FIELD SCALE SCENARIOS FOR IMPROVED WATER AND LAND PRODUCTIVITY BY SIMULATION MODELING

SCENARIOS AU CHAMP POUR AMELIORER LA PRODUCTIVITE DE LE'AU ET DE LA TERRE EN UTILISANT LE MODELE DE SIMULATION

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ABSTRACT

Water scarcity, irrigation scheduling, undesirable and non economical water use are the most important limiting factors of agricultural development and production in arid and semi-arid regions. For desirable and optimum use of land and water, different themes that are under discussion include; irrigation scheduling, improvement of land and water management, improvement in water and land productivity and profitability. This study was conducted to evaluate the effect of field scale water and land management, irrigation scheduling (time and depth) for winter wheat under different water quantity to improve water and land productivity in Abshar irrigation systems, Esfahan, Iran. This was performed by using a well tested AquaCrop simulation model for crop growth and irrigation scheduling at field scale. Optimal irrigation depth, schedule and yield function for winter wheat was defined using combined fixed and variable cost, return from yield, on farm and simulated data for different water quantites. Accordingly, crop yield and water productivity of winter wheat were simulated and compared to the on farm condition. Results of on farm research indicated that at the current situation, 800 mm of water annually applied for winter wheat gives an average wheat production of about 5000 kg/ha. For improved water and land management, twenty five generalized scenarios were studied based on limitations or non-limitations in land, water quantity and time and irrigation depth and their effect on the water balance and crop yields. The first scenario is the baseline scenario, which describes the current situation and will function as a reference for the other scenarios. Contour plots generated from the AquaCrop output were used to analyze these scenarios and suggest options for improved land and water management practices in the field. According to the results, an almost linear relationship exists between the amount of

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water applied by irrigation and the amount of deep percolation. Soil evaporation was also linearly related to the irrigation supply. The winter wheat yield increased by 18% by improving irrigation scheduling. With improveed agronomic practices and a reduction in irrigation depth by 20% (from 100 to 80mm), crop yield reduction was very small. Increasing depth of applied water until the optimal value caused increased economic water productivity, but water applied more than optimal level had no significant effect on water productivity and economic water productivity. According to the results, proper irrigation scheduling by AquaCrop model together with improved agronomic management, increased land and water productivity about 16 and 47 percent, respectively.

Key words: *Land and water management, Irrigation scheduling, AquaCrop model.*

RESUME

La pénurie d'eau, le pilotage de l'irrigation, l'utilisation indésirable et non économique de l'eau sont les facteurs importants qui limitent le développement et la production agricole dans les régions arides et semi-arides. Pour l'utilisation désirable et optimum de la terre et des eaux, suivent les divers thèmes en cours de d'étude: pilotage de l'irrigation, amélioration de la gestion des terres et des eaux, amélioration de la productivité de l'eau et de la terre et rentabilité. Cette étude a été menée pour évaluer l'effet de la gestion de l'eau et de la terre au niveau du champ, le pilotage de l'irrigation (temps et profondeur) sur le blé hivernal en vertu de la quantité différente de l'eau utilisée pour améliorer la productivité de l'eau et de la terre dans les systèmes d'irrigation d'Abshar, Esfahan, Iran.

Cette étude fut réalisée en utilisant AquaCrop, modèle de simulation bien évalué, pour la croissance des cultures et le pilotage d'irrigation au niveau du champ. La profondeur optimale d'Irrigation, le pilotage et le fonctionnment de rendement pour le blé hivernal ont été définis avec l'aide des coûts fixes et variables, du rendement de culture, et des données simulées pour différentes quantités d'eau. Donc, le rendement de culture et la productivité de l'eau du blé hivernal ont été simulées et comparées avec les conditions du champ. Les résultats de la recherche agricole ont indiqué que dans la situation actuelle, l'application de 800 mm d'eau par an pour le blé hivernal donne lieu à la production moyenne d'environ 5000 kg / ha. Pour l'amélioration de la gestion de l'eau et de la terre, 25 scénarios généralisés étaient étudiés compte tenu des contraintes ou non sur la terre, la quantité d'eau, le temps et la profondeur d'irrigation et leur effet sur le bilan d'eau et les rendements des cultures. Le premier scénario est le scénario de référence, qui décrit la situation actuelle et agit en tant qu'une référence pour d'autres scénarios.

Le champ selon les courbes de niveau étudié dans AquaCrop était utilisé pour analyser ces scénarios et proposer les meilleures pratiques de gestion d'eau et de terre. Les résultats ont montré qu'il existe presqu'une relation linéaire entre la quantité d'eau appliquée et l'importance de la percolation. Il existe aussi une relation linéaire entre l'évaporation du sol et l'apport d'eau d'irrigation; il y a une augmentation de 18% dans le rendement hivernal du blé; une moindre réduction du rendement et une augmentation de productivité économique de l'eau sont notées; le pilotage approprié de l'irrigation accompagné d'une propre gestion agricole a augmenté la productivité de l'eau et de la terre.

Mots clés: *Gestion de l'eau et de la terre, pilotage d'irrigation, modèle AquaCrop*

1. INTRODUCTION

Globally, agriculture uses about 70% of freshwater resources, and irrigation represents the major use of diverted water worldwide. Reducing irrigation water use is crucial to meeting the ever-increasing water demands from other users. Improvements in irrigation efficiency have already been achieved in recent decades (Molden, 2007), but significant improvements in the biological efficiency of crop consumptive use are not possible (Steduto et al., 2007). Thus, irrigated agriculture is faced with pressures to decrease its share of water usage, while at the same time producing sufficient food and fiber for a growing population and other needs. Today, farmers are subjected to many economic and environmental constraints. Those located in the arid and semiarid regions where water is scarce face uncertainties in water supply due to periodic droughts that severely impact water resources and threaten agriculture sustainability (Fereres and Connor, 2004).

Zayandeh Rud irrigation systems is located in central Iran, with arid and semi-arid climate. Irrigated agriculture is the primary water consumer in Zayandeh Rud. Any attempt to increase the productivity of water should therefore originate from changes in agricultural practices, including irrigation system management, crop selection, soil management, field scale water management and irrigation scheduling, among others. Nowadays, well-tested and validated simulation models are available and are ready to be applied to answer questions related to field and water management, and their effects on water productivity (Droogers et al., 2001). Therefore, finding an alternative to empirical production functions would be the important outcome of using of crop simulation models for irrigation management (Jones et al., 1980; Singh and Singh, 1996). Although some models are very complex, most of them represent a compromise between rigor and utility (Monteith, 1996), But in most of the models, the number of parameters required to run them is very high, and many of them are seldom available and must be experimentally determined. For this reason, detailed models may be less reliable than simpler but robust models. Hence, it would be useful to have a simple model that can predict the yield response to water supply, irrigation schedule and field and soil management. AquaCrop (Steduto et al., 2009) is a simple, comprehensible, versatile, and robust model that could be used in determining the optimal water application for the main crops under different sets of conditions. For the Rudasht Area in Zayandeh Rud, simulation model was used to explore salinity processes for one soil type and one crop (Akbari et al., 2008; Droogers et al., 2001). In the current study, a similar setup has been used, but focus here is on the Abshar irrigation project in the Zayandeh Rud basin, on the exploration of options for improved field scale water management and water productivity. Economic optimization also assumes that emphasis is placed on producing more per unit water, thereby increasing the Water Productivity (Kassam et al., 2007). Additionally, there are many factors that must be taken into account when optimizing irrigation water application in wheat, such as water costs, product prices, and agricultural policies.

In summary, the objectives of this paper are to demonstrate the possibility of making combined use of data and a simulation models for a rapid assessment of yield functions, net returns and use this information to perform scenario analysis for improved farm management practices, irrigation management, irrigation scheduling and water productivity. This approach was tested by analyzing the water balance and yields in relation to the quantity and time of water applied for irrigation.

2. MATERIALS AND METHODS

Study area

The Abshar irrigation project (52° E lon., 32.5° N lat) is one of the main irrigated areas in the Zayandeh Rud basin, Esfahan, Iran, was selected to analyze the performance of irrigated agriculture (Fig 1). The main river, the Zayandeh Rud, runs for 350 km roughly in west-east direction from the Zagros Mountains to the Gavkhuni Swamp. The majority of the basin is a typical arid and semi-arid desert. The gross command area of the Abshar systems is about 40,000 ha. Cropped area is between 70 and 80% of the gross command area. Main crops are wheat, barley, rice, alfalfa, corn, sugar beet, vegetables and orchards. Rainfall in this area, which is situated at an elevation of 1500 m, is very limited, around 120 mm annually, mostly occurring in the winter months from December to April. Temperatures are hot in summer, reaching an average of 30°C in July, but are cool in winter dropping to an average minimum temperature of 3°C in January. Annual potential evapotranspiration is 1500 mm, and it is almost impossible to have any economic form of agriculture without reliable irrigation. The most fertile parts of the Abshar systems are the alluvial deposits flanking the Zayandeh Rud. Detailed description of the study area can be found in Salemi et al. (2001).

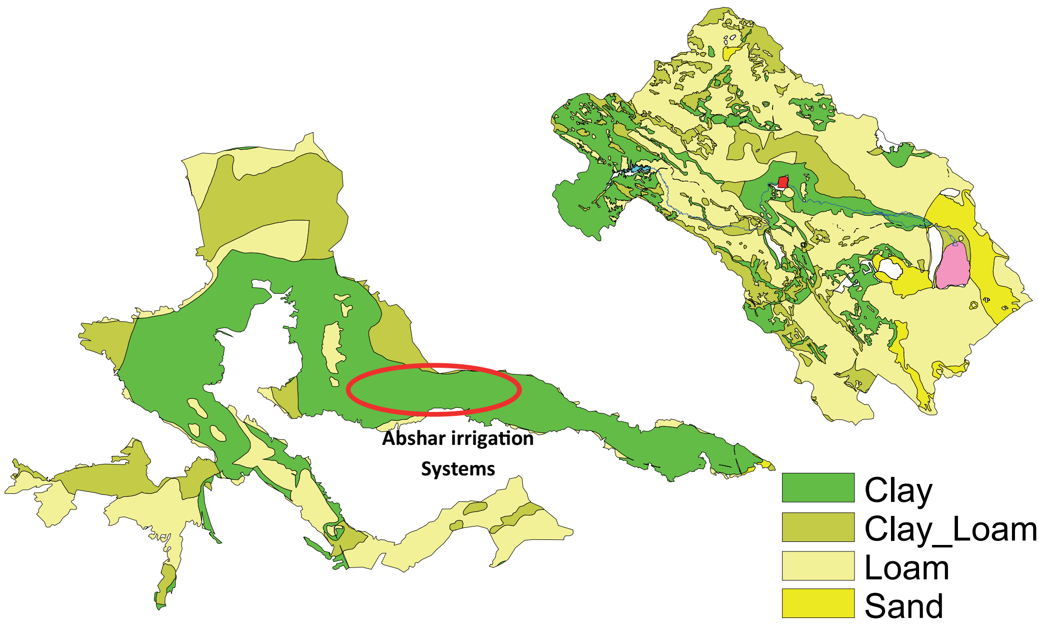

Fig.1. Generalized soil map of Zayandeh Rud basin and irrigation systems.

AquaCrop Simulation model:

AquaCrop has been developed by FAO to help project managers, consultants, irrigation engineers, agronomists, and even farm managers with the formulation of guidelines to increase the crop water productivity for both rain-fed and irrigated production systems. By linking a robust soil water model to the newly developed crop water productivity model, the expected crop development and production for specific climate and growing conditions can be estimated with AquaCrop. Examples of this are given in several related literatures (Akbari et al., 2010; Farahani et al., 2009; Garcia-Vila et al., 2008 and 2009; Geerts et al., 2008 and 2009; Heng et al., 2009; Hsiao et al., 2009). Further improvements of AquaCrop are planned, including soil salinity and capillary rise of water from a shallow water table. Steduto et al. (2009) has presented the concepts, rationale, approaches, and procedures selected or synthesized to simulate the processes in AquaCrop. A distinction is made between the input requirements and basic elements of the model, the calculation procedures with the corresponding equations, and the outputs of the model. Further details of the subroutines of AquaCrop are fully described in its Reference Manual (Raes et al., 2009). The crop grows by developing a green canopy that transpires water, and a root system that deepens and takes up water. The transpired water is in exchange for biomass produced (via the assimilation of carbon dioxide, not directly simulated). At a certain phenological stage, a part of the biomass is partitioned to the yield component as determined by the harvest index.

Input data

Soils

In order to simulate the flow of water, the soil properties are required. Variation in soil properties was limited in the area and therefore only clay soil was considered. Table 1 shows the measured soil properties and the derived soil hydraulic characteristics.

Climate data

Daily meteorological data was available for Kabutarabad station in the center of Abshar irrigated area over a period of 20 years, and were used in simulation models. This ensured us that the most variable meteorological factor was correctly taken into account in the simulations.

Table 1. Soil properties and and the derived soil hydraulic characteristics.

depth cm	clay %	sand %	silt %	OM %	θ_{res} m m^{-3}	θ_{sat} m^3 m^{-3}	α cm^{-1}	n -	K_{sat} cm d^{-1}	L -
0-30	35	21	44	0.5	0.000	0.482	0.027	1.117	38.34	-2.354
30-55	64	10	26	0.4	0.000	0.505	0.013	1.140	26.72	-0.293
> 55	46	5	49	0.3	0.000	0.468	0.017	1.097	7.88	-2.252

OM is soil organic matter, θ_{res} is residual soil moisture content, θ_{sat} is saturated soil moisture content, K_{sat} is saturated hydraulic conductivity, α, n, and L are the fitted parameters.

Crops

In the present study, winter wheat was selected to analyze the effect of different irrigation management scenarios. Winter wheat was sown at the beginning of November and was harvested at the end of June. Potential yields for winter wheat in this area are around 7000 kg ha-1, but actual yields are frequently reported to be less due to water scarcity and environmental stress problems.

Water and field management

The purpose of irrigation scheduling is to determine the exact amount of water to be applied to the field and its time of application. Irrigation applications according to the farmers' normal practices in the Abshar irrigated area are very high in an attempt to compensate for the poor water quality and agronomy management. For winter wheat, a total application will reach between 700 and 1000 mm, given as 200 mm for first irrigation and 100 mm each for the others. The baseline irrigation applications were defined based on detailed information of irrigation applications. The salinity of the irrigation water varied between 0.5 and 4 dS m^{-1}, during the year, but mostly, it was less than 1.5 dS m^{-1}. Therefore, the salinity of the irrigation water was considered to be constant at 1.5 dS m^{-1}during the year. In order to increase land and water productivity, twenty five generalized scenarios were studied based on limitations or non-limitations in land, water quantity, time and irrigation depth and their effect on the water balance and crop yields in four parts (Table 2). The first scenario is the baseline scenario, which describes the current situation and will function as a reference for the other scenarios. In the first part, it was assumed that farmers irrigated the crop at the most appropriate time, and 7 times as described above. In this part, in order to increased land and water productivity, farmers only can omit some irrigation.

In the 2nd and the 3rd part, it was assumed that farmers could improve farm management and decrease irrigation depth for first and all other irrigations to increase land and water productivity. In the last part, it was assumed that farmers could use the simulation-produced irrigation scheduling for improving field and water management to achieve better water productivity. At the previous parts, it was assumed that farmers irrigated the crop at the most appropriate time, but in this part AquaCrop was used to distribute the water based on the allowable depletion of RAW and fixed application depth of 100mm. Different ratios, ranging from 0.6 to 1.6, were used, resulting in total irrigation application between 200 and 700 mm. Results of these simulations were compared with the baseline scenario of a total of 800 mm water applied.

Calibration and Validation of models

Before using models for analyses of different scenarios, the model must be calibrated and validated for the relevant conditions. We used results of one irrigation experiment in winter wheat that was performed at the Kabutarabad research station of Esfahan Agricultural Research Center, in 1999-2000 to calibrate and 18 fields observation in Abshar irrigated area in the Zayandeh Rud basin, Esfahan, Iran, in 2000-2001 to validate the models (Akbari et al., 2009). Simulated and observed yield for wheat are depicted in Fig 2.

Table 2. Different scenario was defined base on limitations or non-limitations in land, water quantity, time and irrigation depth.

Scenarios	Assumption	First irrigation (mm)	Other irrigation (mm)	Scenario description (Some of the omitted irrigations in the current situation)
1	Farmers only can omit some irrigation in current situation	200	100	Current situation(baseline)
2		200	100	The omitted second irrigation
3		200	100	The omitted second and third irrigation
4		200	100	The omitted second, third and seventh irrigation
5		200	100	The omitted second, third, fourth and seventh irrigation
6		200	100	The omitted second, fourth and seventh irrigation
7		200	100	The omitted second, third, fifth and seventh irrigation
8		200	100	The omitted second, third, sixth and seventh irrigation
9	Farmers can decreased irrigation depth except f irst one	200	80	Decreased irrigation depths in scenario No.2
10		200	80	Decreased irrigation depths in scenario No.3
11		200	80	Decreased irrigation depths in scenario No.4
12		200	80	Decreased irrigation depths in scenario No.5
13		200	80	Decreased irrigation depths in scenario No.6
14		200	80	Decreased irrigation depths in scenario No.7
15		200	80	Decreased irrigation depths in scenario No.8
16	Farmers can ecreased irrigation depth	100	100	Decreased first irrigation depth in baseline
17		100	100	Decreased first irrigation depth in scenario No.2
18		100	80	Decreased all irrigation depths in scenario No.2
19		80	80	Decreased all irrigation depths in scenario No.2
20	Farmers using first irrigation+ Irrigation schedule with constant depth	100	100	First irrigation + one other one that proposed by model
21		100	100	First irrigation + two other one that proposed by model
22		100	100	First irrigation + three other one that proposed by model
23		100	100	First irrigation + four other one that proposed by model
24		100	100	First irrigation + five other one that proposed by model
25		100	100	First irrigation + six other one that proposed by model

3. RESULTS

Models performance

After calibrating the model, its validity was tested. Results showed that the performance of the model for 18 selected fields were more or less accurate, showing a slight over and under estimated yields at the different sites compared to measured data. This validity was evaluated by using four statistical parameters to compare observed and simulated yield of winter wheat. Fig 2 shows this comparison and some statistics. Simulated values were close to observed ones, especially for yields about 6000 Kg ha^{-1}

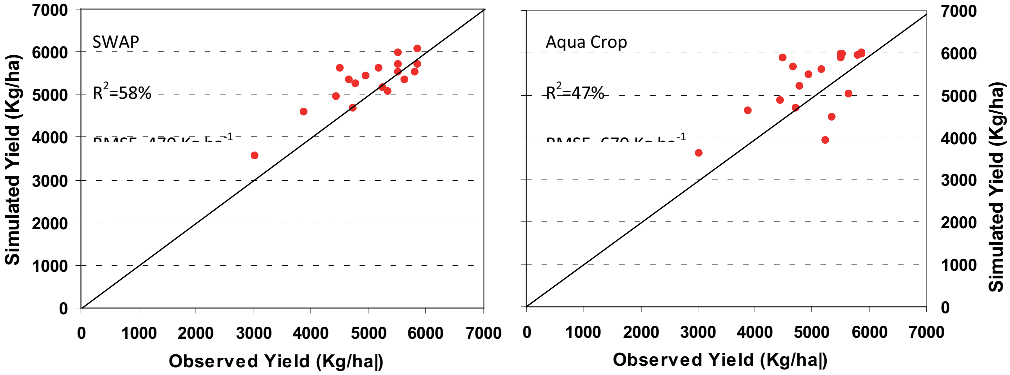

Fig. 2. Simulated and observed yield of winter wheat in Abshar area in 2001.

Baseline

All the terms of the water balance as simulated by AquaCrop for the baseline and other scenarios that are described in Table 2 are shown in Table 3. From table 3 is appears that the irrigation application was almost more than the potential transpiration. However, part of this irrigated water could not be used directly by the crop, as a consequence of percolation to the groundwater and losses by soil evaporation, for Example in the baseline scenario, percolated water was about 50 percent of irrigated water. In order to increase land and water productivity, based on limitations or non-limitations in land, water quantity, time and irrigation depth, different scenarios were studied in four parts. In the first part (scenarios1 to 8), it was assumed that farmers irrigated the crop at the most appropriate time, or they ccould not change the date of irrigation application, due to the fixed rotational water supply, but the farmers could omit some irrigations to improved water productivity. Results of simulated water balance parameters showed that the scenario 2, 3 and 4 had no significant impact on actual yield, biomass, soil evaporation and other water balance parameters except percolation compared to the baseline scenario. Because the amount of water extractions for crop transpiration and soil evaporation were relatively low compared to the irrigation water applied. However decreased irrigation depth reduced deep percolated water to the groundwater by 48 and 91% in scenario 2 and 3, respectively. In the 4th scenario 77% of available water was used by evapotranspiration and only 3% of water applied percolated to the groundwater. Therefore this scenario (scenario 4, the omitted second, third and seventh irrigation in the current situation) selected as optimized scenario for this part. Results of this scenario showed that, If farmers irrigated the winter wheat at the proposed schedule, the yield and water productivity can be increased by 16 and 45 per cent, respectively, as compared to the baseline production.

Improved agronomy management

In the second part (scenarios 9 to 15), it was assumed that farmers irrigated the crop at the most appropriate time, or they could not change the date of irrigation application, but they could improve agronomy management and reduce the depth of all irrigations except first and omit some irrigations to improve water productivity. Results show that in scenario 11, the water applied for irrigation decreased by 45% and caused winter wheat yield reduction by 16%, but water productivity increased by 45%.

In the third part, it was assumed that farmers could decrease the depth of all irrigations (scenarios 16 to 19). The results show that, decreasing irrigation depth in first irrigation had no significant impact on actual yield, biomass, soil evaporation and other water balance components except percolation, compared to the baseline scenario. However decreased irrigation depth in scenario 16, reduced deep percolated water by 50% from 194 mm down to 94 mm. High water productivity in this part received from scenario 18 was 43 % higher than the baseline value. As shown in Table 3, the scenario 4 was the best scenario for all the considered three, in terms of high yield and water productivity. Therefore this scenario was recommended to farmers for improving water and land management.

Changes in water quantity

The effect of a change in irrigation supplies in terms of total water applied was analyzed using the result of the AquaCrop model (scenarios 20 to 25 in Table 3). In general, it appears that the current practice of applying 800 mm of irrigation is more than the optimal amount. However, with increasing competition of water less water might become available for irrigation in the near future. Results displayed in Table 3, can be used to estimate the expected crop yields given a certain amount of water available for irrigation. With the current water management, crop yields are about 75% of potential one. In scenarios 20 to 25 in Table 3 the relationship between water applied and the annual terms of the water balance, expected crop yields and crop transpiration are displayed. Fig 3 shows the trend of the water balance parameters, irrigation, crop transpiration, yield, biomass, water productivity and percent of increased water productivity for different defined scenarios in this part.

Table 3. Effect of the different scenarios for irrigation water quantity on yields and water balance using AquaCrop.

Scenario	Precipitation	Irrigation	Percolation	Tpot	Tact	Epot	Eact	Yield	Biomass
----------------------------------				mm			----------------------------------	Kg ha^{-1}	Kg ha^{-1}
1	67.1	800	194	516	457	198	95	5218	14199
2	67.1	700	101	519	456	400	89	5214	14175
3	67.1	600	18	505	443	211	86	5143	13738
4	67.1	500	18	505	439	211	69	5009	13648
5	67.1	400	18	390	314	308	80	3576	9844
6	67.1	500	56	490	393	220	77	4651	12390
7	67.1	400	18	439	330	248	71	3844	10754
8	67.1	400	18	475	355	229	64	3076	11663
9	67.1	600	61	511	420	201	89	4776	13298
10	67.1	520	18	490	383	222	89	4537	12200
11	67.1	440	18	490	380	222	72	4388	12111
12	67.1	360	18	372	278	319	81	3177	8945
13	67.1	440	36	477	355	226	78	4163	11438
14	67.1	360	18	439	313	255	66	2425	10553
15	67.1	360	18	406	288	273	74	3296	9605
16	67.1	700	94	516	457	198	95	5218	14199
17	67.1	600	2	514	456	200	89	5209	14133
18	67.1	500	0	507	412	205	91	4889	13053
19	67.1	480	0	489	386	222	91	4552	12241
20	67.1	200	10	308	224	364	76	2708	7488
21	67.1	300	10	446	336	274	75	3748	10563
22	67.1	400	10	470	419	255	78	4852	12726
23	67.1	500	10	505	503	215	71	6095	15119
24	67.1	600	53	519	519	198	73	6135	15639
25	67.1	700	120	521	521	196	78	6145	15699

These results (Fig 3) show that, deep percolation is very low (9.8 mm) as long as annual irrigation applications are lower than 500 mm, and higher irrigation applications will increase this percolation noticeably. An almost linear relationship exists between the amount of water applied by irrigation and the amount of percolation, with a slope of 70%. Soil evaporation is also related to the irrigation supply. With increased water application, the potential soil evaporation decreased and relative yields reach their top at an irrigation input of about 500 mm.

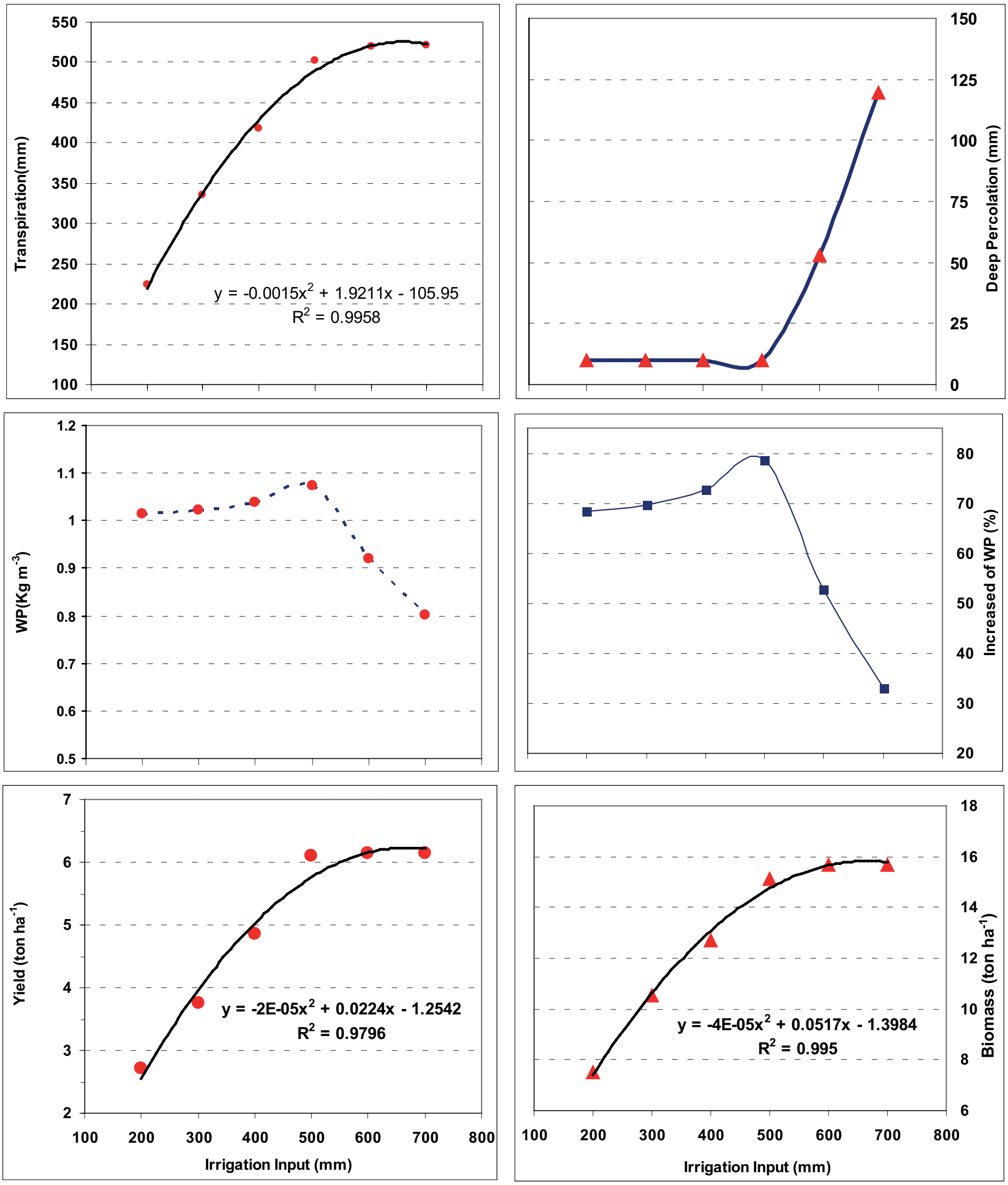

Fig. 3. Annual water balance for baseline and other scenarios using AquaCrop.

As can be observed from the Table 3 and Fig 3, the optimum yield can be expected for an irrigation depth of 500 mm, with a 16% increase as compared to the baseline scenario. Therefore, optimal water applied for winter wheat was about 500 mm. Increase in applied irrigation water until optimal depth caused yield and water productivity increase, but water applied more than optimal level has no significant effect on actual water productivity (WPdepleted) and economic water productivity, but decreased irrigation water productivity. For other combinations of water quantity values, expected yields and biomass can be obtained using this figure too. Furthermore, all other terms of the water balance can be analyzed for the different possible irrigation water application.

4. CONCLUSIONS AND RECOMMENDATION

Water scarcity and land and water scheduling problems require proper field scale management practices taking into consideration overall water resources. The methodology developed during this study can be used to assess the impact of changes in water quantity and irrigation scheduling on yields, gross, net return and water and land productivity. At the same time, the impact of changes at field scale practices on basin water resources, in terms of water quantity as well as land productivity issues, can be evaluated too with the results presented here.

The AquaCrop models have proven to be able to produce a wide range of scenarios to study expected yields for different crops, soil types, irrigation depths and water and land limitation. Plot experiments would in principle be able to generate the same data, but from a practical point of view this would be impossible considering the numerous combinations to be studied. Moreover, AquaCrop generates not only yields, but all the terms of the water balance enables a more realistic assessment, such as real water used versus water applied, percolation water, beneficial versus non-beneficial depletion, etc.

For the Abshar irrigated area studied here it can be concluded that given the current practice of about 800mm of irrigation with an average water salinity level of

1.5dS m^{-1}, yields of winter wheat are expected to be around 75% of the yield potential of 7000 kg ha^{-1}. Results of simulated water balance parameters show that, decreasing irrigation depth to 100 mm had no significant impact on actual yield, biomass, soil evaporation and other water balance components except percolation. Decreased irrigation depth, reduces deep percolation to the groundwater by 49 to 1 % from 193mm down to 94 and 2 mm, respectively. Results show that, if farmers irrigated the winter wheat at the appropriate time, and 5 times, using 100mm at each irrigation, the optimal yield can be expected for an irrigation depth of 500 mm that will be 16% higher in land productivity, as compared to the baseline scenario. Increase in applied irrigation water until optimal depth caused yield and water productivity increase, but water applied more than optimal level, decreased irrigation water productivity.

The main advantage of the approach applied here is that it is a nonspecific one and can be easily adapted to other conditions in terms of soil, weather, and crop. The study presented was setup to demonstrate the use of existing models, data, and techniques for a rapid assessment. Input data for the current study was readily available and required data was obtained by converting the existing data to the required ones in stead of starting extensive measurement efforts. The use of an existing well-tested simulation model and well-established data conversion methods was assumed to generate reliable results. Besides the benefits of this non-specific approach, the methodology applied here gives a wealth of information in comparison to field trials, in terms of spatial and temporal resolution as well as in terms of difficult to measure processes such as crop transpiration, soil evaporation, and percolation.

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