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Simulation of Yield Decline as a Result of Water Stress Using BUDGET Model

M. Malekpour[1]; H. Babazadeh[1*]

1: Department of Water Sciences, College of Agriculture and Natural Resources, Science and Research Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

In this paper, to account for the effect of water stresses in the various growth stages under deficit irrigation, the multiplicative, seasonal and minimal approaches are integrated in the BUDGET model. To evaluate the model, the simulated yields for winter wheat (was grown in Sharif Abad district) under various levels of water stress were compared with observed yields. The result showed, simulated crop yields agreed well with observed yields for this location using multiplicative approach (in comparison with minimal and seasonal approaches). The determination coefficient (R^2) between observed and simulated yields ranged from 0.81 to 0.92 with very high modeling efficiencies. The root of mean square error (RMSE) values is relatively small and ranged between 6 to 14. A sensitivity analysis showed that the model is robust and that good estimates can be obtained by using indicative values for the required crop and soil parameters.

Keywords: BUDGET; Seasonal approach; Minimal approach; Multiplicative approach.

[*] **Corresponding Author Email**: h_babazadeh@srbiau.ac.ir

INTRODUCTION

Iran, with an area of 1,648,195 square kilometer is placed in dry belt of the world and precipitation and evapotranspiration rate is equal 0.33 percent and 3 times the world average, respectively. Spatial and temporal distribution is inappropriate. Hence water shortage is one of the major challenges in the arid region of Iran. This challenge is likely to intensify with population growth (Ehsani, 2005). For instance, the population in Iran has increased with a factor of 6.8 during the last 90 years, from under 10 million in 1922 to 75 million in 2010. 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 1922 to 1733 m^3 in 2010. Countries with annual per capita water availability of less than 1700 m^3 are denoted as 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 ground water are utilizable (Ehsani, 2005). Irrespective of certain assumptions and uncertainties involved in these future water and food demand projections, it is obvious that the agriculture sector has to produce more food with the same or less amount of water resources. One appropriate technique for obtain 'more crop per drop' is deficit irrigation, whereby less water than required is applied during the growing period (English, 1990; Kipkorir, 2002). Under this strategy, high yields can still be obtained by supplying the required amount of irrigation water during sensitivity crop growth stages, and by restricting the water stress to tolerant growth stages.

In this paper, the applicability of the k_y approach for estimates of crop yield as a result of water stress under former's management conditions (well growing conditions), is verified for winter wheat cultivated in Sharif Abad district (in Qazvin plain irrigation network, Iran). To determine the water stress and relative evapotranspiration the k_y approach is incorporated in BUDGET model. Different approaches for combing the effect on seasonal yield and water stress in various growth stages can be selected in the model and were compared. Finally, the robustness of the model is tested by studying the effect of the quality of the input (crop, soil and climate) on the seasonal yield estimate.

MATERIALS AND METHODS

Irrigation network

The Gazvin irrigation network located between 35º 24´ N to 36º 48´ N latitude and 48º 45´ E to 50º 51´ E longitude. The average annual precipitation and evaporation in the region are 312 and 1345 mm, respectively and the mean annual temperature is 13.5ºC. The distribution of rainfall is extremely uneven in time and space, resulting in serious water shortages. Geographically the irrigation area is in Qazvin plain in the north west of Iran. It serves an estimated gross irrigation area of 5800 ha, which the needed water is supplied from Taleghan dam reservoir and 102 integrated wells scattered along the command area. The crops cultivated in the region include wheat, barley, pear, corn, suger beet, alfalfa, sunflower, cucumber, onion, potato, tomato, bean and lentil. Irrigation system commonly used across the network is of the furrow and border types. In this paper, we selected one experimental field in Sharif Abad district (Figure 1).

Fig. 1: The study area

BUDGET model

In the soil water balance model BUDGET, the charge of water stored in the root zone is determined on a daily basis by keeping track of incoming (rainfall, irrigation) and outgoing (evapotranspiration, deep percolation) water fluxes at its boundary. Given the simulated soil water content in the root zone and corresponding crop water stress, the yield decline is subsequently estimated with k_y approach. Various approaches for combining the effect of water stress in the individual stages exist and can be selected in BUDGET model. These approaches allow one to consider the magnitude of water stress and the difference in effect on seasonal yield of each of the stages. To account for the stresses in the various growth stages, the seasonal, minimal and multiplicative approach integrated in the model.

In seasonal approach (1), the effect of water stress on seasonal yield during one specific growth can be estimated with Eq.(1) by using a stage specific yield response factor (Doorenbos & Kassam, 1979):

$$1 - \frac{Y_a}{Y_m} = k_y \left(1 - \frac{ET_a}{ET_c}\right) \qquad (1)$$

Where $\frac{Ya}{Ym}$ is the relative yield or $\left(1 - \frac{Ya}{Ym}\right)$ is the relative yield decrease, $\frac{ETa}{ETc}$ is the relative evapotanspiration or $\left(1 - \frac{ETa}{ETc}\right)$ is the relative evapotanspiration deficit and K_y is yield response factor. In this approach, the relationship between yield decline and water stress is linear as long as water stress is smaller than 50%.

In the minimal approach (2), the minimum of the determined relative yields for each of by means of Eq. (1) for each of the individual stages and for the growing season is considered as the expected seasonal relative yield (Allen, 1994):

$$\frac{Y_a}{Y_m} = \min\left[\frac{Y_{a,1}}{Y_{m,1}}, \frac{Y_{a,2}}{Y_{m,2}}, \ldots, \frac{Y_{a,n}}{Y_{m,n}}, \frac{Y_{a,tot}}{Y_{m,tot}}\right] \qquad (2)$$

Where $\frac{Ya,1}{Ym,1}, \frac{Ya,2}{Ym,2}, \ldots, \frac{Ya,n}{Ym,n}$ are the expected yields as a result of water stress in the growth stages 1,2,…,N and $\frac{Ya,tot}{Ym,tot}$ is the computed relative yield by the seasonal k_y factor and the seasonal relative evapotranspiration.

In the multiplicative approach (3), total relative yield is obtained by(Jensen, 1968):

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{N} \left[1 - k_{y,i} \left(1 - \frac{ET_{a,i}}{ET_{c,i}}\right) \right] \quad (3)$$

Where $\prod$ stands for the product of the N functions (total number of growth stages) between the square brackets and $k_{y,i}$ and $\frac{ETa,i}{ETc,i}$ for the yield response factor and the relative evapotranspiration for growth stage i.

To express the combined effect on yield of water deficiency at time steps smaller than growth stages, each of the N functions of (3) is replaced in BUDGET model by a product of M functions (Raes, 2004):

$$1 - k_{y,i} \left(1 - \frac{ET_{a,i}}{ET_{c,i}}\right) = \prod_{j=1}^{M} \left[1 - k_{y,i} \left(1 - \frac{ET_{a,j}}{ETc,j}\right) \right]^{\frac{\Delta t}{L_i}} \quad (4)$$

Where $\prod$ stands for the product of the M functions between square brackets, M for the number of time steps with length Δt_j (days) during the growth stage i , L_i for the total length (days) of the stage and $Et_{a,j}$ and $Et_{c,j}$ for respectively the actual and maximum evapotranspiration during the time step J. Note that $(\Delta t_1+\Delta t_2+\ldots+\Delta t_m)/ L_i=1$.

Simulation

Winter wheat was cultivated under farmer's growing conditions during the 2004-2005 growing period (21 December-17 June) in three plots (40m× 40m) in Sharif Abad district. Table 1 shows physical and chemical properties of the soil experimental field. The curve number was derived from tables presented by the United States Department of Agriculture (1964) by considering K_{sat}. Each plot was subjected to a different water supply (table 2). The observed yield is reported in table 2.

The daily reference evapotranspiration (ET_0), rainfall (P) and irrigation (I) define the climatic input. The ET_0 is estimated by Penman-Montieth equation using daily meteorological data (Allen *et al.*, 1998). The daily meteorological data and rainfall data are acquired from Magsal weather station (Figure 1). The amount and number of irrigation are registered for experimental fields in Sharif Abad district. To specify yield decline as a result of water stress, BUDGET model requires the following inputs: length of crop cycle (LCC), crop coefficient (K_c), rooting depths (Z_r), soil water depletion factors for no stress (P), length of the sensitivity stages and yield response factor (K_y). These values for winter wheat are presented in tables 3 and 4. The crop coefficient for the initial growth stage varies in BUDGET model between 0.17 when the soil surface is dry and 1.1 when the soil surface is wet from irrigation or rainfall. The values of the crop parameter were derived from indicative values presented by Doorenbos and Kassam (1979) and Allen *et al.* (1998). An effective rooting depth (Zr) of 1 m at the beginning of the mid season stage is considered. The 40/30/20/10 % water extraction pattern proposed by Soil Conservation Service (1991) for plants growing in a well-watered uniform soil was selected to determine the variation of maximum sink term at different soil depths. The values refer to the percentage of water extracted at the upper, second, third and bottom quarter of the root zone.

Table 1: Physical and chemical properties of the soil within experimental field

Soil characteristics	Soil depth (cm)		Soil characteristics	Soil depth (cm)	
	0-15	15-30		0-15	15-30
Sand (%)	28	23	Permanent wilting point (%)	14.4	13.6
Silt (%)	18	20	Available P2O5 (kg/ ha)	25.6	23.1
Clay (%)	54	57	Available K2O (kg/ ha)	210	218
Bulk density (g/ cm3)	1.48	1.51	Available nitrogen (kg/ ha)	243	237
pH	7.8	7.3	Organic carbon (%)	0.91	0.83
Saturation water content (%)	45	49	EC (dS/ m)	0.21	0.2
Field capacity (%)	31	33	Saturation hydraulic conductivity (mm/day)	550	345

Table 2: Observed yield of winter wheat, reference evapotranspiration (ET_0), rainfall and irrigation during the agricultural year 2004- 2005 in Sharif Abad district for different treatments of water application

Data	T0: (rainfed)	T3: irrigated (three application)	T4: irrigated (four application)
ETo (mm)	736	736	736
Rainfall (mm)	131.6	131.6	131.6
Irrigation (mm)	0	211	273
Observed yield (ton/ha)	1.18	2.36	3.12

Table 3: Crop growth stages and crop parameters for winter wheat

Growth stage	Length (day)	Kc(-)	Zr(m)	P(-)
Initial	30	0.3	0.3	0.55
Crop development	80	0.3-1.1	0.3-1.0	0.55
Mid season	40	1.1	1.0	0.55
Late season	30	1.1-0.2	1.0	0.55

Table 4: Sensitivity stages and yield response factor (ky) of winter wheat for five district stage considered in Eq. (2) and (3), and for total growing period

Sensitivity stage	Establi-shment	vegetative		Flow-ering	Grain formation	Ripe-ning	Total growing period
		Early	Late				
Length (day)	10	35	60	25	35	15	180
K_y (-)	1.0	0.2	0.2	0.6	0.5	0.2	1.05

Assess of simulation results

The root mean square error (RMSE), the coefficient of determination (R^2) and the model efficiency (EF) between root mean square and simulated values were used to assess the accuracy of the BUDGET model for simulation of yield decline (Green & Stephenson, 1986; Loague & Green, 1991).

The root mean square error (RMSE) is a statistical estimator, shows how much the model over or under-estimates the observations (5).

Coefficient of determination (R^2) gives the amount of variance explained by the model compared to the total observed variance. R^2 ranges from 0 to 1, with higher values expressing a better relationship between the observed and predicted relative yield (6).

The model efficiency (EF) indicates the robustness of the model. EF ranges from $-\infty$ to 1 with higher values indication a better agreement. If EF is negative, the model prediction is worse than the mean observation (7).

$$RMSE = \sqrt{\frac{1}{\mathrm{n}}\sum_{i=1}^{\mathrm{n}}(\mathrm{O_i} - P_i)^2} \qquad (5)$$

$$R^2 = \frac{\sum_{i=1}^{n} O_i P_i - n\bar{O}\bar{P}}{\sqrt{\left(\sum_{i=1}^{n} O_i^2 - n\bar{O}^2\right)\left(\sum_{i=1}^{n} P_i^2 - n\bar{P}^2\right)}} \quad (6)$$

$$EF = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum\left(O_i - \bar{O}\right)^2} \quad (7)$$

Where O_i and P_i are observed and predicted (Simulated) relative yields for each of the n study cases, respectively and $\bar{O}$ and $\bar{P}$ are mean observed and predicted values respectively. n is 3 for the yields estimates of wheat.

Sensitivity analysis

Variations in simulated yield as a result of variations in climatic, crop and soil input were evaluated to study the robustness of the BUDGET model and the required quality of input data. The need to use daily rainfall was tested by performing simulations with 10-daily and monthly rainfall. The effect on simulated yields of a 5,10 and 15% increase and decrease of the k_c for the mid season stage, the k_y for the sensitive flowering stage, the rooting depth of the full grown crop (z_r) and the depletion factor for no stress (p) was assessed.

RESULTS AND DISCUSSION

Yield estimation

The simulated and observed relative yields for winter wheat for the three water application in Sharif Abad district is plotted in Fig. 2. The results refer to simulations performed with the multiplicative approach (Eqs. (3) and (4)), by considering the relative transpiration (T_a/T_c) and by integrating the effect of water stress on yield on a 10 day basis (Δt_j=10 days in Eq. (4)). The statistical analysis of the results for these and other settings for the k_y approach in BUDGET model are listed in table 5.

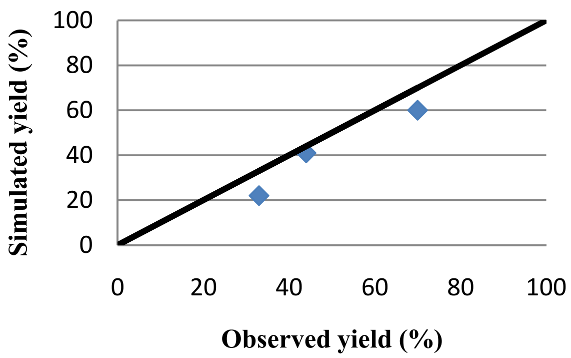

Fig. 2: Observed versus simulated relative yield for winter wheat

The slope of the correlation line between observed and simulated yield is almost parallel to the 1:1 line (Figure 2). This also reflected by the relative small RMSE in Table 5. The difference in performance of the three different approaches of cumulating the effect of water stress over the growing period, are only significant between the multiplicative approach and the minimal approach and between the seasonal and minimal approach (α=0.05). Therefore, the multiplicative approach is the best model (in comparison with minimal and seasonal approaches) as it was reported by Raes *et al*. (2005) in the north of Tunisia (Morang district). Combining water stress over smaller time steps than a stage in multiplicative approach doesn't have a significant effect (α=0.05). Estimating yields on basis of the relative transpiration instead of the relative transpiration did not have a significant effect in the experimental field (Table 5).

The results of sensitivity analysis

The robustness of the model was tested by altering rainfall, crop and soil data input data. The resulting differences in yield (ΔY) are reported in table 6. All simulation were performed with the multiplicative approach by considering relative transpiration and by considering a 10-day time step for estimates of yield decline (Eq. (4)). The following conclusion can be drawn:

-The use of 10-day and monthly rainfall data might result in wrong estimates of the soil water content in the root zone and hence in poor estimates of crop water stress and the corresponding yield decline.

- With indicative values of crop parameter, published by FAO (Doorenbos & Kassam, 1979; Allen *et al.*, 1998), good yield estimates can be obtained. Alerting yield response factor (ky), allowable depletion (p) or effective rooting depth (Zr), did not result in large variations of simulated relative yield, as long as they were in a reasonable range. Alerting the crop coefficient (kc) however will result in an over or under estimation of the crop transpiration, the crop water stress and the yield decline. Therefore, crop coefficients should be selected with care as it was reported by Raes *et al*. (2005) (Table 6).

Table 5: Assessment of yield simulations with different approaches to combine the effect of water stress on seasonal yield over the growing period

	Multiplicative approach				Minimal approach	Seasonal approach
	Δt_i=stage	Δt_i=10d	Δt_i=5d	Δt_i=3d		
	a. Yield estimates on basis of relative transpiration (Ta/Tc)					
RMSE	5.57	6.23	6.17	6.10	11.51	9.25
EF(-)	0.86	0.81	0.79	0.8	0.08	0.72
R^2	0.84	0.85	0.90	0.87	0.79	0.91
	b. yield estimates on basis of relative evapotranspiration (Eta/Etc)					
RMSE	5.53	6.53	6.10	5.98	14.12	9.88
EF(-)	0.85	0.83	0.81	0.83	-0.08	0.75
R^2	0.88	0.88	0.88	0.87	0.78	0.89

Table 6: Average change (ΔY) and standard deviation (σ) of relative yield as a result of altering climate and crop data, as simulated with BUDGET by using the multiplicative K_y approach (Eq.(5) with time step= 10 day) for three study case for winter wheat

Input	Winter wheat		Input	Winter wheat	
	ΔY (absolute%)	σ		ΔY (absolute%)	σ
Rainfall					
Ten daily	+1.2	3.33	Monthly	-0.28	3.1
Crop data					
Kc,mid +5%	-1.7	1.68	P +5%	0	0
Kc, mid +10%	-3.6	2.3	P +10%	0	0
Kc,mid +15%	-6.1	3.2	P +15%	0	0
Kc,mid -5%	+1.9	1.7	P -5%	0	0
Kc,mid -10%	+4.25	2.5	P -10%	0	0
Kc,mid -15%	+6.95	4.1	P -15%	0	0
Kc,flower +5%	-0.1	0.8	Zr +5%	+0.4	0.7
Kc,flower +10%	-0.7	0.7	Zr +10%	+0.75	0.6
Kc,flower +15%	-1.1	1.5	Zr +15%	+0.26	0.9
Kc,flower -5%	0.2	0.6	Zr -5%	-0.5	0.5
Kc,flower -10%	0.3	0.8	Zr -10%	-0.85	0.8
Kc,flower -15%	0.7	1.6	Zr -15%	-0.8	0.6

CONCLUSION

The following conclusion can be drawn:

1-The multiplicative approach, in comparison with minimal and seasonal approaches, is the best method that considers the effect of water stress during the various stages on seasonal yield and relatively high modeling efficiency and correlation between observed and simulated values in multiplicative approach were obtained as well.

2- The presented model is robust and requires only a minimum of input data which are readily available or easily can be collected. The sensitivity analysis illustrated this robustness of the model to yield simulation.

3- Except for the crop coefficient (k_c), simulations are not very sensitive to the values of the crop parameters as long as they are in the right range and the start and length of the growing period are locally obtained.

4- The model will be useful to develop an irrigation strategy under water deficit conditions that quarantines an optimal response to the applied water. It can also be used to determine the size of the area that should be irrigated when water resources are limiting, and to find the most suitable crop scheduling for rainfed conditions.

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