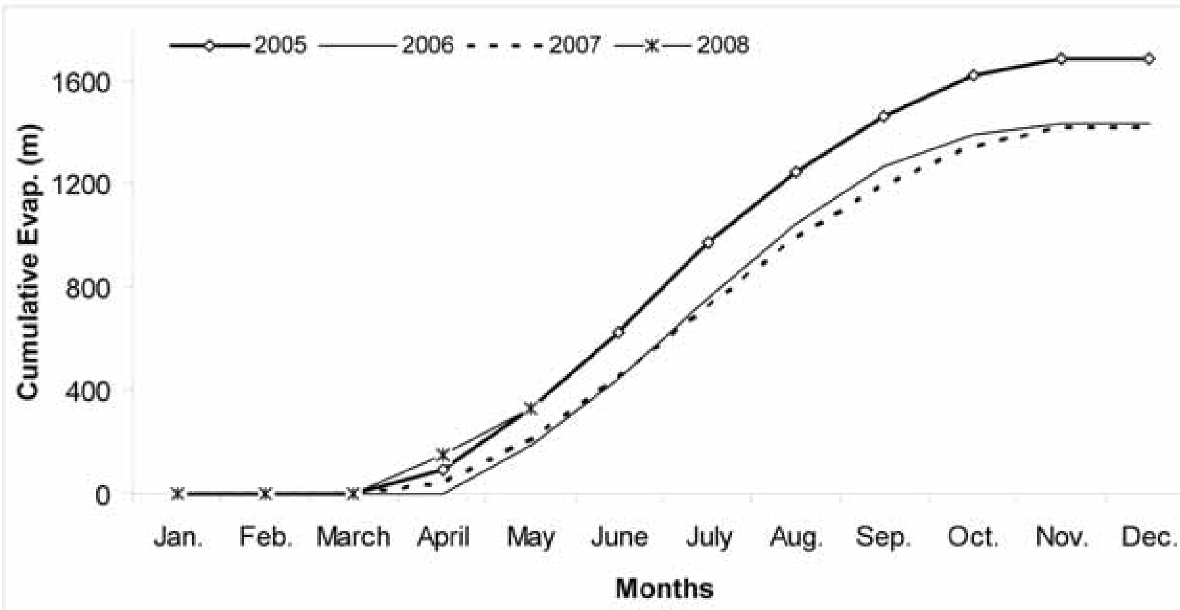

Fig. VI -19- Cumulative pan evaporation for the months of March-Dec, Honam 2005/08.

CGIAR Challenge Program on
WATER & FOOD

Benchmark river basins

The CP Water & Food is a research, extension and capacity building program aims at increasing the productivity of water used for agriculture. The CP Water & Food is managed by an 18-member consortium, composed of five CGIAR/Future Harvest Centres, six National Agricultural Research and Extension Systems (NARES) institutions, four Advanced Research institutes (ARIs) and three international NGOs. The project is implemented at nine river basins (shown above) across the developing world. The Karkheh River Basin (KRB) in western Iran is one of the selected basins. The program's interlocking goals are to allow more food to be produced with the same amount of water that is used in agriculture today, as populations expand over the coming twenty years. And, do this in a way that decreases malnourishment and rural poverty, improves people's health and maintains environmental sustainability.

Improving On-farm Agricultural Water Productivity in the Karkheh River Basin Project (CPWF PN 8)

Project partner institutions and contacts
Website: http://www.karkheh-cp.icarda.org/karkheh-cp/default.asp

ICARDA
Theib Oweis and Adriana Bruggeman
P.O. Box 5466, Aleppo, Syria
Tel.: +963 21 2213433,
Fax: +963 21 2213490
E-mail: t.oweis@cgiar.org

IWMI
Asad Qureshi
P.O. Box 3185-845, Karaj, Iran
Tel.: +98-261 2716840,
Fax: +98-261 2716921
E-mail: a.sarwar@cgiar.org

AEERO (AERI, SCWMRI, NSRC, DARI, SWRI, RIFR, RRC)
Arzhang Javadi and Jahangir Pourhemmat
P.O. Box 31585-845 Karaj, Iran
Tel.: +98-21 3130078,
Fax: +98-261 2704846
E-mail: email2arzhang@yahoo.com

University of California, Davis
Theodore Hsiao
Davis, CA 95616, USA
Tel.: +1-530 7520691; Fax: +1-530 7525262
E-mail: tchsiao@ucdavis.edu