European Scientific Journal May 2015 edition vol.11, No.14 ISSN: 1857 – 7881 (Print) e - ISSN 1857- 7431

ESTIMATING SHALLOW WATER TABLE CONTRIBUTION TO SOYBEAN WATER USE IN ARGENTINA

Horacio R. Videla Mensegue, MSc
Americo J. Degioanni, PhD
Jose M. Cisneros, PhD
Departamento de Ecología Agrícola. Facultad de Agronomía y Veterinaria. Universidad Nacional de Río Cuarto, Argentina.

Abstract

The existence of a shallow water table can be an important water source for rainfed agricultural production. The objective of this study is to quantify the water contribution of the water table to soybean water requirements in the center of Argentina by means of a crop simulation model that relates water balance to grain production. The model was calibrated and validated considering soil water records up to 1 m deep, and the oscillation in the water table depth and grain yield during two climatically contrasted growth seasons (2004/05 - 2005/06). The adjustment obtained between observed and simulated values was: 1.8 mm for soil humidity, between 0.26 and 0.01 m for oscillation of the water table and between 49 and 920 kg ha^{-1} for grain yield. The results obtained with the simulation indicate that the water table contributed between 12 and 30% of the total water used by the crop in each growing season studied. It was concluded that, in rainfed agricultural conditions, a water table oscillating between 1.5 and 2 m deep makes it possible to stabilize the yield of rainfed soybean.

Keywords: Water table, crop model simulation, water balance, soybean

Introduction

Soybean [*Glycine max* (L.) Merr.] is the most important crop in Argentina regarding annual cultivated area, with more than 14 million hectares (INDEC, 2006). Crop yield varies between 1000 and 6000 Kg ha^{-1} each year depending on type of soil. This variation in rainfed production can be partially attributed to rainfall variation (Hall et al., 1992). The water contribution of a shallow water table to crop water balance can influence yield positively and decrease annual variation. In the Pampeana region, more than 6 million hectares are subject to the influence of a water table that oscillates at depths reached by the roots of the plants (Martini and Baigorri, 2002).

Numerous studies have emphasized the importance of the shallow water table as a potential crop water source in arid and semi-arid regions (Mejia et al., 2000; Dardanelli and Collino, 2002; Sepaskhah et al., 2003). Mueller et al. (2005) have measured water contributions of the water table of 100 - 400 mm and 20 - 250 mm in corn and wheat, respectively. Kang et al. (2001), on the other hand, have indicated that, with water table depths between 0.5 and 2.5 m, water contribution was of approximately 33% to 50% of the evapotranspiration for corn and wheat respectively.

In Argentina, Dardanelli and Collino (2002) have estimated that a water table located at approximately 6 m deep supplies up to 23% of the annual water use of alfalfa. In field studies, Kahlown et al. (2005) have indicated that the optimal depth of the water table to obtain maximum yield is 2 m for corn and sunflower, and 1.5 m for wheat. In tests with lysimeters, Sarwar (2002) concluded that, with the water table below 0.15 m, soybean yield was 48% less than when the water table oscillated around 0.60 m, during the crop growing season. In sum, these investigations state that a water table oscillating between 1.2 and 2 m deep is optimal to obtain a high yield in corn, sunflower, wheat and sorghum.

Most of these studies have been carried out with lysimeters (Kahlown et al., 2005; Kang et al., 2001; Mueller et al., 2001; Sepaskhah and Karimi-Goghari, 2005). The application of this method is complex, expensive and it cannot be made without disturbing the soil. However, the contribution of a shallow water table to the water requirement of a crop can also be studied with an indirect method using a crop simulation model. These models have been used in several investigations (Lamsal et al., 1999; Hurst et al., 2004; Degioanni et al., 2006; Sepaskhah et al., 2006).

At the moment, several models exist that simulate the soil-plant-atmosphere system using mechanistic bases such as CropSyst (Stockle et al., 1994), CROPGRO (Jones et al., 2003) and SWB (Campbell and Stockle, 1993; Marks, 1997; Marks and Campbell, 2002). These models require great amounts of data on climate, soil and crop, causing application problems. The simplest models, as the ones described by Beyazgül et al. (2000), Jorenush and Sepaskhah (2003) and Sepaskhah et al.(2003) are more appropriate to simulate scenarios where weather, soil and crop data are limited. These models have their physical-mathematical basis in the methodology proposed by Doorenbos and Pruitt (1975) and recently updated by Allen et al. (1998) and Allen (2000). The objective of this study is to quantify the contribution of the water table to the water requirements of soybean in the centre of Argentina using a crop model simulation.

Model description

Conceptual model

Figure 1 presents a conceptual diagram of the model from the perspective of the symbol system proposed by Forrester (1969). Matter and energy sources and flows were identified as well as state and flow variables in the soil-plant-atmosphere system.

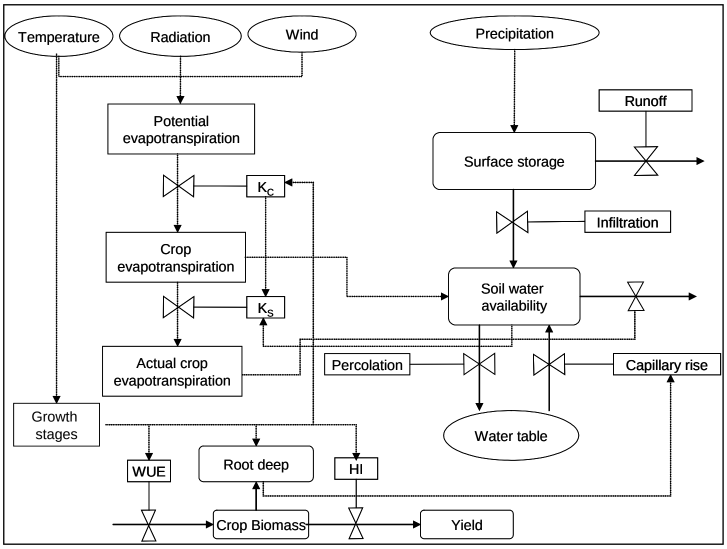

Fig. 1. Flow chart of the processes simulated by the model. The lines represent matter and energy (water, carbon, and radiation) flows, the dashes represent the information flow, the circles represent matter and energy sources, the rounded squares are state variables (water and carbon), and the rectangles are the flow variables.

Actual crop evapotranspiration

The potential evapotranspiration (ET_o) was calculated from the FAO-Penman-Monteith method (Allen et al., 1998) which estimates the daily la ET_o with the following equation (1):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \lambda\left(1 + 0.34 u_2\right)} \quad (1)$$

where R_n is the net radiation at crop surface (MJ m^{-2} day^{-1}), G is the density of soil heat flow (MJ m^{-2} day^{-1}), T is the average daily air temperature (ºC), u_2 is the wind speed (m s^{-1}), e_s - e_a is the deficit of vapor pressure at saturation (kPa), Δ is the slope of the vapour pressure curve (kPa °C^{-1}) and γ is the constant psycrometic (kPa °C^{-1}).

Crop evapotranspiration (ET_C) is estimated according to the model proposed by Doorenbos and Pruitt (1975). The model relates the ET_0 with ET_C with crop coefficient (K_C), using the following equation:

$$ET_C = K_C \times ET_0 \quad (2)$$

K_C values are different depending on the crop growth stage: initial, medial and final (Allen et al., 1998). If the crop is subjected to water stress, it is quantified by the ratio K_S that emerges from the following equation:

$$K_S = \frac{TAW - D_r}{TAW - RAW} \quad \text{being} \quad RAW = TAW \times p \quad (3)$$

where TAW is the amount of water available in the root zone (mm), RAW is the amount of water readily available in the root zone (mm), D_r is the water depletion in the root zone in mm, and p is a fraction of TAW that the crop can extract from the root zone without being subjected to water stress. This factor varies from one crop to another and is tabulated for a large number of crops. Normally it varies from 0.3 for shallow rooted plants in environmental conditions of high rates of ET_C (> 8 mm day^{-1}) to 0.7 for deep rooted plants in environmental conditions of low rates of ET_C (<3 mm day^{-1}). A numerical approximation to p estimated by the ET_C is shown in Equation 4:

$$p = p_{table} + 0.04 \times (5 - ET_C) \quad (4)$$

TAW in the root zone is the difference between field capacity water volume (θ_{CC}) and the wilting point (θ_{PMP}) affected by the rooting depth (Z_r).

$$TAW = 1000 \times (\theta_{CC} - \theta_{PMP}) \times Z_r \quad (5)$$

The depth of the root system is quantified by the model of root growth proposed by Borg and Grimes (1986) whose equation is as follows:

$$D^* = \frac{1}{\left[1 + 44.2 \exp\left(-8.5 t^*\right)\right]} \quad (6)$$

where D^* is the relative depth of the root (fraction of the maximum depth of rooting) and t^* is the relative time (fraction of the maximum physiological time of root growth).

Finally the crop evapotranspiration adjusted by water stress (ET_{Cadj}) is calculated using Equation 7:

$$ET_{C\,adj} = (K_C \times K_S) \times ET_0 \quad (7)$$

Soil water balance

The daily water balance, expressed in terms of depletion of soil water at the end of each day, is established according to Equation 8:

$$D_{r,i-1} = D_{r,i-1} - (P - RO)_i - CR_i + ET_{C,i} + DP_i \quad (8)$$

where *P* is precipitation (mm), *RO* is surface runoff (mm), *CR* is the capillary rise (mm), *DP* is the loss of water from the root zone by deep percolation (mm) and *i* refers to the day. The equation assumes that water can be stored in the root zone until it reaches field capacity. If it exceeds that limit, the model assumes that the total amount of excess water over field capacity is lost on the same day by deep percolation and/or evapotranspiration. In the absence of rainfall, the water content will steadily decline until it reaches a minimum value at the wilting point.

When water balance begins, the depletion initial water ($D_{r\ i-1}$) is estimated by Equation 9:

$$D_{r,i-1} = 1000 \times (\theta_{CC} - \theta_{i-1}) Z_r \quad (9)$$

where θ_{CC} is the water content at field capacity (cm^3 cm^{-3}), θ_{i-1} is soil water content average in the root zone (cm^3 cm^{-3}) and Z_r is the depth of the roots (m). Surface runoff is estimated by the method of the Number Curve (CN) proposed by the Soil Conservation Service of the United States (USDA-SCS, 1972). Capillary rise to the surface (CR_i - Equation 8) is estimated as a constant flow between the water table and the soil surface by the equation proposed by De Laat (1995):

$$q = -\int_0^h \frac{K(h)}{(Z_r - WT)} - K(h)dh \quad (10)$$

where *q* is the constant upward flow (m^3 m^{-2} day^{-1}), *WT* is the water table depth (m), *h* is the matric potential of the soil per water weight unit (m) and *K(h)* is the saturated hydraulic conductivity (m day^{-1}). The amount of water which goes upward can be removed at the same rate that it evapotranspirated on the surface. For this reason, the upward flow can never exceed the evapotranspiratory demand.

The rise and fall of the water table is quantified by Equation 11:

$$WT_i = WT_{i-1} - \left(\frac{V_S}{\mu} \right) \quad (11)$$

where V_s is the net flow into the water table (mm day^{-1}) and μ is the drainable porosity.

Crop yield estimation

Total crop biomass production was calculated with equation 12:

$$B = \sum_{n=0}^{d} ET_{C\,adj} \times WUE \quad (12)$$

where B is biomass production (kg ha^{-1}), WUE is water use efficiency, (kg mm^{-1} evapotranspirated), and d is the duration of the crop growth period (day). Finally, grain yield – Y (kg ha^{-1}) is the product of B by harvest index (HI).

$$Y = B \times HI \qquad (13)$$

If in the calculation of biomass production (Equation 12) ET_{Cadj} is replaced by ET_C estimated in Equation 2, biomass production with no water stress is obtained as a result, which is equivalent to the potential production limited only by water availability (assuming there is no other limiting production factor).

Material and methods

Study area

The study area is located in the south of the province of Córdoba, the flooding pampas (Cabido et al., 2003). This region presents a sub-humid climate with dry winters, an average annual rainfall of 798 mm and an average annual temperature of 16.4 °C. The soil used in this study is an udorthentic Haplustoll (INTA and SMAGyRR, 1987), with a sandy loam texture, well-drained, located in topographically flat and slightly undulating hills, good for agricultural use with a water table oscillating less than two meters deep and with an average salinity of 9 dS m^{-1}. The main characteristics of the soil are presented in Table 1.

Table 1. Soil characteristics (udorthentic Haplustoll).

Horizons	Ap	A12	AC	C
Depth (cm)	0-12	12-22	22-44	44 a +
Organic matter (%)	1.81	2.01	0.83	
Bulk density (gr cm^{-3})	1.30	1.30	1.41	1.35
Clay (%)	9.7	9.3	14.5	12.9
Silt (%)	24.5	23.5	29	28.1
Sand (%)	65.8	67.2	56.5	59
Field capacity water content (v v^{-1})	0.17	0.16	0.21	0.20
pH in water 1 : 2.5	6	6.1	5.9	6.5
Soil water salinity (dS m^{-1})	0.67	0.35	0.44	0.53

Data collection

The experimental plot has been cultivated with a soybean variety, "Don Mario 3700", with undetermined growth, for two growing seasons. In the first season, the crop was planted 2/12/2004 and was harvested 5/04/2005, and in the second, from 12/11/2005 to 28/02/2006. The average number of plants at harvest of was 35 plants m^{-2}. The climate variables that were measured daily were: precipitation, solar radiation, maximum and minimum temperature, relative humidity and wind speed recorded by a meteorological station. During the growing season 2004/05 the gravimetric water content of soil was measured at depths of 0.10, 0.25, 0.50 and 1 meter. In both growing seasons, the crop was monitored according to the phenological scale proposed by Fehr and Caviness (1977). Yield evaluation was achieved manually by taking ten samples of 0.25 m^2 each. The depth of the water table was also recorded every fifteen days with an observation hole.

Model parameters, validation and statistical methods

The model was calibrated using data from the 2004/05 growing season. The date considered were soil water content, water table oscillation, and yield. The parameters required by the model are shown in Table 2. Data obtained in the growing season 2005/06 were: groundwater depth and grain yield which were used to evaluate the predictive capability of the model. The capacity of adjustment of the processes calculated by the model was evaluated by means of root mean square error - RMSE - (Willmott, 1982).

Table 2. Model parameters for soybean.

Parameters	
K_C initial	0.5[a]
K_C medium	1.15[a]
K_C end	0.5[a]
p_{table}	0.5[a]
Water use efficiency (kg MS ha^{-1} mm $evapotranspirated^{-1}$)	26.1[b]
Maximum rooting depth (m)	1.8[c]
Harvest index	0.42[d]

a. Allen et al. (1998); [b.] Della Maggiora (2002); [c.] Stockle et al. (1997); [d.] Dardanelli et al. (2004).

Results and discussion

Adjustment of the model for soil water, water table level, and crop yield

The contrast between the observed soil water content during the 2004/05 growing season and the one estimated by the model presents a RMSE of 1.80 mm (Fig. 2). With respect to water table level oscillation, the model predicts with a good fit measure depths with RMSE of 0.26 m for the 2004/05 cycle and 0.01 m for the 2005/06 cycle. This predictive capability of the model is similar to the one reported by Thompson et al. (2004), Pavelic et al. (1999) and Degioanni et al. (2006) using mechanistic models (Figs. 3 and 4). The difference between the yield estimated with water stress and the observed one was of 1 and 1.5% for the growing seasons 2004/05 and 2005/06 respectively, which confirms an adequate degree of model adjustment (Table 5).

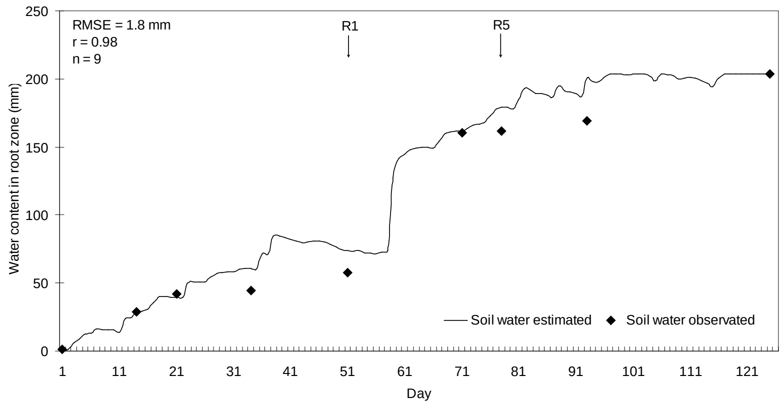

Fig. 2. Available water quantity in the root zone estimated and observed during the soybean crop 2004/05 growth season. R1 and R5 are phonologic stages in Fehn and Caviness (1977) scale.

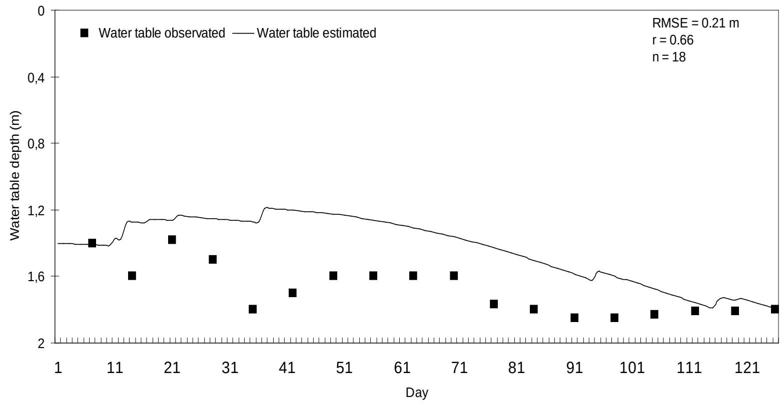

Fig. 3. Estimated and mean water table level measured during the crop 2004/05 growth season.

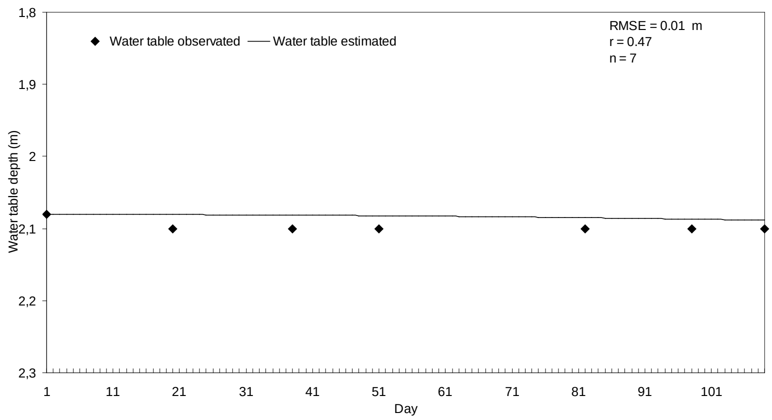

Fig. 4. Estimated and mean water table level measured during the crop 2005/06 growth season.

Crop evapotranspiration

Both growing seasons showed periods of water deficit for the soybean crop. Figures 5 and 6 show the ET_C and ET_{Cadj} estimated for the two growing seasons. The 2004/05 season showed two decreases in the ET_{Cadj} due to water stress suffered by the crop immediately after planting and during the flowering period for no more than three days. In the 2005/06 growing season, there were also two decreases in the ET_{Cadj}: one at pre-flowering and another at post-flowering for a period of 11 days. These differences between ET_C and ET_{Cadj} affected crop water availability.

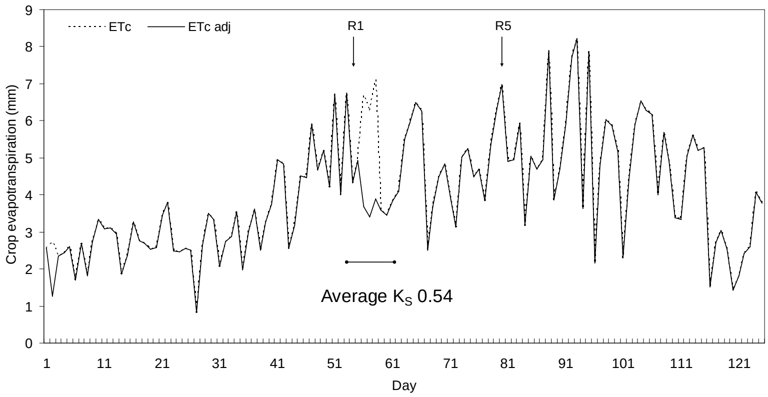

Fig. 5. Daily potential (ET_C) and real ($ET_{C\ adj}$) soybean evapotranspiration during the 2004/05 growth season. R1 and R5 are crop phenologic stages in the Fehr and Caviness (1977) scale.

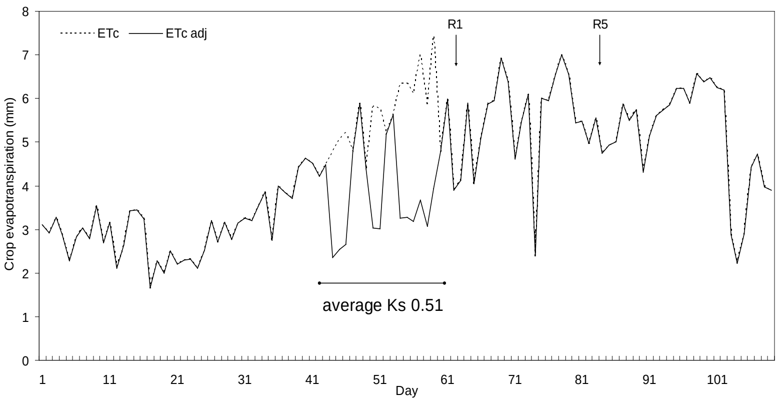

Fig. 6. Daily potential (ET_C) and real ($ET_{C\ adj}$) soybean evapotranspiration during the 2005/06 growth season. R1 and R5 are crop phenologic stages in the Fehr and Caviness (1977) scale.

Crop water availability

Figures 7 and 8 shows the results of the estimation of amount of water available for the crop (*TAW*), the amount of water readily available (*RAW*) and the depletion in soil water (D_r) for each of the crop growing seasons. In the growing season 2004/05, *TAW* (Equation 5) increased until the end of root growth period (approximately R5) reaching 200 mm. Moreover, it is observed that during most of the growing season, D_r remained above the threshold of water readily available (*RAW*), with the exception of the period near flowering in which D_r descends for a short period below *RAW*, determining an average K_S of 0.54 for the water stress period.

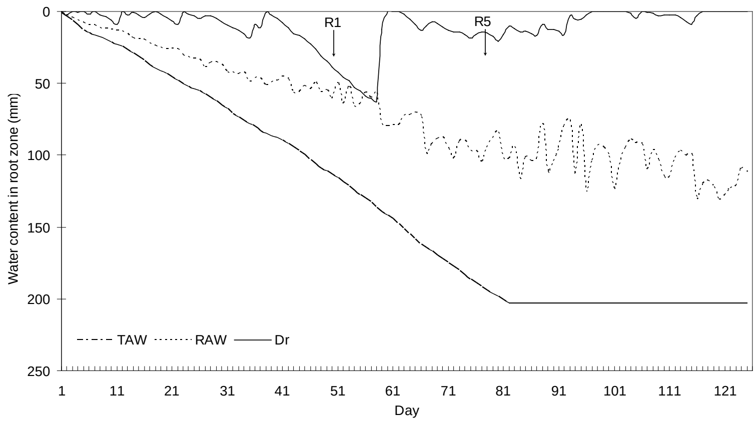

Fig. 7. Water quantity availability for crop (TAW), easily available water (RAW), and water decrease in the root zone (D_r) during the 2004/05 growth season. R1 and R5 are crop phenologic stages in the Fehr and Caviness (1977) scale.

The 2005/06 growing season showed an evolution of *TAW* similar to the one in the previous season but with a marked depletion of water in the radical zone (D_r) during the vegetative stage of the crop, determining an average K_S value of 0.51 for 11 days.

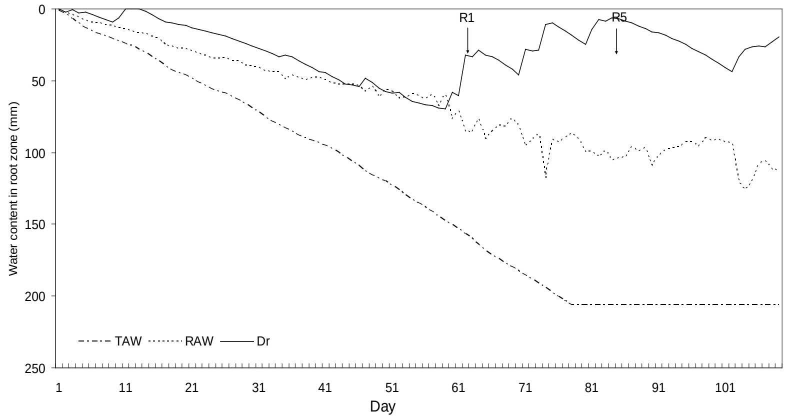

Fig. 8. Water quantity availability for crop (TAW), easily available water (RAW), and water decrease in the root zone (D_r) during the 2005/06 growth season. R1 and R5 are crop phenologic stages in the Fehr and Caviness (1977) scale.

Capillary rise and root growth

Figures 9 and 10 shows the water uptake by capillary rise and the root depth estimated by the model. It can be observed that for the two growing seasons, capillary rise varied between 0.4 and 1 mm day^{-1} during the early stages of the crop, reaching 3.5 mm day^{-1} towards the grain filling period (R5). As posed by Hess et al. (2000), Jorenush and Sepaskhah (2003), Raes and Deproost (2003), Hurst et al. (2004) and Mueller et al. (2005) the rate of capillary rise is strongly linked to the depth of the root system. This was corroborated in our study since, the depth reached 1.7 m deep towards the end of the crop cycle, coinciding with several reported values (Norman, 1983; Borg and Grimes, 1986; Stockle and Nelson, 1996).

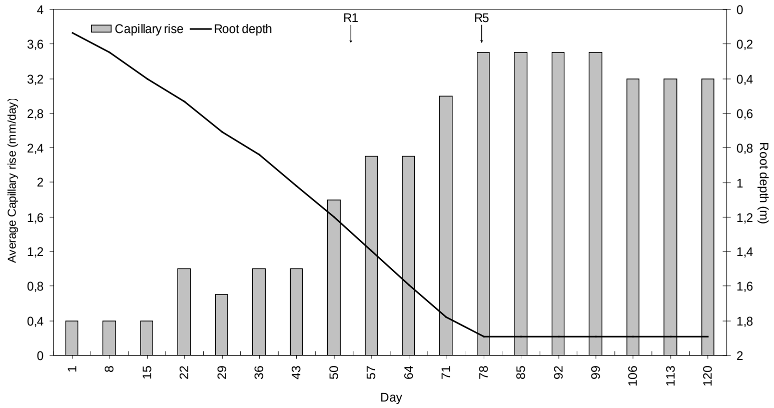

Fig. 9. Relationship between weekly average capillary uptake and root depth during the growing 2004/05 season. R1 and R5 are phonologic stages in Fehn and Caviness (1977) scale.

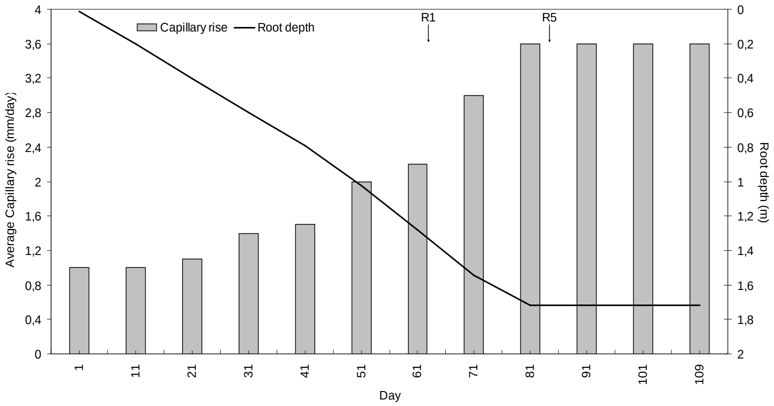

Fig. 10. Relationship between weekly average capillary uptake and root depth during the 2005/06 growth season. R1 and R5 are phonologic stages in Fehn and Caviness (1977) scale.

Water balance

The results of the overall water balance calculated by the model (Table 3) show that the effective rainfall for the 2004/05 growing season was 409 mm (79% of the total precipitation), potential evapotranspiration was 623 mm of which 80.2% -500 mm was evapotranspirated by the crop, and the contribution by capillary rise from the water table was 256 mm. In the 2005/06 growing season, effective precipitation was 186 mm (79.3% of the total precipitation), potential evapotranspiration reached 589 mm of which 77% -457 mm was evapotranspirated by the crop, and the contribution by capillary rise from the water table was 249 mm.

Table 3. Water balance components estimated by the model.

	Precipitation (mm)	Effective Precipitation (mm)	ET_0 (mm)	$ET_{C\ adj}$ (mm)	Capillary rise (mm)
Growth season 2004/05	517	410	623	500	256
Growth season 2005/06	234	186	589	457	249

To estimate the net contribution of the water table to the water requirements of the crop, the water balance without water table contribution was calculated (Table 4). Under these conditions, ET_{Cadj} showed values of 438 and 321.5 mm in contrast to the 500 and 457 mm from the ET_{Cadj} with water table uptake for the two growing seasons. In this regard, the model would indicate that the water table contributed a 12% (62 mm) of the total water used by the crop in the first season (wet year) and a 30% (135 mm) in the second season (dry year). This result confirms that the water table can be an additional source of water for rain-fed crops (Grismer and Gates, 1988; Racca et al., 2001; Kang et al., 2002).

Table 4. ET_C with and with no capilary rise.

	$ET_{C\ adj}$ (mm)	$ET_{C\ adj}$ with no contribution water table (mm)	Difference (mm)
Growth season 2004/05	500	438	62
Growth season 2005/06	457	321	135

This contribution is necessarily linked to water table depth. Mejia et al. (2000), in studies with lysimeters, conclude that a water table depth of 0.75 m is recommended for corn and soybean production. Mueller et al. (2005), in field studies, conclude that the recommended depth for an effective contribution to crop in corn and soybean production is twice the depth determined by lysimeters. In this study, the recorded depths were of 1.8 and 2 m for two seasons.

In the case of the flooding areas of the center of Argentina, the optimal water table depth is related to a soil with a low risk of flooding, which occurs at depths greater than 1.5 m in the actuals weather conditions (Cisneros et al., 1999; Degioanni et al., 2002; Degioanni et al., 2005).

Crop yield

If yield estimated with no water stress is compared to the measured one, a decrease of 10.4 and 14.3% for each growing season is observed (Table 5). This decrease in performance is linked to crop water stress during the beginning of the reproductive stage in the 2004/05 growing season and vegetative stage during the 2005/06 season. This low effect on yield was due to the fact that water stress did not affect plant growth in the critical period resulting in a low level of floral abortion, thus allowing the plant to continue to flourish once the stress was overcome (Andriani et al., 1991; Andrade and Sadras, 2002).

Table 5. Estimated yield with and with no water stress, yield not influenced by the water table, and mean yield in both growing seasons.

	Estimated yield without water stress (kg ha^{-1})	Estimated yield with water stress (kg ha^{-1})	Observed yield (kg ha^{-1})
Growth season 2004/05	6000	5490	5441
Growth season 2005/06	5740	5000	4920

Finally, if we compare grain yield in both growing seasons, we can observe that yield in the 2005/06 growing season was 10% lower than in the 2004/05 season. Rain water contribution was 45% lower in the 2005/06, which demonstrates the magnitude of the contribution made by the water table. Consequently, the presence of a water table at a depth which allows availability of water to the root zone enables the stabilization of crop yields in rainfed crops, as several investigations have indicated (Mejia et al., 2000; Kang et al. , 2001; Dardanelli and Collino, 2002; Muller et al., 2002; Sepaskhah et al., 2003).

Conclusion

This study has helped quantify the contribution of water from the water table to the water requirements of soybeans. In situations where the depth of oscillation of the water table allows the roots to reach the capillary fringe, water contribution from the water table is very important because in these conditions the crop has a greater capacity to overcome periods of water stress in times of lack of rainfall and to stabilize yield inter-annually.

The model used in this study showed consistent results in terms of the estimation of grain yield and its relationship to water balance and fluctuations of the water table. This tool has made it possible to estimate that the water contribution from a water table located approximately 1.5 to 2 m deep can represent up to 30% of the water requirements of soybeans in environments representative of the flooding sandy pampas, thus stabilizing the inter-annual variability of grain yield.

Acknowledgements

This research was financed by the Nacional University of Rio Cuarto. The authors of this paper are grateful to the Ph. D. Javier Marcos for his selfless cooperation in the investigation.

References:

Allen, R., Pereira, L., Roes, D., & Smith, P. (1998). *Crop evapotranspiration guidelines for computing crop water requirements*. FAO Irrigation and drainaje. Paper 56.

Allen, R.G. (2000). Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J. Hydrol.* 229, 27-41.

Andrade, F., & Sadras, V. (2002). Efecto de la sequía sobre el crecimiento y rendimiento de los cultivos. In F. Andrade & V. Sadras (Eds.), *Bases para el manejo del maíz, el girasol y la soja*. EEA INTA Balcarce - Fac. de Ciencias Agrarias UNMP, Balcarce, Argentina.

Andriani, J.M., Andrade, F.H., Suero, E.E., & Dardanelli, J.L. (1991). Water deficits during reproductive growth of soybeans. 1. Their effects on dry matter accumulation, seed yield and its components. *Agronomie 11*, 737-746.

Beyazgül, M., Kayam, Y., & Engelsman, F. (2000). Estimation methods for crop water requirements in the Gediz Basin of western Turkey. *J. Hydrol. 229*, 19-26.

Borg, H., & Grimes, D.W. (1986). Depth development of roots with time: An empirical description. *Trans. ASAE 29*, 194-197.

Cabido, D., Cabido, M., Garré, S.M., Gorgas, J.A., Miatello, R., Ravelo, A., Rambaldi, S., & Tassile, J.L. (Eds.). (2003). *Regiones naturales de la provincia de Córdoba*. AGENCIA CÓRDOBA D.A.C.yT. - Dirección de Ambiente, Córdoba, Argentina.

Campbell, G.S., & Stockle, C.O. (1993). Prediction and simulation of water use in agricultural systems. In *Proceeding of the International Crop Science Congress*, Iowa State University. Iowa, USA.

Cisneros, J.J., Cantero, J.J., & Cantero G., A. (1999). Vegetation, soil hydrophysical properties, and grazing relationships in saline-sodic soils of Central Argentina. *Can. J. Soil Sci. 79*, 399-409.

Dardanelli, J.L., & Collino, D. (2002). Estimation of the water table contribution to alfalfa crops in the Argentinean Pampa Region. *Agriscientia 19*, 11-18.

Dardanelli, J.L., Collino, D., Otegui, E., & Sadras, V., (2004). Bases funcionales para el manejo del agua en los sistemas de producción en los cultivos de grano. In E. Satorre, R. Benech Arnold, G. Slafer, E. de la Fuente, D. Miralles, M. Otegui & R. Savin (Eds.), *Producción De Granos. Bases Funcionales Para Su Manejo*. Editorial FAUBA, Buenos Aires, Argentina, p. 375-440

de Laat, P.J. (1995). Design and operation of a subsurface irrigation scheme with MUST. In L.S. Pereira, B. van den Broek, P. Kabat & R.G. Allen (Eds.), *Crop - Water Simulation Models in Practice*, Wageningen, Holanda.

Degioanni, A., Cisneros, J.J., Cantero G., A., & Rang, S. (2005). Simulación del nivel freático en suelos con riesgo de anegamiento. *XXº Congreso Nacional del Agua*, Mendoza, Argentina.

Degioanni, A., Cisneros, J.J., Cantero G., A., & Videla Mensegue, H. (2006). Modelo de simulación del balance hídrico en suelos con freática poco profunda. *Rev. Ci. Suelo (ARGENTINA) 24*, 1-10.

Degioanni, A., Cisneros, J.J., Marcos, J., & Cantero G., A. (2002). Balance hidrológico en una cuenca representativa de las llanuras del sur de Córdoba, Argentina. *Rev. Universidad Nacional de Río Cuarto 22*, 15-26.

Della Maggiora, A.I., Gardiol, J.M., & Irigoyen, A.I. (2002). Requerimientos hídricos. In F. Andrade & V. Sadras (Eds.), *Bases para el manejo del maíz, el girasol y la soja*. EEA INTA Balcarse - F.C.A. U.N.M.P., Balcarce, Argentina, p. 157-173

Doorenbos, J., & Pruitt, W.O. (Eds.). (1975). *Guidelines for predicting crop water requirements.* FAO. Irrigation and Drainage Paper 24, Roma, Italia.

Fehr, W.R., & Caviness, C.E. (Eds.). (1977). *Stages of Soybean Development*. Special Report 80. Iowa State University, Iowa, USA.

Forrester, J.W. (Eds.). (1969). *Urban dynamics*. M.I.T. Press, Cambridge.

Grismer, M.E., & Gates, T.K., (1988). Estimating saline water table contribution to crop water use. *Calif. Agric. 42*, 23-24.
Hall, A.J., Rebella, C.M., Ghersa, C.M., & Culot, J.P. (1992). Field-crop systems of the pampas. In C. J. Pearson (ed.), *Ecosystems of the world: field crop ecosystems*. Elsevier, Amsterdam, p. 413-449
Hess, T., Leeds-Harrison, P., & Counsell, C. (Eds.). (2000). *Wasim. Technical Manual*, Oxfordshire, Inglaterra.
Hurst, C.A., Thorburn, P.J., Lockington, D., & Bristow, K.L. (2004). Sugarcane water use from shallow water tables: implications for improving irrigation water use efficiency. *Agr. Water Manage. 65*, 1-19.
INDEC (Eds.). (2006). *Superficie implantada de oleaginosas, por cultivo. Total del país. Campañas 2000-01 a 2004-05*. Ministerio de Economía y Producción. Secretaría de Agricultura, Ganadería, Pesca y Alimentación., Argentina.
INTA & SMAGyRR (Eds.). (1987). *Carta de Suelos de la República Argentina. Hoja Laboulaye*. Editorial Fundación Banco de la Provincia de Córdoba, Córdoba, Argentina.
Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., & Ritchie, J.T. (2003). DSSAT Cropping System Model. *Eur. J. Agron. 18*, 235-265.
Jorenush, M.H., & Sepaskhah, A.R. (2003). Modelling capillary rise and soil salinity for shallow saline water table under irrigated and non-irrigated conditions. *Agr. Water Manage. 61*, 125-141.
Kahlown, M.A., Ashraf, M., & Zia-ul-Haq, (2005). Effect of shallow groundwater table on crop water requirements and crop yields. *Agr. Water Manage. 76*, 24-35.
Kang, S., Zhang, F., Hu, X., Peter, J., & Zhang, L. (2001). Effects of shallow water table on capillary contribution, evapotranspiration, and crop coefficient of maize and winter wheat in a semi-arid region. *Aust. J. Agric. Res. 52*, 317-327.
Kang, S.Z., Zhang, L., Liang, Y., Hu, X.T., Cai, H.J., & Gu, B.J. (2002). Effects of limited irrigation on plant biomass and water use efficiency of winter wheat in the loess plateau of China. *Agr. Water Manage. 55*, 203-216.
Lamsal, K., Paudyal, G.N., & Saeed, M. (1999). Model for assessing impact of salinity on soil water availability and crop yield. *Agr. Water Manage. 41*, 57-70.
Marcos, J. (1997). *Corn production under dryland conditions in eastern Washington*, Thesis Master Science. Washington State University, Pullman, USA.
Marcos, J., & Campbell, G.S. (Eds.). (2002). *SWBModel 11. Modelo de simulación de balance hídrico del suelo y crecimiento de cultivos*. Río Cuarto, Argentina.

Martini, E., & Baigorri, H. (2002). Manejo del cultivo de soja en suelos con influencia de napa freática. In INTA (Ed.), *Soja Actualización 2002*, Vol. A-9 - A-13, Marcos Juárez, Argentina.

Mejia, M.N., Madramootoo, C.A., & Broughton, R.S. (2000). Influence of water table management on corn and soybean yields. *Agr. Water Manage. 46*, 73-89.

Mueller, L., Behrendt, A., Schalitz, G., & Schindler, U. (2005). Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate. *Agr. Water Manage. 75*, 117-136.

Muller, K., Bach, M., Hartmann, H., Spiteller, M., & Frede, H.G. (2002). Point- and Nonpoint-Source Pesticide Contamination in the Zwester Ohm Catchment, Germany. *J. Environ. Qual. 31*, 309-318.

Norman, A.G. (Ed.). (1983). *Fisiología, mejoramiento, cultivo y utilización de la soja*. Hemisferio Sur, Buenos Aires, Argentina.

Pavelic, P., Dillon, P., Narayan, K., Herrmann, T., & Barnett, S. (1999). Integrated groundwater flow and agronomic modelling for management of dryland salinity of a coastal plain in southern Australia. *Agr. Water Manage. 3*, 75-93.

Racca, R., Collino, D., Dardanelli, J.L., Basigalup, D., González, N., Brenzoni, E., Hein, N., & Balzarini, M. (Eds.). (2001). *Contribución de la fijación biológica de nitrógeno a la nutrición nitrogenada de la alfalfa en la Región Pampeana*. Ediciones INTA, Buenos Aires, Argentina.

Raes, D., & Deproost, P. (2003). Model to assess water movement from a shallow water table to the root zone. *Agr. Water Manage. 62*, 79-91.

Sarwar, T. (2002). Physiological response of soybean to shallow water table depths. *Pakistan J. Biol. Sci. 5*, 1300-1308.

SCS-USDA, (1972). *Hydrology*, National Enginnering Handbook, Washington D.C., EEUU.

Sepaskhah, A.R., Bazrafshan J., A.R., & Shirmohamadi A., Z. (2006). Development and evaluation of a model for yield production of wheat, maize and sugarbeet under water and salt stresses. *Biosystems Engineering 93*, 139-152.

Sepaskhah, A.R., Kanooni, A., & Ghasemi, M.M. (2003). Estimating water table contributions to corn and sorghum water use. *Agr. Water Manage. 58*, 67-79.

Stockle, C.O., Cabelguenne, M., & Debaeke, P. (1997). Comparision of CropSyst performance for water management in southwestern France using submodels of different levels of complexity. *Eur. J. Agron. 7*, 89-98.

Stockle, C.O., Martin, S., & Campbell, G.S. (1994). CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agric. Syst. 46*, 335-359.

Stockle, C.O., & Nelson, R. (Eds.). (1996). *CropSyst: Cropping systems simulation model user's manual*. Washington State University, Pullman, USA.

Thompson, J., Refstrup S., H., Gavin, H., & Refsgaard, A. (2004). Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. *J. Hydrol. 293*, 151-179.

Willmott, C.J. (1982). Some comments on the evaluation model performance. *Bull. Am. Meteorol. Soc. 63*, 1309-1313.