WATER PRODUCTIVITY OF FOUR EXPRIMENTAL FIELDS IN QAZVIN PLAIN IRRIGATION NETWORK

PRODUCTIVITE DE L'EAU SUR LE QUATRE CHAMPS D'EXPERIMENTATION DU RESEAU D'IRRIGATION DE LA PLAINE DE QAZVIN

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ABSTRACT

In this paper, water productivity for cotton and wheat was analyzed with SWAP and SWAP-WOFOST models for four experimental fields of Sharif Abad district (located in Qazvin plain irrigation network) during the agricultural year 2005- 06. Using the SWAP model the average WP_T, WP_{ET} and WP_{ETQ} were 0.34, 0.28 and 0.25 for cotton and 1.23, 1.1 and 0.92 for wheat, respectively. The average WP_T, WP_{ET} and WP_{ETQ} with SWAP- WOFOST model were 0.41, 0.32 and 0.29 for cotton and 1.58, 1.39 and 1.18 for wheat, respectively. The result showed that the factors responsible for low values of water productivity in each model (with comparison WP_T) include a high share of soil evaporation (10-28%), percolation and seepage losses from fields and conveyance system (21-55%) that must be reduced.

The average WP_{ET} for wheat obtained from SWAP- WOFOST was 26% higher than that obtained from SWAP. Improving crop management in by timely sowing and optimal fertilizer, and better pest and disease control is expected to achieve this significant increase in the WP_{ET} for wheat. Also, the WP_T, WP_{ET} and WP_{ETQ} values for cotton obtained from SWAP-WOFOST were slightly higher than those obtained from SWAP model. This suggests that ensuring the irrigation supplies, especially during the dry year, and improved crop management will increase cotton yields and subsequently its water productivity in Sharif Abad district.

Key words: *Irrigation network, Qazvin plain, cotton and wheat productivity, SWAP model, Water and salt balance.*

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RESUME

Le rapport analyse la productivité de l'eau pour le coton et le blé utilisant les modèles SWAP et SWAP-WOFOST dans quatre champs d'expérimentation du périmètre de Sharif Abad (situé dans le réseau d'irrigation de la plaine de Qazvin) durant l'année agricole 2005-06. En utilisant le modèle SWAP, la moyenne de WP_T, WP_{ET} et WP_{ETQ} pour le coton était de 0,34, 0,28 et 0,25 et pour le blé 1,23, 1,1 et 0,92 respectivement. Dans le modèle SWAP-WOFOST, la moyenne de WP_T, WP_{ET} et WP_{ETQ} pour le coton était de 0,41, 0,32 et 0,29 et pour le blé 1,58, 1,39 et 1,18 respectivement. Le résultat a montré que les facteurs chargés des valeurs inférieures de la productivité de l'eau dans chaque modèle (par rapport au WP_T) comprenaient une haute part d'évaporation du sol (10-28 %). Il faut réduire les pertes de percolation, d'infiltration des champs et de système de transport (21-55 %).

La moyenne de WP_{ET} pour le blé obtenue par SWAP-WOFOST était 26 % plus haute que celle obtenue par SWAP. L'amélioration de la gestion agricole est attendue par l'ensemencement opportun, l'engrais optimal et le meilleur contrôle de parasite et de maladie pour réaliser cette augmentation significative de WP_{ET} pour le blé. Les valeurs de WP_T, WP_{ET} et WP_{ETQ} pour le blé du modèle SWAP-WOFOST étaient également élevées par rapport aux celles du modèle SWAP. Cela propose que la fourniture d'irrigation particulièrement lors de l'année sèche et l'amélioration de la gestion agricole augmentera les rendements du coton et, par la suite, la productivité de l'eau dans le périmètre de Sharif Abad.

Mots clés : *Réseau d'irrigation, plaine de Qazvin, productivité du coton et du blé, SWAP model, bilan d'eau et de sel.*

1. INTRODUCTION

Iran, with an area of 1,648,195 km^2 is placed in the dry belt of the world and precipitation and evaporation rate is equal 0.33% and 3 times of the world average, respectively. Spatial and temporal distribution of precipitation is erratic . Hence water shortage is one of the major challenges in the arid region of Iran. This challenge is likely to intensify with population growth. For instance, the population in Iran has increased by a factor of 6.8 during the last 80 years, from under 10 million in 1925 to 68 million in 2004. With the current population growth rate, Iran's population will reach 100 million by the year 2025, which may outweigh the growth of food production. The annual per capita utilizable fresh water in Iran has decreased from 13000 m^3 in 1925 to 1900 m^3 in 2004. Countries with annual per capita water availability of less than 1700 m^3 are water stressed, and less than 1000 m^3 as water scarce (Falkenmark et al., 1989). Taking into account the increase in population up to 100 million by the year 2025, Iran will need 170 billion m^3 of water per year to be above the water stress zone and 100 billion m^3 of water per year to avoid being a water scarce country. However, the total annual renewable water resources in Iran are assessed at 130 billion m^3, of which 95 billion m^3 of surface water and 25 billion m^3 of groundwater are utilizable. Irrespective of certain assumptions and uncertainties involved in these future water and food demand projections, it is obvious that the agricultural sector has to produce more food with the same or less amount of water resources. One important strategy for overcoming this crisis is to increase the productivity of water (Molden, 1997; Molden et al., 2001). In other words, the future food production must focus on the improvement of water productivity i.e. ´more crop per drop' (IWMI, 2000).

Water productivity analysis requires the quantification of the hydrological variables transpiration, evapotranspiration and percolation, and the biophysical variables dry matter or grain yield. Measurement of the hydrological variables under field conditions is difficult, and needs sophisticated instruments or installation of lysimeters. The ecohydrological models like SWAP in combination with field experiments quantify these difficult-to-measure hydrological and biophysical variables in space and time. The accuracy of these predictive models depends upon the proper identification of input parameters. In this paper, a comprehensive analysis of input parameters and predicted results of SWAP was conducted at farmers' fields in Sharif Abad district. Most of the input parameters were measured directly in field experiments with high accuracy, but some remained uncertain. Inverse modelling was used to determine indirectly the remaining uncertain soil hydraulic parameters (Jhorar, 2002; Ritter et al., 2003), where the observed soil moisture was used as system response. Firstly, SWAP with simple crop module, denoted as SWAP, was calibrated and validated using measurements at different farmers' fields representing various combinations of soil, crop, and irrigation amount and quality. Secondly, the applicability of SWAP-WOFOST for regional simulations was tested by a comparison with the calibrated and validated SWAP. Finally, water productivity for cotton and wheat were analyzed with SWAP(simple crop module) and SWAP WOFOST(detailed crop module) models in four experimental fields (wheat in field 1 and 2, and cotton in field 3 and 4) under the Qazvin plain irrigation network in Sharif Abad district during the agricultural year 2005- 06.

2. MATERIALS AND METHODS

2.1 Irrigation network

The Qazvin irrigation network lies between 35º24'N to 36º48'N latitude and 48º45'E to 50º51'E longitude. The average annual precipitation and evaporation in the region are 312 and 1345 mm, respectively, and the mean annual temperature is 13.2ºC. The distribution of rainfall is extremely uneven in time and space, resulting in serious water shortages. Geographically, the irrigation area located in Qazvin plain is in the northwest of Iran (Fig. 1). It serves an estimated gross irrigated area of 58,000 ha, using water from the Taleghan Dam reservoir and 102 integrated wells scattered over the command area. The crops cultivated in the region include: wheat, barley, pear, cotton, corn, sugar beet, alfalfa, sunflower, cucumber, onion, potato, tomato, bean and lentil. The common method of water application is in furrows or borders. For the study reported in this paper, we selected four experimental fields in Sharif Abad district. Locations of experimental fields are shown in Fig. 1.

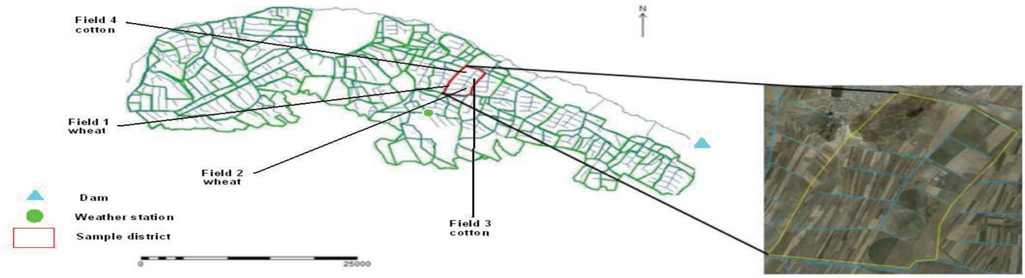

Fig. 1: the study of area (l'étude de la zone)

2.2 Soil- Water- Atmosphere- Plant (SWAP) Model

The Soil-Water-Atmosphere-Plant (SWAP) is an ecohydrological model based on the deterministic and physical laws for essential hydrological, chemical and biological processes occurring in the soil-water-plant-atmosphere continuum. Assuming the main flow process in vertical direction, SWAP simulates the vertical soil water flow and salt transport in close interaction with the crop growth.

The soil water balance of a vertical soil profile under field conditions can be stated as:

$$\Delta W = P + I - SR - P_i - T - E - E_w + Q_{bot} \quad (1)$$

Where: ΔW is the change in soil water storage, P is the rainfall, I is the irrigation, SR is the surface runoff, P_i is the rainfall interception by vegetation, T is the actual transpiration, E is the actual soil evaporation, E_w is the evaporation from ponded water and Q_{bot} is the water percolation at the bottom of the soil column (positive upward). All parameters have the dimention of L.

The salt balance of the soil column over that time interval also can be written as:

$$\Delta C = PC_p + IC_i + Q_{bot}C_{bot} \quad (2)$$

Where ΔC is the change in salt storage [ML^2], C is the solute concentration [ML^3], and subscript ‘p’ refers to rainfall, ‘i’ to irrigation, and ‘bot’ to bottom flux.

Swap contains a simple but a detailed crop module in which. the crop development with time is prescribed. The user should specify leaf area index (or soil cover fraction), crop height and rooting depth as functions of developing stage. The simple crop module doesn’t simulate any interaction between the crop growth and the water and salt stress conditions. Therefore, it has disadvantage for situations that have a different water and salt stress than in the situation for which crop growth was measured. The detailed crop module is based on the crop growth model WOrld FOod STudies (WOFOST: Supit et al., 1994). The detailed generic crop growth model (WOFOST) has the advantage of a feedback between the crop growth and the water and salt stress conditions.

To calculate soil water flow, SWAP employs Richards’ equation for soil water movement in the soil matrix extended by the sink term, S:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a(z) \quad (3)$$

where C is the differential soil water capacity [L^{-1}], h is the soil water pressure head [L], K is the hydraulic conductivity [$L\,T^{-1}$], S_a is the root water extraction rate [T^{-1}], and z is the vertical coordinate [L] (positive upward).

SWAP solves the Richards' equation numerically using an implicit finite difference scheme as described by Van Dam and Feddes (2000). The numerical solution of Eq. 3 is subjected to specified initial and boundary conditions, and requires known relationships between soil hydraulic variables: moisture (θ), pressure head (h) and hydraulic conductivity (K). The following relations between these variables have been used (Van Genuchten, 1980; Mualem, 1976):

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{\left[1 + (\alpha \mathrm{h})^n\right]^{\frac{n-1}{\mathrm{n}}}} \quad (4)$$

$$K(\theta) = K_{sat} S_e^{\lambda} \left[1 - (1 - \mathrm{S}_{\mathrm{e}}^{\frac{\mathrm{n}}{\mathrm{n-1}}})^{\frac{n-1}{n}} \right]^2 \quad (5)$$

where θ_{res} is the residual water content [L^3 L^{-3}], θ_{sat} is the saturation water content [L^3 L^{-3}], $S_e = (\theta - \theta_{res}) / (\theta_{sat} - \theta_{res})$ is the relative saturation [-], α is the empirical shape factor [L^{-1}], n [-], K_{sat} is the saturated hydraulic conductivity [L T^{-1}], and λ is an empirical coefficient [-].

Most of the input parameters of SWAP are site specific, and can be obtained by field measurements. Some of the input parameters such as soil hydraulic parameters are difficult to measure directly under field conditions, and might be determined through the calibration and validation of the model.

To obtain the soil parameters at the experimental fields, samples were taken from five depths: 0-20, 20-40, 40-60, 60-80 and 80-120 cm. These samples were analyzed for basic physio-chemical properties such as soil texture, bulk density, saturated hydraulic conductivity, saturation percentage, pH, electrical conductivity (EC) and organic carbon. The source (canal or tubewell), amount and quality of each irrigation were recorded. The detailed crop growth in terms of density (number of tillers per unit area), height, leaf area index, dry matter and its partitioning, and rooting depth at different crop development stages were measured. The Sunscan canopy analysis system was used for the measurement of light interception i.e. photosynthetically active radiation (PAR) absorbed by the canopy. Total dry matter was measured at the harvest time of the crop.

2.3 Input parameters of SWAP Model

Most of the input parameters of SWAP could be measured directly in the field or laboratory. The input parameters of SWAP could be categorized into parameters required to define the upper boundary, crop, soil, lower boundary and initial conditions.

2.3.1 Upper boundary

The potential evapotranspiration (ET_p), rainfall (P) and irrigation (I) fluxes define the upper boundary of the soil profile. The ET_p was estimated by the Penman-Monteith equation using the daily meteorological data, which were acquired from Magsal weather station (Fig. 1). The amount and number of irrigations were registered for cotton and wheat fields in Sharif Abad district. Table 1 shows the mean of maximum and minimum temperature, radiation, rainfall, wind speed, sunshine, humidity, eavapotranspiration and vapour pressure in Qazvin plain during the agricultural year 2005-2006.

Table 1. Climatological variables in Qazvin basin(Variables climatologiques à Qazvin basin)

Parameter	Value	Parameter	Value
Maximum temperature(ºC)	20.7	Radiation (MJ/m^2/day)	17.5
Minimum temperature(ºC)	6.3	Rainfall (mm)	342
Humidity (%)	53	Vapour pressure (kpa)	1.2
Wind speed (Km/day)	156	ET_0 (mm/year)	1358
Sunshine (hour)	8.2	ET_0 (mm/day)	3.7

2.3.2 Crop parameters

For specifying a simple crop module and the detailed crop module, SWAP and SWAP-WOFOST require the following inputs: temperature sum from crop emergence to anthesis, and from anthesis to crop maturity (TSUMEA & TSUMAM), minimum canopy resistance (r_{crop}), light extinction coefficients for diffused and direct visible light (KDIF & KDIR), leaf area index (LAI) or soil cover fractions (SCF), crop factors (kc) or crop height (CH), rooting depth (RD), yield response factors (K_y), critical pressure head (*h*) for crop root water uptake, light use efficiency(ε) and maximum CO_2 assimilation rate (A).

TSUMEA and TSUMAM were estimated from average air temperatures recorded at the weather stations during the respective crop development stages. SWAP default values of 0.60 and 0.75 for KDIF and KDIR were assumed and used in the simulation. LAI, CH and RD as functions of crop development were observed under field conditions. K_y values as functions of crop development stage were obtained from FAO records for wheat and cotton crops (Allen et al., 1998). The various input parameters used for wheat and cotton are summarized in Table 2.

Table 2. Main crop parameter specified for SWAP and SWAP- WOFOST models in Sharif Abad district (Tableau de principal paramètre de cultures spécifiées pour les modèles SWAP SWAP et-WOFOST dans Sharif Abad district).

parameter	Wheat	cotton
Temperature sun from emergence to anthesis, TSUMEA(ºC)	1300	2240
Temperature sun from anthesis to maturity, TSUMAM(ºC)	750	830
Minimum canopy resistance, rcrop (s m^{-1})	70	70
Critical pressure heads, h(cm)		
h_1	-1	-1
h_2	-18	-18
h_{3l}	-600	-800
h_{3h}	-1500	-2100
h_4	-16000	-16000
Light extinction coefficient, K_{gr}	0.38	0.43
Light use efficiency, ε (kg $ha^{-1}hr^{-1}/Jm^2s^{-1}$)	0.4	0.38
Maximum CO_2 assimilation rate, A (kg $ha^{-1}hr^{-1}$)	43	55
Salinity		
Critical levels, EC_{max} (dS m^{-1})	6	7.7
Decline per unit EC, EC_{slope} (% dS m^{-1})	7.1	5.2

2.3.3 Soil hydraulic parameter

Initial parameters of the van Genuchten-Mualem analytical PTFs (Eq. 4 and 5), which are inputs to SWAP, were estimated with the Rosetta model (Schaap et al., 2005) using soil texture data. Initial estimates of θ_s by Rosetta were later replaced by field observed values. However, estimated K_{sat} values were retained for the input, as no observed values were available from the field, and estimates were within common ranges of K_{sat} for the soils studied. Since a value near to zero can be used for θ_r (Kool et al., 1987, van Genuchten, 1980), a constant value of 0.01 was used for all soil profiles to allow a more flexible range on simulated soil moisture. Initial λ estimates were retained for input into SWAP. Soil hydraulic property simulations are generally sensitive to parameters α and n, and for reliable estimates, optimized values of these parameters are desirable.

A 200-cm deep soil profile was specified for simulating the soil water balance. The soil profile was specified to a depth of about 120 cm and divided into soil horizons ranging from one up to four layers per soil profile. The soil column was further discretized into a total of 32 compartments with a nodal distance of 1 cm for the top 10 compartments, followed by 5 cm for the next 10 compartments and 10 cm for the remaining compartments. This scheme of soil profile discretization was important since for accurate simulation of dramatic changes in soil water content, the thickness of the top compartments should not be more than 1 cm (Kroes and van Dam 2003).

Successful prediction of water transport using SWAP depends on reliable estimates of soil hydraulic conductivity and moisture contents. To minimize uncertainties in estimates of the soil water balance, the soil K - θ relationships were optimized with the non-linear parameter estimation program (PEST: Doherthy et al., 1995) linked automatically to SWAP. The objective function Φ(b) was specified for the optimization process as (Eq. 6):

$$\Phi(b) = \sum_{i=1}^{N} \left[W_\theta (\theta_{obs}(t_i) - \theta_{sim}(b, t_i)) \right]^2 \quad (6)$$

Where: θ_{obs} (t_i) is the observed soil moisture at time t_i, N is the number of observations, θ_{sim} (b, t_i) is the simulated value of θ using an array with parameter values b, W_θ (=1) is the weight associated with θ_{obs}.

Daily values of θ_{obs} were measured with a soil moisture probe for each field at depths of 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 100 cm below the soil surface. Observed soil moisture profiles were used for calibration and validation of soil hydraulic parameters within SWAP using a simple crop module.

The Mean Error (ME) and the Root Mean Square Error (RMSE) between observed and simulated moisture content for each soil profile layer were used to assess the accuracy of the SWAP and SWAP- WOFOST models for soil water balance simulation:

$$ME = \frac{1}{N} \sum_{i=1}^{N} (\theta_0 - \theta_s) \quad (7)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\theta_0 - \theta_s)^2} \quad (8)$$

Where: θ_o and θ_s are observed and simulated moisture content, and N is the number of observations over which ME and RMSE values were calculated.

2.3.4 Lower boundary and initial conditions

Piezometric water levels from shallow piezometers installed in each of the experimental fields were utilized to define the bottom boundary condition for SWAP simulation. Water levels in the piezometers were recorded at daily intervals. Water levels in open boreholes recorded at the beginning of the season or initial soil moisture generated by running SWAP for the previous rainy season (May-September/June-October) were used as model initial conditions.

2.4 Water productivity

Water productivity is defined as ‘crop production’ per unit ‘amount of water used’ (Molden, 1997). It can be further defined in several ways according to the purpose, scale and domain of analysis (Molden et al., 2001).

Water productivity was expressed in terms of corn grain (or seed) yield Y_g per unit amount transpiration T:

$$WP_T = \frac{Y_g(kgm^{-2})}{T(m^3m^{-2})} = \frac{Y_g}{T}(kgm^{-3}) \qquad (9)$$

WP_T depends on the crop type (C3 or C4) and its variety, and indicates the physiological performance of a certain crop. The dry matter production and transpiration rate of a crop are related to the diffusion rates of CO_2 and H_2O molecules at leaf stomata.

The inevitable loss of water due to soil evaporation E decreases the water productivity from WP_T to WP_{ET}, which is expressed in terms of Y_g per unit of evaporation ET:

$$WP_{ET} = \frac{Y_g}{E+T} = \frac{Y_g}{ET}(kgm^{-3}) \qquad (10)$$

The ET represents the actual amount of water used in crop production, and must be used as productive as possible.

Similarity, including percolation Q_{bot} from field irrigations enlarges the denominator in expression of water productivity, and hence decreases it from WP_{ET} to WP_{ETQ}:

$$WP_{ETQ} = \frac{Y_g}{ET+Q_{bot}} = \frac{Y_g}{ETQ}(kgm^{-3}) \qquad (11)$$

Apparently it seems percolation losses reduce the WP_{ETQ} at field scale.

3. RESULTS

3.1 Parameter estimation

Soil types and soil hydraulic parameters for the van Genuchten-Mualem analytical PTFs were determined (Table 3). The parameters α and *n* were optimized using PEST.

Table 3. Soil texture and analytical PTFs soil hydraulic parameters (La texture du sol et d'analyse des paramètres hydrauliques du sol PTF)

Field No.	Soil layer (cm)	Texture	Soil hydraulic parameter					
			θ_{res} (cm³ cm⁻³)	θ_{sat} (cm³ cm⁻³)	α (cm⁻¹)	n	K sat (cm day⁻¹)	λ
1	0-20	L	0.01	0.41	0.018	1.56	14.85	-1.51
	20-40	CL	0.01	0.44	0.023	1.37	13.2	-1.82
	40-80	CL	0.01	0.43	0.027	1.92	11.55	-1.72
	80-200	CL	0.01	0.42	0.013	1.51	14.23	-0.63
2	0-20	SiL	0.01	0.42	0.02	1.63	25.2	-0.78
	20-40	CL	0.01	0.44	0.018	1.54	10.1	-1.93
	40-80	CL	0.01	0.51	0.013	1.47	9.8	-1.1
	80-200	CL	0.01	0.53	0.01	1.32	11.3	-1.17
3	0-40	CL	0.01	0.51	0.014	1.78	11.8	-0.88
	40-80	SCL	0.01	0.45	0.023	1.63	17.7	-1.92
	80-200	CL	0.01	0.56	0.017	1.59	10.2	-0.77
4	0-20	SL	0.01	0.39	0.027	1.83	42.8	-0.38
	20-40	CL	0.01	0.49	0.024	1.72	9.8	-1.58
	40-80	CL	0.01	0.51	0.017	1.64	11.3	-1.82
	80-200	CL	0.01	0.53	0.02	1.45	7.8	-0.78

At wheat fields (field 1 and field 2), the soils were mainly clay loam in the sub-soils and a layer of loam and silty loam, respectively; with θ_{sat} of about 0.42 cm^3 cm^{-3} and moderate Ksat of 25.2 cm d^{-1} for silty loam and slow of 9.8 cm d^{-1} for clay loam (Table 3).

At cotton fields (field 3 and field 4), the top soils were mainly clay loam and sandy loam with sub-soils varying from sandy clay loam to clay loam. Saturated water content was 0.39 cm^3 cm^{-3} for silt loam and 0.45 cm^3 cm^{-3} for silty clay loam. Saturated water content ranged from 0.49 to 0.53 cm^3 cm^{-3} for clay loam. K_{sat} ranged from 7.8-11 cm d^{-1} for clay loam, 17.7 cm d^{-1} for sandy clay loam and 42.8 cm^3 cm^{-3} for sandy loam (Table 3).

The parameters ***α*** and n were successfully optimized as indicated by relatively small mean errors (ME: Table 4) and root mean squared errors (RMSE: Table 5) between observed and simulated soil water contents for the different layers of the soil profile.

Table 4. ME between observed and simulated soil moisture content ($cm^3\ cm^{-3}$)(ME entre la teneur en humidité du sol observées et simulées ($cm^3\ cm^{-3}$))

Profile depth (cm)	Field 1	Field 2	Field 3	Field 4
0-20	-0.002	0.019	0.0054	-0.0047
20-30	-0.0014	-0.0077	-0.0041	-0.0015
30-40	0.0052	0.0014	0.0067	-0.0177
40-60	-0.0042	-0.0025	-0.0085	0.0069
60-100	-0.0015	0.0047	-0.0014	-0.0055

Table 5. RMSE between observed and simulated soil moisture content ($cm^3\ cm^{-3}$) (RMSE entre la teneur en humidité du sol observées et simulées ($cm^3\ cm^{-3}$))

Profile depth (cm)	Field 1	Field 2	Field 3	Field 4
0-20	0.031	0.014	0.032	0.029
20-30	0.016	0.032	0.028	0.014
30-40	0.011	0.021	0.026	0.012
40-60	0.021	0.025	0.018	0.019
60-100	0.025	0.016	0.024	0.022

The analysis results show that predicted soil moisture for the top-soils is relatively more variable than that of the sub-soils (Fig. 2). The discretization of soil layers to a thickness of 1 cm in the topsoil profile makes it possible for SWAP to simulate small changes in soil moisture with high accuracy. However, the general trend in simulated soil moisture content is not different from that of measured soil moisture content. Although the ME does not indicate systematic under-/or over-estimation relative to measured soil moisture levels, differences between the observed and the simulated soil water contents could result from installation and/or sampling errors in the measurement of moisture contents which are inevitable under field conditions.

3.2 Water and salt balances

The calibrated soil hydraulic parameters (Table 3) were used in both SWAP and SWAPWOFOST to simulate the water and salt balances at different fields. To avoid confusion in this section only, the water and salt balance components simulated by SWAP are distinguished with the superscript 's', and by SWAP-WOFOST with the superscript 'sw'. For example, the potential evapotranspiration ET_p is denoted as ET_p^s when simulated by SWAP, and as ET_p^{sw} when simulated by SWAP-WOFOST. First, the water and salt balances simulated by SWAP are analysed, and second they are compared with those simulated by SWAP-WOFOST.

The deviation between T_p^{sw} and T_p^s varied from 5 to 20% of the T_p^s at the corresponding field. The T_p^s was slightly higher than the T_p^{sw}, excluding at field 3 (Table 6). It was expected due to the linear interpolation between two LAI measurements by SWAP. This linear interpolation results into slightly overestimation of LAI, especially in the beginning of crop season, and hence slightly overestimation of T_p^s .

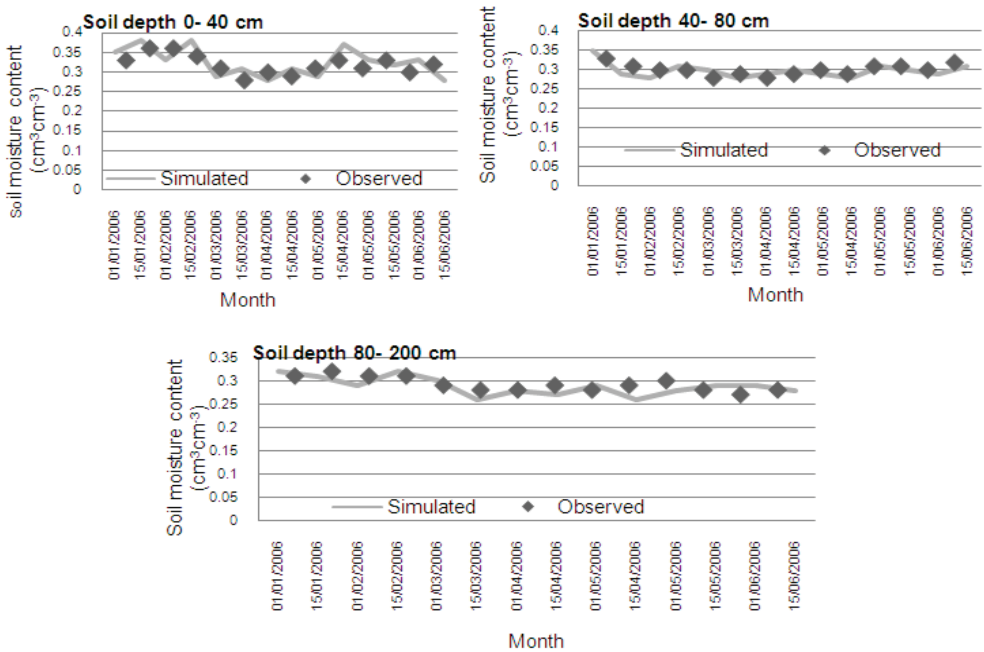

Figure 2: Observed and simulated soil moisture profiles at field 3 (cotton) in Sharif Abad district during agricultural year 2005-06 (Observées et simulées des profils d'humidité du sol au domaine 3 (coton) dans Sharif Abad district durant l'année agricole 2005-06)

Similar to the T_p^{sw} and T_p^{s}, the deviation between ET^{sw} and ET^{s} varied from 2 to 9% of the ET^{s} during their respective crop seasons at the corresponding field (Table 6). The ET^{sw} at field 3 was only 7.2% higher than the ET^{s}. Other water and salt balance components such as Q_{bot}, ΔW and ΔC simulated by SWAP-WOFOST also compared well with those obtained from the calibrated and validated SWAP (Table 6). Water and salt balances simulated by SWAP-WOFOST were in good agreement with the results of the calibrated and validated SWAP, the latter used the measured crop parameters at the corresponding field. Further, the simulation of crop yields by SWAP-WOFOST was found to have good correlation with the water and salt stress at different fields. For instance, the low simulated water and salt limited yield of 1.0 ton ha^{-1} for cotton at field 3 was a result of the low irrigation of 350 mm and use of poor quality groundwater (3.8 dS m^{-1}).

3.3 Water productivity

Water productivity for wheat and cotton was analyzed with both SWAP and SWAP- WOFOST models (Table 7 and 8). Generally, WP was higher at wheat fields than at cotton fields for all WP indicators. At wheat fields, average values of WP_T, WP_{ET} and WP_{ETQ} were 1.23, 1.1 and 0.92 kg m^{-3} in SWAP model, respectively, while in SWAP- WOFOST these value were 1.58, 1.39 and 1.18 kg m^{-3}, respectively. At cotton fields, average values of WP_T, WP_{ET} and WP_{ETQ} were, respectively, 0.39, 0.28 and 0.25 kg m^{-3} in SWAP model and 0.41, 0.32 and 0.28 kg m^{-3}, respectively, in SWAP- WOFOST model.

Table 6. Simulated water and salt balances at wheat and cotton fields during the agricultural year 2005-06 (Tableau d'eau simulés et les soldes de sel dans les champs de coton et blé au cours de l'année agricole 2005-06)

Component	SWAP model				SWAP- WOFOST model			
	Field 1	Field 2	Field 3	Field 4	Field 1	Field 2	Field 3	Field 4
	Water balance (mm)							
P	83	83	115	115	83	83	115	115
I	540	500	350	1000	540	500	350	1000
T	452	412	312	833	428	441	337	777
ET	505	462	400	967	491	498	431	1000
Q_{bot}	-143	-63	-54	-103	-175	-34	-69	-129
ΔW	-25	58	11	45	-43	51	-35	-14
	Salt balance (mg cm^{-2})							
$I\ C_i$	40	45	113	74	40	45	113	74
$Q_{bot}\ C_{bot}$	-14	-8	-14	-14	-17	-4	-18	-18
ΔC	26	37	99	60	23	41	95	56

The differences in WP_T for different crops are due to the differences in the chemical composition, harvest index and evaporative demands during the respective seasons. In Qazvin plain irrigation network, temperatures and vapour pressure deficit are high during summer season, which results into high evaporative demands. Consequently, The WP_T, WP_{ET} and WP_{ETQ} of summer crop (cotton) are lower than those for winter crop (wheat).

To improve the WP_{ET} for a crop, the fraction of soil evaporation E in evapotranspiration ET is important (Eq. 10). The high evaporative demands and continuously surface water ponding result in high soil evaporation during the growing season. The WP_{ET} for wheat and cotton was 10 to 28% lower than the WP_T through both SWAP and SWAP- WOFOST at different fields (Table 7 and 8).

The percolation Q_{bot} further reduces the WP_{ET} to WP_{ETQ} at field scale (Eq. 11). The WP_{ETQ} for wheat and cotton was 21 to 55% lower than the WP_T through both SWAP and SWAP- WOFOST at different fields (Table 7 and 8).

As expected, SWAP- WOFOST simulated water and salt limited Y_g for wheat were 25 to 35% higher than the actual Y_g at corresponding field (Table 7). Further, the simulated water and salt limited Y_g for wheat were almost equal to the simulated potential Y_g. The relative transpiration (T/T_p) at the selected wheat fields ranged from 0.81 to 1.00. This presents almost negligible water and salt stress on wheat in Sharif Abad district, while substantial nutritional, pest or disease control. The differences in WP_T, WP_{ET} and WP_{ETQ} values for wheat obtained from SWAP and SWAP-WOFOST are mainly due to the differences in actual (measured) and simulated Y_g at the corresponding field. The average WP_{ET} for wheat obtained from SWAPWOFOST was 26% higher than that obtained from SWAP (Table 7). Improved crop management in terms of timely sowing and optimal fertilizer, and better pest and disease control is expected to achieve this significant increase in the WP_{ET} for wheat in Sharif Abad district.

The relative transpiration (T/T_p) at the selected cotton fields ranged from 0.53 to 0.7, and shows water and salt stress on cotton crop. Further, the low actual Y_g of 0.8 ton ha^{-1} at cotton field 3 indicates the crop failure, mainly due to water stress: 350 mm irrigation only. The low rainfall of 115 mm only will have contributed to the water stress on summer crops, especially cotton (Table 6). The corresponding lower simulation of water and salt limited Y_g of 1 ton ha^{-1} confirms that SWAP- WOFOST responds well towards the water stress at field 3. The water and salt limited Yg for cotton were 1.6 to 3.1 times lower than the potential Y_g at corresponding field (Table 8). Also, the WP_T, WP_{ET} and WP_{ETQ} values for cotton obtained from SWAP-WOFOST were slightly higher than those obtained from SWAP (Table 8). This suggests that ensuring the irrigation supplies, especially during the dry years, and improved crop management at cotton fields will increase cotton yields, and subsequently its water productivity in Sharif Abad district.

Table 7. Water productivity (kg/m^3) for wheat at field 1 and field 2 in Sharif Abad district (la productivité pour le blé aux champs des agriculteurs (champ 1 et sur le terrain 2 dans Sharif Abad district)

Water productivity	SWAP model			SWAP- WOFOST model		
	Field 1	**Field 2**	**average**	**Field 1**	**Field 2**	**average**
For wheat						
WP_T	1.06	1.4	1.23	1.4	1.76	1.58
WP_{ET}	0.95	1.25	1.1	1.22	1.56	1.39
WP_{ETQ}	0.74	1.1	0.92	0.9	1.46	1.18
Y_g (ton)	4.8	5.2	5	6	7	6.5
Potential Y_g (ton)				6.3	7.2	6.75

Table 8. Water productivity (kg/m^3) for cotton at field 3 and field 4 in Sharif Abad district(productivité de l'eau pour le coton aux champs des agriculteurs (zone 3 et zone 4) dans district de Sharif Abad)

Water productivity	SWAP model			SWAP- WOFOST model		
	Field 1	**Field 2**	**average**	**Field 1**	**Field 2**	**average**
For cotton						
WP_T	0.32	0.36	0.34	0.37	0.45	0.41
WP_{ET}	0.25	0.31	0.28	0.29	0.35	0.32
WP_{ETQ}	0.22	0.28	0.25	0.25	0.31	0.28
Y_g (ton)	0.8	1.8	1.3	1	2.1	1.55
Potential Y_g (ton)				3.1	3.5	3.3

4. CONCLUSIONS

Les principales conclusions, qui pourraient être tirées de cette analyse à grande échelle sur le terrain, sont les suivants:

- SWAP a été calibré et validé avec succès en reliant le modèle avec PEST à optimiser les paramètres α et n de la PTF hydrauliques du sol. Les paramètres ont été optimisés de manière efficace, et le ME et RMSE, caractérisant observés par rapport à la teneur en eau du sol simulé à différentes profondeurs du sol, ont été assez bonnes.
- L'utilisation de mauvais résultats de qualité des eaux souterraines dans une accumulation de sel dans le sol. Notez que le changement de stockage du sel Ac au domaine 3 (coton) était élevé, soit 99 mg cm^{-2}, malgré une Q_{bot} significative de -54 mm (tableau 6). Cela est dû à l'utilisation des eaux souterraines de mauvaise qualité (3,8 dS m^{-1}), qui a fourni une grande quantité de sels (113 mg cm^{-2}). Dans le cas des eaux souterraines de mauvaise qualité, l'utilisation combinée de l'eau du canal et des eaux souterraines est bénéfique en termes de l'accumulation de sel.
- Un potentiel existe pour améliorer WP_{ETQ} à l'échelle sur le terrain, par exemple en réduisant la percolation profonde, qui a largement eu lieu à la suite d'une irrigation au début de la saison des cultures. WP_{ET} pourrait également être améliorée par des pratiques de gestion sur le terrain comme le paillage, ce qui réduit l'évaporation directe d'humidité de sol superficiel nu entre les rangées de culture et de plantes qui ne contribue pas à la production agricole.
- L'eau de la productivité peut être améliorée par des pratiques de meilleure gestion, tels que le bon temps de l'implantation des cultures dans la fourniture saison, correcte et fiable de l'eau d'irrigation, de semences améliorées, et l'application correcte et adéquate d'intrants chimiques. En Sharif Abad district, les efforts pour améliorer WP devrait se concentrer sur la minimisation appauvrissement non-bénéfiques, qui représentaient plus de 50% de l'approvisionnement en eau d'irrigation à l'échelle parcellaire. Cependant, il n'y a pas beaucoup d'espoir pour l'amélioration WP basée sur la gestion de l'eau dans Sharif Abad district. Au lieu de cela, les stratégies devraient être orientées vers les facteurs qui favorisent le rendement des cultures, telles que le contrôle des ravageurs et des maladies, les variétés améliorées, le calendrier meilleure récolte, et l'utilisation correcte des engrais.

REFERENCES

Doherty, J., L. Brebber and P. Whyte, 1995. PEST: Model independent parameter estimation. Australian Centre for Tropical Freshwater Research, James Cooke University, Townsville, Australia, 140 p.

Falkenmark, M., Lundquist, J., and Widstrad C.,1989. Macro- scale water scarcity requires micro- scale approaches: aspect of vulnerability in semi- arid development . Natural Resources Forum 13: 258- 267.

IWMI, 2000. Water issues for 2025. A research perspective. Research contribution to the World Water Vision. International Water Management Institute, Colombo, Sri Lanka, 50 p.

Jhorar, R.K., 2002. Estimation of effective soil hydraulic parameters for water management studies in semi-arid zones. PhD Thesis, ISBN 90-5808-644-5, Wageningen University and Research Centre, Wageningen, The Netherlands, 157 p.

Kool, J.B., and J.C. Parker, 1988. Analysis of the inverse problem for transient unsaturated flow. Water Resour. Res., 24: 817-830.

Kroes, J.G. and J.C. van Dam (eds), 2003. Reference Manual SWAP version 3.03. Alterra Green World Research, Alterra report 773, ISSN 1566-7197. Wageningen University and Research Centre, Wageningen, The Netherlands, 211 p.

Molden, D., 1997. Accounting for water use and productivity. SWIM Paper 1. International Irrigation Management Institute, Colombo, Sri Lanka.

Molden D, and R. Sakthivadivel, 1999. Water accounting to assesses and productivity of water. J. Water Resources Development, 15 (1/2): 55-72.

Molden, D., H. Murray-Rust, R. Sakthivadivel and I. Makin, 2001. A water productivity framework for understanding and action. Workshop on Water productivity. Wadduwa, Sri Lanka, November 12 and 13, 2001.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resou. Res., 12: 513-522.

Ritter, A., F. Hupet, R. Munoz-Carpena, S. Lambot and M. Vanclooster, 2003. Using inverse methods for estimating soil hydraulic properties from field data as as alternative to direct methods. Agric. Water Manage., 59: 77-96.

Schaap MG, Leij FJ and van Genuchten MTh (2001) ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchial pedotransfer functions. J. Hydrol. 251:163-176.

Supit, I., A.A. Hooyer and C.A. van Diepen (Eds.), 1994. System description of the WOFOST 6.0 crop simulation model implemented in CGMS. Vol. 1: Theory and algorithms. EUR publication 15956, Agricultural series, Luxembourg, 146 p.

Van Dam, J.C. and R.A. Feddes, 2000. Numerical simulation of infilteration, evaporation and shallow groundwater levels with Richards's equation. Simulation of field-scale water flow and bromide transport in a cracked clay soil. J. Hydrol. 233: 72-85.

Van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44: 892-898.