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Agricultural Water Use and Management in Arid and Semi-arid Areas: Current Situation and Measures for Improvement

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Abstract: Water is rapidly becoming scarcer especially in arid and semi-arid areas such as Central West Asia and North Africa Region (CWANA), while irrigated agriculture is critical for national and world food security in these regions. Due to large gaps between crop demands and rainfall, most countries of these regions cannot have productive form of agriculture without assured irrigation supplies. Continuous decrease in the surface water resources has put enormous pressure on groundwater resources and as a result; throughout the regions groundwater tables are declining. Since water is the most limited factor in these regions, improving the productivity of existing water resources is an attractive alternative to sustain irrigated agriculture. Therefore, there is a strong need to educate farmers to shift their thinking from "maximizing crop yields" to "optimizing crop yields". This paper reviews the current situation of water scarcity, agricultural water productivity, and suggests options for sustainable management of land and water resources in these regions. The results of this study showed that substantial and sustainable improvements in water productivity can be achieved through integrated management of farm-resources. On-farm irrigation water management techniques such as deficit irrigation, if coupled with better cropping patterns together with appropriate cultural practices, and improved genetic make-up, will help to achieve this objective. Conventional water-management and cropping pattern guidelines, designed to maximize yield per unit area, need to be revised for achieving maximum water productivity. The wide ranges recorded in crop water productivities suggest that agricultural production can be maintained to its current level by using 20 to 40% less water if new efficient water management practices are adopted.

Key words: Semi-arid areas, CWANA, water productivity, deficit irrigation, pressurized irrigation systems, irrigated agriculture, water scarcity.

Increasing global population is projected to reach 7.8 billion in 2025 (Cai and Rosegrant, 2003). The growing population will result in considerable additional demand for food, especially in developing countries where more than 80% of the population increase is expected to occur (Sekler *et al.*, 1998). Simultaneously, water is rapidly becoming scarce especially in arid and semi-arid regions of CWANA (Central West Asia and North Africa Region), Arabian Peninsula, India and China. Moreover, the water demand from non-agricultural sectors in industry and households, as well as for environmental purposes will keep growing in both developed and developing countries. Irrigated agriculture has been an important contributor to the expansion of national and world food supplies since the 1960s and is expected to play a major role in future in feeding the growing world population. At the global scale, irrigated agriculture uses about 70% of the available fresh water resources (Cornish *et al.*, 2004), which accounts for about 80% in arid and semi-arid regions. With growing demand for irrigation water and increasing competition across water-using sectors, the world now faces a major challenge to produce more food with less water. This goal will be realistic only if an appropriate strategy or a combination of strategies are found for water saving and for more efficient uses of water in agriculture.

Allan (1997, 1999) analyzed the available alternatives to overcome water scarcity in a given society. He suggested three strategies of using more virtual water; improving economic efficiency of water and improving technical efficiency to perform the same activities, but using less water. Considering these three alternatives (which are used simultaneously in most regions of the world) the preferred order is coincident with the order of presentation. However, regional decision makers prefer technical efficiency overall. According to Allan (1999), the reasons for choosing technical efficiency arise from the following facts: (a) it is an uncompromising choice; (b) it catalyses some economic sectors, such as construction; and (c) it does not produce explicit ''losers''. These reasons seem important, but in fact all of them are negative and unsupportive of decision makers.

A common perception is that irrigation wastes enormous quantities of water. Since water is scarce not land, if we could just be more efficient with irrigation, water would be made available for irrigating more land and diverting water to other uses and we might not have to develop more water infrastructure. However, this perception is in many cases not correct. The major reason of our believe that enormous amount of water is wasted in agriculture is due to technical use of the word "efficiency" in irrigation (Seckler *et al.*, 2003). Irrigation efficiency (IE) is commonly defined as IE = ETc/WD, where WD is the amount of water that needs to be withdrawn or diverted from a source (river, aquifer or reservoir) and ETc is the amount of evapotranspiration (ETc) by crops. This efficiency ratio can vary between 90% in modernized irrigation systems such as drip irrigation to as low as 20% in the case of traditional paddy (rice) irrigation systems (IWMI, 2000).

Irrigation efficiency can be increased by restricting the drainage water flow to saline areas or to the oceans where the water is effectively lost to further human uses. This will considerably increase the basin level of irrigation efficiency. For example, in Egypt, the typical efficiency of irrigation at the farm level is only 40 to 50%. But for the Egyptian irrigation sector as a whole, at the basin level it is close to 80%, because of recycling (IWMI, 2000).

A problem with the concept of efficiency, even with basin efficiency, is that it refers only to physical quantities of water, both in the denominator and the numerator. It does not capture differences in the value of water in alternative uses. This is the subject of the more general concept of productivity. Since water is just one important factor in agricultural production, improving overall agricultural water productivity (WP) would require coordination of water and land management. This includes use of improved cultivars and other inputs in a viable cropping system.

A higher crop WP results in either the same production from less water resources, or a higher production from the same water resources. Indeed, the greatest increases in the productivity of water in irrigation have not only been from better irrigation technology or management, but rather from increased crop yields due to better seeds and fertilizers (Zobel, 2002).

However, water-use efficiency and irrigation efficiency remain useful parameters, especially under local conditions and for the aggregation level of farmers or irrigation projects. For example, they are the only proper toolkit to use where, for whatever economic, financial or political reason, the decision to go ahead with irrigation practices or devices has been made (Zoebl, 2002).

The objectives of this study were to review the water resources and water productivity in arid and semi-arid regions and evaluate ways of improvement in use of land and water resources.

Agricultural Water Resources and Productivity

Climate and surface water resources

The CWANA countries, Arabian Peninsula, and some parts of India and China regions are good examples of countries that could face physical water scarcity in 2025. This means that, even with the highest feasible efficiency and productivity of water use, these countries do not have sufficient water resources to meet their agricultural, domestic, industrial and environmental needs in 2025. Indeed, many of these countries cannot even meet their present needs. Annual precipitation in some of these countries is not very low. However, distribution of precipitation is very irregular and non-equitable, and does not coincids with growing seasons. In Iran annual precipitation is about 252 mm; west, and southwest regions cover only 30% of the country's total area while receive around 56% of the total precipitation. The central and eastern parts of the country, which cover 70% of the country area, receive only 44% of total country's precipitation (Dehghanisanij *et al*., 2006). Half of China's territory is arid and semi-arid. In the north-western parts of China, the annual rainfall is less than 250 mm and without irrigation there would be no agriculture. In the north-eastern and northern parts of China the annual rainfall is 400-600 mm, most of which substantially falls in summer and there is a spring drought almost every year. Irrigation in these areas is necessary for agricultural development. To the south of the Yangtze River, the annual rainfall is some 1000 mm. Despite high rainfall, its distribution is uneven and droughts occur very often both in summer and in autumn. In order to obtain high-level of agricultural production, supplementary irrigation has to be applied. Drought and water shortages have become major constraints for the development of agriculture in China. China's agriculture is to a large extent dependant on irrigation (ESCAP, 1997). In Pakistan, the climate is arid with low rainfall and humidity and high solar radiation over most parts of the country. Most areas receive less than 200 mm annual rainfall, except for the high altitude northern mountains, which receive more than 500 mm annually. The rainfall distribution varies widely, 60% of rainfall in Sind and Punjab Provinces occurs during the monsoon season i.e., from July to early September. Balochistan and the northern mountains receive maximum rainfall during October to March (PNCID, 1991).

An overview of the physical water scarcity situation for the 8 countries is presented in Table 1. Physical water scarcity was simply defined as the percentage of primary water supply (PWS) to utilizable water supply (UWS). Primary water supply (PWS) was used to express upper limit to the amount of water that can be depleted by various users. The PWS is a good indicator of the available potential of water resources development. The PWS could be much smaller than water diversions because diversions include both PWS and the amount of PWS that is recycled through various uses in the system (Seckler *et al.*, 1998). Utilizable water supply (UWS) is the amount of water that can ultimately be utilized, with full development of surface and subsurface storage and conveyance facilities. In principle, this value includes the sustainable use of groundwater supplies (which is essentially the amount of natural and artificial recharge of aquifers), but there is very little data on this.

Multiplying the renewable water resources (RWR) by PUF results in the (potentially) utilizable water supply (UWS) of a country. RWR was defined as the average annual flow of rivers and recharge of groundwater generated from indigenous precipitation plus incoming flow originating outside the country, taking into consideration the quantity of flows committed to upstream and downstream countries through formal and informal agreements or treaties. This gives the maximum theoretical amount of water available for the country (definition by FAO, data by WRI mainly Shiklimanov, 1999; WRI, 1998 and national estimates). Potential utilization factor (PUF) expressing the percentage of the annual RWR that could be controlled and managed with full development of storage and conveyance facilities.

Based on Seckler *et al.* (1999), when physical water scarcity (PWS) exceeds 60%, the country is experiencing physical water scarcity. Accordingly, the countries listed in Table 1 are facing physical water scarcity. It was noted that some countries exceed this percentage by several times, which is presumably because of unsustainable groundwater mining. Yearly evaporation in selected countries was high, which was on an average about 70% of PWS (Seckler *et al.*, 1999). Irrigation was and will remain the largest single user of diverted water. For example, agricultural sector was using 89% and 94% of the total water diverted in Iran and Pakistan in the year 2004, respectively.

Groundwater resources

As a general rule, in arid and semi-arid regions agriculture cannot be carried out productively without full irrigation or supplemental irrigation. Herein, groundwater accounts for a significant portion of the water supply in most of those regions. Groundwater use in India, USA and China is reported to be the highest in the world, its was 150, 101 and 75 billion m^3 during 1980 and the ground water use in Iran and

Table 1. Physical water scarcity situation in selected countries of arid and semi-arid regions

Country	Renewable water resources (RWR)	Factor potentially utilizable RWR	Utilizable water resources of RWR	Water scarcity criteria			Evaporation of primary water supply	Total diversions	Total irrigation diversions	Total irrigation diversions
				Primary Water Supply (PWS) % of utilizable water supply		Increase PWS				
				2004	2025	2004-25	2004	2004	2004	2025
	km^3	%	%	%	%	%	%	km3	km^3	km^3
Pakistan	226	55	124	145	156	8	74	266.4	250.4	275.0
Jordan	1	80	1	113	113	0	67	1.2	0.6	0.7
Iran*	130	60	83	88	80	-8	77	94.5	84.1	83.2
Syria	26	60	16	69	80	16	72	13.6	12.0	14.3
Iraq	75	60	45	65	67	3	73	34.8	31.3	34.5
India	2037	38	774	53	62	17	73	676.2	588.3	702.0
China	2700	30	910	47	62	27	71	764.5	519.9	627.5

Pakistan has been 29 and 45 billion m^3. However, throughout the world, regions that have sustainable groundwater balance are shrinking by every day (Shah *et al*., 2000). Three problems dominate groundwater use: depletions due to overdraft; water logging and salinization, due mostly to inadequate drainage and insufficient conjunctive use; and pollution due to agricultural, industrial and other human activities. In arid and semi-arid regions ground water depletion, are becoming increasingly evident (Shah *et al*., 2000). In North China's Henan province, China's largest, where some 2 Mha (52% of irrigated lands) are served by tube wells, water table monitoring data on 358 observation wells encompassing 75,000 km^2 showed water table declines of 0.75-3.68 m during 1975 to 87. In the Fuyang river basin of North China where IWMI has been studying basin, surface water supplies to agriculture have been drastically curtailed over a 20 year period for meeting industrial needs; farmers have responded by resorting to groundwater irrigation; the number of tube wells in the basin has increased to some 91,000, mostly during the 1970s and the water table has fallen from 8 to 50 m during 1967-2000 (Shah *et al*., 2000).

Groundwater problems in West and South Asia are as pernicious as or even worse than those in China. A groundwater basket case is Yemen. A recent World-Bank memorandum on water management in Yemen noted: "the problem of groundwater mining represents a fundamental threat to the well-being of the Yemeni people. In the highland plains, for example, abstraction is estimated to exceed recharge by 400% (Briscoe, 1999). Yemen is probably the only country where groundwater abstraction exceeds the recharge for the country as a whole.

In Iran, where ground water is the main water source for agriculture, the number of wells has increased from 230,000 to 470,000 over last 10 years (Tamaab, 2004). In Kerman province, located in south part of Iran, water table monitoring data showed an annual water table declines of 0.12 to 1.79 m and it depended on location in province.

The situation in South Asia is no better. In western, north-western and peninsular India and Pakistan, where in recent times, over a million irrigation wells have got added every year, groundwater withdrawal far exceeds annual recharge in vast areas that are growing every year. In region where this process has been rapid, the consequences are serious and visible. In the two Punjabs, Haryana and Western Rajasthan, the main consequence has been salinity; in North Gujarat and Southern Rajasthan, it is fluoride contamination of groundwater; in hard-rock Southern India, it is declining well yields and increasing pumping costs arising from competitive deepening of wells (Shah *et al.*, 2000).

The Concept of Water Productivity

Crop water productivity (WP) is defined as the crop yield/production (Y) per unit of water consumed (WC), including 'green' water (effective rainfall) for rain-fed areas and both 'green' water and 'blue' water (diverted water from water systems) for irrigated areas. De Wit (1958) was among the first to do this and he expressed the water-use efficiency in kilogram of crop produced per cubic-meter of water transpired. The definition of WP is scale and user dependent. Molden (1997) introduced the broader term water productivity, for analysis of water use at different aggregation levels. Molden *et al.* (2003) refer to this problem as "which crop and which drop". As the numerator total dry or fresh biomass or harvested product can be used, expressed in physical (kg) or economic terms ($). As the denominator, there are numerous options as WC which refers to diversion or consumption of irrigation water, such as deficit water applied (DI), ETc, water diverted (WD), beneficial water consumption (BWC) and/or non-beneficial water consumption (NBWC), etc.

$$WP_1 = Y/DI \qquad ...(1)$$

$$WP_2 = Y/ETc = IE \times Y/WD \qquad ...(2)$$

$$WP_3 = Y/BWC = Y/(IE \times WD) \qquad ...(3)$$

$$WP_4 = Y/(BWC+NBWC) = Y/(ICUC \times WD) \qquad ...(4)$$

$$WP_5 = Y/WD \qquad ...(5)$$

The values of the water productivity change based on the hydrological domain at the denominator. Herein, WP value of the calculated water productivity decreases in the sequence WP_1 to WP_5, which could be explained through different forms of technical efficiency (Playan and Mateos, 2005). Under deficit irrigation (WP_1) it has been assumed that all applied water is used as evapotranspiration (Hexem and Heady, 1978). The WP_2 is related to irrigation efficiency (IE), which is based on the hydrological domain, could be related to the water conveyance efficiency (Burman *et al.*, 1981) and unit irrigation efficiency (Burman *et al.*, 1981). Irrigation efficiency (IE) is water diversion divided by irrigation requirements or crop evapotranspiration (ETc) minus effective rainfall (Molden *et al.*, 1998; Burman *et al.*, 1981). The WP_3 is related to the irrigation efficiency (Burt *et al.*, 1997), the volume of irrigation water beneficially used divided by the volume of irrigation water applied (IE), and WP_4 to the irrigation consumptive use coefficient (Burt *et al.*, 1997). The irrigation consumptive use coefficient (ICUC) is the volume of irrigation water consumptively used divided by the volume of irrigation water applied.

The pertinence of one or another concept of WP depends on the hydrological domain such as crop, field, irrigation unit, basin (Playan and Mateos, 2005). The concepts of WP_1, WP_2 and WP_3 are valid at any scale. However, they are more meaningful at the field or crop level since they are related mainly to agronomic aspects of the crops related to transpiration (Playan and Mateos, 2005). If the water that is used, but all not consumed in an irrigation unit and remaining amount cannot be reused within the domain, etc. evaporated, flow to saline areas or to the oceans, then WP_5 is pertinent. However, if the water used in upstream, but the percolated cannot be consumed in the downstream of the same domain, then WP_4 is more appropriate. Several strategies could be applied for enhancement of crop WP by integrating varietal improvement and better managements of resources at different hydrological domains.

Water Productivity

A comprehensive database on measured water productivity (WP_1 and WP_2) from the field experiments that were reported in the international literature for wheat, maize, and rice on CWANA regions is presented in Table 1. The majority of field experiments were conducted at experimental stations under varying geographical conditions, including variations in climate, irrigation, fertilization, soils, cultural practices, etc. In the selected database, experiments based on the reference evapotranspiration method (Allen *et al.*, 1998) has not been regarded as being suitable for the current review instead lysimeters were used to calibrate the data on soil water balance methods that monitor soil water content during the growing season by measurements of gravimetric soil moisture, or by neutron scattering equipment (neutron probes) or by time-domain-reflectometry (TDR). Yield is defined as the marketable part of the total above ground biomass produced (grain yield).

The frequency distribution histograms of wheat, rice, and cotton are presented in Fig. 3. Wheat has the largest number of experimental points (n = 557) and the WP range is between 0.1 and 2.7 kg m^{-3}. Doorenbos and Kassam (1979) give a lower range of 0.8 to 1.0 kg m^{-3}. Two highest wheat WP values were 2.67 and 2.50 kg m^{-3} from China and Iran, respectively. The maximum values are found by Jin *et al.* (1999) in China where application of manure led to higher production and straw mulching improved soil water and soil temperature conditions. Crop WP for the experiment with straw mulching was 2.67 and 2.41 kg m^{-3} for a combination of straw mulching and manure. The ETc in the winter season was tempered to 268 and 236 mm, respectively, while yields were relatively high with 7150 and 5707 kg ha^{-1} (Jin *et al.*, 1999). The next high value of wheat water productivity was 2.27 kg m^{-3}, where irrigation was terminated from wheat flowering stage (WP_1). Total irrigation water applied (DI) during the growing season was 2203 m^3 and related yield was 5570 kg ha^{-1}. In 62% of the publications the maximum value of WP for wheat was higher than 1.0 kg m^{-3} provided by Doorenbos and Kassam (1979).

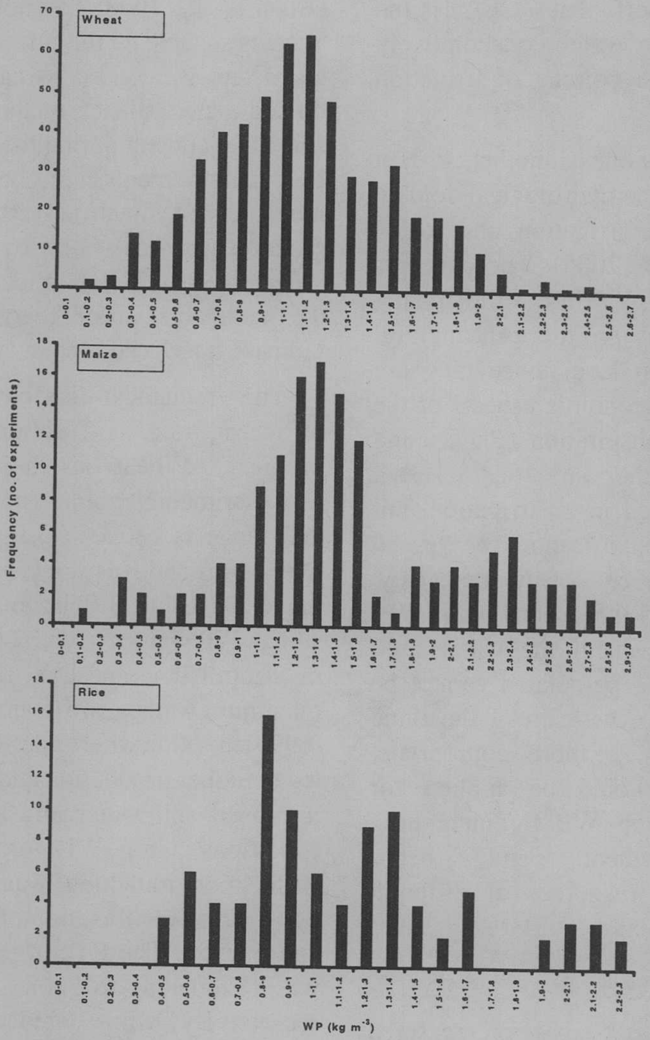

Fig 1. *Frequency of crop water productivity (WP) for wheat, maize and rice.*

Water productivity (WP) for maize is ranging from 0.10 kg m^{-3} up to a maximum of 3.0 kg m^{-3} (Fig. 1), which exhibits a large range of variation. In 67% of the publications the maximum value of the source exceeds the value of 1.6 kg m^{-3} provided by Doorenbos and Kassam (1979). The WP range of 1.1 to 2.7 kg m^{-3} for maize, a C_4-crop, is significantly higher than wheat, which is C_3-crop. The maximum values were measured by Kang *et al.* (2000) under Chinese conditions, where less amounts of irrigation water (deficit irrigation) were alternately applied to one of the two neighboring furrows. The ETc with 226 mm was very low, whereas grain yield was still 9058 kg ha^{-1} (Fig. 1). The other highest value of maize WP was 2.87

Table 2. Water productivity of wheat, maize and rice from literature

Location	Country	Minimum-Maximum (kg m^{-3})	Median (kg m^{-3})	Experimental year(s)	Reference
Wheat					
Tel Hadya, Syria	0.48-1.10	0.78	1991-1996	Oweis *et al.* (2000)	
Orumieh	Iran	0.23-1.44	0.90	1998-1999	Tayefehrezaei and Ivazi (2003)
Karaj	Iran	0.86-2.50	1.40	1999-2000	Abbasi and Mehrpour (2004)
Mashhad	Iran	0.66-1.98	1.23	1998-1999	Baghani and Zare (2002)
Quzhou, China	1.38-1.95	1.58	1988-1989	Deju and Jingwen (1993)	
Xifeng, China	0.65-1.21	0.84	1988-1991	Fengrui *et al.* (2000)	
Wangtong, China	1.49-2.67	2.23	1995-1996	Jin *et al.* (1999)	
Gansu	China	0.58-1.45	1.00	1997	Li *et al.* (2001)
Luancheng	China	1.07-1.29	1.26	1984-1996	Wang *et al.* (2001)
Yucheng	China	0.88-1.16	1.04	1986-1990	Xianqun (1996)
Beijing	China	0.92-1.55	1.19	1991-1995	Zhang *et al.* (1998)
Luancheng	China	1.28-1.82	1.63	1998-2000	Zhang *et al.* (2003)
Pantnagar	India	0.86-1.31	1.11	1983-1985	Mishra *et al.* (1995)
Uttar Pradesh	India	0.48-0.71	0.64	1993–1994	Sharma *et al.* (2001)
Bhakra	India	1.23-1.49	1.36	2000-2001	Hussain *et al.* (2003)
Karnal	India	0.27-0.82	0.67	1986-1988	Sharma *et al.* (1990)
Pantnagar	India	1.06-1.23	1.11	979-1985	Singh and Chauhan (1996)
Meknes	Morocco	0.11-1.15	0.58	1993-1995	Corbeels *et al.* (1998)
Sidi El Aydi	Morocco	0.32-1.06	0.61	1995-1999	Mrabet (2002)
Konni	Niger	0.42-0.93	0.61	1996-1998	Pandey *et al.* (2001)
Jehlum	Pakistan	1.08-1.62	1.37	2000-2001	Hussain *et al.* (2003)
Faisalabad	Pakistan	0.70-2.19	1.28	1991-1994	Waheed *et al.* (1999)
Cukurova	Turkey	1.33-1.45	1.39	1991-1992	Sezen and Yazar (1996)
Tashkent	Uzbekistan	0.44-1.02	0.73	2001-2002	Kamilov *et al.* (2003)
Rice					
Rasht	Iran	0.83-1.21	1.02	1997-1998	Yazdani and Fatollahzadeh (2000)
Ahvaz	Iran	0.34-0.57	0.41	2003-2003	Gilani and Absalan (2005)
Zhanghe	China	1.04-2.20	1.41	1991-2000	Dong *et al.* (2001)
Nanchang	China	1.63-2.04	1.84	2002	Shi *et al.* (2003)
Pantnagar	India	0.80-0.99	0.89	1983-1984	Mishra *et al.* (1990)
New Delhi	India	0.55-0.67	0.67	2001	Singh *et al.* (2002)
Punjab	India	0.87-1.46	1.15	1996-1997	Singh *et al.* (2001)
Kadawa	Nigeria	0.50-0.79	0.59	1991-1992	Nwadukwe and Chude (1998)

Table 1 contd...

Table 2. contd......

Location	Country	Minimum–Maximum (kg m^{-3})	Median (kg m^{-3})	Experimental year(s)	Reference
Maize					
Orumieh	Iran	1.07-2.87	1.72	1998-2000	Ahmedali and Khalili (2002)
Karaj	Iran	1.00-1.40	1.16	1998	Abbasi *et al.* (2000)
Mashhad	Iran	0.70-1.60	1.20	2001-2003	Afshar (2004)
Dezful	Iran	0.19-0.45	0.34	2000-2001	Khorramian (2003)
Esfahan	Iran	0.86-1.42	1.07	1999-2000	Salemi (2003)
Xifeng	China	1.26-2.31	2	1989-1991	Fengrui *et al.* (2000)
Wangtong	China	1.49-2.67	2.23	1995-1996	Jin *et al.* (1999)
Changwu	China	1.36-1.65	1.56	1987	Liu and Li (1995)
Gansu province	China	2.14-2.99	2.92	1997-1998	Kang *et al.* (2000)
Pantnagar	India	1.17-1.74	1.47	1993-1995	Mishra *et al.* (2001)
Tal Amara	Lebanon	1.36-1.89	1.64	1998	Karam *et al.* (2003)
Harran plain	Turkey	1.94-2.25	2.02	2000	Yazar *et al.* (2002)
Harran plain	Turkey	1.04-1.38	1.24	1998-1999	Oktem *et al.* (2003)
Cukurova	Turkey	0.22-1.25	1.01	1993-1994	Gencoglan and Yazar (1999)

kg m^{-3} reported by Ahmedali and Khalili (2002) in a combination of deficit irrigation and irrigation scheduling in Iran: where irrigation water applied was based on 50% of the maize water requirement under an 11- day irrigation interval. Total DI was 3950 m^{3} ha^{-1} and related yield was 11400 kg ha^{-1}.

Water productivity of rice ranges between 0.6 and 1.6 kg m^{-3} (Fig. 1). The maximum crop WP value of 1.1 kg m^{-3} for rice given by Doorenbos and Kassam (1979) is exceeded in 6 out of 13 data sources. The shape of the frequency distribution of rice is not as smooth as for wheat because fewer points are available. The maximum values go up to 2.20 kg m^{-3} and were measured in China on alternate wetting and drying rice plots (Dong *et al.*, 2001). Rice grain yields of over 10 t ha^{-1} were amongst the highest measured, whereas ETc was on the lower side with 465 mm.

The correlation between the irrigation water applied (I) and Y is not straightforward as it is often assumed that crop yield increases with increase in applied irrigation water. Results of yield and irrigation water applied during 5 years (1995-2000) of field experiments on wheat and maize in different locations of Iran are presented in Figs. 2 and 3. The *r*-squared values for the relation between I and Y in both crops were low; the correlation for wheat ($r^2 = 0.49$) was higher than that for maize ($r^2 = 0.36$). The wheat yield was ranging between about 1.0 to 7.0 Mg ha^{-1} which corresponded to 100 and 550 mm irrigation water applied. Maize yield was ranging between about 5.0 and 14.0 Mg ha^{-1} which corresponded to 550 and 1200 mm irrigation water applied. The minimum values of Y related to low amount of irrigation water applied were due to the deficit irrigation over the entire growth period. Hussain *et al.* (2003) reported

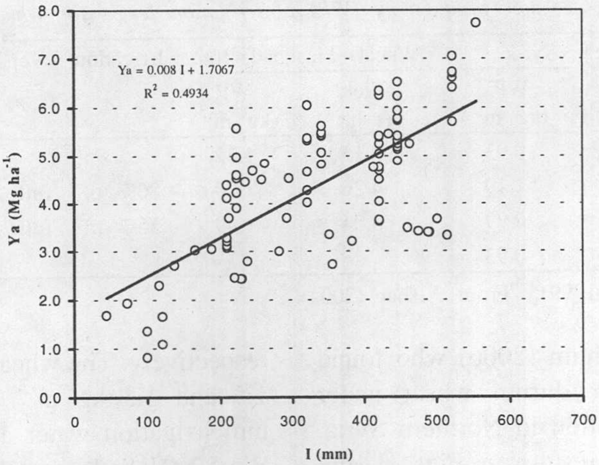

Fig 2. Relation between actual yield of wheat (Y) and irrigation water applied (I) for different location/climate in Iran.

yields of 4.48 and 4.11 Mg ha^{-1} for wheat production in India (Bhakra region) and Pakistan (Punjab region), respectively, where full irrigation was applied. The results of Table 1 and Figs. 2 and 3 show that there are ample opportunities to improve productivity of water through better water management.

Cropping Pattern System

In Figs. 4 and 5, the crop WP of wheat and maize are plotted against the irrigation water applied for different locations of Iran. Figs. 4 and 5 demonstrate how crop WP can be increased while simultaneously saving water by reducing irrigation water applied. These results are supported by those

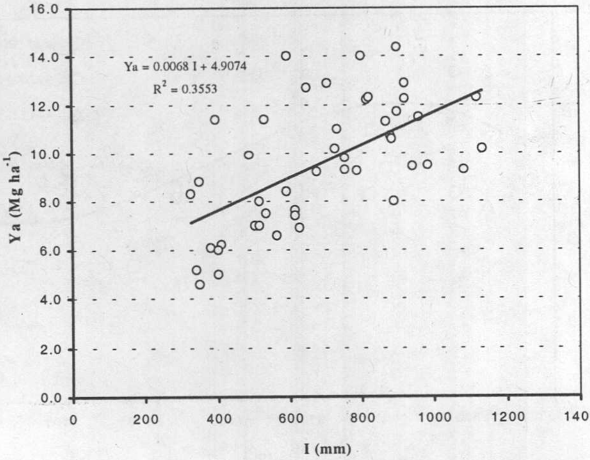

Fig 3. Relation between actual yield of maize (Y) and irrigation water applied (I) for different location/climate in Iran.

Table 3. Comparison of water productivity (WP) of irrigation levels for wheat and maize

Irrigation level	Wheat, Syria[a]		Wheat, Mashhad, Iran		Irrigation level	Maize, Mashhad, Iran[b]	
	Yield (t ha^{-1})	WP (kg m^{-3})	Yield (t ha^{-1})	WP (kg m^{-3})		Yield (t ha^{-1})	WP (kg m^{-3})
Full	5.79	0.93	5.15	1.32	Full	11.25	1.00
67% of full	5.24	1.19	4.26	1.70	80% of full	10.95	1.24
33% of full	5.15	0.99	3.04	1.49	55% of full	5.99	0.98
Rain-fed	3.27	0.93					

[a]From Oweis *et al.* (1999); [b]From Afshar (2004).

of Oweis and Hachum (2006) who found similar pattern for durum wheat under supplemental irrigation in Northern Syria. According to the results in Figs. 4 and 5, wheat WP in Orumieh was less compared to the other regions for any amount of irrigation water, while the maize WP was higher. Irrigation water applied for maize in Dezful was almost 60-200% higher than at other experimental sites. Low maize WP at site Dezful caused a reduction in average maize WP among the experimental sites. Water productivity decreased when applied irrigation water was increased to more than 300 and 600 mm for wheat and maize, respectively. The wheat and maize WP was 1.5 and 1.3 kg m^{-3} when 300 and 600 mm irrigation water applied, respectively. We concluded that these two values of WP as optimum level for wheat and maize production, which should be considered in cropping system to improve crop WP in Iran. A maximum crop WP will often not coincide with farmers' interests, whose aim is to maximize land productivity or economic returns (Molden *et al.*, 2003). It requires a shift in irrigation science, irrigation water management and basin water allocation to move away from 'maximum irrigation-maximum yield'

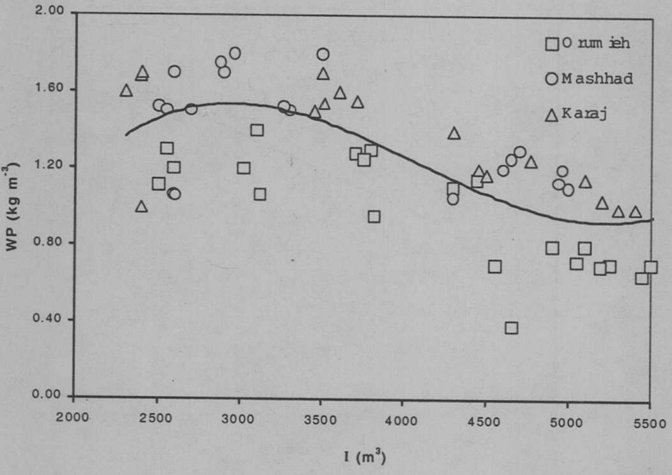

Fig. 4. The relationship between measured wheat water productivity (WP_2) and amount of irrigation water applied (I).

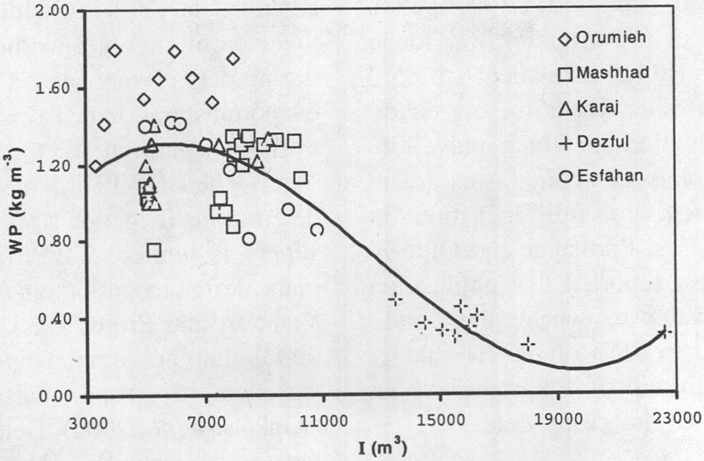

Fig 5. The relationship between measured maize water productivity (WP_2) and amount of irrigation water applied (I).

strategies to 'less irrigation-maximum crop WP' policies (Oweis and Hachum, 2006).

Deficit Irrigation (Fully and Regulated)

One common irrigation practice is to apply the amount of water necessary to bring the soil to field capacity. This practice avoids crop water deficit by assuring maximum crop evapotranspiration. But deficit irrigation can be economically desirable depending on the cost of the applied water, the price of the agricultural product and the yield response to water deficit. The relation between crop yield and the productivity of applied water showed that higher productivity is achieved at a level of water supplied lower than that at maximum yield (Figs. 2-5). Many irrigation trails on applying different levels of irrigation water have also shown that deficit irrigation usually has higher WP than full irrigation. For example, two-third of full irrigation increased WP by 28-29% for wheat and 24% for maize when 80% of full irrigation water was applied (Table 3).

Using the principle developed by English and Raja (1996) and Zhang and Oweis (1999), we can derive different irrigation scenarios. Two of the most important scenarios are those for maximizing production and maximizing farmers' net profit under limited-water-resources conditions. The scenario for maximizing production is referred to as full irrigation and the other scenario with water supply less than full irrigation which is defined as deficit irrigation (DI). According to the Table 3, we concluded that deficit irrigation can increase the productivity of applied water by producing more yield with the same amount of water resources for crops. Accordingly, a considerable amount of water can be saved without a significant yield reduction compared with full irrigation. Zhang and Oweis (1999) reported that DI strategy allows one to apply 40-70% less irrigation water for a grain-yield loss of only 13%. Similarly, English and Raja

(1996) reported that deficit irrigation averaging 64% of full irrigation was found to be economically equivalent to full irrigation when water was a limiting factor, and deficit irrigation in which only 30% of full irrigation was applied was found to be equivalent to full irrigation in land-limiting cases. Prathapar and Qureshi (1999) have also reported that application of irrigation water to wheat and cotton can be reduced to 75% of the ETc under semi-arid conditions of Pakistan without significant losses in crop yields.

Deficit irrigation may be applied on the basis of reduced irrigation during certain periods of the annual plant cycle, which is called as regulated deficit irrigation (RDI). The periods are selected when ongoing growth process are less sensitive to water stress and when the derived effects of water stress are advantageous for yield, as in the case of reducing vigor in high density orchards (Chalmers *et al.*, 1981). The RDI reduced excessive vegetative growth (Chamers *et al.*, 1981; Li *et al.*, 1989; Girona *et al.*, 1993, 2003) and improved fruit quality (Li *et al.*, 1989).

For successful and reliable DI or RDI, however, information is needed to guide farmers on when and how much deficit irrigation need to be applied in order to reduce the unwanted effect of water stress on crop yield. Crop water production function (CWPF) was computed using the functional model presented by Steward *et al.* (1977) and Doorenbos and Kassam (1979) describing the relation between water stress and corresponding expected yield. In this model CWPF is expressed based on relative yield (1 – (Ya/Ym)) and relative evapotranspiration (1 – (ETa/ETc)), where actual yield (Ya) is divided by maximum yield from the plot without water stress during the growing season (Ym) and actual evapotranspiration (ETa) is divided by crop evapotranspiration (ETc) corresponding to Ym. The CWPF is very useful in determining irrigation strategies when water supply is limited. CWPF is always linear in the deficit irrigation range (Ritchie, 1983; Vaux Jr. and Pruitt, 1983; Kipkorir *et al.*, 2002), but not unique and varies among varieties of crops and climate zones (Kipkorir *et al.*, 2002). Determining CWPF for a site-specific location is usually required. The relation between yield and evapotranspiration becomes curvilinear as more of the applied water goes to deep drainage. Under deficit irrigation it has been assumed that all applied water is used as evapotranspiration (Hexem and Heady, 1978). The slope of linear relationship between evapotranspiration stress and yield depression called the yield response factor (ky):

$$1-\frac{\mathrm{Ya}}{\mathrm{Ym}}=\mathrm{Ky}\left(1-\frac{\mathrm{ETa}}{\mathrm{ETc}}\right) \quad \text{...(6)}$$

Doorenbos and Kassam (1979) reported ky for several crops, for individual growth stages and also for the total growing season. Seasonal yield response factor is based on the effect of water deficit for the total growing season, while growth stage yield response factor is based on water deficit for individual growth stage.

Using data presented in Figs. 1-4, a linear model best fitted the relationship between relative yield (1 – (Ya/Ym)) and relative evapotranspiration (1 – (ETa/ETc)) for wheat and maize, as shown at Figs. 6 and 7. Since the growing conditions varied between the locations, some scatter in ky

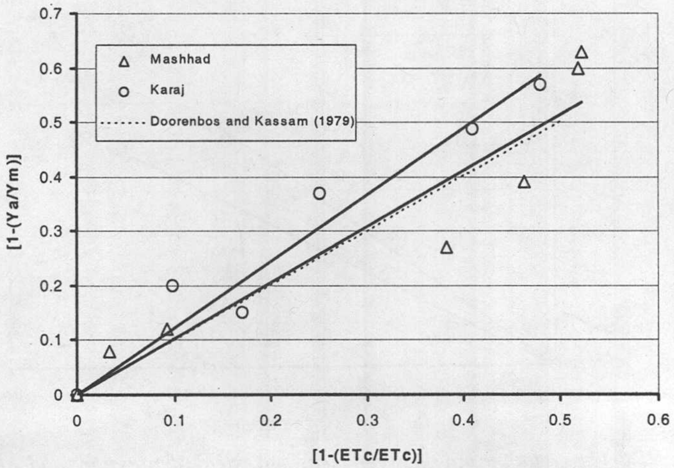

Fig. 6. The relationship between seasonal yield depression and seasonal water deficit for wheat.

was found (Figs. 6 and 7). In Figure 6, seasonal yield depression for wheat is plotted against seasonal water deficit for Mashhad and Karaj. The slope (ky) of wheat water production function in Mashhad ($R^2 = 0.90$) and Karaj ($R^2 = 0.94$) was 1.03 and 1.22, respectively. The seasonal ky for wheat computed by Doorenbos and Kassam (1979) was 1.0.

Maize grown on a clay loam soil under furrow irrigation produced a curvilinear relationship between relative yield and relative evapotranspiration, possibly due to the deep percolation (Kipkorir *et al.*, 2002). Based on Fig. 6, applying deficit irrigation to wheat in Mashhad was more productive than in Karaj. There was a similar result for maize in Orumieh (Fig. 7). The ky for maize in Orumieh ($R^2 = 0.92$) was 1.03, while it was 1.46 ($R^2 = 0.94$) in Mashhad. The higher variation in seasonal ky of maize (1.03-1.46) compared to that for wheat (1.03-1.22) than that computed by Doorenbos and Kassam (1979), might be attributed to the sensitivity of maize to deficit irrigation. These results support the low drought tolerance of maize under moderate or sever water deficits in other environments (Rhoads and Bennet, 1990; Pandey *et al.*, 2000; Cakir, 2004). The high sensitivity of maize to water stress means that under water limited conditions it is difficult to implement irrigation management strategies without incurring important losses (Lamm *et al.*, 1994). Accordingly, under DI practices, Ky also is a useful factor to select the best cropping pattern system.

Regulated deficit irrigation (RID), or the imposition of water deficit at only certain crop development stages, may reduce crop evapotranspiration with minimum or no reduction in yield. Therefore, regulated deficit irrigation may improve all forms of WP, from WP_1 to WP_5. Fereres and Goldhamer (2003) foresee potential in the use of regulated deficit irrigation in tree crops (where fruit rather than biomass is the marketable product and fruit quality is important) for reducing water use and

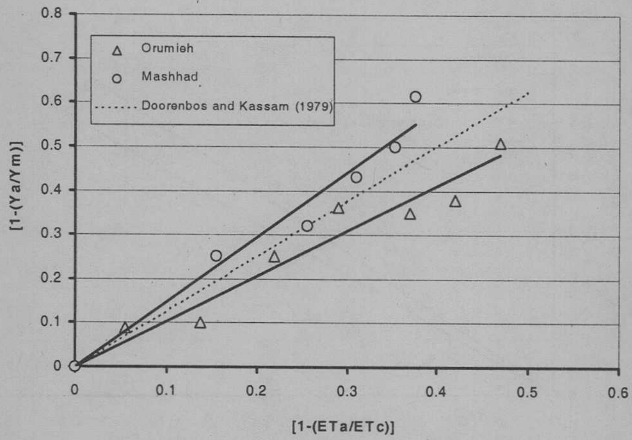

Fig. 7. The relationship between seasonal yield depression and seasonal water deficit for maize.

consumption while maintaining or even improving grower profit. Jensen (1968) developed a model to quantify the effect of water deficits during certain growth stages on grain yield, using the following equation:

$$\frac{Ya}{Ym} = \prod_{i=1}^{n} \left(\frac{ETa_i}{ETc} \right)^{\lambda i} \qquad ...(7)$$

where, ETa is the actual evapotranspiration (mm) during the growing stage i, λi is the sensitivity index of the crop to water stress and *i* is the growth stage. Using Jensen's (1968) model, the sensitivity indexes (ë values) of crop to water stress at different crop growth stages were quantified for wheat in northern Syria (Zhang and Oweis, 1999) and in the North China Plain (Zhang *et al.*, 1999). These authors concluded that the most sensitive stage for water stress for wheat is from the stem elongation to the grain-filling stage. The variation of ë values indicates that crop grain yield depends not only on total water use during the growing period, but also on water use during different growth stages. For example, a 40% decrease in evapotranspiration (ET) from heading to milking reduced grain yield by 15% for winter wheat in the North China Plain, while this deficit in ET during the period from winter freezing to reviving reduced grain yield by only 3% (Zhang *et al.*, 1999). Similarly, a 40% deficit in ET during the period of stem elongation to grain-filling reduced yield by 15 to 20% for spring wheat in northern Syria, while this deficit in ET at seedling stage and late grain-filling stage hardly affected the grain yield at all (Zhang and Oweis, 1999). Water-stress sensitivity indices have an important implication for irrigation scheduling, in particular for deficit irrigation. Since water stress during growth stages with high ë values has a much greater effect on final yield, to prevent stress during these stages irrigation would be advisable and consequently a higher WP could be achieved, especially in the areas where water resources are limited. The RDI is usually the case when irrigation water comes from shallow tube wells that are operated by the farmers. However, in countries where irrigation water is supplied through canals according to a strict rotational schedule (as is the case, for example, in much of the Indian subcontinent), there is no flexibility in the delivery of irrigation water. The implication is that under these circumstances deficit irrigation is different to practice.

Modernization and Optimization of Irrigation Systems

The volume of water consumed in the field consists of mainly evapotranspiration (ET) and deep percolation. The ET includes the amount of water used for transpiration and that evaporated directly from the soil surface. In addition, ET often includes the amount of water intercepted by the foliage, e.g. under overhead sprinkle irrigation, and evaporated without ever entering either the soil or the plant. Therefore, any method of irrigation that minimizes ETo and deep percolation is likely to increase the efficiency of water utilization by the crop. Pressurized Irrigation Systems (PIS) are capable of doing just that (Dehghanisanij *et al.*, 2007). Sprinkle and trickle irrigation together represent the broad class of pressurized irrigation methods, in which water is carried through a pipe system to a target point near plant where it will be absorbed by the root (Keller and Bliesner, 1990). This is in contrast to surface irrigation, in which water needs to move over the soil surface for rather long distance before it reaches the point where it is expected to infiltrate and be consumed. Thus, surface irrigation methods depend on critical uncertainties associated with water infiltration into the soil while being conveyed as well as at receiving site. Under PIS, evaporation or seepage from channels, border checks or furrows is almost zero and deeper collation under the root zone is minimal if managed properly.

The concept of PIS has evolved over the last century. Originally it was restricted to the introduction of new physical structures and equipments. However, now a days it is understood as a fundamental transformation of the management of irrigation water resources aiming to improve the utilization of resources. Specific objectives of modernization could be increase in WP by increasing the reliability and flexibility of irrigation deliveries (Playan *et al.*, 2005). A reliable service allows efficient irrigation management within the constraints of the system. The reliability of irrigation water under PIS gives farmers the opportunities to predict irrigation scheduling and accordingly integrating other practices such as fertilization and pest control. Based on the flexibility of PIS, the farmer can adapt the irrigation schedules to optimize production. Therefore, both reliability and flexibility lead to higher irrigation efficiency and crop yield (Playan *et al.*, 2005). Since, the quality of irrigation water (underground and surface water) is low in most part of the arid and semi-arid regions, the quality of water need to be considered in irrigation scheduling (Dehghanisanij *et al.*, 2006) and irrigation system design (Dehghanisanij *et al.*, 2005) to achieve the true advantages of the PIS, high irrigation efficiency. There are many examples regarding this argument for CWANA regions. In Jordan, for example, drip irrigation reduced water use by an average of 35% for crops such as tomatoes and cucumbers while produced 15% higher yield (Brown, 2006). The reduction in water use coupled with higher yields raised water productivity by more than 50%. India, in 1998, was irrigating 225,000 ha with drip irrigation. Thirteen experiments at Indian Agriculture Research Institutes on crops showed gains in water productivity that ranged from 46% to 280%. On an average water productivity was raised by 152%, more than double (Brown, 2006). In Iran irrigated area under drip irrigation system increased from 44,800 ha to 180,000 ha during 1990-2002 (IMJA, 2004). Increase in WP due to application of irrigation water using drip system on different crops is reported by Iranian Agriculture Engineering Research Institute (Sadrghaen and Dehghanisanij, 2003). Cotton WP of 0.25, 0.22 and 0.17 kg m^{-3} under furrow irrigation increased to 0.36, 0.35 and 0.33 kg m^{-3} under drip irrigation when 50%, 75% and 100% of crop water requirement was applied, respectively (Afshar, 2003). The WP of green pepper increased 20% when irrigation water was applied through drip irrigation compared to furrow irrigation (Sadrghaen and Dehghanisanij, 2004). The WP of watermelon increased from 3.9-4.6 to 10.1 to 15.1 kg m^{-3}, when drip irrigation was applied compared to furrow irrigation (Baghani, 1998).

However, modern irrigation technologies in developed countries are very sophisticated and expensive, which makes it unaffordable for the poor farmers. They are automated and computerized, equipped with such components as sensing devices, pressure regulators, filters and sensors. All this is helpful because it saves labor, which is usually expensive in industrial countries, but irrigation technologies do not need to be so complicated and expensive in developing countries. It would be better to simplify these technologies and adapt them to the needs of the resource-poor farmers of developing countries.

Major Research Issues in Water-scarce Areas

There is no doubt that improving the productivity of water in dry areas will continue to be a priority. As discussed above under irrigated areas deficit irrigation, changes in cropping patterns, and adaptation of modern irrigation technologies can be effective tools to improve WP. Integrated with these practices are; improvement of current irrigation system efficiency, on-farm practices, selection and development of high yielding and water efficient crop varieties, efficient use of fertilizer, combating pests and diseases, optimal crop rotation and crop calendar. Moreover, efforts to direct new research and the transfer of available technologies to overcome water shortages are very much needed. Coordination of these efforts within an agreed-upon framework may enhance their impact. Elements of the research and technology framework would include:

1. The development of new guidelines for irrigation scheduling based on when and how much to irrigate is needed in order to reduce unwanted effects of water stress on crops.

2. The development of new cropping patterns for improved water productivity which are also economically competitive with current situations.

3. The development and transfer of alternative irrigation technologies with high water productivity and suitability for different land use systems.
4. The determination of agricultural water productivity at different scales; from field to basin.
5. The assessment of quantitative effects of irrigation modernization and optimization plans on water use at different domains.

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