BIOSYSTEMS ENGINEERING 103 (2009) 536–551

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper: SW—Soil and Water

Assessing economic impacts of deficit irrigation as related to water productivity and water costs

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ARTICLE INFO

Article history:
Received 21 October 2008
Received in revised form
20 March 2009
Accepted 13 May 2009
Published online 3 July 2009

This study aims at assessing the feasibility of deficit irrigation of maize, wheat and sunflower through an analysis of the economic water productivity (EWP). It focuses on selected sprinkler-irrigated fields in Vigia Irrigation District, Southern Portugal. Various scenarios of water deficits and water availability were considered. Simulations were performed for average, high and very high climatic demand. The potential crop yields were estimated from regional climatic data and local information. Using field collected data on yield values, production costs, water costs, commodity prices and irrigation performance, indicators on EWP were calculated. Results show that a main bottleneck for adopting deficit irrigation is the presently low performance of the irrigation systems used in the considered fields, which leads to high water use and low EWP. Decreasing water use through deficit irrigation also decreases the EWP. Limited water deficits for maize are likely to be viable when the irrigation performance is improved if water prices do not increase much, and the commodity price does not return to former low levels. The sunflower crop, despite lower sensitivity to water deficits than maize, does not appear to be a viable solution to replace maize when water restrictions are high; however it becomes an attractive crop if recently high commodity prices are maintained. With improved irrigation performance, wheat deficit irrigation is viable including when full water costs are applied, if former low prices are not returned to. However, under drought conditions full water costs are excessive. Thus, adopting deficit irrigation requires not only an appropriate irrigation scheduling but higher irrigation performance, and that the application of a water prices policy would be flexible, thus favouring the improvement of the irrigation systems.

1. Introduction

Water plays a decisive role in the world's development. Its increasing scarcity imposes the need to optimize its use in all human activities, particularly in irrigation, the main water use sector worldwide. Irrigation water deficits may lead to economic yield losses while excessive irrigation leads to non-beneficial water use. Appropriate water management at crop/farm level, referring to when and how much to irrigate, assumes therefore an important role. In drought years, farmers may have to adopt deficit irrigation to cope with the limited water availability, which makes this technique of great importance for Portuguese agriculture. Deficit irrigation consists of deliberately applying irrigation depths smaller than those required to satisfy the crop water requirements (CWR) at certain periods in the crop season, thus affecting

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1537-5110/$ – see front matter
doi:10.1016/j.biosystemseng.2009.05.002

Nomenclature

ASWD	allowed soil water depletion fraction, dimensionless
CR	capillary rise, mm
CWR	crop water requirements, mm
D_{MAD}	application depth when depletion equals MAD, mm
E	evaporation from the upper soil layer, mm
ET_a	actual crop evapotranspiration, mm
ET_m	potential (maximum) seasonal crop evapotranspiration, mm
ET_O	reference evapotranspiration, mm
EWP	economic water productivity, € m^{-3}
EWPR	economic water productivity ratio, dimensionless
f_c	fraction of ground covered by the crop, dimensionless
f_{ew}	fraction of soil wetted and exposed to radiation, dimensionless
f_w	fraction of soil wetted by irrigation, dimensionless
GID	gross irrigation depth, mm
IWU	irrigation water use, m^3
IWU_{Farm}	farm irrigation water use, m^3
K_{cb}	basal crop coefficient, dimensionless
K_e	soil evaporation coefficient, dimensionless
K_s	water stress coefficient, dimensionless
K_y	yield response factor, dimensionless
MAD	management-allowed depletion, dimensionless
NIR	net irrigation requirements, mm
P	seasonal precipitation, mm
p	soil water depletion fraction for no-stress, dimensionless
PELQ	potential efficiency of the low quarter, %
T	crop transpiration, mm
TAW	total available water, mm m^{-1}
TWU	total water use, m^3
TWU_{Farm}	total water use at farm level, m^3
WP	water productivity, kg m^{-3}
WP_{Farm}	farm water productivity, kg m^{-3}
$WP_{I\text{-}Farm}$	farm irrigation water productivity, kg m^{-3}
Y_a	actual crop yield, kg ha^{-1}
Y_m	maximum crop yield, kg ha^{-1}
Z_{lqMAD}	average low quarter depth infiltrated when depletion equals MAD, mm
ΔSW	variation in soil water content between planting and harvesting, mm
θ_{FC}	soil water content at field capacity, $m^3 m^{-3}$
θ_{WP}	soil water content at the wilting point, $m^3 m^{-3}$

evapotranspiration and yields, but keeping a positive return from the irrigated crop (English & Raja, 1996; Kang *et al.*, 2000). However, the impacts of irrigation deficits on yields and related economic results may or may not be negative, depending upon the irrigation scheduling adopted, the irrigation system performance, the production costs and the yield values (Lorite *et al.*, 2007). Support to farmers through the use of simulation models may help them to adopt an irrigation management that controls water deficits in such a way that these are applied during the less sensitive crop development stages (Pereira *et al.*, 2009b; Popova & Pereira, 2008).

Increasing water productivity (WP) may be the best way to achieve efficient water use. Depending on how the terms in the numerator and denominator are expressed, WP can be expressed in general physical or economic terms (Seckler *et al.*, 1998). Pereira *et al.* (2009a) define WP as the ratio between the actual yield achieved and the total water use (TWU). However, WP may be defined with different perspectives (Kijne *et al.*, 2003; Zwart & Bastiaanssen, 2004, 2007; Playan & Mateos, 2006; Molden, 2007; Pereira *et al.*, 2009a), i.e., WP may have different meanings, which may lead to contradictory interpretations when the considered target is not specified. Also commonly used as synonymous with WP is the term water use efficiency (Steduto, 1996) but, recently, the term biomass WP was introduced to clearly refer to the physiological and ecophysiological processes of biomass production (Steduto *et al.*, 2007). Relative to irrigation, it is preferable to assess the WP relative to either TWU or the irrigation water use (IWU) when that assessment aims at evaluating the performance of given irrigation systems as discussed by Pereira *et al.* (2009a). Nevertheless, expressing WP only in physical terms does not allow the economic impacts of water use to be understood; thus alternative indicators having an economic meaning are required, i.e. relative to the economic water productivity, EWP (Cook *et al.*, 2006; Pereira *et al.*, 2009b). However, few studies refer to the assessment of EWP at various scales (Igbadun *et al.*, 2006; Palanisami *et al.*, 2006; Teixeira *et al.*, 2008; Vazifedoust *et al.*, 2008). Related studies adopt different concepts for defining EWP, e.g. Hellegers *et al.* (2009) define EWP from the net productive value, and thus it is negative when farming is non-profitable.

In a former study it was verified that analysing the ratios between the gross margins and net irrigation volumes (which is an alternative way to define EWP) together with the ratios between the same gross margins and the land area cropped, it was possible to assess when deficit irrigation could be an acceptable alternative to full irrigation (Pereira *et al.*, 2002; Rodrigues *et al.*, 2003). Results then obtained, as well as the simulation approaches used, suggested that the economic impacts of irrigation water deficits could be assessed through the analysis of EWP.

The main goal of this study is to assess the economic impacts of water deficits and water costs through the evaluation of economic water productivities. Adopting this approach it may be possible to define a methodology easily usable in engineering assessment or appraisal studies. Developing and testing this methodology is therefore one main objective of this study, including the use of the novel model SIMDualKc (Rolim *et al.*, 2007; Godinho *et al.*, 2008) allowing the estimation of crop transpiration and soil evaporation. It is applied to three sprinkler-irrigated fields in Vigia Irrigation District, Alentejo region (Southern Portugal) and to three field crops: maize, sunflower and wheat. The second main objective is to assess the feasibility of deficit irrigation as influenced by the irrigation performance and the water costs. With this purpose, the irrigation systems performance was evaluated in those fields, costs were assessed and various scenarios of water demand and irrigation water costs are considered, the latter relating to the application of the European Water Directive to the irrigated agriculture sector.

2. Material and methods

2.1. Study area and irrigation systems

The study area is the Vigia Irrigation District, Évora District. The meteorological station is located in Évora (38.77°N, 7.71°W, and 472 m elevation). The respective monthly climate data are presented in Table 1.

The predominant soil types in the area are Mediterranean red and brown soils derived from quartz-diorite rocks and other non-calcareous materials. The unsaturated soil hydraulic properties were determined from a survey and using laboratory methods for the full range of soil water tension. Appropriate pedo-transfer functions and mapping were developed to describe the soil hydraulic properties of the soils in the region (Pereira, 2007). Mild to medium slopes characterize land relief. Groundwater tables are not present in the area.

The Vigia Irrigation District, built from 1976 to 1985, has an equipped area of 1834 ha and is located in the municipalities of Évora and Redondo. The area presently irrigated is 1505 ha. The irrigation network project (DGRAH, 1978) was designed and constructed to supply pressurized irrigation water for sprinkler set systems. However, large farms adopted centre-pivot irrigation systems, which presently cover nearly 50% of the total irrigated area. A pumping station located near the dam at the upstream end of the pipe system pressurizes the irrigation water. The system operates on-demand, thus farmers have no limitations on timing and duration of irrigation events. The hydrants are not yet equipped with pressure regulators which means that the system is discharge-driven, creating some service performance problems. The system performance has been evaluated using purposefully installed pressure and discharge measurement devices (Calejo, 2003; Pereira, 2007). Results of the performance analysis have shown that the relative pressure deficit at the hydrants is often low and that the reliability of the system referring to the service at the hydrants is also low, often below 0.5. These conditions are indicative of frequent variations of pressure and discharge at the hydrants that impact on the performance of the field irrigation systems.

The main crops in these irrigation districts are cereal grains, industrial crops and forage crops, mainly irrigated with centre-pivot sprinkler systems. Olive trees and grapevines are increasing steadily with the adoption of micro-irrigation. The crops selected for this study are winter wheat, maize and sunflower. Table 2 shows some main characteristics of these crops.

Field evaluations of irrigation systems in operation were performed through several years in the region (Pereira, 2007). The evaluation procedures used were those described by Merriam & Keller (1978) and Keller & Bliesner (1990). Several performance indicators were adopted including the potential efficiency of the low quarter, PELQ (%) used in this application:

$$\mathrm{PELQ} = 100\frac{Z_{\mathrm{lqMAD}}}{D_{\mathrm{MAD}}} \quad (1)$$

where Z_{lqMAD} is the average low quarter depth infiltrated, in mm, when equal to the management-allowed deficit (MAD), and D_{MAD} is the average of water applied, in mm, when the soil water deficit equals MAD. $D_{\mathrm{MAD}} = 15$ mm was adopted because it was the most commonly used by the farmers. Soil samples were taken to complement information collected from the farmers to identify MAD. PELQ was selected because depths applied were small (5–15 mm) and could easy induce a large error in estimating the actual application efficiency. In addition, using PELQ is appropriate for design and management and, because it refers to the quarter of the field receiving less water, it closely relates to the distribution uniformity.

Results of a number of field evaluations are presented by Valín *et al.* (2003) and Pereira (2007) and show that irrigation performance is often low. Causes include the variations in discharge and pressure at hydrants as referred above, ageing and relatively poor maintenance of equipment, evaporation and wind drift losses, excessive sprinkler spacings, high head losses in laterals for the set systems, and poor selection of sprinkler heads. Given the willingness of the farmers to cooperate, the fact that systems have been evaluated two or more times and the need for understanding of how poor performance could influence economic results, three case studies relative to poorly performing irrigation systems were selected for this analysis. They correspond to a large, a medium/small and a small farm, and the respective fields are identified as M. Igreja, T-134 and T-104.

A centre-pivot system with nearly 20 years of operation was evaluated in M. Igreja. The radius of the wetted area is 320 m and the system irrigates an area of 32 ha. The lateral is equipped with sprinkler heads mounted on the lateral nearly

Table 1 – Average monthly climatic data, Évora meteorological station (1942–2000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum temperature, °C	12.6	13.9	16.5	18.6	21.9	26.7	30.5	30.3	27.2	21.8	16.6	13.3
Minimum temperature, °C	5.8	6.4	7.8	9.1	11.2	14.0	16.0	16.2	15.4	12.7	9.2	6.7
Relative humidity, %	84.4	81.5	77.1	72.5	69.2	65.2	59.8	60.9	65.9	74.1	50.6	84.8
Wind speed, m s^{-1}	4.3	4.4	4.4	4.5	4.5	4.4	4.6	4.7	4.2	4.0	4.1	4.3
Sunshine duration, h	153	163	206	233	279	315	396	346	258	210	162	146
ET_o, mm d^{-1}	1.5	1.8	2.7	3.8	5.3	6.6	7.0	6.5	4.8	2.8	1.6	1.4
Precipitation, mm	84.2	74.9	71.9	57.3	49.0	23.5	6.1	5.0	28.4	68.0	82.0	94.3

Table 2 – Crop development stages for winter wheat, maize and sunflower

Crop	Lengths of crop development stages			
	Initial	Development	Mid-season	Late season
Wheat	15/11–24/02	25/02–09/04	10/04–04/06	05/06–20/06
Maize	01/05–31/05	01/06–04/07	05/07–17/08	18/08–16/09
Sunflower	10/04–09/05	10/05–13/06	14/06–15/07	16/07–18/08

three metres above the ground, thus highly exposed to the wind. Irrigation depths of 15 mm were applied. An average season PELQ = 65.5% was observed. The field T-134 is equipped with a solid set sprinkler irrigation system consisting of two laterals, 309 and 328 m long and having respectively 17 and 18 sprinklers. The sprinklers spacing is 18 × 18 m. All pipes are buried. The estimated PELQ is 61.5%. The system of the field T-104 consists of a single buried lateral, with 16 sprinklers with 11 m spacing. The field has a rectangular shape (171 × 18 m) with a slope averaging 0.6%. The resulting performance is very poor (PELQ = 47%) because the edges of the field are under-irrigated. In both fields T-134 and T-104, application depths close to 15 mm were also adopted. Soil data relative to the three locations are summarized in Table 3.

The performance indicators relative to these systems indicate the need for upgrading the systems, eventually to be replaced by modern and well designed ones. This condition allows assessment of how the current poor performance impacts on the economic results of deficit irrigation and prediction of how the EWP could increase if the systems were to be improved. The related scenarios are described under Section 2.4.

2.2. *Water productivity*

As referred before, there is not a common agreement on the use of the term WP: WP may express a physical ratio between yields and water use (Kijne *et al.*, 2003; Zwart & Bastiaanssen, 2004, 2007; Playan & Mateos, 2006; Molden, 2007), or between the value of the product and water use (Igbadun *et al.*, 2006; Palanisami *et al.*, 2006; Teixeira *et al.*, 2008; Vazifedoust *et al.*, 2008). Concepts may be applied to different scales, from the field to the basin. Moreover, as analysed by Pereira *et al.* (2009a), WP concepts may be extended to non-agricultural water uses. Therefore, it is important to properly define herein the concepts used in this study. WP is defined here as the ratio between the actual crop yield and the TWU, in kg m^{-3} (Pereira *et al.*, 2009a), thus:

$$WP = \frac{Y_a}{TWU} \quad (2)$$

where Y_a is the actual yield, in kg, and TWU is the total water use including rainfall, in m^3, to achieve Y_a. When considering the water use at farm or field level (TWU_{Farm}), including rainfall, soil water storage, capillary rise (CR) and irrigation, the farm WP (WP_{Farm}) is defined as:

$$WP_{Farm} = \frac{Y_a}{TWU_{Farm}} \quad (3)$$

when considering the farm IWU (IWU_{Farm}) only, then it gives the farm irrigation WP:

$$WP_{I\text{-}Farm} = \frac{Y_a}{IWU_{Farm}} \quad (4)$$

Eqs. (3) and (4) may take a different form when distinguishing the water use components, for instance:

$$WP_{Farm} = \frac{Y_a}{P + CR + \Delta SW + IWU_{Farm}} \quad (5)$$

where P is the season precipitation, CR is the capillary rise, ΔSW is the difference in soil water content between planting and harvest, and IWU is the seasonal irrigation depth, all in mm or m^3 ha^{-1}, and Y_a is expressed in kg ha^{-1}. The variables in the denominator may be obtained by field observations or through modelling; when known they allow pathways to improve WP and save irrigation water to be identified.

The meaning of these indicators is necessarily different and may lead to contradictory interpretations when the term "water productivity" is used without identifying the denominator in the WP equations. Improving the WP does not necessarily lead to a water saving because it is necessary to distinguish between consumptive and non-consumptive water use (Pereira *et al.*, 2002, 2009a). However, that distinction is often not made. It is important to consider the economic issues relative to WP since the objective of a farmer is to achieve the best income and profit. Replacing the numerator of equations above by the monetary value of the achieved yield, the EWP is expressed as € m^{-3} and defined by:

$$EWP = \frac{\text{Value}(Y_a)}{TWU} \quad (6)$$

or

Table 3 – Soil textural classes, field capacity (θ_{FC}), wilting point (θ_{WP}), total available water (TAW) and readily and total evaporable water (REW and TEW) of the evaluated fields

Fields	Soil depth (m)	% Sand	% Loam	% Clay	θ_{FC}, m^3 m^{-3}	θ_{WP}, m^3 m^{-3}	TAW, mm m^{-1}	REW, mm	TEW, mm
M. Igreja	1.20	52	9	39	0.44	0.28	160	10	38
T-104	1.00	54	13	33	0.24	0.16	80	11	20
T-134	1.10	47	18	35	0.35	0.18	170	11	32

$$EWP_{Farm} = \frac{Value(Y_a)}{TWU_{Farm}} \quad (7)$$

The economics of production may be better understood when the numerator is expressed in terms of gross margin or net income relative to the considered crop (Rodrigues *et al.*, 2003), but these approaches require more demanding economic information. Alternatively, as for this study, the economics of production is considered when expressing both the numerator and the denominator in monetary terms, respectively the yield value and the TWU cost, thus yielding the EWP ratio (EWPR):

$$EWPR = \frac{Value(Y_a)}{Cost(TWU)} \quad (8)$$

Assuming that all water costs are due to the costs of irrigation, it results

$$EWPR = \frac{Value(Y_a)}{Cost(IWU)} \quad (9)$$

which allows an easy comparison with the price to be paid for the water.

Fig. 1 describes the procedure used to estimate WP, WP_{Farm} and EWP from both the actual and the potential crop yield (Y_a and Y_m). A field assessment of irrigation systems performance provided data on the actual irrigation efficiency for various fields and data on yields and economics of production. The potential yields Y_m were estimated using the agro-ecological zone (AEZ) method proposed by Doorenbos & Kassam (1979); results were validated by comparing them with the best yields achieved in the region.

Several scenarios for deficit irrigation were simulated with the SIMDualKc model, as described in the next sections, which allowed the net irrigation requirements (NIR) relative to every scenario to be estimated. Using these irrigation data with the Stewart model (Eq. (11) analysed below) the Y_a values were computed for each scenario. NIR values were converted into gross irrigation depths (GIDs) using a set of potential application efficiency values (Eq. (1)) representing various scenarios for improving the irrigation performance, starting with those obtained from field evaluations. The water productivities (WP, $WP_{I\text{-}Farm}$ and EWP) were then determined for the various combinations of yield and seasonal gross irrigation.

2.3. Irrigation scheduling simulation

The methodology for computing the crop evapotranspiration using the dual crop coefficient approach is slowly receiving increased attention. It consists (Allen *et al.*, 1998, 2005a, 2007) of adopting the following approach:

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (10)$$

where ET_c is crop evapotranspiration, in mm d^{-1}, K_{cb} is the basal crop coefficient, dimensionless, K_e is the soil evaporation coefficient, dimensionless, K_s is the water stress

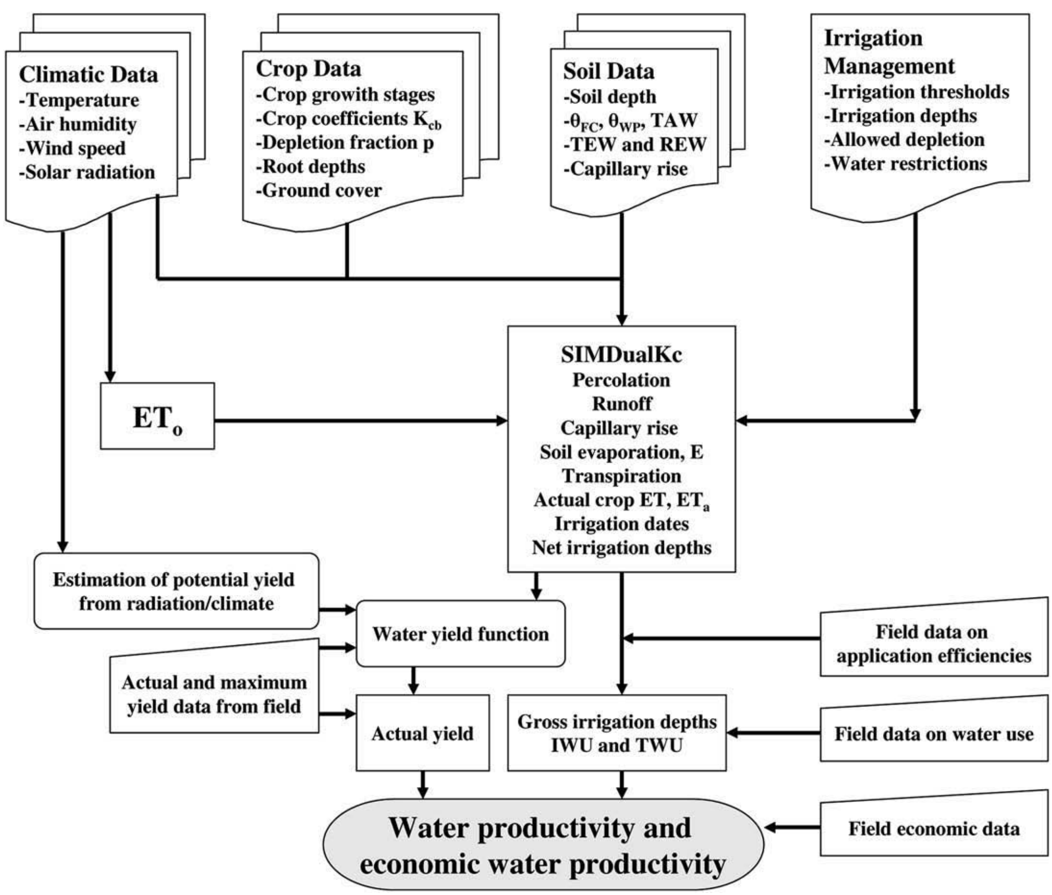

Fig. 1 – Flow-chart for the WP calculation.

coefficient, dimensionless, and ET_o is the reference crop evapotranspiration, in mm d^{-1}. This approach allows the two components of ET_c to be estimated: one consisting of the water consumed by the crop through transpiration (computed through K_{cb}), the other relative to the water consumed as evaporation from the upper layer of the soil (relative to K_e). K_s is smaller than 1.0 when the crop is water stressed.

This method has various advantages relative to using the single K_c. In general: (1) it allows the partition of water consumption into the beneficial and the non-beneficial fractions, respectively transpiration and evaporation from the soil; (2) it provides for the estimation of benefits of soil management practices to control evaporation; (3) it better represents the dynamics of water consumption for crops that partially cover the ground; (4) it represents better the water consumption when frequent irrigation is practised; and (5) it adapts well when remote sensing provides the estimate of K_{cb}. These advantages are important when deficit irrigation is considered. However it has some disadvantages such as: (1) it requires a daily water balance of the evaporative soil surface layer for computing the daily K_e values; (2) it needs the estimation of the soil evaporative properties in addition to the soil hydraulic properties required for the soil water balance; and (3) calculations require an appropriate computational tool. The methodology has performed well in various parts of the world and with a variety of crops and space scales (Hunsaker, 1999; Allen, 2000; Allen *et al.*, 2005b; Er-Raki *et al.*, 2007; Zhao & Nan, 2007).

The SIMDualKc model (Rolim *et al.*, 2007; Godinho *et al.*, 2008), which computes crop ET and performs a soil water balance simulation based on the dual crop coefficient approach, is used in this application. SIMDualKc is developed in Visual Basic 6.0 and includes a database in Access 2003. The model has three main components (Fig. 2): the graphical user-friendly interface, the mathematical models and the database. The database stores information about the soil, crop, climate, irrigation system and simulation data, which is a specific combination of the factors representing the cropped field under analysis. SIMDualKc performs the soil water balance at field level using a daily time step. The soil evaporation computations follow the methodology described by Allen *et al.* (1998) extended by Allen *et al.* (2005a). The crop evapotranspiration is computed as described by Allen *et al.* (1998) including the modifications reported by Allen *et al.* (2007). The reference evapotranspiration is computed externally with EVAP56, an algorithm of model WINISAREG that uses the methodology proposed by Allen *et al.* (1998). The computations of the soil water balance follow those used in WINISAREG model (Pereira *et al.*, 2003; Popova *et al.*, 2006), including for estimating the CR and percolation (Liu *et al.*, 2006).

Input data include daily rainfall and reference evapotranspiration, total and readily available soil water, total and readily evaporable soil water, soil water content at planting, and basal crop coefficients (K_{cb}), soil water depletion fractions for no-stress (p) and root depths relative to four crop growth stages (initial, crop development, mid-season and late season). Daily climatic data refer to Évora's meteorological station for the period 1965–2000. Soil hydraulic properties relative to the selected fields (Table 3) were obtained through pedo-transfer functions relative to a soils database (Pereira, 2007). Soil evaporation data were obtained from laboratory and from exploring the database information using pedo-transfer and geostatistical functions (Mateus, 2007). Crop data were collected locally and/or derived from Allen *et al.* (1998, 2007).

For computing the soil evaporation coefficient K_e, input data include the fraction of ground covered by the crop (f_c) at various dates and the fraction of soil wetted by the irrigation (f_w). For irrigation scheduling purposes, input data refer to the irrigation thresholds relative to the MAD and the restrictions on the available irrigation water. The model is therefore able to simulate a variety of reduced irrigation strategies. The model has been tested for several field and orchard crops in various climates by comparing field observed and simulated soil water data (Rolim *et al.*, 2007; Godinho *et al.*, 2008).

The model output is graphical and numerical. The latter includes the daily values of soil evaporation and crop ET, as well as the values of every coefficient such as K_s and K_e and the

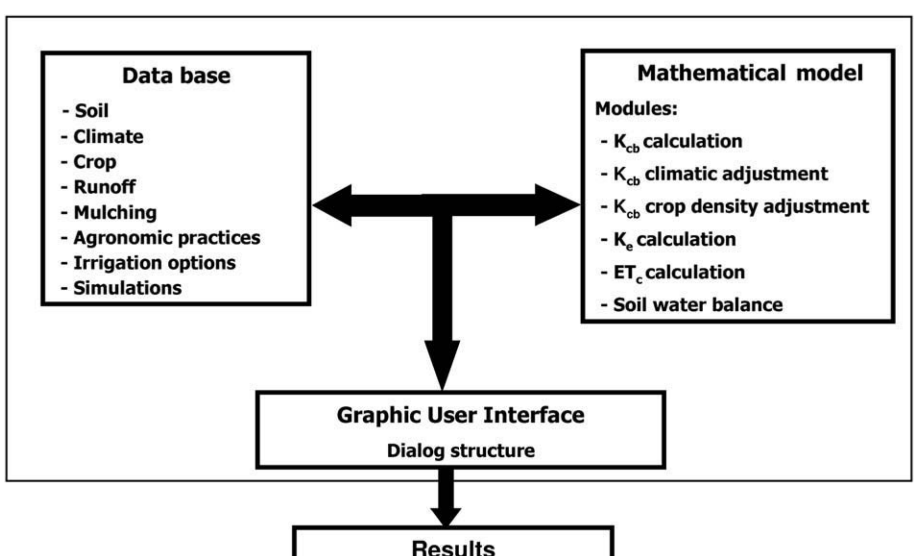

Fig. 2 – Conceptual structure of SIMDualKc model.

fractions f_c, f_w, and f_{ew}, this one relative to the fraction of soil wetted and exposed to radiation. All output data may be exported to an Excel file to be further analysed.

In the current version of the model, the computation of the yield impacts of water stress is performed externally using the same yield–water function adopted in model WINISAREG, the equation proposed by Stewart et al. (1977) and Doorenbos & Kassam (1979) that expresses a linear relation between the relative yield loss and the relative evapotranspiration deficit:

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ET_a}{ET_m}\right) \tag{11}$$

where ET_a and ET_m are respectively the actual and potential (maximum) seasonal crop evapotranspiration, in mm, and Y_a and Y_m are respectively the actual and potential (maximum) yield, in $kg\,ha^{-1}$, when crop ET equals ET_a and ET_m. This equation has been widely used including for WP studies (Igbadun et al., 2006). It was tested when exploring the model WINISAREG (e.g. Teixeira et al., 1995; Popova et al., 2006; Popova & Pereira, 2008; Pereira et al., 2009b). In future applications of the model a phasic water–yield function may be applied since the data output allows grouping ET or transpiration data by crop development phases. In this study, the K_y values used are 1.05 for winter wheat, 1.25 for maize and 0.95 for sunflower, following data from Alves & Pereira (1998) and from other applications in the region.

The actual yield data (Y_a) were obtained first by questionnaire to the farmers and later, for each scenario, through resolving Eq. (11) in order to obtain Y_a as referred by Allen et al. (1998). For solving this equation, appropriate estimates of the potential yield Y_m are required. As referred above, these data were obtained using the AEZ method (Doorenbos & Kassam, 1979) and the results were validated with observed data. This method assumes that the maximum yield of a crop is the harvested yield of a high producing variety, well-adapted to the given growing environment, under conditions where water, nutrients and pests and diseases do not limit the yield. The AEZ parametric equations refer to the main climatic factors which determine Y_m: temperature, radiation and length of the total growing season in addition to any specific temperature and day length requirements for crop development. As discussed by Steduto et al. (2007), crop growth and yield are affected by the total radiation received during the growing period and the crops' radiation use efficiency. At a given radiation and temperature, crops differ in their efficiency of conversion of the intercepted solar radiation into biomass. It means that the physiology of the crop determines how much biomass is produced by each unit of intercepted solar radiation. This difference has an important effect on how water can be efficiently utilized for crop production. However, consideration of these differences is only possible through crop modelling which requires the field calibration of a large number of parameters (e.g. Singh et al., 2006; Vazifedoust et al., 2008). Other methods exist for determining the maximum or potential yield, mostly using parametric equations referring to the same climatic variables as AEZ as well as to the radiation use efficiency (Price et al., 2004). However, the methodology proposed by Doorenbos & Kassam (1979) is still appropriate for assessing maximum potential yields aimed at estimating the WP of irrigated crops (Reynolds et al., 2000). Alternatively, potential yields may be defined using local expertise (Droogers & Kite, 1999), or empirical equations based upon local observations (Siddique et al., 2001).

2.4. *Irrigation scenarios*

The irrigation scenarios simulated were built assuming various restrictions on the seasonal water available for irrigation and different allowed soil water depletion fractions (ASWDs). These are defined by a percentage increase of the depletion fraction for no-stress p (Table 4).

The crop NIR were computed for no restrictions on water availability and ASWD = p. It resulted, for each crop, in an NIR data series relative to the period covered by the weather data set (1965–2000), which were analysed assuming a normal distribution. Hence, the years when NIR values are not exceeded with probabilities of 50, 80 and 95% were identified to represent average, high and very high climatic demand (Table 5). The latter typically identifies a drought year. All irrigation scenarios (Table 4) were simulated for the weather conditions corresponding to those observed in the years identified in Table 5.

The season NIR for those identified years and all scenarios described in Table 4 were computed adopting irrigation depths of 15 mm per event as usually practised in the area. They were later transformed into seasonal gross irrigation requirements (GID) considering the observed potential efficiencies PELQ defined above: 65.5% for M. Igreja (centre-pivot system), 47% for T-104 and 61.5% for T-134 (solid set sprinkler

Table 4 – Irrigation scenarios for maize, sunflower and wheat

Irrigation scenarios	Deficit irrigation thresholds	Restrictions on water availability
Maize		
R-0	ASWD = p[a]	Not restricted
R-1	ASWD = 1.05p	420 mm
R-2	ASWD = 1.10p	390 mm
R-3	ASWD = 1.20p	360 mm
R-4	ASWD = 1.30p	330 mm
R-5	ASWD = 1.40p	300 mm
R-6	ASWD = 1.50p	270 mm
Sunflower		
R-0	ASWD = p	Not restricted
R-1	ASWD = 1.05p	300 mm
R-2	ASWD = 1.15p	270 mm
R-3	ASWD = 1.15p	240 mm
R-4	ASWD = 1.25p	210 mm
R-5	ASWD = 1.25p	180 mm
R-6	ASWD = 1.40p	120 mm
Wheat		
R-0	ASWD = p	Not restricted
R-1	ASWD = 1.05p	165 mm
R-2	ASWD = 1.05p	150 mm
R-3	ASWD = 1.05p	120 mm
R-4	ASWD = 1.05p	105 mm
R-5	ASWD = 1.10p	90 mm
R-6	ASWD = 1.10p	60 mm

a p – soil water depletion fraction for no-stress.

systems). To consider upgrading the irrigation systems and an improvement in management that allows wind drift losses to be controlled, as well as higher distribution uniformity and appropriate irrigation schedules, two improved performance scenarios based upon data suggested by Keller (1992) were considered where PELQ are 70 and 85%.

2.5. Irrigation water costs

The calculation of EWPR requires that the cost of each cubic metre of water is known. Data by Noéme et al. (2004) were used for estimating the investment costs reported to 2003 and using appropriate lifetimes for various types of equipment, which consist of fixed costs, and the operation, maintenance and management (OM & M) costs, the variable costs (Table 6). The fixed costs per unit of water use are given by:

$$\text{Fixed costs} = \frac{\text{Investment costs}}{\text{Total water use}} \tag{12}$$

and the variable costs are:

$$\text{Variable costs} = \frac{\text{OMM costs}}{\text{Total water use}} \tag{13}$$

where the OM & M costs comprise the full energy costs for delivering pressurized water to the farms. The fixed and variable costs for this example were 0.0308 € m^{-3} and 0.0834 € m^{-3} respectively. Based on these values, the scenarios for water costs to be paid by the farmers are the following:

(a) Present cost, as practised by the Water Users Association: 0.04 € m^{-3}
(b) OM & M cost, as required to fully cover these activities: 0.0834 € m^{-3}
(c) Full cost, as required for covering both the OM & M and investment costs: 0.1144 € m^{-3}.

3. Results

3.1. Consumptive water use

The consumptive water use comprises crop transpiration (T) and evaporation from the upper soil layer (E). The first is a beneficial water use for crop production while the latter is non-beneficial. Results for both components are given in Table 7 for the three crops, the three farms and the three scenarios for climatic demand. For all cases, values for E and T relative to irrigating without restrictions (R-0) and when water availability is restricted are compared in this table. The scenario referred to in Table 7 for deficit irrigation with water restrictions corresponds to the one where water use is reduced as much as possible but the consequent relative yield loss is smaller than 25%.

Results in Table 7 show that the proportion of soil evaporation in the total consumptive use is higher for sunflower and smaller for wheat. This relates to the fact that the fraction of soil covered by vegetation during the periods of high solar radiation – the main driving force for evaporation – is smaller for sunflower and larger for wheat, in proportion to the canopy density during those periods.

The highest E/T ratios for maize occur under conditions of very high climatic demand. These years are those with higher solar radiation, thus when more energy is available at the soil surface to produce high soil evaporation, mainly when the fraction of soil covered is small. For sunflower, the E/T ratio does not show any trend in relation to the climatic demand because less irrigation is applied and the number of wetting events by rainfall is smaller in years when solar radiation is higher. In the case of wheat, because wetting events are mainly due to rainfall since irrigation is supplemental to precipitation, the evaporation component is larger for the average demand years, when rainfall is higher and more frequent, and smaller for the years of very high demand when fewer wettings by rainfall occur.

Results in Table 7 show that for the summer crops, maize and sunflower, transpiration decreases more than soil evaporation when water restrictions are considered, i.e., the ratio E/T increases then for all cases. This indicates that to fully explore deficit irrigation it may be necessary to adopt water conservation practices such as mulching to control soil evaporation. In contrast to the summer crops, which have a low fraction of soil covered by vegetation during a large period of the summer season, there is no evidence of changes in the E/T ratio for wheat when comparing irrigations with and without restrictions on water availability. In fact, wettings for this crop are mainly due to rainfall and irrigation occurs in spring, when the fraction of soil covered by the vegetation is maximal or near the maximum.

Results in Table 7 also show that, when restrictions on water availability are considered, the net water required for achieving a yield reduction smaller than 25% are higher for the farm T-104 because the soil water holding capacity is smaller on this farm, near half of that for T-134 and M. Igreja (Table 3). Under these unfavourable water holding conditions, crops use the soil water storage and precipitation less.

3.2. Water productivity

Results for maize WP (WP and $WP_{I\text{-Farm}}$) in the three farms are summarized in Table 8 for conditions when water availability

Table 5 – Identification of the years representative of the climatic demand scenarios for the crops under assessment

Climatic demand	Maize	Sunflower	Wheat
Average (Av)	1969	1993	1985/1986
High (Hi)	1981	1981	1986/1987
Very high (VH)	1998	2000	1998/1999

Table 6 – Water costs estimation for the Vigia Irrigation District (adapted from Noéme et al., 2004)

	Annual cost, € $year^{-1}$	Cost per unit surface, € ha^{-1}	Cost per unit water, € m^{-3}
Investment cost	145469	96.66	0.0308
OM & M cost	393799	261.66	0.0834
Total cost	539268	358.32	0.1142

Table 7 – Evaporation (*E*), transpiration (*T*) and *E*/*T* ratios values for the different fields and climatic demand scenarios, with and without water availability restrictions

Crop	Farm	Climatic demand	Full irrigation, without restrictions			Deficit irrigation, with restrictions				
			E, mm	T, mm	E/T	E, mm	T, mm	E/T	Net available water (mm)	Restriction[a]
Maize	M. Igreja	Av	169	486	0.35	149	391	0.38	270	R-6
		Hi	145	505	0.29	124	409	0.30	330	R-4
		VH	244	572	0.43	212	462	0.46	360	R-3
	T-104	Av	161	483	0.33	138	389	0.35	330	R-4
		Hi	174	502	0.35	155	408	0.38	390	R-2
		VH	265	569	0.47	227	462	0.49	420	R-1
	T-134	Av	162	486	0.33	143	393	0.36	300	R-5
		Hi	135	506	0.27	115	406	0.28	360	R-3
		VH	225	573	0.39	189	479	0.39	420	R-1
Sunflower	M. Igreja	Av	178	371	0.48	156	303	0.51	180	R-5
		Hi	175	416	0.42	154	340	0.45	210	R-4
		VH	217	495	0.44	190	406	0.47	240	R-3
	T-104	Av	169	372	0.45	148	304	0.49	240	R-3
		Hi	163	417	0.39	144	341	0.42	240	R-3
		VH	204	498	0.41	178	408	0.44	300	R-1
	T-134	Av	174	372	0.47	153	303	0.50	210	R-4
		Hi	178	415	0.43	156	339	0.46	240	R-3
		VH	216	496	0.44	185	420	0.44	300	R-1
Wheat	M. Igreja	Av	124	362	0.34	104	303	0.34	60	R-6
		Hi	121	387	0.31	102	323	0.31	60	R-6
		VH	113	522	0.22	95	438	0.22	90	R-5
	T-104	Av	91	367	0.25	77	306	0.25	90	R-5
		Hi	122	387	0.31	102	323	0.32	120	R-3
		VH	101	522	0.19	86	438	0.20	165	R-1
	T-134	Av	90	366	0.25	77	305	0.25	60	R-6
		Hi	102	433	0.24	86	363	0.24	120	R-3
		VH	105	520	0.20	89	437	0.20	120	R-3

a The restrictions are defined in Table 4. The restriction identified is the one producing the highest demand reduction when yields decrease <25%.

restrictions are applied. The restriction scenarios are the same as in Table 7. Results, including the seasonal GIDs, allow the influence of climate conditions to be assessed through consideration of the average, high and very high climatic demand, and the impacts of various performance scenarios relative to the PELQ indicator. For the actual PELQ, a comparison between WP and $WP_{I\text{-}Farm}$ obtained with and without water availability restrictions is presented in Fig. 3. Results in Fig. 3a show that adopting a reduced demand scheduling due to limited water availability leads to higher WP and $WP_{I\text{-}Farm}$, particularly the latter because it depends only on the IWU. When no restrictions to water use are considered, WP varies from 0.76 to 1.35 $kg\,m^{-3}$, and when water availability is restricted WP ranges 0.76–1.62 $kg\,m^{-3}$. Under full irrigation, $WP_{I\text{-}Farm}$ ranges 0.82–1.82 $kg\,m^{-3}$, while adopting deficit irrigation it varies from 1.11 to 2.24 $kg\,m^{-3}$. Results also show that water productivities are lower under very high climatic demand because CWR are then the highest. Under these conditions, because under deficit irrigation the consequent reduction in yields is larger than the decrease in water use, it also results in a decrease in WP. Results in Table 8 show that the irrigation performance greatly influences WP. When PELQ increases it results in a decrease in water use, and hence an increase in WP. This increase is higher for average climatic demand and is smaller when that demand is very high because deficit irrigation impacts yields more strongly as referred to above. However, that behaviour varies from one farm to another.

Results for sunflower WP and $WP_{I\text{-}Farm}$ in the three farms are summarized in Table 9 and Fig. 3b for various irrigation management, climatic demand and systems performance conditions. Fig. 3b shows that WP and $WP_{I\text{-}Farm}$ (for the present PELQ performance) improve when deficit irrigation is applied, however being lower and having smaller increases under very high climatic demand and for the poorer performing irrigation system, T-104. WP ranges 0.4–0.83 $kg\,m^{-3}$,without restrictions in water use, and 0.45–0.97 $kg\,m^{-3}$ when water availability restrictions are considered. $WP_{I\text{-}Farm}$ shows a larger increase when restrictions are applied, with their range values changing from 0.47–1.20 $kg\,m^{-3}$ to 0.61–1.90 $kg\,m^{-3}$. Results in Table 9 show that both WP and $WP_{I\text{-}Farm}$ are highly influenced by the irrigation system performance, thus increasing with

Table 8 – WP indicators (WP, $WP_{I\text{-}Farm}$) and GID for maize under deficit irrigation as related with the climatic demand and the system performance (PELQ)

Climatic demand	PELQ, %	M. Igreja			T-104			T-134		
		GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}
Average	Present	435	1.23	1.92	702	1.21	1.54	488	1.46	2.24
	70	407	1.31	2.05	471	1.80	2.29	428	1.66	2.55
	85	335	1.60	2.49	388	2.19	2.79	353	2.02	3.10
High	Present	504	1.62	2.12	829	0.95	1.28	585	1.31	1.69
	70	471	1.73	2.27	557	1.41	1.91	515	1.49	1.92
	85	388	2.10	2.75	458	1.72	2.31	424	1.81	2.34
Very high	Present	550	1.32	1.78	893	0.76	1.11	658	0.97	1.28
	70	514	1.41	1.90	599	1.13	1.66	579	1.10	1.46
	85	424	1.71	2.31	494	1.37	2.01	476	1.34	1.77

PELQ. $WP_{I\text{-}Farm}$ decreases when the climatic demand increases because less rainfall is available, water applications increase and yields decrease due to deficit irrigation. As for maize, results vary from one farm to another.

Fig. 3c compares WP and $WP_{I\text{-}Farm}$ for wheat with and without water restrictions, considering the observed irrigation performance conditions. In contrast to the summer crops, because irrigation is supplemental to rainfall, which is the main source for wheat water use, results for WP show only a small increase when water restrictions are considered. Instead, $WP_{I\text{-}Farm}$ increases greatly when restrictions are applied to the irrigation water, from a range of 1.17–4 kg m^{-3} to 1.48–11.9 kg m^{-3}. The smaller values correspond to the poorer performing case (T-104) and to the very high climatic demand, when irrigation requirements are the highest. The highest values refer to the best performing farm (M. Igreja). Results in Table 10, relative to the water restriction scenarios identified in Table 7, show that the WP depends greatly upon the irrigation performance, with both WP and $WP_{I\text{-}Farm}$ increasing with PELQ but decreasing when the climatic demand increases. $WP_{I\text{-}Farm}$ is much larger than WP because IWU in supplemental irrigation of wheat is smaller than rainfall water use, in contrast to the water use of the summer crops.

3.3. *Economic water productivity*

Results for maize EWP when deficit irrigation is practised (Table 11), which were computed for the unit value of maize grain of 0.223 € kg^{-1}, show quite low values, from 0.25 to 0.36 € m^{-3} when the present irrigation performance is considered, and ranging from 0.36 to 0.47 € m^{-3} when PELQ = 85%. If prices experienced during the last 5 years are considered (0.16 € kg^{-1}) EWP decreases to 0.18–0.33 € m^{-3} and 0.25–0.47 € m^{-3} respectively. The variation in EWP follows that for WP, thus being highly dependent on the irrigation system performance and the climatic demand.

EWP values are small to very small when we compare their values with the current water price (0.04 € m^{-3}). In fact, the water costs represent 8–16% of the production costs when the present PELQ is considered and could decrease to 6–9% when water use decreases due to a higher PELQ of 85%. Considering these data, it becomes evident that EWP values are presently quite low and the yield value barely covers the production costs, particularly under high or very high demand conditions. If the irrigation systems were improved, EWP would increase to acceptable levels. However, the farm irrigation costs would rise if new systems were installed to achieve high performance. EWP values are much too small in case of the field T-104; however, because the labour is provided by the farmer himself and he reduces other production costs, the conclusion is that he keeps farming because he accepts a very low remuneration for his labour.

EWP for sunflower was computed for a unit value of sunflower grain of 0.243 € kg^{-1}. Results in Table 11, relative to deficit irrigation, show low EWP values, from 0.11 to 0.24 € m^{-3} for the present irrigation performance. If PELQ increases to 85%, EWP would improve to a range of 0.19–0.31 € m^{-3}. Considering the recently experienced price of 0.5 € kg^{-1}, EWP values increase to 0.23–0.49 € m^{-3} for the actual PELQ, and to 0.39–0.64 € m^{-3} if a high system performance (PELQ = 85%) is attained. EWP varies similarly to WP, i.e., depending from the climatic demand and the performance of the adopted irrigation system.

The water costs for sunflower represent 6–19% of the total production costs when the present PELQ is considered, and could decrease to 4.5–10% when PELQ = 85% is achieved. Considering these data and the current water price of 0.04 € m^{-3} it becomes evident that EWP (Table 11) are quite low and likely to be insufficient to cover the production costs, mainly under high or very high demand conditions. This justifies, among other reasons, why farmers in the area prefer maize relative to sunflower. However, considering the recently experienced prices of 0.5 € kg^{-1}, when the demand for sunflower increased for biodiesel production, EWP data indicate that sunflower may become an attractive summer crop.

Table 11 summarizes the results for wheat EWP computed for the unit value of grain of 0.267 € kg^{-1}. EWP follows the variation of WP, hence highly depending upon the climatic demand and the irrigation system performance. Wheat EWP has higher values than for the summer crops, varying from 0.19 to 0.46 € m^{-3}, when present irrigation performance is considered, and from 0.28 to 0.59 € m^{-3} for PELQ = 85%. However, if the average price obtained for the last 5 years of 0.16 € kg^{-1} is considered, EWP reduces to 0.11–0.28 € m^{-3} for the current PELQ, or to 0.17–0.35 € m^{-3} when PELQ = 85%. Since the water costs represent 3–12% of the production costs for the current

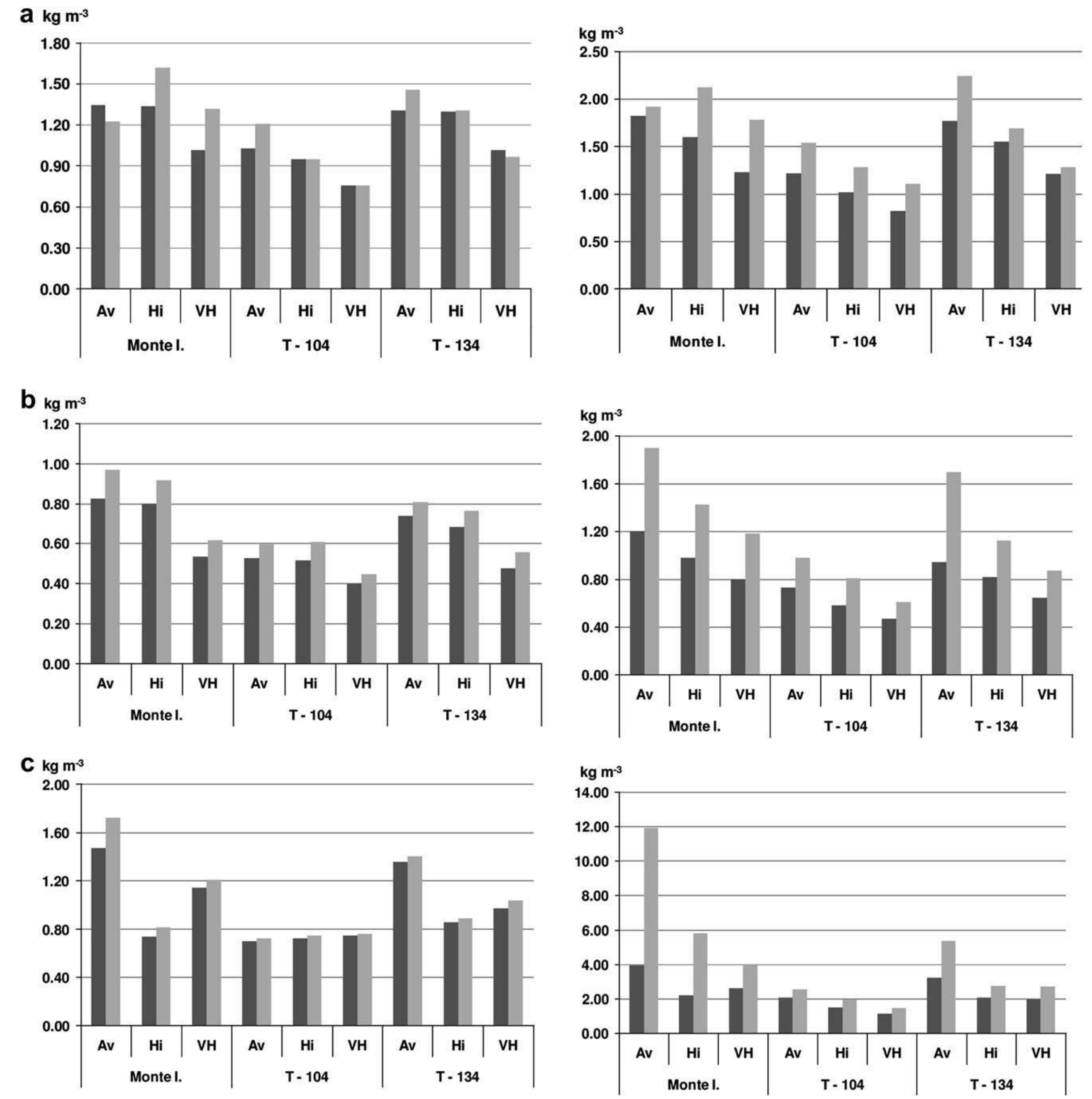

Fig. 3 – WP (on left) and $WP_{I\text{-}Farm}$ (on right) for average (Av), high (Hi) and very high (VH) climatic demand with (■) and without (■) water availability restrictions for: (a) maize, (b) sunflower, and (c) wheat considering the observed irrigation performance.

PELQ and 2.4–5.6% if the demand decreases due to an improvement of PELQ to 85% considering the current cost for irrigation water (0.04 € m^{-3}), results for EWP appear to be low, particularly if the commodity prices reduce to 16 € kg^{-1}. These results justify the common farmer's option for adopting wheat supplemental irrigation only in drought years when irrigation at grain filling improves crop yields greatly.

3.4. *Assessing the impacts of water prices*

The EWPR (Eq. (9)) is used to compare the yield values per unit water with the unit water costs relative to the three water price scenarios. Analysing the EWPR for maize (Fig. 4a), it may be observed that these ratios are presently in the range 7.2–12.5, for the current water prices (0.04 € m^{-3}). If these were to be maintained, EWPR would increase to 9.8–17.2 if PELQ = 85% was achieved. Considering that water costs are 6–19% of the total production costs for the current PELQ, the EWPR results show that farmers have a low or negative return from farming maize with the currently poor performing irrigation systems, particularly if commodity prices fall to the former 0.16 € kg^{-1}. However, if irrigation performance could be improved the income would be acceptable since the water costs could decrease to 4.5–10% of the total production costs.

Table 9 – WP indicators (WP, $WP_{I\text{-}Farm}$) and GID for sunflower under deficit irrigation as related with the climatic demand and the system performance (PELQ)

Climatic demand	PELQ, %	M. Igreja			T-104			T-134		
		GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}
Average	Present	183	0.97	1.90	383	0.60	0.98	195	0.81	1.70
	70	171	1.04	2.03	257	0.89	1.46	171	0.92	1.93
	85	141	1.26	2.46	211	1.08	1.77	141	1.12	2.35
High	Present	275	0.92	1.43	447	0.61	0.81	341	0.76	1.13
	70	257	0.98	1.52	300	0.90	1.25	300	0.87	1.28
	85	212	1.19	1.85	247	1.10	1.52	247	1.05	1.56
Very high	Present	321	0.62	1.19	575	0.45	0.61	439	0.56	0.88
	70	300	0.66	1.27	386	0.67	0.91	386	0.64	1.00
	85	247	0.80	1.54	318	0.81	1.10	318	0.77	1.21

If the water prices increase to fully cover the OM & M costs (0.0834 € m^{-3}), EWPR would decrease to 3.4–6.0 and maize production with the presently poor performance would not be profitable any more. If system performance were to be improved, EWPR would range from 4.7 to 8.3 and farming returns would keep being unprofitable under high to very high demand conditions or if commodity prices fall to previous levels. If full costs are considered (0.1144 € m^{-3}), then EWPR decreases to 2.5–6 for the actual PELQ or to 3.5–8.3 with PELQ = 85%. Then, considering the share of irrigation water in the total farming costs, maize production would lead to a negative income to the farmer including for average demand conditions.

Results for sunflower EWPR (Fig. 4b) vary in the range 3.4–10.4, considering the present water price (0.04 € m^{-3}) and would range from 6.1 to 13.5 with higher values of PELQ. Taking into account that water costs presently average 13% of the production costs, results show that farmers have then a negative income. However, after improving the irrigation performance, the water costs would average 7% of the total production costs, and a low but positive income would be attained. Alternatively, if recently high commodity prices are maintained (0.5 € kg^{-1}), farming sunflower becomes attractive with the present water prices. If the water price increases to fully cover OM & M (0.0834 € m^{-3}), then EWPR decreases to a range of 1.6–5 with the actual PELQ, and of 2.9–6.5 with PELQ = 85%. This price policy that covers the investment costs would also lead to negative incomes, even with a high irrigation system performance. However, results could be positive if high commodity prices are considered.

Results for wheat (Fig. 4c) show that for the present water price (0.04 € m^{3}) EWPR varies from 15.7 to 34.2 for the present PELQ, and from 21.6 to 44.4 with an improved system performance; hence, taking into account that water costs average 8% of the total farming costs, results show that, with current water prices, wheat supplemental irrigation is profitable even if commodity prices fall to the former 0.16 € kg^{-1}. If water prices rise to 0.0834 € m^{-3} EWPR ranges from 7.5 to 16.4 and 10.4–21.3 respectively for present and improved PELQ, while for water prices that fully cover the total costs (0.1144 € m^{-3}), EWPR decreases to 5.5–12 and 7.6–15.5 for the same performance scenarios. Results show that covering the OM & M costs would lead to positive results if higher performances are achieved but it is not evident that when prices rise to cover full costs positive returns could be attained. Very likely, farming returns would then be low or negative if former commodity prices (0.16 € kg^{-1}) are experienced again.

Table 10 – WP indicators (WP, $WP_{I\text{-}Farm}$) and GID for wheat under deficit irrigation as related with the climatic demand and the system performance (PELQ)

Climatic demand	PELQ, %	M. Igreja			T-104			T-134		
		GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}	GID, mm	WP, kg m^{-3}	$WP_{I\text{-}Farm}$, kg m^{-3}
Average	Present	92	1.72	11.90	192	0.72	2.57	98	1.40	5.35
	70	86	1.83	12.72	129	1.08	3.83	86	1.59	6.09
	85	71	2.23	15.44	106	1.31	4.65	71	1.94	7.40
High	Present	92	0.81	5.80	255	0.75	1.96	195	0.89	2.76
	70	86	0.87	6.20	171	1.11	2.92	171	1.01	3.14
	85	71	1.05	7.53	141	1.35	3.55	141	1.23	3.82
Very high	Present	137	1.21	3.99	351	0.76	1.48	195	1.04	2.72
	70	129	1.29	4.26	206	1.29	2.53	171	1.18	3.10
	85	106	1.56	5.17	169	1.57	3.07	141	1.43	3.76

Table 11 – EWP of maize, sunflower and wheat under deficit irrigation as related with the climatic demand and the system performance PELQ (all units in € m^{-3})

Climatic demand	PELQ, %	Maize			Sunflower			Wheat		
		M. Igreja	T-104	T-134	M. Igreja	T-104	T-134	M. Igreja	T-104	T-134
Average	Present	0.27	0.27	0.33	0.24	0.14	0.20	0.46	0.19	0.37
	70	0.29	0.40	0.37	0.25	0.22	0.22	0.49	0.29	0.43
	85	0.36	0.49	0.45	0.31	0.26	0.27	0.59	0.35	0.52
High	Present	0.36	0.21	0.29	0.22	0.15	0.19	0.22	0.20	0.24
	70	0.39	0.32	0.33	0.24	0.22	0.21	0.23	0.30	0.27
	85	0.47	0.38	0.40	0.29	0.27	0.26	0.28	0.36	0.33
Very high	Present	0.29	0.17	0.22	0.15	0.11	0.14	0.32	0.20	0.28
	70	0.31	0.25	0.25	0.16	0.16	0.15	0.34	0.34	0.31
	85	0.38	0.31	0.30	0.19	0.20	0.19	0.42	0.42	0.38

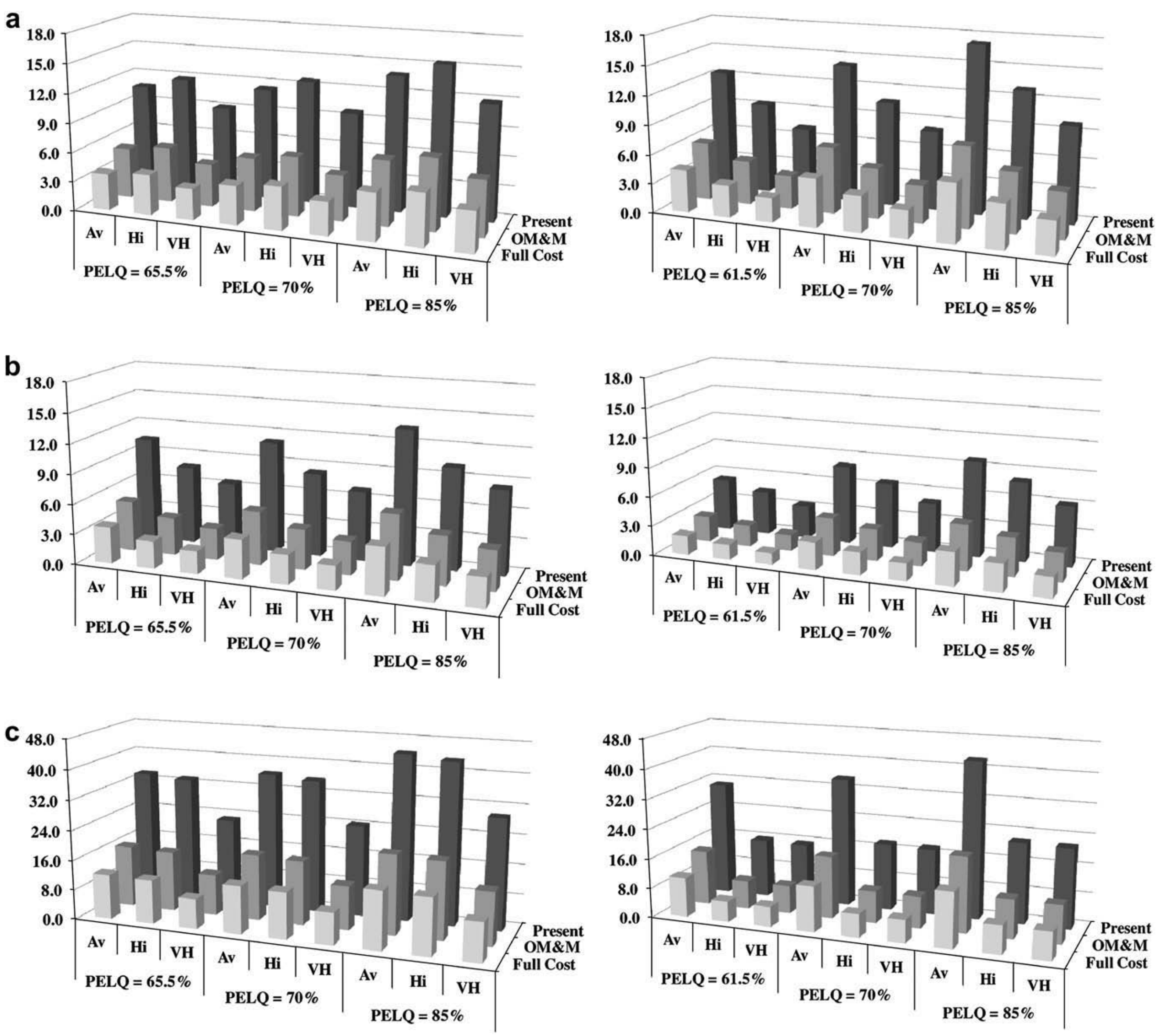

Fig. 4 – EWPRs relative to fields M. Igreja (on the left) and T-134 (on the right) under deficit irrigation for (a) maize, (b) sunflower and (c) wheat, considering three system performance scenarios (PELQ for present, 70 and 85%) and three water price scenarios (present, OM & M costs and full costs).

Results presented above show that water prices may greatly influence the profitability of irrigated agriculture. Moreover, the analysis shows that the variability of crop irrigation water demand due to system performance greatly influences the EWPR, i.e. the impacts of water costs and prices are tied to the irrigation performance PELQ. In general, results show that using poorly performing irrigation systems do not allow deficit irrigation to be practised if water price policies which follow the European Water Directive are abruptly enforced, i.e., some flexibility must be adopted in view of progressively improving the irrigation performance and the demand for water.

4. Conclusions

This study shows that WP indicators, mainly those of an economic nature, may be appropriate tools for assessing impacts of deficit irrigation and water costs. Comparing water productivities with or without restrictions in water availability, i.e. with and without crop water stress, may help to assess when deficit irrigation is or is not feasible but an analysis of economic water productivities is definitely helpful for this purpose. In this study, it is observed that the small differences between water productivities of maize and sunflower with and without water availability restrictions are not enough to determine when the adoption of deficit irrigation may or may not be feasible.

This study compared the soil evaporation and transpiration components of the consumptive use of water for two irrigated summer crops, maize and sunflower, and for supplemental irrigation of wheat under full irrigation and deficit irrigation. It was observed that soil evaporation is a large fraction of the consumptive use of the summer crops, increasing when the climate demand also increases as for drought years, attaining then values larger than 30% of the total consumptive use. These conditions indicate that to explore deficit irrigation fully may require adoption of water conservation measures for controlling soil evaporation, e.g. mulching. By contrast, for wheat supplemental irrigation soil evaporation is smaller that 17% when demand is very high. This indicates more favourable conditions for deficit irrigation of wheat because when solar radiation is high the ground cover by the crop is also high.

The analysis of WP and irrigation WP (WP and $WP_{I\text{-}Farm}$) shows they strongly depend upon the performance of the farm irrigation systems, in this study represented by the potential low quarter application efficiency, PELQ, hence increasing with the latter. Results also show that WP and $WP_{I\text{-}Farm}$ decrease when the climatic demand increases because IWU then increases.

The EWP varies similarly to WP. Results in this study are different for the three crops considered. For maize, EWP indicates that the yield value only covers the production costs if commodity prices keep high and the water costs still are low as presently practised. For sunflower, results indicate that if recent high commodity prices are experienced sunflower may become an attractive crop, in contrast to the conditions analysed when it was of marginal interest. Supplemental irrigation of wheat may continue to be interesting for drought years, particularly if irrigation systems have high performance.

The EWPRs, relating the yield values per unit water use with the water prices, appear adequate to assess the feasibility of deficit irrigation as influenced by the water prices. In case of maize, the analysis confirms that the feasibility of deficit irrigation depends greatly upon the system performance, is doubtful when the climatic demand is high to very high, and may not be feasible if water prices rise to cover the OM & M costs, mainly if commodity prices fall to former lower levels. Sunflower may cover the water prices if systems allow a high PELQ and recent high prices are experienced; otherwise it is generally not feasible. Wheat under supplemental irrigation, thus with relatively small IWU, may respond positively to increased water prices if irrigation systems perform well and commodity prices do not fall.

This study shows that analysing deficit irrigation and, consequently, defining the corresponding issues for appropriate feasibility, requires not only knowledge of the crop yield responses to water but also of the structure of the production costs, including the impacts of irrigation costs and performances on the crops' profitability. Appropriately modelling is then required since the prices of commodities pay a very important role. The present analysis using EWP and EWPR appeared adequate for assessing the feasibility of deficit irrigation but further developments on the relationships between irrigation practices and economic results are required.

Acknowledgements

This study was developed in the framework of projects MIPAIS – MEDOC 2004-04-4.4-1-108 and PLEIADeS – GOCE n° 037095. The support of the Agricultural Engineering Research Center (Project POCTI-SFA-7-245) is also acknowledged.

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