XVII^th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

SEARCHING FOR IMPROVED IRRIGATION SCHEDULING ALTERNATIVES FOR HORTICULTURAL CROPS IN THE HUMID TROPICS

YOÍMA CHATERLÁN[1,2], MARÍA LEÓN[1], CARMEN DUARTE[1], TERESA LÓPEZ[1], PAULA PAREDES[2], GONÇALO C. RODRIGUES[2], LUIS S. PEREIRA[2*]

[1]Instituto de Investigaciones de Riego y Drenaje, La Habana, Cuba
[2]CEER – Biosystems Engineering, Institute of Agronomy, Technical University of Lisbon, Portugal, lspereira@isa.utl.pt

CSBE101118 – Presented at Section I: Land and Water Engineering Conference

ABSTRACT Excess water is often applied to horticultural crops irrigation, which contributes to inefficient water use and lower yields in horticultural production. However, these problems may be controlled when improved irrigation scheduling is adopted. The water balance and irrigation scheduling simulation model ISAREG was selected for searching improved irrigation schedules for selected horticultural crops in Cuba. The calibration and validation of the model was first performed using two independent data sets for each studied crop. The calibration refers to the crop coefficients (K_c) and the soil water depletion fraction for no stress (p). Results show a good agreement between observed and model predicted available soil water, with the root mean square error ranging 0.97 – 2.82 mm, and a index of agreement ranging 0.93 - 0.99. After this calibration and validation process the simulation model ISAREG was used to analyze the current irrigation schedules and develop appropriate alternatives that control percolation and may support improved yields and water use as well as productivity. Improved schedules may lead to nearly 30% increase in water productivity or 50% if deficit irrigation is adopted.

Keywords: soil water balance, simulation model, water productivity, horticultural crops, humid climate

INTRODUCTION To cope with the increasing water conflicts between irrigation and other uses, it is very important to define management strategies that are efficient, reliable and economically feasible. Vegetables are among the most important irrigated food crops in Cuba and large areas are cultivated to satisfy demand. In this country, vegetables are always irrigated since they are mainly cropped during the dry season. Usually farmers tend to over-irrigate vegetables because these crops are believed to be sensitive to water stress, and marketable yields can be dramatically reduced if water requirements are not adequately met. According to several authors (e.g. Doorenbos and Kassam, 1979; Pelter *et al*., 2004; Mermoud *et al*., 2005; Bekele and Tilahun, 2007; González-Dugo *et al*., 2007; Shock *et al*., 2007) vegetables' irrigation scheduling should be managed to avoid water stress especially during flowering and yield formation. Thus, reliable information on vegetables water requirements is useful for irrigation management proposes.

Several studies have been performed relative to vegetables water requirements and irrigation scheduling. Imtiyaz *et al*. (2000a,b) analyzed the yield, water productivity and economic impacts of various irrigation schedules, defined according to the cumulative pan evaporation (*CPE*), for different vegetables: cabbage, spinach, rape, carrot, tomato, onion and broccoli. Numerous studies refer to the impact of deficit irrigation schedules on onion yield and quality, e.g., Santa Olalla *et al*. (2004), Kadayifci *et al.* (2005), Kumar *et al*. (2007) and Enciso *et al*. (2009). Studies on bell pepper are reported by Sezen *et al*. (2006), and studies on garlic were published by Fabeiro *et al*. (2003) and Ayars (2008).

Proper irrigation scheduling is required for maximizing yield and water use. This study was performed with the objective of assess alternative irrigation schedules aiming at improved water productivity and water saving in the irrigation of garlic, onion, sweet pepper, and carrots. With this objective the soil water balance and irrigation simulation model ISAREG was selected, calibrated and validated for the same horticultural crops in Cuba conditions (Chaterlán *et al*., 2009).

MATERIALS AND METHODS

Modeling The ISAREG model (Teixeira and Pereira, 1992; Pereira *et al*., 2003) was selected to simulate and assess alternative irrigation schedules for four horticultural crops (garlic, onion, sweet pepper, and carrots). Its calibration and validation for these crops in environmental conditions of Havana, Cuba, is reported by Chaterlán *et al*. (2009). The model allows different options to define and evaluate the irrigation schedules as described in former applications (Cancela *et al*., 2006; Popova and Pereira, 2008; Pereira *et al*., 2009). Depending on weather data availability, the model may use various time steps (daily, 10-day, month) for the computation of the soil water balance. The model computes the water balance for a multilayered soil and is able to consider the impacts of salinity (Pereira *et al*., 2007) and to estimate the groundwater contribution (*GC*) through a parametric function (Liu *et al*., 2006).

The ISAREG model computes the crop evapotranspiration (ET_a) using the methodology proposed by Allen *et al*. (1998). The potential crop evapotranspiration ET_c (mm) is given by

$$ET_c = K_c \; ET_o \tag{1}$$

where ET_o (mm) is the reference evapotranspiration and K_c is the crop coefficient. The actual crop evapotranspiration (ET_a) is lower than ET_c when the soil water depletion exceeds the depletion fraction for no stress (p). ET_a is estimated through the soil water balance as a function of the available soil water in the root zone as described by Teixeira and Pereira (1992), and depletion is limited to the management allowed depletion (MAD). When water stress is not admitted, then $MAD \le p$ is adopted; when deficit irrigation is applied then $MAD > p$.

The model uses the methodology proposed by Stewart *et al*. (1977) and Doorenbos and Kassam (1979) to evaluate the water stress impacts on crop yields by computing the relative yield losses (*RYL*) from the relative evapotranspiration deficit through the water-yield response factor (K_y):

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ET_a}{ET_c}\right) \tag{2}$$

where ET_a and ET_c are respectively the seasonal actual and potential crop evapotranspiration (mm), Y_a is the yield (kg) achieved when $ET = ET_a$, and Y_m is the potential achievable yield (kg) of a well adapted crop variety under pristine cropping conditions when $ET = ET_c$.

The maximum or potential crop yield (Y_m) may be obtained from field observations (Popova *et al.*, 2006), or may be estimated using the approach proposed by Doorenbos and Kassam (1979) when local experimental data is not available. These authors define Y_m as the harvestable yield of a high producing crop variety, well-adapted to the local growing environment, under non-limiting yield conditions in terms of water, nutrients, pests and diseases. They estimate it as a function of several climatic factors such as temperature, radiation and length of the total growing season. In this application, the response factor K_y was derived from literature referring to the studied horticultural crops (Imtiyaz *et al*., 2000; Fabeiro *et al*., 2003; Santa Olalla, *et al*., 2004; Sezen *et al*., 2006; Kumar *et al*., 2007; Sarkar *et al*. 2008). The following K_y values were used: 1.1, 0.8, 0.88 and 0.93 respectively for onion, garlic, sweet pepper and carrots. However observed data do not allow extrapolations to high relative *ET* deficits.

The different irrigation scheduling results were assessed by comparing the predicted water productivity, *WP* (kg m^{-3} or kg mm^{-1}). *WP* is defined (Pereira, 2007) by the ratio between the actual yield, Y_a (kg) and the total water use, *TWU* (m^3), or indicating the components of *TWU,* respectively:

$$WP = \frac{Y_a}{TWU} \tag{3}$$

$$WP = \frac{Y_a}{\left(P + \Delta SW + I\right)} \tag{4}$$

where *P* is the season precipitation (mm), *ΔSW* is the difference in soil water content between planting and harvesting (mm), and *I* is the seasonal gross irrigation depth (mm). In this formulation *WP* is expressed in kg mm^{-1} and the yield refers to the unit surface.

The ISAREG model input data includes:

- *Meteorological data* concerning precipitation, *P* (mm) and reference evapotranspiration, ET_o (mm), or weather data to compute ET_o with the FAO-PM methodology, including alternative computation methods for missing climate data.
- *Crop data* referring to dates of crop development stages, crop coefficients (K_c); root zone depths Z_r (m); soil water depletion fractions for no-stress (*p*); and the seasonal water-yield response factor (K_y).
- *Soil data for a multi-layer soil*: relative to each layer, the respective depth *d* (m); the soil water content at field capacity, θ_{FC} (m^3 m^{-3}), and the wilting point, θ_{WP} (m^3 m^{-3}), or the total available water, *TAW* (mm); an additional file is used to parameterize the equations relative to groundwater contribution, *GC,* and deep percolation, *DP*; the available soil water (*ASW*) at planting is provided by the user.

The model allows several options to define the irrigation depths and dates, and to adopt restrictions on the water availability during a specific time period or for the crop season. Net irrigation depths (D) may be variable or fixed.

In the present study an evaluation of the current irrigation schedules was performed and an alternative management strategy aimed at achieving the maximal yield ($MAD = p$, *i.e.* when the soil water threshold is θ_p, with θ_p representing the average soil water in the root zone when depletion equals the fraction p) was defined; a fixed D = 6 mm for onion, garlic and carrots and D = 8 mm for sweet pepper were selected in order to minimize percolation and to improve micro-sprinkler irrigation efficiency. Analyzing observed field and simulation results for all alternative irrigation schedules, the date of the last irrigation is fixed 10 days before harvesting; available data show that the quality of the selected vegetables is affected when its moisture content at harvest is high (Doorenbos and Kassam, 1979).

Experimental site characterization Field experiments were performed at the Irrigation Station of Alquízar, situated at south of La Havana, Cuba. The weather data were observed daily at the local meteorological station (22 46' N; 82 37'W, and altitude 6 m) during the period 1985-1998; data include maximum and minimum temperature, precipitation, relative humidity and wind speed observed at 2 m height. The climatic characterization of the experimental site is given in Fig. 1. The maximum temperature occurs in July-August and the minimum by January. Precipitation occurs mainly during the period May to October (rainy season). The reference evapotranspiration (ET_o) was computed using the FAO-PM methodology when limited data is available (Allen *et al*., 1998). In the present study, solar radiation was estimated from maximum and minimum temperatures differences as described by Popova *et al*. (2006a).

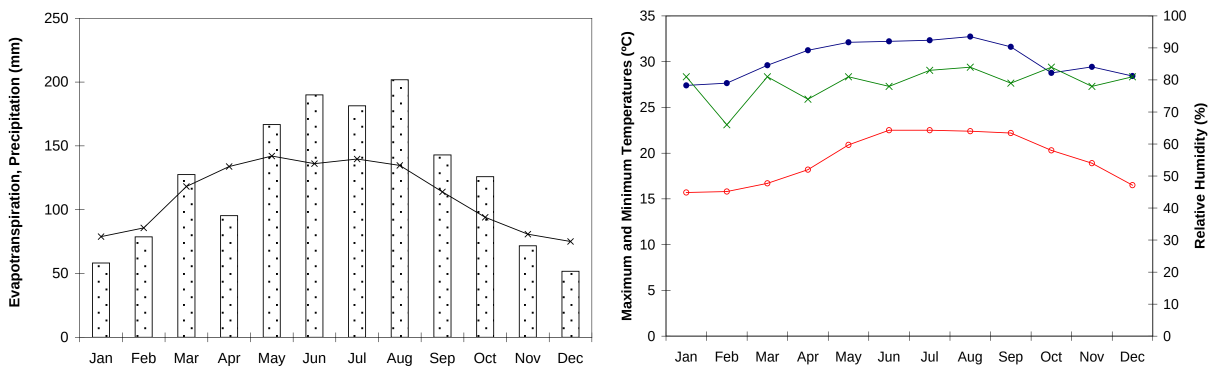

Figure 1. Climatic characteristics of the experimental site for the period 1985-1998: average monthly precipitation (□) and reference evapotranspiration (ET_o) (–×–), maximum (–●–) and minimum (–○–) temperature and relative humidity (–×–).

The main soils in the experimental site are Rhodic Ferralsols (Instituto de Suelos, 1996a, b), and usually have 1 m depth. The unsaturated soil hydraulic properties were determined from an appropriate survey and using laboratory methods for the full range of the soil water tension; the average values are θ_{FC} = 0.43 $m^3\ m^{-3}$ and θ_{WP} = 0.29 $m^3\ m^{-3}$; the total available water is TAW = 146 mm.

The crop parameters K_c and p obtained from the calibration (Chaterlán *et al*., 2009) are presented in Table 1 together with the dates of the crop growth stages.

Table 1. Calibrated crop coefficients (K_c) and depletion fractions for no stress (p), and dates of crops growth stages for the calibration and validation experiments, La Havana.

		Period length (dates)			
Crop growth stages		Onion	Garlic	Carrots	Sweet pepper
Initial	Cal.	20/11-20/12	04/12-24/12	22/11-08/12	16/12-20/01
	Val.	25/12-24/01	23/12-12/01	20/11-04/12	05/12-09/01
Development	Cal.	21/12-29/01	25/12-28/01	09/12-17/01	21/01-19/02
	Val.	25/01-05/03	13/01-16/02	05/12-11/01	10/01-08/02
Mid season	Cal.	30/01-20/03	29/01-09/03	18/01-11/02	20/02-14/03
	Val.	06/03-24/04	17/02-27/03	12/01-30/01	09/02-04/03
End season	Cal.	21/03-17/04	10/03-08/04	12/02-11/03	15/03-18/04
	Val.	25/04-24/05	28/03-26/04	31/01-16/02	05/03-07/04
Parameter		*Crop coefficients and depletion fractions for no stress*			
K_{cini}		0.40	0.70	0.55	0.80
K_{cmid}		1.04	0.83	0.96	1.22
K_{cend}		0.45	0.75	0.80	0.62
p_{ini}		0.30	0.30	0.30	0.40
p_{mid}		0.60	0.30	0.30	0.40
p_{end}		0.60	0.30	0.30	0.40

Cal – calibration year; Val – validation year

An example of the results of calibration when comparing the simulated with observed available soil water is given in Figure 2. Results show a good agreement between observed and computed available soil water, which is confirmed by the indicators used to evaluate the goodness of fitting. The results for all four crops are reported by Chaterlán *et al.* (2009). The indicators for goodness of fitting express the ability of the model to predict the available soil water for micro-sprinkled irrigated vegetables and support the use of K_c and p determined through this procedure to other locations having not very distinct climates and soils.

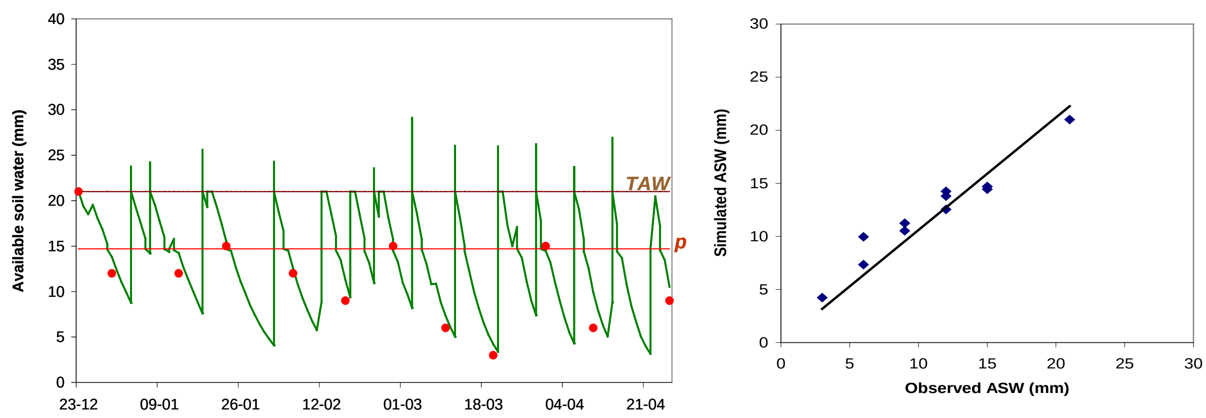

Figure 2. Example of the comparison between observed and simulated available soil water content for garlic at the Irrigation Station of Alquízar, Cuba, 1988-89 (calibration): on the left, the simulated available soil water curve (—) and observed values (●); on the right the regression between observed and simulated available soil water.

RESULTS

Evaluation of the current irrigation schedules Current irrigation schedules used in the calibration and validation experiments were evaluated using the crop coefficients and depletion fractions for no stress previously calibrated (Table 2).

Table 2. Summary of main outputs of the soil water balance performed for the calibration and validation of the four crops.

Crops	Water balance components	Calibration	Validation
Garlic	Season irrigation (mm)	151.8	194.4
	ASW at planting (mm)	21	21
	ASW at harvesting (mm)	6	10.5
	Precipitation (mm)	92.9	126.8
	Non-used precipitation (mm)	26.3	39.2
	Percolation (mm)	26.1	48.3
	ET_m (mm)	295.6	315.5
	ET_a(mm)	207.4	244.2
	RYL (%)	23.9	18.1
Onions	Season irrigation (mm)	170.3	144.9
	ASW at planting (mm)	21	21
	ASW at harvesting (mm)	2.5	12
	Precipitation (mm)	394.1	1204.1
	Non-used precipitation (mm)	199	878.8
	Percolation (mm)	53.1	44.9
	ET_m (mm)	381.9	455.5
	ET_a(mm)	330.7	434.3
	RYL (%)	14.7	5.1
Sweet pepper	Season irrigation (mm)	240.1	192
	ASW at planting (mm)	28	28
	ASW at harvesting (mm)	6.9	9.8
	Precipitation (mm)	100.6	182
	Non-used precipitation (mm)	17.2	64.1
	Percolation (mm)	46.52	12.89
	ET_m (mm)	381.6	366.3
	ET_a(mm)	298.1	315.2
	RYL (%)	20.4	13
Carrots	Season irrigation (mm)	239.8	179.4
	ASW at planting (mm)	21	21
	ASW at harvesting (mm)	18.1	13.5
	Precipitation (mm)	290.3	246.5
	Non-used precipitation (mm)	210.8	180.5
	Percolation (mm)	110.27	74.31
	ET_m (mm)	236.4	183.8
	ET_a(mm)	212.0	178.6
	RYL (%)	9.1	2.5

Results show that, for all cases, deep percolation may attain very high values, it ranges 6 to 46% of the total irrigation, and largely exceeds the leaching requirements (5 % of the irrigation depths). Farmers also tend to adopt high irrigation depths (up to 24 mm), which favour deep percolation and poor use of precipitation. Furthermore, schedules are inadequate since mild to high water stress ($ET_a < ET_c$) is observed because water was not always available in due time, thus leading to relative yield losses of up to 24%.

Results show that the current irrigation schedules are not appropriate to cope with the water scarcity conditions but require a more efficient use of the irrigation water. This implies that irrigation dates should be better adjusted and irrigation depths controlled to decrease deep percolation. In addition, water productivity should be improved, however taking into consideration that farmers' incomes are quite small in the region.

Improved irrigation schedules For the experimental years conditions, improved irrigation schedules were designed for water saving and percolation control and, simultaneously, maximizing crop yields (Table 3). As previously mentioned fixed irrigation depths were used: D = 6 mm for onion, garlic and carrots and D = 8 mm for sweet pepper.

Table 3. Irrigation strategy optimized for the calibration and validation when *MAD* = *p*.

Crops	Water balance components	Calibration	Validation
Garlic	Season irrigation (mm)	216	228
	ASW at harvesting (mm)	6.0	10.9
	Non-used precipitation (mm)	31.2	57.8
	ET_a (mm)	292.7	307.0
	RYL (%)	0.8	2.1
Onions	Season irrigation (mm)	174	150
	ASW at harvesting (mm)	2.7	12.0
	Non-used precipitation (mm)	211.3	907.6
	ET_a (mm)	375.1	455.5
	RYL (%)	1.9	0
Sweet pepper	Season irrigation (mm)	296	264
	ASW at harvesting (mm)	6.9	9.8
	Non-used precipitation (mm)	44.3	101.7
	ET_a (mm)	373.4	362.5
	RYL (%)	2.0	1.0
Carrots	Season irrigation (mm)	156	114
	ASW at harvesting (mm)	17.1	13.5
	Non-used precipitation (mm)	219.7	184.5
	ET_a (mm)	230.5	183.5
	RYL (%)	2.2	0.1

The season rainfall varied from 93 to 1204 mm, and season crop *ET* from 179 to 456 mm. The *ASW* at harvesting is adequate and indicates that the crop uses well the soil water when irrigation is ceased 10 days before harvesting. Results show that under these conditions ET_a approximately equals ET_c, thus indicating that water stress is not apparent.

Comparing the improved irrigation schedules with the current irrigation schedules in Table 2, because the irrigation depths per event are smaller than those currently practiced, both the number of irrigation events and the total irrigation applied is higher. The *ASW* at harvesting is smaller than those simulated for the current schedules (Table 2), thus indicating better use of soil water and rainfall.

Results demonstrate that when appropriate irrigation depths and timings are selected both the deep percolation and yield losses could be controlled.

Water productivity and water saving The water productivity (Eq. 3 and 4) are presented in Table 4 for all the improved irrigation schedules. The simulated yield results are in accordance with the ones measured in field experiments (non published reports). Results show that improvements in *WP* are achieved and range 5 to 24%.

Results indicate the need for improving irrigation scheduling strategies, namely the deficit irrigation ones, in order to highly improve *WP*.

Table 4. Simulated gross irrigation, total water use (*TWU*), yield and water productivity (*WP*) for various irrigation strategies.

Crops	Year	Irrigation strategy	Gross Irrigation (mm)	*TWU* (mm)	Yield (kg ha^{-1})	WP (kg m^{-3})
Garlic	Calibration	Current	151.8	282.7	9200	3.30
		Improved	216.0	362.9	12160	3.35
	Validation	Current	194.4	369.8	11300	2.75
		Improved	228.0	4118.0	12130	2.95
Onion	Calibration	Current	170.3	607.0	15500	2.64
		Improved	174.0	611.6	18460	3.02
	Validation	Current	144.9	1385.2	13200	1.06
		Improved	150.0	1391.6	15460	1.11
Pepper	Calibration	Current	121.3	400.7	11000	2.51
		Improved	120.0	470.6	12370	2.63
	Validation	Current	135.5	422.0	9840	2.57
		Improved	136.0	512.0	12360	2.41
Carrot	Calibration	Current	239.8	590.0	13000	2.27
		Improved	156.0	485.3	14440	2.98
	Validation	Current	179.4	470.8	10000	2.42
		Improved	114.0	389.0	11680	3.00

CONCLUSIONS The current irrigation schedules for vegetables practiced in Habana, Cuba show high non-beneficial water use as deep percolation, and an inadequate use of the available soil water. To adopt water saving practices and controlling deep percolation improved irrigation schedules were defined. These were based on the use of a water balance and irrigation simulation scheduling model (ISAREG model) that was previously calibrated for the selected crops. The improved irrigation schedules lead to very mild deficits, producing relatively small yield losses, not exceeding 3%, may be considered for further improving irrigation in the study area. Further developments will be produced by studying the use of deficit irrigation schedules and modified irrigation depths.

Acknowledgements Thanks are due to IIRD-Cuba for making available the data used in this study, and to CEER for the support provided through the FCT (POCTI/U0245/2003). Authors acknowledge the fellowship grant awarded by FCT to Yoíma Chaterlán.

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy, 300p.

Ayars, J.E. 2008. Water requirement of irrigated garlic. Transactions of the ASABE Vol.51(5): 1683-1688.

Bekele, S., and K. Tilahun. 2007. Regulated deficit irrigation scheduling of onion in a semiarid region of Ethiopia. Agricultural Water Management 89 (1–2), 148– 152.

Cancela, J.J., T.S. Cuesta, X.X. Neira, and L.S. Pereira. 2006. Modelling for improved irrigation water management in a temperate region of Northern Spain. Biosystems Eng. 94 (1), 151-163

Chaterlán, Y., C. Duarte, M. León, P. Paredes, T. Lopez, and L.S. Pereira. 2009. Determination of crop coefficients for horticultural crops in Cuba through field experiments and water balance simulation. Acta Horticulturae (ISHS) (submitted)

Doorenbos, J., and A.H. Kassam. 1979. Yield Response to Water. FAO Irrig. and Drain. Paper 33, FAO, Roma.

Enciso, J., B. Wildenfeld, J. Jifon, and S. Nelson. 2009. Onion yield and quality response to two irrigation sheduling strategies. Scientia Horticulturae 120: 301-305.

Fabeiro, C., F.J. Santa Olalla, and R. López Urrea. 2003. Production of garlic (*Allium sativum* L.) under controlled deficit irrigation in semi-arid climate. Agric. Water Manage. 59, 155–167.

González-Dugo, V., F. Orgaz, and E. Fereres. 2007. Responses of pepper to deficit irrigation for paprika production Scientia Horticulturae 114: 77–82

Imtiyaz, M., N.P. Mgadla, B. Chepete, S.K. Manase. 2000a. Response of six vegetable crops to irrigation schedules. Agricultural Water Management 45: 331-342.

Imtiyaz, M., N.P. Mgadla, S.K. Manase, K. Chendo, and E.O. Mothobi. 2000b. Yield and economic return of vegetables crops under variable irrigation. Irrig Sci 19: 87-93.

Instituto de Suelos 1996a. Nueva versión de la Clasificación Genética de los Suelos de Cuba. MINAG, Editorial Academia, La Habana, 102 pp. (in Spanish)

Instituto de Suelos 1996b. Correlación de la Nueva Versión de Clasificación Genética de los Suelos de Cuba, con Clasificaciones Internacionales (Soil Taxonomy y FAO-UNESCO) y Clasificaciones Nacionales (2da. Clasificación Genética y Clasificación de Series de Suelos). MINAG, Publicación Interna. La Habana, 22p. (in Spanish).

Kadayifci, A., G.I. Tuylu, Y. Ucar, and B .Cakmak. 2005. Crop water use of onion (*Allium cepa* L.) in Turkey. Agricultural Water Management 72: 59-68.

Katerji, N., M. Mastrorilli, and G. Rana. 2008. Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. J. Agronomy 28: 493-507.

Kumar, S., M. Imtiyaz, A. Kumar, and R. Singh. 2007. Response of onion (*Allium cepa* L.) to different levels of irrigation water. Agricultural Water Management 89: 161-166.

Liu, Y., L.S. Pereira, and R.M. Fernando. 2006. Fluxes through the bottom Boundary of the root zone in silty soils: parametric approaches to estimate groundwater contribution and percolation. Agric. Water Manage. 84: 27-40.

Mermoud, A., T.D. Tamini, and H. Yacouba. 2005. Impacts of deficit irrigation schedules on the water balance components of an onion crop in a semi-arid zone. Agricultural Water Management 77, 282–295.

Pelter, G.Q., R. Mittelstadt, B.G. Lieb, and C.A. Redulla. 2004. Effects of water stress at specific growth stages on onion bulb yield and quality. Agricultural Water Management 65, 107-115

Pereira, L.S. 2007. Relating water productivity and crop evapotranspiration. In: Lamaddalena, N., Shatanawi, M., Todorovic, M., Bogliotti, C., Albrizio, R. (Eds.) Water Use Efficiency and Water Productivity (Proc. WASAMED Workshop, Amman, Jordan, Oct. 2005), Options Méditerranéennes, Series B, 57, 31-50.

Pereira, L.S., P.R. Teodoro, P.N. Rodrigues, and J.L. Teixeira. 2003. Irrigation scheduling simulation: the model ISAREG. pp. 161-180, In: G. Rossi, A. Cancelliere, L.S. Pereira, T. Oweis, M. Shatanawi and A. Zairi (eds.) Tools for Drought Mitigation in Mediterranean Regions. Kluwer, Dordrecht.

Pereira, L.S., J.M. Gonçalves, B. Dong, Z. Mao, S.X. Fang. 2007. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the Upper Yellow River Basin, China. Agric. Water Manage. 93 (3), 109–122

Pereira, L.S., P. Paredes, E.D. Cholpankulov, O.P. Inchenkova, P.R. Teodoro, and M.G. Horst, 2009. Irrigation scheduling strategies for cotton to cope with water scarcity in Central Asia. Application to the Fergana Valley. Agric. Water Manage, 96:723-73

Popova, Z., M. Kercheva and L.S. Pereira. 2006. Validation of the FAO methodology for computing ETo with missing climatic data. Application to South Bulgaria. Irrig. and Drain. 55(2): 201-215.

Popova, Z., and L.S. Pereira. 2008. Irrigation scheduling for furrow irrigated maize under climate uncertainties in the Thrace Plain, Bulgaria. Biosystems Eng. 99, 587-597.

Santa-Olalla, F., A. Dominguez-Padilla, and R. López. 2004. Production and quality of the onion crop (*Allium cepa* L.) cultivated under controlled deficit irrigation conditions in semi-arid climate. Agric. Water Manage. 68, 77-89.

Sarkar, S., S.B. Goswami, S. Mallick, and M.N. Nanda. 2008. Different indices to characterize water use pattern of micro-sprinkler irrigation onion (*Allium cepa* L.). Agric. Water Manage. 95, 625–632.

Sezen, SM., A. Yazar, and S. Eker. 2006. Effect of drip irrigation regimes on yield and qualiy of field grown bell pepper. Agric Water Manage 81: 115-131

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2007. Short duration water stress produces multiple center onion bulbs. Hortic. Sci. 42, 1450–1455

Smith, M., L.S. Pereira, J. Berengena, B. Itier, J. Goussard, R. Ragab, L. Tollefson, and P. Van Hoffwegen (eds.) 1996. Irrigation Scheduling: From Theory to Practice. FAO Water Report 8, FAO, Rome, 384 pp.

Stewart, J.L., R.J. Hanks, R.E. Danielson, E.B. Jackson, Pruitt W.O., W.T. Franklin, J.P. Riley, and R.M. Hagan. 1977. Optimizing crop production through control of water and salinity levels in the soil. Utah Water Res. Lab. Rep. PRWG151-1, Utah St. Univ., Logan.

Teixeira, J.L., and L.S. Pereira. 1992. ISAREG, an irrigation scheduling model. ICID Bulletin 41: 29-48.