8 - STRATEGIES FOR IRRIGATION SCHEDULING TO COPE WITH WATER SCARCITY

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Abstract: Excess irrigation water applied both at cotton and winter wheat in Central Asia countries cause problems of water logging and, mainly, lead to water wastes and losses, which may be controlled when an improved irrigation scheduling is used. After appropriate testing, the ISAREG model was explored to simulate the present and improved irrigation scheduling alternatives for cotton and winter wheat. Results show that using the present irrigation scheduling a large part of the applied water percolates to the watertable, averaging 13 and 49%, respectively in Hunger Steppe and Fergana Valley. When irrigation scheduling is improved, the seasonal irrigation could be reduced by 15 to 60% in Fergana Valley and percolation may be controlled.

Keywords: Cotton, Winter wheat, Irrigation requirements, Deficit irrigation, Water savings.

Introduction

Excess irrigation water applied to the main crops in Central Asia, associated with poor supply and distribution management, cause important problems of water wastes and losses, as well as waterlogging and salinity. To find improved solutions for these problems, research was carried out both in field and using the ISAREG irrigation scheduling simulation model (Teixeira and Pereira, 1992; Pereira *et al*., 2003; Fortes *et al.*, 2005). Model testing for cotton and winter wheat is described by Cholpankulov *et al*. (2004; 2005).

An appropriated irrigation scheduling plays an important role in achieving water saving, higher irrigation performances, and in controlling the percolation resulting from excess water irrigation (Smith *et al*., 1996; Pereira *et al*., 2002). Computer models are an easy approach for developing and evaluating alternative strategies for irrigation, and a large number of models are available

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for computing the soil water balance and generating improved irrigation schedules.

The objectives of this study were the development of appropriate irrigation scheduling practices leading to more efficient water use and water savings. In particular, the study aimed at the application of the model to evaluate the current irrigation scheduling practices in the area and to provide for more appropriate irrigation scheduling strategies which could improve the water management practices in the region, including water savings and salinization control.

Soil water balance and modelling

The ISAREG model performs the soil water balance using different options to define and evaluate the irrigation schedules (Teixeira and Pereira, 1992, Liu *et al*. 1998, Fortes *et al*., 2005). The use of the model for generating improved irrigation schedules for surface irrigation or to evaluate the respective potential for reducing water applications are described among others by Liu *et al*. (2000), Campos *et al*. (2003), and Zairi *et al*. (2003).

The reference evapotranspiration is computed with the FAO-Penman-Monteith method (Allen *et al*., 1998) and crop evapotranspiration is estimated with the updated methodology proposed by Allen *et al*. (1998). The crop coefficients (K_c), the soil water depletion fraction for no stress (p), and root depths Zr have been through model calibration, and the groundwater contribution and percolation have been calibrated to the Central Asia conditions (Cholpankulov *et al*., 2004; 2005).

The ISAREG model computes the irrigation water requirements throughout the soil water balance that is calculated for the effective root depth as:

$$\theta_i = \theta_{i-1} + \frac{\left(P_i - RO_i\right) + I_{w\,i} - ET_{c\,i} - DP_i + GW_i}{1000 z_{r\,i}} \qquad [1]$$

where θ_i and θ_{i-1} are soil water content in the root zone ($m^3\ m^{-3}$ or $mm\ mm^{-1}$), in the days i and i-1, P_i is the precipitation (mm), RO_i is the runoff (mm), I_{ri} is the net irrigation depth (mm) that infiltrates the soil, ET_{ci} (mm) is the crop evapotranspiration (mm), DP_i represents deep percolation (mm), GW_i is the capillary rise/groundwater contribution (mm), and $z_{r\,i}$ is the rooting depth (m) in day i. GW and DP are estimated from soil hydraulic properties the water table depth as described by Cholpankulov *et al.* (2005).

The irrigation threshold relative to the depletion fraction for no stress p is

$$\theta_p = (1-p)\left(\theta_{FC} - \theta_{WP}\right) + \theta_{WP} \qquad [2]$$

and the corresponding net irrigation depth is then

$$I_{ni} = 1000 z_{ri}\left(\theta_{FC} - \theta_p\right) \qquad [3]$$

Irrigation is scheduled when the management-allowed depletion, MAD, is attained. When water stress is not admitted, then MAD = p; a MAD < p is adopted when there is risk aversion or uncertainty, and MAD > p when crop water stress is allowed, i.e. when deficit irrigation is applied, which means to adopt an irrigation that only partly satisfies the crop irrigation requirements but is able to provide for a yield reduction that allows the economic return of irrigation. Therefore, irrigations are scheduled (Eq. 1) for

$$\theta_i = \theta_{\mathrm{MAD}} = (1 - \mathrm{MAD})(\theta_{FC} - \theta_{WP}) + \theta_{WP} \quad [4]$$

and the applied depth (norm) is either a user selected fixed quantity D (mm), or a variable D = θ_{FC}-θ_i.

The season net crop irrigation requirements is given by

$$IWR = \frac{ET_c - P_e - GW - \Delta S}{1 - LR} \quad [5]$$

where P_e is the effective precipitation (mm), *GW* is the cumulated capillary rise flux during the crop vegetative period (mm), ΔS is the cumulative variation of the soil water storage in the root zone during the crop vegetative period, and *LR* is the leaching fraction. The gross irrigation water requirement is computed as

$$GIWR = \frac{IWR}{Eff} \quad [6]$$

where *Eff* is the efficiency of the irrigation system.

The yield losses due to water stress are estimated using the yield response factors (K_y) proposed by Doorenbos and Kassam (1979) for the relationship between the seasonal relative evapotranspiration deficit (RED = 1 – ET_d / ET_c) and the relative yield losses (RYL = 1 – Y_d / Y_c):

$$\left(1 - \frac{Y_d}{Y_c}\right) = K_y\left(1 - \frac{ET_d}{ET_c}\right) \quad [8]$$

where ET_d and ET_c are the seasonal crop evapotranspiration (mm) under deficit and full satisfaction, respectively, and Y_d and Y_c are the yields achievable when crop evapotranspiration is ET_d and ET_c, respectively.

The model ISAREG permits several irrigation options according to users objectives. In addition to determine the net irrigation requirements when it is intended to obtain maximum crop yields, it is also allow to develop alternative irrigation schedules based on users defined irrigation depths and dates, which may be selected in various ways and are computed according to the water depth limits and soil water thresholds, as well as considering restrictions to water demand during selected periods (Pereira *et al.*, 2003; Fortes *et al.*, 2005).

Materials and methods

The methodology adopted in this research results from the combination of field experiments and simulation modelling (ISAREG model). The observation data from previous experiments in Hunger Steppe (1982-87) and from recent field trials in the Fergana Valley were analysed and used to calibrate the ISAREG model and to derive crop coefficients and other crop parameters (Cholpankulov *et al*., 2005). The irrigation experiments in Fergana Valley were performed at the farms “Azizbek-1”, Fergana oblast, and “Sandik” and “Toloikon”, Osh oblast. The field observations included climate, crop, soil, and groundwater variables as described in the companion paper (Cholpankulov *et al*., 2005).

The following two irrigation strategies have been simulated:

(a) *Irrigations to maximize yields and reducing percolation*: Irrigations are applied when the average soil water content equals θ_p (eq. 2) and irrigation depths are those required to refill the soil moisture to the field capacity $D = \theta_{FC} - \theta_p$. One restriction was adopted according the actual conditions: no irrigation is applied during the last 20 or 35 days before harvest, respectively for cotton and winter wheat;

(b) *Deficit irrigation*: The irrigation threshold is the same as for alternative (a) but application depths are larger. Various management allowed deficits (MAD) and p values were applied as defined below. Restrictions are the same as for (a).

Cotton irrigation strategies for the Hunger Steppe

Net irrigation requirements

The net irrigation requirements (NIR) (Eq. 5) were computed for all the years comprised in the study (1982-87) for the cotton crop (Table 1).

Table 1. Net irrigation requirements of the cotton crop (1982-87).

Year	NIR (mm)
1982	521
1983	426
1984	576
1985	422
1986	523
1987	423

Optimal irrigation, without water stress

The optimal irrigation schedules were computed with the crop parameters listed in Table 2. Summary results are presented in Table 3.

Table 2. Calibrated cotton growth stages, crop coefficients (K_c) (Hunger Steppe, 1982–1987).

Parameters	*Initial*	*Development*	*Mid season*	*End season*
1982				
Period length (dates)	1/04 –14/04	15/04 24/05	25/05 – 19/08	20/08 – 15/09
Crop coefficients, K_c	0.4	0.42-1.08	1.08	1.08-0.8
1983				
Period length (dates)	22/04 – 8/06	9/06 – 9/07	10/07 – 6/09	7/09 – 30/09
Crop coefficients, K_c	0.5	0.5-1	1	1-0.25
1984				
Period length (dates)	29/04 – 5/06	6/06 – 25/06	26/06 – 31/08	1/09 – 30/09
Crop coefficients, K_c	0.35	0.35-1.2	1.2	1.2-0.6
1985				
Period length (dates)	22/04 – 9/06	10/06 – 27/06	28/06 – 24/08	25/08 – 30/09
Crop coefficients, K_c	0.55	0.55-1.05	1.05	1.05-0.25
1986				
Period length (dates)	1/04 – 16/04	17/04 – 14/06	15/06 – 31/08	1/09 – 20/09
Crop coefficients, K_c	0.55	0.55-1.1	1.1	1.1-0.4
1987				
Period length (dates)	6/05 – 5/06	6/06 – 21/07	22/07 – 31/08	1/09 – 30/09
Crop coefficients, K_c	0.45	0.45-1.1	1.1	1.1-0.4

Table 3. Cotton irrigation scheduling aiming at maximizing yields, Hunger Steppe.

	Irrigations					
	1982		***1983***		***1984***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	23 Jun	294	3 Jul	214	23 Jun	180
	8 Aug	298	12 Aug	236	16 Jul	180
					6 Aug	180
Season irrigation (mm)	592		450		540	
Season rainfall (mm)	35		47		15	
TAW (mm/m)	240		210		200	
ASW at planting (mm)	403		284		240	
ASW at harvesting (mm)	316		119		69	
Capillary rise (mm)	0		16		29	
ET_c (mm)	714		678		755	
	1985		***1986***		***1987***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	29 Jun	210	22 May	135	9 Jul	202
	6 Aug	242	28 Jun	143	16 Aug	225
			22 Jul	143		
			20 Aug	143		
Season irrigation (mm)	452		564		427	
Season rainfall (mm)	41		117		70	
TAW (mm/m)	230		130		200	
ASW at planting (mm)	335		163		270	
ASW at harvesting (mm)	140		95		103	
Capillary rise (mm)	7		0		24	
ET_c (mm)	694		748		688	

Results in Table 3 refer to schedules simulated aiming at maximizing crop yields, thus when $ET_{c\ adj} = ET_c$. The net season irrigation varies in the range 427 to 592 mm, season rainfall ranges from 15 to 117 mm and season crop ET from 678 to 755 mm. The season irrigation relates also with the available soil water (ASW) at planting and at harvesting, being higher when the later is higher, i.e. the crop thus not adequately uses the stored soil water. The irrigation depths are very high, as thy use to be currently practiced there; an alternative could be to increase the number of irrigations and apply less water at each time.

Current irrigation scenario

The current cotton irrigation schedules used in Hunger Steppe were simulated for the irrigation depths and dates used by the farmers (Table 4). Because farmers tend to anticipate applications and use very large irrigation depths (see Horst *et al*., 2005), the depletion fraction is small (p = 0.4).

Table 4. ISAREG simulation of the current average irrigation schedules for the cotton crop at Hunger Steppe.

	Irrigations					
	1982		***1983***		***1984***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	1 Jul 6 Aug	260 260	20 Jun 22 Jul 27 Aug	230 200 200	18 Jun 31 Jul 21 Aug	161 250 219
Season irrigation (mm)	520		630		630	
Season rainfall (mm)	35		47		15	
TAW (mm/m)	480		315		300	
ASW at planting (mm)	302		284		240	
ASW at harvesting (mm)	186		194		157	
Percolation (mm)	50		116		87	
Capillary rise (mm)	18		3		17	
Non-used rainfall (mm)	0		0		0	
$ET_{c\ adj}$ (mm)	638		653		657	
ET_c (mm)	714		678		755	
	1985		***1986***		***1987***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	16 Jul	310	3 Jun 3 Jul 11 Aug	62 200 170	14 Jul 30 Aug	220 180
Season irrigation	310		432		400	
Season rainfall	41		117		70	
TAW (mm/m)	345		156		300	
ASW at planting (mm)	335		163		270	
ASW at harvesting (mm)	89		66		141	
Percolation (mm)	52		67		26	
Capillary rise (mm)	19		29		17	
Non-used rainfall (mm)	0		0		0	
$ET_{c\ adj}$ (mm)	564		608		590	
ET_c (mm)	694		748		688	

Results in Table 3 indicate that the farmers irrigation scheduling corresponds to irrigate before the optimal date, thus resulting in percolation (e.g. Fig. 1). However, water was not always available in due time so also some water stress was identified with the actual ET_c smaller than the potential ET_c. The irrigation depths per application are very high, generally ranging from 160 mm to 260 mm, depending on the specific characteristics of the year and water availability, which favour percolation. The overall season irrigation ranges from 310 mm to 630 mm. Results in Table 3 indicate that rainfall is fully used and percolation often exceeds the leaching requirements (c.a. 5 % of the irrigation depths).

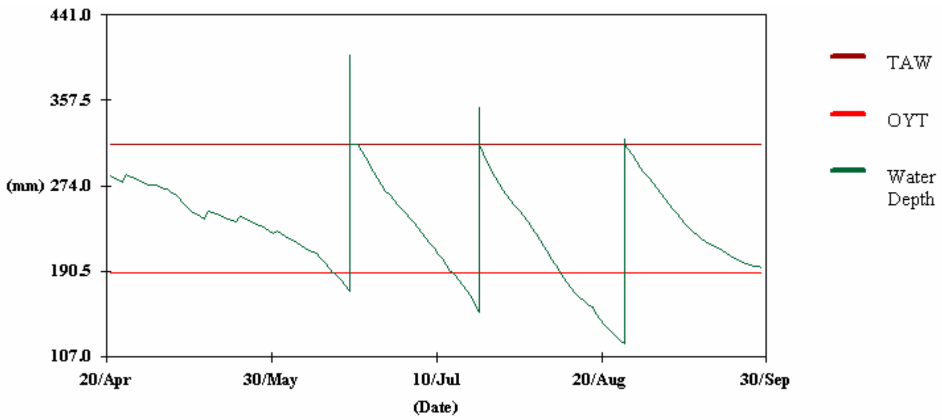

Fig. 1. Seasonal soil water variation for a typical current irrigation schedule showing the occurrence of both percolation and water stress, Hunger Steppe, 1983.

Improved scenarios for maximal yields and percolation control

The improved irrigation schedules were designed with two main objectives: water saving and percolation control (Table 5 and 6). A time limit of 20 days imposed to the last irrigation before cotton harvesting was considered. Two irrigation thresholds MAD = p were adopted, one with constant p = 0.4, the other with constant p = 0.6. The irrigation depths are constant for each year, and range from 82 to 144 mm when p = 0.4, and from 123 to 216 mm in case p = 0.6. Of course, the number of irrigations is higher than for the current schedules.

Results presented in Table 5 for p = 0.4 show that actual ET_c is about equal to potential ET_c (Table 3), thus indicating that water stress is not induced. Relative to the actual schedule (Table 4), the seasonal irrigation applied is higher, however with smaller event depths, which favours percolation control. The total number of irrigation events is higher, in agreement with field studies by Horst *et al*. (2005).

Table 5. Cotton irrigation scheduling aiming at minimizing percolation and avoiding crop water stress using a constant soil water depletion fraction p = 0.4, Hunger Steppe.

	Irrigation					
	1982		***1983***		***1984***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	16 May	144	16 Jun	126	9 Jun	120
	25 Jun	144	10 Jul	126	29 Jun	120
	19 Jul	144	29 Jul	126	16 Jul	120
	8 Aug	144	21 Aug	126	30 Jul	120
					14 Aug	120
					2 Sep	120
Season irrigation (mm)	576		504		720	
ASW at planting (mm)	302		284		240	
ASW at harvesting (mm)	202		161		222	
Capillary rise (mm)						
$ET_{c\ adj}$ (mm)	713		675		755	
	1985		***1986***		***1987***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	16 Jun	138	3 May	82	22 Jun	120
	11 Jul	138	29 May	82	17 Jul	120
	29 Jul	138	23 Jun	82	3 Aug	120
	25 Aug	138	6 Jul	82	22 Aug	120
			20 Jul	82		
			6 Aug	82		
			22 Aug	82		
Season irrigation	552		574		481	
ASW at planting (mm)	335		163		270	
ASW at harvesting (mm)	235		106		142	
Capillary rise (mm)			0		3	
$ET_{c\ adj}$ (mm)	694		747		683	

Results for irrigation scheduling when p = 0.6 are presented in Table 6. They show that irrigation depths applied per event are closer to those actually applied in surface irrigation, ranging 123 to 216 mm; however, in theory, percolation may be avoided; however, in practice it becomes more difficult with such large depths if the irrigation timing is not accurately considered.

$ET_{c\ adj}$ is also close to ET_c (cf. Table 3), thus water stress and yield losses are avoided. In Fig. 2, an example of the soil water dynamics of the improved schedule when p = 0.6 is given.

Table 6. Cotton irrigation scheduling aiming at minimizing percolation and avoiding crop water stress with p = 0.6, Hunger Steppe.

	Irrigations					
	1982		***1983***		***1984***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	10 Jun	216	27 Jun	189	23 Jun	180
	19 Jul	216	30 Jul	189	16 Jul	180
	22 Aug	216	1 Sep	189	6 Aug	180
					3 Sep	180
Season irrigation (mm)	648		567		720	
ASW at planting (mm)	302		284		240	
ASW at harvesting (mm)	273		225		227	
Capillary rise (mm)	0		5		6	
$ET_{c\ adj}$ (mm)	714		678		755	
	1985		***1986***		***1987***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	28 Jun	207	20 May	123	3 Jul	180
	29 Jul	207	23 jun	123	3 Aug	180
	8 Sep	207	13 Jul	123	2 Sep	180
			6 Aug	123		
			30 Aug	123		
Season irrigation	621		614		540	
ASW at planting (mm)	335		163		270	
ASW at harvesting (mm)	306		146		200	
Capillary rise (mm)	2		0		6	
$ET_{c\ adj}$ (mm)	694		748		688	

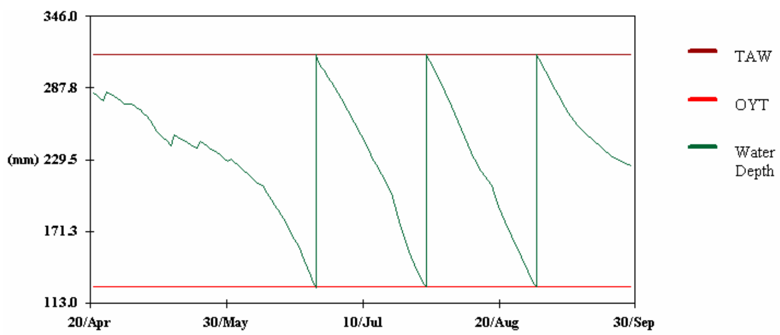

Fig. 2. Soil water dynamics for an improved irrigation schedule aiming at no percolation and avoiding cotton water stress, assuming p=0.6. Hunger Steppe, 1983.

Deficit irrigation schedule

In Table 7 are presented the results of an improved irrigation schedule were a water stress during the crop development was allowed. The threshold MAD = 0.75 was adopted and the depletion fraction p 0.6 was assumed.

Table 7. Deficit irrigation scheduling for cotton adopting MAD=0.75, Hunger Steppe.

	Irrigations					
	1982		***1983***		***1984***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	20 Jun	252	6 Jul	221	27 Jun	210
	1 Aug	252	13 Aug	221	25 Jul	211
					21 Aug	210
Season irrigation (mm)	504		442		631	
ASW at planting (mm)	302		284		240	
ASW at harvesting (mm)	145		121		159	
Capillary rise (mm)	5		16		13	
$ET_{c\ adj}$ (mm)	701		666		740	
	1985		***1986***		***1987***	
	Dates	Depth (mm)	Dates	Depth (mm)	Dates	Depth (mm)
	6 Jul	242	25 May	143	912 Jul	210
	14 Aug	242	30 Jun	143	16 Aug	210
			28 Jul	143		
			25 Aug	143		
Season irrigation (mm)	484		572		420	
ASW at planting (mm)	335		163		270	
ASW at harvesting (mm)	181		122		108	
Capillary rise (mm)	5		3		23	
$ET_{c\ adj}$ (mm)	683		733		676	

The results show that even though the total irrigation applied is lower then the required to fully satisfy the irrigation requirements, the relative yield losses are non-significant (2%). An example of the respective soil water dynamics is given in Fig. 3.

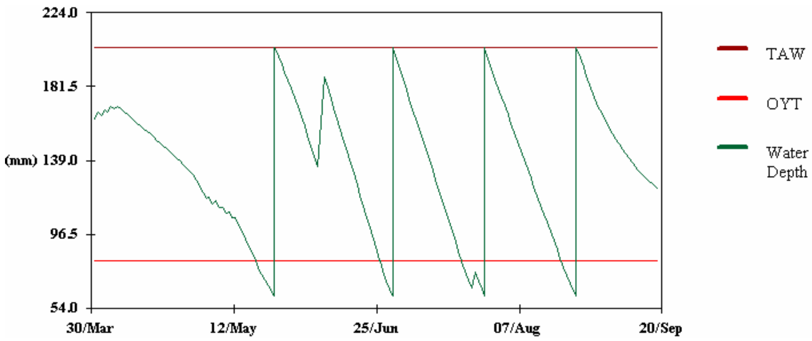

Fig. 3. Example of soil water dynamics of a deficit irrigation schedule for cotton adopting MAD = 0.75, Hunger Steppe, 1986.

Adopting MAD = 0.75 may lead in some years to considerable water savings as summarized in (Table 8), about 25% of the seasonal irrigation. These savings are higher when the irrigation systems are improved as described by Horst *et al*. (2005); however, despite improving schedules and systems both lead to water saving, these are not cumulative.

Table 8. Comparing seasonal cotton irrigation requirements when full irrigation (MAD=0.6) or deficit irrigation (MAD=0.75) is adopted for p = 0.6.

	1982	1983	1984	1985	1986	1987
MAD=0.6	649	567	720	621	614	541
MAD=0.75	504	442	631	484	572	420
Net saving	145	125	89	137	32	121

Results for Hunger Steppe show that adopting the soil water depletion fraction p = 0.6 is appropriate for cotton irrigation and that the best water saving strategy is to irrigate with a MAD = 0.75.

Cotton and Winter wheat in Fergana Valley

Three locations were selected in the Fergana Valley (Fig. 4) to perform experimental research: one "Azizbek-1" farm, Fergana oblast, Uzbekistan, and two in "Sandik" and "Toloikon" farms, Osh oblast, Kyrgyzstan. The weather data sets used are relative to Fergana (Uzbekistan) and Karasu, Osh (Kyrgyzstan) meteorological stations. The climate and soils characterization of these locations is described in the companion paper, as well as the crop parameterization (Chopankulov *et al*., 2005).

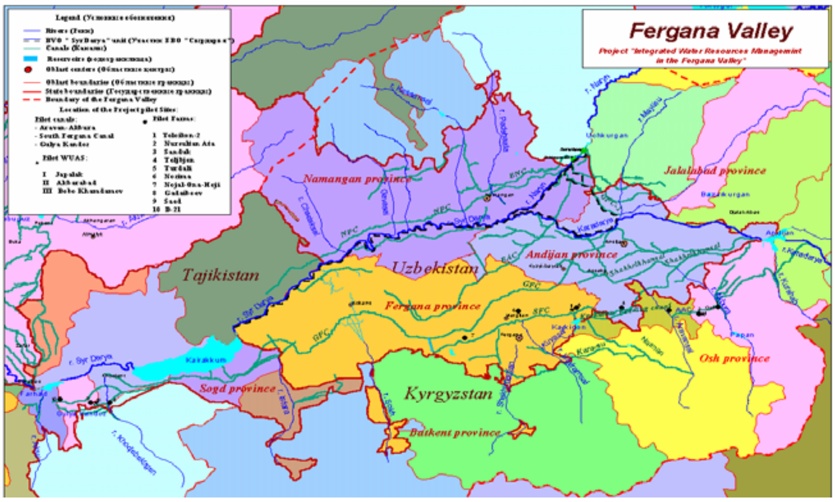

Fig. 4. Map of Fergana Valley with indication of experimental farms.

Crop parameters and net irrigation requirements

The irrigation schedules scenarios were computed with the crop parameters listed in Tables 9 and 10 respectively for the cotton and winter wheat crops.

Table 9. Crop growth stages, crop coefficients (K_c) and depletion fraction for no stress (p) for the cotton crop in Fergana Valley.

Azizbek-1 farm (Fergana oblast), 2001				
	Initial	*Development*	*Mid season*	*End season*
Period lengths (dates)	8/04 – 7/06	8/06 – 4/07	5/07 – 27/08	28/08 – 1/10
K_c	0.11	0.11 – 1.0	1.0	1.0 - 0.55
p	0.6	0.6	0.6	0.7
Sandik farm (Osh oblast), 2003				
Period lengths (dates)	4/05 – 14/06	15/06 – 14/07	15/07 – 30/08	1/09 -14/10
K_c	0.67	0.67-1	1	0.65
p	0.4	0.55	0.65	0.7

Table 10. Crop growth stages and crop coefficients (K_c) for the winter wheat crop in e Fergana Valley.

Azizbek-1 Farm (Fergana oblast) 2001-2002					
	Planting	*Frozen soil*	*Development*	*Mid season*	*End season*
Period lengths	5/10 – 30/11	1/12 – 7/03	08/03 – 14/04	15/04 – 25/05	26/05 – 22/06
K_c	1.14	0.2	1.20	1.20	0.35
p	0.2	0.2	0.3	0.7	0.8
Toloikon farm (Osh oblast) 2001-2002					
	Planting	*Frozen soil*	*Development*	*Mid season*	*End season*
Period lengths	28/09 – 30/11	1/12 – 28/02	1/03 – 14/06	15/06 – 24/07	25/07 – 10/08
K_c	0.9	0.4	0.9	1.1	0.5
p	0.3	0.2	0.4	0.7	0.5

Net irrigation requirements

The net irrigation requirements (NIR) for the cotton and winter wheat crops were determined for all the years comprised in the data sets. Results for Fergana oblast are shown in Fig 5.

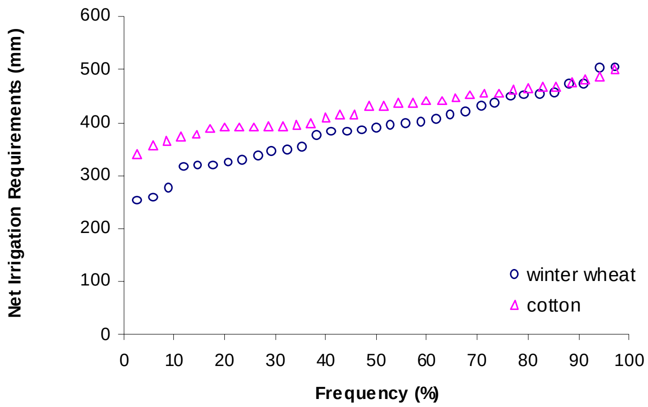

Fig. 5. Net irrigation requirements for cotton and winter wheat, Fergana (1970-2003).

Results for the experimentation years are shown in Tables 11 and 12 for both crops. Differences for cotton are small among both locations but those relative to winter wheat are relatively large due to differences in precipitation during the crop season.

Table 11. Net irrigation requirements for the cotton crop.

Location	*Fergana Oblast*	*Osh oblast*
Year	2001	2003
NIR (mm)	391	370

Table 12. Net irrigation requirements for the winter wheat crop.

Location	*Fergana oblast*	*Osh oblast*
Year	2001-02	
NIR (mm)	280	358

Cotton in Fergana Valley

Irrigation for maximizing yields

This irrigation schedule scenario (Table 13) refers to schedules simulated aiming at maximizing crop yields, thus without allowing water stress and producing $ET_{c\,adj} = ET_c$. Constant irrigation depths were considered. Results shows that the groundwater contribution may play a non-negligible role in the decrease of the irrigation requirements at Fergana oblast. In this location ET_c is smaller than in Osh oblast due to climate differences between the experimentation years considered.

Table 13. Cotton irrigation scheduling aiming at maximizing yields, Fergana Valley.

Location	***Fergana oblast, 2001***		***Osh oblast, 2003***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	1 Jul	67	29 Jun	120
	14 Jul	67	23 Jul	120
	3 Aug	67	17 Aug	120
	3 Sep	67	13 Sep	120
Season irrigation (mm)	268		480	
Season rainfall (mm)	58		140	
TAW (mm/m)	155		200	
ASW at planting (mm)	100		180	
ASW at harvesting (mm)	75		182	
Capillary rise (mm)	138		-	
ET_c (mm)	492		618	

Current irrigation scenario

Using daily weather data for the selected years and the computed watertable depth, simulations were performed for each TAW soil classes adopting the average irrigation depths and irrigation frequency typically used, as observed in farmer's fields (Table 14). The soil water depletion fraction is very small (p = 0.4) when compared with that recommended by Allen *et al*. (1998) and in agreement with observations by Horst *et al*. (2005), very high percolation occurs (see Fig. 6).

Table 14. ISAREG simulation of the current average irrigation schedules for the cotton crop, Fergana Valley.

Location	***Fergana oblast, 2001***		***Osh oblast, 2003***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	08 Jun	119	24 Jun	177
	04 Jul	202	13 Jul	78
	17 Jul	113	27 Jul	58
	30 Jul	155	9 Aug	14
	14 Aug	183	12 Aug	100
Season irrigation (mm)	865		427	
Season rainfall (mm)	45		140	
TAW (mm/m)	155		200	
ASW at planting (mm)	100		180	
ASW at harvesting (mm)	94		77	
Percolation (mm)	491		98	
Capillary rise (mm)	61		-	
Non-used rainfall (mm)	0		0	
$ET_{c\ adj}$ (mm)	486		573	
ET_c (mm)	492		618	

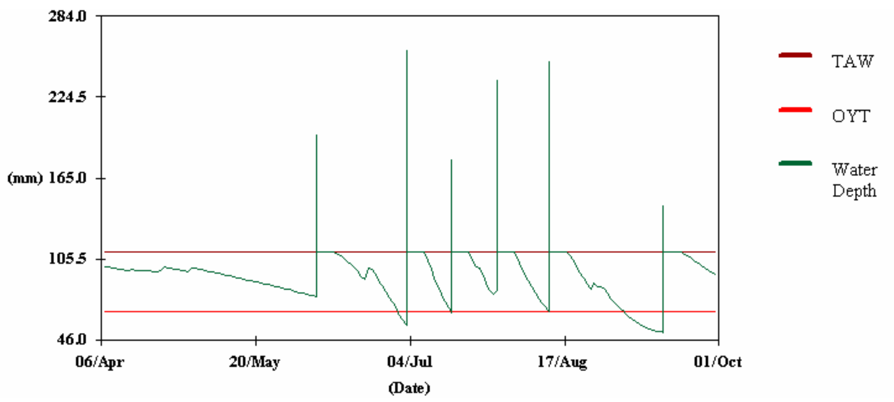

Fig. 6. Typical current irrigation schedule for cotton showing excess water application and related percolation, Azizbek-1 farm, Fergana oblast, 2001.

Results show that the current irrigation scheduling is not appropriate for the existing soil water conditions: too much water is applied, the soil water is maintained always high, including at harvesting, thus producing high percolation, extremely high in case of Fergana oblast (23 and 57% of the total water applied at Osh and Fergana oblast, respectively).

The results also show that the irrigation timings are not adequate which induces crop water stress; thus, the actual crop evapotranspiration ($ET_{c\ adj}$) is smaller than the potential crop ET (ET_c) and consequently yield losses occur. This indicates that improved schedules must be implemented together with the improvement of the farm irrigation systems (Horst *et al.*, 2005) for controlling the percolation losses and to achieve water savings. Therefore, further studies focused in improving the irrigation schedules taking into consideration these perspectives.

Improved scenarios for avoiding water stress no stress and percolation

The irrigation schedules proposed aimed at controlling the percolation by adjusting the irrigation depths used by traditional irrigation in agreement with those considered in studies for improving furrow irrigation (Horst *et al.*, 2005) and, simultaneously maximizing crop yields or accepting a limited yield decrease.

The following irrigation thresholds were assumed: p = 0.4 and p = 0.6, the first being close to the strategies used by farmers. Tables 15 and 16 present examples of these improved irrigation schedules.

Table 15. Irrigation scheduling for cotton aiming at minimizing percolation and avoiding water stress, using p = 0.4, Fergana Valley.

Location	***Fergana oblast, 2001***		***Osh oblast, 2003***	
	Dates	Irrigation (mm)	Dates	Irrigation (mm)
Irrigations after planting	17 Jun	45	15 Jun	80
	2 Jul	44	7 Jul	80
	10 Jul	45	23 Jul	80
	19 Jul	45	9 Aug	80
	1 Aug	44	25 Aug	80
	10 Aug	45	13 Sep	80
	25 Aug	45		
Season irrigation (mm)	313		480	
ASW at planting (mm)	100		180	
ASW at harvesting (mm)	52		182	
Capillary rise (mm)	83		-	
$ET_{c\ adj}$ (mm)	486		618	
ET_c (mm)	492		618	

Results presented in Table 15 show that the actual ET_c is similar to the potential ET_c thus indicating that water stress is not induced. In relation with the actual irrigation schedule (Table 14) the total irrigation applied is much lower, and the irrigation depths per event are also lower, respectively 45 and 80 for

Fergana and Osh oblast. The groundwater contribution keeps important at Fergana oblast, and the available soil water at harvesting decreases relative to the simulated current schedules, thus indicating better use of soil water and rainfall.

In Table 16 are shown the results for the case when p raises to 0.6, as for the respective results obtained from calibration.

Table 16. Irrigation scheduling for cotton aiming at minimizing percolation, refilling the soil reservoir to field capacity and avoiding water stress using p = 0.6, Fergana Valley.

Location	***Fergana oblast, 2001***		***Osh oblast, 2003***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	1 Jul	67	29 Jun	120
	14 Jul	67	23 Jul	120
	3 Aug	67	17 Aug	120
	3 Sep	67	13 Sep	120
Season irrigation (mm)	268		480	
ASW at planting (mm)	100		180	
ASW at harvesting (mm)	59		183	
Capillary rise (mm)	137		-	
$ET_{c\ adj}$ (mm)	492		618	
ET_c (mm)	492		618	

The results in Table 16 show an increase of the groundwater contribution in the Fergana oblast case study and a consequent decrease of the season irrigation when p=0.6 is adopted. ET_c corresponds to the maximum evapotranspiration, thus water stress and yield losses are avoid. In the case of the Osh oblast no significant differences are obtained from considering a higher p (p = 0.6).

The results, summarized in Table 15 and 16, show that when appropriate irrigation depths and timings are selected the seasonal irrigation could be highly reduced relative to present and deep percolation could be avoided, so avoiding that the water rises with consequent impacts on soil salinization.

Deficit irrigation schedule for p=0.6 and MAD=0.75

In Table 17 is presented an improved irrigation schedule when a limited water stress is allowed. This condition corresponds to irrigate when the soil water content reaches 25% of the TAW, i.e. MAD = 0.75. The depletion fraction p = 0.6 is assumed.

Results show that comparative to the previous non-stressed strategy for MAD = p = 0.6, the groundwater contribution increases and the cumulative season irrigation decreases in case of Azizbek, Fergana, without inducing a great crop water stress; for Osh, differences between both strategies are smaller. In Table 18 are summarized the differences in water use due to both schedules, showing that the water saving resulting from a limited deficit are foreseen to be quite high with yield losses lower than 8%.

Table 17. Deficit irrigation scheduling for cotton adopting MAD=0.75, Fergana Valley case study.

Location	***Fergana oblast, 2001***		***Osh oblast, 2003***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	5 Jul	78	4 Jul	140
	26 Jul	78	1 Aug	140
			31 Aug	140
Season irrigation (mm)	156		420	
ASW at planting (mm)	35		180	
ASW at harvesting (mm)	197		132	
Capillary rise (mm)	197		-	
$ET_{c\ adj}$ (mm)	456		609	
ET_c (mm)	492		618	

Table 18. Comparing seasonal cotton irrigation requirements when full irrigation or deficit irrigation is adopted (p = 0.6 for both cases).

	Fergana oblast	***Osh oblast***
MAD = 0.6	268	480
MAD = 0.75	156	420
Net saving	112	60

The proposed improved schedules in Table 16 may be proposed for adoption but adapted to the climate conditions of the current year.

Winter wheat

Irrigation for maximizing yields

The irrigation schedule scenario shown in Table 19 refers to schedules simulated aiming at maximizing crop yields, not allowing water stress, so with $ET_{c\ adj} = ET_c$.

The results presented in the Table 19 show that, similarly to the case for the cotton crop, the groundwater contribution plays a non-negligible role in the decrease of the irrigation requirements at Fergana oblast. Results indicate that the irregular distribution of precipitation makes that rainfall is not fully used and that at harvest the soil water is relatively high. This is particularly evident for the Osh oblast case study.

Table 19. Irrigation scheduling aiming at maximizing yields for winter wheat crop for the prevailing soil classes, Fergana Valley.

Location	Fergana oblast		Osh oblast	
Irrigations after planting	Dates	Depth (mm)	Dates	Depth (mm)
	20 Nov	105	8 Nov	132
	12 May	105	16 Jun	132
	5 Jun	105	10 Jul	132
Season irrigation (mm)	315			396
Season rainfall (mm)	219			524
TAW (mm/m)	175			220
ASW at planting (mm)	105			132
ASW at harvesting (mm)	134			88
Capillary rise (mm)	58			-
Non used rainfall (mm)	98			271
ET_c (mm)	465			694

Actual irrigation scenario

As for cotton simulations, this one is performed adopting the average irrigation depths and dates observed in farmer's fields (Table 20). Also as for the cotton crop, it may be observed that the farmers use to irrigate before the optimal date, therefore adopting a secure non-stress irrigation scheduling, but producing quite high percolation and a limited use of rainfall. The fact they irrigated out of appropriate dates, mainly due to a relatively poor delivery scheduling (see Dukhovny and Tuchin, 2005), makes that excess water is nevertheless associated with water stress ($ET_{c\ adj} < ET_c$).

Table 20. ISAREG simulation of the current average irrigation schedules for the winter wheat crop, Fergana Valley.

Location	***Fergana oblast***		***Osh oblast***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	10 Oct	163	1 Oct	124
	16 Feb	119	20 May	141
	08 Mar	130		
	20 Apr	137		
Season irrigation (mm)	548		265	
Season rainfall (mm)	219		524	
TAW (mm/m)	175		220	
ASW at planting (mm)	105		132	
ASW at harvesting (mm)	55		30	
Percolation (mm)	400		118	
Capillary rise (mm)	62		-	
Non-used rainfall (mm)	70		236	
$ET_{c\ adj}$ (mm)	409		537	
ET_c (mm)	465		694	

An example of an irrigation scheduling with excess water depths applied is show in Fig. 7. Results show that an irrigation before soil freezing, by October, is currently practiced to refill the soil profile. This pre-planting irrigation provides water to the early stages of the crop. The current irrigation scheduling is not appropriate and too much applied water results in percolation (73% and 45% of the season irrigation total respectively for Fergana and Osh oblast).

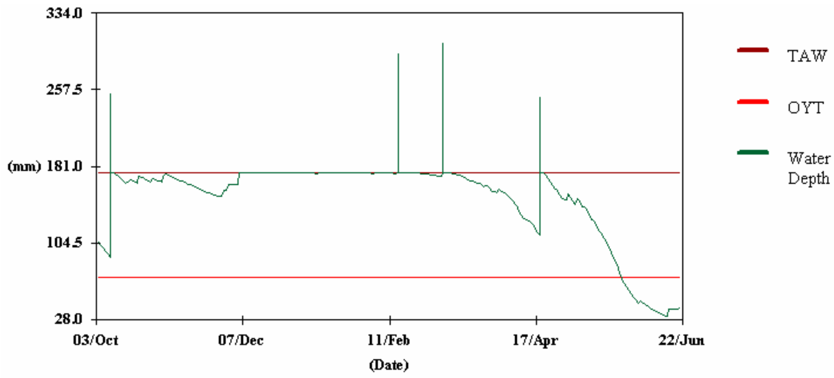

Fig. 7. Soil water dynamics for a typical current irrigation schedule evidencing excess water application and resulting percolation, Azizbek-1 farm, Fergana oblast.

Improved scenarios for no stress

The irrigation schedules aimed at reduction of percolation and maximizing crop yield were simulated for MAD = p = 0.6 (Table 21). The results for Fergana oblast show an increase of the groundwater contribution and a small difference between the actual ET_c and the potential ET_c, thus inducing only slight yield losses; for Osh results are less good. In Fig. 8 is presented an example of an improved irrigation scheduling aiming at no percolation.

Table 21. Irrigation scheduling for winter wheat crop aiming at minimizing percolation, and avoiding water stress, using p = 0.6, Fergana Valley.

Location	***Fergana oblast***		***Osh oblast***	
	Dates	Depth (mm)	Dates	Depth (mm)
Irrigations after planting	20 Nov	105	8 Nov	132
	12 May	105	16 Jun	132
Season irrigation (mm)	210		264	
ASW at planting (mm)	105		132	
ASW at harvesting (mm)	51		28	
Capillary rise (mm)	69		-	
Non used rainfall (mm)	99		271	
$ET_{c\ adj}$ (mm)	453		622	
ET_c (mm)	465		694	

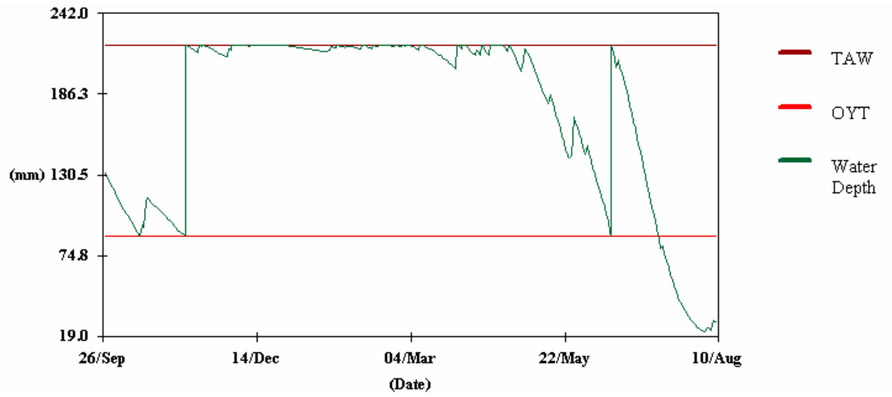

Fig. 8. Soil water dynamics for an improved wheat irrigation schedule aiming at water saving, no percolation and maximizing yields, Toloikon farm, Osh oblast.

Deficit irrigation scenario

An improved irrigation schedule when water stress is allowed along the crop development is presented in Table 22. The threshold imposed was to irrigate when the soil water content reached 25% of the TAW (MAD = 0.75), thus leading to yield losses. A constant p = 0.6 is adopted.

Table 22. Irrigation scheduling for winter wheat crop adopting MAD = 0.75 and p = 0.6, Fergana Valley.

Location	***Fergana oblast***		***Osh oblast***	
Irrigations after planting	Dates	Depth (mm)	Dates	Depth (mm)
			23 Jun	154
Season irrigation (mm)	No irrigation required		154	
ASW at planting (mm)	105		132	
ASW at harvesting (mm)	34		32	
Capillary rise (mm)	87		-	
Non used rainfall (mm)	0		139	
$ET_{c\ adj}$ (mm)	453		637	
ET_c (mm)	492		694	

Results that an important water saving may be achieved (ranging 100% as depicted in Fig. 9 and a year with high rainfall, and 42% respectively in Fergana and Osh oblast) without significant yield losses (less than 19%). The capillary fluxes constitute a very high contribution, in the case of Fergana oblast to compensate for evapotranspiration thus highly complementing rainfall. However, such schedule is no more than indicative and may not be applicable in most years since net irrigation requirements range generally 250 to 500 mm (Fig. 5).

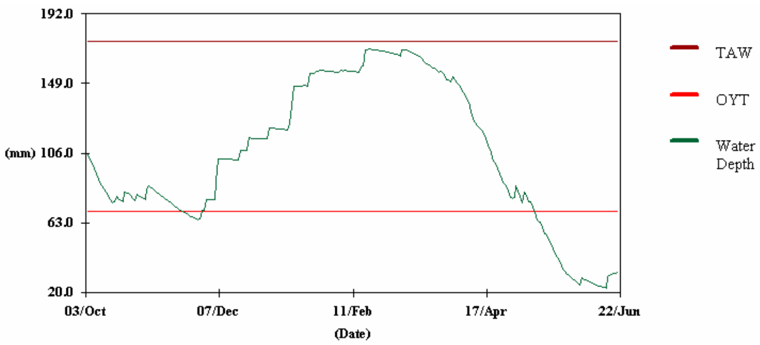

Fig. 9. Example of soil water dynamic of a wheat crop under deficit irrigation schedule (MAD = 0.75), Azizbek-1 farm, Fergana oblast, resulting in rainfed conditions.

Conclusions

The presented study shows that due to the present conditions of water scarcity faced by Central Asia countries the use of irrigation simulation models to generate alternative irrigation schedules is useful. Furthermore, results show that the WINISAREG version of the ISAREG model was successfully applied to simulate the current and foreseen irrigation schedules for the Hunger steppe and Fergana Valley case studies. In both experimental areas and for the cotton and winter wheat crops, the actual irrigation schedules reflect high non-beneficial water use as percolation, which may contribute to soil salinization. Thus the farmers' option for anticipating the timings for irrigation and adoption of very high application depths should be avoided by proposing them alternative irrigation schedules similar to those presented herein but adapted to the actual climate and soil conditions.

To achieve this purpose, schedules for p = 0.6 and MAD in the range 0.6 to 0.75 for cotton, and for p = 0.55 and MAD between 0.55 and 0.7 for winter wheat should be prepared similar to the ones in this paper for the years in the data set where the climatic demand corresponds to wet, average, dry and very dry conditions. These schedules could be selected early in the crop season, proposed to farmers for them to plan irrigation, and then periodically adjusted to the actual climate. Using the GISAREG version with this purpose could be useful for disseminating the information on a spatial scale. Further water savings can be achieved when improvements in scheduling and furrow irrigation could be combined.

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