IMPROVING SIMULATION OF SOIL WATER BALANCE USING LYSIMETER OBSERVATIONS IN A SEMIARID CLIMATE

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RESUMEN. La simulación del balance de agua en sistemas de cultivo es una herramienta muy útil para estudiar cómo utilizar el agua eficientemente. Esto requiere que los modelos simulen un balance de agua preciso. Comparar los resultados de los modelos con observaciones de campo proveerá información sobre la aptitud de los modelos. El objetivo de este estudio fue probar el funcionamiento del modelo Decision Support System for Agrotechnology Transfer (DSSAT) en la simulación del balance de agua. Un lisímetro de pesada continua fue utilizado para obtener los valores observados de drenaje y evapotranspiración (ET). El modelo simuló con precisión el agua en el suelo, el drenaje y la ET después de la optimización de los parámetros de suelo. Los pequeños cambios en drenaje y ET no fueron captados con precisión por el modelo. Estos resultados sugieren la necesidad de comparar las salidas de DSSAT con algún modelo hidrológico que simule movimiento de agua en el suelo de un modo mecanístico.

ABSTRACT. Water balance simulation in cropping systems is a very useful tool to study how water can be used efficiently. This requires that models simulate water balance accurately. Comparing model results with field observations provides information on model performance. The objective of this study was to test the performance of the Decision Support System for Agrotechnology Transfer (DSSAT) model in simulating the soil water balance. A continuous weighing lysimeter provided the observed values of drainage and evapotranspiration (ET). The model simulated accurately soil water content, drainage, and ET after optimizing soil parameters. The small changes in daily drainage and ET were not accurately captured by the model. These results suggested the need to compare outputs of DSSAT and some hydrological model that simulates soil water movement with a more mechanistic approach.

1.- Introduction

Soil water balance simulation in cropping systems is essential to determine crop available water and the possible environmental impact due to the solutes lixiviation. Comparing model results with field observations provides information on model performance and reveals strengths and weaknesses of such a model. This is essential in selecting appropriate models for practical application in water resources analysis and/or identifying required model improvements. In this work the water balance of the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2010) was evaluated. DSSAT is a suite of crop models sharing a common simulation of soil processes. In previous work we found some problems in the DSSAT simulation of the soil water balance components. The main issues were related to the simulation of drainage and evapotranspiration (ET). In this experiment, various irrigation cycles were applied to a weighting lysimeter to generate a number of combinations of drainage and ET.

The objective of this study was to test the performance of DSSAT when simulating the water balance components by comparing simulations and observed measurements. Two surface parameters (drainage rate, runoff curve number) and three per-layer parameters (lower limit, drained upper limit and saturated limit), were optimized and then the model was tested for a separate set of irrigation cycles. Once the DSSAT water balance simulation is checked, the influence of soil water movement on solutes lixiviation could be analyzed in future studies.

1.1.- DSSAT soil water model

The soil water balance in DSSAT is based on Ritchie's model which uses a one dimensional "tipping bucket" soil water balance approach (Ritchie1972; Ritchie 1981a; Ritchie 1981b). Per-layer available soil water is determined by the drained upper limit (DUL), lower limit (LL) and saturated water content (SAT), defined for each layer of the soil profile in the SOIL.SOL file. The water in the upper layer cascades to the lower layers mimicking the process of a series of reservoirs. Soil water infiltration is computed by subtracting runoff from rainfall/irrigation. Runoff is calculated with the SCS method (Soil Conservations Service, 1972) based on a curve number defined in the soil profile. Downward saturated flow takes place when a layer water content is above the drained upper limit. Upward flow caused by transpiration and soil evaporation is calculated within the Soil-Plant-Atmosphere module in DSSAT. Potential evapotranspiration (ET_0), is calculated and partitioned into potential plant evaporation and potential soil evaporation. Then, the actual ET is calculated by applying reduction factors, considering the soil moisture conditions.

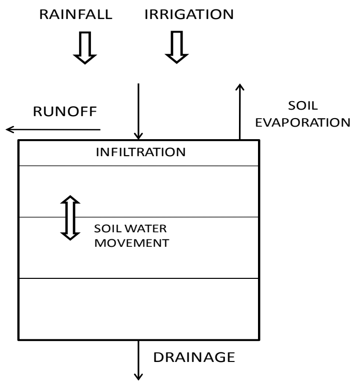

Fig. 1. Scheme of the soil water balance simulated by DSSAT

2.- Materials and methods

2.1.- Experimental design

Field observations were monitored in the experimental lysimeter station "*Las Tiesas*" (Albacete, Spain, 39ºN, 2ºW, 695 m), supported by the "*Instituto Técnico Agronómico Provincial*" (ITAP), during 2011 and 2012. A weighting lysimeter on bare soil with continuous electronic data reading devices was used in the experiment. The soil was cultivated previously with sunflower that was harvested and the residues removed before the beginning of the experiment. The dimensions of the lysimeter recipient are 2.3 m x 2.7 m and 1.7 m depth, with approximately 14.5 Mg total mass. The lysimeter recipient is surrounded by a square protection plot to avoid runoff and is located in the center of a 1-ha plot cultivated following the same procedures. The essay hosted also another weighing lysimeter cultivated with grass monitoring reference evapotranspiration (ET_0). In the bare soil lysimeter, ET was calculated daily based on the registered weight, corrected by drainage. Daily weather and soil parameters were measured at the site. The study was divided in two periods: calibration (2/8/2012-3/29/2012) and validation (10/30/2012-2/27/2013).

2.2.-Water management

Water management in the calibration period was done in two irrigation cycles: First cycle (February 8th , 2012 until March 1st, 2012) was used to replenish the soil water profile. In the second cycle (March 1st until March 29th, 2012) , the soil was irrigated with 77 mm of water letting it to dry during one month. In the validation period (October 30th , 2012 until February 27th, 2013) the soil was irrigated with 41 mm at the beginning letting it to dry after.

2.3.- Weather data

Weather information was collected by a weather station located in the experimental field. The area has a semi-arid, continental climate. The registered weather data was: relative air humidity, air temperature at 2 m, net short wave radiation at 2 m, net long wave radiation at 2 m, soil heat flux at 0.05, 0.1, 0.2 and 0.3 m, atmospheric pressure at 2 m, wind speed and direction and precipitation.

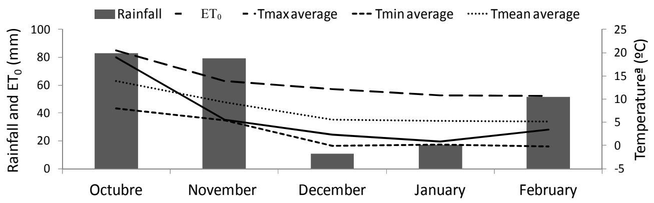

Fig.2. Monthly rainfall, average of maximal temperatures, average of minimal temperatures, and average of mean temperatures measured by the weather station in Las Tiesas and ET_0 measured in the reference lysimeter during the evaluated studied period (Oct 2012-Feb 2013)

2.4.- Soil characteristics

The soil is classified as Petrocalcic Calcixerepts (Soil Survey Staff, 2003). The soil depth of the experimental plot is 170 cm, with a fragmented petrocalcic horizon at 60 cm depth approximately. Texture is silty-clay-loam, with a uniform basic pH across the profile. Additional information is available elsewhere (López-Urrea et al., 2006).

Table 1. Physical and chemical properties of the experimental soil at different depths

	Layer (cm)					
Property	0-5	5-15	15-63	63-67	67-96	96-170
BD	1.39	1.39	1.49	1.8	1.49	1.7
pH	8.1	8.1	8.1	8.1	8.2	8.2
CEC cmol kg^{-1}	27.8	27.8	17.9	17.9	10.4	10.4
Organic C , %	0.96	0.96	0.46	0.46	0.24	0.23
Total N , %	0.13	0.13	0.08	0.01	0.08	0.01
Texture , %						
Coarse fraction	21	21	50	95	60	90
Silt	48.9	48.9	46.4	46.4	50.8	50.8
Clay	37.7	37.7	30.8	30.8	23.2	23.2

Bulk density (BD), coarse fraction, saturated hydraulic conductivity (Ks), and gravimetric and volumetric humidity (VH) were measured at the beginning of the experiment from soil samples extracted from the studied field. The BD was determined in ten samples at 20 and 40 cm depth by the core method. Hydraulic conductivity was measured in the laboratory in 20 undisturbed core samples taken at 20 and 40 cm depth by using a permeameter (Klute and Dirksen, 1986). Gravimetric and volumetric moisture were calculated on 20 kg of extracted soil at 20 and 40 cm depth by weighting the soil before and after drying (in the oven 5 days at 110Cº). The other parameters were taken from doctoral dissertations (Maturano, 2002; López-Urrea 2004).

2.5.- Drainage measurement

Drainage was continuously measured with a tipping bucket rain gauge (HOBO 200, Davis Instruments, Hayward, California, USA) installed at the outlet of the lysimeter bottom and connected to a data logger registering the information. The pluviometer was previously calibrated in the laboratory showing a ratio of 6.5 ml tip^{-1}

2.6.- Soil moisture measurement

The soil water content was monitored hourly using capacitance sensors (10HS ECH2O, Decagon Devices Inc., Pullman, WA) located at 10 and 40 cm depth. The sensors outputs were normalized with a normalization equation based on frequency readings of the sensors exposed to air and water, to determine a scale frequency (SF). The average SF was transformed into volumetric water content (θv) using a calibration equation that was obtained under laboratory conditions using soil samples from the experimental site according to the procedure described by Gabriel et al. (2010). This calibrated relationship (θv = 1.1052 SF-0.0927) covered a θv range from 0.07 to 0.8 m^3 m^{-3}, and had a correlation coefficient $r^2 = 0.95$.

2.7.- Model optimization and simulation

In this study we used DSSAT v4.5. The soil profile was divided into six soil layers, with the upper two layers of 5 and 10 cm to improve simulation accuracy. The soil water content in DSSAT was initialized according to the field measurements. Readings from the capacitance sensors at 10 and 40 cm depth were complemented with gravimetric soil sampling for deeper layers. The methods used in the DSSAT simulations were: FAO-56 (Doorenbos y Pruitt, 1977) for evapotranspiration, Ritchie (Ritchie, 1998) for water balance and infiltration, and Suleiman-Ritchie (Suleiman and Ritchie, 2003; Ritchie et al., 2009) for soil evaporation. To reduce the uncertainty associated to soil inputs, the optimization algorithm, Simulated annealing (SA), as implemented by Goffe et al. (1994), was used. Simulated annealing found the best collection of soil inputs by minimizing the sum of squares of the difference between predicted and measured outputs (SSE) of soil water content in the upper layers, drainage, and ET. The optimized soil inputs included surface parameters (drainage rate, runoff curve number), and per-layer parameters (LL, DUL, SAT).The optimization started with reasonable ranges of SAT, calculated from the total porosity obtained from field measures of bulk density. DUL and LL were subsequently optimized. Observed and simulated outputs were normalized using the range of measured values, to provide the same weight to outputs of different magnitudes during the optimization process.

3.-Results

3.1.- Soil parameters optimization

Table 2 shows the soil parameters before and after the optimization, and Figure 3 depicts the impact of input optimization on the simulated components of the soil water balance.

Table 2. Soil parameters before and after optimization used in DSSAT simulations. LL : Lower limit (cm^3 cm^{-3}) ; DUL : Drained upper limit (cm^3 cm^{-3}) ; SAT : Saturated limit (cm^3 cm^{-3})

Soil Layer (cm)	DR	RO	LL	DUL	SAT
Before optimization	0.75	45			
0-5			0.254	0.374	0.449
5-15			0.254	0.374	0.449
15-63			0.242	0.414	0.497
63-67			0.120	0.414	0.497
67-96			0.160	0.414	0.497
96-170			0.160	0.414	0.497
After optimization	0.31	27			
0-5			0.050	0.197	0.499
5-15			0.253	0.282	0.305
15-63			0.239	0.249	0.259
63-67			0.068	0.201	0.221
67-96			0.012	0.168	0.179
96-170			0.011	0.168	0.239

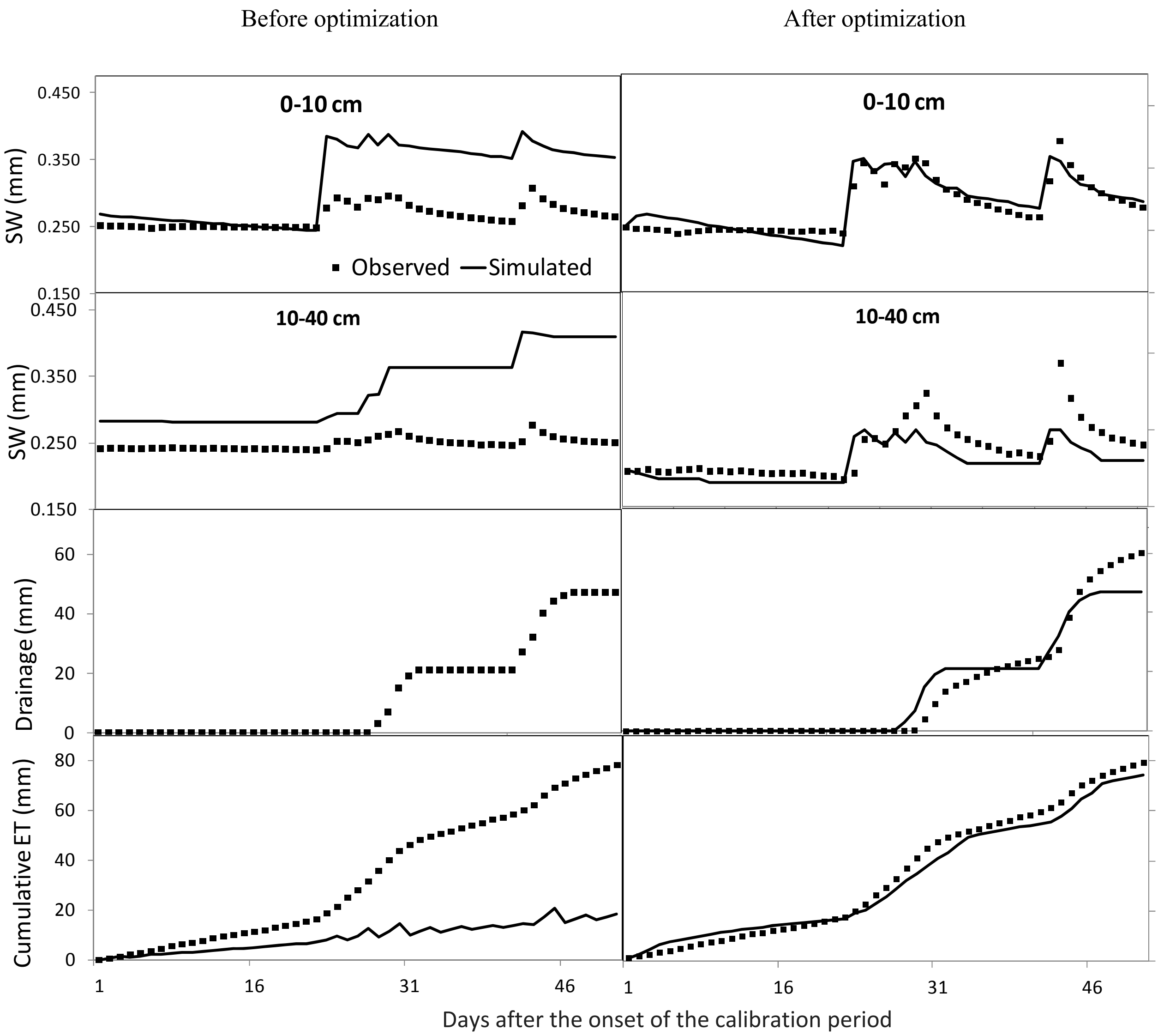

Fig. 3. Observed and simulated soil water balance components (soil water content, drainage and daily and cumulative ET) before and after optimization during the period 8-February 2012-March 2012

Figure 3 shows that parameter optimization greatly improved DSSAT simulations of soil water content, reducing the RMSE in 80% and 90% for the 0-10 cm and 10-40 cm, respectively. Also the drainage simulation was improved since the model was not simulating drainage before the optimization. However, the model was not able to capture small changes in daily drainage and ET. These small errors accumulated with time (Figure 3).

3.2.- Soil water balance

Once the soil profile was calibrated for the first time period (2/8/2012-3/29/2012), the second period (10/30/2012-2/27/2013) of the experiment was simulated with the improved soil inputs. Figure 4 shows that the soil moisture and the ET were simulated quite accurately with low RMSE, 0.011 and 0.006 cm^3 cm^{-3} for SW at 10 and 40 cm respectively, and 3.768 mm for ET. Drainage was very well simulated at the beginning of the period but the final cumulative values showed differences of more than 15 mm between simulated and observed values.

Table 3 shows the root mean square errors (RMSE) and the Nash and Sutcliffe (1970) efficiency coefficient for both periods. The SW was very well simulated by DSSAT in both periods with RMSE below 0.01cm^3 cm^{-3} for the two depths. The main differences between periods were observed in drainage simulation. While the calibration period presented a reasonably good drainage simulation, with an efficiency coefficient of 0.954, the drainage simulation in the validation period was poor, with an efficiency coefficient of 0.274, and a high RMSE (15.588)

(Table 3). Finally, the simulation of soil evaporation with DSSAT was good in both periods, with an efficiency coefficient close to one and a RMSE lower than 4 mm.

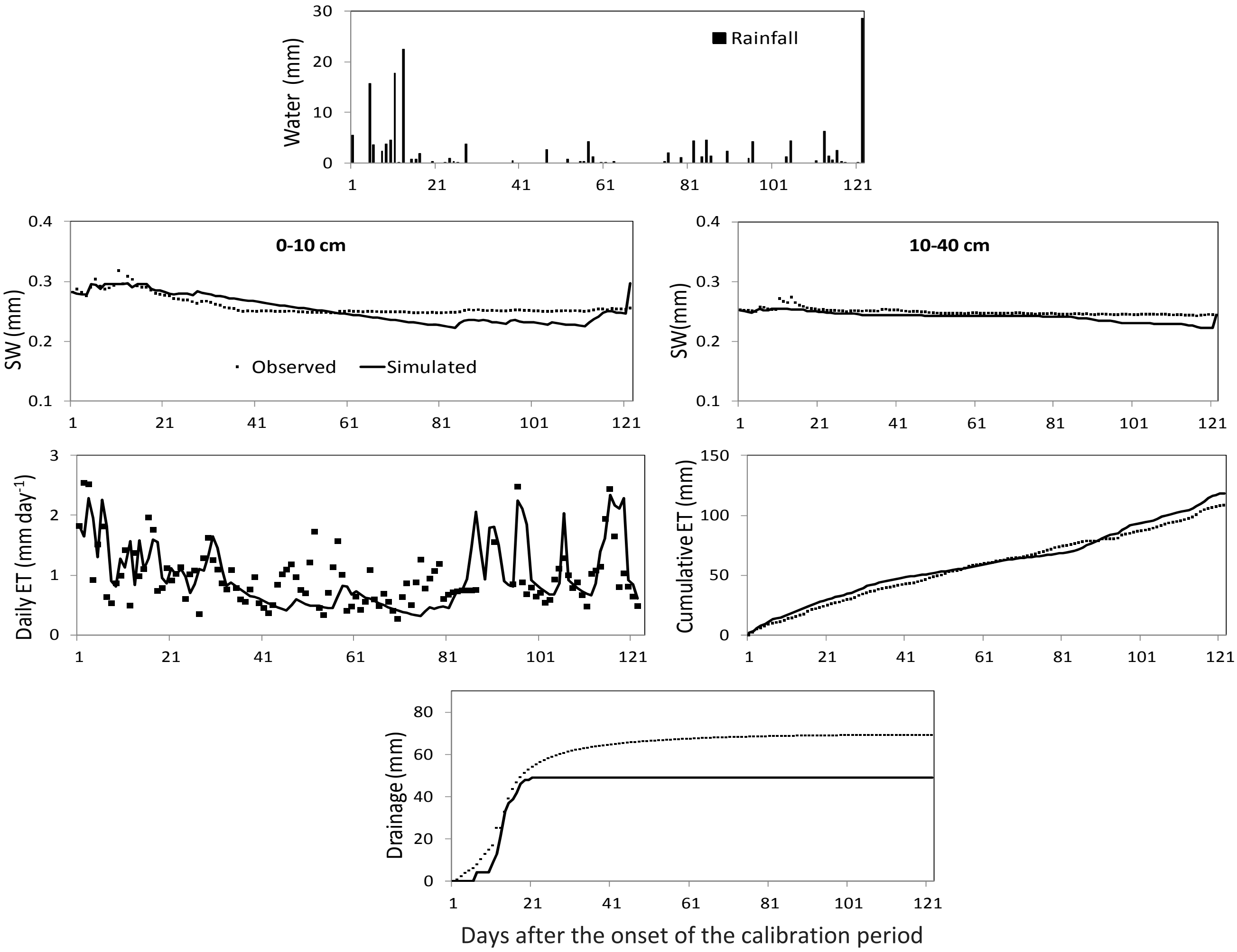

Fig. 4. Simulated and observed soil water balance components (soil water content, drainage and ET) during the second period (October 2012- February 2013) of the experiment

Table 3. Statistical analysis of the DSSAT simulated soil water components for the calibration and validation periods considering a 2% of error in the measurements (manufacturer specs.)

	Calibration		Validation	
	RMSE[1]	C eff[2]	RMSE[1]	C eff[2]
SW 10 (cm^3 cm^{-3})	0.003 [0.002-0.004][4] (cm^3 cm^{-3})	0.969[3] [0.946-0.985][4] p-value[5]: 0.00	0.011 [0.008-0.014][4] (cm^3 cm^{-3})	0.557[3] [-0.766-0.864][4] p-value[5]: 0.651
SW 40 (cm^3 cm^{-3})	0.004 [0.002-0.006][4] (cm^3 cm^{-3})	0.821[3] [0.718-0.938][4] p-value[5]: 0.00	0.006 [0.003-0.009][4] (cm^3 cm^{-3})	0.665[3] [0.273-0.793][4] p-value[5]: 0.923
Drainage (mm)	4.136 [2.289-5.811][4] (mm)	0.954[3] [0.843-0.976][4] p-value[5]: 0.00	15.588 [12.138-17.878][4] (mm)	0.274[3] [0.055-0.792][4] p-value[5]: 0.919
Soil evaporation (mm)	3.011 [2.4-3.653][4] (mm)	0.986[3] [0.966-0.992][4] p-value[5]: 0.00	3.768 [2.759-4.542][4] (mm)	0.983[3] [0.968-0.989][4] p-value[5]: 0.00

[1]: Root mean square error
[2]: Nash and Sutcliffe (1970) efficiency coefficient
[3]: Mean values
[4]: 95% Confidence interval obtained from Bca bootstrapping using Politics and Romano (1994) block bootstrap method for stationary dependent data
[5]:p-value for Ceff<=0.6

Table 4. Total observed and simulated soil water balance with DSSAT for the second experimental period

Water balance	Observed	Simulated
ΔSW*	20	5.1
Effective Irrigation (I)	0.0	0.0
Precipitation (P)	164	164
Drainage (D)	69	49
Runoff (R)	0.0	0.0
Soil Evaporation (P)	108	120
Final Balance†	5	0.1

* ΔSW: Variation in soil water content
†Final balance = (P+I)-(D+R+E) ± ΔSW

4.- Discussion

The optimization algorithm, SA (Goffe et al., 1994), was successfully used in this work. Simulated annealing demonstrated to be a very effective optimization technique decreasing the RMSE and increasing the efficiency coefficients of the model. This methodology was used successfully in previous works (Confalone et al.,2011; Calmon et al., 1999 a,b; Lizaso et al., 2001).

We were unable to detect any possible error in the simulated daily water balance of the optimized model. Also, the balance for the whole period equaled to zero as shown in Table 3. However, although the simulated global balance is correct, the distribution of water between the components needs to be improved. The soil water content in the first 40 cm of soil was greatly enhanced after the optimization in both studied periods. Drainage and ET simulations were also improved after optimization, however the drainage was still not accurately simulated, especially in the validation period. DSSAT drainage simulation seemed unable to reproduce the small drainage amounts occurring over extended time periods. It rather exhibited a steep curve with strong variations of drainage in a short period of time. Drainage was underestimated in both periods. We found similar results in previous studies that we carried out dealing with drainage simulation using DSSAT (no publish yet). It seems to be a trend on underestimating drainage with DSSAT model in the studied conditions. Cumulative ET however, was accurately simulated in both periods. These results suggested the need to compare outputs of DSSAT and some hydrological model that simulates soil water movement with a more mechanistic approach. The comparison of the two models might allow finding which mechanism could be modified or incorporated in the DSSAT model to improve the simulations.

5.- Conclusions

The SA global optimization method was used successfully for the optimization of the soil parameters in the DSSAT model. After the optimization with SA, DSSAT performed well simulating all the soil water balance components for the calibrated period. For the validation period, the model predicted quite well soil water content in the upper layers and very well the soil evaporation over time. An exception to this good performance was found in the drainage simulation especially in the calibration period. Further studies will be conducted to identify modifications in the DSSAT model that could improve the simulation quality, in particular of drainage.

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