

UNIVERSIDADE DE LISBOA  
INSTITUTO SUPERIOR DE AGRONOMIA

**MODELAÇÃO ECONÓMICA VISANDO O APOIO À DECISÃO NO  
USO E PRODUTIVIDADE DA ÁGUA EM REGADIO**

TESE APRESENTADA PARA OBTENÇÃO DO GRAU DE DOUTOR EM  
ENGENHARIA DOS BIOSISTEMAS

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## RESUMO

Melhorar a produtividade da água de uma cultura requer novas aproximações à modelação económica, considerando alternativas na calendarização da rega e desempenho de sistemas. O presente estudo visa a modelação económica aplicada ao uso e produtividade da água em regadio. Pretende-se determinar o potencial dos sistemas de rega à escala da parcela para atingir um uso eficiente e sustentável da água, dando particular atenção à maximização dos usos benéficos da água e da produtividade física e económica da mesma. Desenvolveram-se vários cenários de poupança de água tendo em conta soluções alternativas para as técnicas e práticas de rega adoptadas nas parcelas em estudo. Em particular, foram desenvolvidas, aplicadas e avaliadas metodologias de análise económica e análise multicritério, sendo incorporadas em modelos de projecto (MIRRIG, PROASPER, DEPIVOT). Recorrendo à modelação económica acoplada a módulos de análise multicritério, considerando benefícios e custos inerentes aos equipamentos e à gestão da rega, foi possível identificar as melhores estratégias para atingir produtividades da água melhoradas através de controlo da procura, tanto recorrendo a rega deficitária, como melhorando os desempenhos dos sistemas de rega. A metodologia desenvolvida mostra ser uma ferramenta útil na tomada de decisão ao nível da parcela, visando a sustentabilidade dos sistemas agrícolas.

**Palavras-chave:** Produtividade da água; Análise económica; Desempenho dos sistemas de rega; Rega deficitária; Modelação.



## **ABSTRACT**

Improving crop water productivity requires new approaches to economic modelling, considering alternative irrigation scheduling and irrigation systems performance. The present study aims at applying an economic modelling to water use and productivity in irrigated areas. It intends to determine the potential of irrigation systems at field scale to achieve an efficient water use, giving particular attention to maximizing the beneficial water use and the physical and economic water productivities. Thus several water-saving scenarios were developed taking into account alternative solutions to the irrigation practices adopted at the selected fields. Economic analysis and multicriteria analysis methodologies have been developed, implemented, evaluated, and incorporated in system design models (MIRRIG, PROASPER, DEPIVOT). It was possible to identify the best strategies to achieve improved water productivities using the economic modelling coupled with multicriteria analysis modules. The benefits and costs related to irrigation systems and management, through managed water demand, using deficit irrigation, and through the improvement of irrigation systems performance were also considered. The methodology developed proves to be a useful tool to support decision making at the field level, aiming at the sustainability of agricultural systems.

**Keywords:** Water productivity; Economic analysis; Irrigation systems performance; Deficit irrigation; Modelling.



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## LISTA DE SIMBOLOS E ABREVIATURAS

€	euro
a	exponente de Kostidiakov
$A_{inv}$	investimento anual (€ year <sup>-1</sup> , BRL year <sup>-1</sup> )
ASWD	depleção de água no solo permitida ( )
BRL	Real brasileiro
BWU	uso benéfico da água, m <sup>3</sup>
BWUF	fração do uso benéfico da água ( )
$C_a$	investimento anual por unidade de área regada (€ ha <sup>-1</sup> year <sup>-1</sup> , BRL ha <sup>-1</sup> year <sup>-1</sup> )
$C_d$	taxa de uso de energia (€ kW <sup>-1</sup> , BRL ha <sup>-1</sup> year <sup>-1</sup> )
$C_{en}$	somatório dos custos anuais de energia (€, BRL)
$C_{inv}$	custos de investimento (€, BRL)
$C_m$	custos anuais de manutenção (€, BRL)
CR	ascensão capilar (mm)
CRF	fator de amortização ( )
CU	coeficiente de uniformidade de Christiansen (%)
D	dotação líquida aplicada (mm)
DI	rega deficitária
DU	uniformidade de distribuição (%)
EE	eficiência energética ( )
$E_{electricity}$	<i>input</i> energético direto relacionado com a eletricidade (GJ ha <sup>-1</sup> )
$E_{fertilizers}$	<i>input</i> energético indireto relacionado com os fertilizantes (GJ ha <sup>-1</sup> )

$E_{\text{fuel}}$	<i>input</i> energético direto relacionado com o combustível ( $\text{GJ ha}^{-1}$ )
$E_i$	<i>input</i> energético ( $\text{GJ ha}^{-1}$ )
$E_{i/o}$	<i>input/output</i> energético ( $\text{GJ ha}^{-1}$ )
$E_{id}$	<i>input</i> energético direto ( $\text{GJ ha}^{-1}$ )
$E_{ii}$	<i>input</i> energético indireto ( $\text{GJ ha}^{-1}$ )
$E_{\text{irrigationsystems}}$	<i>input</i> energético indireto relacionado com os sistemas de rega ( $\text{GJ ha}^{-1}$ )
$E_{\text{labour}}$	<i>input</i> energético indireto relacionado com a mão-de-obra ( $\text{GJ ha}^{-1}$ )
$E_{\text{machines}}$	<i>input</i> energético indireto relacionado com as máquinas ( $\text{GJ ha}^{-1}$ )
$E_o$	<i>output</i> energético ( $\text{GJ ha}^{-1}$ )
$E_{\text{pesticides}}$	<i>input</i> energético indireto relacionado com os pesticidas ( $\text{GJ ha}^{-1}$ )
$E_r$	taxa energética ( $\text{€ kWh}^{-1}$ )
$E_{\text{seeds}}$	<i>input</i> energético indireto relacionado com as sementes ( $\text{GJ ha}^{-1}$ )
$ET_a$	evapotranspiração cultural ( )
$ET_c$	evapotranspiração cultural máxima (mm)
$ET_{c \text{ adj}}$	evapotranspiração cultural ajustada (mm)
$ET_o$	evapotranspiração de referência (mm)
$EWP$	produtividade económica da água ( $\text{€ m}^{-3}$ , $\text{BRL m}^{-3}$ )
$EWP_{\text{BWU}}$	produtividade económica da água relativa ao uso benéfico da água ( $\text{BRL m}^{-3}$ )
$EWP_{\text{Irrig}}$	produtividade económica da água de rega ( $\text{BRL m}^{-3}$ )
$EWPR$	razão da produtividade económica da água ( )
$EWPR_{\text{full-cost}}$	razão da produtividade económica da água considerando os custos totais de produção ( )
$EWPR_{\text{irrig-cost}}$	razão da produtividade económica da água considerando os custos da rega ( )

$f_c$	fração de solo coberto pela vegetação ()
$f_{\text{eff mulch}}$	fração da superfície do solo efetivamente coberto pelo <i>mulch</i> ()
$f_{\text{ew}}$	fração molhada do solo exposta ()
$f_{\text{r mulch}}$	fração da superfície do solo coberto pelo <i>mulch</i> ()
$f_w$	fração molhada do solo ()
GID	dotação bruta de rega (mm)
h	altura da cultura (m)
I	taxa de infiltração ( $\text{mm h}^{-1}$ )
i	taxa de juro (%)
I	dotação de rega sazonal (mm)
ILR	rega com precipitação escassa
ISR	rega de complemento à precipitação
IWU	uso da água de rega ( $\text{m}^3$ )
$\text{IWU}_{\text{Farm}}$	uso da água de rega ao nível da parcela ( $\text{m}^3$ )
$K_{\text{cb}}$	coeficiente cultural de base ()
$K_e$	coeficiente de evaporação do solo ()
$K_{\text{en}}$	coeficiente energético ()
$k_p$	parâmetro de Kostidiakov ( $\text{h}^{-a}$ )
$K_r$	coeficiente de redução da evaporação ()
$K_s$	coeficiente de défice hídrico ()
$K_y$	fator de quebra da produção ()
MAD	défice permitido por gestão ()
MCA	análise multicritério

NEV	valor energético líquido ( $\text{GJ ha}^{-1}$ )
NIR	necessidades líquidas de rega ()
P	potência da estação de bombagem (kW)
p	fração de esgotamento da água solo em conforto hídrico ()
P	precipitação, mm
pa	percentagem da área adequadamente regada (%)
PELQ	eficiência potencial do quartil mínimo (%)
$Q_{\text{factor/yield}}$	quantidade de um fator de produção ou produção obtida
REW	água facilmente evaporável (mm)
RMSE	erro médio quadrático (mm)
S1	modelo de Stewart
S2	modelo fásico de Stewart
SAD	sistema de apoio à decisão
SAU	superfície agrícola útil
t	tempo (h)
$T_{\text{adj}}$	transpiração ajustada (mm)
TAW	água no solo total utilizável (mm)
$T_{\text{d}}$	défice de transpiração (mm)
$T_{\text{d,f}}$	défice de transpiração durante o período de floração (mm)
$T_{\text{d,m}}$	défice de transpiração durante o período de maturação (mm)
$T_{\text{d,v}}$	défice de transpiração durante o período vegetativo (mm)
TEW	água total evaporável (mm)
$T_{\text{i}}$	tempo total de operação da bomba (h)

$T_m$	transpiração máxima da cultura (mm)
TWU	uso total de água ( $m^3$ )
$TWU_{Farm}$	uso total de água ao nível da parcela ( $m^3$ )
$U_j$	utilidade relacionada com o critério j
WP	produtividade da água ( $kg\ m^{-3}$ )
$WP_{BWU}$	produtividade da água ( $kg\ m^{-3}$ )
$WP_{Farm}$	produtividade da água ao nível da parcela ( $kg\ m^{-3}$ )
$WP_{I-Farm}$	produtividade da água de rega ao nível da parcela ( $kg\ m^{-3}$ )
$WP_{Irrig}$	produtividade da água de rega ( $kg\ m^{-3}$ )
$x_j$	atributo
$Y_a$	produção ( $kg\ ha^{-1}$ )
$Y_a$	produção máxima ( $kg\ ha^{-1}$ )
$Z_e$	profundidade da camada evaporativa (m)
$Z_r$	profundidade radicular (m)
$\alpha$	declive do gráfico
$\beta$	valor da utilidade
$\beta_f$	fator da quebra de produção durante o período de floração ()
$\beta_m$	fator da quebra de produção durante o período de maturação ()
$\beta_v$	fator da quebra de produção durante o período vegetativo ()
$\Delta SW$	variação de água no solo entre a sementeira e a colheita (mm)
$\theta_{FC}$	capacidade de campo ( $m^3\ m^{-3}$ )
$\theta_{WP}$	coeficiente de emurchimento ( $m^3\ m^{-3}$ )
$\lambda_j$	peso



# **Capítulo 1**

## **Introdução**



## **1. INTRODUÇÃO**

### **1.1. CONSIDERAÇÕES GERAIS**

A população mundial está em forte crescimento nas últimas décadas, registando-se um aumento de 2.5 mil milhões de habitantes, em 1950, para 6.7 mil milhões, na atualidade. Este crescimento deverá continuar, prevendo-se um valor de 9.1 mil milhões de habitantes em 2050 (UN, 2008), representando um aumento de um terço da população mundial atual.

Este crescimento populacional leva a um aumento da pressão sobre a produção agrícola e sobre os recursos hídricos. A água estará menos disponível para a produção agrícola devido também ao aumento da procura dos sectores industrial e doméstico. Mas a produção de alimentos terá de aumentar para abastecer a crescente população mundial.

Presentemente, mais de 1.5 mil milhões de hectares da superfície do globo (cerca de 12% da área total) são utilizados para produção de culturas para fins alimentares, distribuídos entre terra arável e terra ocupada por culturas perenes (FAO, 2012). A FAO (2012) considera pouco exequível a expansão da terra agrícola, apesar da existência de uma quantidade considerável de terra potencialmente agrícola, a qual é geralmente ocupada por floresta, protegida por razões ambientais ou utilizada para expansão urbana. Notar que a produção agrícola aumentou entre 2.5 a 3 vezes durante os últimos 50 anos enquanto a terra cultivada apenas cresceu 12%. E por sua vez, mais de 40% do aumento da produção alimentar vem de áreas regadas, as quais duplicaram naquele período.

A agricultura é o sector com maiores necessidades hídricas, pelo que o regadio é usualmente considerado como causa de escassez da água, de desperdício e de degradação da sua qualidade. Contudo, é irrefutável que a agricultura de regadio fornece subsistência a uma grande parte da população mundial rural e disponibiliza uma grande porção dos bens alimentares (Pereira et al., 2009).

Os desafios que surgem face à crescente escassez hídrica podem ser abordados através de duas estratégias: (1) gestão do abastecimento, envolvendo atividades de localizar, desenvolver e explorar novas fontes de água; e (2) gestão da procura, que exige incentivos e mecanismos para promover a conservação e um uso mais eficiente da água (Rosegrant, 1997). A gestão da procura, de que resulta a conservação e poupança de água, assenta essencialmente sobre dois domínios (Pereira et al., 2009): (1) a adopção de calendários de rega que permitam, tanto a satisfação das necessidades hídricas das culturas, minimizando paralelamente o uso da água, como a maximização do retorno sob as limitações da escassez hídrica; e (2) a apropriada

seleção, projeto e uso dos sistemas de rega. Em suma, os principais objectivos da gestão da procura de água podem ser descritos como (Pereira et al., 2009):

- Redução das necessidades hídricas através da seleção de variedades culturais pouco exigentes e adoptando rega deficitária;
- Poupança e conservação da água, principalmente através da melhoria dos sistemas de rega, traduzida pelo aumento da uniformidade de distribuição e eficiência de aplicação, reuso de perdas, controlo da evaporação do solo, e a adopção de práticas de gestão do solo que levem ao aumento da sua reserva de água.
- Maior produção por unidade de volume de água, ou seja, maior produtividade da água, através de melhores práticas culturais agronómicas e de regadio, bem adaptadas às condições ambientais e evitando o stresse da cultura nos períodos críticos.
- Maior retorno económico, através de maior qualidade do produto e seleção de culturas mais rentáveis, melhoria esta relacionada com as decisões económicas e oportunidades de mercado.

Como referido, a resposta às pressões para diminuir o uso da água pode incluir a adopção de técnicas de rega deficitária. A rega deficitária controlada pode ser genericamente definida como a rega deliberada abaixo do nível de máxima produção que corresponda ao óptimo económico (Pereira, 2004; Pereira et al., 2002). Contudo, estas técnicas requerem a melhoria dos calendários de rega, incluindo conhecimento, modelos de cálculo e flexibilidade sobre a decisão de oportunidade e dotação de rega. A rega deficitária pode ser uma opção viável para mitigar a escassez hídrica, devido à optimização que leva à viabilidade económica e onde o stresse hídrico permitido favorece a poupança de água. A adopção de técnicas de rega deficitária controlada implica o conhecimento da evapotranspiração cultural, da reposta da cultura ao défice hídrico, a identificação dos períodos do ciclo vegetativo e dos impactos económicos das estratégias de redução da produção. Assim, é necessário desenvolvimento tecnológico para apoiar a decisão sobre a adopção destas técnicas (Pereira et al., 2009).

Contudo, os impactos da rega deficitária na produção e os resultados económicos daí resultantes, podem ser ou não negativos, dependendo do calendário de rega adoptado, do desempenho do sistema de rega e dos custos e valor da produção (Lorite et al., 2007). O apoio aos agricultores através do uso de modelos de simulação permite a adopção de uma gestão de rega que controle os défices hídricos para que as dotações sejam aplicadas durante os estágios de desenvolvimento menos sensíveis (Popova e Pereira, 2008; Pereira et al., 2009).

O indicador produtividade da água (WP), expresso em termos físicos ou económicos, é bem adequado para avaliar a eficiência de uso da água. Pereira et al. (2012) definem produtividade da água como a razão entre a produção real e o total da água usada (TWU). Em regadio é mais ajustado avaliar a produtividade da água relativamente a TWU, ou ao total de água de rega usada (IWU) quando a análise tem como objectivo a avaliação do desempenho de um dado sistema de rega, como discutido por Pereira et al. (2009). Contudo, é insuficiente exprimir a WP apenas em termos físicos, visto ser necessário entender os impactos económicos do uso da água; assim, são necessários indicadores alternativos para a produtividade económica da água, EWP (Cook et al., 2006; Pereira et al., 2009b; Rodrigues e Pereira, 2009). Porém, poucos estudos se reportam à análise da EWP a diversas escalas espaciais (Igbadun et al., 2006; Palanisami et al., 2006; Rodrigues e Pereira, 2009; Teixeira et al., 2008; Vazifedoust et al., 2008) e outros adoptam conceitos diferentes para definir a EWP, e.g., Hellegers et al. (2009), que definem a EWP a partir valor produtivo líquido, assumindo um valor negativo quando a cultura não é rentável.

De acordo com o Recenseamento Agrícola de 2009 (INE, 2011), o número de explorações agrícolas em Portugal à data era de 305 mil. No Alentejo existem apenas 10% dessas explorações que, no entanto, exploram 53% da Superfície Agrícola Útil (SAU) nacional. A heterogeneidade da agricultura nacional é demonstrada pela grande variabilidade da dimensão das explorações, evidenciada pelo facto de um reduzido número de explorações de grande dimensão (266), com mais de 1 000 hectares, explorar 12% da SAU. As explorações agrícolas, com uma superfície total de 4,7 milhões de hectares, ocupavam em 2009 cerca de 51% da superfície territorial do país. Neste ano, mais de metade das explorações agrícolas do país dispunham de infraestruturas de rega, equivalente a uma área potencialmente irrigável de 541 mil hectares, i.e., cerca de 15% da SAU. As regiões do Ribatejo e Oeste e do Alentejo são responsáveis por metade desta superfície, mas são as regiões do Entre Douro e Minho e da Beira Litoral aquelas que em termos relativos detêm o maior potencial de regadio, ocupando cerca de 95 mil e 61 mil hectares, respectivamente.

Quanto aos métodos de rega, em mais de metade das terras aráveis predomina a rega por aspersão, enquanto nas culturas permanentes cerca de 87% da área é regada por gota-a-gota. Nas pastagens permanentes, cerca de 2/3 da área é regada por gravidade. As explorações agrícolas de grande dimensão são responsáveis por 45% do consumo nacional de água para rega, mas são também estas explorações que originam anualmente mais de metade do valor de produção agrícola nacional. Cerca de 34% do volume total de água é consumido pelas

grandes explorações do Alentejo e Ribatejo e Oeste e 12% pelas explorações de média dimensão destas regiões (INE, 2011).

De forma a melhorar o uso da água e a sua produtividade, os agricultores deverão melhorar os seus sistemas de rega, já que a melhoria dos métodos e respetivos desempenhos através duma mais elevada uniformidade de distribuição é essencial para reduzir o consumo ao nível da parcela (Brennan, 2008; Pereira et al., 2002). A procura de soluções alternativas pode passar pelo uso de análise multicritério incorporada em sistemas de apoio à decisão (SAD), tomando a economia da água como atributo para a ordenação. Possibilitando uma melhoria no processo decisório, um SAD trata uma abordagem integrada para resolver problemas complexos, combinando o cálculo computacional e armazenamento de dados, com o conhecimento e discernimento humano, fornecendo apoio decisório à identificação de problemas, criando e avaliando alternativas (Pomerol e Romero, 2000). SADs como o MIRRIG, para avaliação e projeto de sistemas de microrrega (Pedras et al., 2009), e o SADREG, para avaliação e projeto de sistemas de rega por gravidade (Gonçalves e Pereira 2009), e modelos como o DEPIVOT, para rampas pivotantes de aspersão (Valín et al., 2012), e o PROASPER, para sistemas de aspersão fixa (Rodrigues et al., 2010), permitem a identificação e projeto de sistemas mais apropriados.

A aplicação de SADs e de análise multicritério em problemas de engenharia da rega é ainda limitado, recorrendo-se com mais frequência a SADs para procurar soluções de planeamento e afectação de recursos hídricos em agricultura (Raju et al., 2006; Rao et al., 2004; Recio et al., 2005; Riesgo e Gómez-Limón, 2006). Diversas aplicações de análise multicritério à rega são descritas na literatura (Bartolini et al., 2010; Bazzani, 2005; Darouich et al., 2012; Gonçalves et al., 2007, 2011; Manos et al., 2006; Pedras et al., 2009; Teclé and Yitayew, 1990). Contudo, poucas aplicações se dedicam ao impacto económico da implementação de sistemas de rega ao nível da parcela. Torna-se, assim, necessário o desenvolvimento de um modelo económico, e sua posterior integração em módulos de análise multicritério, que permita a avaliação e seleção de alternativas de gestão mais eficientes.

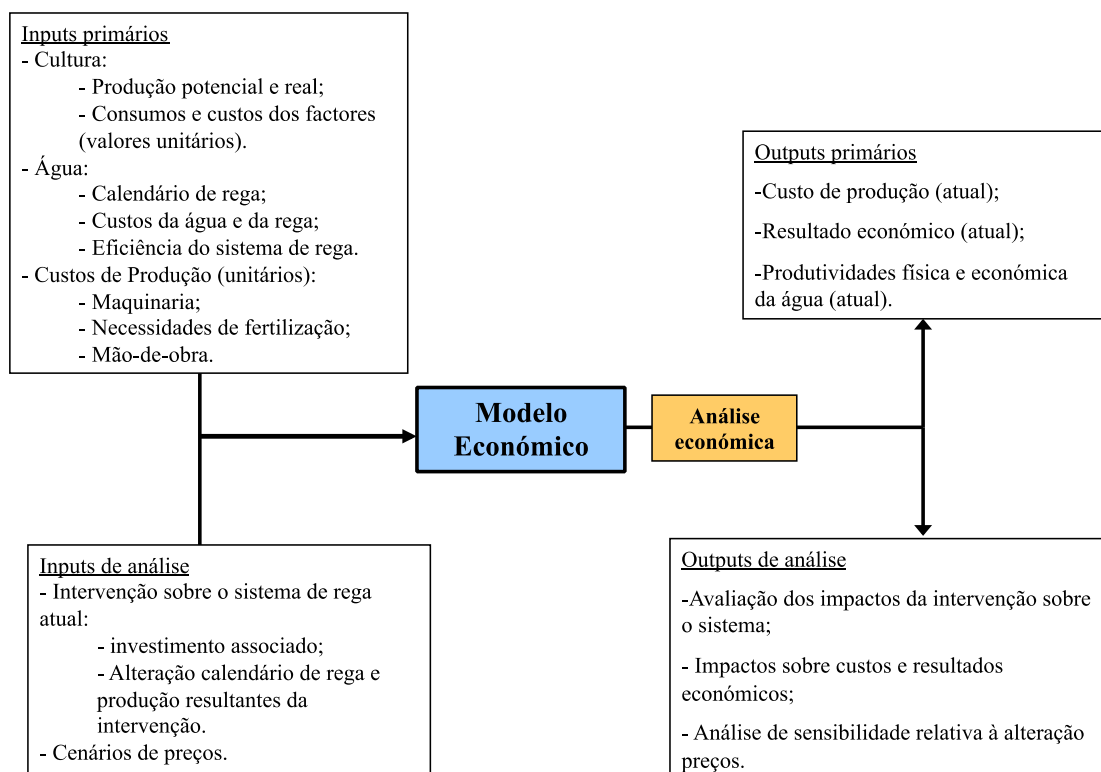
Tendo como propósito a integração num sistema de apoio à decisão para a gestão da rega, o modelo desenvolvido é mais simplificado do que outros modelos existentes, mas atende a todos os parâmetros económicos inerentes à gestão da rega de uma dada cultura. O modelo foi desenvolvido no sentido de prover à tomada de decisão ao nível da parcela, visando à sustentabilidade dos sistemas agrícolas. Numa fase final, procedeu-se à integração de um

módulo de análise multicritério de forma a avaliar cenários alternativos, com realce aos pontos de vista de carácter económico e ambiental.

## 1.2. OBJECTIVOS

O objectivo deste estudo é a modelação económica aplicada ao uso e produtividade da água em regadio. Pretende-se determinar o potencial dos sistemas de rega à escala da parcela para se atingir um uso eficiente da água, dando particular atenção à maximização dos usos benéficos da água e da produtividade física e económica da mesma. Foram, assim, desenvolvidos vários cenários de poupança de água tendo em conta soluções alternativas para as técnicas e práticas de rega aplicadas às culturas predominantes nos casos de estudo a abordar. Em particular, foram desenvolvidas, aplicadas e avaliadas metodologias de análise económica e de análise multicritério, visando a sua associação a modelos de projeto – MIRRIG (Pedras et al., 2009), PROASPER (Rodrigues et al., 2010) e DEPIVOT (Valín et al., 2012) – e de condução da rega – SIMDualKc (Rosa et al., 2012).

O estudo da modelação económica foi efectuado através da concepção e aplicação de um conjunto de indicadores que permitiu avaliar as diferentes alternativas e apoiar à tomada de decisão para escolha das alternativas economicamente aceitáveis (Fig. 1.1).



**Figura 1.1.** Esquema conceptual do modelo económico.

Recorrendo à modelação económica agrupada a módulos de análise multicritério, considerando benefícios e custos inerentes aos equipamentos e à gestão da rega, é possível identificar as melhores estratégias para atingir altas produtividades da terra e da água através de controlo da procura, tanto recorrendo à rega deficitária, como melhorando os desempenhos dos sistemas de rega. Recorrendo a estas ferramentas computacionais, foram desenvolvidos e analisados vários cenários de tecnologias e de gestão da rega para os casos de estudo, visando:

1. Identificar as práticas de gestão que conduzem a melhor produtividade da água;
2. Identificar melhorias nos sistemas de rega visando a poupança através de melhores desempenhos;
3. Avaliar os impactos do preço da água, preço dos produtos e custos de produção;
4. Avaliar os impactos económicos das soluções de gestão e de investimento, com recurso a análise multicritério;
5. Reconhecer os estrangulamentos e limites dos sistemas de rega na perspectiva da sustentabilidade do regadio.

### **1.3. ESTRUTURA DA TESE**

De forma a alcançar os objectivos anteriormente descritos esta tese encontra-se estruturada em 10 capítulos.

O Capítulo 1, aqui apresentado, tem o propósito de contextualizar as questões associadas à escassez dos recursos hídricos, a necessidade de metodologias e de conhecimento em questões associadas ao uso e produtividade da água em regadio, de forma a esclarecer a pertinência e aplicabilidade do estudo aqui apresentado, e estabelecer os objetivos onde assenta o estudo.

No Capítulo 2 avalia-se a viabilidade da adopção de calendários de rega deficitária das culturas do milho, girassol e trigo através de uma análise da produtividade económica da água. Tendo como base diversos campos agrícolas regados por aspersão, foram criados e avaliados vários cenários de défice hídricos tendo em conta diferentes procuras climáticas. Considerando vários preços e custos de produção afectos a diferentes preços de água e desempenhos dos sistemas de rega, foram criados diferentes cenários de forma a avaliar a viabilidade da adopção de calendários de rega deficitária.

No Capítulo 3 procede-se à análise da viabilidade de calendários de rega deficitária das culturas de milho e trigo numa situação de escassez hídrica extrema. São aqui introduzidos os

impactos dos custos totais de produção da exploração agrícola sobre os indicadores económicos da produtividade da água.

No Capítulo 4 apresenta-se o desenvolvimento de um modelo energético que pretende avaliar os impactos no balanço energético de diferentes cenários de: rega completa e deficitária; diferentes procuras climáticas; e de uma melhoria no desempenho dos sistemas de rega. Para tal, teve-se por base os cenários de rega deficitária descritos no Capítulo 2. O modelo permitiu determinar a eficiência e o balanço energéticos das diferentes culturas, quando regadas por aspersão fixa e rampa pivotante, de forma a avaliar quais as produtoras e sumidouras de energia. Comparam-se, também, estes resultados com as produtividades física e económica da água.

De forma a dar resposta à necessidade de avaliar o desempenho potencial dos sistemas de aspersão, identificando a modernização adequada, surge o modelo PROASPER, o qual é descrito no Capítulo 5. Este modelo procura responder à necessidade de produzir informação para agricultores e gestores, que possa auxiliar na tomada de decisão no projeto dos sistemas de rega. O modelo constitui uma ferramenta “amiga” do utilizador para suporte na decisão à concepção de um novo sistema, sendo capaz de simular várias alternativas de projeto para sistemas de aspersão. Neste Capítulo, o modelo é apresentado no que toca à sua base de dados, ao processo de cálculo de dimensionamento e à análise de desempenho.

No Capítulo 6 calculam-se as necessidades de rega da cultura do milho, como uma medida de preparação para enfrentar a escassez de água. Através da definição de várias estratégias de rega, com o objectivo de redução da procura de água de rega com impactos aceitáveis na produção, foram simuladas as necessidades de água para condições de seca severa e extrema. O estudo foi realizado para milho regado por aspersão e aplicado a várias localidades de Portugal Continental. As alternativas de rega foram avaliadas tendo em consideração a poupança de água de rega e o impacto nas produções. De forma a inferir a viabilidade económica da rega deficitária, foram determinados indicadores da produtividade física e económica da água recorrendo a dados sobre o valor da produção e desempenho de sistemas.

A apropriada gestão da rega requer a avaliação dos impactos económicos não só da calendarização da mesma, mas também dos sistemas de rega adoptados. Surgem, assim, os Capítulos 7 e 8 que têm por objectivo avaliar a produtividade económica da água da cultura do milho no Sul do Brasil quando sujeita a diversos défices hídricos e regada por diferentes sistemas de rega. No Capítulo 7 apresentam-se a calibração e validação do modelo

SIMDualKC, recorrendo a diferentes tratamentos de milho regado por aspersão e microrrega, sob rega completa e deficitária. A calibração e validação do modelo permitiu a determinação dos dados necessários para a avaliação dos impactos dos défices hídricos sobre a produção, produtividade da água e rentabilidade económica, a qual é descrita no Capítulo 8. Os dados recolhidos e simulados permitiram ainda desenvolver diferentes cenários de rega por rampa pivotante, de forma a avaliar a viabilidade da rega deficitária.

No Capítulo 9 apresenta-se a avaliação da viabilidade da rega completa e deficitária do milho sob diferentes sistemas de rega recorrendo a análise multicritério. Para tal, foram avaliados e comparados diferentes tratamentos em termos de uso e produtividade da água, quando considerados dois preços do produto e três sistemas de rega – aspersão fixa, rampa pivotante e microrrega – em dois campos regados no perímetro de rega da Vigia. Os diferentes cenários foram comparados e classificados recorrendo à análise multicritério. Para isso, foram criados três esquemas de prioridades: um referente à poupança de água; outro referente aos resultados económicos; e um terceiro representando um cenário equilibrado entre os anteriores.

Finalmente, no Capítulo 10 apresentam-se as conclusões decorrentes deste estudo baseadas nos resultados alcançados, em resposta aos objetivos inicialmente propostos.

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## **Capítulo 2**

# **Assessing Economic Impacts of Deficit Irrigation as Related to Water Productivity and Water Costs**

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**Rodrigues, G.C. Pereira, L.S., 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosystems Engineering, 103, 536-551**

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## 2. ASSESSING ECONOMIC IMPACTS OF DEFICIT IRRIGATION AS RELATED TO WATER PRODUCTIVITY AND WATER COSTS

**Abstract:** 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 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 due to 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 prices. The sunflower crop, despite less sensitive 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 practiced again;. 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.

**Key-words:** water balance, water-yield relations, economic water productivity, irrigation scheduling, irrigation performance.

### 2.1. INTRODUCTION

Water plays a decisive role in world's development. Its increasing scarcity imposes the need to optimize its use in all human activities, mainly 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 to be of great importance for the Portuguese agriculture. Deficit irrigation consists in deliberately apply irrigation depths smaller than those required to satisfy the crop water requirements at certain periods in the crop season, thus affecting evapotranspiration and yields, but keeping a positive return from the irrigated crop (English & Raja, 1996; Kang et al., 2000). However, impacts of irrigation deficits on yields and related economic results may or 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 the water productivity (WP) may be the best way to achieve an efficient water use. Depending on how the terms in the numerator and denominator are expressed, water productivity 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 (Molden, 2007; Kijne et al., 2003; Zwart & Bastiaanssen, 2004, 2007; Playan & Mateos, 2006; 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 of WP is the term water use efficiency (Steduto, 1996) but, recently, the term biomass water productivity was introduced to clearly refer to the physiological and ecophysiological processes of biomass production (Steduto et al., 2007). Relative to irrigation, it is preferably to assess the water productivity 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 do not allow to understand the economic impacts of water use; 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 assessing 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.

## **2.2. MATERIAL AND METHODS**

### **2.2.1. 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 2.1.

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.

**Table 2.1.** 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 <sup>-1</sup>	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 <sub>o</sub> , mm d <sup>-1</sup>	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

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 center-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 what makes that the system is discharge driven, which creates 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 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 center pivot sprinkler systems. Olive trees and grapevines have presently a steadily increase with adoption of microirrigation. The crops selected for this study are the winter wheat, maize and sunflower. Table 2.2 shows some main characteristics of these crops.

**Table 2.2.** 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

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 and Keller (1978) and Keller & Bliesner (1990). Several performance indicators were adopted including the potential efficiency of the low quarter, *PELQ* (%) used in this application:

$$PELQ = 100 \frac{Z_{lqMAD}}{D_{MAD}} \quad (2.1)$$

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.  $D_{MAD} = 15$  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 to 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 with 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, aging 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. Considering the willingness of the farmers to cooperate, that systems were evaluated twice or more times and the need for understanding 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 center-pivot system with near 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, 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, with 309 and 328 m length having respectively 17 and 18 sprinklers. The sprinklers spacing is 18 x 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 x 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 2.3.

**Table 2.3.** Soil textural classes, field capacity ( $\theta_{FC}$ ), wilting point ( $\theta_{WP}$ ), total available water (TAW) and readily and total evaporable water (REW and TEW) of the evaluated fields

Fields	Soil depth (m)	% Sand	% Loam	% Clay	$\theta_{FC}$ ( $\text{m}^3 \text{m}^{-3}$ )	$\theta_{WP}$ ( $\text{m}^3 \text{m}^{-3}$ )	TAW ( $\text{mm m}^{-1}$ )	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

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 to assess how currently poor performance impacts the economic results of deficit irrigation and to predict how the economic water productivity could increase in case the systems would be improved. The related scenarios are described under subheading 2.2.4.

### 2.2.2. Water productivity

As referred before, there is not a common agreement on the use of the term water productivity, WP may express a physical ratio between yields and water use (Molden, 2007; Kijne et al., 2003; Zwart & Bastiaanssen, 2004, 2007; Playan & Mateos, 2006), 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 herein as the ratio between the actual crop yield and the total water use, in  $\text{kg m}^{-3}$  (Pereira et al., 2009a), thus:

$$WP = \frac{Y_a}{TWU} \quad (2.2)$$

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

$$WP_{\text{Farm}} = \frac{Y_a}{TWU_{\text{Farm}}} \quad (2.3)$$

When considering the farm irrigation water use ( $IWU_{\text{Farm}}$ ) only, then it results the farm irrigation water productivity:

$$WP_{I-\text{Farm}} = \frac{Y_a}{IWU_{\text{Farm}}} \quad (2.4)$$

Equations 2.3 and 2.4 may take a different form when distinguishing the water use components, for instance:

$$WP_{\text{Farm}} = \frac{Y_a}{P + CR + \Delta SW + IWU_{\text{Farm}}} \quad (2.5)$$

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

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 water productivity 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 water productivity 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 economic water productivity (EWP) is expressed as  $\text{€ m}^{-3}$  and defined by:

$$EWP = \frac{Value(Y_a)}{TWU} \quad (2.6)$$

or

$$EWP_{Farm} = \frac{Value(Y_a)}{TWU_{Farm}} \quad (2.7)$$

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 economic water productivity ratio (EWPR):

$$EWPR = \frac{Value(Y_a)}{Cost(TWU)} \quad (2.8)$$

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

$$EWPR = \frac{Value(Y_a)}{Cost(IWU)} \quad (2.9)$$

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

Figure 2.1 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 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 estimating the net irrigation requirements (NIR) relative to every scenario. Using these irrigation data with the Stewart model (equation 2.11 analysed below) the  $Y_a$  values were computed for each scenario. NIR values were converted into gross irrigation depths (GID) 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,  $WP_{I-Farm}$ , and EWP) were then determined for the various combinations yield – seasonal gross irrigation.

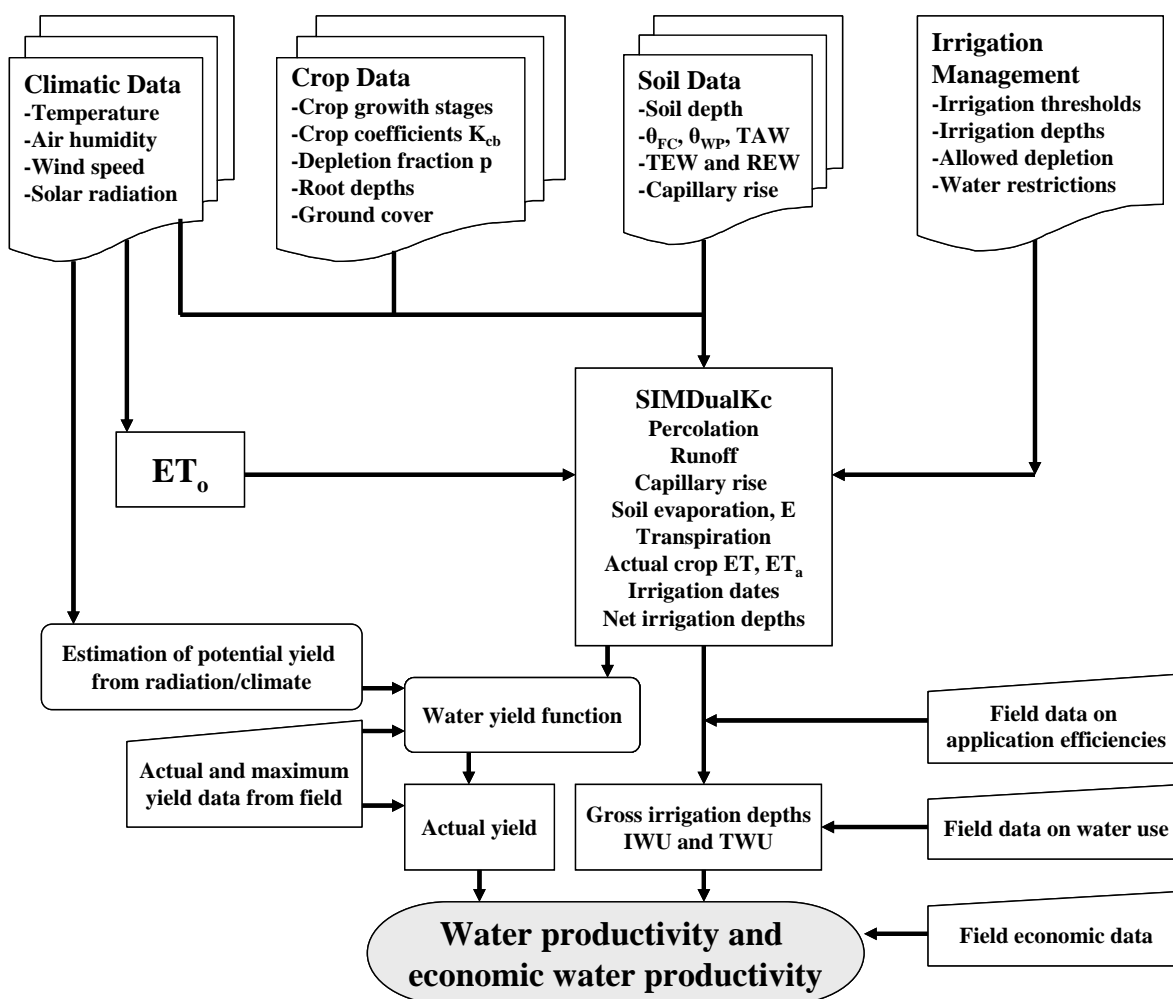


Figure 2.1. Flow-chart for the water productivity calculation

### 2.2.3. Irrigation scheduling simulation

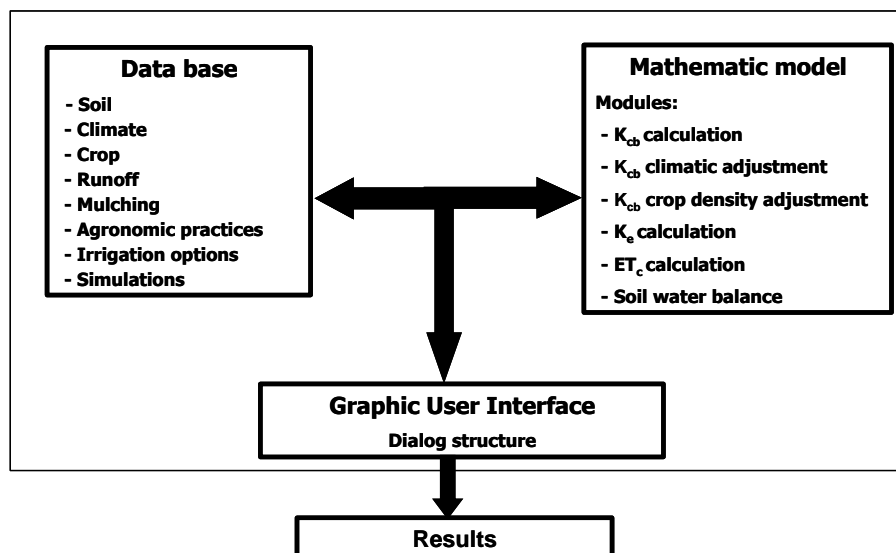
The methodology for computing the crop evapotranspiration using the dual crop coefficient approach is slowly receiving increased attention. It consists (Allen et al., 1998, 2005a, 2007) of adopting the following approach:

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (2.10)$$

where  $ET_c$  is crop evapotranspiration, in  $\text{mm d}^{-1}$ ,  $K_{cb}$  is the basal crop coefficient, dimensionless,  $K_e$  is the soil evaporation coefficient, dimensionless,  $K_s$  is the water stress coefficient, dimensionless, and  $ET_o$  is the reference crop evapotranspiration, in  $\text{mm d}^{-1}$ . This approach allows to estimate the two components of  $ET_c$ : 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 practiced; and (5) it adapts well when remote sensing provides for estimating  $K_{cb}$ . 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 proved 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 (Figure 2.2): the graphic 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 capillary rise and percolation (Liu et al., 2006).



**Figure 2.2.** Conceptual structure of SIMDualKc model.

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 refers to Évora's Meteorological Station for the period 1965-2000. Soil hydraulic properties relative to the selected fields (Table 2.3) 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 management allowed depletion (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 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:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_m}\right) \quad (2.11)$$

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  $\text{kg ha}^{-1}$ , when crop ET equals  $ET_a$  and  $ET_m$ . This equation has been widely used including for water productivity 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 equation 2.11 in order to  $Y_a$  as referred by Allen et al. (1998). For solving this equation it is required to have appropriate estimates of the potential yield  $Y_m$ . As referred above, these data were obtained using the AEZ method (Doorenbos & Kassam, 1979) and validating the results 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 the efficiency to convert 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, considering 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 water productivity 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 (Sidiqqe et al., 2001).

#### 2.2.4. 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 (ASWD). These are defined by a percentage increase of the depletion fraction for no stress  $p$  (Table 2.4).

**Table 2.4.** Irrigation scenarios for maize, sunflower and wheat

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

\*- ASWD - allowed soil water depletion fraction;  
 $p$  - soil water depletion fraction for no-stress

The crop net irrigation requirements (NIR) were computed for no restrictions on water availability and  $ASWD = p$ . It resulted for each crop a 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 are not exceeded with the probabilities of 50, 80 and 95% were identified to represent average, high and very high climatic demand (Table 2.5). The latter typically identifies a drought year. All irrigation scenarios (Table 2.4) were simulated for the weather conditions corresponding to those observed in the years identified in Table 2.5.

**Table 2.5.** Identification of the years representative of the climatic demand scenarios for the crops under assessment

<b>Climatic Demand</b>	<b>Maize</b>	<b>Sunflower</b>	<b>Wheat</b>
Average (Av)	1969	1993	1985/1986
High (Hi)	1981	1981	1986/1987
Very High (VH)	1998	2000	1998/1999

The season NIR for those identified years and all scenarios described in Table 2.4 were computed adopting irrigation depths of 15 mm per event as usually practiced 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 (center-pivot system), 47% for T-104 and 61.5% for T-134 (solid set sprinkler systems). To consider the upgrading of the irrigation systems and an improvement in management that allow to control wind drift losses, 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%.

### 2.2.5. Irrigation water costs

The calculation of EWPR requires that the cost of each cubic meter of water is known. Data by Noéme et al. (2004) were used for estimating the investment costs reported to 2003 and using appropriate life time for various types of equipment, which consist of fixed costs, and the operation, maintenance and management (OM&M) costs that consist of variable costs (Table 2.6). The fixed costs per unit of water use are given by:

$$\text{Fixed Costs} = \frac{\text{Investment costs}}{\text{Total water use}} \quad (2.12)$$

and the variable costs are:

$$\text{Variable Costs} = \frac{\text{OM \& M costs}}{\text{Total water use}} \quad (2.13)$$

where the OM&M costs comprise the full energy costs for delivering pressurized water to the farms. It results that fixed and variable costs amount for 0.0308 € m<sup>-3</sup> and 0.0834 € m<sup>-3</sup> respectively. Based on these values, the scenarios for water costs to be paid by the farmers are the following:

- a) Present cost, as practiced by the WUA (Water Users Association): 0.04 € m<sup>-3</sup>
- b) OM&M cost, as required for fully cover these activities: 0.0834 € m<sup>-3</sup>
- c) Full cost, as required for covering both the OM&M and investment costs: 0.1144 € m<sup>-3</sup>.

**Table 2.6.** Water costs estimation for the Vigia Irrigation District (adapted from Noéme, 2004).

	Annual cost, € year <sup>-1</sup>	Cost per unit surface, € ha <sup>-1</sup>	Cost per unit water, € m <sup>-3</sup>
<b>Investment cost</b>	145469	96.66	0.0308
<b>OM&amp;M cost</b>	393799	261.66	0.0834
<b>Total cost</b>	539268	358.32	0.1144

## 2.3. RESULTS

### 2.3.1. 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 2.7 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 in Table 2.7 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 2.7 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, thus in proportion to the canopy density during those periods.

**Table 2.7.** 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*
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

\* The restrictions are defined in Table 2.4. The restriction identified is the one producing the highest demand reduction when yields decrease < 25%

Results in Table 2.7 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 required to adopt water conservation practices such as mulching to control soil evaporation. Differently of summer crops, that 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 in case of 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 2.7 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 in this farm, near half of that for T-134 and M. Igreja (Table 2.3). Under this unfavourable water holding conditions crops use less the soil water storage and precipitation.

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 case of wheat, because wetting events are mainly due to rainfall since irrigation is supplemental of 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.

### **2.3.2. Water productivity**

Results for maize water productivity ( $WP$  and  $WP_{I-Farm}$ ) in the three farms are summarized in Table 2.8 for conditions when water availability restrictions are applied. The restrictions scenarios are the same as in Table 2.7. Results, including the seasonal gross irrigation depths  $GID$ , allow assessing the influence of climate conditions 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  $WP_{I-Farm}$  obtained with and without water availability restrictions is presented in Fig. 2.3. Results in Fig. 2.3a show that adopting a reduced demand scheduling due to limited water availability

leads to higher WP and  $WP_{I-Farm}$ , particularly the latter because it depends only from the irrigation water use. 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 to 1.62  $kg\ m^{-3}$ . Under full irrigation,  $WP_{I-Farm}$  ranges 0.82 to 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 crop water requirements 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 results also a decrease in WP. Results in Table 2.8 show that the irrigation performance highly influences water productivity. When PELQ increases it results a decrease in water use, hence an increase in water productivity. 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 before. However, that behaviour varies from a farm to another.

**Table 2.8.** Water productivity indicators (WP,  $WP_{I-Farm}$ ) and gross irrigation depth (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, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	GID, mm	WP, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	GID, mm	WP, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$
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

Results for sunflower WP and  $WP_{I-Farm}$  in the three farms are summarized in Table 2.9 and Fig. 2.3b for various irrigation management, climatic demand and systems performance conditions. Fig. 2.3b shows that WP and  $WP_{I-Farm}$  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 less performing irrigation system, T-104. WP ranges

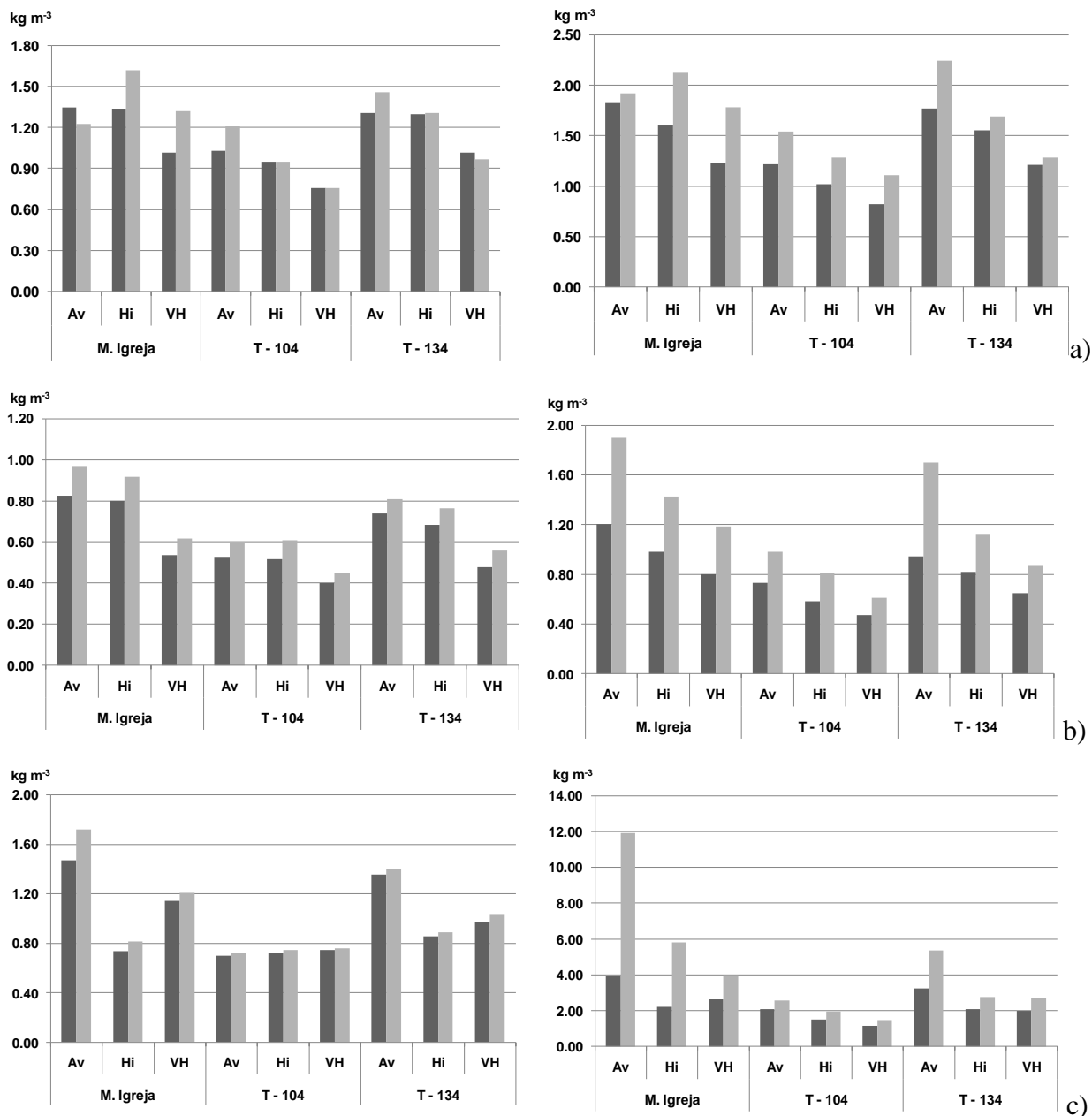
0.4 to 0.83 kg m<sup>-3</sup>, without restrictions in water use and 0.45 to 0.97 kg m<sup>-3</sup> when water availability restrictions are considered. WP<sub>I-Farm</sub> shows a larger increase when restrictions are applied, with their range values changing from 0.47 - 1.20 kg m<sup>-3</sup> to 0.61 - 1.90 kg m<sup>-3</sup>. Results in Table 9 show that both WP and WP<sub>I-Farm</sub> are highly influenced by the irrigation system performance, thus increasing with PELQ. WP<sub>I-Farm</sub> decreases when the climatic demand augments 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.

**Table 2.9.** Water productivity indicators (WP, WP<sub>I-Farm</sub>) and gross irrigation depth (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 <sup>-3</sup>	WP <sub>I-Farm</sub> , kg m <sup>-3</sup>	GID, mm	WP, kg m <sup>-3</sup>	WP <sub>I-Farm</sub> , kg m <sup>-3</sup>	GID, mm	WP, kg m <sup>-3</sup>	WP <sub>I-Farm</sub> , kg m <sup>-3</sup>
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

Fig. 2.3c compares WP and WP<sub>I-Farm</sub> for wheat with and without water restrictions considering the observed irrigation performance conditions. Differently from the summer crops, because irrigation is supplemental of 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<sub>I-Farm</sub> very much increases when restrictions are applied to the irrigation water, augmenting from a range of 1.17 - 4 kg m<sup>-3</sup> to 1.48 - 11.9 kg m<sup>-3</sup>. The smaller values correspond to the less 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 2.10, relative to the water restriction scenarios identified in Table 2.7, show that the water productivity highly depends upon the irrigation performance, with

both WP and  $WP_{I-Farm}$  increasing with PELQ but decreasing when the climatic demand increases.  $WP_{I-Farm}$  is much larger than WP because irrigation water use in supplemental irrigation of wheat is smaller than rainfall water use, contrarily to the water use of the summer crops.



**Figure 2.3.** WP (on left) and  $WP_{I-Farm}$ (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 under the observed irrigation performance.

**Table 2.10.** Water productivity indicators (WP,  $WP_{I-Farm}$ ) and gross irrigation depth (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, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	GID, mm	WP, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	GID, mm	WP, $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$
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

### 2.3.3. Economic water productivity

Results for maize EWP when deficit irrigation is practiced (Table 2.11), which were computed for the unit value of maize grain of  $0.223\ \text{€ kg}^{-1}$ , show quite low values, from  $0.17$  to  $0.36\ \text{€ m}^{-3}$  when the present irrigation performance is considered, and ranging  $0.30$  to  $0.47\ \text{€ m}^{-3}$  when  $PELQ = 85\%$ . If prices practiced during the last 5 years are considered ( $0.16\ \text{€ kg}^{-1}$ ) EWP decreases to  $0.13$  to  $0.33\ \text{€ m}^{-3}$ .and  $0.25$  to  $0.40\ \text{€ m}^{-3}$  respectively. The variation in EWP follows that for WP, thus being highly dependent of 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 ( $0.04\ \text{€ m}^{-3}$ ). In fact, the water costs represent 8 to 16% of the production costs when the present PELQ is considered and could decrease to 6 to 9% when water use decreases due to higher  $PELQ = 85\%$ . Considering these data, it becomes evident that EWP are presently quite low and the yield value barely covers the production costs, mainly under high or very high demand conditions. When the irrigation systems would be improved EWP would increase to acceptable levels. However, the farm irrigation costs will rise if new systems are installed to achieve high performance. EWP values are much too small in case of the field T-104;

however, because the labour is by the farmer himself and he reduces other production costs, it results that he keeps farming because accepting a very low remuneration to his labour.

**Table 2.11.** Economic water productivity of maize, sunflower and wheat under deficit irrigation as related with the climatic demand and the system performance PELQ (all units in  $\text{€ m}^{-3}$ )

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

EWP for sunflower was computed for a unit value of sunflower grain of  $0.243 \text{ € kg}^{-1}$ . Results in Table 2.11, relative to deficit irrigation, show low EWP values, from  $0.11$  to  $0.24 \text{ € m}^{-3}$  for the present irrigation performance. If PELQ increases to 85% EWP would improve to a range of  $0.19$  -  $0.31 \text{ € m}^{-3}$ . Considering the recently practiced price of  $0.5 \text{ € kg}^{-1}$ , EWP increase to  $0.23$  -  $0.49 \text{ € m}^{-3}$  for the actual PELQ, and to  $0.39$  -  $0.64 \text{ € m}^{-3}$  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 to 19% of the total production costs when the present PELQ is considered, and could decrease to 4.5 to 10% when PELQ = 85% is achieved. Considering these data and the current water price of  $0.04 \text{ € m}^{-3}$  it becomes evident that EWP (Table 2.11) are quite low and likely 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 practiced prices of  $0.5 \text{ € kg}^{-1}$ , when the demand for sunflower increased for biodiesel production, EWP data indicates that sunflower may become an attractive summer crop.

Table 2.11 summarizes the results for wheat EWP computed for the unit value of grain of  $0.267 \text{ € kg}^{-1}$ . EWP follows the variation of WP, hence highly depending upon the climatic demand and the irrigation system performance. Wheat EWP show higher values than the summer crops, varying from  $0.19$  to  $0.46 \text{ € m}^{-3}$ , when present irrigation performance is considered, and from  $0.28$  to  $0.59 \text{ € m}^{-3}$  for  $\text{PELQ} = 85\%$ . However, if the average price practiced for the last 5 years of  $0.16 \text{ € kg}^{-1}$  is considered, EWP reduces to  $0.11 - 0.28 \text{ € m}^{-3}$  for the current PELQ, or to  $0.17 - 0.35 \text{ € m}^{-3}$  when  $\text{PELQ} = 85\%$ . Since the water costs represent 3 to 12% of the production costs for the current PELQ and 2.4 to 5.6% if the demand decreases due to an improvement of PELQ to 85% considering the current cost for irrigation water ( $0.04 \text{ € m}^{-3}$ ), results for EWP show to be low, mainly if the commodity prices reduce to  $16 \text{ € kg}^{-1}$ . These results justify the common farmer's option for adopting wheat supplemental irrigation only in drought years when irrigation at grain filling highly improves crop yields.

#### 2.3.4. Assessing the impacts of water prices

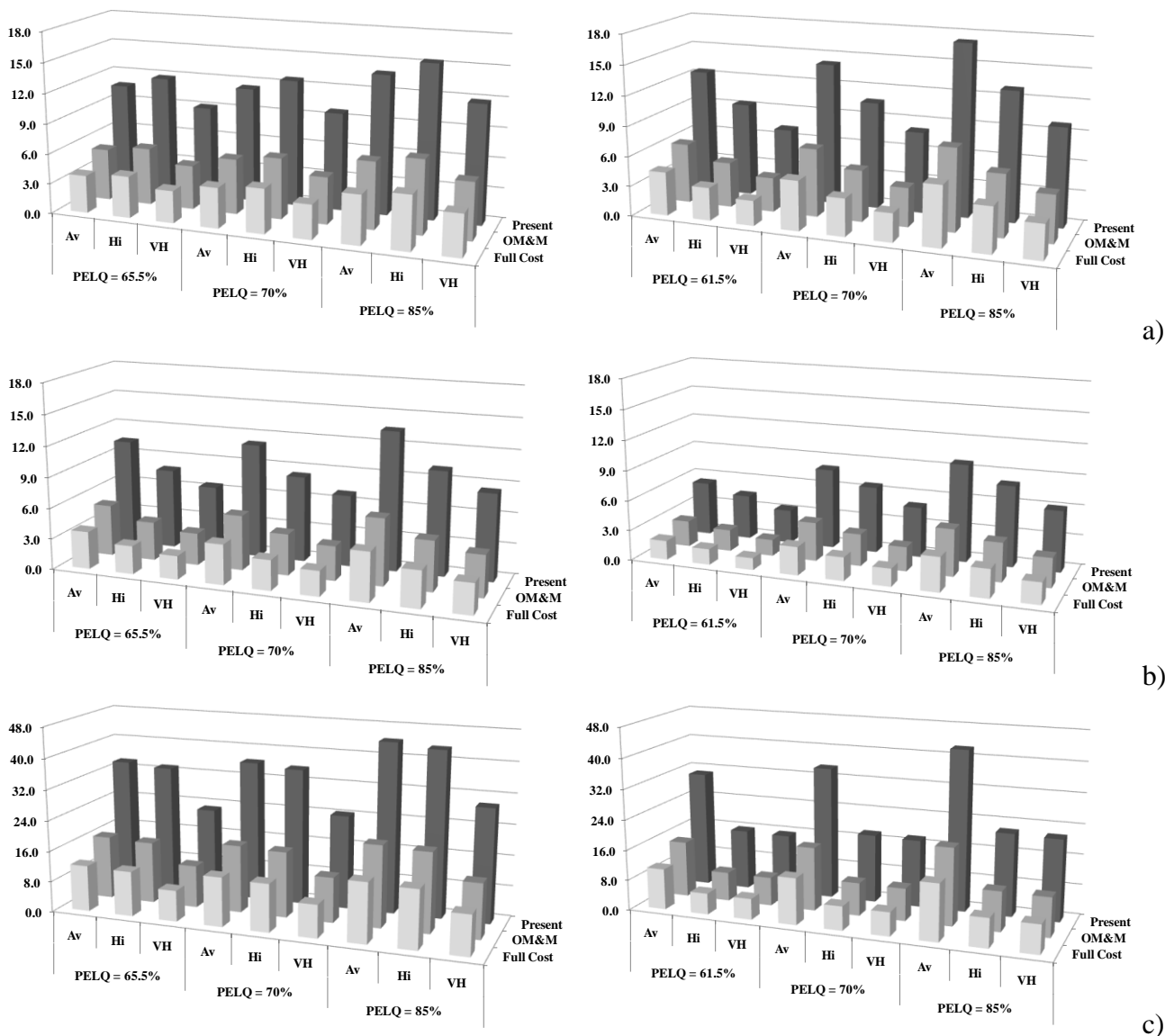
The economic water productivity ratio (EWPR, equation 2.9) is used to compare the yield values per unit water with the unit water costs relative to the three water price scenarios. Analysing the EWPR for maize (Fig. 2.4a), it may be observed that these ratios are presently in the range 7.2 to 12.5, for the current water prices ( $0.04 \text{ € m}^{-3}$ ). If these would be maintained, EWPR would increase to 9.8 - 17.2 if  $\text{PELQ} = 85\%$  is achieved. Considering that water costs are 6 to 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, mainly if commodity prices fall to the former  $0.16 \text{ € kg}^{-1}$ . However, if the irrigation performance could be improved the income would be acceptable since the water costs could decrease to 4.5 to 10% of the total production costs.

If the water prices increase to fully cover the OM&M costs ( $0.0834 \text{ € m}^{-3}$ ) EWPR would decrease to 3.4 – 6.0 and maize production with the presently poor performance would not anymore be profitable. If system performance would be improved EWPR would range 4.7 - 8.3 and farming returns would keep being not profitable under high to very high demand conditions or if commodity prices fall to precedent levels. If full costs are considered ( $0.1144 \text{ € m}^{-3}$ ), then EWPR decrease to 2.5 - 6 for the actual PELQ or to 3.5 to 8.3 with  $\text{PELQ} = 85\%$ . 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. 2.4b) vary in the range 3.4 to 10.4, considering the present water price ( $0.04 \text{ € m}^{-3}$ ) and would range 6.1 - 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, improving the irrigation performance the water costs would average 7% of the total production costs, and a low but positive income would be attained. Differently, if recently high commodity prices are maintained ( $0.5 \text{ € kg}^{-1}$ ) farming sunflower becomes attractive with the present water prices. If the water price increases to fully cover OM&M ( $0.0834 \text{ € m}^{-3}$ ), then EWPR decreases to a range of 1.6 to 5 with the actual PELQ, and of 2.9 to 6.5 with  $\text{PELQ} = 85\%$ . This price policy, as well as practicing a price to also cover the investment costs, would 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. 2.4c) show that for the present water price ( $0.04 \text{ € m}^{-3}$ ) EWPR vary 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 including if commodity prices fall to the former  $0.16 \text{ € kg}^{-1}$ . If water prices rise to  $0.0834 \text{ € m}^{-3}$  EWPR range 7.5 - 16.4 and 10.4 - 21.3 respectively for present and improved PELQ, while for water prices that fully cover the total costs ( $0.1144 \text{ € m}^{-3}$ ) EWPR decrease 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 ( $0.16 \text{ € kg}^{-1}$ ) are practiced again.

Results presented above show that water prices may largely influence the profitability of irrigated agriculture. Moreover, the analysis shows that the variability of crop irrigation water demand due to system performance highly influences the economic water productivity ratio, 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 practicing deficit irrigation if water price policies following 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.



**Figure 2.4.** Economic Water Productivity Ratios relative to farms 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 and three water costs scenarios (present, OM&M costs and full costs).

**2.4. CONCLUSIONS**

This study shows that water productivity indicators, mainly those of 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 not feasible but an analysis of economic water productivities is definitely helpful with 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 justify when the adoption of deficit irrigation may or 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 fully explore deficit irrigation may be required to adopt water conservation measures for controlling soil evaporation, e.g., mulching. Differently, for wheat supplemental irrigation soil evaporation is smaller than 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 water productivity and irrigation water productivity ( $WP$  and  $WP_{I-Farm}$ ) 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  $WP_{I-Farm}$  decrease when the climatic demand increase because irrigation water use then increases.

The economic water productivity ( $EWP$ ) 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 practiced. For sunflower, results indicate that if recent high commodity prices are practiced sunflower may become an attractive crop, differently from 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 economic water productivity ratios  $EWPR$ , relating the yield values per unit water use with the water prices, reveals 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 highly depends 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 practiced; otherwise it is generally not feasible. Wheat under supplemental irrigation, thus with relatively small

irrigation water use, 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 require not only the knowledge of the crop yields responses to water but also to know the structure of the production costs, including relatively to 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 revealed adequate for assessing the feasibility of deficit irrigation but further developments on the relationships between irrigation practices and economic results are required.

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# **Capítulo 3**

## **Análise Económica e da Produtividade da Água em Rega em Condições de Seca: Aplicação às Culturas de Milho e Trigo no Regadio Da Vigia**

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Rodrigues, G.C., Silva, F.G., Pereira, L.S., 2010. Análise económica e da produtividade da água em rega em condições de seca: aplicação às culturas de milho e trigo no regadio da Vigia. In: Pereira, L.S., Mexia, J.T., Pires, C.A.L. (Eds.), *Gestão do Risco em Secas. Métodos, tecnologias e desafios*. Edições Colibri e CEER, Lisboa, pp. 321–344.

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### **3. ANÁLISE ECONÓMICA E DA PRODUTIVIDADE DA ÁGUA EM REGA EM CONDIÇÕES DE SECA: APLICAÇÃO ÀS CULTURAS DE MILHO E TRIGO NO REGADIO DA VIGIA**

**Resumo:** Este estudo tem como objetivo avaliar a viabilidade da rega deficitária das culturas do milho e trigo em condições de seca utilizando um estudo de caso de rega por aspersão no regadio da Vigia, Alentejo. Foi adotada a análise da razão da produtividade da água (EWPR). Considerando procuras climáticas muito elevadas, foram criados vários cenários de défice hídrico e de disponibilidade de água limitada. Foram calculados vários valores de EWPR utilizando dados de campo observados, incluindo produções, custos de produção, preços da água, valores unitários da produção e desempenho dos sistemas de forma a determinar limiares económicos. Os resultados mostram que o maior impedimento à adoção da rega deficitária é o baixo desempenho dos sistemas de rega, levando a baixas EWPR. Porém, os défices hídricos de ambas as culturas podem não ser economicamente viáveis mesmo melhorando os desempenhos dos sistemas de rega. Conclui-se que a adoção da rega deficitária requer desempenhos de rega elevados e flexibilidade na aplicação da política de preços da água de forma a apoiar a melhoria da rega em condições de seca.

**Abstract:** This study aims at assessing the feasibility of deficit irrigation of maize and wheat under drought conditions when farmed in selected sprinkler-irrigated fields in Vigia Irrigation District, Alentejo, Southern Portugal. An analysis of the economic water productivity ratio (EWPR) is adopted. Considering a very high climatic demand, various scenarios of water deficits and limited water availability were developed. Various EWPR values were calculated using field collected data on yield, production costs, water costs, commodity prices and irrigation performance in order to determine positive economic thresholds. Results show that the main bottleneck for adopting deficit irrigation under drought conditions is the presently low performance of the farm irrigation systems, which leads to low EWPR. Hence, limited water deficits for both crops may not to be viable even when improving the irrigation performance. It is concluded that adopting deficit irrigation requires high irrigation performance, and that the application of a water prices policy would be flexible, thus supporting the improvement of the irrigation systems and of drought irrigation management policies.

### 3.1. INTRODUÇÃO

A escassez crescente da água impõe a otimização do seu uso em todas as atividades humanas, principalmente na agricultura de regadio, o principal sector consumidor a nível mundial. Défices hídricos podem levar a perdas económicas, enquanto que um uso excessivo da água de rega leva a uso não-benéfico. Uma gestão da água apropriada ao nível da cultura/parcela, i.e., quando e quanto regar, assume-se como um fator extremamente importante. Em anos de escassez, com disponibilidade de água limitada, os agricultores poderão ter que adotar rega deficitária, o que torna esta técnica de grande importância para a agricultura portuguesa. A rega deficitária consiste na aplicação deliberada de dotações inferiores às necessárias para satisfazer as necessidades hídricas da cultura em determinados períodos do ciclo vegetativo, afetando assim a evapotranspiração e a produção, mas mantendo positivo o retorno económico da cultura regada (English e Raja, 1996; Kang *et al.*, 2000). Contudo, os impactos da rega deficitária na produção, e os resultados económicos daí resultantes, podem ser ou não negativos, dependendo do calendário de rega adotado, do desempenho do sistema de rega, e dos custos e valor da produção (Lorite *et al.*, 2007). O apoio aos agricultores através do uso de modelos de simulação permite a adoção de uma gestão de rega que controle os défices hídricos para que as dotações sejam aplicadas durante os estágios de desenvolvimento menos sensíveis (Popova e Pereira, 2008; Pereira *et al.*, 2009b).

O aumento da produtividade da água (*WP*) é, provavelmente, a melhor forma de alcançar um uso eficiente da água. Dependendo dos termos em que o numerador e o denominador são definidos, a produtividade da água pode ser expressa em termos físicos ou económicos. Pereira *et al.* (2009a) definem *WP* como a razão entre a produção real e o total da água usada (*TWU*). Contudo, a *WP* pode ser definida de várias formas (Kijne *et al.*, 2003; Zwart e Bastiaanssen, 2004, 2007; Playan e Mateos, 2006; Molden, 2007; Pereira *et al.*, 2009a), i.e., a *WP* pode ter diferente significados, o que pode levar a interpretações contraditórias quando o objetivo final não é especificado. O termo eficiência do uso da água é frequentemente usado como sinónimo de *WP* mas o seu uso deve limitar-se a relações ecofisiológicas assimilados/transpiração ou à relação entre a biomassa produzida e a transpiração (Pereira *et al.*, 2009a). Relativamente à rega, é mais correto avaliar a produtividade da água relativamente a *TWU*, ou ao total de água de rega usada (*IWU*) quando a análise tem como objetivo a avaliação do desempenho de um dado sistema de rega, como discutido por Pereira *et al.* (2009a). Contudo, é insuficiente exprimir a *WP* apenas em termos físicos visto ser necessário entender os impactos económicos do uso da água; assim, são necessários

indicadores alternativos para a produtividade económica da água, *EWP* (Cook *et al.*, 2006; Pereira *et al.*, 2009b). Porém, poucos estudos se reportam à análise da *EWP* a diversas escalas (Igbadun *et al.*, 2006; Palanisami *et al.*, 2006; Teixeira *et al.*, 2008; Vazifedoust *et al.*, 2008; Rodrigues e Pereira, 2009) e outros adotam conceitos diferentes para definir a *EWP*, e.g., Hellegers *et al.* (2009), que definem *EWP* a partir valor produtivo líquido, assumindo um valor negativo quando a cultura não é rentável.

Num estudo anterior foi verificado que analisando as razões entre as margens brutas e os volumes líquidos de rega juntamente com as razões entre as mesmas margens brutas e a área cultivada era possível avaliar quando a rega deficitária pode ser uma alternativa aceitável à rega completa (Pereira *et al.*, 2002; Rodrigues *et al.*, 2003). Os resultados então obtidos, assim como as aproximações usadas, sugerem que os impactos económicos dos défices hídricos podem ser avaliados através da análise da *EWP*.

O principal objetivo deste estudo é a análise dos impactos económicos de défices hídricos e preços da água através da avaliação das produtividades económicas da água. Adotando esta aproximação, pode ser possível definir uma metodologia facilmente utilizável numa análise de engenharia. O desenvolvimento desta metodologia constitui objetivo central deste estudo, incluindo o uso do modelo SIMDualKc (Rosa *et al.*, 2010), para a estima da transpiração das culturas e da evaporação do solo. A metodologia foi aplicada a duas parcelas regadas por aspersão no regadio da Vigia, Alentejo, e ao milho e trigo de Inverno. O segundo objetivo principal é a avaliação da viabilidade da rega deficitária quando influenciada pelo desempenho dos sistemas de rega e preços da água. Com este propósito, o desempenho dos sistemas de rega foi avaliado no campo, os custos de produção foram avaliados e foram considerados vários cenários de procura e preços de água, relacionando-se estes últimos com a aplicação da Diretiva Quadro da Água ao sector agrícola.

## **3.2. MATERIAL E MÉTODOS**

### **3.2.1 Área de estudo e sistemas de rega**

A área de estudo é o Perímetro de Rega da Vigia, distrito de Évora. Os dados climáticos utilizados referem-se ao período 1965-2009 e à estação meteorológica de Évora (38.57° N, 7.71° W, e 309 m de altitude). Os solos predominantes na área são solos mediterrâneos vermelhos e castanhos derivados de rochas quartzo-dioríticas e outros materiais não calcários.

As propriedades hidráulicas do solo não saturado foram determinadas a partir de trabalho de campo e de métodos laboratoriais para a banda completa de tensão de água no solo. Foram desenvolvidas funções de pedo-transferência (Paz *et al.*, 2009) e técnicas de mapeamento para descrever a propriedades hidráulicas do solo na região (Mateus *et al.*, 2007). O terreno apresenta declives suaves a médios. Não existe toalha freática na área.

O Perímetro de Rega da Vigia, construído entre 1976 e 1985, tem uma área equipada de 1834 ha e localiza-se nos concelhos de Évora e do Redondo. A área presentemente regada é de 1505 ha. O projeto de rede de rega (DGRAH, 1978) foi projetado e construído para disponibilizar água de rega sob pressão a sistemas de aspersão fixa. Contudo, as parcelas maiores adotaram sistemas de rega por rampa pivotante, que presentemente cobrem aproximadamente 50 % da área regada total. Uma estação de bombagem localizada junto à barragem, a montante do sistema de condutas, pressuriza a água de rega. O sistema funciona a pedido, não limitando os agricultores no quanto e quando regar. Os hidrantes, porém, não se encontram equipados com reguladores de pressão, criando alguns problemas no desempenho do serviço. O desempenho do sistema foi avaliado utilizando equipamentos de medição de pressão e caudal (Calejo, 2003; Pereira, 2007). Os resultados da análise de desempenho mostram que o défice relativo de pressão nos hidrantes é normalmente baixo e que a fiabilidade do sistema no que toca ao serviço nos hidrantes é também baixa, normalmente inferior a 0.5. Estas condições são indicativas de variações frequentes de pressão e caudal nos hidrantes, com impacto no desempenho dos sistemas de rega das parcelas.

As culturas principais no Perímetro são os cereais, as culturas industriais e as forragens, regadas na sua maior parte por rampa pivotante. A área de olival e a vinha tem vindo a crescer com adoção de rega localizada. As culturas selecionadas para este estudo são o milho e o trigo. Na Tabela 3.1 são apresentadas algumas características dessas culturas.

**Tabela 3.1.** Períodos típicos de desenvolvimento das culturas de trigo e milho

Cultura	Duração dos períodos de desenvolvimento da cultura			
	Inicial	Desenvolvimento rápido	Intermédio	Final
<b>Trigo</b>	15/11 – 24/02	25/02 - 09/04	10/04 – 04/06	05/06 – 20/06
<b>Milho</b>	01/05 – 31/05	01/06 - 04/07	05/07 – 17/08	18/08 – 16/09

Foram efetuadas avaliações dos sistemas de rega em funcionamento durante vários anos (Pereira, 2007). Os procedimentos de avaliação são os descritos por Merriam e Keller (1978)

e Keller e Bliesner (1990). Foram adotados vários indicadores de desempenho incluindo a eficiência potencial do quartil mínimo,  $PELQ$  (%):

$$PELQ = 100 \frac{Z_{lqMAD}}{D_{MAD}} \quad (3.1)$$

onde  $Z_{lqMAD}$  é a média do quartil mínimo da dotação infiltrada (mm) quando igual ao défice permitido por gestão ( $MAD$ ), e  $D_{MAD}$  é a dotação média aplicada (mm) quando o défice de água no solo iguala  $MAD$ . Neste estudo, foi adotada  $D_{MAD} = 15$  mm, pois é a mais adequada entre as utilizadas pelos agricultores. Foram colhidas amostras de solo para complementar a informação recolhida junto dos agricultores para identificar o  $MAD$ . Foi escolhida a  $PELQ$  pois as dotações aplicadas foram baixas (5 a 15 mm), o que pode levar a um erro considerável ao estimar a eficiência de aplicação real. Além disso, é apropriado utilizar a  $PELQ$  para projeto e gestão, tanto mais que se refere ao quartil da parcela que recebe menos água, pelo que pode ser relacionada com a uniformidade de distribuição.

Os resultados de várias avaliações (Valín *et al.*, 2003; Pereira, 2007) mostram que o desempenho de rega é frequentemente baixo. As causas para tal incluem variações no caudal e pressão nos hidrantes, envelhecimento e fraca manutenção do equipamento, perdas por evaporação e pelo vento, e má escolha dos bicos dos aspersores. Considerando a disponibilidade dos agricultores em cooperar, os sistemas foram avaliados, pelo menos, duas vezes, e face à necessidade de compreender de que forma o baixo desempenho pode influenciar os resultados económicos, foram selecionados casos de estudo relativos a sistemas de rega com baixo desempenho. Um corresponde a uma parcela grande e o outro a uma média, identificadas como M. Igreja e T-134, respetivamente. As características hidráulicas relativas aos solos das parcelas são apresentadas na Tabela 3.2.

**Tabela 3.2.** Classes texturais do solo, capacidade de campo, coeficiente de emurchecimento, água disponível total ( $TAW$ ), e água facilmente e totalmente evaporável ( $REW$  e  $TEW$ ) para as parcelas avaliadas

Parcelas	Prof. (m)	% Areia	% Limo	% Argila	$\theta_{FC}$ ( $m^3 m^{-3}$ )	$\theta_{WP}$ ( $m^3 m^{-3}$ )	$TAW$ ( $mm m^{-1}$ )	$REW$ (mm)	$TEW$ (mm)
M. Igreja	1.20	52	9	39	0.44	0.28	160	10	38
T-134	1.10	47	18	35	0.35	0.18	170	11	32

Na parcela M. Igreja, foi avaliada uma rampa pivotante com aproximadamente 20 anos de funcionamento. O raio da área molhada é de 320 m e o sistema rega uma área de 32 ha. A

rampa é equipada com aspersores colocados sobre a tubagem e, por tal, expostos ao vento. Eram aplicadas dotações de rega de 15 mm. Na parcela T-134 foi avaliado um sistema de aspersão fixa consistindo em duas rampas, enterradas, de 309 e 328 m de comprimento com 17 e 18 aspersores, respetivamente. O espaçamento dos aspersores era de 18 x 18 m.

Os indicadores de desempenho relativos a estes sistemas indicavam a necessidade de melhoria, eventualmente de serem substituídos por sistemas mais modernos e melhor projetados. Estas condições permitem avaliar quais os impactos dos baixos desempenhos nos resultados económicos da rega deficitária e prever como a produtividade económica da água aumentaria no caso de melhoria dos sistemas. Os correspondentes cenários são descritos posteriormente.

### 3.2.2. Produtividade da água

Como referido anteriormente, não existe acordo no uso do termo produtividade da água,  $WP$ . Como analisado na introdução com referência a vários estudos,  $WP$  pode expressar tanto uma razão física entre a produção e a água utilizada, como uma razão económica entre o valor da produção e a água utilizada. Os conceitos podem ser aplicados a diferentes escalas, desde a parcela até à bacia. Além disso, o conceito de  $WP$  pode ser estendido a usos não agrícolas da água. Assim, seguindo a análise proposta por Pereira *et al.* (2009a), definem-se apropriadamente os conceitos utilizados neste estudo.  $WP$  é definida como a razão entre a produção real da cultura e o total de água utilizado, expressa em  $\text{kg m}^{-3}$ :

$$WP = \frac{Y_a}{TWU} \quad (3.2)$$

onde  $Y_a$  é a produção real, em kg, e  $TWU$  é o total de água utilizado incluindo a precipitação, em  $\text{m}^3$ , para alcançar  $Y_a$ . Quando considerada a água utilizada ao nível da parcela ( $TWU_{Farm}$ ), incluindo a precipitação, armazenamento de água no solo, ascensão capilar e rega, a produtividade da água na parcela ( $WP_{Farm}$ ) é definida como:

$$WP_{Farm} = \frac{Y_a}{TWU_{Farm}} \quad (3.3)$$

Quando é apenas considerado o uso da água de rega na parcela ( $IWU_{Farm}$ ), resulta a produtividade da água de rega:

$$WP_{I-Farm} = \frac{Y_a}{IWU_{Farm}} \quad (3.4)$$

A equação 3.3 pode tomar uma forma diferente quando distinguidas as diferentes componentes do uso da água:

$$WP_{Farm} = \frac{Y_a}{P + CR + \Delta SW + IWU_{Farm}} \quad (3.5)$$

onde  $P$  é a precipitação sazonal,  $CR$  é a ascensão capilar,  $\Delta SW$  é a diferença do teor de água no solo entre a plantação e a colheita, e  $IWU_{Farm}$  é a dotação de rega sazonal, expressos em mm ou  $m^3 ha^{-1}$ , e  $Y_a$  expressa em  $kg ha^{-1}$ . As variáveis no denominador podem ser obtidas através de observações de campo ou de modelação; quando conhecidas permitem a identificação de alternativas para melhorar  $WP$  e poupar água de rega.

O significado destes indicadores é necessariamente diferente e pode levar a interpretações contraditórias quando o termo “produtividade da água” é utilizado não identificando o denominador das diferentes equações. De salientar que aumentos de  $WP$  não levam obrigatoriamente a uma poupança de água pois é necessário distinguir entre uso de água consumptivo e não consumptivo (Pereira *et al.*, 2002; 2009a). Contudo, infelizmente, tal distinção não é por norma feita.

É importante considerar as questões económicas relativas à produtividade da água já que o objetivo do agricultor é alcançar o melhor retorno possível. Substituindo o numerador das equações anteriores pelo valor monetário da produção obtida, a produtividade económica da água ( $EWP$ ) é expressa em  $\text{€ } m^{-3}$  e definida por:

$$EWP = \frac{Valor(Y_a)}{TWU} \quad (3.6)$$

ou

$$EWP_{Farm} = \frac{Valor(Y_a)}{TWU_{Farm}} \quad (3.7)$$

A economia da produção pode ser melhor compreendida quando o numerador é expresso em termos de margem bruta ou do retorno líquido relativo à cultura considerada (Rodrigues *et al.*, 2003), mas estas aproximações requerem uma informação económica algo exigente. Alternativamente, como neste estudo, a economia da produção pode ser considerada ao exprimir tanto o numerador como o denominador em termos monetários, respetivamente o

valor da produção e o custo da água usada,  $TWU$  (incluindo os custos dos fatores de produção), tendo como resultado a razão da produtividade económica da água ( $EWPR$ ):

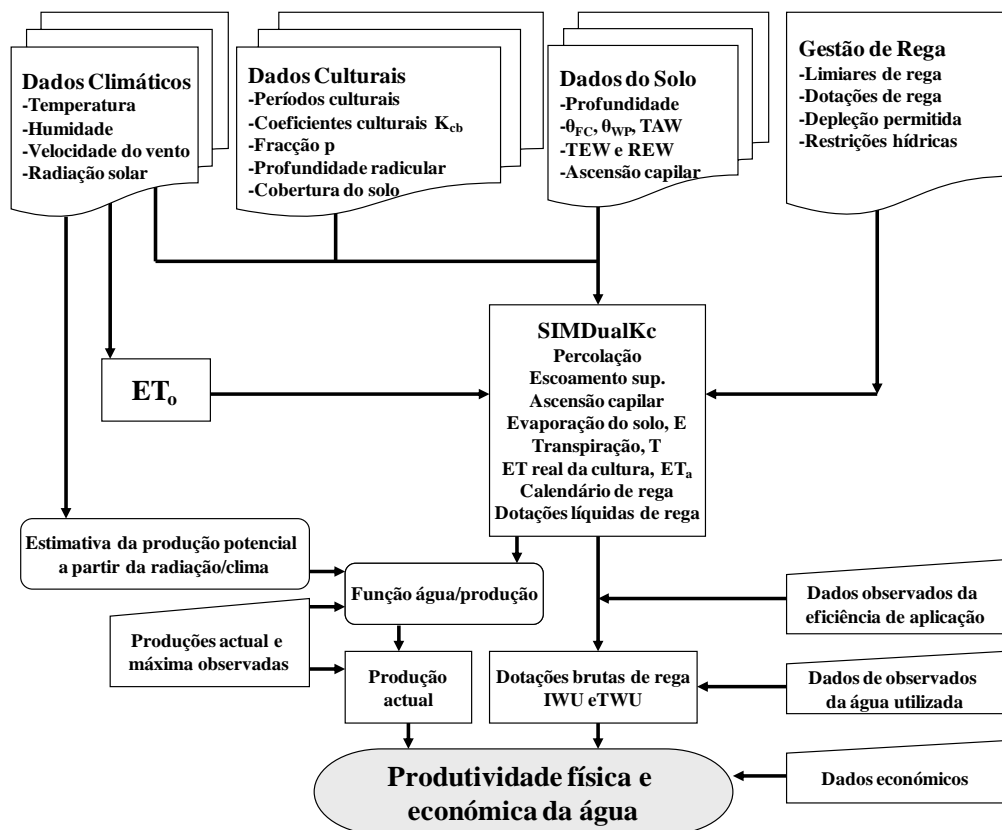
$$EWPR = \frac{Valor(Y_a)}{Custo(TWU)} \quad (3.8)$$

Assumindo que todos os custos da água se devem ao custo da rega, resulta:

$$EWPR_{I-Farm} = \frac{Valor(Y_a)}{Custo(IWU)} \quad (3.9)$$

que permite uma simples comparação com o preço a ser pago pela água.

A Figura 3.1 descreve o procedimento utilizado para estimar  $WP$ ,  $WP_{Farm}$  e  $EWP$  a partir da produção real e potencial da cultura ( $Y_a$  e  $Y_m$ ): as observações de campo permitiram recolher dados da produção real e do desempenho dos sistemas de rega, nomeadamente quanto à  $PELQ$  para as diversas parcelas, enquanto as produções potenciais  $Y_m$  foram estimadas utilizando o método AEZ proposto por Doorenbos e Kassam (1979), cujos resultados foram validados por comparação com a melhores produções alcançadas na região.



**Figura 3.1.** Algoritmo de cálculo da produtividade da água (Adaptado de Rodrigues e Pereira, 2009)  
Os cenários de rega necessários à aproximação foram simulados utilizando o modelo SIMDualKc, que permitiu estimar as necessidades líquidas de rega ( $NIR$ ) relativas a cada

cenário. Utilizando estes dados de rega conjuntamente com o modelo de Stewart (equação 3.10, abaixo) foram determinados os valores de  $Y_a$  para cada cenário. Os valores de NIR foram convertidos em dotações brutas de rega ( $GID$ ) utilizando os valores de  $PELQ$  relativos a vários cenários de melhoria dos desempenhos da rega. As produtividades  $WP$ ,  $WP_{I-Farm}$ , e  $EWP$  foram então determinadas para diferentes combinações produção – rega sazonal total.

### 3.2.3. Simulação de calendários de rega

A metodologia para simular a evapotranspiração cultural utilizando a aproximação dos coeficientes culturais duais (Allen *et al.*, 1998, 2005, 2007) consiste na adoção da seguinte aproximação:

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (3.9)$$

onde  $ET_c$  é a evapotranspiração cultural, em  $\text{mm d}^{-1}$ ,  $K_{cb}$  é o coeficiente cultural basal, adimensional,  $K_e$  é o coeficiente de evaporação da água do solo, adimensional,  $K_s$  é o coeficiente de stress, adimensional, e  $ET_o$  é a evapotranspiração de referência, em  $\text{mm d}^{-1}$ . Esta aproximação permite estimar as duas componentes da  $ET_c$ : uma consiste na água consumida pela cultura através da transpiração (calculada através do  $K_{cb}$ ), e a outra é relativa à água consumida por evaporação a partir da camada superficial do solo. O coeficiente  $K_s$  é inferior a 1.0 quando a cultura se encontra sob stress hídrico.

Foi utilizado nesta aplicação o modelo SIMDualKc, que simula a ET da cultura e efetua a simulação do balanço hídrico do solo com baseado na aproximação da equação 3.9 (Rosa *et al.*, 2010). O modelo apresenta 3 componentes principais: uma interface “amiga do utilizador”, os modelos matemáticos e uma base de dados. A base de dados armazena dados de solo, cultura, sistema de rega e simulação, sendo esta uma combinação específica dos fatores que representam a parcela analisada. O modelo efetua o balanço hídrico do solo ao nível da parcela usando um passo de tempo diário.

A determinação da evaporação do solo segue a metodologia descrita por Allen *et al.* (1998; 2005). A evapotranspiração cultural é determinada como descrito por Allen *et al.* (1998) incluindo as modificações propostas por Allen *et al.* (2007) e Allen e Pereira (2009). A evapotranspiração de referência é calculada externamente utilizando o EVAP56, um algoritmo do modelo WinISAREG (Pereira *et al.*, 2003) que utiliza a metodologia proposta

por Allen *et al.* (1998) para o cálculo da equação FAO-PM, incluindo com dados incompletos.

O dados a introduzir no modelo incluem a precipitação e  $ET_o$  diárias, o teor de água no solo total e facilmente utilizável ( $TAW$  e  $RAW$ ), o teor de água total e facilmente evaporável ( $TEW$  e  $REW$ ), o teor de água no solo aquando da sementeira e, para os quatro períodos de crescimento da cultura (inicial, desenvolvimento rápido, intermédio e final), os valores iniciais dos coeficientes culturais basal ( $K_{cb}$ ), a fração de água do solo que pode ser extraída sem afetar a produção ( $p$ ) e as profundidades radiculares. O modelo foi previamente testado para diversas culturas (Rosa *et al.*, 2010).

Os resultados do modelo são gráficos e numéricos. Estes últimos incluem os valores diários da evaporação do solo e da evapotranspiração da cultura, assim como os valores calculados para todos os coeficientes e parâmetros calculados. Todos os resultados podem ser exportados para um ficheiro Excel para posterior análise. Na presente versão do modelo, a determinação dos impactos do stress hídrico na produção é efetuada externamente utilizando a equação proposta por Stewart *et al.* (1977) e Doorenbos e Kassam (1979) que exprime uma relação linear entre a perda relativa de produção e o défice relativo de evapotranspiração:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{ET_m}\right) \quad (3.10)$$

onde  $ET_a$  e  $ET_m$  são respetivamente a evapotranspiração sazonal real e potencial (máxima) da cultura (mm), e  $Y_a$  e  $Y_m$  a produção ( $\text{kg ha}^{-1}$ ) real e potencial (máxima), i.e., quando  $ET_a = ET_m$ . Esta equação tem sido largamente utilizada, incluindo em estudos de produtividade da água (Igbadun *et al.*, 2006). Neste estudo, os valores  $K_y$  adotados são 1.25 para o milho e 1.05 para o trigo, segundo dados calibrados por Alves e Pereira (1998). A equação 10 foi testada para o modelo ISAREG (e.g. Teixeira *et al.*, 1995; Popova *et al.*, 2006; Popova e Pereira, 2008; Pereira *et al.*, 2009b). Em aplicações futuras do modelo, poderá ser aplicada uma função física água-produção já que os dados de saída permitem agrupar os dados de ET ou de transpiração por fases do ciclo vegetativo.

Existem outros métodos para determinar a produção máxima ou potencial, a maior parte usando equações paramétricas referentes às mesmas variáveis climáticas que o método AEZ, ou considerando a eficiência do uso da radiação (Price *et al.*, 2004). Porém, a metodologia proposta por Doorenbos e Kassam (1979) é ainda apropriada para avaliar as produções potenciais máximas com o objetivo de estimar a produtividade da água de culturas regadas

(Reynolds *et al.*, 2000). Alternativamente, as produções potenciais podem ser determinadas utilizando conhecimento local (Droogers e Kite, 1999), ou recorrendo a equações empíricas baseadas em observações locais (Sidiqqe *et al.*, 2001).

Como discutido por Steduto *et al.* (2007), o crescimento da cultura e a sua produção são afetados pela radiação total recebida durante o período de crescimento e pelo uso eficiente da radiação por essa cultura. Para uma dada radiação e temperatura, as culturas diferem quanto à eficiência para converter a radiação solar intercetada em biomassa. Isto significa que a fisiologia da cultura determina quanta biomassa é produzida por cada unidade de radiação solar intercetada. Estas diferenças entre culturas e variedades têm um efeito importante em como a água pode ser eficientemente utilizada para a produção. Contudo, é apenas possível considerar estas diferenças através da modelação da cultura, o que requer a calibração de um vasto número de parâmetros (e.g. Singh *et al.*, 2006; Vazifedoust *et al.*, 2008).

Neste estudo, os valores de  $Y_a$  foram obtidos por meio de questionário aos agricultores e posteriormente, para cada cenário, através da aplicação da equação 3.10, como referido por Allen *et al.* (1998). Para aplicar esta equação é necessário estimar de forma apropriada os valores de produção potencial  $Y_m$ . Como referido acima, estes dados foram obtidos utilizando o método AEZ (Doorenbos e Kassam, 1979) e validados recorrendo a dados observados. Este método assume que a produção máxima de uma cultura é o produto colhido de uma variedade altamente produtiva, bem adaptada ao clima, sob condições onde a água, os nutrientes e as doenças não são fatores limitantes da produção. As equações paramétricas do método AEZ referem-se aos principais fatores climáticos que determinam  $Y_m$ : temperatura, radiação e duração do ciclo vegetativo, bem como valores da temperatura e duração do dia necessários especificamente para calcular o desenvolvimento de dada cultura.

#### **3.2.4. Custo da água de rega**

Os cálculos da  $EWPR$  e  $EWPR_{I-Farm}$  necessitam que seja conhecido o custo de cada metro cúbico de água. Foram usados os dados recolhidos por Noéme *et al.* (2004) para estimar os custos de investimento, reportados a 2003; tendo em conta o tempo de vida esperado para diversos tipos de equipamento, determinaram-se os custos fixos. Foram também considerados os custos de operação, manutenção e gestão (OM&M) que constituem os custos variáveis (Tabela 3.3).

Assim, os custos fixos por unidade de água são dados por

$$\text{Custos fixos} = \frac{\text{Custos de investimento}}{\text{Uso total de água}} \quad (3.11)$$

e os custos variáveis são calculados por

$$\text{Custos variáveis} = \frac{\text{Custos de OM\&M}}{\text{Uso total de água}} \quad (3.12)$$

**Tabela 3.3.** Preços da água no regadio da Vigia (adaptado de Noéme, 2004)

Preços da água	Valor anual, € ano <sup>-1</sup>	Valor por unidade de superfície, € ha <sup>-1</sup>	Valor por unidade de água, € m <sup>-3</sup>
<b>Custos de investimento</b>	145469	96.66	0.0309
<b>Custos de OM&amp;M</b>	393799	261.66	0.0834
<b>Custo Total</b>	539268	358.32	0.1144

Os custos de OM&M contemplam os custos energéticos para a distribuição de água pressurizada às parcelas. Resultou que os custos fixos e variáveis são 0.0308 €/m<sup>3</sup> e 0.0834 €/m<sup>3</sup>, respetivamente. Baseados nestes valores, os cenários de custo de água a ser pago pelos agricultores são os seguintes:

- Custo atual, como praticado pela Associação de Beneficiários: 0.04 € m<sup>-3</sup>;
- Custos de OM&M, cobrindo a totalidade estas atividades: 0.0834 € m<sup>-3</sup>;
- Custo total, cobrindo a totalidade dos custos de OM&M e de investimento: 0.1144 € m<sup>-3</sup>.

### 3.2.5. Cenários de rega

Os cenários de rega simulados foram elaborados assumindo diversas restrições na água disponível para rega e diferentes frações de depleção de água no solo (*ASWD*). Estes são definidos por incrementos em percentagem da fração *p* de esgotamento da água solo em conforto hídrico (Tabela 3.4).

**Tabela 3.4.** Cenários de rega para as culturas de milho e trigo

Cenário	Limiares de rega deficitária	Restrições na disponibilidade de água
Milho		
R-0	$ASWD = p^*$	Sem restrição
R-1	$ASWD = 1.05 p$	420 mm
R-2	$ASWD = 1.10 p$	390 mm
R-3	$ASWD = 1.20 p$	360 mm
R-4	$ASWD = 1.30 p$	330 mm
R-5	$ASWD = 1.40 p$	300 mm
R-6	$ASWD = 1.50 p$	270 mm
Trigo		
R-0	$ASWD = p$	Sem restrição
R-1	$ASWD = 1.05 p$	165 mm
R-2	$ASWD = 1.05 p$	150 mm
R-3	$ASWD = 1.05 p$	120 mm
R-4	$ASWD = 1.05 p$	105 mm
R-5	$ASWD = 1.10 p$	90 mm
R-6	$ASWD = 1.10 p$	60 mm

\*-  $ASWD$  - frações de depleção de água no solo;  $p$  - fração de esgotamento da água solo em conforto hídrico

As necessidades líquidas de rega ( $NIR$ ) foram simuladas para uma situação sem restrições hídricas e  $ASWD = p$ . Foi assim criada, para cada cultura, uma série de valores de  $NIR$  cobrindo o mesmo período que a série de dados meteorológicos (1965-2009). Esta série dos  $NIR$  foi analisada considerando que à mesma se ajusta uma distribuição normal. Os anos em que os  $NIR$  não são excedidos com uma probabilidade de 50, 95 e 97 % foram identificados com representativos de uma procura climática média, muito alta e extrema, respetivamente (Tabela 3.5). Os últimos tipificam anos de seca. Todos os cenários de rega (Tabela 3.4) foram simulados para as condições climáticas correspondentes às observadas nos anos identificados na Tabela 3.4.

**Tabela 3.5.** Identificação dos anos representativos dos cenários de procura climática

<b>Procura climática</b>	<b>Milho</b>	<b>Trigo</b>
<b>Média (Av)</b>	1969	1985/1986
<b>Muito Alta (VH)</b>	1998	1998/1999
<b>Extrema (Ext)</b>	2004	1994/1995

As *NIR* sazonais para os anos identificados e todos os cenários descritos na Tabela 3.3 foram simulados adotando dotações de rega de 15 mm por evento. Foram posteriormente transformadas em necessidades brutas de rega (*GID*) considerando as eficiências potenciais observadas *PELQ* anteriormente ( $GID = NIR/PELQ$ ): 65.5 % para a parcela M. Igreja (rampa pivotante) e 61.5 % para a T-134 (aspersão fixa). Para considerar a melhoria dos sistemas de rega e uma melhor gestão que permita controlar a perdas por vento, assim como uma maior uniformidade de distribuição e calendários de rega apropriados, foram adotados dois cenários de desempenho melhorado, com *PELQ* de 70 e 85 %.

### 3.3. RESULTADOS

#### 3.3.1. Produtividade da água

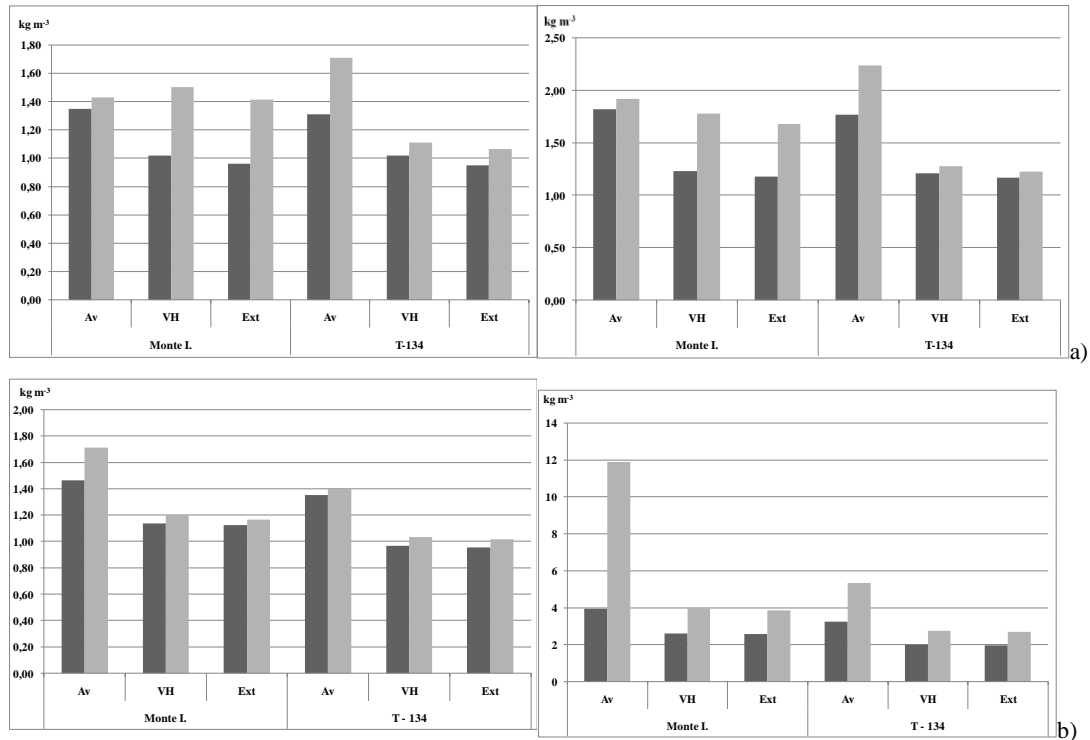
Os resultados para a produtividade da água (*WP* e  $WP_{I-Farm}$ ) na cultura do milho e para ambas as parcelas são apresentados na Tabela 3.6 considerando a aplicação de restrições nas disponibilidades de água. Os resultados, incluindo as *GID*, permitem avaliar a influência das condições climáticas e os impactos de diversos cenários de desempenho dos sistemas com recurso ao indicador *PELQ*. Para a *PELQ* atual, é apresentada na Figura 3.2 uma comparação entre a *WP* e  $WP_{I-Farm}$  obtidas para uma situação com e sem restrições hídricas.

**Tabela 3.6.** Indicadores de produtividade da água ( $WP$ ,  $WP_{I-Farm}$ ) para a cultura do milho sob rega deficitária relacionados com a procura climática e o desempenho dos sistemas (restrições R são definidas na Tabela 3.4)

Procura Climática $PELQ$ , %		M. Igreja			T-134				
		Restrição	$GID$ , mm	$WP$ , $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	Restrição	$GID$ , mm	$WP$ , $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$
Av	Presente		435	1.23	1.92		488	1.46	2.24
	70	R-6	407	1.31	2.05	R-5	428	1.66	2.55
	85		335	1.60	2.49		353	2.02	3.10
VH	Presente		550	1.32	1.78		658	0.97	1.28
	70	R-3	514	1.41	1.90	R-1	579	1.10	1.46
	85		424	1.71	2.31		476	1.34	1.77
Ext	Presente		550	1.25	1.68		658	0.93	1.23
	70	R-3	514	1.33	1.79	R-1	579	1.06	1.40
	85		424	1.62	2.18		476	1.29	1.70

Na Figura 3.2a estão presentes os resultados da  $WP$  e  $WP_{I-Farm}$  da cultura do milho para as duas parcelas e três procuras climáticas. Os resultados mostram que a adoção de um calendário de procura reduzida face à uma disponibilidade de água limitada leva a maiores  $WP$  e  $WP_{I-Farm}$ , principalmente este último pois depende apenas da água de rega. Quando não são aplicadas restrições,  $WP$  varia entre 0.96 e 1.35  $kg\ m^{-3}$ , enquanto que numa situação de rega deficitária  $WP$  varia entre 1.06 e 1.71  $kg\ m^{-3}$ . Em rega sem restrições,  $WP_{I-Farm}$  varia de 1.17 a 1.82  $kg\ m^{-3}$  e entre 1.23 e 2.24  $kg\ m^{-3}$  se se adotar rega com restrições. Os resultados mostram que as produtividades da água são inferiores sob uma procura climática extrema visto as necessidades hídricas da cultura serem maiores. Nestas condições, face ao facto da rega deficitária levar a quebras de produção superiores à diminuição da água de rega, resulta numa diminuição da produtividade da água.

Os resultados na Tabela 3.6 mostram que o desempenho dos sistemas influencia fortemente a produtividade da água. Quando a  $PELQ$  aumenta resulta num decréscimo do uso da água, levando a um aumento da produtividade da água. Este aumento é maior para uma procura climática média e menor para uma procura climática extrema pois os impactos da rega deficitária na produção são superiores. Contudo, o comportamento varia consoante a parcela.



**Figura 3.2.**  $WP$  (na esquerda) e  $WP_{I-Farm}$  (na direita) para uma procura climática média (Av), muito alta (VH) e extrema (Ext) com (■) e sem (□) restrições na disponibilidade de água para: a) milho e b) trigo.

A Figura 3.2b compara a  $WP$  e a  $WP_{I-Farm}$  para o trigo com e sem restrições de água. Contrariamente à cultura do milho, visto a rega ser um suplemento da precipitação, que constitui a fonte principal de água para o trigo de Inverno, os resultados para a  $WP$  mostram um aumento reduzido quando as restrições são consideradas. Pelo contrário, a  $WP_{I-Farm}$  aumenta largamente quando são aplicadas restrições à água de rega, passando de um intervalo de 1.98 - 4 kg m<sup>-3</sup> para 2.7 - 11.9 kg m<sup>-3</sup>. Os valores mais baixos correspondem ao caso da parcela T-134 e a uma procura climática extrema, quando as necessidades de rega são superiores.

Tal como no caso do milho, os resultados para o trigo apresentados na Tabela 3.7 demonstram a influência da  $PELQ$  na produtividade da água, com ambas as  $WP$  e  $WP_{I-Farm}$  a aumentar conjuntamente com o desempenho mas a diminuir com o aumento da procura climática. A  $WP_{I-Farm}$  é superior à  $WP$  pois a o uso de água na rega suplementar do trigo é menor do que o uso da água de chuva, contrariamente ao uso da água das culturas de Verão.

**Tabela 3.7.** Indicadores de produtividade da água ( $WP$ ,  $WP_{I-Farm}$ ) para a cultura do trigo sob rega deficitária relacionados com a procura climática e o desempenho dos sistemas (restrições  $R$  são definidas na Tabela 3.4)

Procura Climática	$PELQ$ , %	M. Igreja					T-134		
		Restrição	GID, mm	$WP$ , $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$	Restrição	GID, mm	$WP$ , $kg\ m^{-3}$	$WP_{I-Farm}$ , $kg\ m^{-3}$
Av	Atual		92	1.72	11.90		98	1.40	5.35
	70	R-6	86	1.83	12.72	R-6	86	1.59	6.09
	85		71	2.23	15.44		71	1.94	7.40
VH	Atual		137	1.21	3.99		195	1.04	2.72
	70	R-5	129	1.29	4.26	R-3	171	1.18	3.10
	85		106	1.56	5.17		141	1.43	3.76
Ext	Atual		137	1.17	3.86		195	1.02	2.71
	70	R-5	129	1.25	4.13	R-3	171	1.16	3.09
	85		106	1.52	5.02		141	1.41	3.75

### 3.3.2. Produtividade económica da água

Os resultados da  $EWP$  do milho quando adotada a rega deficitária (Tabela 3.8), calculados com o valor unitário do grão de milho de  $0.20\ €\ kg^{-1}$ , mostram valores relativamente baixos, variando de  $0.19$  a  $0.29\ €\ m^{-3}$  quando considerado o presente desempenho dos sistemas, e de  $0.27$  a  $0.40\ €\ m^{-3}$  para uma  $PELQ = 85\ %$ . Se for considerado o preço médio dos últimos 5 anos ( $0.16\ €\ kg^{-1}$ ), a  $EWP$  diminui para  $0.13$  a  $0.24\ €\ m^{-3}$  e  $0.22$  a  $0.32\ €\ m^{-3}$ , respetivamente. A variação da  $EWP$  demonstra que este indicador é bastante sensível ao desempenho dos sistemas de rega e à procura climática.

A Tabela 3.8 resume igualmente os resultados da  $EWP$  do trigo calculada com o valor unitário de  $0.17\ €\ kg^{-1}$ . A  $EWP$  do trigo mostra valores mais altos do que os do milho, variando de  $0.17$  a  $0.29\ €\ m^{-3}$  quando se considera o desempenho presente e de  $0.24$  a  $0.38\ €\ m^{-3}$  para  $PELQ = 85\ %$ . Se for considerado o preço médio dos últimos 5 anos,  $0.16\ €\ kg^{-1}$ , a  $EWP$  diminui para  $0.11$  a  $0.28\ €\ m^{-3}$  para a  $PELQ$  atual, e para  $0.17$  a  $0.35\ €\ m^{-3}$  quando a  $PELQ = 85\ %$ . A  $EWP$  da cultura do trigo mostra-se também altamente sensível à procura climática e ao desempenho dos sistemas de rega.

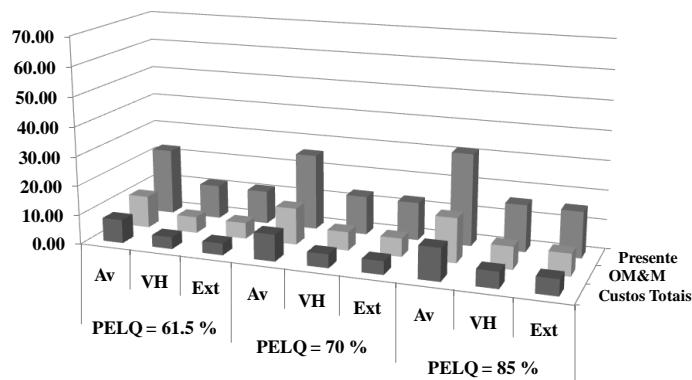
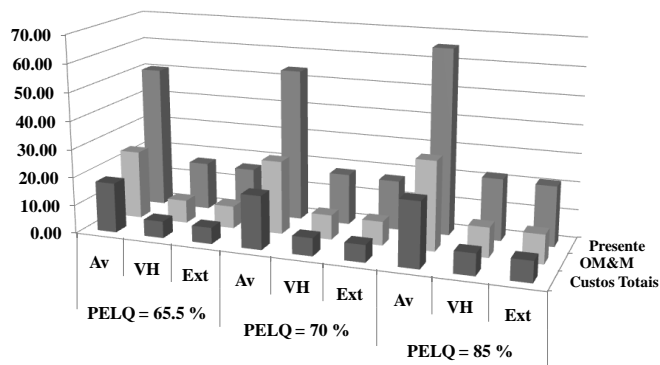
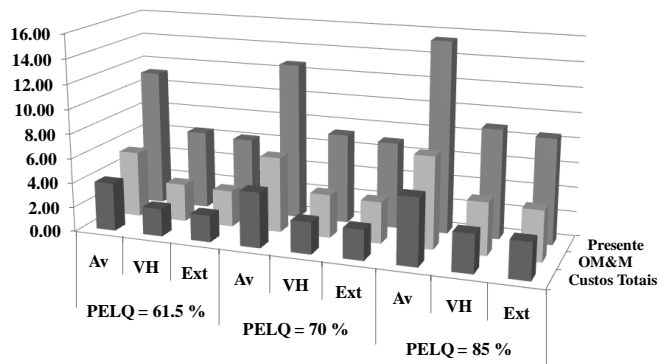
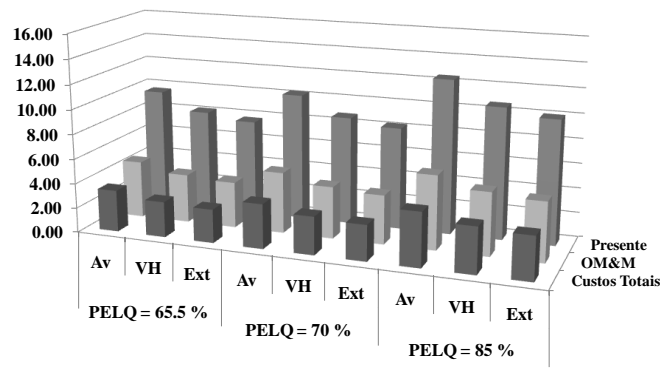
**Tabela 3.8.** Produtividade económica da água (EWP, € m<sup>-3</sup>) sob gestão da rega deficitária e respetivos cenários de restrição de água, relacionados com a cultura, procura climática e desempenho do sistema de rega

Procura climática	PELQ, %	Milho		Trigo	
		M. Igreja	T-134	M. Igreja	T-134
Av	Presente	0.25	0.29	0.29	0.24
	70	0.26	0.33	0.31	0.27
	85	0.32	0.40	0.38	0.33
VH	Presente	0.26	0.19	0.20	0.18
	70	0.28	0.22	0.22	0.20
	85	0.34	0.27	0.27	0.24
Ext	Presente	0.25	0.19	0.20	0.17
	70	0.27	0.21	0.21	0.20
	85	0.32	0.26	0.26	0.24

### 3.3.3. Avaliação dos impactos do preço da água

A razão da produtividade económica da água de rega ( $EWPR_{I-Farm}$ , Eq. 9) é utilizada para comparar os valores da produção por unidade de água, com o custo da água relativo a três cenários de preço de água. Analisando a  $EWPR_{I-Farm}$  do milho (Figura 3.3a), pode observar-se que as razões variam entre 6.1 e 11.2, para o preço de água atual (0.04 € m<sup>-3</sup>). Se este for mantido, a  $EWPR_{I-Farm}$  aumentaria para 8.5 a 15.5 se fosse alcançada uma PELQ de 85 %.

Se o preços da água cobrirem os custos de OM&M (0.0834 € m<sup>-3</sup>), a  $EWPR_{I-Farm}$  iria decrescer para 3.0 a 5.4. Porém, se o desempenho dos sistemas fosse melhorado, a  $EWPR_{I-Farm}$  variaria de 4.1 a 7.4. Se forem considerados os custos totais (0.1144 € m<sup>-3</sup>), a  $EWPR_{I-Farm}$  diminuiria para o intervalo 2.2 – 3.9 para a PELQ atual e para 3.0 a 5.4 para uma PELQ = 85 %. Contudo se o valor da produção baixasse para os valores anteriores estes indicadores baixariam também.



**Figura 3.3.** Razão da produtividade económica da água de rega das parcelas M. Igreja. (primeiro) e T-134 (segundo) sob rega deficitária para as culturas do a) milho e b) trigo, considerando três desempenhos do sistema de rega e três cenários do preço da água (presente, custos de OM&M e custos totais)

Os resultados para o caso da cultura do trigo (Figura 3.3b) mostram que para o preço corrente da água ( $0.04 \text{ € m}^3$ ) a  $EWPR_{I-Farm}$  varia de 11.4 a 50.6 com os desempenhos atuais dos sistemas de rega, e de 15.7 a 65.6 com um desempenho de sistema melhorado. Se o preço da água subir para  $0.0834 \text{ € m}^3$ , a  $EWPR_{I-Farm}$  diminuí para os intervalos 5.5 – 24.26 e 7.5 – 31.5, respetivamente para a  $PELQ$  atual e melhorada, enquanto que para um preço que cubra o total dos custos ( $0.1144 \text{ € m}^3$ ) a  $EWPR_{I-Farm}$  baixaria para 4.0 – 17.7 e 5.5 – 22.9 para os mesmos cenários de desempenho.

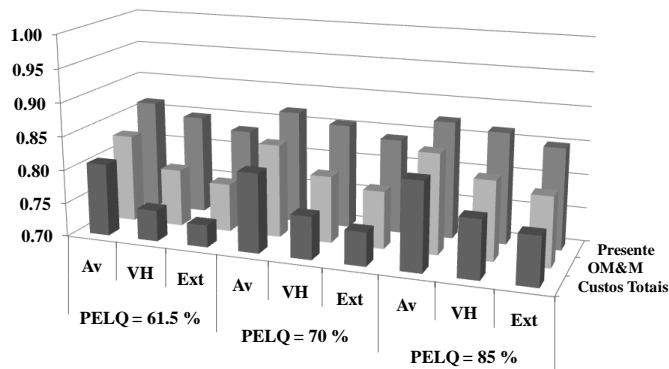
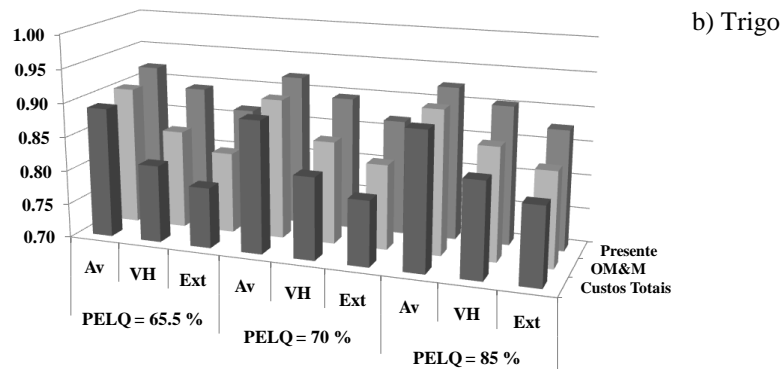
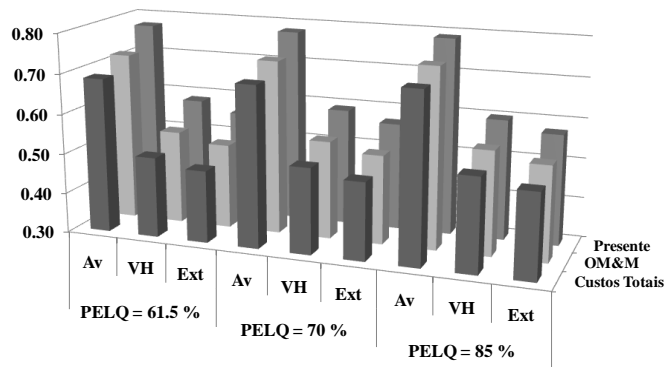
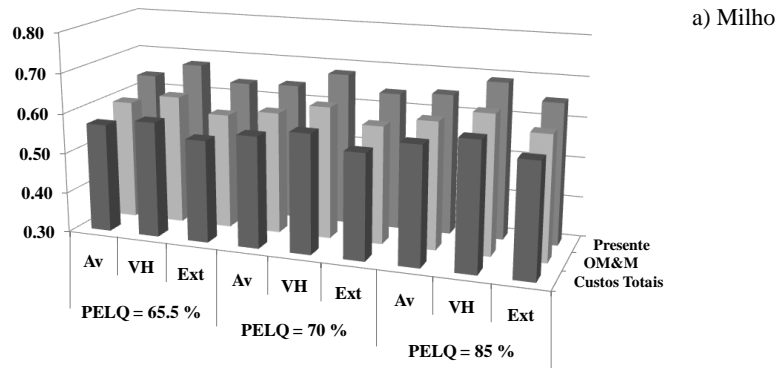
Os resultados mostram que cobrindo os custos de OM&M se produziriam resultados aceitáveis se fossem alcançados desempenhos mais elevados mas não é possível tirar conclusões recorrendo apenas ao indicador  $EWPR_{I-Farm}$  quanto a verificar se o retorno se mantém ou não positivo se os preços da água subirem de forma a cobrir todos os custos.

### 3.3.4. Avaliação dos impactos dos custos dos fatores de produção

A razão da produtividade de rega ( $EWPR$ , Eq. 3.8) introduz a possibilidade de avaliar se uma determinada gestão de uma cultura gera retornos positivos ( $\geq 1$ ) ou negativos ( $< 1$ ) pois compara o valor unitário da produção com os custos de produção. Tal como no caso da  $EWPR_{I-Farm}$ , a  $EWPR$  será analisada considerando três cenários de preço da água.

Analisando a  $EWPR$  para a cultura do milho em condições de rega deficitária (Figura 3.4a), pode ser observado que as razões se encontram no intervalo 0.56 a 0.77, para o preço atual da água de  $0.04 \text{ € m}^3$  (as razões mais baixas referem-se às condições de seca e as mais altas a procura climática média). Se o presente preço fosse mantido, a  $EWPR$  aumentaria para 0.58 - 0.79 se fosse alcançada uma  $PELQ = 85\%$ . Os resultados mostram que os agricultores terão um retorno negativo ao cultivar milho com o presente baixo desempenho dos sistemas e com os valores unitários da produção atualmente praticados.

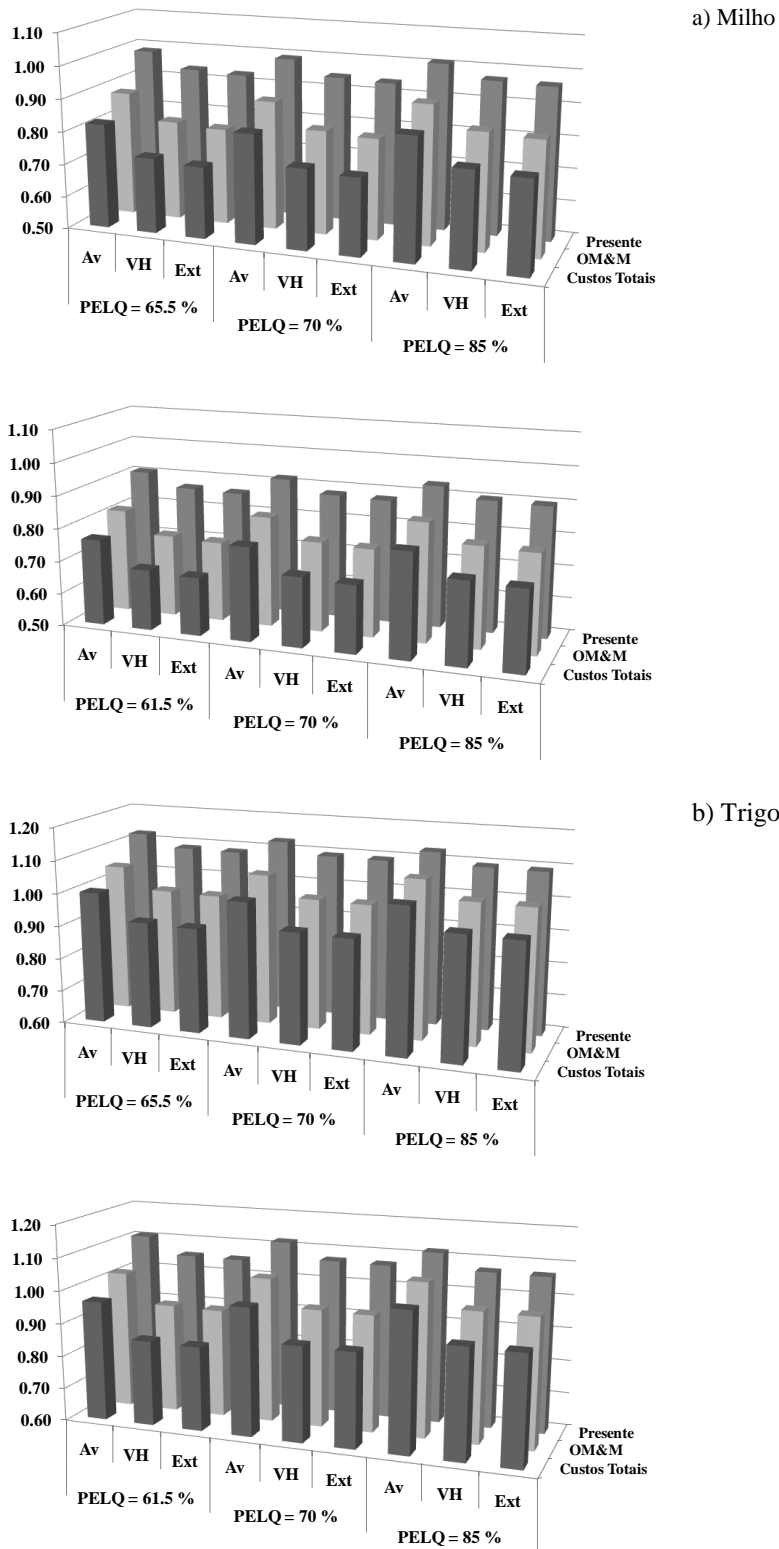
Com o aumento do preço da água para cobrir os custos de OM&M ( $0.0834 \text{ € m}^3$ ), a  $EWPR$  baixaria para o intervalo de 0.51 a 0.72 e a produção de milho com o presente baixo desempenho seria ainda menos rentável. Se o desempenho do sistema for melhorado, a  $EWPR$  aumentaria para 0.54 – 0.75; contudo o retorno manter-se-ia negativo para todas as procuras climáticas. Se forem considerados os custos totais ( $0.1144 \text{ € m}^3$ ), a  $EWPR$  diminuiria para 0.48 a 0.69 para a  $PELQ$  atual ou para 0.51 a 0.72 com uma  $PELQ = 85\%$ .



**Figura 3.4.** Razão da produtividade económica da água das parcelas M. Igreja. (primeiro) e T-134 (segundo) sob rega deficitária para as culturas do a) milho e b) trigo, considerando três desempenhos do sistema de rega e três cenários do preço da água (presente, custos de OM&M e custos totais)

Os resultados para o trigo em condições de restrição na disponibilidade de água (Figura 3.4b) mostram que, para o atual preço da água  $0.04 \text{ € m}^{-3}$ , a *EWPR* varia de 0.83 a 0.92 para a *PELQ* atual e passaria a 0.85 a 0.93 para um desempenho melhorado. Assim, os resultados mostram que com os preços correntes a rega de suplemento não é rentável. Se os preços da água aumentarem para  $0.0834 \text{ € m}^{-3}$  a *EWPR* varia de 0.77 a 0.90 e de 0.80 a 0.91 para a *PELQ* atual e melhorada, respetivamente; se o preço da água cobrisse os custos totais ( $0.1144 \text{ € m}^{-3}$ ) a *EWPR* diminuiria para 0.73 – 0.89 e 0.77 – 0.90 para os mesmos cenários de desempenho. Os resultados mostram que cobrir os custos de OM&M poderia levar a resultados quase positivos se fossem alcançados melhores desempenhos, mas tal não aconteceria se o preço da água aumentasse de forma a cobrir os custos totais face à variação recente do valor unitário da produção.

Face aos resultados alcançados ao adotar a rega deficitária, torna-se necessário analisar a *EWPR* em condições de rega completa, i.e., em condições sem restrições hídricas, como se apresenta na Figura 3.5. Para a cultura do milho (Figura 3.5a) pode ser observado que as *EWPR* se encontram no intervalo 0.86 a 0.98, para o preço da água de  $0.04 \text{ € m}^{-3}$ . A *EWPR* aumentaria para 0.90 – 1.01 se fosse alcançada uma *PELQ* = 85%, mantendo o presente preço da água. Os resultados mostram que os agricultores terão um retorno negativo com o presente desempenho, mas atingiriam valores positivos se melhorassem a eficiência dos sistemas e se o valor unitário da produção atingisse os valores de há poucos anos atrás, cerca de  $0.23 \text{ € kg}^{-1}$ . Se o preço da água cobrisse os custos de OM&M ( $0.0834 \text{ € m}^{-3}$ ), a *EWPR* baixaria para o intervalo de 0.74 a 0.88. Se o desempenho do sistema fosse melhorado, a *EWPR* aumentaria para 0.80 – 0.92; contudo, o retorno manter-se-ia negativo. Sendo considerados os custos totais ( $0.1144 \text{ € m}^{-3}$ ), a *EWPR* diminuiria para 0.68 a 0.82 para a *PELQ* atual ou para 0.75 a 0.87 com uma *PELQ* = 85%. Ambas as situações produziriam retornos positivos se o valor unitário da produção regressasse ao nível de cerca de  $0.23 \text{ € kg}^{-1}$ .



**Figura 3.5.** Razão da produtividade económica da água das parcelas M. Igreja. (primeiro) e T-134 (segundo) sob rega completa para as culturas do a) milho e b) trigo, considerando três desempenhos do sistema de rega e três cenários do preço da água (presente, custos de OM&M e custos totais)

Os resultados para o trigo sem restrição na disponibilidade de água (Figura 3.5b) mostram que para o atual preço da água a *EWPR* varia de 1.05 a 1.12 para a *PELQ* atual e passaria a 1.07 a 1.13 para um desempenho melhorado. Assim, os resultados mostram que com os preços correntes a rega de suplemento do trigo é rentável independentemente do desempenho dos sistemas ou da procura climática. Se os preços da água aumentassem para  $0.0834 \text{ € m}^{-3}$  a *EWPR* passaria respetivamente a 0.93 a 1.05 ou 1.02 a 1.08 para a *PELQ* atual ou melhorada. Se o preço da água cobrisse os custos totais ( $0.1144 \text{ € m}^{-3}$ ) a *EPWR* diminuiria para 0.86 – 1.00 ou 0.93 – 1.04 para os mesmos cenários de desempenho. Os resultados mostram que cobrir os custos de OM&M poderia levar a resultados positivos se fossem alcançados melhores desempenhos, mas tal não aconteceria se o preço da água aumentasse de forma a cobrir os custos.

Os resultados apresentados mostram que o preço da água afeta fortemente o rendimento da agricultura regada. A análise demonstra que a variabilidade da procura de água de rega face ao desempenho dos sistemas influencia a razão da produtividade económica da água de rega, i.e., os impactos do preço da água estão interligados com a *PELQ*.

Em suma, os resultados demonstram que a adoção de sistemas de rega com baixo desempenho não permite o uso da rega deficitária, principalmente se as políticas de preços impostas pela Diretiva Quadro da Água forem adotadas; seria necessária alguma flexibilidade na política de preços de forma a favorecer uma melhoria progressiva do desempenho dos sistemas de rega e a gestão de água.

### 3.4. CONCLUSÕES

O estudo mostra que os indicadores da produtividade económica da água podem ser uma ferramenta apropriada para avaliar os impactos da rega deficitária e do preço da água. Comparar as produtividades da água com e sem restrições de disponibilidade de água, i.e., com e sem stress hídrico, pode auxiliar na análise da viabilidade da rega deficitária; contudo, uma análise das produtividades económicas da água é muito mais útil. A análise das produtividades da água (*WP* e *WP<sub>I-Farm</sub>*) mostra que ambas dependem fortemente do desempenho dos sistemas de rega, aumentando com o acréscimo do desempenho. Os resultados mostram também que a *WP* e *WP<sub>I-Farm</sub>* diminuem quando a procura climática aumenta, como é o caso dos anos de seca.

A produtividade económica da água (*EWP*) varia de forma similar à da *WP*. Os resultados, porém, são diferentes para as duas culturas consideradas. Para o milho, a *EWP* indica que o valor da produção apenas cobriria os custos de produção se o valor unitário da produção fosse superior e se o preço da água se mantivesse ao nível presentemente praticado. Por seu lado, a rega suplementar do trigo apresenta-se como menos vulnerável.

A razão da produtividade económica da água, que relaciona o valor da produção com os custos de produção (incluindo o preço da água), revela-se adequada para avaliar a viabilidade da rega deficitária e os impactos do preço da água. No caso do milho, a análise mostra não existir viabilidade para a rega deficitária. O trigo em rega de complemento pode responder positivamente se o valor da produção for superior. Considerando a rega para conforto hídrico, i.e., sem restrições, verifica-se que a rega do milho só é viável para desempenhos melhorados relativamente aos atuais e para os preços da água atuais. Diferentemente, a rega de complemento do trigo mostra viabilidade.

Este estudo mostra que a análise da rega deficitária, e a definição consequente dos métodos para uma viabilidade apropriada, não requer apenas o conhecimento da resposta das culturas à água, nem o da estrutura dos custos de produção, mas antes deve incluir os impactos dos custos da rega e do desempenho dos sistemas de rega na rentabilidade das culturas.

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## **Capítulo 4**

# **Relating Energy Performance and Water Productivity of Sprinkler Irrigated Maize, Wheat and Sunflower Under Limited Water Availability**

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**Rodrigues, G.C., Carvalho, S., Paredes, P., Silva, F.G., Pereira, L.S., 2010. Relating energy performance and water productivity of sprinkler irrigated maize, wheat and sunflower under limited water availability. Biosystems Engineering, 106, 195–204.**

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## **4. RELATING ENERGY PERFORMANCE AND WATER PRODUCTIVITY OF SPRINKLER IRRIGATED MAIZE, WHEAT AND SUNFLOWER UNDER LIMITED WATER AVAILABILITY**

**Abstract:** The energy potential of a crop may be evaluated through life cycle assessment methodologies. These refer to the computation of the crop's energy balance and related indicators, such as the energy efficiency. This study concerns sprinkler irrigated sunflower, wheat and maize crops using data relative to the campaign of 2008. It is applied to selected farms in the Vigia Irrigation District, Alentejo, using pressurized water distribution systems. A model was developed and various scenarios were considered in order to assess the impacts on the crops' energy balance of (1) full and deficit irrigation, (2) climatic demand scenarios, and (3) upgrading irrigation systems performance. The model allows computing the energy efficiency and the energy balance of the three referred crops using centre-pivot and solid set sprinkler systems. The different irrigation scenarios and crop yield thresholds were defined in a previous study (Rodrigues and Pereira, 2009). The modelling results lead to the conclusion that the maize crop is the most efficient in producing energy and wheat is the least one for all the alternative scenarios considered. The results of full irrigation scenarios present higher energy performance than deficit irrigation because it highly depends on yields achieved. When relating energy efficiency and water productivity weak relations were found because while the first mainly depends upon yields, the second is highly influenced by water use. Results also show that improving irrigation systems performance has small impact on energy performance, which contrasts with water productivity.

**Keywords:** energy balance, bioenergy, sprinkler irrigation, irrigation performance, deficit irrigation, climatic demand scenarios.

### **4.1. INTRODUCTION**

The growing consumption of non-renewable energy and its inherent impacts on climate change led to policies favouring the use of renewable energy and to develop related biomass production and conversion (McKendry, 2002a, b; Venturi and Venturi, 2003). Among crops considered for biofuel production, maize and wheat are used to obtain bioethanol, and sunflower for biodiesel. However, few studies were developed worldwide relative to the

energy efficiency or the net energy gain of irrigated crops when cultivated as a source of renewable energy. Moreover, the use of those crops for energy production may be questionable. As analyzed by Pimentel (2003) and Pimentel and Patzek (2005), the energy balance of various crops, including maize and sunflower, as well as related economic and environmental impacts, is often negative. Differently, Venturi and Venturi (2003) show positive crop energy balances for a variety of crops in Europe, which present a wide range of energy outputs. This variation is observed among countries and within selected regions. These authors stress the fact that the main factor to be considered is crop yield potential.

The use of water to irrigate energy crops when this resource is becoming more and more scarce is also questionable. Analyzing this question, Berndes (2002) concludes that assessments of bioenergy potentials need to consider restrictions from competing demand for water resources.

To assess the energy value of a crop, the computation of the energy input-output balance is often achieved by performing a life cycle assessment study (e.g. Hülsbergen et al., 2001). Rathke et al. (2007), in a study relative to maize and soybean rotations and tillage methods in eastern Nebraska, demonstrated that energy gains were higher when input energy relative to tillage is lower, e.g. no-till vs. conventional tillage, and when crop rotations include legumes that minimize fertilizer inputs. A study by Bertocco et al. (2008), comparing various conservation tillage methods for maize, confirmed that the highest energy efficiency is obtainable when adopting the no-till method. When irrigation is considered, the share of tillage in the total energy consumption decreases due to the energy input of the irrigation water. An example for various surface irrigated field crops, including maize and wheat, is provided by Canakci et al. (2005), which shows that the highest energy requirements were for seedbed preparation and irrigation, the latter with shares ranging 26.3–40.4%; however, the ratio energy input-output was found positive but energy incorporated in equipment was not considered.

For crops requiring supplemental irrigation only, the share of energy relative to irrigation is small when surface irrigation is practiced. Akcaoz et al. (2009) nearly neglect the impacts of energy relative to surface irrigation of pomegranates, while Guzmán and Alonso (2008) found that energy consumption increased by 1.8 to 2.5 times when comparing dryland and irrigated olives. This increase in energy consumption relates to both the irrigation system and the higher use of production factors such as fertilizers and agro-chemicals that results from crop intensification when irrigation is adopted. When irrigation requirements are high, the share for

energy in irrigation water may be the largest, as shown in a case study for cotton in Australia (Chen and Baillie, 2009). In this study, it is evidenced that this share highly depends upon the irrigation method, water source (surface vs. deep well water) and irrigation management and performance.

Results in studies referred above are sometimes contradictory. While Pimentel (2003) definitely question the use of maize for bio-ethanol, other authors show positive energy gains for this crop including under irrigation (Canakci et al., 2005; Persson et al., 2009). Differences result from adopting different energy coefficients and assessment methodologies, mainly due to considering or not the indirect energy inputs relative to the energy incorporated in machinery and irrigation equipment. Examples of this approach are the studies by Pimentel (2003) and Guzmán and Alonso (2008). Relative to irrigation, and just to compare irrigation methods used for citrus and cotton, it is important to mention the life cycle assessment study by Stibbe (1986), who demonstrated the importance of considering not only the energy relative to water use but also that incorporated in the sprinkler and drip irrigation systems.

A study on assessing water productivities of maize, wheat and sunflower as depending from irrigation scheduling and irrigation systems performance has shown that raising water productivity implies the improvement of the performance of the irrigation systems and improved crop irrigation management, including for reduced irrigation demand (Rodrigues and Pereira, 2009). Thus, complementing this study, the present one aims at assessing the energy efficiency of maize, wheat and sunflower crops as influenced by the irrigation system performance and the availability of irrigation water under various climatic demand conditions. In addition, the energy efficiency is cross-checked with the physical and economic water productivity.

## **4.2. MATERIAL AND METHODS**

The study area is the Vigia Irrigation District, located in the municipalities of Évora and Redondo in southern Portugal. The area presently irrigated is 1505 ha. Pressurized irrigation water is supplied for sprinkler set systems and centre–pivot irrigation systems. A pumping station located near the dam at the upstream end of the pipe system pressurizes the irrigation water. The system operates on-demand. The main crops are cereal grains and industrial crops. The crops selected for this study are the winter wheat, maize and sunflower, the same as for the water productivity study (Rodrigues and Pereira, 2009). 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 and Keller (1978) and Keller and Bliesner (1990). Considering the willingness of the farmers to cooperate, two case studies relative to a centre-pivot and a set sprinkler irrigation system were selected for this analysis. They correspond to a large and a medium/small farm, identified as A and B, respectively. The working pressure of the irrigation systems were, respectively, 300 and 170 kPa for farm A and B. 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 assessing how currently poor performance impacts the economic results of deficit irrigation, and predicting how the economic water productivity could increase in case the systems would be upgraded. These results are reported by Rodrigues and Pereira (2009). The crop energy budget was performed for the same farms aiming at assessing how improved irrigation performance could also lead to increase the energy gains in relation to the amounts of water use.

Several indicators may be used to assess the energy budget of a crop (Pervanchon et al., 2002; Mani et al., 2007). The energy efficiency (EE) and the net energy gain or net energy value (NEV) are used in this study. EE is defined by the ratio between the energy output ( $E_o$ ) and the total energy input ( $E_i$ ), which indicates the amount of energy produced by the crop per unit of consumed energy (Hülsbergen et al., 2001). NEV is the difference between the energy produced by the crop ( $E_o$ ) and the total energy consumed during its production ( $E_i$ ).

The total energy input is the sum of all direct and indirect energy inputs ( $E_{id}$  and  $E_{ii}$ ):

$$E_i = E_{id} + E_{ii} \quad (4.1)$$

Direct inputs concern fuel and electricity used in farm operations and for pumping irrigation water:

$$E_{id} = \sum (E_{fuel}, E_{electricity}) \quad (4.2)$$

The indirect inputs concern the energy incorporated in all production factors and labour used, and in all equipment utilized, including the off-farm irrigation system, in relation to the respective life cycle.

$$E_{ii} = \sum (E_{seeds}, E_{fertilizars}, E_{pesticides}, E_{machines}, E_{irrigationsystems}, E_{labour}) \quad (4.3)$$

Direct energy inputs were estimated for each farm operation and  $E_{ii}$  were estimated for every applied production factor. Data relative to crop practices and used production factors were

obtained from the typology description available from the Ministry of Agriculture and through questionnaires to farmers. Indirect energy inputs and outputs are estimated adopting the following approach:

$$E_{i/o} = K_{en} Q_{factor/yield} \quad (4.4)$$

where  $E_{i/o}$  is the energy input or output,  $K_{en}$  is the energy coefficient, and  $Q_{factor/yield}$  is the quantity of a production factor used or the yield achieved.

The energy coefficients were selected from different authors, generally looking for the most updated information. Table 4.1 resume these different coefficients and presents their source.

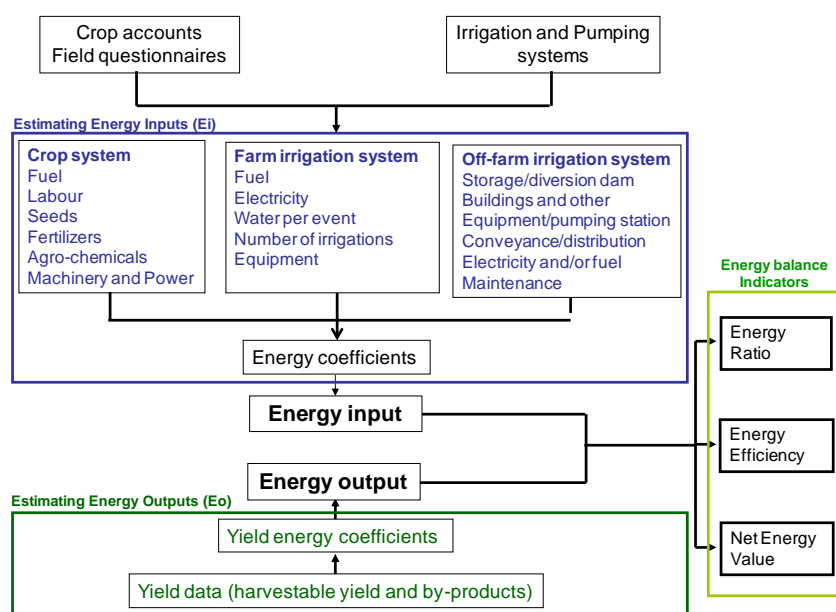
**Table 4.1.** Energy coefficients for the different system inputs and outputs.

System Input	Energy coefficient	Unit	Reference
<b>Seeds</b>			
Sunflower	52.6	MJ kg <sup>-1</sup>	Adapted from Kallivroussis <i>et al.</i> (2002)
Maize	29.4	MJ kg <sup>-1</sup>	Adapted from Mani <i>et al.</i> (2007)
Wheat	28.36	MJ kg <sup>-1</sup>	Adapted from Tabatabaefar <i>et al.</i> (2009)
<b>Fertilizers</b>			
Nitrogen	67	MJ kg <sup>-1</sup>	Pimentel e Patzek (2005)
P <sub>2</sub> O <sub>5</sub>	17.4	MJ kg <sup>-1</sup>	Pimentel e Patzek (2005)
K <sub>2</sub> O	13.6	MJ kg <sup>-1</sup>	Pimentel e Patzek (2005)
Fungicides	181.90	MJ kg <sup>-1</sup>	Tabatabaefar <i>et al.</i> (2009)
Herbicides	418.6	MJ kg <sup>-1</sup>	Pimentel e Patzek (2005)
Pesticides	418.6	MJ kg <sup>-1</sup>	Pimentel e Patzek (2005)
<b>Farm operations</b>			
Agricultural machinery	357.2	MJ h <sup>-1</sup>	Tabatabaefar <i>et al.</i> (2009)
Diesel	52.5	MJ l <sup>-1</sup>	Pimentel e Patzek (2005)
Labour	169.2	MJ h <sup>-1</sup>	Pimentel e Patzek (2005)
<b>Irrigation</b>			
Electricity	1.76	MJ m <sup>-3</sup>	Data from the Vigia Water Users Association
Water	0.84	MJ m <sup>-3</sup>	Adapted from Alcorn and Wood (1998)
Centre-pivot	4.87	MJ m <sup>-3</sup>	Adapted from Tardieu (1984)
Solid set sprinklers	4.97	MJ m <sup>-3</sup>	Adapted from Stibbe (1986)
<b>System Output</b>			
<b>Seeds</b>			
Sunflower	26.3	MJ kg <sup>-1</sup>	Kallivroussis <i>et al.</i> (2002)
Maize	14.7	MJ kg <sup>-1</sup>	Mani <i>et al.</i> (2007)
Wheat	14.48	MJ kg <sup>-1</sup>	Tabatabaefar <i>et al.</i> (2009)

Data relative to irrigation resulted from field observations and information made available by the Vigia Water Users Association. The approaches used by Pervanchon *et al.* (2002). Stibbe (1986) and Tardieu (1984) were applied to compute the direct and indirect energy inputs

relative to irrigation. The water energy coefficient was computed from various components relative to the storage dam and related constructions ( $K_{en} = 0.21 \text{ MJ m}^{-3}$ ), the pumping station and related equipment ( $K_{en} = 0.15 \text{ MJ m}^{-3}$ ), the off-farm irrigation network ( $K_{en} = 0.27 \text{ MJ m}^{-3}$ ), and system operation and maintenance ( $K_{en} = 0.21 \text{ MJ m}^{-3}$ ). These coefficients were computed according to Alcorn and Wood (1998). Computations based on design data assuming life cycles of 100, 50 and 25 years respectively for the dam and respective constructions, and the pumping station, and the irrigation network. Data relative to the annual expenditures for operation and management of the system, and the total annual water use were made available by the Vigia Water Users Association. Therefore it was possible to refer the indirect energy inputs to the unit of water used.

A computational model was developed to determine the energy balance per unit area cropped considering for each production factor and farm operation, including irrigation, the direct and indirect energy inputs, the latter in relation to the life cycle of every equipment (Figure 4.1). It allows estimating all the energy inputs and outputs under different irrigation and yield scenarios for the three crops and the farms taken as case study, and therefore to compute the respective EE and NEV.



**Figure 4.1.** Schematic representation of the computation model for the energy balance of irrigated crops.

To analyze the relationships between energy indicators and irrigation performance for the three crops, a few irrigation indicators used in the study relative to irrigation management applied to the same crops and farms (Rodrigues and Pereira, 2009) were adopted: (1) the

potential efficiency of the low quarter, PELQ (%), ratio between the average low quarter depth infiltrated when equal to the management allowed depletion (MAD) and the average of water applied when the soil water deficit equals MAD; (2) the water productivity, WP ( $\text{kg m}^{-3}$ ), defined as the ratio between the actual crop yield and the total water use; (3) the farm irrigation water productivity,  $\text{WP}_{\text{I-Farm}}$  ( $\text{kg m}^{-3}$ ), ratio between the actual crop yield and the irrigation water use at the farm; and (4) the economic water productivity, EWP ( $\text{€ m}^{-3}$ ), ratio between the monetary value of the actual yield and the total water use.

These irrigation indicators were calculated for various irrigation demand scenarios: average, high and very high demand, which correspond respectively to net irrigation requirements (NIR) that have the probabilities of 50, 80 and 95% for not being exceeded. In addition, various irrigation scheduling strategies were analysed including full irrigation and various levels of controlled deficit irrigation as defined in Table 4.2.

**Table 4.2.** Irrigation scenarios for maize, sunflower and wheat (Rodrigues and Pereira, 2009)

<b>Irrigation scenarios</b>	<b>Deficit irrigation thresholds</b>	<b>Restrictions on water availability</b>
<b>Maize</b>		
R-0	ASWD = p*	Not restricted
R-1	ASWD = 1.05 p	420 mm
R-2	ASWD = 1.10 p	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
<b>Sunflower</b>		
R-0	ASWD = p	Not restricted
R-1	ASWD = 1.05 p	300 mm
R-2	ASWD = 1.15 p	270 mm
R-3	ASWD = 1.15 p	240 mm
R-4	ASWD = 1.25 p	210 mm
R-5	ASWD = 1.25 p	180 mm
R-6	ASWD = 1.40 p	120 mm
<b>Wheat</b>		
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

\*- ASWD - allowed soil water depletion fraction; p - soil water depletion fraction for no-stress

The scenarios are those defined by Rodrigues and Pereira (2009), assuming various degrees of restrictions on seasonal water availability and limited yield decrease due to the water deficits. Each scenario corresponds to assume an allowed soil water depletion fraction (ASWD) progressively larger than the soil water depletion fraction for no stress (p). The deficit

irrigation scenario selected to compare with full irrigation is the one that uses less water but does not produce a relative yield deficit larger than 25%. All scenarios were simulated for the observed PELQ and for an achievable PELQ = 85% corresponding to the upgrade of the irrigation system.

### 4.3. RESULTS AND DISCUSSION

#### 4.3.1. Energy budgets and indicators

The irrigation management currently adopted by farmers in Vigia Irrigation District as well as the respective performance are presently poor as analysed by Rodrigues and Pereira (2009). Table 4.3 presents the average results for the energy balance of sunflower, maize and wheat irrigated with centre-pivot and solid set systems under present irrigation management conditions. Data were obtained by questionnaires and crop accounts and refer to several farmers.  $E_{ii}$  (Eq. 4.3) components for each crop are presented in Table 4.3. Results show that all the crops have positive EE and NEV. However, sunflower and wheat show low energy performance, while maize presents much higher energy indicators. Results for sunflower are due to a management aiming at reduced water application as currently practiced. Differently, farmers use upgraded maize crop husbandry and irrigation is managed for higher yields.

**Table 4.3.** Energy budget for sprinkler irrigated crops at Vigia Irrigation District with present management

Crop	Sunflower		Maize		Wheat	
	Centre-pivot	Solid set system	Centre-pivot	Solid set system	Centre-pivot	Solid set system
<b><math>E_{id}</math> (GJ ha<sup>-1</sup>)</b>	21.4	22.0	30.2	30.8	21.8	22.3
$E_{seeds}$	0.5	0.5	0.7	0.7	5.9	5.9
$E_{fertilizers}$	9.7	9.7	21.9	21.9	12.9	12.9
$E_{pesticides}$	0.7	0.7	1.4	1.4	0.5	0.5
<b><math>E_{ii}</math> (GJ ha<sup>-1</sup>)</b>						
$E_{machines}$	1.1	1.1	1.6	1.6	1.3	1.3
$E_{irrigation\ systems}$	17.1	19.8	16.9	18.4	15.8	17.3
$E_{labor}$	2.6	2.6	10.4	10.4	3.1	3.1
<b><math>E_i</math> (GJ ha<sup>-1</sup>)</b>	53.1	56.4	83.1	85.2	61.3	63.3
<b><math>E_o</math> (GJ ha<sup>-1</sup>)</b>	65.8	65.8	176.4	176.4	72.4	72.4
<b>EE</b>	1.24	1.17	2.12	2.07	1.18	1.14
<b>NEV (GJ ha<sup>-1</sup>)</b>	12.7	9.4	93.3	91.2	11.1	9.1

In order to assess the potential energy budgets for the three crops, several scenario alternatives have been simulated for each crop (Tables 4.4 to 4.6). The  $E_{ii}$  values were computed using the same values for all the all production factors and labour presented in Table 4.3, except for the case of  $E_{irrigation\ systems}$ ; the values for this indicator may be obtained by  $E_{irrigation\ systems} = E_i - (E_{id} + E_{seeds} + E_{fertilizars} + E_{pesticides} + E_{machines} + E_{labour})$ . Results for the three crops and both selected fields, adopting respectively centre-pivot and solid set sprinkler systems, refer to the three climatic demand scenarios – average (Av), high (Hi) and very high (VH) - under full and deficit irrigation following the previous study on water productivity (Rodrigues and Pereira, 2009).

**Table 4.4.** Energy budgets for sunflower under full and deficit irrigation

<b>Field identification</b>	<b>A</b>			<b>B</b>		
<b>Irrigation system</b>	<b>Centre-pivot, PELQ = 65.5%</b>			<b>Solid set, PELQ = 61.5%</b>		
<b>Demand condition</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>
<b>Full irrigation</b>						
<b>NIR (mm)</b>	255	330	377	344	434	461
<b>GID (mm)</b>	390	506	575	560	705	750
<b>WP</b>	0.82	0.80	0.54	0.74	0.68	0.48
<b>WP<sub>L-Farm</sub> (kg m<sup>-3</sup>)</b>	1.21	0.98	0.8	0.95	0.82	0.65
<b>EWP (€ m<sup>-3</sup>)</b>	0.20	0.19	0.13	0.18	0.17	0.12
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	22.0	25.0	26.8	26.4	32.3	30.2
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	32.8	32.8	41.6	43.2	52.9	50.7
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	54.8	57.8	68.4	69.6	85.2	80.9
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	121.0	136.8	131.5	115.7	130.6	120.1
<b>EE</b>	2.21	2.37	1.92	1.66	1.53	1.48
<b>NEV (GJ ha<sup>-1</sup>)</b>	66.2	79.0	63.1	46.1	45.4	39.2
<b>Deficit irrigation</b>						
<b>NIR (mm)</b>	180	210	240	210	240	300
<b>GID (mm)</b>	275	321	366	341	390	488
<b>Deficit alternative</b>	R-5	R-4	R-3	R-4	R-3	R-1
<b>WP</b>	0.97	0.92	0.62	0.81	0.76	0.56
<b>WP<sub>L-Farm</sub> (kg m<sup>-3</sup>)</b>	1.90	1.43	1.19	1.70	1.13	0.88
<b>EWP (€ m<sup>-3</sup>)</b>	0.24	0.22	0.15	0.20	0.19	0.14
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	19.0	20.2	21.4	20.7	22.0	24.5
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	27.4	29.6	31.7	31.9	34.4	39.5
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	46.4	49.8	53.1	52.6	56.4	64.0
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	92.1	102.6	99.9	86.8	99.9	92.1
<b>EE</b>	1.98	2.06	1.88	1.65	1.77	1.44
<b>NEV (GJ ha<sup>-1</sup>)</b>	45.7	52.8	46.8	34.2	43.5	28.1

For the sunflower crop results show (Table 4.4) that, adopting appropriate crop management and an irrigation scheduling aiming at maximum yield, an EE ranging 1.48 – 2.37 can be achieved. The highest value corresponds to centre-pivot irrigation under average demand conditions. NEV ranges 63.1 to 79.0 GJ ha<sup>-1</sup> for centre-pivot and is smaller for solid set sprinkling, ranging 39.2 to 46.1 GJ ha<sup>-1</sup>. EE and NEV are smaller for the case of a solid set system because these systems demand more energy and there are differences in crop husbandry and soil quality that differentiate yields in both farms. EE and NEV are smaller under very high demand conditions because more irrigation and related energy are then required. When deficit irrigation management is adopted, EE and NEV become smaller than for full irrigation management (EE ranges 1.44 – 2.06 and NEV values range 28.1 and 52.8 GJ ha<sup>-1</sup>) because under these circumstances yields decrease due to a reduction of the total water amount applied, which leads to lower energy efficiency. The highest EE and NEV values correspond to centre-pivot systems as for full irrigation. The best results correspond now to high demand conditions because the deficit irrigation condition retained produces less impact on yields than that for the average demand.

Results for maize (Table 4.5) show that adopting a centre-pivot system and a full irrigation schedule, EE varies between 2.06 and 2.23, while for the solid set sprinkler system EE ranges 1.89 to 2.18. Differences between both systems are negligible for average and high demand conditions. Differently, because soil water retention conditions are less good for the farm having the solid set system, more irrigation is then required under very high demand, which also increases the energy demand. Results for NEV follow the same trend. When adopting deficit irrigation, EE decreases with the reductions in yields, ranging 1.59 – 1.85 for farm A (centre-pivot), and 1.53 to 1.84 for farm B. Differences between farms and irrigation systems are then not noticeable. The highest values for both farms correspond to the deficit irrigation alternative that less affects yields. NEV under full irrigation ranges 77.4 to 102.2 GJ ha<sup>-1</sup> with the highest values when the irrigation demand is lower. When adopting deficit irrigation NEV values decrease to 43.2 – 66.7, GJ ha<sup>-1</sup>.

Table 4.5. Energy budgets for maize under full and deficit irrigation

<b>Field identification</b>	<b>A</b>			<b>B</b>		
<b>Irrigation system</b>	<b>Centre-pivot, PELQ = 65.5%</b>			<b>Solid set, PELQ = 61.5%</b>		
<b>Demand condition</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>
<b>Full irrigation</b>						
<b>NIR (mm)</b>	552	606	674	572	677	738
<b>GID (mm)</b>	842	925	1029	930	1100	1200
<b>WP</b>	1.35	1.34	1.02	1.31	1.30	1.02
<b>WP<sub>I-Farm</sub> (kg m<sup>-3</sup>)</b>	1.82	1.60	1.23	1.77	1.55	1.21
<b>EWP (€ m<sup>-3</sup>)</b>	0.30	0.30	0.23	0.29	0.29	0.23
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	29.2	30.1	30.9	30.1	31.5	32.4
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	52.7	52.9	53.1	54.3	54.6	54.8
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	81.9	83.0	84.0	84.4	86.1	87.2
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	169.1	185.2	177.9	183.8	186.7	164.6
<b>EE</b>	2.06	2.23	2.12	2.18	2.17	1.89
<b>NEV (GJ ha<sup>-1</sup>)</b>	87.2	102.2	93.9	99.4	100.6	77.4
<b>Deficit irrigation</b>						
<b>Deficit alternative</b>	R-5	R-4	R-3	R-4	R-3	R-1
<b>NIR (mm)</b>	300	330	360	330	360	420
<b>GID (mm)</b>	458	504	550	537	585	683
<b>WP</b>	1.23	1.62	1.32	1.46	1.31	0.97
<b>WP<sub>I-Farm</sub> (kg m<sup>-3</sup>)</b>	1.92	2.12	1.78	2.24	1.69	1.28
<b>EWP (€ m<sup>-3</sup>)</b>	0.27	0.36	0.29	0.33	0.29	0.22
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	25.7	26.5	26.9	26.4	27.2	28.0
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	51.9	52.1	52.2	53.4	53.6	53.8
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	77.6	78.6	79.1	79.8	80.8	81.8
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	123.5	145.3	133.8	147.0	145.5	125.0
<b>EE</b>	1.59	1.85	1.69	1.84	1.80	1.53
<b>NEV (GJ ha<sup>-1</sup>)</b>	45.9	66.7	54.7	67.2	64.7	43.2

For wheat (Table 4.6), results show that EE is nearly constant for the three demand conditions because irrigation of wheat is supplemental, thus relatively small when compared to maize and sunflower (see Table 4.7). Under deficit irrigation, EE averages 1.32 for centre-pivot, and 1.23 for set systems. The difference between these systems is due to differences in soil water retention characteristics of both farms and less energy used by centre-pivot systems. Results for the net energy gain indicator NEV follow trends similar to EE. Differently from the other two crops, the best NEV values for wheat are relatively low, 43.5 and 19.4 GJ ha<sup>-1</sup>, respectively for full and deficit irrigation.

Results above indicate that sunflower and maize may achieve high energy performance when farmers adopt appropriate crop husbandry and irrigation management. The wheat crop, under the conditions of the present study, attains only a medium to low energy performance, i.e. wheat is not a prime alternative crop for biofuel production unless that crop husbandry practices, including the selection of varieties, will be highly improved.

**Table 4.6.** Energy budgets for wheat under full and deficit irrigation

<b>Field identification</b>	<b>A</b>			<b>B</b>		
<b>Irrigation system</b>	<b>Centre-pivot, PELQ = 65.5%</b>			<b>Solid set, PELQ = 61.5%</b>		
<b>Demand condition</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>	<b>Av</b>	<b>Hi</b>	<b>VH</b>
<b>Full irrigation</b>						
<b>NIR (mm)</b>	210	226	347	240	252	388
<b>GID (mm)</b>	320	345	530	390	410	631
<b>WP</b>	1.47	0.73	1.14	1.36	0.85	0.97
<b>WP<sub>I-Farm</sub> (kg m<sup>-3</sup>)</b>	3.96	2.20	2.63	3.25	2.07	2.00
<b>EWP (€ m<sup>-3</sup>)</b>	0.39	0.20	0.30	0.36	0.23	0.26
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	22.6	22.7	24.3	23.2	23.3	25.2
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	39.6	39.7	40.0	41.1	41.2	41.6
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	62.2	62.4	64.3	64.3	64.5	66.8
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	105.7	104.3	105.7	100.0	102.1	101.4
<b>EE</b>	1.70	1.67	1.64	1.56	1.58	1.52
<b>NEV (GJ ha<sup>-1</sup>)</b>	43.5	41.9	41.4	35.7	37.6	34.6
<b>Deficit irrigation</b>						
<b>Deficit alternative</b>	R-5	R-4	R-3	R-4	R-3	R-1
<b>NIR (mm)</b>	90	105	120	105	120	165
<b>GID (mm)</b>	137	160	183	171	195	268
<b>WP</b>	1.72	0.81	1.21	1.40	0.89	1.04
<b>WP<sub>I-Farm</sub> (kg m<sup>-3</sup>)</b>	11.9	5.8	3.99	5.35	2.76	2.72
<b>EWP (€ m<sup>-3</sup>)</b>	0.46	0.22	0.32	0.37	0.24	0.28
<b>E<sub>id</sub> (GJ ha<sup>-1</sup>)</b>	20.6	20.6	21.0	20.7	21.5	21.5
<b>E<sub>ii</sub> (GJ ha<sup>-1</sup>)</b>	39.2	39.2	39.3	40.6	40.8	40.8
<b>E<sub>i</sub> (GJ ha<sup>-1</sup>)</b>	59.8	59.8	60.3	61.3	62.3	62.3
<b>E<sub>o</sub> (GJ ha<sup>-1</sup>)</b>	79.2	78.2	79.6	75.3	76.7	75.3
<b>EE</b>	1.32	1.31	1.32	1.23	1.23	1.21
<b>NEV (GJ ha<sup>-1</sup>)</b>	19.4	18.4	19.3	14.0	14.4	13.0

EE and NEV results are generally better for centre-pivot irrigation. However, despite energy inputs for these systems are smaller than those for solid set systems, results do not clearly indicate their superiority. Several other factors have to be considered, such as those influencing irrigation management as discussed above.

Results for all three crops (Tables 4.4 to 4.6) indicate that full irrigation leads to higher EE and NEV than deficit irrigation. Results for deficit irrigation also show that EE and NEV highly depend upon the yields achieved, i.e., upon the level of water stress imposed. Thus, higher the water restrictions applied smaller are the energy performance indicators. Results confirm that crop energy performance highly depends on the achieved yields (Venturi and Venturi, 2003).

To better understand results in Tables 4.4 to 4.6, the share (%) of energy relative to irrigation in total energy input is shown in Table 4.7 comparing the present and foreseen irrigation performance. These results show that the share of irrigation in the total energy input is higher for sunflower and lower for wheat, with maize having a position close to sunflower. The highest share for sunflower results from a lower level of non-irrigation inputs comparatively to maize, which has the highest demand for water. Therefore, factors influencing irrigation management, such as soil water retention, have a larger impact on the energy performance as referred above for sunflower. The share of irrigation energy for every crop depends on the total amount of water applied to that crop. Thus, it is higher for the very high demand conditions and is smaller when deficit irrigation is applied.

The impacts of irrigation performance (PELQ) on the energy performance are relatively small. For the sunflower crop, when improving PELQ to 85%, the share of irrigation energy in the total energy input decreases 3.8 to 5.4%. For the maize crop, that share that share decreases 1.15% in average, while for wheat, because supplemental irrigation is used, a lower decrease is predicted. Differences between both irrigation systems are small.

Results comparing the three crops show that sunflower and maize may achieve a high energy performance while for wheat, in the present conditions of this study, achieve a medium energy performance, i.e. wheat is not the prime alternative crop for biofuel production unless that crop husbandry practices, including the selection of varieties, will be improved.

**Table 4.7.** Irrigation energy input as a percentage of the total energy input for sunflower, maize and wheat under present and foreseen irrigation performance for full and deficit irrigation under different climatic demand conditions

Irrigation scenarios		Full irrigation			Deficit irrigation		
		Av	Hi	VH	Av	Hi	VH
<b>Sunflower</b>							
<b>Field A, centre-pivot</b>	Present PELQ	44.7	48.9	50.9	38.6	41.5	43.6
	Improved PELQ	40.4	44.7	46.7	34.8	37.2	39.3
<b>Field B, solid set</b>	Present PELQ	52.1	56.5	55.6	44.0	46.2	49.9
	Improved PELQ	46.8	51.5	50.6	38.6	40.8	44.5
<b>Maize</b>							
<b>Field A, centre-pivot</b>	Present PELQ	42.0	42.7	43.4	38.8	39.5	39.9
	Improved PELQ	40.5	41.1	41.7	37.3	38.6	38.9
<b>Field B, solid set</b>	Present PELQ	43.7	44.8	45.5	40.4	41.2	41.9
	Improved PELQ	41.8	42.7	43.2	39.4	39.9	40.5
<b>Wheat</b>							
<b>Field A, centre-pivot</b>	Present PELQ	35.2	35.5	37.2	32.6	32.6	33.2
	Improved PELQ	30.2	34.6	36.1	32.4	32.4	32.8
<b>Field B, solid set</b>	Present PELQ	37.3	37.5	39.6	34.2	35.3	35.3
	Improved PELQ	36.2	36.3	38.0	33.9	34.7	34.7

#### 4.3.2. Relating energy efficiency and water productivity

Table 4.4 shows that, for sunflower, EE and  $WP_{I-Farm}$  behave similarly when both full or deficit irrigation schedules are adopted. However, while  $WP_{I-Farm}$  decreases when irrigation demand increases, the highest EE values do not have correspondence with the  $WP_{I-Farm}$  values because the later largely depend on the water use, while EE is mainly impacted by the achieved yield. The correlation between these two indicators using all data shows a quite low  $R^2 = 0.32$ , indicating a weak relationship between EE and  $WP_{I-Farm}$ . In fact, main factors influencing irrigation water productivity are different of those affecting the energy performance of sunflower.

The maize EE and  $WP_{I-Farm}$  (Table 4.5) show a similar behaviour of that analyzed for sunflower. In fact, as for sunflower, maize yields and respective energy output highly depend upon the irrigation water that is applied, but  $WP_{I-Farm}$  decreases when irrigation demand increases while the highest EE values correspond to highest yield values. Thus, there is not a

clear correspondence between EE and  $WP_{I-Farm}$  values because the later largely depend on the water use while EE is mainly impacted by the achieved yield,. The correlation between EE and  $WP_{I-Farm}$  has a small  $R^2 = 0.44$ , indicating that factors explaining their variability are largely different. For the studied cases, irrigated maize shows to be a good energy crop, leading also to a positive monetary incomes when systems performance is adequate (Rodrigues and Pereira, 2009).

Table 4.6 shows a different behaviour for wheat. Supplemental irrigation of wheat is an interesting alternative from the water productivity viewpoint – it varies from 2.00 to 3.96  $kg\ m^{-3}$ , for full irrigation, and 2.72 to 11.90  $kg\ m^{-3}$  under deficit irrigation -, but has low impact on energy production – with EE ranging 1.52 – 1.70 and 1.21 – 1.32, for full and deficit irrigation, respectively. The correlation between EE and  $WP_{I-Farm}$  shows to be weak ( $R^2 = 0.36$ ).

When analysing the results for the studied crops, it can be concluded that when increasing  $WP_{I-Farm}$  using deficit irrigation EE tends to decrease. This is explained because a high EE is achievable when yields increase despite these are achieved with higher energy input. In other words, the increase in irrigation energy input is much smaller than the increase in energy output due to irrigation.

### 4.3.3. Relating energy and irrigation performance

An acceptable energy income was obtained for almost all the cases when considering the actual irrigation performance PELQ. Since the assessment of water productivities for the same crops indicated the need to improve the irrigation system performance, it is analysed if improving this performance also impacts the energy performance. Therefore, considering a target  $PELQ = 85\%$ , it is summarized in Table 4.8 how EE and NEV would change for the scenarios previously considered.

Table 4.8 shows that improving the irrigation system performance leads to increase EE and NEV. The resulting increase is higher for sunflower because the share of irrigation energy input in the total energy input is the highest (Table 4.7), while that increase is much smaller for maize. When irrigating with a centre-pivot system, sunflower EE increases more than NEV (in percentage), with that increase of EE ranging from 5.5 to 16.9 %. However, when set sprinkler irrigation is used, EE increases less than NEV, with the latter increasing by 26.0 to 38.8 %. This fact relates to the fact that the irrigation energy input for solid set sprinkling is

higher than for centre-pivots. The changes are higher for the solid set sprinkling because its current performance is lower.

Improving the system performance when irrigating maize leads to an increase of EE, ranging 1.6 to 5.2 %, and of NEV 1.8 to 4.4 %. Those increases are smaller than for sunflower because water use and productivity change less for maize. These changes are also higher for the solid set system under full irrigation.

Results for wheat show that improving PELQ leads to a small increase of EE and NEV; except for the case of centre-pivot under full irrigation and average climatic demand conditions. The increase of NEV is higher than the one of EE, for all the cases. The relatively small increase in energy performance relates to the fact that supplemental irrigation is used for this crop, and that the energy performance of irrigated wheat is generally low.

**Table 4.8.** Changes (%) in EE and NEV of sunflower, maize and wheat crops when the irrigation systems performance (PELQ) is improved to 85%

Irrigation scenarios Demand condition	Full irrigation			Deficit irrigation		
	Av	Hi	VH	Av	Hi	VH
<b>Sunflower</b>						
Centre-pivot, EE increase (%)	13.7	5.5	16.9	11.5	12.2	13.2
Centre-pivot, NEV increase (%)	10.0	3.8	15.7	10.5	10.2	13.2
Solid set, EE increase (%)	20.8	25.3	23.1	16.1	17.5	19.6
Solid set, NEV increase (%)	26.0	37.9	38.8	21.3	19.3	37.4
<b>Maize</b>						
Centre-pivot, EE increase (%)	2.4	2.7	2.9	3.2	1.6	1.7
Centre-pivot, NEV increase (%)	2.2	2.2	2.6	5.2	1.8	2.4
Solid set, EE increase (%)	3.3	3.6	4.1	1.8	2.1	2.5
Solid set, NEV increase (%)	2.7	3.0	4.4	2.1	2.6	4.6
<b>Wheat</b>						
Centre-pivot, EE increase (%)	12.5	1.3	2.1	0.3	0.2	0.5
Centre-pivot, NEV increase (%)	15.9	1.9	3.1	1.0	0.5	1.6
Solid set, EE increase (%)	1.9	1.9	2.8	0.5	0.8	0.8
Solid set, NEV increase (%)	3.4	3.2	5.2	2.1	3.5	3.8

#### 4.4. CONCLUSIONS

The results for the Vigia Irrigation District conditions show that maize present a favourable energy performance, sunflower may also be viable for biofuel production, but wheat is not an

appropriate crop for bioenergy production. Moreover, results show that bioenergy production highly depends upon the irrigation scheduling strategies adopted, particularly those for deficit irrigation. The energy performance highly depends on yields and therefore the best results refer to full irrigation. However, results show that, to cope with water scarcity conditions, deficit irrigation is an appropriate management alternative leading to high water productivity and energy efficiency when yields are not heavily affected by the imposed water deficit.

A comparison between the energy efficiency and the irrigation water productivity shows that the relationships between those indicators are weak. This is explained by the fact that the main factors influencing those indicators are different. Results are influenced by the share of irrigation energy input in the total energy input. This share may be higher than 50% for sunflower, is close to 42% for maize, and smaller than 40% for wheat. The highest share corresponds to solid set systems when compared to centre-pivot systems. This fact makes that centre-pivot irrigation favour attaining higher net energy values.

Results also show that impacts of improving the irrigation system performance has less impact on energy performance than on water productivity. Impacts are higher for sunflower and smaller for maize and wheat. This fact relates to the relative importance of energy inputs relative to irrigation, which are higher for sunflower in conditions of the present assessment study. Further research is required to assess differences in crop energy performance due to alternative crop husbandry combined with irrigation management and related economic costs and benefits.

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## Capítulo 5

# **PROASPER, um Modelo de Apoio à Decisão para Projeto de Sistemas de Rega Por Aspersão**

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**Rodrigues, G.C., Sequeira, B., Paredes, P., Pereira, L.S., 2010. PROASPER, um SAD para projeto de sistemas de rega por aspersão. In: Pereira, L.S., Victória, F.R.B., Paredes, P., Garcia, M., Palácios, E., Torrecillas, A. (eds) Tecnologias para o Uso Sustentável da Água em Rega. Edições Colibri e CEER, pp. 15-19.**

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## 5. PROASPER, UM MODELO DE APOIO À DECISÃO PARA PROJETO DE SISTEMAS DE REGA POR ASPERSÃO

**Resumo:** Os sistemas de rega por aspersão têm vindo a substituir os sistemas de rega de superfície tradicionais. Contudo, devido aos modelos que apoiam as decisões de projeto serem escassos e o apoio técnico para o seu funcionamento e manutenção ser insuficiente, o desempenho dos sistemas de aspersão é muitas vezes inadequado. É, portanto, necessário avaliar o desempenho dos sistemas de aspersão em operação com o objetivo de melhorar a sua gestão, identificando a modernização adequada e medidas de reabilitação, bem como fornecer informações que apoio ao projeto. O modelo PROASPER foi desenvolvido com estes objetivos. Trata-se de uma ferramenta amigável do utilizador para suporte à decisão para a conceção de um novo sistema, sendo capaz de gerenciar dados de avaliações de campo e simular várias alternativas de design para sistemas de aspersão. O modelo suporta projetos na procura de soluções que satisfaçam os indicadores de desempenho selecionados, e permite ao utilizador analisar e selecionar as alternativas que melhor satisfaçam os seus objetivos. O modelo é aqui apresentado no que toca à sua base de dados, ao processo de cálculo de dimensionamento e à análise de desempenho. São apresentados resultados da aplicação do modelo a vários sistemas no Sul de Portugal, incluindo a procura de soluções alternativas de conceção para a sua melhoria. Os resultados mostram que o PROASPER é uma ferramenta de fácil operação e que apoia a tomada de decisões no projeto de sistemas de aspersão respeitando o desempenho previamente definido pelo utilizador. Outros desenvolvimentos serão introduzidos a fim de melhorar o suporte à decisão, integrando-o com um modelo de calendarização de rega e incorporando uma componente de análise económica, bem como um módulo de análise multicritério.

**Palavras-chave:** análise de desempenho, apoio à decisão, simulação de sistemas de rega por aspersão, uniformidade e eficiência.

### 5.1 INTRODUÇÃO

Os sistemas de rega por aspersão são bastante populares mas necessitam de uma adequada gestão da água e fertilizantes o que não é factível na prática quando os sistemas são mal concebidos ou o projeto não é realizado com cuidado. Resultam desempenhos bastante baixos, por vezes a um nível inaceitável, piores do que os obtidos nos sistemas de rega tradicional (Pitts *et al.*, 1996). Na rega por aspersão a uniformidade depende essencialmente

das variáveis de projeto, nomeadamente da pressão de funcionamento, variação de pressão dentro do sistema, espaçamento entre os aspersores, dimensão do bico, forma de distribuição da água pelo aspersor e velocidade e direção do vento (Pereira, 1999; Pereira e Trout, 1999; Pereira *et al.*, 2002). Em muitos casos a uniformidade de aplicação de água à parcela, medida por indicadores como o coeficiente de uniformidade e a uniformidade de distribuição, é inferior aos padrões considerados aceitáveis (Ortega *et al.*, 2002; Valín *et al.*, 2003).

Muitos autores têm estudado a problemática da inadequação do projeto, da gestão e manutenção destes sistemas (*e.g.* Dubalen *et al.*, 1993; Ortega *et al.*, 2002). Os fracos desempenhos dos sistemas levam a investimentos menos produtivos, baixos rendimentos dos agricultores, desperdício de água e a uma consequente gestão pobre dos recursos hídricos disponíveis, a perdas de fertilizantes, e a impactos ambientais negativos.

Têm sido desenvolvidos vários modelos para projeto de sistemas de rega por aspersão, muitos deles “amigos do utilizador” (*e.g.* Hernandez e Sanchez, 1998; Carrión *et al.*, 2001; Montero *et al.*, 2001; Camacho e Alabanda, 2002). Estes modelos têm frequentemente interfaces gráficas, dão particular atenção à distribuição da água pelos aspersores (Carrión *et al.*, 2001), ou dão particular atenção à rede de distribuição de água à parcela (Andrade e Allen, 1999), ou incluem ferramentas topográficas para representarem as parcelas em projeto (Abreu e Pereira, 2002). O modelo PROASPER, tendo ainda muitas limitações, consegue suprir algumas das de outros modelos, nomeadamente a simulação de curvas da carga piezométrica.

As avaliações de campo dos sistemas em operação produzem informações importantes que podem servir de base para o desenho/projeto de novos sistemas e melhoria dos desempenhos do projetos futuros. Estas avaliações são particularmente úteis para o apoio aos agricultores no sentido de permitir que estes possam melhorar a gestão e a manutenção dos sistemas de rega (Merriam e Keller, 1978; Pereira e Trout, 1999; Valin *et al.*, 2003). No entanto, estes sistemas de apoio aos agricultores são mais eficientes se os dados colhidos no campo puderem ser facilmente manipuláveis utilizando modelos que gerem novas soluções alternativas e que possam ser discutidas com os agricultores quase em tempo real.

O SAD PROASPER foi desenvolvido com o objetivo de auxiliar os agricultores, vendedores e técnicos extensionistas na tomada de decisão a nível de projeto (dimensionamento) de sistemas estacionários e para a avaliação de sistemas já instalados. Este SAD será aperfeiçoado para apoiar a implementação de serviços de aconselhamento aos regantes, tanto para fornecer informação quando as avaliações de campo são efetuadas como para funcionar à

distância através da WEB. Outra possível melhoria será a integração deste SAD com modelos de calendarização da rega e de análise económica.

Neste artigo apresentam-se as principais características do SAD PROASPER, assim como resultados da sua aplicação a sistemas avaliados e da geração de alternativas melhoradas para os mesmos sistemas.

## 5.2. O PROASPER

### 5.2.1. Características do modelo

O SAD PROASPER foi desenvolvido em linguagem Visual Basic 6.0 e inclui uma base de dados em Access 2003. O modelo possui uma interface “amiga” do utilizador, uma base de dados de aspersores, de condutas, de culturas, de solos e dos sectores regados em análise, bem como módulos de dimensionamento, de simulação e de análise do desempenho para aspersão fixa. Permite uma redução significativa do tempo de cálculo e tem a capacidade de apoiar no projeto mediante a aplicação de indicadores de desempenho.

A estrutura conceptual do modelo é apresentada na Figura 5.1 que mostra que o modelo é constituído por um módulo de projeto, onde se efetua o dimensionamento, outro de análise de desempenho dos sistemas em projeto, e outro de avaliação, que permite a análise de desempenho dos sistemas em operação no campo. No entanto, quando os sistemas em operação necessitem de ser melhorados podem ser considerados como sistema em projeto e deste modo o modelo permite simular opções alternativas otimizando o dimensionamento. Toda a informação é armazenada na base de dados para posterior utilização/consulta.

O modelo permite ao utilizador optar por um controlo indireto (simulação otimizada) ou direto dos cálculos (simulação com componentes selecionadas pelo utilizador). Quando o utilizador controla diretamente a simulação, são mostradas mensagens que indicam as condições de projeto que não estão a ser satisfeitas para que o utilizador procure a solução desejada por iterações. Optando pelo controlo indireto, a simulação é efetuada de modo a otimizar o dimensionamento, com pesquisa automática na base de dados das características das condutas que permitem respeitar as escolhas prévias do utilizador em termos de espaçamento, comprimento e características hidráulicas das condutas, das características do aspersor selecionado e atender aos critérios de desempenho selecionados.

Os critérios de projeto são previamente impostos pelo utilizador relativamente à variação de caudal e da pressão (expressas em % dos valores seleccionados para o caudal e pressão dos aspersores), velocidade de escoamento nos tubos, percentagem de área adequadamente regada e eficiência de projeto (Keller e Bliesner, 1990) de forma a que o sistema projetado atinja padrões de desempenho adequados. Nestas condições o modelo permite obter um conjunto de resultados relativos a: (a) dimensão das tubagens; (b) carga hidráulica ( $H_i$ ) de cada aspersor em cada rampa, com representação da variação da pressão nas rampas mais e menos favoráveis; (c) caudal  $Q_i$  de cada aspersor, (d) distribuição da água na quadrícula formada por 4 aspersores, e (e) indicadores de desempenho.

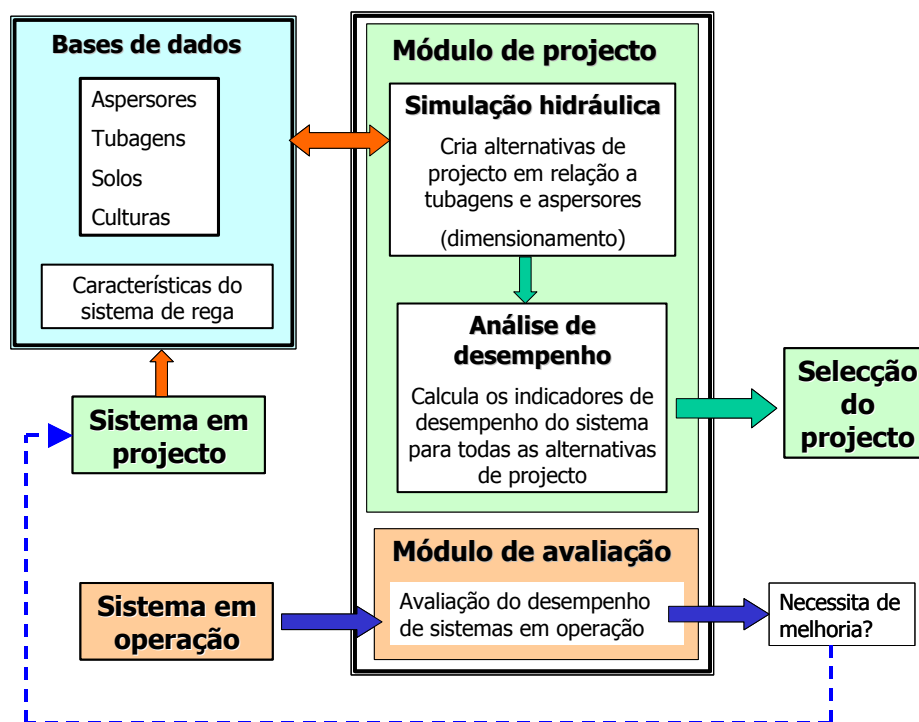


Figura 5.1. Estrutura conceptual do modelo PROASPER.

O módulo de dimensionamento da instalação inclui informação sobre o espaçamento entre rampas e aspersores, comprimento e características hidráulicas das tubagens e permite a escolha dos aspersores. A simulação do dimensionamento é efetuada com base em critérios de projeto previamente estabelecidos como referido acima. A dimensão ótima das tubagens é obtida por seleção do diâmetro mínimo que satisfaça os critérios impostos pelo utilizador tendo em conta o caudal e pressão admitidos.

O modelo apresenta uma interface “amiga” do utilizador (Figura 5.2) que permite aceder às bases de dados e aos comandos de cálculo (dimensionamento e avaliação).



**Figura 5.2.** Interface de acesso às bases de dados e de comando dos cálculos

### 5.2.2. Bases de dados

Os dados de entrada são inseridos pelo utilizador recorrendo à base de dados (Figura 5.3) e referem-se a:

- *Características dos aspersores* - denominação, diâmetro(s) do(s) bico(s) (mm), caudal ( $\text{m}^3 \text{h}^{-1}$ ), pressão (m) e alcance (m);
- *Características das tubagens* - referência, tipo de material, pressão nominal (kPa) e diâmetro interno (mm);
- *Dados dos solos* - textura, capacidade de campo e coeficiente de emurchecimento ( $\text{m}^3 \text{m}^{-3}$ ), taxa de infiltração ( $\text{mm h}^{-1}$ ) e água utilizável ( $\text{mm m}^{-1}$ ).

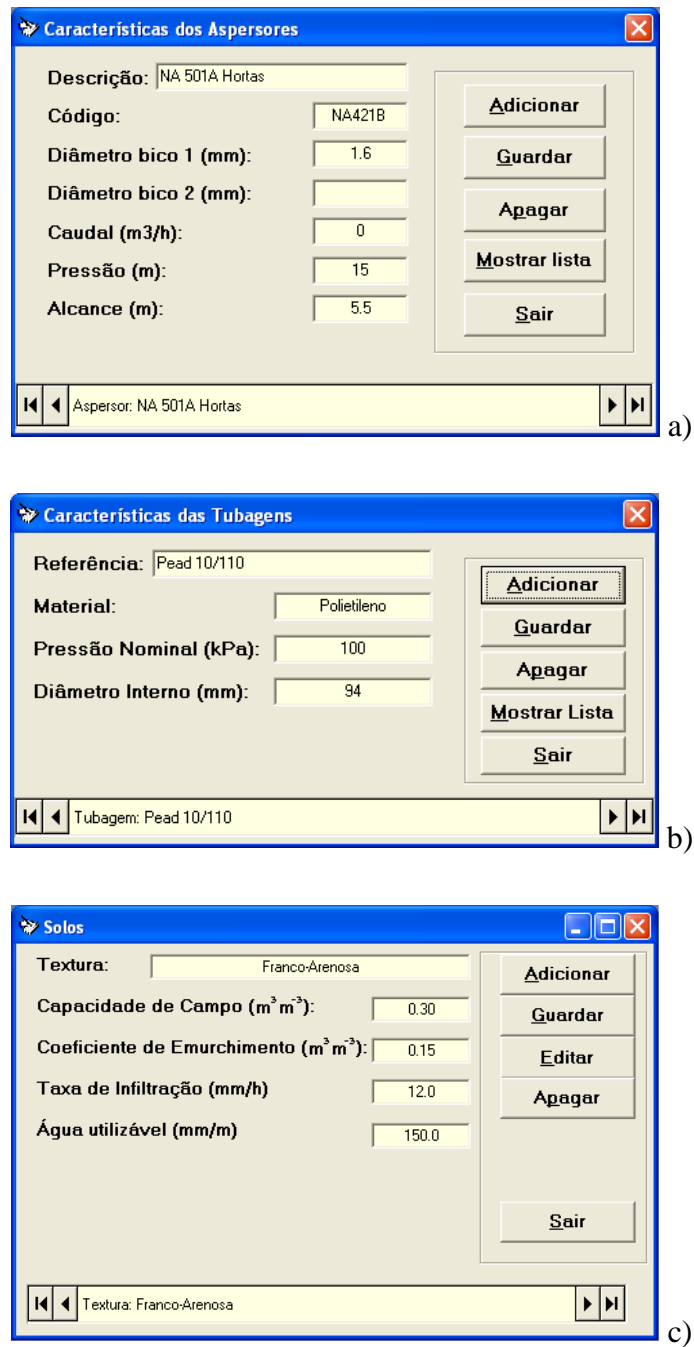


Figura 5.3. Janelas das bases de dados de: a) aspersores, b) tubos e c) solos

### 5.2.3. Módulo de dimensionamento

O módulo de simulação hidráulica requer uma variedade de dados de entrada (Fig. 5.4), tais como: comprimento, características hidráulicas das diversas condutas características dos aspersores e espaçamento a ser adotado.

**Cálculos de Concepção Preliminar**

**Sector**  
Nome: Sorgo

**Cultura**  
Cultura: Sorgo

Prof. radicular efectiva (m): 0.55  
MAD (%): 0.00  
Coef. Sensib. Hidrica: 0.90  
Cons. máx. diário água (mm):  
Cons. máx. sazonal água (mm):  
Produção/ha:  
Valor Unitário:

**Características do clima**  
Velocidade do vento (m/s): 2.00  
Evaporação potencial (mm/dia): 7.00  
Precipitação efectiva (mm):  
Água Armazenada (mm):

**Regas**  
Dotação útil (mm): 0.00  
Dotação líquida (mm): 55.00  
Eficiência de projecto (%): 85.00  
Dotação preliminar (mm): 64.71  
Intervalo máximo (d): 1  
Duração (h):  
Taxa de aplicação (mm/h): 7.50  
Área adequadamente regada (%): 70.00

**Necessidades de água**  
Dotação a aplicar por rega (mm): 55.00  
Dotação Total (mm): 64.71  
Nº de regas previstas: 1

**Características do solo**  
Textura: Franco Limosa

Capacidade de campo: 0.35  
Coef. emurchecimento: 0.17  
Densidade aparente: 1.59  
Declive (%): 9.30  
Profundidade média do solo (m): 1.00  
Água utilizavel (mm/m): 180.00  
Taxa infiltração (mm/h): 8.00

**Sistema**  
Guardar  
Sair

a)

---

**Características do Sistema**

**Sector a dimensionar**  
Sector: Sorgo

**Pressão e Caudal Impostos**  
 Carga (m): 30.00  
 Caudal (m3/h): 100.00

**Limites Impostos ao Sistema**  
Velocidade máxima admitida nas tubagens (m/s): 1.50  
Variação de carga admitida na conduta principal (%): 10.00  
Variação de carga admitida na conduta secundária (%): 5.00  
Variação de carga admitida no porta-rampas (%): 5.00  
Variação de carga admitida nas rampas (%): 10.00  
Perdas de água nas condutas (%): 1.00

Variação Pressão Sistema: 15

**Simulação**  
Simulação Optimizada  
Simulação Sistema  
Guardar  
Sair

**Esquema admitido** | **Conduta Principal** | **Conduta Secundária** | **Porta Rampas** | **Rampas** | **Aspersores**

Código do aspersor: Rain Bird 40B TNT 2 Bicos  
Altura da haste (m): 1.00  
Diâmetro do 1º bico (mm): 4.36  
Diâmetro do 2º bico (mm):  
Pressão de funcionamento (m): 20.00  
Caudal nominal (m3/h): 1.01  
Alcance (m): 13.80  
Perfil de distribuição: Elíptica  
Espaçamento entre aspersores (m): 15.00  
Tipo de espaçamento: Em Rectângulo

b)

Figura 5.4. Entrada de dados para o dimensionamento.

Os dados são armazenados na base de dados, podendo o utilizador, no caso de optar pelo controlo direto, substituir os diversos componentes até que seja encontrada a solução ótima. A variação da carga à cabeceira nas diferentes condutas é imposta assim como o caudal nas tubagens. A variação dos caudais nas rampas nunca deve ser superior a 10% e a variação da pressão nas rampas deve ser inferior a 20% (Merriam e Keller, 1978). O módulo de simulação hidráulica (Figura 5.5) segue as aproximações propostas por Heermann e Kohl (1980) e Keller e Bliesner (1990).

Dadas as limitações correntes no uso da equação de Darcy-Weisbach, como sugerido por Allen (1996) é utilizada a equação de Hazen-Williams:

$$J = \frac{h_f}{L/100} = K \left( \frac{Q}{C} \right)^{1.852} D^{-4.87} \quad (5.1)$$

onde,  $J$  é o gradiente de perda de carga (m/100 m),  $K$  é a constante de conversão,  $1.212 \times 10^{12}$ ,  $h_f$  é a perda de carga devido ao atrito da conduta (m),  $L$  é o comprimento da conduta (m),  $Q$  é o caudal na conduta ( $l \text{ s}^{-1}$ ),  $C$  é o coeficiente de atrito (Keller e Bliesner, 1990),  $D$  é o diâmetro interno da conduta (mm). Os cálculos são realizados de jusante para montante, iniciando-se no último aspersor da rampa localizada a jusante.

A Figura 5.5 resume os resultados da simulação hidráulica, apresentando: a) as tubagens selecionadas; b) a distribuição das cargas hidráulicas para todos os aspersores e rampas bem como o gráfico das distribuições das cargas nas rampas mais e menos favorecida; c) a distribuição dos caudais para todos os aspersores e rampas e a variação de caudal.

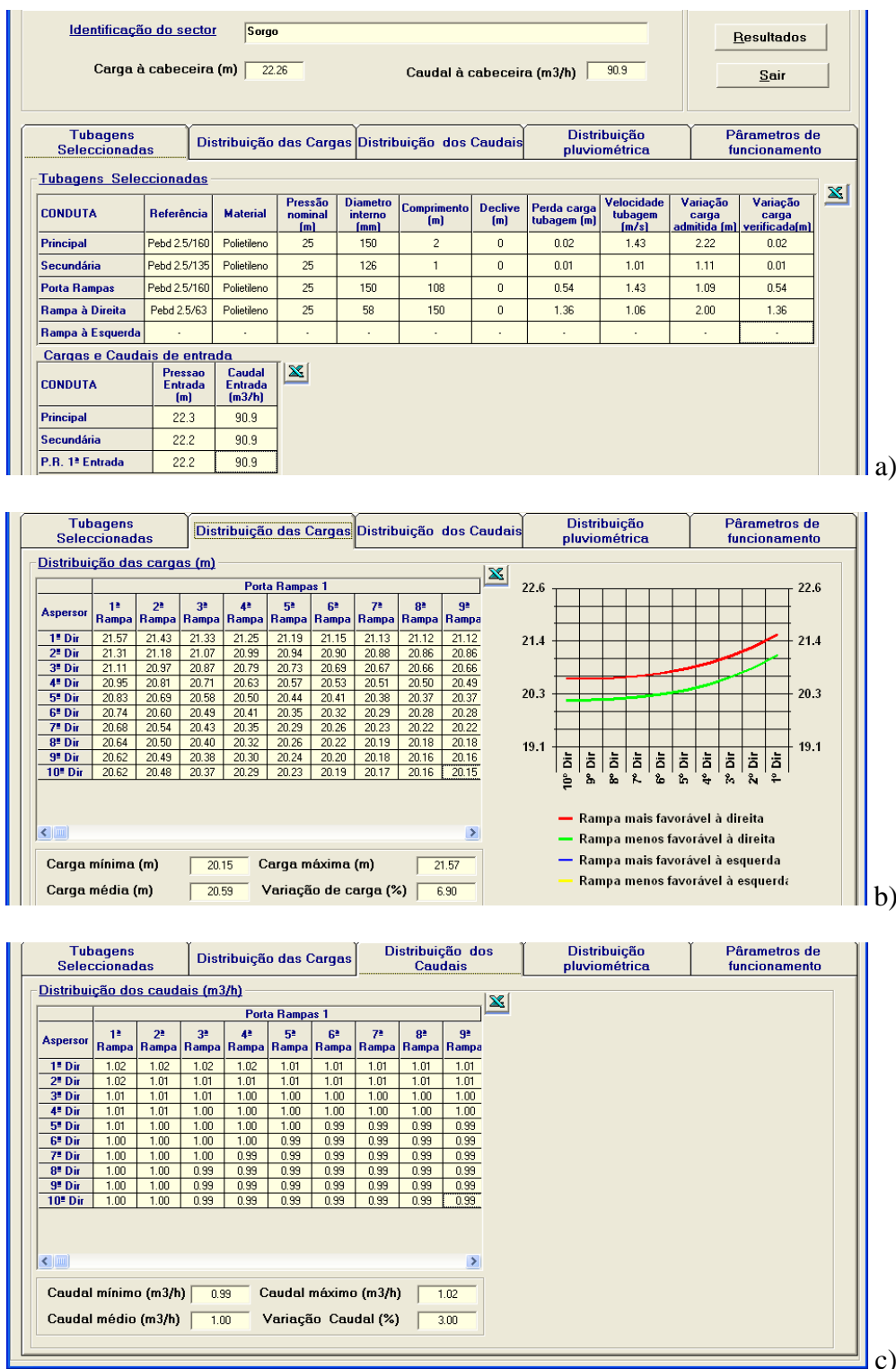


Figura 5.5. Resultados da simulação hidráulica: a) dimensões das tubagens, b) distribuição das cargas hidráulicas, c) distribuição dos caudais

### 5.2.4. Módulo de análise de desempenho

O módulo de análise de desempenho utiliza os dados obtidos no módulo de simulação hidráulica de forma a encontrar, através de um processo iterativo, as soluções desejadas (pressão e caudal apropriados) ou em alternativa utiliza os dados recolhidos nas avaliações de campo, calculando vários indicadores de desempenho. Quando se usam dados de campo, o modelo utiliza os indicadores propostos por Merriam e Keller (1978) e adotados por Pereira e Trout (1999) e Pereira (2004), nomeadamente:

1. *Uniformidade de distribuição, UD (%)*, definida como

$$UD = 100 \frac{AMQ_{min}}{AM} \quad (5.2)$$

onde  $AMQ_{min}$  é a altura média de água recolhida no quarto dos coletores, que receberam as menores alturas de água (mm) e  $AM$  é a altura média de água recolhida em todos os coletores (mm).

2. *Coefficiente de uniformidade de Christiansen, CU (%)*,

$$CU = 100 \left( 1 - \frac{\sum X}{n AM} \right) \quad (5.3)$$

onde  $X$  é o desvio absoluto das alturas de água recolhidas em relação a  $AM$  (mm) e  $n$  é o número de coletores utilizados no teste como se refere abaixo

3. *Uniformidade de distribuição do sistema, UDsist (%)*,

$$UDsist = UD \frac{1 + 3 \left( \frac{P_{min}}{P_{med}} \right)^{0.5}}{4} \quad (5.4)$$

4. *Coefficiente de uniformidade do sistema, CUsist (%)*,

$$CUsist = CU \frac{1 + \left( \frac{P_{min}}{P_{med}} \right)^{0.5}}{2} \quad (5.5)$$

onde  $UD$  e  $CU$  são definidos pelas Eq. 5.2 e 5.3,  $P_{min}$  é a menor pressão observada no sistema e  $P_{med}$  é a pressão média do sistema.

5. *Eficiência potencial do quartil mínimo, PELQ (%)*,

$$EPQ_{min} = 100 \frac{TMAQ_{min}}{I_a} \quad (5.6)$$

sendo  $TMAQ_{min}$  a taxa média de aplicação de água no quartil mínimo ( $\text{mm h}^{-1}$ ) e  $I_a$  é a taxa de aplicação ou pluviometria ( $\text{mm h}^{-1}$ ) dos aspersores.

Em projeto, o modelo utiliza os indicadores propostos por Keller e Bliesner (1990) e Pereira (2004):

1. *Eficiência de distribuição,  $DE_{pa}$  (%)*,

$$DE_{pa} = 100 + \left( 606 - 24.9 pa + 0.349 pa^2 - 0.00186 pa^3 \right) \left( 1 - \frac{CU}{100} \right) \quad (5.7)$$

onde:  $DE_{pa}$  é a eficiência de distribuição para uma percentagem  $pa$  de área adequadamente regada (%),  $CU$  é o coeficiente de uniformidade (Eq. 5.3) (%), e  $pa$  é a percentagem da área regada que recebe a dotação pretendida ou área adequadamente regada (%). De salientar que  $pa$  é definido pelo utilizador em função dos objetivos de uniformidade e eficiência pretendidos.

2. *Eficiência de projeto,  $E_{pa}$  (%)*, expressa como

$$E_{pa} = DE_{pa} R_e O_e \quad (5.8)$$

onde:  $E_{pa}$ , eficiência de projeto (%) relativa a uma percentagem  $pa$  de área adequadamente regada,  $R_e$ , fração efetivamente aplicada pelos aspersores, i.e., depois de descontadas as perdas por evaporação e arraste pelo vento, e  $O_e$ , fração efetivamente fornecida aos aspersores, i.e., depois de descontadas as perdas devidas a fugas nas condutas.

A fração de água efetivamente aplicada pelos aspersores,  $R_e$  (0.1 - 1.0) exprime em que medida a eficiência de aplicação é influenciada pelo vento e é estimada por

$$R_e = 0.976 + 0.005 ET_o - 0.00017 ET_o + 0.0012 WS - CI(0.00043 ET_o - 0.0018 WS + 0.000016 ET_o WS) \quad (5.9)$$

portanto em função do poder evaporante da atmosfera, representado pela evapotranspiração de referência  $ET_o$  ( $\text{mm d}^{-1}$ ) média durante o período de ponta a que se refere o dimensionamento, da velocidade do vento  $WS$  ( $\text{km h}^{-1}$ ) média para o mesmo período de ponta, e da dimensão das gotas, representada pelo índice da dimensão das gotas  $CI$ . Este índice pode ser estimado por

$$CI = K \frac{P^{1.3}}{B} \quad (5.10)$$

onde  $P$  é a pressão de funcionamento dos aspersores (kPa),  $B$  é o diâmetro do bocal do aspersor (mm) e  $K$  é a constante de conversão, 0.032 para as unidades adotadas.

3. *Perdas de produção devidas à não uniformidade do sistema* ( $\text{kg ha}^{-1}$ ) calculadas como

$$Y_a = Y_p \left( 1 - K_y + K_y \frac{D'_n + R_n}{D_n + R_n} \right) \quad (5.11)$$

onde,  $Y_a$  é a produção real da cultura ( $\text{kg ha}^{-1}$ ),  $Y_p$  é a produção potencial ( $\text{kg ha}^{-1}$ ),  $K_y$  é o fator de resposta da cultura à água (adimensional),  $D'_n$  é a dotação líquida média real para a totalidade da campanha de rega e que se encontra disponível para a cultura (mm),  $D_n$  é a dotação líquida média necessária na totalidade da campanha de rega (mm) e  $R_n$  é a precipitação efetiva (mm).

De salientar que existindo a seguinte relação entre a uniformidade da distribuição ( $UD$ ) e a eficiência de aplicação ( $e_a$ ):

$$e_a \leq UD \quad (5.12)$$

$UD$  é o valor limite que pode ser alcançado pela eficiência de aplicação se toda a água aplicada na parcela ficar disponível na zona radicular, ou seja, se não ocorrer percolação da água para camadas mais profundas do solo, evaporação ou escoamento superficial.

Um exemplo de saída de resultados de desempenho de um sistema projetado é apresentado na Figura 5.6.

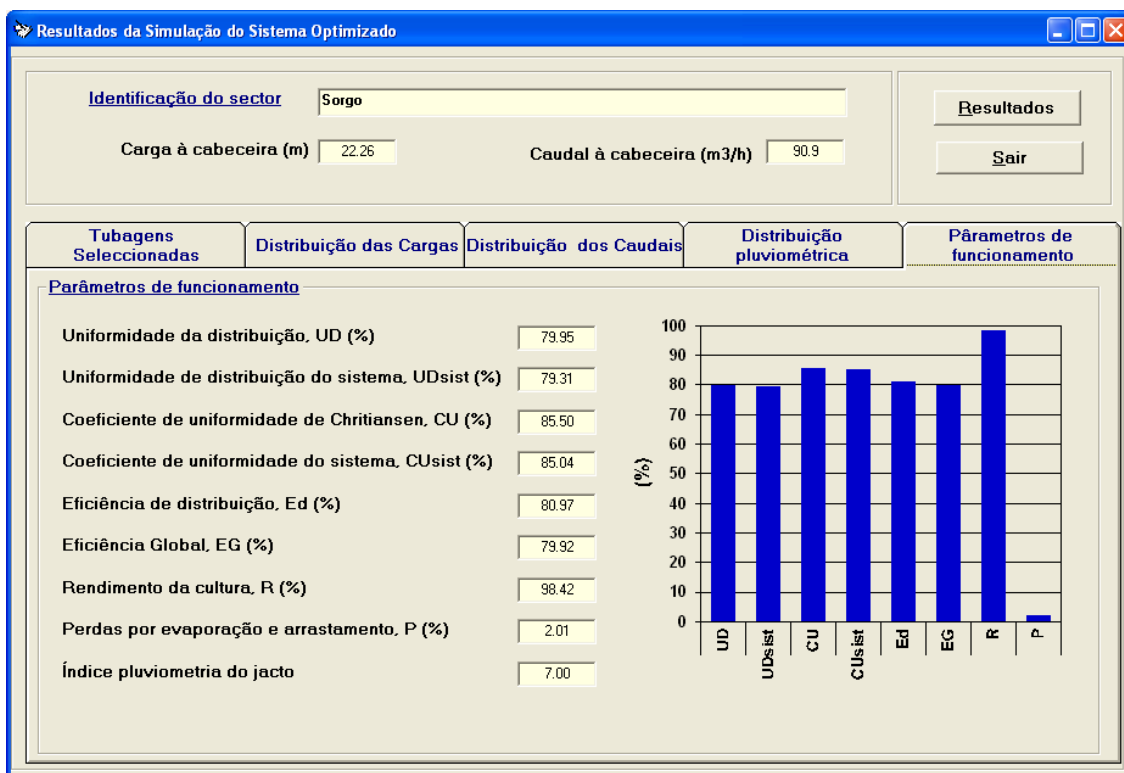


Figura 5.6. Janela de resultados da análise de desempenho

### 5.3. RESULTADOS E DISCUSSÃO

Nas primeiras simulações efetuadas foram utilizados os dados recolhidos nas avaliações de campo efetuadas nos aproveitamentos hidroagrícolas da Vigia e Lucefecit, Região do Alentejo, Sul de Portugal, durante as campanhas de rega de 2000 e 2001 (Pereira, 2002).

Nas avaliações de campo efetuadas verificou-se a ocorrência das seguintes situações: 1) espaçamento excessivo, inadequado para os diâmetros do bolbo molhado observados; 2) fraca manutenção, com bocais danificados em alguns casos; 3) para alguns sistemas, perdas de carga excessivas devido a reduzidos diâmetros das condutas; 4) em condições extremas, uma seleção deficiente do equipamento, com o uso de diferentes aspersores e diferente espaçamento na mesma parcela; 5) rega desprezando a velocidade e direção do vento; 6) fraco conhecimento dos agricultores acerca dos sistemas e da sua gestão.

A Tabela 5.1 resume os indicadores de desempenho relativos a 4 sistemas onde as avaliações foram repetidas 2 a 3 vezes. Analisando esta Tabela verifica-se que todos os sistemas apresentam baixos desempenhos, com *CU* geralmente abaixo dos 80% e *UD* abaixo dos 75%. *CU* e *UD* do sistema não são muito inferiores a estes valores. Estes resultados podem ser explicados pelas deficiências acima referidas.

**Tabela 5.1.** Indicadores de desempenho de sistemas em operação

Cultura	Sistemas						
	Vigia H-104		Lucefecit H-304			Vigia H-134	
	Milho		Sorgo			Milho	
Pressão média dos aspersores (kPa)	243	224	252	254	256	83	94
Caudal médio dos aspersores (m <sup>3</sup> h <sup>-1</sup> )	1.6	1.6	1.3	1.3	1.3	1.0	1.0
Carga piezométrica a montante (kPa)	325	318	390	390	380	162	177
Caudal a montante (m <sup>3</sup> h <sup>-1</sup> )	24.0	23.8	64.6	58.3	63.9	36.3	36.6
Velocidade do vento (m s <sup>-1</sup> )	2.4	1.9	1-3	1-3	1-3	<2.0	>2.0
Altura média de água recolhida (mm)	14.0	14.0	5.1	5.2	5.7	5.0	5.6
Taxa média de aplicação (mm h <sup>-1</sup> )	8.0	8.2	3.9	3.9	4.0	3.0	3.0
Uniformidade de distribuição, <i>UD</i> (%)	41.4	52.7	59.7	65.8	78.3	73.7	53.5
Coefficiente de uniformidade, <i>CU</i> (%)	68.6	66.4	75.5	78.9	85.3	77.4	70.1
<i>UD</i> do sistema (%)	40.5	50.5	57.7	63.5	76.5	60.0	43.5
<i>CU</i> do sistema (%)	67.6	64.5	73.8	77.0	83.9	67.9	61.4
Eficiência potencial, <i>PELQ</i> (%)	45.0		56.6			61.5	
Eficiência potencial do sistema (%)	43.8		55.2			53.1	

Nos sistemas da Vigia, a pressão média variou de avaliação para avaliação devido ao fraco desempenho do sistema de distribuição em pressão, o que produz variações na carga piezométrica a montante. As taxas de aplicação foram baixas e, para a maior parte dos casos, estão de acordo com as características hidráulicas do solo. Contudo, verificou-se que existia escoamento superficial em locais onde os terrenos possuem maior declive.

Como os regantes gerem os seus sistemas fixos de modo igual ao das rampas pivotantes, utilizam uma elevada frequência de rega e baixas dotações (5 a 14 mm). Verificou-se, que neste caso de estudo, os sistemas fixos são utilizados para regar os cantos não regados pelas rampas pivotantes. A *PELQ* é muito baixa devido à baixa *UD* e às perdas adicionais provocadas pelo vento e evaporação. A *PELQ* foi estimada a partir de uma quadrícula de coletores colocada entre 4 aspersores.

Os resultados apontam para um mau projeto visto que os sistemas foram adotados pelos regantes de acordo com o seu custo e não pela sua adequação técnica. Demonstrem, também, que os agricultores não têm qualquer serviço de apoio e que os vendedores possuem fraco conhecimento acerca do equipamento que representam.

Por forma a resolver os problemas identificados no decurso das avaliações de campo foram efetuadas simulações, modificando diversas características do sistema (Tabela 5.2) tais como

redução do espaçamento entre aspersores, limitação da variação de pressão ( $< 15\%$  para todas as condutas), redução da velocidade ( $< 1.5 \text{ m s}^{-1}$ ). A disposição dos sistemas não foi alterada. Nas simulações efetuadas dispuseram-se os aspersores em quadrícula em alternativa ao existente (em triângulo), diminuíram-se os espaçamentos entre aspersores (*e.g.*, no Lucefecit H-304 de 16 para 14 m) e aumentou-se o diâmetro interno das rampas e porta-rampas (*e.g.*, no Vigia H-104 de 70 para 80 mm). O número médio de iterações foi 8 no caso das parcelas do Lucefecit e de 11 para as da Vigia. Nas simulações, foram utilizados aspersores com as mesmas características dos avaliados, assumindo os mesmos caudal e pressão médios.

**Tabela 5.2.** Indicadores de desempenho obtidos por aplicação do PROASPER aos sistemas referidos na Tabela 5.1 melhorando os espaçamentos e as dimensões dos tubos

	Sistemas		
	Vigia H 104	Lucefecit H-304	Vigia H 134
Taxa média de aplicação ( $\text{mm h}^{-1}$ )	8.44	5.07	2.32
Uniformidade de distribuição, <i>UD</i> (%)	81.13	83.33	78.95
Coefficiente de uniformidade, <i>CU</i> (%)	85.90	87.06	88.76
<i>UD</i> do sistema (%)	80.32	82.01	77.72
<i>CU</i> do sistema (%)	85.32	86.14	87.84
Eficiência potencial, <i>PELQ</i> (%)	81.49	83.01	85.25
Eficiência potencial do sistema (%)	80.68	82.17	84.40
Variação máxima de caudal (%)	4.73	6.67	7.59
Variação máxima de pressão (%)	7.49	11.59	11.21

Os resultados demonstram que todos os sistemas teriam melhor desempenho se o projeto tivesse sido mais cuidado. Além disso, teriam sido obtidos melhores desempenhos se o limiar objetivo de *CU* fosse aumentado para 85 %. Porém, reduzindo o espaçamento resultaria um aumento da taxa de aplicação pelo que aumentando *CU* teria conduzido a menores espaçamentos que levariam a que a taxa de infiltração do solo fosse excedida.

## 5.4. CONCLUSÕES

Um sistema de rega bem projetado é condição necessária a um regadio rentável e “amigo” do ambiente. Um sistema mal projetado, ainda que bem gerido, acarreta perdas de produção e baixa produtividade da água. Para alcançar tal objetivo torna-se necessário produzir informação para agricultores e gestores que possa auxiliar na tomada de decisão no projeto

dos sistemas de rega. O modelo PROASPER responde a estes objetivos devido a sua fácil utilização e capacidade de suporte para avaliações de campo.

Os resultados de avaliações de campo efetuadas demonstram que os desempenhos dos sistemas em operação são baixos. A aplicação do modelo PROASPER a estes sistemas, com o objetivo de solucionar os problemas identificados durante as avaliações, produziu resultados claramente melhorados para os mesmos aspersores.

Conclui-se, assim, que se os gestores dos sistemas e os regantes dispuserem de ferramentas informáticas de projeto simples podem encontrar soluções que levam a melhores desempenhos. O modelo PROASPER pode ser aplicado com este objetivo quando integrado num sistema de informação para regantes, em conjunto com informação sobre a calendarização de rega. O modelo necessita de melhorias adicionais que estendam as suas capacidades, nomeadamente em termos de formulação de escolhas recorrendo à análise multicritério de forma a tomar em consideração conjuntamente critérios hidráulicos, económicos e ambientais.

### **Agradecimentos**

Estes estudos foram apoiados pelo Centro de Estudos de Engenharia Rural (POCTI-SFA-7-245) e pelo projeto “Gestão do risco em secas: Identificação, monitorização, caracterização, predição e mitigação” (PTDC/AGR-AAM/71649/2006).

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# **Capítulo 6**

## **Necessidades de Água e Produtividade Económica da Rega de Milho Em Condições de Escassez**

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**Rodrigues, G.C., Paredes, P., Rosa, RD, da Silva, F.G., Pereira, L.S., 2011.  
Necessidades de água e produtividade económica da rega de milho em condições  
de escassez. In: VI Congresso Ibérico de Agro-Engenharia, Évora, Portugal**

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## 6. NECESSIDADES DE ÁGUA E PRODUTIVIDADE ECONÓMICA DA REGA DE MILHO EM CONDIÇÕES DE ESCASSEZ

**Resumo:** A identificação das necessidades de rega do milho, uma das principais culturas regadas em Portugal Continental, constitui uma medida de preparação para enfrentar as secas e a escassez de água. Definiram-se várias estratégias de rega com o objetivo de redução da procura de água de rega com impactos aceitáveis na produção. O modelo de balanço hídrico e de simulação de calendários de rega SIMDualKc, anteriormente calibrado e validado para a cultura do milho em Portugal, foi utilizado para simular as necessidades de água para condições de seca severa e extrema. Este estudo foi realizado para milho regado por aspersão e aplicado a várias localidades: Vila Real, Bragança e Miranda do Douro no Norte, Coimbra e Viseu no Centro, e Beja, Évora e Elvas no Sul. As alternativas de rega foram avaliadas tendo em consideração a poupança de água de rega e o impacto nas produções; para inferir a viabilidade económica da rega deficitária foram determinados indicadores da produtividade física e económica da água recorrendo a dados sobre o valor da produção e desempenho de sistemas. Os resultados mostram que as estratégias de rega deficitárias poderão ser viáveis quando os défices hídricos forem muito baixos. Como alternativa poder-se-á optar pela satisfação das necessidades totais da cultura mas diminuindo a área cultivada.

**Abstract:** The water irrigation requirements identification of the maize, a main crop in Portugal is a strategy to cope with water scarcity and droughts. Several deficit irrigation strategies were design with the goal of reducing water demand with acceptable impacts on yields as part of the preparedness measures required to cope with drought and water scarcity. The water balance and irrigation scheduling simulation model SIMDualKc, which was previously calibrated and validated for the maize crop in Portugal, was used to simulate various irrigation schedules under severe and extreme drought conditions. Strategies include full irrigation and moderate and high deficit irrigation to cope with water scarcity conditions. This study applies to the maize crop under sprinkler irrigation in several regions of Portugal; Vila Real, Bragança and Miranda do Douro in North, Coimbra and Viseu in Center, and Beja, Évora and Elvas in South. The alternative irrigation schedules are assessed taking into consideration the reduction in demand for irrigation water (water savings), related impacts on yields and physical and economical water productivity. Results show that deficit irrigation

strategies for maize may be feasible only when the irrigation deficit is small. Otherwise, the best practice is to fully satisfy crop needs while reducing the cropped area.

**Palavras chave:** modelação, secas, rega deficitária, gestão da rega, análise económica, Portugal Continental

## 6.1. INTRODUÇÃO

Em situação de carência de água a gestão desta em agricultura desempenha um papel fundamental no restabelecimento do equilíbrio ambiental e na manutenção dos recursos hídricos (Pereira, 2004). A gestão de recursos em condições de seca centra-se na água e na prioridade para a eficiência de utilização desta, i.e., na produtividade da água. O desafio deste tipo de estratégias de gestão é produzir mais utilizando menor quantidade de água. No entanto, como analisado por Rodrigues *et al.* (2010), é muito importante aferir as relações económicas da produção.

A gestão da procura para combater a escassez de água, ao nível da exploração agrícola, engloba quer a adoção de práticas de rega apropriadas que conduzam a poupança de água, quer a determinação do calendário de rega otimizado para condições de aplicação de volumes de água limitados (Pereira *et al.*, 2009). Se o objetivo é, no entanto, a maximização dos benefícios da produção, a gestão da rega requer uma abordagem diferente. A maximização da produção implica que se efetue a rega necessária a suprir as necessidades totais de água das plantas; se o objetivo for, no entanto, maximizar os benefícios ou o lucro tal pode significar a adoção de rega deficitária controlada, ou seja, regar deliberadamente abaixo do nível de máxima produção que corresponda ao ótimo económico (Pereira, 2004; Pereira *et al.*, 2002).

O milho é uma cultura com elevada exigência de água, mas é também uma das mais eficientes na produção de matéria seca e no uso da água. Em condições ótimas, a produção de milho está estreitamente relacionada com a água disponível. No entanto, a sua qualidade e quantidade está dependente da ocorrência de stress nas fases críticas do seu desenvolvimento, i.e. na floração, frutificação e no enchimento do grão (Doorenbos e Kassam, 1979).

A programação e a condução da rega desempenham um papel importante na gestão da rega em condições de escassez de água, dado permitirem determinar quando e quanto regar de forma a maximizar o uso de água pelas culturas e a minimizar as perdas por excesso de aplicação. Existem vários modelos de simulação do balanço hídrico que constituem

ferramentas preciosas para a determinação das necessidades de rega e para a condução da rega. Neste estudo foi utilizado o modelo SIMDualKc (Rosa *et al.*, 2010).

A avaliação de calendários de rega alternativos em termos de poupança de água e produtividade física ( $WP$ ,  $\text{kg m}^{-3}$ ) e económica da água ( $EWP$ ,  $\text{€ m}^{-3}$ ) pode mostrar-se útil no apoio à decisão quer dos agricultores quer de gestores de projetos de rega. Assim, desenharam-se e avaliaram-se diferentes estratégias de rega em termos de poupanças de água e redução da produção e os seus impactos económicos ( $WP$  e  $EWP$ ). A aplicação foi efetuada em 8 localidades de Portugal Continental: Beja, Elvas e Évora no Sul, Coimbra e Viseu no Centro e Vila Real, Bragança e Miranda do Douro no Norte.

## 6.2. MATERIAIS E MÉTODOS

### 6.2.1. Modelação

A evapotranspiração cultural ( $ET_c$ ,  $\text{mm d}^{-1}$ ) em condições padrão é definida como a taxa de evapotranspiração de uma cultura que se desenvolve numa extensa área de solo, com um teor de humidade ótimo, sujeita a uma gestão excelente e com as condições ambientais mais adequadas de modo a que a sua produção potencial seja atingida (Allen *et al.*, 1998; Pereira, 2004). Os fatores que induzem um crescimento vegetativo deficiente, tais como a salinidade do solo, a baixa fertilidade do solo, a aplicação insuficiente de fertilizantes, a presença de camadas impermeáveis no perfil do solo, a insuficiência do controlo de pragas e doenças, a gestão inapropriada (mobilização) do solo e práticas agrícolas inadequadas, assim como rega que não satisfaça por completo as necessidades da planta, levam a uma diminuição da  $ET_c$  que passa a ser referida como evapotranspiração cultural real ou ajustada ( $ET_a$  ou  $ET_{c\text{adj}}$ ) (Allen *et al.*, 1998; Pereira, 2004).

O modelo SIMDualKc (Rosa *et al.*, 2010) utiliza a aproximação dual e a  $ET_c$  é calculada pelo produto entre a evapotranspiração de referência ( $ET_o$ ,  $\text{mm d}^{-1}$ ) e a soma dos coeficientes cultural basal ( $K_{cb}$ ) e de evaporação do solo ( $K_e$ ), sendo que o primeiro é ajustado pelo coeficiente de stress ou de défice de humidade do solo ( $K_s$ ) no caso de existir stress (Allen *et al.*, 1998; Pereira, 2004; Allen *et al.*, 2005, 2007).

$$ET_c = (K_s K_{cb} + K_e) ET_o \quad (6.1)$$

A  $ET_o$  define-se como a taxa de evapotranspiração de uma cultura de referência hipotética, a qual se assume ter uma altura de 12 cm, uma resistência de superfície constante ( $70 \text{ s m}^{-1}$ ) e um albedo também constante (0.23), semelhante à evapotranspiração de um coberto extenso

de relva verde de altura uniforme, em crescimento ativo, cobrindo totalmente o solo e bem abastecido de água; a  $ET_o$  foi assim calculada utilizando a equação de Penman-Monteith para períodos diários (Allen *et al.*, 1998; Pereira, 2004). Sempre que a velocidade do vento foi medida a uma altura superior a 2.0 m efetuou-se a respetiva correção.

As séries de dados de temperatura e precipitação foram primeiramente analisadas quanto à sua homogeneidade e os dados em falta foram preenchidos utilizando o método MOVE.4 (Maintenance Of Variance Extension) o qual recorre a técnicas de extensão de dados com preservação da variância. Nos casos em que não havia observação da humidade do ar, radiação solar ou velocidade do vento, recorreu-se aos processos de estimação propostos por Allen *et al.*, (1998), comprovados por Adaixo (1999) e Popova *et al.* (2006b).

### 6.2.2. Calendarização da rega

Os fatores que devem ser considerados quando se elabora um calendário de rega são: quantidade de água disponível, limitações nas disponibilidades de água, estado de desenvolvimento da cultura e rendimento potencial, precipitação e evapotranspiração, método de rega e limitações do sistema de rega, e conteúdo de água do solo (Pereira, 2004). Na condução da rega, e se esta se faz de forma a evitar que ocorra défice hídrico, a data limite para realizar a rega será quando o teor de água do solo ( $\theta_i$ ,  $m^3 m^{-3}$ ) atinja o limiar  $\theta_i = (1-p)(\theta_{FC} - \theta_{WP}) + \theta_{WP}$ , onde  $\theta_{FC}$  e  $\theta_{WP}$  são respetivamente o teor de água do solo à capacidade de campo e no coeficiente de emurchecimento e em que  $p$  é a fração da capacidade máxima de armazenamento ( $TAW$ , mm) que pode ser extraída sem produzir stress hídrico. Este procedimento, tomando como limiar a fração  $p$ , é assumido quando se pretende evitar stress hídrico e atingir a produção potencial. A quantidade de água facilmente disponível para as plantas ( $RAW$ , mm) é a fração descrita pelo produto  $p TAW$ .

A rega pode ser conduzida para um limiar diferente, o qual traduz a extração desejada em termos de gestão ( $MAD$ , "management allowed depletion"). Toma-se  $MAD < p$  quando se pretende diminuir o risco de ocorrência de stress ou as incertezas ligadas à gestão da rega. Ao contrário, toma-se  $MAD > p$  quando se assume intencionalmente a gestão da rega com stress em determinados períodos, ou quando os recursos hídricos disponíveis são insuficientes para que a rega se pratique em conforto hídrico. Em ambos os casos, a dotação ( $I$ , mm) a aplicar para restabelecer a água do solo à capacidade de campo é  $I_{ni} = 1000z_{ri}(\theta_{FC} - \theta_{WP})$ , correspondendo à maior quantidade a aplicar sem que ocorra percolação. Podem utilizar-se

dotações mais pequenas, seja definindo um valor máximo para  $\theta$  inferior à capacidade de campo, seja adotando uma dotação fixa conforme o método de rega utilizado. A dotação bruta a aplicar deverá ser  $G = I_{ni} / E_a$ , em que  $E_a$  é a eficiência de aplicação, podendo esta ser corrigida para casos de remoção de sais acumulados no perfil conforme Pereira (2004).

*Necessidades líquidas de rega (NIR)* – são calculadas mediante o balanço hídrico para todos os anos das séries meteorológicas disponíveis (precipitação e evapotranspiração de referência) determinando uma nova série referente às NIR e efetuando uma análise de frequência para esta série. A esta série é geralmente ajustável uma função de distribuição normal que permite estimar as necessidades de rega para o ano de seca severa (correspondente a uma probabilidade de não excedência de 80%) e para o ano de seca extrema (correspondente a uma probabilidade de não excedência de 95%). O balanço hídrico é depois simulado para as condições climáticas dos anos correspondentes a estes níveis de procura climática.

*Rega para maximização da produção* - a prática mais generalizada na agricultura de regadio, consistindo em maximizar o rendimento da cultura por unidade de terra aplicando a quantidade de água necessária a suprir as necessidades da cultura.

*Rega deficitária* - é uma estratégia de otimização na qual as culturas são deliberadamente sujeitas a um certo grau de défice de água e de redução de rendimento (English e Raja, 1996). A cada estratégia de rega deficitária corresponde uma evapotranspiração relativa  $ET_d/ET_c$  que induz uma diminuição do rendimento da cultura  $Q_y = (1 - Y_d/Y_c)$ , em que  $ET_c$  e  $ET_d$  são respetivamente a evapotranspiração potencial da cultura e a  $ET$  real deficitária, e  $Y_c$  e  $Y_d$  são respetivamente os rendimentos das culturas correspondentes a  $ET_c$  e  $ET_d$ . A adoção da rega deficitária implica a adoção de calendários apropriados construídos após validação dos modelos de simulação (e.g. Teixeira *et al.*, 1995; Popova *et al.*, 2006a; Rosa *et al.*, 2010).

Nas estratégias de rega definidas neste estudo optou-se por considerar uma dotação fixa  $I = 15$  mm e fixar os limiares  $\theta_{MAD}$  como segue: (a)  $MAD = p$ ; (b)  $MAD = 1.10 p$ ;  $1.20 p$ ,  $1.05 p$ ;  $1.20 p$ , respetivamente para as fases inicial, de desenvolvimento, média e final do ciclo cultural; e (c)  $MAD = 1.10 p$ ;  $1.30 p$ ,  $1.05 p$ ;  $1.30 p$  para as mesmas fases do ciclo.

De modo a determinar as quebras de produção decorrentes do stress hídrico utilizou-se o modelo água-produção descrito por Stewart *et al.* (1977), divulgado por Doorenbos e Kassam (1979). Baseia-se no conhecimento do facto de resposta da cultura à água ( $K_y$ ), que exprime a relação linear entre o défice relativo de evapotranspiração sazonal ( $1-ET_d/ET_c$ ) e as perdas

relativas de produção  $(1-Y_a/Y_m)$ , onde  $Y_a$  e  $Y_m$  representam a produção real e a potencial, respetivamente. No presente estudo utilizou-se  $K_y = 1.25$  (Alves e Pereira, 1998).

### 6.2.3. Produtividade física e económica da água

Não existe acordo no uso do termo produtividade da água,  $WP$ . Como analisado com referência a vários estudos,  $WP$  pode expressar quer uma razão física entre a produção e a água utilizada, quer uma razão económica entre o valor da produção e a água utilizada. Os conceitos podem ser aplicados a diferentes escalas, desde a parcela até à bacia. Seguindo a análise proposta por Pereira *et al.* (2009), definem-se apropriadamente os conceitos utilizados neste estudo.  $WP$  é definida como a razão entre a produção real da cultura e o total de água utilizado, expressa em  $\text{kg m}^{-3}$ :

$$WP = \frac{Y_a}{TWU} \quad (6.2)$$

onde  $Y_a$  é a produção real, em kg, e  $TWU$  é o total de água utilizado incluindo a precipitação, em  $\text{m}^3$ , para alcançar  $Y_a$ . Quando considerada a água utilizada ao nível da parcela ( $TWU_{Farm}$ ), incluindo a precipitação, armazenamento de água no solo, ascensão capilar e rega, a produtividade da água na parcela ( $WP_{Farm}$ ) é definida como:

$$WP_{Farm} = \frac{Y_a}{TWU_{Farm}} \quad (6.3)$$

É importante considerar as questões económicas relativas à produtividade da água já que o objetivo do agricultor é alcançar o melhor retorno possível. Substituindo o numerador das equações anteriores pelo valor monetário da produção obtida, a produtividade económica da água ( $EWP$ ) é expressa em  $\text{€ m}^{-3}$  e definida por:

$$EWP = \frac{\text{Valor}(Y_a)}{TWU_{Farm}} \quad (6.4)$$

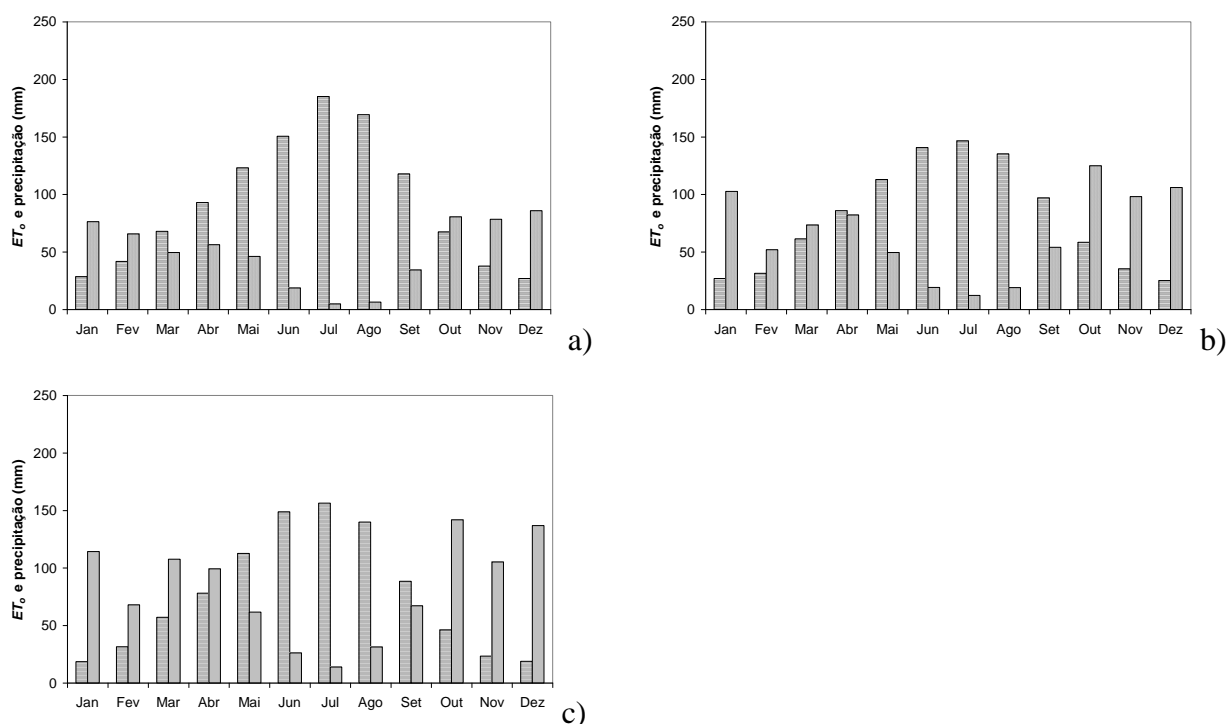
A economia da produção pode ser melhor compreendida quando o numerador é expresso em termos de margem bruta ou do retorno líquido relativo à cultura considerada (Rodrigues *et al.*, 2003), mas estas aproximações requerem uma informação económica muito exigente.

Para os diferentes calendários de rega deficitária, e recorrendo ao modelo Stewart, os valores de  $Y_a$  foram calculados para cada cenário. Os valores de NIR foram posteriormente convertidos em dotações brutas de rega (GID) utilizando uma eficiência potencial de aplicação média obtida através de avaliações de sistemas de rega em funcionamento. Assim,

os valores de  $WP$  e  $EWP$  foram determinados para a combinação produção – rega bruta sazonal. Rodrigues *et al.* (2010) avaliaram o efeito da variação do desempenho dos sistemas de rega sobre a  $WP$  e  $EWP$ .

#### 6.2.4. Características climáticas, da cultura e solo

A criação de calendários de rega foi aplicada às seguintes localidades do país: Beja, Elvas e Évora no Sul, Coimbra e Viseu no Centro e Vila Real, Bragança e Miranda do Douro no Norte (Paredes e Rodrigues, 2010). Na Fig. 6.1 apresentam-se as características climáticas médias ( $ET_o$  e precipitação) de cada local. A  $ET_o$  foi determinada pelo método FAO-PM referido atrás (Allen *et al.*, 1998). Analisando a Fig. 6.1 verifica-se que em todas as regiões estudadas, nos meses de Verão, a  $ET_o$  é muito superior à precipitação pelo que a rega é condicionante para que se atinjam as produções potenciais. Os parâmetros característicos da cultura constam da Tabela 6.1.



**Figura 6.1.**  $ET_o$  (□) e precipitação (▨) (mm) médias para as estações meteorológicas do Sul, Évora (a), do Centro, Coimbra (b), e do Norte Vila Real (c).

Para evitar que os resultados fossem afetados pela natureza do solo nos diversos locais, optou-se por realizar todas as simulações para um solo franco-limoso com uma capacidade de campo ( $\theta_{FC}$ ) de  $0.35 \text{ m}^3 \text{ m}^{-3}$  e um coeficiente de emurchecimento ( $\theta_{WP}$ ) de  $0.10 \text{ m}^3 \text{ m}^{-3}$ . Descrição detalhada é apresentada em Paredes e Rodrigues (2010). O solo apresenta uma

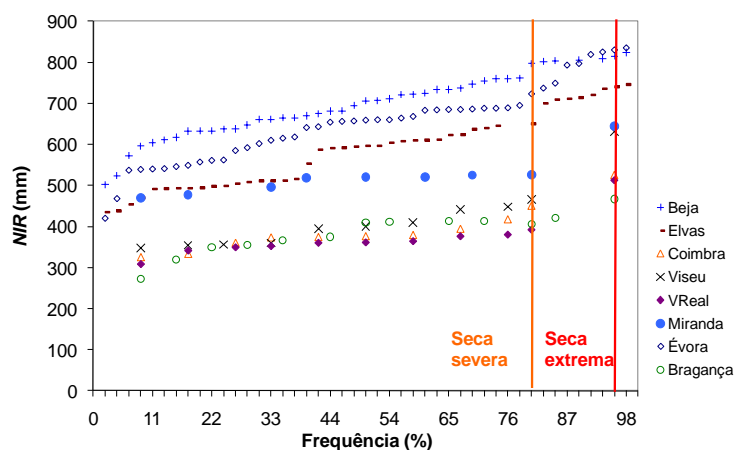
quantidade de água disponível total,  $TAW = 253$  mm, tendo-se considerado que a camada evaporativa tem 0.15 m, com um teor total de água evaporável  $TEW = 38$  mm e um teor de água facilmente evaporável  $REW = 12$  mm.

**Tabela 6.1.** Coeficiente cultural basal ( $K_{cb}$ ) e fração de água do solo esgotável sem causar stress hídrico ( $p$ ) e datas das fases de desenvolvimento da cultura do milho

Parâmetros culturais	Estágios de desenvolvimento da cultura			
	Período inicial	Período de .cresc rápido	Período intermédio	Período final
Coeficiente cultural basal, $K_{cb}$	0.40	0.40-1.15	1.15	1.15-0.35
Fração $p$	0.50	0.50-0.50	0.50	0.50-0.50
Datas	25-05 a 10-06	11-06 a 17-07	18-07 a 03-09	04-09 a 13-10

### 6.3. RESULTADOS E DISCUSSÃO

A simulação da rega em condições de disponibilidade de água limitada foi estudada tomando em consideração dois níveis de procura climática, forte e a muito forte, correspondendo a seca severa e seca extrema. Estes níveis estão diretamente relacionados com as reservas de água do solo e com as necessidades de rega da cultura. Na Fig. 6.2 são apresentadas as séries das necessidades de rega para a cultura do milho para as diferentes localidades, as quais serviram para identificar os anos de seca severa e extrema a simular. Verifica-se que as necessidades de rega do milho são mais elevadas nas regiões do Sul onde a  $ET_c$  é mais elevada e a precipitação mais reduzida; as  $NIR$  variam entre 392 e 797 mm nos anos de seca severa e 467 a 830 mm nos anos de seca extrema. De salientar que, para todos os casos, o ano de seca severa foi o de 2005, com exceção de Elvas pois a série de dados utilizada é mais curta não contemplando o ano de 2005.



**Figura 6.2.** Necessidades líquidas de rega do milho em várias localidades de Portugal identificando-se as necessidades para as condições de seca severa e extrema.

**Tabela 6.2.** Características dos anos de seca severa e extrema para as localidades estudadas

Local	Procura climática	Anos	Prec. sazonal (mm)	$ET_c$ (mm)	$NIR$ (mm)
Beja	Severa	1991	38	892	797
	Extrema	2005	43	893	810
Elvas	Severa	1965	175	752	650
	Extrema	1991	32	805	740
Évora	Severa	2008	61	832	723
	Extrema	2005	66	921	830
Coimbra	Severa	2006	153	619	450
	Extrema	2005	79	620	525
Viseu	Severa	2001	155	643	466
	Extrema	2005	107	759	631
Vila Real	Severa	2001	150	545	392
	Extrema	2005	81	611	513
Bragança	Severa	1986	142	545	406
	Extrema	1994	54	563	467
Miranda do Douro	Severa	2000	92	655	526
	Extrema	2005	33	724	645

Na Tabela 6.3 apresentam-se os resultados das alternativas de calendários de rega para todas as regiões estudadas, incluindo os valores de  $WP_{Farm}$  e  $EWP$  para os diferentes cenários. Os

resultados foram obtidos considerando as GID obtidas para uma eficiência de aplicação de 75%, valor que representa um desempenho de um sistema com uma manutenção algo regular.

Verifica-se por análise dos resultados constantes da Tabela 6.3 que em condições de seca severa, a cultura do milho para ser gerida sem carência hídrica (estratégia a) requer uma dotação total de rega de 645 a 795 mm, nas localidades do Sul de Portugal; em contraste, nas localidades do Norte necessita apenas de 390 a 525 mm; no Centro necessita de 450 mm. No que toca à  $WP$  os valores apresentam uma variação de 0.83 a 1.09  $\text{kg m}^{-3}$  para o Sul do País, de 1.00 a 1.24  $\text{kg m}^{-3}$  para o Norte e 1.05 a 1.27  $\text{kg m}^{-3}$ . Já a  $EWP$  apresenta uma variação de 0.17 a 0.22  $\text{€ m}^{-3}$  nas localidades mais a Sul e de 0.22 a 0.25  $\text{€ m}^{-3}$  e 0.20 a 0.26  $\text{€ m}^{-3}$  nas localidades do Norte e Centro, respetivamente. Verifica-se que os valores de  $WP$  e  $EWP$  são maiores nas localidades do Centro face às necessidades serem inferiores nesta região.

Numa mesma óptica de gestão, em condições de seca extrema o milho necessita de 735 a 810 mm no Sul, 525 mm no Centro e 465 a 645 mm no Norte. Para as mesmas condições de procura climática, a  $WP_{Farm}$  varia nos intervalos 0.94 – 1.07  $\text{kg m}^{-3}$ , 0.95 – 1.24  $\text{kg m}^{-3}$  e 1.09 – 1.19  $\text{kg m}^{-3}$  para o Sul, Norte e Centro, respetivamente. A  $EWP$ , para as mesmas regiões, varia nos intervalos 0.19 – 0.22  $\text{€ m}^{-3}$ , 0.20 – 0.25  $\text{€ m}^{-3}$  e 0.22 – 0.24  $\text{€ m}^{-3}$ . Contrariamente ao que acontece para os anos de procura climática severa, para condições de seca extrema a região com maiores produtividades física e económica é a do Norte, traduzindo uma menor sensibilidade ao aumento das necessidades hídricas.

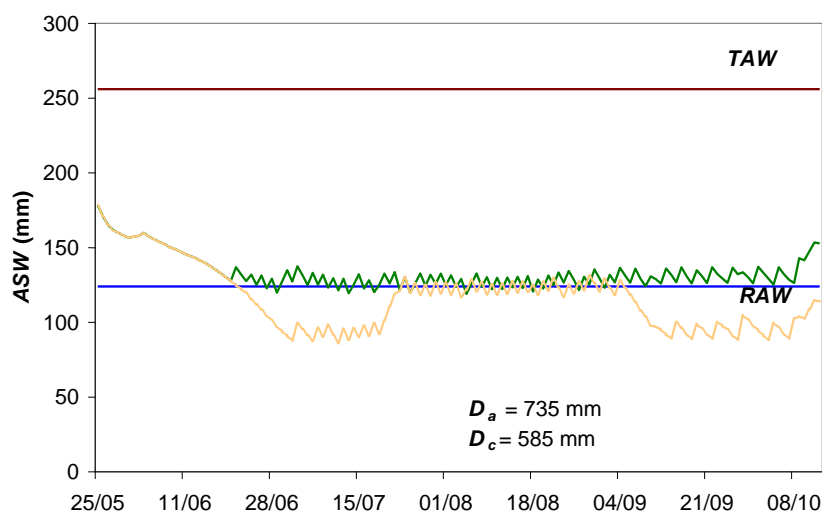
Se, no entanto, se optar pela utilização de rega deficitária moderada (estratégia c) ou seja com perdas relativa de produção ( $Q_y$ )  $\leq 16\%$ , verifica-se uma poupança para os anos de seca severa que varia entre 11 e 19% da água utilizada para os calendários de rega em conforto hídrico, i.e., 6 a 8 regas; se seleccionarmos a mesma estratégia nos anos de seca extrema a poupança de água de rega varia então entre 14 e 15% a Sul, 17 a 19% no Centro e 15 a 16% no Norte.

Na Figura 6.3 apresenta-se a aplicação das estratégias (a) e (c) no ano de seca extrema para o caso de Elvas. O exemplo da Fig. 6.3 corresponde a uma poupança de água de 150 mm (10 regas) quando se opta pelo calendário de rega deficitária; porém correspondem-lhe 21% de perdas de produção (Tabela 6.3). A  $WP_{Farm}$  apresenta um decréscimo de 1.07 para 1.02  $\text{kg m}^{-3}$  e a  $EWP$  de 0.22 para 0.21  $\text{€ m}^{-3}$ . Este facto traduz que a poupança de água não justifica as perdas de produção que daí advêm.

**Tabela 6.3.** Resultados das simulações da rega do milho para diferentes localidades em condições de seca severa e extrema e várias estratégias de rega (I = 15 mm).

Local	Procura climática	Est. rega	$\Delta ASW$ (mm)	Prec. (mm)	NIR (mm)	$ET_a$ (mm)	Perda relativa de produção (%)	$WP_{Farm}$ ( $kg\ m^{-3}$ )	$EWP$ ( $\text{€}\ m^{-3}$ )
Beja	Severa	a	-45	38	795	880	2	0.83	0.17
		b	-65		705	794	14	0.80	0.16
		c	-86		645	755	19	0.80	0.16
	Extrema	a	-27	43	810	880	2	0.94	0.19
		b	-46		690	780	16	0.92	0.19
		c	-62		645	736	22	0.89	0.18
Évora	Severa	a	-44	61	720	823	1	0.99	0.20
		b	-58		630	731	15	0.95	0.20
		c	-81		570	695	21	0.94	0.19
	Extrema	a	-19	66	825	910	2	0.96	0.20
		b	-40		705	811	15	0.94	0.19
		c	-56		660	767	21	0.91	0.19
Elvas	Severa	a	79	175	645	744	1	1.09	0.22
		b	54		540	661	15	1.07	0.22
		c	41		495	629	20	1.06	0.22
	Extrema	a	-25	32	735	794	2	1.07	0.22
		b	-53		630	701	16	1.03	0.21
		c	-64		585	668	21	1.02	0.21
Coimbra	Severa	a	-13	153	450	614	1	1.27	0.26
		b	-33		375	559	4	1.37	0.28
		c	-57		345	539	16	1.23	0.25
	Extrema	a	-13	79	525	617	1	1.19	0.24
		b	-39		435	553	13	1.18	0.24
		c	-52		405	521	20	1.13	0.23
Viseu	Severa	a	-16	155	465	637	1	1.05	0.22
		b	-44		390	590	10	1.05	0.21
		c	-59		360	575	13	1.05	0.22
	Extrema	a	-12	107	630	749	2	1.09	0.22
		b	-48		510	665	15	1.09	0.22
		c	-58		480	630	21	1.06	0.22
Vila Real	Severa	a	-33	150	390	543	1	1.24	0.25
		b	-51		330	500	10	1.23	0.25
		c	-70		300	489	13	1.23	0.25
	Extrema	a	-15	81	510	607	1	1.24	0.25
		b	-27		435	544	14	1.21	0.25
		c	-41		390	512	20	1.21	0.25
Bragança	Severa	a	-4	142	405	542	1	1.04	0.21
		b	-35		330	499	11	1.04	0.21
		c	-38		315	486	14	1.03	0.21
	Extrema	a	-44	54	465	560	1	0.95	0.20
		b	-81		390	506	13	0.92	0.19
		c	-85		360	480	18	0.91	0.19
Miranda Do Douro	Severa	a	-33	92	525	651	1	1.00	0.20
		b	-51		435	578	15	0.97	0.20
		c	-66		405	548	20	0.95	0.19
	Extrema	a	-6	66	645	719	1	1.03	0.21
		b	-31		540	638	15	1.01	0.21
		c	-39		495	601	21	1.00	0.21

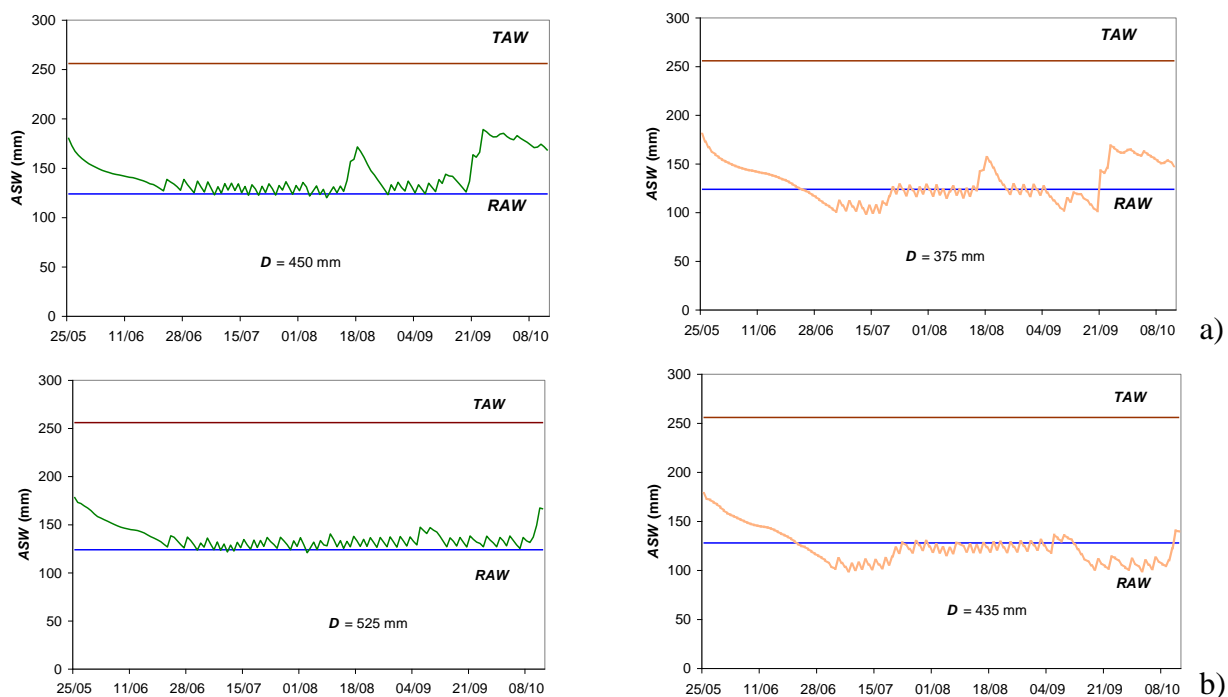
Nota:  $\Delta ASW$  é a variação da água disponível no solo



**Figura 6.3.** Variação do teor de água disponível no solo (ASW) para as condições de seca extrema, Elvas, para dois calendários de rega da cultura do milho: a) em conforto hídrico (a verde), b) em rega deficitária controlada - estratégia c (a laranja) (nota:  $D_a$  e  $D_c$  são as dotações totais de rega para cada uma das estratégias).

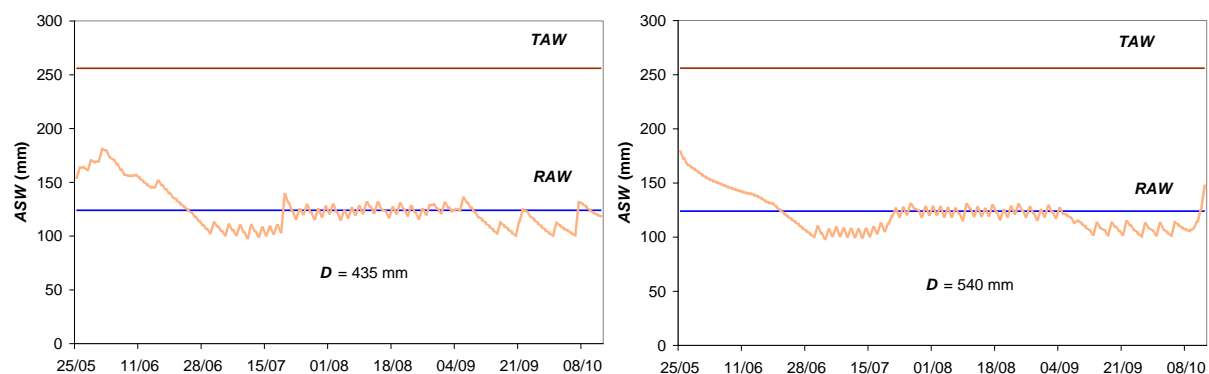
Os resultados gráficos da aplicação das estratégias (a) e (b) para Coimbra em anos de seca severa e extrema são apresentados na Fig. 6.4a e b respetivamente. Neste exemplo, observa-se uma poupança de água de rega correspondente a 5 e 6 regas respetivamente quando se opta pelo calendário de rega em conforto hídrico e deficitária, que correspondem respetivamente a 4 e 13% de perdas de produção (Tabela 6.3). Considerando o ano de seca severa a  $WP_{Farm}$  aumenta de 1.27 para 1.37  $\text{kg m}^{-3}$  e a  $EWP$  aumenta de 0.26 para 0.28  $\text{€ m}^{-3}$ . Já no ano de seca extrema a  $WP_{Farm}$  sofre um decréscimo de 0.01  $\text{kg m}^{-3}$ ; contudo a  $EWP$  mantém-se. Conclui-se que, face a um aumento dos indicadores, a gestão de rega deficitária poderá ser eficaz num ano de procura climática severa; contudo o mesmo não é claro num ano de seca extrema.

Comparando as Figs. 6.3 e 6.4 percebe-se bem que as grandes diferenças entre as  $NIR$  no Sul e no Centro se devem à precipitação durante o período do ciclo da cultura. Tal ocorrência de precipitação pode viabilizar a rega deficitária, mas não é certo que isso aconteça.



**Figura 6.4.** Variação do teor de água disponível no solo (ASW) para a cultura do milho em Coimbra regada em conforto hídrico (esq.) e utilizando a estratégia b (dir.) para condições de seca severa (a) e extrema (b).

A aplicação em Miranda do Douro da estratégia de rega deficitária (b) comparando um ano húmido com um de seca extrema é apresentada na Fig. 6.5. A Figura ilustra as diferenças em termos de água do solo quando se adota uma estratégia de rega deficitária em ano húmido (precipitação de 161 mm) e em ano de seca extrema (precipitação 66 mm); verificou-se que, apesar de existir uma diferença de 105 mm na quantidade de rega, a diferença na quantidade de água utilizada  $TWU$  (mm), isto é a quantidade total de água utilizada pela cultura (rega, chuva e variação da água do solo) é de apenas 14 mm.



**Figura 6.5.** Variação temporal do teor de água disponível no solo (ASW) para a cultura do milho em Miranda do Douro adotando um calendário de rega deficitária (estratégia b) para as condições de ano húmido (esq.) e de seca extrema (dir.).

## 6.4. CONCLUSÕES

Para uma adequada programação e condução da rega, com o objetivo de gerir recursos hídricos escassos, devem ser utilizados modelos, como o modelo SIMDualKc, para simular o comportamento das culturas face a diferentes estratégias de rega. A aplicação daquele modelo, após se ter procedido à sua calibração e validação para a cultura do milho em Portugal, efetuou-se com o intuito de gerir eficientemente a água disponível. Procedeu-se à seleção de estratégias de rega em condições de carência hídrica, as quais se basearam na otimização das disponibilidades de água associada a uma quebra de produção relativamente pequena que permitisse maximizar o uso da água de rega.

Verificou-se que em condições de disponibilidade de água limitada, a seleção de uma estratégia de rega que otimize as disponibilidades de água em relação à menor quebra de produção possível depende não só da cultura e do local onde esta é praticada, mas ainda das condições de seca (severa e extrema) a que está sujeita. Os resultados mostram que as estratégias que conduzem a maiores poupanças de água (6 a 11% da dotação total de rega em conforto hídrico) levam a perdas de produção que variam entre 6 e 10%, o que na conjuntura atual de preços do milho e torna muito difícil a sua adoção pelos agricultores.

A análise das produtividades da água *WP* mostra que depende fortemente da região, tendo a ser maior na região centro. Os resultados mostram também que a *WP* diminui quando a procura climática aumenta, como é o caso dos anos de seca extrema. A produtividade económica da água (*EWP*) varia de forma similar à da *WP*. Contudo, os valores de produção atuais poderão não cobrir os custos de produção se se mantivesse ao nível presentemente praticado, e se não se verificarem melhores desempenhos de rega. Assim, considera-se que em situação de seca severa e extrema a melhor opção será a adoção quer de défices muito pequenos ou quer da rega para satisfação das necessidades totais do milho mas reduzindo a área cultivada.

Verificou-se que o modelo SIMDualKc comprovou ter capacidade para apoiar eficientemente o gestor na prática da rega, tanto em conforto hídrico como na rega deficitária.

### Agradecimentos

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## **Capítulo 7**

# **Dual Crop Coefficients For Maize in Southern Brazil: Model Testing for Sprinkler and Drip Irrigation and Mulched Soil**

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**Martins, J.D., Rodrigues, G.C., Paredes, P., Carlesso, R., Oliveira, Z.B., Knies, A.E., Petry, M.T., Pereira, L.S., 2013. Dual crop coefficients for maize in southern brazil: model testing for sprinkler and drip irrigation and mulched soil. Biosystems Engineering, 115(3), 291-310**

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## 7. DUAL CROP COEFFICIENTS FOR MAIZE IN SOUTHERN BRAZIL: MODEL TESTING FOR SPRINKLER AND DRIP IRRIGATION AND MULCHED SOIL

**Abstract:** The study sought to determine the appropriate basal crop coefficients for maize through the calibration and validation of the model SIMDualKc using various treatments of maize irrigated with sprinkler and drip methods under full and deficit irrigation and cropped with organic mulch. The model computes crop evapotranspiration ( $ET_c$ ) using the dual crop coefficient methodology, thus separating crop transpiration,  $T_c$ , and soil evaporation,  $E_s$ . Two experiments were carried out and the model was calibrated for one treatment of each experiment and validated with the remaining treatments. The corresponding results show good agreement between the simulated and observed available soil water through the season, with regression coefficients of 0.99 to 1.02, and the root mean square error ranging 2.0 to 3.3% of the total available water. The calibrated  $K_{cb}$  for the initial and mid-season are respectively 0.20 and 1.12; the  $K_{cb}$  at end season is 0.2 for grain maize and 0.8 for maize harvested for silage. Results show that the evaporation component of evapotranspiration is less than 9% of  $ET_c$  for both sprinkler and drip experiments, thus indicating the suitability of using mulch for water conservation.

**Keywords:** evapotranspiration; soil evaporation; crop transpiration; straw mulch; irrigation scheduling; soil water dynamics; SIMDualKc model.

### 7.1. INTRODUCTION

Quantifying crop water use and consumption is essential in agriculture, mainly for irrigation management and planning, and hydrologic and water resources applications. Crop evapotranspiration ( $ET_c$ ) represents the water consumption of agricultural crops by crop transpiration ( $T_c$ ) and soil evaporation ( $E_s$ ).  $ET_c$  may be calculated by multiplying the reference evapotranspiration ( $ET_o$ ) by a crop coefficient ( $K_c$ ).  $ET_o$  represents the atmospheric evaporative demand and  $K_c$  integrates the factors that differentiate the considered crop from the reference crop in terms of ET (Allen et al., 1998). There are two approaches to define  $K_c$ : one uses the time-averaged single crop coefficient, representing the combined effects of soil evaporation and crop transpiration; the other is the dual crop coefficient approach considering separately  $T_c$  and  $E_s$  (Allen et al., 1998, 2005). The dual  $K_c$  consists of two coefficients: the

evaporation coefficient ( $K_e$ ) and the basal crop coefficient ( $K_{cb}$ ); a third coefficient is used when the crop is stressed ( $K_s$ ). It results  $K_c = K_s K_{cb} + K_e$ .

Most irrigation scheduling/management simulation models use the single  $K_c$  approach to compute  $ET_c$ , which provides satisfactory results for the estimation of daily evapotranspiration, with adequate precision for most applications. However for high frequency irrigation, for crops that only cover part of the soil, and when the soil is often wetted by rain or irrigation, the dual  $K_c$  approach can lead to more accurate estimates of  $ET_c$ , e.g., Liu and Pereira (2000), Tolk and Howell (2001) and Howell et al. (2004). In particular, it allows analysing  $T_c$  and  $E_s$  accurately and capturing impacts of wetting frequency and soil management on total water use (Fandiño et al., 2012; Paço et al., 2012; Rosa et al., 2012b; Zhang et al., 2013; Zhao et al., 2013).

Properly calibrated crop water simulation models are valuable tools that can be used to compute crop water requirements, supporting upgraded irrigation management practices, to assess impacts of water stress on crop yields. Examples of model applications for maize irrigation scheduling adopting empirical water balance models or water flux and crop growth models are numerous (Liu et al. 1998; Huang, 2004; Panda et al., 2004; Popova and Kercheva, 2004; Stulina et al., 2005; Ko et al., 2009). Khaledian et al. (2009) modelled soil water and irrigation in presence of mulch.

The performance of both single and dual  $K_c$  methods depends upon the appropriate selection of crop coefficient values for each of the four crop growth stages (initial, crop development, mid-season and late season), the adoption of locally adjusted of growth stage lengths, and the accurate estimation of  $ET_o$  from climatic data (Piccinni et al., 2009; Popova and Pereira, 2011). Allen et al. (1998) present standard crop coefficients and growth stage lengths for various crops, but using them without local adjustment may lead to large errors in the estimation of  $ET_c$ . Actual crop coefficients and lengths of growth stages are influenced by many factors including crop varieties, soils and salinity, management practices (e.g., plant density, row spacing, fertilising, disease and weeds control, irrigation) and climatic conditions, hence they should ideally be derived experimentally for each crop and region under various management practices for more accurate estimation of  $ET_c$  (Odhiambo and Irmak, 2012). However, this is not possible due to costs involved, the exigencies in experimental accuracy, and the complexity related with variability in cultivation, soil and water management practices; a different approach is to calibrate models that allow the problems due to such variability to be overcome (Popova and Pereira, 2011; Zhang et al., 2013; Zhao et al., 2013).

$E_s$  is influenced by various factors affecting soil surface conditions, mainly tillage practices, crop residues cover, ground shadow by the crop depending upon crop density and height, and soil surface moisture and wetting frequency. Crop residues and mulch, as well as shadow by the crop, reduce the solar energy available for evaporation at the soil surface (Allen et al., 1998, 2005; Allen and Pereira 2009). Impacts of mulching and crop residues on  $E_s$  depend upon the cover pattern and type of mulch and residues, as well as their amount on the soil surface (Unger and Parker, 1976; Steiner, 1989; Hatfield et al., 2001; Ji and Unger, 2001; Acharya et al. 2005; Hobbs et al., 2008; Klocke et al., 2009). Odhiambo and Irmak (2012) concluded that  $E_s$  from a soybean field decreased by 5% for each 10% soil covered by residues but that the reduction was only 2.5% during the initial crop stage. In addition, straw mulches may improve yields and water use performance as well as water conservation and saving (Tolk et al., 1999; Ji and Unger, 2001; Hobbs et al., 2008; Mitchell et al., 2012). However, when water is applied by sprinkler irrigation, evaporation losses due to interception by the mulch limit water savings, as analysed by Scopel et al. (2004). Mulching in South America and Brazil is generally associated with no-till direct seeding agricultural systems (Díaz-Zorita et al., 2002; Fabrizzi et al., 2005); benefits of these cropping systems led no-tillage systems to enormously expand in the region, with 35 Mha in Brazil, i.e., 70% of the cropped area. Benefits come from reducing soil evaporation, increasing plant available water, improving nutrient cycling, and controlling soil erosion and runoff (Machado and Silva, 2001; Díaz-Zorita et al., 2002; Fabrizzi et al., 2005; Carlesso et al., 2011). Benefits associated with carbon sequestration are also important (Bayer et al., 2006; Bernoux et al., 2006). Considering the expansion of no-till systems in southern Brazil, related benefits and favourable trends in conservation tillage, deficit irrigation experiments were performed with direct seeding.

Aiming at producing information to parameterise the new dual  $K_c$  model used in the Sistema Irriga™, which now is monitoring more than 90000 ha each year in Brazil (Carlesso et al., 2009), this research was performed using the SIMDualKc software (Rosa et al. 2012a, b). This software uses the dual crop coefficient approach over a range of cultural practices to provide information for use in irrigation scheduling and hydrologic water balances, including deficit irrigation, and is therefore appropriate to support new developments of the operational model used in Irriga™. SIMDualKc performs a soil water balance at the field level using a daily time step. It estimates  $T_c$  and  $E_s$  for full and incomplete cover crops, including presence of mulch or crop residues on the soil surface. Separating  $T_c$  and  $E_s$  allows a better assessment of alternative irrigation management practices relative to deficit irrigation and crop residues. Therefore, the main objectives of this study are: (a) to determine the basal crop coefficients

for maize grown in no-tillage conditions in southern Brazil, (b) to calibrate and validate the dual  $K_c$  methodology using the model SIMDualKc, and (c) to assess impacts of various deficit irrigation strategies using field data obtained with sprinkler and drip irrigation. Yields, water productivity, and economic issues are analysed in Rodrigues et al. (2013).

## 7.2. MATERIALS AND METHODS

### 7.2.1. Description of location, climate and soil conditions

This study was conducted at the experimental station of the Department of Agricultural Engineering, Federal University of Santa Maria (UFSM), Santa Maria, Brazil. The station is located in the central depression of Rio Grande do Sul, at latitude 29°41'24" S, longitude 53°48'42" W, and altitude of 100 m. The climate, according to the classification of Köppen, is a "cfa", i.e., subtropical humid, without dry season and with hot summer (Moreno, 1961). The average monthly climatic data for 1969-2005 at Santa Maria are presented in Table 7.1.

**Table 7.1.** Monthly climatic data relative for the period 1969-2005

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<b>Max. air temperature, °C</b>	30.7	29.9	28.6	25.0	21.9	19.4	19.4	20.8	22.0	24.9	27.4	29.8
<b>Min. air temperature, °C</b>	19.7	19.6	18.2	14.9	11.8	9.9	9.8	10.6	11.8	14.3	16.1	18.4
<b>Average Relative Humidity, %</b>	72.1	77.0	79.0	81.7	82.9	83.3	81.2	78.8	77.6	74.7	70.2	68.4
<b>Wind Speed, m s<sup>-1</sup></b>	1.7	1.7	1.5	1.5	1.5	2.3	2.3	2.3	2.1	2.1	2.1	1.7
<b>ET<sub>0</sub>, mm d<sup>-1</sup></b>	4.0	3.5	2.8	1.7	1.1	0.8	0.9	1.3	1.98	2.7	3.5	4.1
<b>Precipitation, mm</b>	148.0	134.9	137.3	143.4	150.5	155.4	143.0	126.8	159.8	159.1	120.1	133.7

The soil is a silt-clay loam classified as Paleudalf (USDA, 1999; Streck et al. 2008). Soil texture and soil hydraulic properties are given in Table 7.2. Methods used in the Sistema Irriga™ soils laboratory are referred to by Michelon et al. (2010). In particular, the water retention at potentials of -100 to -500 was measured with pressure plates and for -500 to -1500 kPa was measured with a WP4 dewpoint potentiometer (Decagon Devices, Inc.).

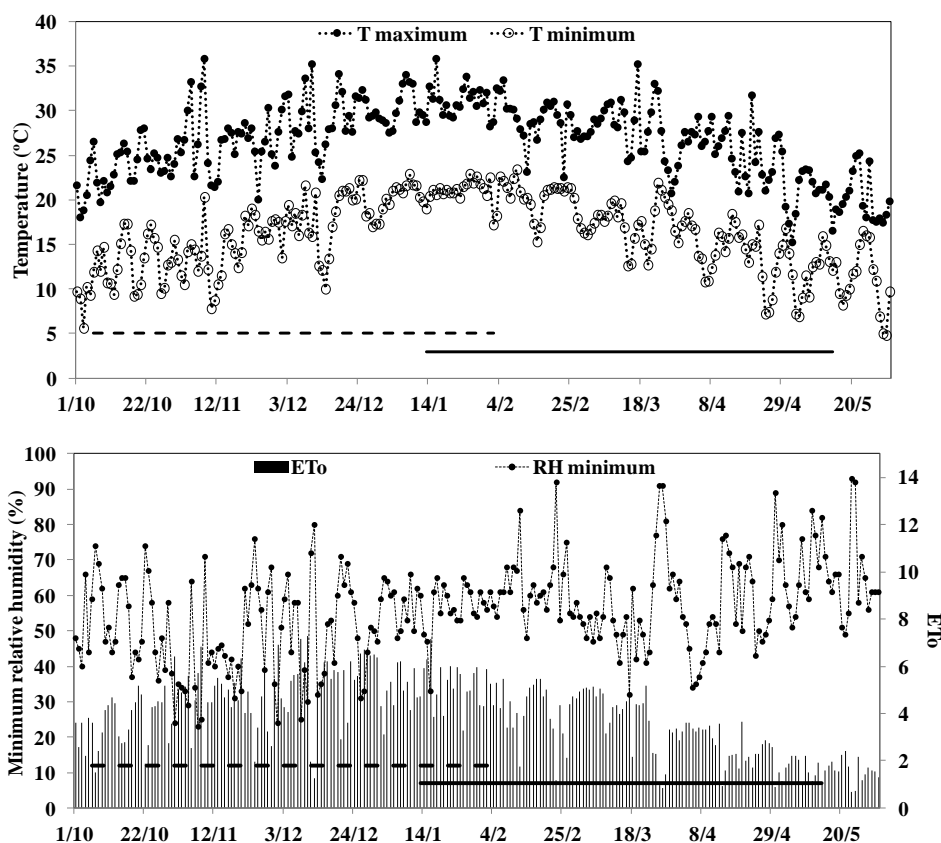
**Table 7.2.** Texture and soil hydraulic properties for both experimental sites

Experiments	Layer	Texture (%)			$\theta$ (cm <sup>3</sup> cm <sup>-3</sup> )		
		Sand	Silt	Clay	$\theta_{FC}$	$\theta_{WP}$	$\theta_{Sat}$
<b>Drip irrigation</b>	0.0 - 0.10	36.0	44.7	19.4	0.385	0.119	0.519
	0.10- 0.25	35.5	40.4	24.2	0.357	0.112	0.491
	0.25- 0.55	32.1	35.4	32.5	0.307	0.117	0.477
	0.55- 0.90	24.2	31.7	44.1	0.329	0.191	0.476
<b>Sprinkler irrigation</b>	0.0 - 0.15	32.3	42.5	25.2	0.380	0.090	0.492
	0.15- 0.45	30.4	38.2	31.4	0.360	0.090	0.494
	0.45- 0.90	23.5	29.0	47.5	0.395	0.201	0.506

$\theta_{FC}$ ,  $\theta_{WP}$  and  $\theta_{Sat}$  represent the soil water content at field capacity, the wilting point and at saturation.

### 7.2.2. Description of the experiments

During the growing season of 2010/2011, two maize experiments were conducted: one irrigated by sprinkler and the other by drip irrigation. The irrigation requirements were determined from the computed crop evapotranspiration estimated through the product  $ET_c = K_c \cdot ET_o$ . The reference evapotranspiration was estimated with the Penman-Monteith equation (Allen et al., 1998) using meteorological data collected from an automatic weather station located less than 200 m away from the experimental area. Precipitation was also measured there.  $K_c$  values were those proposed by Allen et al. (1998). Data relative to maximum and minimum air temperatures (°C), maximum and minimum relative humidity (%) and reference evapotranspiration (mm) for the experimental period are presented in Fig. 7.1. Irrigation was applied following the information automatically provided by the Sistema Irriga™ (<http://www.sistemairriga.com.br/>) in relation to the intended treatment.



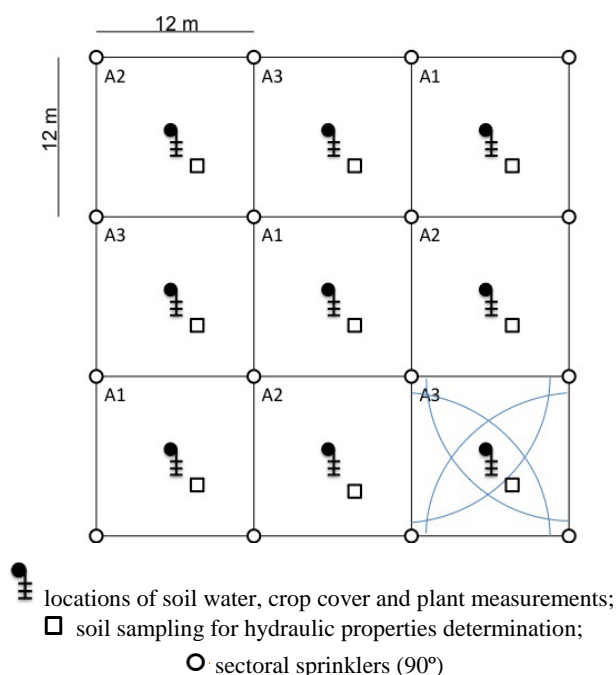
**Figure 7.1.** Daily maximum and minimum temperature, minimum relative humidity and reference evapotranspiration during the experimental periods (sprinkler experiment - -) and (drip experiment —), 2010/11.

The sprinkler irrigation treatments (STs) were conducted under field conditions with three irrigation treatments and 3 replications (Fig. 7.2). The experimental units consisted of plots of  $12 \times 12 \text{ m}^2$ . The set system consisted of 4 sectoral sprinklers per plot with pressure head of 196 kPa, discharge of  $534 \text{ l h}^{-1}$  and throw of 11 m, thus resulting an average application rate of  $14.83 \text{ mm h}^{-1}$ . The coefficient of uniformity (CU) was measured as proposed by Merriam and Keller (1978); for 5 observations CU varied from 80 to 96% due to wind effects. Rainfall during the crop season was 414.5 mm. Applied water depths (D) to the 3 treatments were:

A1, D = 328 mm

A2, D = 234 mm

A3, D = 91 mm.

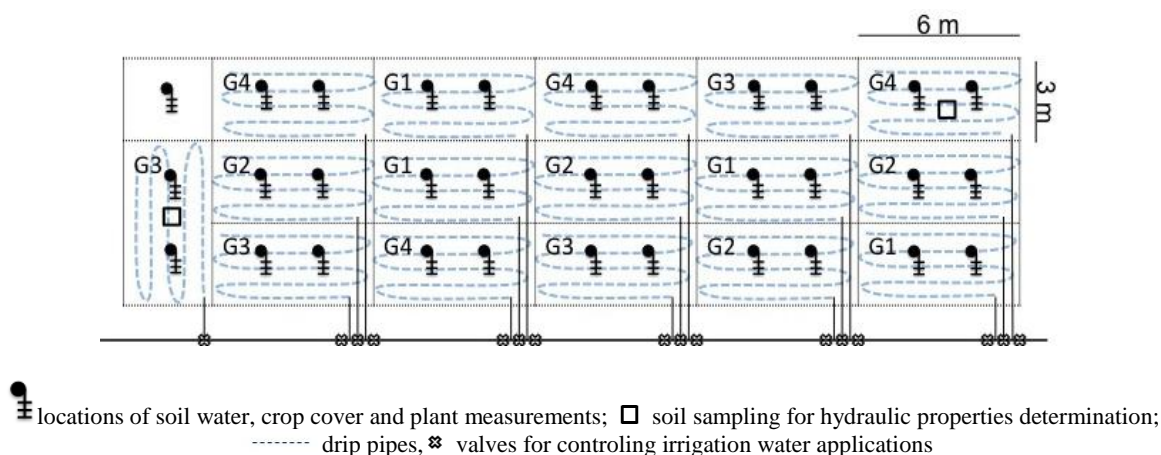


**Figure 7.2.** Experimental layout on the sprinkler irrigation treatments

The drip irrigation treatments (DTs) were performed in an area protected by a rainfall shelter consisting of two metallic structures of  $16 \times 10 \text{ m}^2$ , with an experimental area of  $320 \text{ m}^2$ . This structure is moved on rails with an east-west orientation. The mobile cover was moved as rainfall occurred, covering the experimental area and making it possible to apply deficit irrigation treatments accurately without influence of rainfall. The experimental area was surrounded by an irrigated maize crop planted on the same date to avoid any advection from the surroundings. Four irrigation treatments with 4 replications were adopted (Fig. 7.3). The experimental units consisted of plots of  $3 \times 6 \text{ m}^2$ . The irrigation system consisted of pressure compensating in-line drippers at  $0.20 \text{ m}$  spacings, with operating pressure of  $100 \text{ kPa}$  and a discharge of  $1.3 \text{ l h}^{-1}$ . Drip lines were located between rows, and separated by  $0.50 \text{ m}$ . The application rate was of  $13 \text{ mm h}^{-1}$ . The coefficient of uniformity was measured in 5 plots using the method described by Merriam and Keller (1978) and CU values were greater than 90%. Rainfall ( $73 \text{ mm}$ ) was allowed during the initial crop stage to ensure adequate and uniform establishment of the crop. Water applications to the 4 treatments were:

- G1,  $D = 389 \text{ mm}$ ;
- G2,  $D = 316 \text{ mm}$ ;
- G3,  $D = 218 \text{ mm}$ ;
- G4,  $D = 113 \text{ mm}$ .

The planting dates and the dates limiting the crop development stages are presented in Table 7.3 for both experiments. The STs used direct seeding into oats (*Avena strigosa*) crop residues (5 t ha<sup>-1</sup> of dry biomass, a cover fraction of the soil surface  $f_{r\ mulch} = 1.0$  and an effective fraction of soil coverage  $f_{eff\ mulch} = 0.9$ ). The hybrid AG8011YG was sown with a row spacing of 0.45 m with north-south orientation and a plant density of 6.5 plants per m<sup>2</sup>. This crop was harvested for silage. The DTs experiment used a no-tillage farming system with seeding into bean (*Phaseolus vulgaris L*) crop residues (3 t ha<sup>-1</sup> of dry biomass,  $f_{r\ mulch} = 1.0$  and  $f_{eff\ mulch} = 0.8$ ). The hybrid P1630H was sown with row spacing of 0.50 m with east-west orientation and plant density of 6.5 plants per m<sup>2</sup>. This crop was harvested for grain at 21% moisture.



**Figure 7.3.** Experimental layout on the drip irrigation treatments

**Table 7.3.** Crop growth stage dates for both experiments

Crop growth stages	Sprinkler irrigation	Drip irrigation
	Dates	
Planting	06/10/2010	13/01/2011
End of initial stage	31/10/2010	31/01/2011
Start mid-season	23/11/2010	20/02/2011
Start senescence	15/01/2011	23/04/2011 <sup>(G1)</sup>
		23/04/2011 <sup>(G2)</sup>
		12/04/2011 <sup>(G3)</sup>
		06/04/2011 <sup>(G4)</sup>
Harvesting	02/02/2011	14/05/2011

G1, G2, G3 and G4 refer to the drip treatments

### 7.2.3. Model SIMDualKc and data requirements

The model SIMDualKc adopts the dual  $K_c$  approach as proposed by Allen et al. (1998, 2005) to calculate  $ET_c$  considering separately the E and T components. The model is described in

detail by Rosa et al. (2012a) and its test with field data is presented by Rosa et al. (2012b). The first approach to adopting a dual  $K_c$  was proposed by Wright (1982). The method was subsequently improved by Allen et al. (1998, 2005).

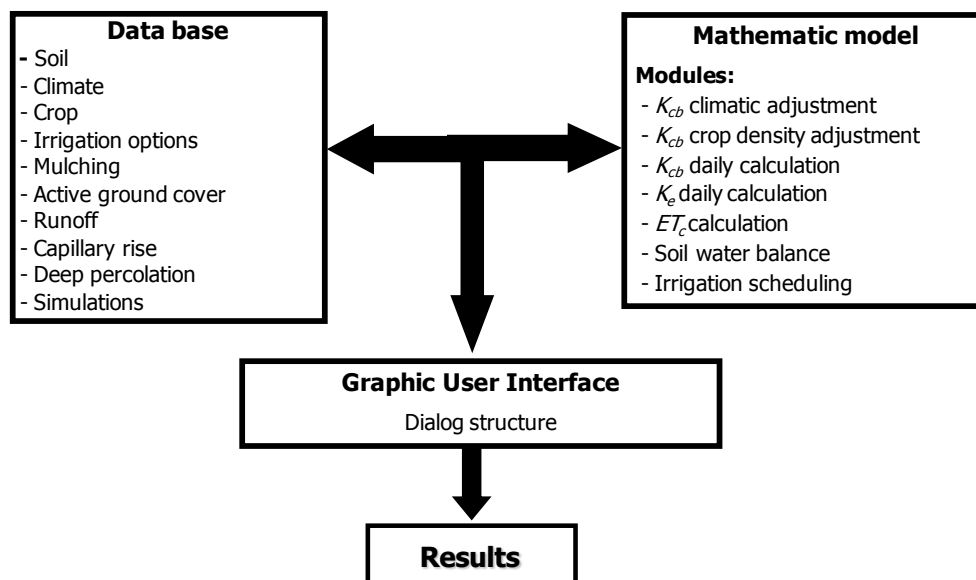
There is a variety of methods to estimate ET from field observations, which include ET from change in soil water (Allen et al., 2011) and consequent modelling (Jensen and Wright, 1978). Various models for estimating ET have been calibrated/validated or tested using soil water observations, e.g., models presented in Pereira et al. (1995). The ISAREG model, which preceded SIMDualKc, has been extensively calibrated/validated for various crops and regions using soil water observations (Liu et al., 1998; Cancela et al., 2006; Popova et al., 2006; Cholpankulov et al., 2008; Cai et al., 2009; Popova and Pereira, 2011). Various applications of the dual  $K_c$  method to estimate ET using soil water observations have been reported in the literature (Bodner et al., 2007; Greenwood et al., 2009; Yang et al., 2009; Descheemaeker et al., 2011; Zhang et al., 2011, Sánchez et al., 2012).

The first dedicated model for estimating ET using the dual crop coefficient approach as proposed by Allen et al. (1998, 2005) is SIMDualKc. Its first published testing was performed with soil water observations (Rosa et al., 2012b). Meanwhile the model has been tested with separately observed T and E in a peach orchard (Paço et al., 2012), for considering the effects of an active ground cover in a vineyard (Fandiño et al., 2012), and for validating the two phases of Ritchie's soil evaporation approach (Ritchie, 1972) in a field cropped with maize and wheat (Zhao et al., 2013). However, SIMDualKc has been also calibrated against ET data obtained from eddy covariance observations (Zhang et al., 2013). It is therefore appropriate to use and test SIMDualKc against soil water changes and consequently derive the basal crop coefficient for maize.

The scheme in Fig. 7.4 shows the various computational modules and databases used by the model. In this application, the following data were used

- a) meteorological data as reported in Fig. 7.1 for climatic variables and daily rainfall;
- b) soil data as summarised in Table 7.2, which allowed the total and readily available soil water (TAW and RAW, mm) to be computed, as well as the initial values for the total evaporable water (TEW, mm), readily evaporable water (REW, mm), and thickness of the evaporation soil layer ( $Z_e$ , m). These parameters are defined by Allen et al. (1998, 2005); values were tested as referred in Section 7.2.5;

- c) crop data referring to dates of crop growth stages (Table 7.3), root depths ( $Z_r$ , m), crop height (h, m), fractions of soil cover by vegetation ( $f_c$ ), and fractions wetted by rain and irrigation ( $f_w$ ), which were observed, and data relative to basal crop coefficients ( $K_{cb}$ ) and soil water depletion fractions for no stress (p) that were the object of calibration, as described below. The values for h and  $f_c$  were different for stressed and non-stressed crop conditions. The calibrated  $K_{cb}$  values are internally corrected for climate and adjusted for water stress during the computation process;
- d) data to estimate deep percolation, i.e., the parameters  $a_D$  and  $b_D$  of the decay function by Liu et al. (2006), were also calibrated as in Section 7.2.5);
- e) observation data on residues mulch consisting of a cover fraction of the soil surface ( $f_{r\_mulch}$ ) and the effective fraction of soil coverage ( $f_{eff\_mulch}$ ), and respective updates through the crop season, as well as the percentage of reduction of soil evaporation in relation to the percentage of soil surface covered by the organic mulch, which are described in next section;
- f) curve number runoff data following Allen et al. (2007), which were adjusted using a trial and error procedure;
- g) irrigation data relative to dates and depths of applied irrigation (Table 7.4).



**Figure 7.4.** Conceptual structure of the SIMDualKc model (from Rosa et al., 2012a)

**Table 7.4.** Irrigation dates and depths for both treatments

Sprinkler Treatments						Drip treatments, under rain shelter							
A1		A2		A3		G1		G2		G3		G4	
Dates	Depths	Dates	Depths	Dates	Depths	Dates	Depths	Dates	Depths	Dates	Depths	Dates	Depths
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
14/10	11.6	14/10	11.6	14/10	11.6	30/01	10.4	01/02	11.2	11/02	30.3	24/02	30.3
18/10	11.6	18/10	11.6	18/10	11.6	02/02	10.4	08/02	24.7	24/02	30.3	17/03	39.3
21/10	11.6	21/10	11.6	21/10	11.6	08/02	23.4	18/02	30.3	07/03	30.3	14/04	43.8
26/10	11.6	26/10	11.6	26/10	11.6	16/02	28.7	27/02	30.3	17/03	39.3		
03/11	13.0	04/11	11.6	09/11	13	21/02	28.7	05/03	30.3	01/04	43.8		
07/11	13.0	09/11	11.1	31/12	15.6	01/03	28.7	12/03	30.3	14/04	43.8		
15/11	19.8	14/11	16.3	25/01	15.6	05/03	28.7	19/03	30.3				
20/11	14.5	22/11	19.8			10/03	28.7	27/03	32.6				
02/12	15.6	16/12	15.6			15/03	28.7	07/04	32.6				
09/12	15.6	18/12	19.5			21/03	28.7	19/04	32.6				
15/12	15.6	27/12	19.5			27/03	28.7	06/05	30.3				
17/12	19.5	31/12	19.5			04/04	28.7						
19/12	15.6	15/01	19.5			12/04	28.7						
24/12	15.6	19/01	19.5			22/04	28.7						
27/12	15.6	25/01	15.6			06/04	28.7						
29/12	15.6												
31/12	15.6												
09/01	15.6												
14/01	15.6												
19/01	29.9												
24/01	15.6												

In this study, SIMDualKc was calibrated for the first time for organic mulches, thus the amount of reduction in the soil surface evaporation due to mulch density and depth as well as the fraction of the soil surface covered by mulch was evaluated. The general rule applied was to reduce the amount of soil water evaporation by 5% for each 10% of soil surface covered by the organic mulch (Allen et al., 1998; Rosa et al., 2012a), which was based upon the studies by Unger and Parker (1976) and Steiner (1989), and was confirmed by Odhiambo and Irmak (2012). Klocke et al. (2009) stated that  $E_s$  was reduced by nearly 50% compared with bare soil  $E_s$  when a mulch nearly covered the ground under a maize canopy. However, since the SIMDualKc model performs a soil water balance, it cannot assess the mulch interception losses, which require an additional reservoir to represent mulch interception storage (Scopel et al., 2004). Hence, mulch interception evaporation is part of the evaporation component of ET.

Model outputs include: the daily available soil water (ASW, mm); daily ET and respective components  $E_s$  and  $T_c$  (mm), the daily  $K_e$  and  $K_s$ , the daily stress adjusted  $K_{cb}$  ( $K_{cb\ adj}$ ) and the  $K_{c\ act} = K_{cb\ adj} + K_e$ . ASW base calculations are described by Liu et al. (1998). The general computational algorithms have been presented by Rosa et al. (2012a). When the model is used for scheduling irrigations, dates and depths of irrigations are also provided.

#### 7.2.4. Crop observations and soil moisture measurements.

In both experiments, crop height, the fraction of soil covered by the crop ( $f_c$ ) and the leaf area index (LAI) were observed once or twice a week. LAI was measured on two plants per plot using a non-destructive method with equipment LI-COR 3000. LAI was determined by the ratio of the photosynthetically active leaf area of each plant to the ground area occupied by it. Data for  $f_c$  and  $h$  are given in Table 7.5.

**Table 7.5.** Crop height ( $h$ ) and fraction of ground covered by the crop ( $f_c$ ) during the crop growing season

		Initial	Crop development	Mid season	End season	
$h$ (m)	A1	0.1	0.22	2.4	2.4	
	A2	0.1	0.22	2.4	2.4	
	A3	0.1	0.22	2.2	2.2	
	G1	0.1	0.38	2.3	2.3	
	G2	0.1	0.38	2.2	2.2	
	G3	0.1	0.38	2.1	2.1	
	G4	0.1	0.38	2.0	2.0	
	$f_c$	A1	0.01	0.20	0.85	0.85
		A2	0.01	0.20	0.90	0.90
		A3	0.01	0.20	0.80	0.80
G1		0.01	0.20	0.90	0.70	
G2		0.01	0.20	0.90	0.70	
G3		0.01	0.20	0.80	0.65	
G4		0.01	0.20	0.85	0.60	

The mulch cover fraction was 1.0 during the entire season but the density decreased. For the STs, the density of oats mulch was 0.9 at planting and 0.8 at 40 days before harvesting; for the DTs, with beans mulch, the density was 0.8 at planting, 0.7 by 17 days later and 0.6 after 33 days.

The dates delimiting the crop stages (Table 7.3) were identified as follows: (a) the initial stage was considered as from sowing to the day when the crop covered approximately 10% of the ground; (b) the development stage was from the end of the initial stage until the crop reached LAI=3; (c) the mid-season was from then until the onset of senescence; and (d) the late season was from the onset of senescence to harvest.

For measuring the soil water content, a set of FDR (Frequency Domain Reflectometry) probes were used, comprising a data logger CR10X, AM16/32 multiplexers and CS626 sensors, all from Campbell Scientific. Readings were taken daily from sowing to harvest. The FDR system was calibrated for soil water contents ranging from near the wilting point up to close to saturation. The sets of sensors were installed in the central point of each sprinkler plot with measurements in the following layer depths 0-0.15, 0.15-0.45, and 0.45-0.90 m. In the DTs experiment there were 2 sets of sensors in each plot and records were made for four layer depths: 0-0.1, 0.1-0.25, 0.25-0.55, and 0.55-0.90 m. FDR sensors were placed between rows and between plants along the row.

The applied water was measured with a flowmeter located upstream of the plots for each treatment. The application depths were obtained by correcting the measured values by 5% in the DT case and for the wind drift evaporation losses and canopy interception storage in the ST case. Various studies on sprinkler interception by a maize canopy show it may vary from 0.4 to 2.7 mm depending on the canopy density, application rate and evaporation power of the atmosphere (Steiner et al., 1983; Tolk et al., 1995; Lamm and Manges, 2000; Li and Rao, 2000; McLean et al., 2000; Kozak et al., 2007). Therefore, the measured gross irrigation depths were corrected for 0.3 mm for the wind effect and 1.5 mm for the interception losses when the canopy was fully developed. A linear interpolation was used for the vegetative growth period.

### **7.2.5. Model calibration and validation**

The calibration procedure sought to adjust the non-observed parameters ( $K_{cb}$  and  $p$  relative to all crop growth stages, TEW, REW and parameters  $a_D$  and  $b_D$  of the deep percolation parametric function, and CN of the runoff curve number algorithm) to minimise the differences between observed and simulated daily available soil water values relative to the entire root depth profile. As described by Popova and Pereira (2011) and Rosa et al. (2012b), a set of soil and crop parameters was first estimated and then a trial and error procedure was developed for selecting the values for  $K_{cb}$  and  $p$ , starting with the standard values (Table 7.6).

When  $K_{cb}$  and  $p$  values were in an acceptable range and estimation errors were small and showing little variation from one iteration to the next, the trial and error was applied to the soil parameters and the CN value. Finally, a last trial was applied to the crop parameters until differences between observed and simulated soil water values were minimised and approximately stabilised from one iteration to the next. A trial and error procedure relative to the effects of mulch in reducing  $E_s$  was also performed.

The calibration and validation of models using independent data sets is often discussed. Sinclair and Seligman (2000) discussed this subject and defined a set of criteria aimed at publishing papers on crop models. These models are defined as dynamic representations of crop processes in a systems context and their generic goal is to simulate and explain crop development and behaviour, yield and quality as a function of environmental and management conditions or of genetic variation. SIMDualKc aims only at representing the water use process considering well defined environmental and management conditions.

The SIMDualKc model was previously presented in terms that agree with recommendations by Sinclair and Seligman (2000), i.e., clearly defined objectives, concept and structure, as well as its background on various aspects of water use and evapotranspiration (Rosa et al., 2012a). As stated by Monteith (1996), readers may benefit from papers on models where the conceptual basis is clear and the logic behind the mechanistic structure is evident. Hence, relationships and algorithms were presented in a simple manner. In addition, to demonstrate the performance of the model, its testing was also presented and, following Sinclair and Seligman (2000), could be analysed in terms of a few main criteria: soundness of the concept, of the data and methodology; and of the analysis of the results. This testing was performed for maize, wheat and cotton (Rosa et al., 2012b; Zhang et al., 2013; Zhao et al., 2013), peaches (Paço et al., 2012) and vineyards (Fandiño et al., 2012). The calibration/validation for maize described by Rosa et al. (2012b) referred to only three treatments performed in the same year. This was considered appropriate because the calibration of a simple water balance model refers to only a few parameters that have a well-established physical and biological meaning and relate to the crop and the soil under consideration. In these circumstances, validation is not to prove the validity of the model approaches but to demonstrate that calibrated parameters are well adjusted for soil water and ET simulation in that particular environment. Therefore, since there is no intention of universality for a soil water balance model but of demonstrating the validity for application of the calibrated parameters in a given environment, the model could be validated for different data sets referring to various treatments applied in the same or in various years depending upon the availability of data (Rosa et al., 2012b).

The SIMDualKc model has also been calibrated/validated for other crops and environments, including for other sets of maize data in addition to the application dealt with in this study. The transpiration and soil evaporation processes were simulated in a peach orchard and the calibration/validation was performed against measurements of  $T_c$  and  $E_s$  (Paço et al., 2012). Two years data were used because there was only one treatment. SIMDualKc was calibrated and validated for a vineyard having active ground cover (Fandiño et al., 2012), thus with separation of  $T_c$ ,  $E_s$  and ground cover  $T$ . An application to a two year data set of maize on the North China Plain was used to test the model and the algorithm of soil evaporation (Zhao et al., 2013) and another to calibrate/validate the model using ET data observed with a eddy covariance system in maize and wheat (Zhang et al., 2013). Therefore, considering the referred applications and related model behaviour, it was considered appropriate to perform two calibration/validation processes using various treatments of sprinkler irrigation and drip irrigation. As shown in the Results Section, because experiments were conducted at locations 100 m apart, only one calibration could have been performed; thus, results of both calibration processes are shown together.

It is worth noting that various studies have reported on the calibration/validation of soil-water simulation models using various treatments of the same experiment and year. This is the case for various water balance, water flux and drainage models included in a book edited by Pereira et al. (1995); however, crop growth and yield models were generally tested for more than one year. Kleemola et al. (1996) used a season's set of nitrogen and water treatments for model calibration and the remaining for validation. Justes et al. (2009) calibrated the residue decomposition module of STICS model with data for several treatments and used the remainder for validation. Damour et al. (2012) used a single cycle of banana production to calibrate and validate the water use module of a simulation model for banana growth and yield. Relative to the model HYDRUS-1, Tafteh and Sepaskhah (2012) used some treatments for calibration and the remaining treatments of the same season for validation. Singh et al. (2008) also used treatments of the same year for calibration and validation of models in a study aimed at evaluating CERES-Wheat and CropSyst models for water–nitrogen interactions. From these discussions, it may be concluded that it is appropriate to use one treatment of each experiment to calibrate SIMDualKc and the remainder for its validation.

The standard values of  $K_{cb}$  and  $p$  for the maize crop used in the initial simulations were taken from Allen et al. (1998) and are presented in Table 7.6 for both experiments. The initial REW, TEW and  $Z_e = 0.15$  m for both experiments are also in Table 7.6. The initial depletion in the evaporable layer for both experiments was 0% of TEW as observed in field. Based on soil

water observations, the initial depletion for the entire effective root zone (0.9 m) was set at 5 and 8% of TAW for the ST and DT experiments, respectively. The percentage reduction of the soil evaporation as a function of the fraction covered by mulch was 50% for both experiments (Allen et al., 1998; Rosa et al., 2012b). The fraction of the soil wetted by irrigation ( $f_w$ ), required to calculate  $K_e$  together with  $f_c$ , was 1.0 for sprinkler irrigation and 0.60 for drip irrigation.

**Table 7.6.** Standard and calibrated basal crop coefficients ( $K_{cb}$ ), depletion fractions for no stress ( $p$ ), soil evaporation, runoff and deep percolation parameters

	Sprinkler irrigation		Drip irrigation	
	Standard	Calibrated	Standard	Calibrated
$K_{cb\ ini}$	0.15	0.20	0.15	0.20
$K_{cb\ mid}$	1.15	1.12	1.15	1.12
$K_{cb\ end}$	0.50	0.80	0.15	0.20
$p\ ini$	0.55	0.50	0.55	0.50
$p\ dev$	0.55	0.50	0.55	0.50
$p\ mid$	0.55	0.50	0.55	0.50
$p\ end$	0.55	0.50	0.55	0.50
<b>REW (mm)</b>	12	12	12	12
<b>TEW (mm)</b>	49	49	49	49
<b><math>Z_e</math> (m)</b>	0.15	0.15	0.15	0.15
<b>CN</b>	75	75	75	75
<b><math>a_D</math></b>	440	390	408	353
<b><math>b_D</math></b>	-0.017	-0.022	-0.017	-0.022

\* REW and TEW are the readily and total evaporable water;  $Z_e$  is the depth of the soil evaporation layer; CN is the curve number;  $a_D$  and  $b_D$  are the parameters of the deep percolation equation (Liu et al., 2006).

For estimation of deep percolation, the parametric decay equation proposed by Liu et al. (2006) was used. The initial and calibrated parameters  $a_D$  and  $b_D$  for both treatments are presented in Table 7.6. Groundwater contribution was not considered in either experiments because a shallow water table was not present.

The model calibration for the STs was performed with data of treatment A2 and validation using the same parameters was performed for treatments A1 and A3. For the DTs, the G3 treatment was used for calibration, and treatments G1, G2, and G4 were used for validation.

The statistical indicators listed below were used to evaluate the goodness of fit of SIMDualKc. They were computed from the pairs of observed and predicted available soil water values  $O_i$  and  $P_i$  ( $i = 1, 2, \dots, n$ ), whose means are  $\bar{O}$  and  $\bar{P}$ , respectively. The

coefficients of regression and determination relating observed and simulated data and forced to the origin,  $b$  and  $R^2$  respectively, were computed as:

$$b = \frac{\sum_{i=1}^n O_i P_i}{\sum_{i=1}^n O_i^2} \quad (7.1)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\left[ \sum_{i=1}^n (O_i - \bar{O})^2 \right]^{0.5} \left[ \sum_{i=1}^n (P_i - \bar{P})^2 \right]^{0.5}} \right\}^2 \quad (7.2)$$

A regression coefficient close to 1 indicates that the predicted values are statistically close to the observed ones and a determination coefficient close to 1.0 indicates that most of the variation of the observed values is explained by the model.

The variance of the errors is expressed through the root mean square error (RMSE, mm) (Loague and Green, 1991):

$$RMSE = \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \right]^{0.5} \quad (7.3)$$

The average absolute error (AAE, mm) was computed to express the mean size of estimation errors, which is associated with the average relative error (ARE, %):

$$AAE = \frac{1}{n} \sum_{i=1}^n |O_i - P_i| \quad (7.4)$$

$$ARE = \frac{100}{n} \sum_{i=1}^n \left| \frac{O_i - P_i}{O_i} \right| \quad (7.5)$$

The modelling efficiency (EF, non-dimensional) proposed by Nash and Sutcliffe (1970), was used to determine the relative magnitude of the residual variance compared to the measured data variance (Moriassi et al., 2007). It is defined by the ratio of the mean square error to the variance in the observed data, subtracted from unity:

$$EF = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (7.6)$$

When EF are close to 0 or negative this means that the mean  $\bar{O}$  is as good or better predictor than the model (Legates and McCabe, 1999; Moriasi et al., 2007). The Willmott (1981) index of agreement ( $d_{IA}$ , non-dimensional) was used to represent the ratio between the mean square error and the "potential error" (Moriasi et al., 2007). It is defined as

$$d_{IA} = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (7.7)$$

From this equation,  $d_{IA} = 1$  indicates perfect agreement between the observed and predicted values, and  $d_{IA} = 0$  indicates no agreement at all (Legates and McCabe, 1999; Moriasi et al., 2007).

### 7.3. RESULTS AND DISCUSSION

#### 7.3.1. Calibration and validation of the model

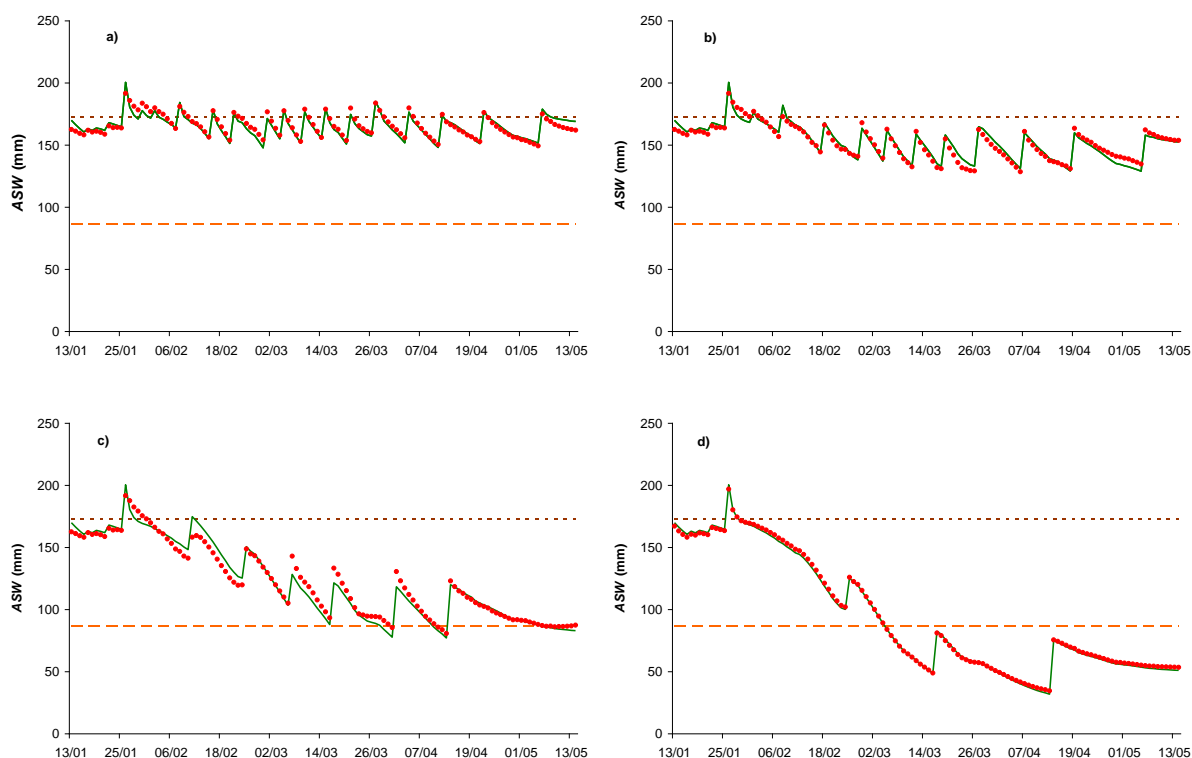
The calibrated and the initial parameters relating to the crop ( $K_{cb}$  and  $p$ ), the soil evaporation ( $Z_e$ , TEW and REW) and the parameters of the equations used to estimate the deep percolation ( $a_D$  and  $b_D$ ) are presented in Table 7.6 for both the sprinkler and drip experiments. Since the initial values used were the standard ones proposed by Allen et al. (1998) and Liu et al. (2006), changes from the initial to the calibrated values were relatively small.

The daily dynamics of the observed and simulated available soil water (ASW, mm) throughout the crop season relative to the sprinkler silage maize experiments used for calibration and validation are presented in Fig. 7.5. Results show that model simulations fit the observations of the three ST treatments well; no biases are detected. Results also show that water stress was not induced in treatments A1 and A2, with all observed ASW above the water stress threshold corresponding to ASW when the depletion fraction is 0.5. For treatment A3, there were a few days (108 and 111 days after planting, DAP) when a light stress occurred. In fact, the initial ASW was close to the total available water (TAW) and a large amount of rainfall occurred during the crop season which masked the effect of different irrigation strategies since the crop mostly used rainfall and soil water.



**Figure 7.5.** Daily comparison between observed (•) and simulated (—) available soil water (ASW) for the sprinkler irrigation experiment with maize treatments: a) A1 (validation), b) A2 (calibration) and c) A3 (validation). The horizontal lines refer to TAW (---) and RAW (···), respectively the total and readily available soil water.

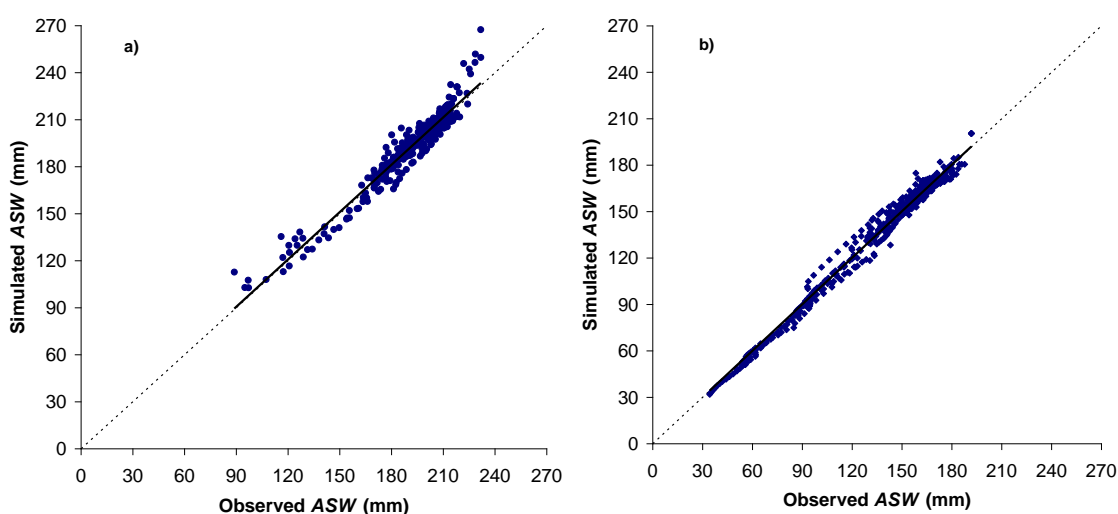
The daily dynamics of the observed and simulated ASW relative to the DTs experiment under the rain shelter are presented in Fig. 7.6. As for the STs, results show a good fit of the observations for all four treatments. Also, results show that treatments G1 and G2 were not water stressed, G3 was stressed for only a few days (76 to 79, 88 to 91 and 115 to 122 DAP), and only G4 was stressed for a long period, from day 53 DAP until harvest. This behaviour was due to the fact that the initial ASW was again close to TAW and 77 mm rainfall occurred during the initial stage of the crop, i.e., soil water and rainfall were enough to provide for the requirements of G2 and G3 crops, however not for G4. Hence, despite a rain shelter being used, ASW and rainfall during the initial stage overcame the impacts of reduced irrigation amounts. Nevertheless, the range of observed ASW was quite wide, from 37 to 197 mm, which allows appropriate calibration and validation of the model.



**Figure 7.6.** Daily comparison between observed (•) and simulated (—) available soil water (ASW) for the drip irrigation experiment with maize treatments: a) G1 (validation), b) G2 (validation), c) G3 (calibration) and d) G4 (validation). The horizontal lines refer to TAW (---) and RAW (— —), respectively the total and readily available soil water.

The regression coefficient (Table 7.7 and 7.8) is close to 1.0 for all treatments, thus demonstrating that the estimated ASW values are close to the observed ones. The determination coefficients ranged from 0.75 to 0.96, for the STs (Table 7.7), and varied from

0.86 to 0.99 for the DTs (Table 7.8). These high  $R^2$  values indicate a small variance of the residuals, thus a good explanation of the variance through the model. The regressions between simulated and observed ASW for all treatments are presented in Fig. 7.7a and b, which show that the assumption of homoscedasticity is respected. Results for both experiments show that both regression lines are close to the 1:1 line and that the variance of the residuals is small, with  $R^2 = 0.94$  for the STs and  $R^2 = 0.99$  for the DTs. For the ST treatments, when rainfall exceeded  $60 \text{ mm day}^{-1}$  and ASW values are much above field capacity, estimation errors are larger. These larger errors may result from the fact that the model does not simulate water storage in the mulch and its further release downwards or as evaporation. This is a model limitation already referred to in Section 7.2.3 and identifies an area requiring further research.



**Figure 7.7.** Comparison between the observed and simulated available soil water (ASW): a) sprinkler irrigation treatments (n=360), and b) drip irrigation treatments (n=488)

For the STs (Table 7.7), the RMSE values were smaller than 7.1 mm, averaging 6.5 mm, i.e., representing less than 3.3% of TAW on average. The errors AAE were also small, not exceeding 5.8 mm, which correspond to ARE lower than 3.5%. Errors relative to the DTs experiment (Table 7.8) were similar, with  $\text{RMSE} < 5.5 \text{ mm}$ , corresponding to less than 3.2% of TAW, and AAE not exceeding 4.2 mm, i.e.,  $\text{ARE} < 3.9\%$ . EF values ranged from 0.55 to 0.96 and  $d_{IA}$  was greater than 0.91 for all STs (Table 7.7), while EF ranged 0.85 to 0.99 and  $d_{IA}$  varied from 0.96 to 1.00 for the DTs (Table 7.8). These results show a good performance of the model and its ability to simulate ASW for common climatic conditions as previously shown by Rosa et al. (2012b) and Zhao et al. (2013).

**Table 7.7.** Indicators of goodness of fit relative to the model simulation of soil water content for the sprinkler irrigation treatments using the calibrated parameters

Goodness of fit indicators	b	R <sup>2</sup>	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	ARE (%)	EF	d <sub>IA</sub>
<b>A2 (calibration)</b>	1.02	0.88	6.0	2.8	4.2	2.2	0.84	0.96
<b>A1 (validation)</b>	1.01	0.75	6.4	3.0	4.5	2.2	0.55	0.91
<b>A3 (validation)</b>	0.99	0.96	7.1	3.3	5.8	3.5	0.96	0.99
<b>All treatments</b>	1.01	0.94	6.5	3.1	4.8	2.6	0.93	0.98

b and R<sup>2</sup> are the coefficients of regression and determination; RMSE is the root mean square error; TAW is the total available water; AAE and ARE are the average absolute and relative errors; EF is the modelling efficiency; d<sub>IA</sub> is the index of agreement

**Table 7.8.** Indicators of goodness of fit relative to the model simulation of soil water content for the drip irrigation treatments using the calibrated parameters

Goodness of fit indicators	b	R <sup>2</sup>	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	ARE (%)	EF	d <sub>IA</sub>
<b>G3 (calibration)</b>	1.00	0.97	5.5	3.2	4.2	3.4	0.97	0.96
<b>G1 (validation)</b>	1.00	0.86	3.4	2.0	2.9	1.7	0.85	0.98
<b>G2 (validation)</b>	1.00	0.93	3.6	2.1	3.0	2.0	0.93	0.99
<b>G4 (validation)</b>	1.02	0.99	5.0	2.9	3.6	3.9	0.99	1.00
<b>All treatments</b>	1.00	0.99	4.5	2.6	3.4	2.8	0.99	1.00

b and R<sup>2</sup> are the coefficients of regression and determination; RMSE is the root mean square error; TAW is the total available water; AAE and ARE are the average absolute and relative errors; EF is the modelling efficiency; d<sub>IA</sub> is the index of agreement

The possibilities for using the model with standard parameters if soil water or ET observations are not available for calibration were also assessed (results not shown). It was observed that RMSE values for the ST experiment were about 3 times larger than those obtained when using calibrated parameters, and for the DT experiment were nearly double; nevertheless, errors were within 10% of TAW. However, it was observed that results are sensitive to the estimation of percolation and runoff due to the occurrence of large precipitation during the maize crop season. Advice provided by Liu et al. (2006) about the use of the parametric functions for deep percolation need to be followed carefully if errors are to be kept low. For the southern Brazil region, using parameter values close to the ones calibrated in this study is advisable. Moreover, to overcome problems of soil variability that influence soil evaporation and deep percolation, it is also advisable to monitor soil water and

therefore check model simulations when high accuracy is required. Results obtained are very useful for further parameterising Sistema Irriga™ and improving its use in practice; however, specific studies on percolation and runoff for tropical soils are being developed to improve related model responses.

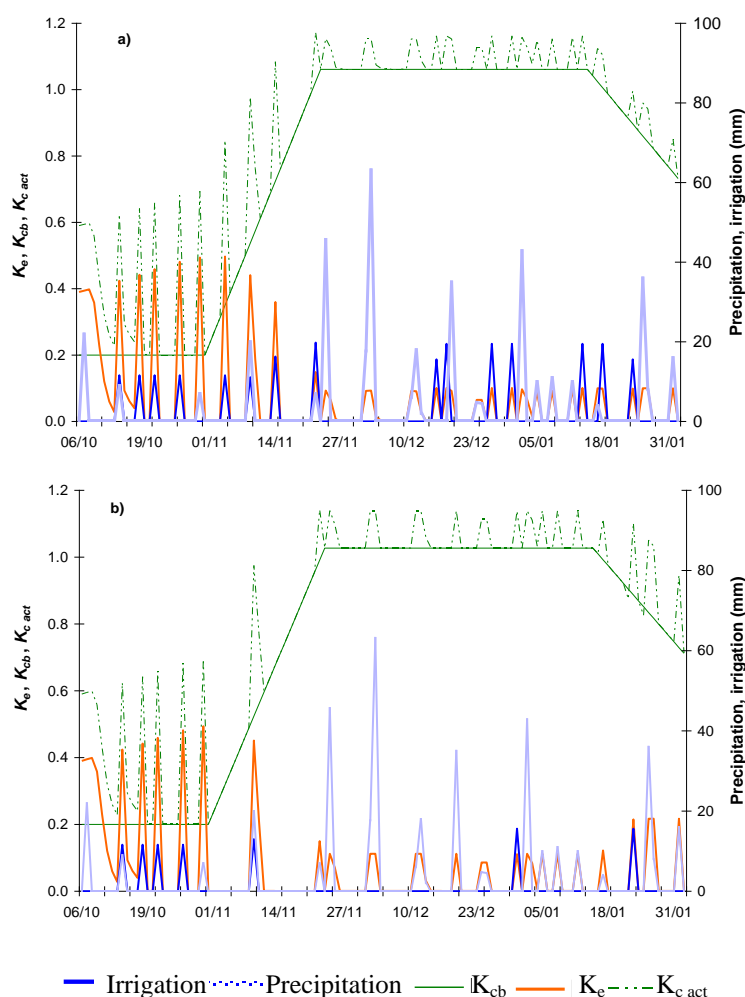
### 7.3.2. Basal crop coefficients

The values of  $K_{cb\ ini}$  generally vary little from one location to another since they represent transpiration from a crop in its initial stage. Values of  $K_{cb\ ini} = 0.20$  are common as occurred with this study (Table 7.6). The variability in wettings are expressed through  $K_e$ , including in presence of mulch, which is well evidenced by the  $K_e$  peaks in Figs. 7.8 and 7.9 during the initial and development crop stages.

The value calibrated for both experiments,  $K_{cb\ mid} = 1.12$ , is slightly smaller than those presented by Allen et al. (1998, 2007) and Zhao et al. (2013),  $K_{cb\ mid} = 1.15$ . That  $K_{cb\ mid}$  value is slightly larger than those obtained by Liu and Pereira (2000), Hsiao et al. (2009) and Rosa et al. (2012b). More often, values for  $K_{c\ mid}$  are reported in literature; thus, assuming  $K_{c\ mid} = K_{cb\ mid} + 0.05$  and  $K_{c\ end} = K_{cb\ end} + 0.05$  as proposed by Allen et al. (1998), it is possible to compare  $K_c$  and  $K_{cb}$  values. Hence, our calibrated value corresponds to  $K_{c\ mid} = 1.17$ , which compares well with the values proposed by Gao et al (2009), with  $K_{c\ mid}$  of 1.18-1.19, and Piccinni et al (2009), who found  $K_{c\ mid} = 1.20$ ; it is higher than values reported by Dominguez et al (2012), and Suyker and Verma (2009). Higher values are reported by many, e.g., Popova and Pereira (2011). By contrast, smaller values were proposed by Liu et al. (1998) and Liu and Pereira (2000) for North China, respectively 0.95 and 1.06. The relatively wide range of  $K_{c\ mid}$  values reported in literature is due to the field methods used for its estimation, the  $ET_o$  definition and computation adopted, the maize varieties used and their response to the climatic evaporative demand, the definition of the crop stages and their duration, as well as the influence of the climate relative to the adjustment factors proposed by Allen et al. (1998).

Values for  $K_{cb\ end}$  essentially depend on crop management prior to harvesting. The STs aimed at early harvesting for silage, thus the adopted  $K_{cb\ end} = 0.80$  is above the common values reported in literature, e.g., Rosa et al. (2012b). By contrast,  $K_{cb\ end} = 0.20$  was found for the drip irrigated grain maize experiment, which is within the range of values proposed by Allen et al. (1998) and Zhao et al. (2013), as well as Gao et al. (2009), who reported  $K_{c\ end}$  ranging from 0.22-0.28.

Fig. 7.8 shows the  $K_{cb}$  curve (with  $K_{cb\ mid}$  and  $K_{cb\ end}$  values corrected for climate as proposed by Allen et al., 1998), the  $K_e$  peaks and the resulting adjusted  $K_c$  curve ( $K_{c\ act}$ ) for the A2 and A3 treatments.  $K_{c\ act}$  results from the daily sum of  $K_e$  with the  $K_{cb\ adj}$ , i.e., the  $K_{cb}$  values adjusted for stress ( $K_{cb\ adj}=K_s \cdot K_{cb}$ ). Rainfall and irrigation are also included in Fig. 7.8 for ease of reading the variation of the parameters. Results show a high frequency of  $K_e$  peaks and, consequently of  $K_{c\ act}$  too, during the initial period. Then these peaks become smaller when the crop grows and shadows the ground, thus limiting the energy available for soil water evaporation. Those peaks relate well with the precipitation and irrigation events. The  $K_{c\ act}$  curve is never below the  $K_{cb}$  curve in case A2, hence indicating that no water stress occurred; by contrast, it is below the  $K_{cb}$  curve for a few days (108 and 111 DAP) in case of treatment A3, thus identifying short stress periods.



**Figure 7.8.** Daily variation of the basal crop coefficient ( $K_{cb}$ ), the evaporation coefficient ( $K_e$ ), and the adjusted crop coefficient ( $K_{c\ act}$ ) along with precipitation and irrigation for the sprinkler irrigation treatments A2 (a) and A3 (b)

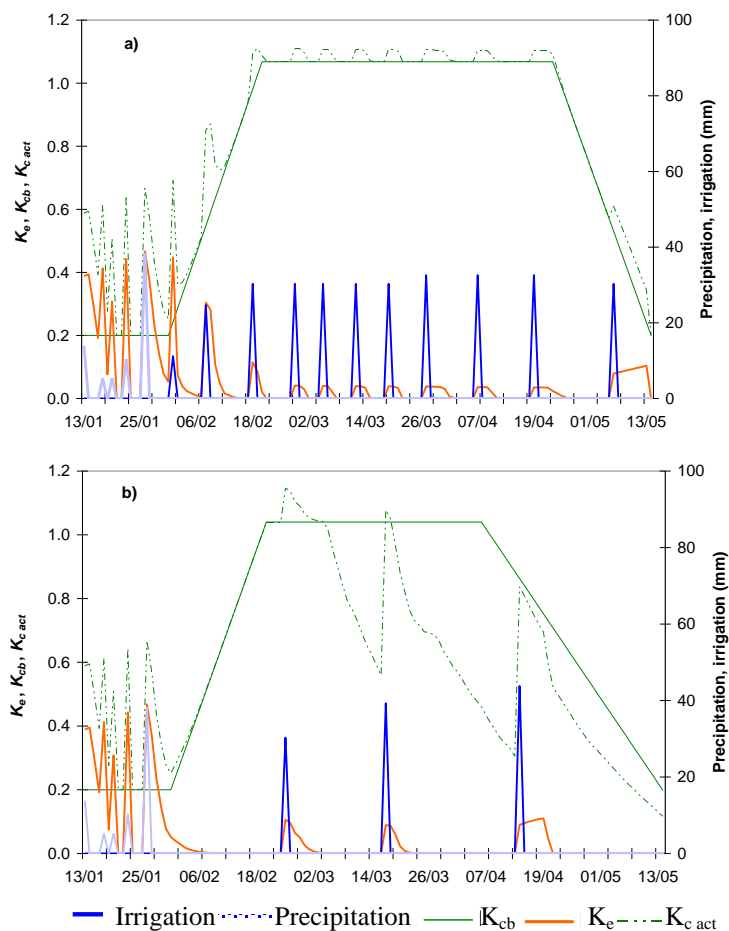
Similar curves are shown in Fig. 7.9 for DTs G2 and G4. Because the rain shelter was operating only after the initial period, the evaporative  $K_e$  peaks are only clearly visible during that period. Peaks are smoothed and much smaller for the drip irrigation events after the shelter was operating. The water stress imposed to G4 is clearly visible in Fig. 7.9b, where the  $K_{c_{act}}$  curve is below the  $K_{c_b}$  curve from April 30 until harvest. It should be noted that this curve reacted well to the irrigation events applied during midseason.

**Table 7.9.** Season water balance components for the sprinkler and drip irrigation treatments (maize cropped with straw mulch, Santa Maria)

Treatments	Precipitation (mm)	Irrigation (mm)	Deep percolation (mm)	Runoff (mm)	$\Delta ASW$ (mm)	$ET_c$ (mm)	
<b>Sprinkler irrigation</b>	A1	415	328	234	15	7	502
	A2	415	234	148	15	10	497
	A3	415	91	93	15	80	479
<b>Drip irrigation</b>	G1	73	389	86	1	3	365
	G2	73	316	33	1	19	361
	G3	73	218	24	1	89	342
	G4	73	113	23	1	122	272

The water balance components, precipitation, irrigation, deep percolation, runoff and ET, are presented in Table 7.9. For the ST treatments, despite large differences in irrigation, differences in ET are small or very small as for A1 and A2. In fact, when less water was applied the crop made better use of the available water. Thus deep percolation decreased when less irrigation was applied; conversely, the seasonal use of soil water increased from 7 mm in A1 to 80 mm in A3. For the DT experiment the increase in soil water use as the applied irrigation decreased is more evident. Deep percolation also decreased; however, these values are much less than for ST because less water was applied. Anyway, percolation occurred only during the initial period when the crop received precipitation. Because the mulch substantially controlled runoff, this was limited to 15 mm for ST and was negligible for

DT due to the shelter effect. These results are definitely usable in practice with Sistema Irriga™.

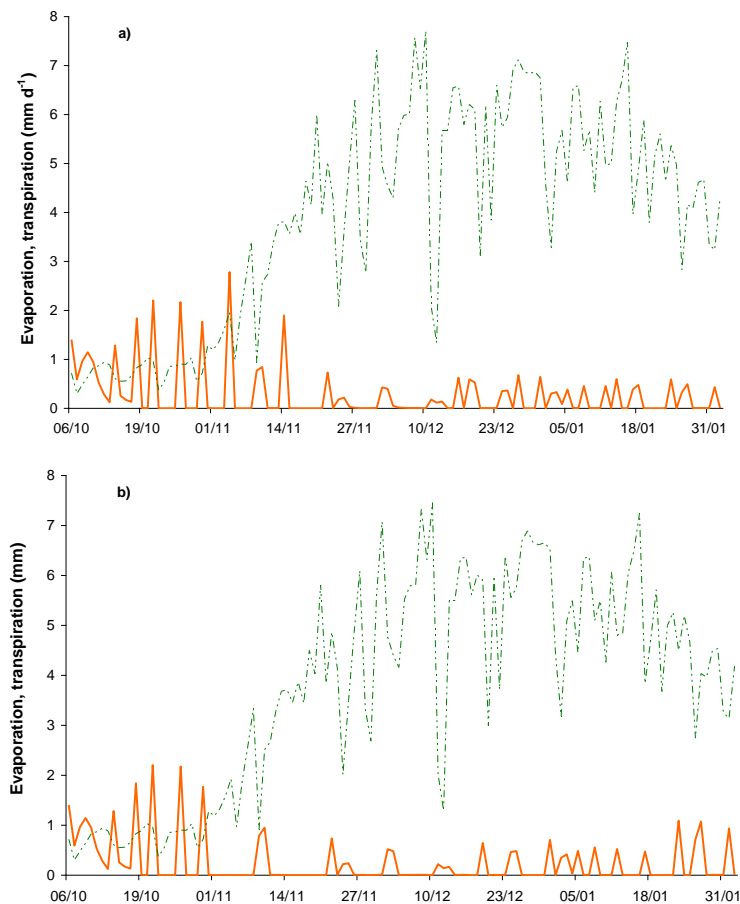


**Figure 7.9.** Daily variation of the basal crop coefficient ( $K_{cb}$ ), the evaporation coefficient ( $K_e$ ), and the adjusted crop coefficient ( $K_{c\ act}$ ) along with precipitation and irrigation, for the drip irrigation treatments G2 (a) and G4 (b)

### 7.3.3. Evaporation and transpiration components

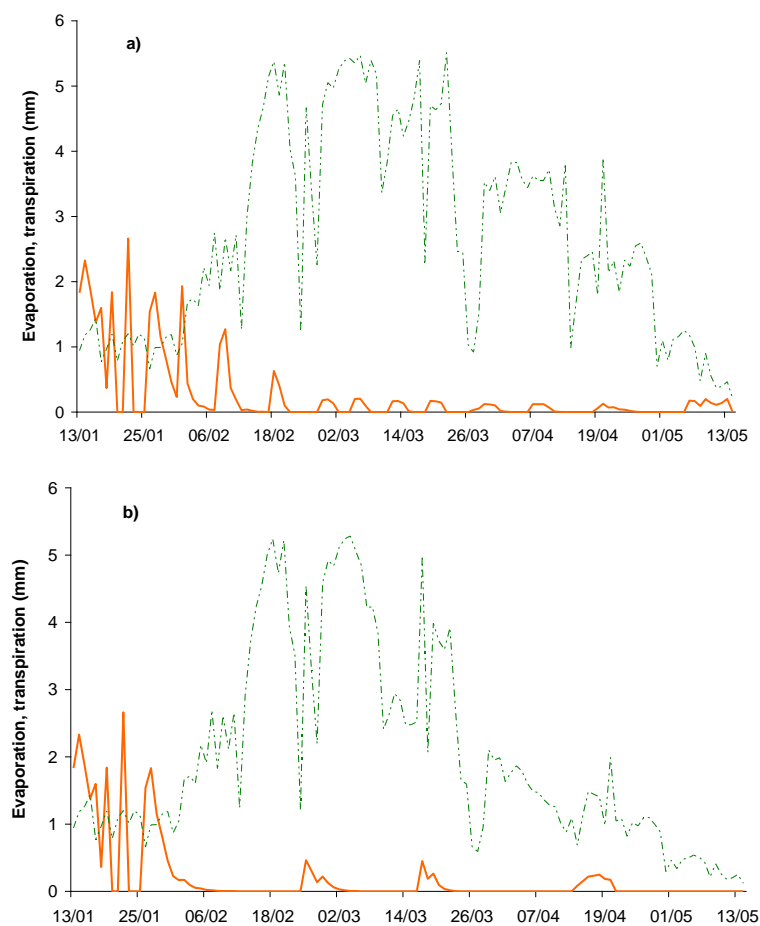
The SIMDualKc model provides both components of  $ET_c$ , soil evaporation ( $E_s$ , mm) and plant transpiration ( $T_c$ , mm). Results for the respective daily values are shown in Fig. 7.10 for the STs A1 and A3, and in Fig. 7.11 for the DTs G1 and G4. Fig. 7.10 shows that  $E_s$  started larger than  $T_c$  for the first days and, due to the effects of mulch, nearly equalled  $T_c$  for the initial crop stage. After this phase,  $E_s$  became progressively much smaller than  $T_c$ , which steadily increased with crop development. The reduction of  $E_s$  was also due to increased ground shading by the crop. After full cover,  $E_s$  remained very small. The effect of mulch is clearly visible, limiting the  $K_e$  peaks during the initial period to half of maximum  $K_c$  (Fig. 7.8). Mulch effect is also visible since  $E_s$  remains very low during late season, contrasting

with the observations of Zhao et al (2013) who noticed an increase of  $E_s$  under maize without mulch. Results so far are adequate but further experiments need to be developed to prove that soil evaporation reduces by 5% for each 10% fraction of soil covered by mulch as assumed by Allen et al. (1998).



**Figure 7.10.** Daily variation of soil evaporation ( $E_s$ , —) and plants transpiration ( $T_c$ , - - -) for the sprinkler irrigation treatments A2 (a) and A3 (b)

Results in Fig. 7.11 for drip irrigation during the initial period, when the shelter was not active, show a smaller reduction of  $E_s$ , which is greater than  $T_c$  during this period. The general pattern of  $E_s$  dynamics is similar to ST treatments,  $E_s$  becomes much lower after the initial crop stage because there was no rainfall after the initial period, there were less irrigation events and the soil was only partially wetted by irrigation.



**Figure 7.11.** Daily variation of soil evaporation ( $E_s$ , —) and plants transpiration ( $T_c$ , -.-) for the drip irrigation treatments G2 (a) and G4 (b).

Results for  $E_s$  and  $T_c$  are presented in Table 7.10 for the crop development stages and the season. Estimates for  $E_s/ET_c$  for the STs were 8, 7 and 6%, respectively for treatments A1, A2 and A3. For the DTs experiment,  $E_s/ET_c$  was 9, 9, 8 and 9% respectively for the treatments G1, G2, G3 and G4.  $E_s$  was proportionally larger for the DTs for various reasons, mainly because different mulches were used: in the STs, 5 t ha<sup>-1</sup> of dry oats mulch with density at planting of 0.9 were applied while mulching for the DTs consisted of 3 t ha<sup>-1</sup> of dry beans mulch with density of 0.8 at planting. It can also be observed that larger values of  $E_s/ET_c$  occurred in treatments that received more water and more frequent irrigations: for the sprinkling experiment, treatments A1, A2 and A3 received respectively 21, 15 and 7 irrigations; for DTs the number of irrigations was 15, 11, 6 and 3 respectively for treatments G1, G2, G3 and G4. The latter had a higher  $E_s/ET_c$  because the  $T_c$  amount was much lower than for the other three.

**Table 7.10.** Evaporation ( $E_s$ , mm) and transpiration ( $T_c$ , mm) for each crop growth stage of the maize crop in Santa Maria.

Treatments		Initial stage		Vegetative growth		Mid season		Late crop Season		Full Crop Season		$E_s/ET_c$ (%)
		$E_s$	$T_c$	$E_s$	$T_c$	$E_s$	$T_c$	$E_s$	$T_c$	$E_s$	$T_c$	
<b>Sprinkler irrigation</b>	A1	16	18	10	68	10	287	3	90	39	463	8
	A2	16	18	7	68	8	287	3	90	34	463	7
	A3	16	18	2	67	7	278	4	87	29	450	6
<b>Drip irrigation</b>	G1	22	19	8	56	3	228	1	28	34	331	9
	G2	20	19	7	56	3	227	1	28	31	330	9
	G3	20	19	4	55	5	218	0	21	29	313	8
	G4	20	19	1	55	4	161	0	12	25	247	9

Evaporation averaged 47% of  $ET_c$  for the STs and 53% for the DTs during the initial period (Table 7.10). This is probably due to the high soil water content in the evaporative layer, the high frequency of wettings, the very limited crop development and very low  $f_c$  at this stage. During the crop development phase,  $E_s$  was higher in treatments with a larger number of irrigation events. By contrast, during this stage  $E_s$  was practically nil in the treatment G4 because the surface layer was dry and did not receive any irrigation by this time. During the midseason, the fraction of wet soil exposed to solar radiation was further reduced due to high ground surface cover  $f_c$ , hence evaporation reduced to near zero. During the late season, in addition to mulch effects,  $f_c$  values decreased but, for STs, harvested for silage, the wetted fraction remained small and evaporation was minimal. In the DTs, despite  $f_c$  being reduced,  $f_w$  was kept low, hence  $E_s$  was very small. As expected,  $E_s$  was smaller for treatments with less water application since the evaporative soil layer remained dry for long periods. However, further experimental analysis is required because, as referred before, a fraction of  $E_s$  originates in the wetted mulch and this was not modelled separately.

The seasonal  $E_s/ET_c$  ranged from 6 to 9% (Table 7.10), which is much lower than for conditions without mulch as in the following examples: Zhao et al. (2013) reported values of 37% or larger, Liu et al. (2002) and Zhang et al (2003) obtained  $E/ET$  of 30%; Kang et al. (2003) found a seasonal value of 33%; Xu and Mermoud (2003) found 25 to 36%; and Tahiri et al (2006) found a maximum  $E/ET$  of 38%. Klocke et al. (2009) observed  $E_s/ET_c$  of 14 to 18% for a maize crop with wheat mulches, and these results are somewhat larger than those obtained in this study. Scopel et al. (2004) found a decrease of 50% on  $E/ET$  ratio when using a crop residues mulch with  $6 \text{ t ha}^{-1}$  and 10% decrease when the mulch amount was  $1 \text{ t ha}^{-1}$ . Chen et al. (2004) reported a decrease of 58% in  $E/ET$  when using wheat straw mulch

compared to the non-mulched treatment. These results also agree with those reported by Odhiambo and Irmak (2012) for soybeans. However, literature data do not refer to drip irrigation of maize and comparison of the mulches used is difficult. Despite our results relating well to the literature, there is the need to better assess the impacts of mulches on soil evaporation from further field experiments considering the environmental conditions prevailing in southern Brazil.

#### **7.4. CONCLUSIONS**

The SIMDualKc model was calibrated and validated for sprinkler and drip irrigated maize with soil surface mulches of oats and beans, respectively. Results were similar for all treatments, and it was probably best to use just one sprinkler and one drip treatment for a common calibration and use the remaining treatments for validation. The statistical indicators used to assess the model's ability to simulate the available soil water showed that the model does not present any trend to over or underestimate the soil water content during the different crop growth stages. Indicators relating to errors have shown that these are small, less than 4% of the total available soil water.

The model allowed  $K_{cb}$  to be determined and it was observed that these parameters are common for sprinkler and drip irrigation. Therefore, crop parameters determined here may be used elsewhere in Southern Brazil unless environmental conditions greatly change. Other soil parameters may be well adapted to other locations using approaches compatible with those in this study.

Results showed that  $E_s$  is an important component of  $ET_c$  during the initial crop growth stage. However, its relative value is highly influenced by mulch. After this stage,  $E_s/ET_c$  progressively decrease until becoming almost negligible due to the combined effects of mulch, crop development and low energy available on the ground. As expected,  $E_s$  was smaller for treatments with less water application since the evaporative soil layer remained dry for large periods.

There is a need to better assess the impacts of mulches on soil evaporation from further field experiments considering the environmental conditions prevailing in southern Brazil. In addition, the SIMDualKc model should be improved to include an additional reservoir representing water storage in the mulch to assess interception losses. Results achieved suggest that corrections used were adequate but their appropriateness may change considerably as pointed out in the literature.

## Acknowledgments

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# **Capítulo 8**

## **Modelling Economic Impacts of Deficit Irrigated Maize in Brazil with Consideration of Different Rainfall Regimes**

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## **8. MODELLING ECONOMIC IMPACTS OF DEFICIT IRRIGATED MAIZE IN BRAZIL WITH CONSIDERATION OF DIFFERENT RAINFALL REGIMES**

**Abstract:** Deficit irrigation is often required to cope with droughts and limited water availability. However, to select an appropriate irrigation management, it is necessary to assess when economic impacts of deficit irrigation are acceptable. Thus, the main goal of this study was to evaluate economic water productivity for maize submitted to various levels of water deficits and different irrigation systems. The study was based on two different experiments conducted in Southern Brazil, one using sprinkler irrigation to supplement rainfall and the other using drip irrigation with precipitation excluded by a rainfall shelter to simulate cultivation under dry conditions. Water productivity indicators were calculated referring to: a) actual field collected data, including yields, commodity prices and production costs; and b) a sensitivity analysis to commodity prices and production costs. Alternative centre-pivot irrigation scenarios were also developed to assess their feasibility in terms of water use and productivity when irrigation is used to supplement rainfall or when rainfall is scarce. Results show that the feasibility of deficit irrigation is highly influenced by commodity prices and by the irrigation (and water) costs when the irrigation costs are a large part of the production costs. Results also show that deficit irrigation applied when rainfall is abundant is easier to implement than deficit irrigation where rainfall is very scarce, when only a mild stress is economically viable. For well designed and managed centre-pivot systems, results confirm that adopting deficit irrigation when rainfall is scarce is less attractive than under conditions of irrigation to supplement rainfall. It could be concluded that farmers are unlikely to choose a deficit irrigation strategy unless they are facing reduced water availability for irrigation.

**Key words:** beneficial water use, centre-pivot irrigation, economic water productivity, irrigation and production costs, irrigation under low rainfall, supplemental irrigation, water productivity

### **8.1. INTRODUCTION**

At present, more than 1.5 billion ha are used worldwide for crop production and there is little scope for further expansion of agricultural land; increasing land productivity, mainly adopting

irrigation, is definitely required. According to FAO (2012), the world agricultural production has grown between 2.5 and 3 times over the last 50 years while the cultivated area has grown only 12%. More than 40% of the global increase in food production came from irrigated areas. However, at global level, agricultural water use represents 70% of all water use. Thus, and because water scarcity is increasing, the need to optimise water withdrawal is also increasing, mainly for irrigation purposes (Pereira et al., 2009). Consequently, farmers are forced to adopt an optimised irrigation management in order to decrease the water demand while increasing land and water productivity.

One commonly used technique that aims to decrease water use is deficit irrigation. This approach consists of deliberately applying irrigation depths smaller than those required to fully satisfy the crop water requirements, thus affecting evapotranspiration and consequently yields, but keeping a positive return from the irrigated crop (Pereira et al., 2002). By avoiding water stress during drought-sensitive stages, deficit irrigation also aims to maximise water productivity (Kang et al., 2000; Geerts and Raes, 2009). However, particularly in arid regions, appropriate management is necessary to control effects of reduced irrigation on soil salinity (Pereira et al., 2007; Xu et al., 2013). Moreover, depending upon water management and available rainfall during the crop season, the impacts of deficit irrigation on yields and related farmer incomes may or may not be negative, also depending upon the adopted irrigation scheduling, production costs and yield values (Lorite et al., 2007; Rodrigues and Pereira, 2009). Katerji et al. (2010) have shown that maize water productivity (WP) varies with total available soil water (TAW), with a high TAW favouring crop responses to deficit irrigation. Various studies have been developed to assess impacts of deficit irrigation on maize yields and economic returns (Dominguez et al., 2012; Farré and Faci, 2009; Payero et al., 2006; Popova et al., 2006). These studies clearly demonstrate that the feasibility of deficit irrigation strategies depends greatly upon the crop variety and the adopted crop and irrigation management, mainly referring to when those deficits are applied, e.g., Grassini et al. (2011) referred to the possibility of reducing irrigation depths by 25% throughout the crop cycle except for a -14 to +7 d window around silking, during which crops must be fully irrigated.

Another way to achieve efficient water use is through increasing WP, including the related economic results; however the term WP may be used with different meanings and at various scales, which may lead to contradictory interpretations. Various studies (Abd El-Wahed and Ali, 2013; Bouman, 2007; Grassini et al., 2011; Molden et al., 2010; Playan and Mateos, 2006; Zwart and Bastiaanssen, 2004) refer to factors influencing WP, including irrigation

management (e.g., supplemental and deficit irrigation), irrigation systems and their performance, crop varieties, soil fertility and TAW, pest and diseases, and soil-water conservation practices (e.g., tillage and mulching). Pereira et al. (2012) defined WP in agriculture as the ratio between the actual yield achieved ( $Y_a$ ) and the total water use (TWU). These authors, and also van Halsema and Vincent (2012), emphasised that WP enables an appropriate thinking about both the numerator and the denominator, i.e., on both crop growth and yield and water use processes. Though expressing WP without assessing the related economic impacts may lead to some misunderstanding, Pereira et al. (2012) also developed some indicators relating to economic water productivity.

Since the economic value of water is of great importance in a world where water scarcity is growing, it is imperative to maximise the farmer's income that results from water savings while taking into account the irrigation system performance. Grassini et al. (2011) reported that the quantification of water use and WP in actual irrigated cropping systems provides critical information to guide policies and regulations about water use and allocation with the goal of maintaining or increasing productivity while protecting natural resources. In order to achieve improved WP, farmers may upgrade/modernise their irrigation systems since the improvement of irrigation performance, mainly the distribution uniformity, is essential to reduce water demand at the farm level (Brennan, 2007; Pereira et al., 2002). This implies improved design, appropriate selection of the irrigation equipment and careful maintenance. When better distribution uniformity is attained, conditions exist to achieve improved beneficial water use (Pereira et al., 2012). However, there is a contradiction between economic results and the adoption of technologies that provide water saving as reported by Darouich et al. (2012) in relation to modernising surface irrigation systems; hence, efforts are required to help farmers investing to achieve better irrigation performance.

Currently, farmers are investing in irrigation modernisation by switching from labour demanding and poorer performing systems to automated ones, such as sprinkler and drip irrigation systems, in order to improve water savings and reduce labour and production costs. However, changes in irrigation systems must consider the need to achieve the best possible distribution uniformity. Several studies have assessed impacts of irrigation non-uniformity on crop yields and evidenced its importance (Brennan, 2007; Dechmi et al., 2003; López-Mata et al., 2010; Mantovani et al., 1995; Salmerón et al., 2012; Sanchez et al., 2010).

Many sprinkler systems have neither been properly designed or operated according to the design rules, or their operation has been hampered by poor maintenance. This results in

inadequate pressures and discharges along the system, leading to actual application rates deviating from the designed ones (Pereira, 1999). Poorly designed or managed set sprinkler systems with low irrigation uniformity may lead to wasted water and energy as well as to yield losses (Dechmi et al., 2003; Salmerón et al., 2012; Salvador et al., 2011). By contrast, well-designed and managed centre-pivot systems may provide highly uniform water application (Valín et al., 2012).

Drip irrigation systems have proved to be an effective alternative in terms of distribution uniformity and water saving. However, the performance of these systems depends greatly on the quality of design and equipment selected (Keller and Bliesner, 1990; Pereira, 1999; Evans et al., 2007; Pedras et al., 2009). Although drip irrigation can provide highly uniform water application when a good design is adopted, related objectives must combine with appropriate irrigation scheduling in practice (Barragan et al., 2010).

Brazil has 12% of the worldwide availability of water resources and the potential for expansion of irrigated agriculture is around 30 million ha (MIN, 2008), which represents an additional 25.5 million ha considering the current irrigated area of approximately 4.5 million ha. Despite the large potential of soils for sustainable irrigation development, only a small fraction is exploited. Therefore in Brazil the ratio of irrigated area/irrigable area is small (about 10%), resulting in a very low value of irrigated land area per capita at 0.018 ha person<sup>-1</sup>, the lowest in South America (ANA, 2009). About 90% of the irrigated area was developed by private enterprise, and less than 10% through public projects. According to the last agricultural census (IBGE, 2009), the irrigation methods used in Brazil are distributed as follows: 24.35% by flooding, 5.76% by furrow, 18.86% by centre-pivot sprinkling, 35.32% with other sprinkler methods, 7.36% by drip irrigation and 8.35% with other methods. In the last 10 years there has been an increase of 39% in the number of farmers using irrigation and of 42% in the total irrigated area, thus resulting an average growth rate of 150,000 ha per year.

Centre-pivot systems are replacing surface and other sprinkler irrigation systems due to easy automation, coverage of a large area, reliability of the systems, high application uniformity, and the ability to operate these systems on relatively rough topography (Montero et al., 2013; Valín et al., 2012). In Brazil, centre-pivot systems irrigate an estimated area of 840,000 ha, mainly in the Central-West region of the country, due to these advantages and potential for achieving high water distribution uniformity (Sandri and Cortez, 2009). The area irrigated by

centre-pivots is rapidly increasing, with 300 new systems (about 20,000 ha) installed in 2012 in Rio Grande do Sul State, where the study reported here was developed.

Recent studies have assessed the impacts of centre-pivot systems in terms of distribution uniformity, energy costs and crop profitability. López-Mata et al. (2010) concluded that improving a centre-pivot to increase the water application uniformity from 75 to 95% may increase the crop gross margin by up to 27%. Ortíz et al. (2010) analysed the effect of water application uniformity on the uniformity of soil water content and crop yields for a centre-pivot system irrigating sugar beet. The authors concluded that yields were affected more by the amount of water available in the soil than by the slight differences in soil water uniformity, hence calling attention to the importance of irrigation scheduling. Montero et al. (2013) analysed the main factors influencing annual water application costs in centre-pivot systems and determined the most cost-effective centre-pivot design. They concluded that the cost of water application with centre-pivot machines was quite sensitive to the uniformity of water application. They also observed that, to achieve high distribution uniformity, it is very important to adopt a proper nozzle package and to perform maintenance regularly. Moreno et al. (2012) developed a methodology for relating water application costs in centre-pivot systems with hydraulic factors, mainly relative to the pump and the pipe system, which mainly relate to energy costs. However, the approach did not lead to a clear assessment of the relationships between water saving, investments and yield incomes. Nevertheless, results agree with earlier analyses relating to sprinkler systems (Mantovani et al., 1995; Pereira et al., 2002; Tarjuelo et al., 1999).

Considering the aspects analysed above and previous developments by Rodrigues and Pereira (2009), the main goal of this study is to assess the economic impacts of water deficits, irrigation systems performance, commodity prices, production costs and water prices upon the physical and economic water productivity of irrigated maize. The application data used in this study are from two experimental maize fields in Santa Maria (Southern Brazil), one irrigated by a set sprinkler system to supplement rainfall, and the other by a drip system where rainfall was excluded through use of a rainfall shelter, as described by Martins et al. (2013). These two experiments made it possible to assess impacts of deficit irrigation comparing situations when rainfall is abundant or scarce. Data were used to develop several alternative centre-pivot irrigation scenarios in the form of different irrigation management options, in order to assess the economic feasibility of deficit irrigation.

## 8.2. MATERIALS AND METHODS

### 8.2.1. Experimental area and irrigation experiments

The experimental study was conducted at the Department of Agricultural Engineering, Federal University of Santa Maria (UFSM), Santa Maria, Brazil, located in the Central Depression of Rio Grande do Sul State. The climate is subtropical humid, a "cfa" according to the climatic classification of Köppen, without a dry season and with hot summers (Moreno, 1961). During the summer months, when the atmospheric evaporative demand is very high, dry spells often occur and rainfall is not sufficient to meet crop needs.

During 2010/2011 growing season, two maize experiments were conducted: one with irrigation to supplement rainfall (ISR) using a set sprinkler system, and the other with very low rainfall (ILR) by using a drip irrigation system under a rainfall shelter. ISR represents rainfall conditions of Southern Brazil, while ILR simulates conditions from dry central Brazil. Conducting the experiments under different rainfall conditions allows an improved basis for the use of the Sistema Irriga™ (Carlesso et al., 2009) under different climatic conditions and for various irrigation strategies throughout Brazil. Sistema Irriga™ is presently monitoring more than 90,000 ha each year in Brazil, including southern areas with high rainfall and areas in Central Brazil with very low rainfall. The ISR experiments were conducted with three irrigation treatments and 3 replications, with plots of 12 x 12 m<sup>2</sup>, irrigated with a set sprinkler system consisting of 4 sectorial sprinklers per plot with an average application rate of 14.83 mm h<sup>-1</sup>. The ILR experiments were performed with drip irrigation in an area protected by a rainfall shelter that covered the experimental area when rainfall occurred; rainfall was only allowed during the initial crop stage to ensure adequate and uniform establishment of the crop. The experiments consisted of four irrigation treatments with 4 replications, with experimental plots of 3 x 6 m<sup>2</sup>. The irrigation system consisted of pressure compensating in-line drippers with a discharge of 1.3 l h<sup>-1</sup> and an application rate of 13 mm h<sup>-1</sup>. The experiments are described in detail by Martins et al. (2013) including the calibration and validation of the water balance model SIMDualKc (Rosa et al., 2012) used in the present analysis.

Adopting the ISR and ILR experiments to base an analysis of deficit irrigation strategies when rainfall is abundant or is scarce is preferable to just performing simulations with actual weather data because it allows the crop responses to these different strategies to be captured. In subtropical areas the main factor differentiating the crop demand for irrigation is rainfall

because it is the main factor controlling the availability of soil water (Rossato et al., 2004) and the spatial variability of ETo is much smaller than the variability of precipitation. This has already been observed for the irrigated areas monitored with the Sistema Irriga™; a better model parameterisation for both high and low rainfall conditions was intended when installing the experiments and analysing them with the model SIMDualKc (Martins et al., 2013).

Both experiments were conducted with mulch since maize is generally cultivated in Brazil with direct seeding. Oats (*Avena strigosa*) crop residues were used for ISR (5 t ha<sup>-1</sup> of dry biomass spread over all the soil surface, so the cover fraction  $f_{r \text{ mulch}} = 1.0$ , and achieving an effective soil coverage  $f_{\text{eff mulch}} = 0.9$ ); beans (*Phaseolus vulgaris L*) crop residues were used for ILR (3 t ha<sup>-1</sup> of dry biomass,  $f_{r \text{ mulch}} = 1.0$  and  $f_{\text{eff mulch}} = 0.8$ ). The hybrid AG8011YG was used for ISR and the hybrid P1630H was used for ILR. In both cases the plant density was 6.5 plants m<sup>-2</sup>. Observations comprised irrigation water depths applied, soil water content down to 0.90 m depth using a calibrated set of FDR (Frequency Domain Reflectometry) sensors, crop height, leaf area index (LAI), ground cover fraction and yields. Detailed information on the experiments and results has been published by Martins et al (2013). Main results for all treatments, either observed or obtained with the model SIMDualKc, are given in Table 8.1: net and gross irrigation depths (NIWU & IWU, mm), precipitation (P, mm), total water use (TWU, mm), actual evapotranspiration (ET<sub>a</sub>, mm), beneficial water use fraction (BWUF) and actual yield (Y<sub>a</sub>, kg ha<sup>-1</sup>). These results show that ISR treatments were without or with only a mild water deficit while the ILR treatments all achieved deficit, which increased from ILR1 to ILR4. TWU was obtained by the sum of IWU, P and the variation of the soil water storage between planting and harvesting.

The irrigation and production costs were set for each treatment, taking into account the water and labour costs, nutrients applied, seeds, machinery, energy required for irrigation and the investment and maintenance required for each system (Table 8.2). Data for labour, machinery and harvest costs were obtained from regional data (CONAB, 2010). Costs concerning seeds, fertilisers and irrigation were obtained from the experimental data.

**Table 8.1.** Irrigation water use and grain yield relative to each treatment (adapted from Martins et al., 2013)

Treatment	Irrigation to supplement rainfall			Deficit irrigation with very low rainfall			
	ISR1	ISR2	ISR3	ILR1	ILR2	ILR3	ILR4
Net irrigation (NIWU, mm)	328	234	91	389	316	218	113
Gross irrigation (IWU, mm)	431	307	120	463	376	259	134
Rainfall (mm)	415	415	415	73	73	73	73
Total water use (TWU, mm)	853	732	615	539	468	421	329
Actual evapotranspiration (ET <sub>a</sub> , mm)	502	497	479	365	361	342	272
Beneficial water use fraction (BWUF)	0.59	0.68	0.78	0.68	0.77	0.81	0.83
Actual grain yield (Y <sub>a</sub> , kg ha <sup>-1</sup> )	13,212	12,548	12,011	9,190	8,340	7,650	5,312

**Table 8.2.** Operation and irrigation costs used in simulations

Items	Costs
<b>Operation Costs</b>	
Machinery (BRL ha <sup>-1</sup> )	204.00
Labour (BRL ha <sup>-1</sup> )	47.00
Seeds (BRL ha <sup>-1</sup> )	
Set Sprinkler	233.00
Drip	208.00
Fertilizers (BRL ha <sup>-1</sup> )	
Set Sprinkler	1,108.00
Drip	797.00
Harvest (BRL ha <sup>-1</sup> )	265.00
<b>Irrigation Costs</b>	
Investment annuity (BRL ha <sup>-1</sup> year <sup>-1</sup> )	
Set Sprinkler	441.00
Drip	778.00
Annual maintenance costs (BRL ha <sup>-1</sup> year <sup>-1</sup> )	
Set Sprinkler	137.50
Drip	225.00
Water (BRL m <sup>-3</sup> )	0.005
Electricity (BRL kWh <sup>-1</sup> )	0.31
Labour (BRL ha <sup>-1</sup> )	40.00

\* 1 BRL = 0.48 USD

### 8.2.2. Water productivity and water use indicators

Water productivity (WP) concepts apply to various definitions of water use and at various scales. Therefore, it is of great importance to properly define the related concepts used in this

study. Here, following Pereira et al., (2012), WP ( $\text{kg m}^{-3}$ ) is defined as the ratio between the actual crop yield ( $Y_a$ , kg) and the total water use (TWU,  $\text{m}^3$ ), thus:

$$\text{WP} = \frac{Y_a}{\text{TWU}} \quad (8.1)$$

When considering only the irrigation water use (IWU,  $\text{m}^3$ ), the result is the irrigation water productivity ( $\text{WP}_{\text{Irrig}}$ ,  $\text{kg m}^{-3}$ ):

$$\text{WP}_{\text{Irrig}} = \frac{Y_a}{\text{IWU}} \quad (8.2)$$

Pereira et al. (2012) proposed new water use indicators which include consideration of water reuse and aim to assist in identifying and providing clear distinctions between beneficial and non-beneficial water use because, from the water economy perspective, it is important to recognise both. The beneficial water use fraction (BWUF) may be defined as the fraction of TWU that is used to produce the actual yield. In the present situation, because there is no need for leaching or other processes such as runoff, and the presence of mulch helps limit ET from weeds, the beneficial water use corresponds to the actual ET. Thus, as an alternative to Eqs. 8.1 and 8.2, WP may be computed in relation to the beneficial water use (BWU,  $\text{m}^3$ ), thus

$$\text{WP}_{\text{BWU}} = \frac{Y_a}{\text{BWU}} \quad (8.3)$$

The water productivity may be considered not only in physical terms, as above, but also in economic terms. Replacing the numerator of equation 8.1 by the monetary value of the achieved yield, the economic water productivity (EWP,  $\text{BRL m}^{-3}$ ) is defined by:

$$\text{EWP} = \frac{\text{Value}(Y_a)}{\text{TWU}} \quad (8.4)$$

The monetary value refers to the Brazilian Real (BRL), for which the exchange rate is 1 BRL = 0.48 USD (as of December 2012). When considering IWU or BWU only, this gives:

$$\text{EWP}_{\text{Irrig}} = \frac{\text{Value}(Y_a)}{\text{IWU}} \quad (8.5)$$

$$\text{EWP}_{\text{BWU}} = \frac{\text{Value}(Y_a)}{\text{BWU}} \quad (8.6)$$

It is important to consider the economic issues relating to water productivity since the objective of a farmer is to achieve the best income and profit. As for this study, the economics of production is better considered when expressing both the numerator and the denominator

of equation 4 in monetary terms, respectively the yield value and the TWU cost (including all the farming costs), thus yielding the economic water productivity ratio ( $EWPR_{full-cost}$ ):

$$EWPR_{full-cost} = \frac{\text{Value}(Y_a)}{\text{Cost}(TWU)} \quad (8.7)$$

$EWPR_{full-cost}$  allows assessment of whether a given management option leads to positive ( $EWPR \geq 1$ ) or negative ( $EWPR < 1$ ) income since it compares the value of production with the farming costs. If, as an alternative, one considers the irrigation costs only, it results in:

$$EWPR_{irrig-cost} = \frac{\text{Value}(Y_a)}{\text{Cost}(IWU)} \quad (8.8)$$

As referred to above, data on  $Y_a$ , IWU, TWU and BWUF (Table 8.1) were obtained from computing the soil water balance (Martins et al., 2013). The monetary values of yields were computed using a grain price of 0.40 BRL  $kg^{-1}$ . The irrigation and production costs are summarised in Table 8.2.

### 8.2.3. Alternative irrigation system scenarios

In order to assess the impacts of adopting centre-pivot systems, the most common system for maize in Brazil at present, several scenarios were developed that allow the economic results of the corresponding investment to be assessed. Simulation scenarios were created with irrigated areas, land slopes, pivot point pressures and sprinkler packages corresponding to five different centre-pivot systems in operation in Rio Grande do Sul monitored by Sistema Irriga™. Data collected from field assessments included the irrigated area, pipe sizes, working pressure and discharge, and pump characteristics. The simulation scenarios were developed with the model DEPIVOT (Valín et al., 2012) using the actual system characteristics.

The model DEPIVOT consists of a simulation package developed in Visual Basic and database in Access. It allows alternative sprinkler packages to be developed and compared based on irrigation performance, including potential runoff. The model comprises five main sub-models for: (a) computation of the gross irrigation requirements; (b) sizing the lateral pipe spans through the hydraulics computation of the friction losses and respective operative simulation considering the effects of topography; (c) selecting a sprinkler package with computation of pressure and discharge at each outlet and including the consideration of pressure regulators; (d) verification of the sprinkler package through estimation of runoff potential by comparing application and infiltration rates at selected locations along the lateral;

and (e) estimating uniformity performance indicators expected when in operation. The user should verify if performance is within target values set at the start and should develop and compare alternative sprinkler packages until appropriate conditions are obtained (Valín et al., 2012).

DEPIVOT was adopted in this study to create alternative sprinkler packages and to compare various working conditions, mainly relating to pressure at the pivot point, pressure variation due to land elevation and the area irrigated. Hence, different sprinkler packages were created adopting equipment from two major sprinkler manufacturers: Super Spray (S) from Senninger® and Rotators R3000 (R) from Nelson®. The corresponding irrigation systems scenarios are presented in Table 8.3, which includes the irrigated area, average slope, pivot point pressure, distribution uniformity (DU) and Christiansen coefficient of uniformity (CU).

Investment costs ( $C_{inv}$ , BRL) were computed for each system scenario. They comprise the pump and respective pipe system, the conveyance and distribution pipe and the centre-pivot costs, including the selected sprinkler package. The investment annuity  $A_{inv}$  (BRL year<sup>-1</sup>) relative to the investment cost  $C_{inv}$  is:

$$A_{inv} = CRF C_{inv} \quad (8.9)$$

where CRF is the capital recovery factor.  $A_{inv}$  was computed considering a life-time  $n = 24$  years for the pump and respective pipe system, the conveyance and distribution pipe and the centre-pivot equipment, and a life-time  $n = 12$  years for the sprinklers. An interest rate,  $i$ , of 5% was considered. CRF was then calculated from the life-time and the interest rate as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (8.10)$$

The investment annuity per unit of irrigated area is  $C_a$  (BRL ha<sup>-1</sup> year<sup>-1</sup>) and is the ratio of  $A_{inv}$  to the irrigated area. The investment annuity values are presented in Table 8.2 for the set sprinkler and drip systems used in experiments, and in Table 8.3 for the various centre-pivot scenarios.

The operation costs were obtained from the sum of the annual energy costs ( $C_{en}$ ), the energy demand tax ( $C_d$ ), and the annual maintenance costs ( $C_m$ ).  $C_{en}$  is calculated as:

$$C_{en} = P E_r T_i \quad (8.11)$$

where  $P$  is the power of the pumping station (kW),  $E_r$  is the energy rate (BRL kWh<sup>-1</sup>) and  $T_i$  is the total annual operation time (h) of the pump. The energy cost per unit of irrigated area

(BRL ha<sup>-1</sup>) is calculated by dividing the annual energy cost  $C_{en}$  by the irrigated area. Calculations were based upon the energy prices in Southern Brazil. The energy demand tax,  $C_d$ , is the fixed amount per kW charged by the regional authorities to operate the pump; the value used herein is 10.07 BRL kW<sup>-1</sup>. The annual maintenance costs ( $C_m$ ) were assumed to be equal to 1% of the investment cost and are also included in Tables 8.2 and 8.3.

**Table 8.3.** Irrigation system scenarios

Sprinkler Package	System Scenario	Irrigated Area	Average Land Slope (%)	Pivot Point Pressure (kPa)	CU (%)	DU (%)	$C_a$ (BRL ha <sup>-1</sup> year <sup>-1</sup> )*	$C_m$ (BRL ha <sup>-1</sup> year <sup>-1</sup> )*
<b>Senninger® Super Spray</b>	<b>S1</b>	32.13	1.46	290	95.27	90.79	385	53
	<b>S2</b>	46.34	1.52	385	96.51	93.00	369	51
	<b>S3</b>	65.03	2.47	455	95.98	91.83	291	40
	<b>S4</b>	81.27	0.65	410	96.61	93.01	269	37
	<b>S5</b>	110.22	1.47	430	96.31	92.65	254	35
<b>Nelson® Rotator R3000</b>	<b>R1</b>	32.13	1.46	330	92.16	87.80	417	56
	<b>R2</b>	46.34	1.52	410	95.83	91.68	395	53
	<b>R3</b>	65.03	2.47	480	93.73	89.81	314	42
	<b>R4</b>	81.27	0.65	440	95.27	91.45	289	39
	<b>R5</b>	110.22	1.47	470	94.19	90.48	272	37

CU = Christiansen coefficient of uniformity; DU = distribution uniformity;  $C_a$  = investment annuity per unit of irrigated area;  $C_m$  = annual maintenance costs

\* 1 BRL = 0.48 USD

## 8.3. RESULTS

### 8.3.1. Water Productivity

Considering the actual commodity prices, where the unit value of maize grain is of 0.40 BRL kg<sup>-1</sup>, results for the physical (WP, WP<sub>Irrig</sub> and WP<sub>BWU</sub>) and economical (EWP, EWP<sub>Irrig</sub> and EWP<sub>BWU</sub>) water productivity for all the field treatments (Table 8.1) are presented in Table 8.4. An analysis of variance (ANOVA) was used to test all water productivity indicators for treatment differences using the least significant difference method with  $P < 0.05$ .

**Table 8.4.** Physical and economic water productivity (WP and EWP) for all treatments.

Treat.	WP (kg m <sup>-3</sup> )		WP <sub>Irrig</sub> (kg m <sup>-3</sup> )		WP <sub>BWU</sub> (kg m <sup>-3</sup> )		EWP (BRL m <sup>-3</sup> )		EWP <sub>Irrig</sub> (BRL m <sup>-3</sup> )		EWP <sub>BWU</sub> (BRL m <sup>-3</sup> )	
	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR
1	1.55a	1.71a,b	3.07a	1.99a	2.63a	2.52a	0.62a	0.68a	1.23a	0.79a	1.05a	1.01a
2	1.71a	1.80a	4.08a	2.24a	2.52a	2.33a,b	0.69a	0.72a	1.63a	0.89a	1.01a	0.93a,b
3	1.95c	1.82a	10.05b	2.95a	2.51a	2.24b	0.78a	0.73a	4.02b	1.18a	1.00a	0.89b
4	-	1.61b	-	3.95a	-	1.95c		0.65a	-	1.58a	-	0.78c

Within column, values with the same letter are not significantly different at  $p < 0.05$ .

WP<sub>Irrig</sub> = irrigation water productivity; WP<sub>BWU</sub> = water productivity relative to the beneficial water use ;EWP<sub>Irrig</sub> irrigation economic water productivity EWP<sub>BWU</sub> = economic water productivity relative to the beneficial water use

Results in Table 8.4 show that adopting a deficit irrigation strategy when farming maize often leads to higher WP and WP<sub>Irrig</sub> when compared with full irrigation. This is particularly evident for WP<sub>Irrig</sub> because it depends only from the irrigation water use. WP for ISR treatments varied from 1.55 to 1.95 kg m<sup>-3</sup>, with the highest value for ISR3. For ILR, because TWU is smaller (Table 8.1), WP results were generally higher than for ISR, ranging from 1.61 to 1.82 kg m<sup>-3</sup>, with ILR3 leading to the highest WP results but with the lowest value for the more stressed treatment ILR4. WP values obtained in this study compare well with the values proposed by Kiziloglu et al. (2009), with 1.50 kg m<sup>-3</sup> for full irrigation, and by Rodrigues and Pereira, (2009) with 1.72 kg m<sup>-3</sup> for deficit irrigation, both under sprinkler irrigation. However, these WP values for sprinkler irrigation are slightly higher than those obtained by O'Neill et al. (2008), with 1.4 kg m<sup>-3</sup> for full irrigation. As for drip systems, results are comparable with the ones proposed by Karam et al. (2003), ranging from 1.54 to 1.68 kg m<sup>-3</sup> and from 1.87 to 1.88 kg m<sup>-3</sup> for full and deficit irrigation, respectively. Other authors also present similar values for drip irrigation, such as O'Neill et al. (2008) with 1.7 kg m<sup>-3</sup> for full irrigation, and Sampathkumar et al. (2012) ranging from 1.60 to 1.72 kg m<sup>-3</sup> and 1.80 to 1.92 kg m<sup>-3</sup> for full and deficit irrigation, respectively.

WP<sub>Irrig</sub> values ranged from 3.07 to 10.05 kg m<sup>-3</sup> for ISR while they varied from 1.99 to 3.95 kg m<sup>-3</sup> for ILR. Higher values of WP<sub>Irrig</sub> for ISR resulted from high precipitation received during the farming season, which contrasted with ILR experiments, conducted without rainfall for most of time, which led to smaller differences between WP and WP<sub>Irrig</sub> for ILR. For both irrigation systems, deficit irrigation strategies generally lead to higher WP<sub>Irrig</sub> due to lower TWU and low yield losses, as previously discussed by Rodrigues and Pereira (2009).

However, this assumption contrasts with the results presented by other authors (Abd El-Wahed and Ali, 2013; Igbadun et al., 2003), where  $WP_{Irrig}$  decreased with the increase of water deficits due to higher yield losses.

$WP_{BWU}$  showed a contrasting behaviour as it decreased with higher deficits. This may be explained by the fact that the rate of yield decrease is higher than the one for BWU, thus leading to higher  $WP_{BWU}$  values for the irrigation treatments receiving more water and yielding more (ISR1 and ILR1).

EWP for ISR varied from 0.62 to 0.78 BRL  $m^{-3}$  while it ranged from 0.65 to 0.73 BRL  $m^{-3}$  for ILR.  $EWP_{Irrig}$  ranged from 1.23 to 4.02 BRL  $m^{-3}$  and from 0.79 to 1.58 BRL  $m^{-3}$  for ISR and ILR, respectively. The full irrigation treatment under the sprinkler system (ISR1) had the lowest EWP value among all treatments and systems. As for  $WP_{Irrig}$ ,  $EWP_{Irrig}$  increased at a smaller rate for ILR compared to ISR due to reduced rainfall contribution to ET. However, this indicator showed a similar behaviour for both ISR and ILR, which reflects the effect of a smaller denominator when deficit irrigation is considered. EWP values were also in accordance with the ones presented by Rodrigues and Pereira (2009) for Portugal. As for  $WP_{BWU}$ , the behaviour of  $EWP_{BWU}$  is contrasting, i.e., because BWU corresponds to the water used for achieving the desired yield,  $EWP_{BWU}$  decreases when water deficits increase.

To assess the feasibility of different irrigation strategies in terms of defining the economic return threshold at which farming becomes profitable, the economic water productivity ratio (EWPR) was used, particularly the indicators  $EWPR_{Irrig-cost}$  and  $EWPR_{full-cost}$  that compare the yield values per unit of irrigation and of farming costs respectively. Table 8.5 shows the variation of both indicators for all the irrigation experiments. When considering the irrigation costs only,  $EWPR_{Irrig-cost}$  was larger when adopting moderate deficit irrigation for the ISR treatments (ISR3 in Table 8.5); however, differences between treatments were small. For the ILR deficit irrigation treatments  $EWPR_{Irrig-cost}$  was larger for ILR1 and decreased when water deficits increased, with the lowest values for ILR4. Results indicate that moderate to heavy deficits are less profitable than mild ones. Apparently, results are in accordance with those obtained by Abd El-Wahed and Ali (2013). The difference in behaviour between ISR and ILR indicates that  $EWPR_{Irrig-cost}$  is particularly sensitive to the amount of rainfall that is available for the crop in addition to irrigation. These results show that it is probable that this indicator should not be used to compare situations referring to supplemental irrigation with those where irrigation is largely the main source for evapotranspiration.

**Table 8.5.** Comparison between economic water productivity ratio for irrigation costs ( $EWPR_{\text{irrig-cost}}$ ) and total farming costs ( $EWPR_{\text{full-cost}}$ ) for all the irrigation experiments.

Treatment	$EWPR_{\text{full-cost}}$	$EWPR_{\text{irrig-cost}}$	Treatment	$EWPR_{\text{full-cost}}$	$EWPR_{\text{irrig-cost}}$
ISR1	1.83	7.00	ILR1	1.27	3.36
ISR2	1.75	6.95	ILR2	1.16	3.09
ISR3	1.71	7.16	ILR3	1.06	2.84
			ILR4	0.74	1.99

Results for  $EWPR_{\text{full-cost}}$  (Table 8.5) show a different behaviour relative to  $EWPR_{\text{irrig-cost}}$  when considering the ISR treatments. Values tend to decrease from a maximum for full irrigation to smaller values relative to deficit irrigation. This is probably due to the fact that irrigation costs in Southern Brazil play a minor role in the total farming costs. The  $EWPR_{\text{full-cost}}$  values ranged from 1.71 to 1.83 for ISR and from 0.74 to 1.27 for the ILR experiments, with smaller values for the larger deficit treatments. These lower values for ILR are due to less water availability, thus smaller  $ET_a$  and smaller yields (Table 8.1). The adoption of irrigation at large deficits when rainfall is lacking, as simulated for ILR4, leads to a negative income ( $EWPR < 1.0$ ). In other words, for the conditions observed, yield losses due to high irrigation deficits are not acceptable when the rainfall contribution is small.

### 8.3.2. Assessing the impacts of commodity prices and farming costs

Changes in commodity prices and in production costs may have strong effects on water use and economic results. Higher commodity prices may lead farmers to increase the optimal levels of input use, thus achieving higher yields (Finger, 2012). To better understand the effects of these economic factors, a sensitivity analysis was conducted considering various levels of change of commodity prices combined with various levels of increase/decrease of production costs, mainly water and labour costs. The analysis was performed by assessing the impacts on  $EWPR_{\text{full-cost}}$  due to increasing the present commodity prices and production costs by 20, 50 and 100% and decreasing by 20 and 50% (Table 8.6).

**Table 8.6.** Sensitivity analysis of the economic water productivity ratio, when considering the total farming costs ( $EWPR_{full-cost}$ ), to commodity prices and production costs

Treatments	Changes in water and irrigation labour costs					
	+100%	+50%	+20%	no change	-20%	-50%
<b>50% decrease in Commodity Prices</b>						
ISR1	0.88	0.90	0.91	0.91	0.92	0.93
ISR2	0.85	0.86	0.87	0.88	0.88	0.89
ISR3	0.83	0.84	0.85	0.85	0.86	0.87
ILR1	0.61	0.62	0.63	0.63	0.64	0.65
ILR2	0.56	0.57	0.58	0.58	0.58	0.59
ILR3	0.51	0.52	0.53	0.53	0.53	0.54
ILR4	0.36	0.36	0.37	0.37	0.37	0.38
<b>20% decrease in Commodity Prices</b>						
ISR1	1.41	1.43	1.45	1.46	1.47	1.49
ISR2	1.36	1.38	1.39	1.40	1.41	1.43
ISR3	1.32	1.35	1.36	1.37	1.38	1.39
ILR1	0.98	1.00	1.01	1.01	1.02	1.03
ILR2	0.90	0.91	0.92	0.93	0.94	0.95
ILR3	0.82	0.83	0.84	0.85	0.85	0.86
ILR4	0.57	0.58	0.59	0.59	0.60	0.60
<b>Present Commodity Prices</b>						
ISR1	1.76	1.79	1.81	1.83	1.84	1.86
ISR2	1.69	1.72	1.74	1.75	1.77	1.79
ISR3	1.66	1.68	1.70	1.71	1.72	1.74
ILR1	1.22	1.24	1.26	1.27	1.28	1.29
ILR2	1.12	1.14	1.15	1.16	1.17	1.18
ILR3	1.03	1.04	1.05	1.06	1.07	1.08
ILR4	0.72	0.73	0.74	0.74	0.74	0.75
<b>20% increase in Commodity Prices</b>						
ISR1	2.11	2.15	2.18	2.19	2.21	2.23
ISR2	2.03	2.07	2.09	2.11	2.12	2.14
ISR3	1.99	2.02	2.04	2.05	2.07	2.09
ILR1	1.47	1.49	1.51	1.52	1.53	1.55
ILR2	1.34	1.37	1.38	1.39	1.40	1.42
ILR3	1.23	1.25	1.26	1.27	1.28	1.30
ILR4	0.86	0.87	0.88	0.89	0.89	0.90
<b>50% increase in Commodity Prices</b>						
ISR1	2.64	2.69	2.72	2.74	2.76	2.79
ISR2	2.54	2.59	2.61	2.63	2.65	2.68
ISR3	2.48	2.52	2.55	2.56	2.58	2.61
ILR1	1.83	1.87	1.89	1.90	1.92	1.94
ILR2	1.68	1.71	1.73	1.74	1.75	1.77
ILR3	1.54	1.56	1.58	1.59	1.60	1.62
ILR4	1.08	1.09	1.10	1.11	1.12	1.13
<b>100% increase in Commodity Prices</b>						
ISR1	3.52	3.59	3.63	3.65	3.68	3.72
ISR2	3.39	3.45	3.48	3.51	3.53	3.57
ISR3	3.31	3.36	3.40	3.42	3.44	3.48
ILR1	2.44	2.49	2.52	2.54	2.56	2.58
ILR2	2.24	2.28	2.31	2.32	2.34	2.37
ILR3	2.05	2.09	2.11	2.12	2.14	2.16
ILR4	1.43	1.46	1.47	1.48	1.49	1.50

As shown in Table 8.5, the  $EWPR_{full-cost}$  ranged from 0.74 to 1.83 for the current commodity prices and production costs. The lower ratio refers to treatment ILR4 due to the low yield

achieved as a consequence of a very high irrigation deficit in absence of rainfall. When cutting commodity prices by half,  $EWPR_{full-cost}$  decreased to values not exceeding 0.93 for treatment ISR1 (Table 8.6). A further reduction would occur if the production costs were to increase by 100%; the highest value would then be 0.88 for ISR1. Lower values were obtained for all other treatments, particularly for the ILR ones. By contrast, considering a decrease of only 20% on the commodity prices, all ISR treatments would have positive but low incomes (Table 8.6). ILR1 then had  $EWPR_{full-cost}$  slightly above 1.0, thus showing it to be somewhat sensitive to commodity price changes. However, because it involves low water availability and high ET deficits, ILR1 is very sensitive to market variations. This indicates that economic results are particularly sensitive to commodity prices as already observed by Rodrigues et al. (2010) for Portugal in a period when maize prices were lower than at present. These results are however different from but not opposed to those by Cortignani and Severini (2009) for Italy, where the adoption of deficit irrigation is mainly motivated by less water availability for irrigation and is favoured by higher commodity prices.

Variations due to labour and water costs were relatively small because their share in the production costs is small. For the present commodity prices, if those production costs increased by 100%,  $EWPR_{full-cost}$  would decrease by 3.1 to 4.6% only; similarly, if the water and labour costs decrease to half of the actual values,  $EWPR_{full-cost}$  would increase by 1.6 to 1.9%.

If the commodity price were to increase by 20%, all treatments, except ILR4, would lead to positive incomes, even for increased production costs (Table 8.6). Nevertheless, the treatment ILR4 has shown  $EWPR_{full-cost}$  values close to 1. An increase of commodity prices by 50% would lead to  $EWPR_{full-cost}$  values ranging from 1.08 to 2.64 if water and labour costs increase 100%, and ranging from 1.13 to 2.79 if the production costs were to decrease to half of the present values. If production costs were to double,  $EWPR_{full-cost}$  would be improved by between 44.5 and 45.2% when commodity prices increased by 50%. Summarising, results show that the viability of deficit irrigation is extremely dependent of commodity prices, while changes in water and labour costs have a low impact on related economic results. This behaviour is due to the price structure actually prevailing in maize farming in Brazil. Results also show that deficit irrigation results are highly influenced by the availability of rainfall in addition to irrigation, i.e., deficit irrigation with supplemental irrigation is more easily viable.

Results presented by other authors on the effects of irrigation costs, mainly water prices, are somewhat contradictory. Gómez-Limón and Riesgo (2004) have shown a great impact of

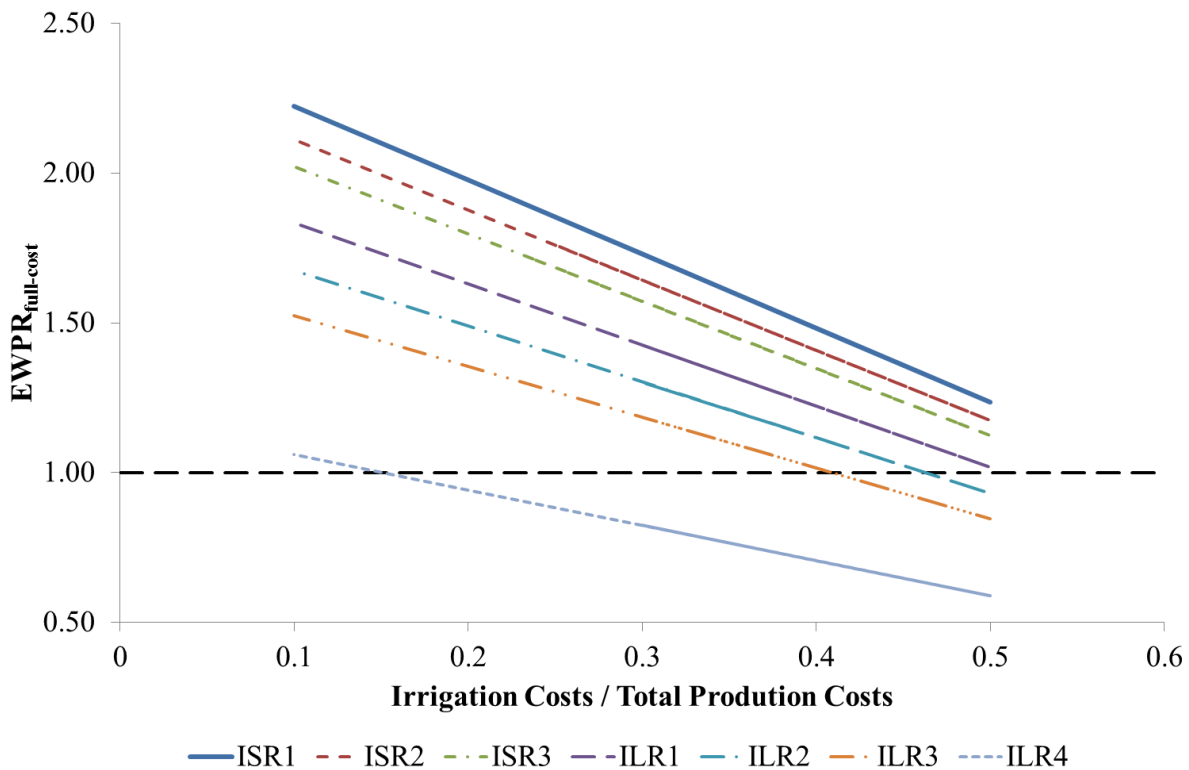
water prices on irrigation water use though the effect depended upon the orientation of farming and the structure of production costs. Bazzani et al. (2005) have also shown a great impact of water prices on water use but varying with the farming systems considered. Bartolini et al. (2007) suggested that a water price increment has a lower effect than a production cost increase; however, the water costs considered were quite low. By contrast, Huffaker and Whittlesey (2003) concluded that increasing the cost of applied water may be an effective water conservation policy, i.e., the impacts of water costs may be important in terms of water use. Also, Kampas et al. (2012) state that deficit irrigation is highly dependent upon the irrigation and water costs. Thus, considering the results above, where impacts of commodity prices are much more relevant than those of irrigation and water costs due to the low share of related costs in the production costs, is important to assess the possible impacts of changing that share fraction. This is shown in Fig. 8.1, where changes in  $EWPR_{full-cost}$  are presented as a function of the irrigation costs share in the total production costs for all the ISR and ILR treatments considering the current commodity prices.

Figure 8.1 shows that ISR treatments would lead to a positive farm income even if the irrigation costs were to represent half of the total production costs, with  $EWPR_{full-cost}$  decreasing by 32.3 to 34.3% relative to present conditions. A decrease of the irrigation costs to only 10% of the total production costs would lead to  $EWPR_{full-cost}$  values greater than 2.0, representing an increase ranging from 18.2 to 21.8% when compared to the current price/costs scenario.

By contrast, ILR seems to be more sensitive to the variation of irrigation costs. An increase of these costs to half of the total production costs would lead to negative farm incomes, i.e.,  $EWPR_{full-cost} < 1.0$  when that share reaches 40%. ILR 4 is already below that threshold. However, if the irrigation costs were to decrease to only 10% of the total production costs all ILR treatments would lead to positive incomes, with  $EWPR_{full-cost}$  increasing more than 43.2%.

These results in Fig. 8.1 show that deficit irrigation results are not only highly influenced by commodity prices but may also be influenced by the irrigation (and water) costs when the share of these costs in the total costs are modified, i.e., when the structure of production costs change as referred to above for a few reported research results (Huffaker and Whittlesey, 2003; Gómez-Limón and Riesgo, 2004; Bazzani et al., 2005; Bartolini et al., 2007; Kampas et al., 2012). These results also support the previous assumption that deficit irrigation results are highly influenced by the availability of rainfall, which is in agreement with Grové et al.

(2010) who stated that more efficient use of rainfall, as for irrigation that supplements rainfall, favours the adoption of deficit irrigation when facing risks due to a variation in production costs.



**Figure 8.1** - Impacts of a variation of the fraction of irrigation costs over the total production costs on the full costs economic water productivity ratio ( $EWPR_{full-cost}$ ) for all treatments

### 8.3.3. Impacts of deficit irrigation with centre-pivot sprinkler systems

Potential water savings due to adopting centre-pivot sprinkler systems (CPs) and resulting from related improved BWUF can be assessed by comparing the different water use and productivity indicators that are expected from their implementation in the practice. Considering the observed ISR and ILR treatments analysed above (Section 8.3.1 and 8.3.2) and assuming that the CPs are well designed and managed as described in Section 8.2.3 and Table 8.3, it is possible to assess deficit irrigation and water saving assuming two different scenarios, one for irrigation supplementing rainfall, as happens in Southern Brazil, and the other for irrigation in conditions where rainfall is scarce, as occurs in Central-West and Northeast Brazil. For the first scenario, with abundant rainfall, the ISR management treatments are adopted; for the second, representing water scarcity conditions, the management treatments ILR1 and 3 are selected.

Water use and productivity indicators resulting from adopting the well designed and managed CPs, described in Table 8.3, and obtained by simulating the three ISR management treatments analysed before, are presented in Table 8.7. The same indicators relative to the same CPs but managed according to treatments ILR1 and ILR3 are presented in Table 8.8.

BWUF increase for all CPs scenarios from ISR1 to ISR3. Since the BWUF is herein defined as the ratio of  $ET_a$  to TWU, ISR3 leads to the highest values due to the fact that TWU is smaller for this treatment, thus increasing that ratio. Consequently, the treatment ISR1 presents the lowest BWUF among all treatments, which results from the highest TWU. Between all CPs, the lowest BWUF correspond to R1 and highest to S4, due to lowest and highest uniformity of distribution DU (and CU), respectively (*vide* Table 8.3).

As for BWUF, WP would increase from ISR1 to ISR3 due to the water savings attained during crop season, which are sufficient to overcome the effects of the corresponding yield losses. WP would vary from 1.66 to 1.71  $kg\ m^{-3}$  for all systems under ISR1 treatment, increasing to the range 2.01– 2.03  $kg\ m^{-3}$  when adopting ISR3. S4 presents the highest WP for all treatments, with R1 presenting the lowest. This is due to a slightly higher distribution uniformity for CPs equipped with Super Spray emitters (Table 8.3), leading to a lower TWU. Wind effects could easily change these results. Thus, we may conclude that results are effectively not different among CPs, which could be expected as a consequence of progress in centre-pivot equipment and emitter characteristics. Results are similar to those presented by Schneider and Howell (1999) for CPs in U.S.A., with  $WP = 1.70\ kg\ m^{-3}$  for full irrigation. As for WP, EWP values are not distinct among CPs.

$EWPR_{irrig-cost}$  increased from the smaller systems (S1 and R1, with 32 ha) to the larger ones because the irrigation costs per unit area decrease when the irrigated area increases, thus also with the increased size of the centre-pivot system. The analysis by Dalton et al. (2004) showed that positive economic impacts of CPs in controlling risks in humid climates is higher for larger systems. Also, O'Brien et al. (1998) and Lamm (2002) reported that CP irrigation was more advantageous for larger fields.  $EWPR_{irrig-cost}$  increased when deficit irrigation was applied (ISR2 and ISR3), thus decreasing the irrigation costs when less water was used, since yields were not highly affected by the mild deficit irrigation considered. Better values were observed for the S equipped CPs because they require less pressure, and therefore have a reduced energy cost relative to the R systems (Table 8.3). CPs equipped with rotators would be advantageous in conditions of wind and low infiltration soils, though these aspects are not considered here.  $EWPR_{full-cost}$  showed very similar behaviour among all CPs, with only very

small differences between S and R equipped systems (Table 8.7), and with all values largely above 1.0, thus indicating that farm returns would be always positive. The very small differences in  $EWPR_{full-cost}$  among all systems are due to the fact that irrigation costs constitute only a small share of the production costs and differ little among treatments (Table 8.3). Results allow the ISR3 management (mild deficit) to be identified as the scenario that would lead to higher economic results when compared with ISR1 and 2. However differences are small and farmers would probably select this management if water availability for irrigation is limited, as referred to by Cortignani and Severini (2009) for Italy.

**Table 8.7.** Water use and productivity indicators relative to the center-pivot systems described in Table 8.3 when adopting the management scenarios ISR1, 2 and 3 for irrigation in supplement of rainfall.

System symbol	Super Spray emitters					Rotator R3000 sprinklers				
	S1	S2	S3	S4	S5	R1	R2	R3	R4	R5
<u>Irrigated area (ha)</u>	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
<b>ISR1</b>										
BWUF	0.641	0.648	0.644	0.648	0.647	0.631	0.644	0.638	0.643	0.640
WP	1.69	1.71	1.70	1.71	1.70	1.66	1.69	1.68	1.69	1.68
EWP	0.67	0.68	0.68	0.68	0.68	0.66	0.68	0.67	0.68	0.67
$EWPR_{irrig-cost}$	4.78	4.81	5.18	6.33	5.40	4.51	4.65	5.02	6.10	5.21
$EWPR_{full-cost}$	1.63	1.63	1.67	1.78	1.70	1.60	1.61	1.66	1.76	1.68
<b>ISR2</b>										
BWUF	0.728	0.735	0.731	0.735	0.734	0.719	0.731	0.725	0.730	0.727
WP	1.84	1.85	1.85	1.85	1.85	1.81	1.84	1.83	1.84	1.84
EWP	0.74	0.74	0.74	0.74	0.74	0.73	0.74	0.73	0.74	0.73
$EWPR_{irrig-cost}$	5.39	5.43	5.97	7.18	6.29	5.07	5.23	5.77	6.89	6.06
$EWPR_{full-cost}$	1.63	1.64	1.68	1.77	1.71	1.60	1.62	1.67	1.75	1.69
<b>ISR3</b>										
BWUF	0.805	0.808	0.806	0.808	0.807	0.800	0.806	0.803	0.806	0.804
WP	2.02	2.03	2.02	2.03	2.02	2.01	2.02	2.01	2.02	2.02
EWP	0.81	0.81	0.81	0.81	0.81	0.80	0.81	0.81	0.81	0.81
$EWPR_{irrig-cost}$	7.19	7.29	8.48	9.73	9.17	6.75	6.96	8.09	9.26	8.77
$EWPR_{full-cost}$	1.71	1.72	1.78	1.83	1.80	1.69	1.70	1.76	1.81	1.79

BWUF = beneficial water use fraction; WP = water productivity; EWP = economic water productivity;  $EWPR_{irrig-cost}$  = economic water productivity ratio for irrigation costs;  $EWPR_{full-cost}$  = economic water productivity ratio for total farming costs

When using well designed and managed CPs under conditions of scarce rainfall (Table 8.8), BWUF increases from a range of 0.703 to 0.739 when adopting ILR1 to the range 0.834 to 0.863 for ILR3. These results relate to a lower TWU for ILR3, which leads to an increase in the ratio of  $ET_a$  to TWU, and thus BWUF. WP and EWP increased similarly to BWUF, reaching higher values for S4 and the lowest for R1, due to highest and lowest DU and CU, respectively (*vide* Table 8.3). The behaviour of BWUF, WP and EWP indicators is therefore similar to those analysed for the ISR treatments but indicators are slightly higher since less water is used with ILR treatments.

As for BWUF, WP increases from ILR1 to ILR3, ranging from 1.77 to 1.86 kg m<sup>-3</sup> and from 1.86 to 1.93 kg m<sup>-3</sup>, respectively. These results are in accordance with those presented by Goyne and McIntyre (2002) for Australian conditions. EWP would slightly improve from the range of 0.71 to 0.74 BRL m<sup>-3</sup> to 0.73 to 0.77 BRL m<sup>-3</sup> when changing to ILR3 instead of ILR1.

$EWPR_{\text{irrig-cost}}$  increased when a irrigation at a larger deficit was considered (ILR3). Since less water is being used, adopting ILR3 would lead to a decrease of the irrigation costs, which could compensate for the yield losses associated with this treatment. Higher  $EWPR_{\text{irrig-cost}}$  values were observed for Spray compared to Rotator equipped systems due to the low energy demand, as referred to above for the ISR cases. However,  $EWPR_{\text{full-cost}}$  values followed a different pattern: adopting ILR3 instead of ILR1 treatment leads to lower  $EWPR_{\text{full-cost}}$  for all centre-pivot alternatives, decreasing from the range 1.19 – 1.35 to 1.11 – 1.23. These results show that, when considering the total production costs, the yield losses due to higher irrigation deficits may not be acceptable when the rainfall contribution is small, unless farmers have not got enough water available for irrigation. However, results do not allow definitive conclusions, particularly taking into account the impacts of changing commodity prices and production costs as analysed in Section 8.3.2.

When comparing the water productivity indicators resulting from adopting CPs, under abundant (ISR) and scarce (ILR) rainfall, results presented in Tables 8.7 and 8.8 show that ILR management leads to higher BWUF, WP and EWP values than ISR1 and 2 due to less water application. However, ISR3, a management strategy with mild deficit irrigation, shows higher values for the same indicators. This results from the fact that abundant rainfall mitigates the impact of deficit irrigation.

**Table 8.8.** Water use and productivity indicators relative to the center-pivot systems described in Table 8.3 when adopting the management scenarios ILR1 and 3 for irrigation when rainfall is lacking

<u>System symbol</u>	<b>Super Spray emitters</b>					<b>Rotator R3000 sprinklers</b>				
	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>R1</b>	<b>R2</b>	<b>R3</b>	<b>R4</b>	<b>R5</b>
<u>Irrigated area (ha)</u>	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
<b><u>ILR1</u></b>										
BWUF	0.724	0.738	0.731	0.739	0.736	0.703	0.730	0.717	0.728	0.721
WP	1.82	1.86	1.84	1.86	1.85	1.77	1.84	1.81	1.83	1.82
EWP	0.73	0.74	0.74	0.74	0.74	0.71	0.73	0.72	0.73	0.73
EWPR <sub>irrig-cost</sub>	3.02	3.03	3.23	3.99	3.35	2.85	2.94	3.14	3.85	3.24
EWPR <sub>full-cost</sub>	1.22	1.22	1.25	1.35	1.27	1.19	1.20	1.24	1.33	1.25
<b><u>ILR3</u></b>										
BWUF	0.851	0.863	0.856	0.863	0.861	0.834	0.855	0.845	0.854	0.849
WP	1.90	1.93	1.91	1.93	1.92	1.86	1.91	1.89	1.91	1.90
EWP	0.76	0.77	0.77	0.77	0.77	0.75	0.77	0.76	0.76	0.76
EWPR <sub>irrig-cost</sub>	3.39	3.42	3.78	4.52	3.98	3.19	3.29	3.64	4.34	3.84
EWPR <sub>full-cost</sub>	1.13	1.13	1.17	1.23	1.19	1.11	1.12	1.16	1.22	1.18

BWUF = beneficial water use fraction; WP = water productivity; EWP = economic water productivity; EWPR<sub>irrig-cost</sub> = economic water productivity ratio for irrigation costs; EWPR<sub>full-cost</sub> economic water productivity ratio for total farming costs

By contrast, the EWPR<sub>irrig-cost</sub> values are much higher, about double, when comparing results for irrigation to supplement rainfall (ISR treatments) with irrigation when rainfall is scarce (ILR). This indicates that the use of irrigation and rainfall together when the latter is abundant results in higher production values when compared with the applied irrigation water in the case of scarce rainfall. Since farmers search for profit, and considering that ILR1 has a EWPR<sub>irrig-cost</sub> higher than ILR3, i.e., EWPR<sub>irrig-cost</sub> decreases for heavier deficits, this indicates that farmers would not be likely to choose a deficit irrigation strategy unless reduced water availability would induce them to do so. However, for a use of irrigation and rainfall together, EWPR<sub>irrig-cost</sub> are higher for mild deficits ISR2 and 3. In this case, though, the EWPR<sub>full-cost</sub> are higher for the management strategies leading to higher yields and having a higher TWU for both ISR and ILR management strategies. Moreover, the EWPR<sub>full-cost</sub> values for ISR are higher than those for ILR for more than 50%. These results confirm that adopting deficit irrigation when rainfall is scarce is less attractive than under conditions of irrigation to supplement rainfall, when irrigation controls the risk of crop failure (Dalton et al., 2004). It is likely that mild deficit irrigation and carefully designed irrigation schedules may lead to

improved irrigation water use under scarce rainfall conditions (e.g. Grassini et al., 2011), not high deficit irrigation, which would have high impacts on yields and farm returns and could have effects on soil salinity. The adoption of improved irrigation and agronomic factors needs to be given appropriate consideration, which implies adequate support to farmers (Ali and Talukder, 2008; Molden et al., 2010; Pereira et al., 2012).

#### **8.4. CONCLUSIONS**

This study shows that economic water use and productivity indicators may be appropriate tools for assessing the impacts of deficit irrigation, particularly the economic water productivity ratio, which represents the yield values per unit of farming costs ( $EWPR_{full-cost}$ ). This indicator appears to be adequate for assessing the feasibility of deficit irrigation as influenced by commodity prices, and water and labour costs. Results show that the viability of deficit irrigation is extremely dependent upon the commodity prices, while changes in water and labour costs have a low impact on related economic results. This behaviour is due to the price structure prevailing in maize farming in Brazil. However, an increase in the share that irrigation costs represent of total production costs would lead to a significant impact of irrigation costs over  $EWPR_{full-cost}$ . These results also support the assumption that deficit irrigation is favoured by the adoption of irrigation to supplement rainfall, especially when facing risks due to a variation in production costs.

The investment in well designed and managed centre-pivot systems may lead to high irrigation uniformity depending on the irrigation system characteristics. Results show that using centre-pivot systems is appropriate for both rainfall regimes considered and best results refer to mild deficit irrigation. Large deficits lead to reduced economic results. When rainfall is scarce, results confirm that adopting deficit irrigation is less attractive than under conditions of irrigation to supplement rainfall; hence farmers would not be likely to choose a deficit irrigation strategy unless they were facing reduced water availability.

This assessment shows that deficit irrigation requires appropriate support to farmers in order to make better selections and adoptions of improved agronomic practices, better performing irrigation systems and irrigation schedules that avoid stress during critical periods.

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## **Capítulo 9**

# **Comparing Sprinkler And Drip Irrigation Systems for Full and Deficit Irrigated Maize using Multicriteria Analysis: Ranking for Water Saving vs. Farm Economic Returns**

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**Rodrigues, G.C., Paredes, P., Gonçalves, J.M., Alves, I., Pereira, L.S., 2013. Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis: ranking for water saving vs. farm economic returns. Agricultural Water Management, 126, 85-96**

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## **9. COMPARING SPRINKLER AND DRIP IRRIGATION SYSTEMS FOR FULL AND DEFICIT IRRIGATED MAIZE USING MULTICRITERIA ANALYSIS AND SIMULATION MODELLING: RANKING FOR WATER SAVING VS. FARM ECONOMIC RETURNS**

**Abstract:** This study aims to assess the economic feasibility of full and deficit irrigated maize using center pivot, set sprinkler systems and drip tape systems through multicriteria analysis. Different irrigation treatments were evaluated and compared in terms of beneficial water use and physical and economical water productivity for two commodity prices and three irrigation systems scenarios applied to a medium and a large field of 5 and 32 ha respectively. Results show that deficit treatments may lead to better water productivity indicators but deficit irrigation (DI) feasibility is highly dependent on the commodity prices. Various well-designed and managed pressurized irrigation systems' scenarios - center pivot, set sprinkler systems and drip tape systems - were compared and ranked using multicriteria analysis. For this, three different prioritization schemes were considered, one referring to water savings, another relative to economic results, and a third one representing a balanced situation between the first two. The rankings of alternative solutions were very sensitive to the decision-maker priorities, mainly when comparing water saving and economic results because the selected alternatives were generally not common to both priority schemes. However, some of the best alternatives for the balanced priorities scheme are common to the other two, thus suggesting a possible trade-off when selecting the best alternatives. Deficit irrigation strategies also rank differently for the various scenarios considered. The study shows that deficit irrigation with exception of mild DI is generally not economically feasible. The adoption of well designed and managed irrigation systems requires consideration of priorities of farm management in terms of water saving and economic results since that some water saving solutions do not allow appropriate recover of the investment costs, particularly with DI. Basing decisions upon multicriteria analysis allows farmers and decision-makers to better select irrigation systems and related management decisions. Results also indicate that appropriate support must be given to farmers when adopting high performance but expensive irrigation systems aimed at sustainable crop profitability.

**Key words:** Economic water productivity, irrigation and production costs, deficit irrigation, multicriteria analysis, alternative irrigation systems.

## 9.1. INTRODUCTION

Maize is one of the main crops in Portugal. It is the fourth most produced commodity in the country, averaging more than 760 thousand tonnes from 1992 to 2010 (FAO, 2012a). The percentage of the cultivated area equipped for irrigation increased from 28.87 to 30.75% from 1990 to 2007 (FAO, 2012b) and the agricultural sector is responsible for more than 73% of the country total water withdrawal. With the increasing water scarcity, there is the need to optimize water use, mainly for irrigation purposes (Pereira et al., 2009). Thus, farmers are forced to adopt improved irrigation managements in order to optimize water use, including the adoption of deficit irrigation and enhancing irrigation performance, thus leading to higher water productivities (WP). The pathway to achieve an efficient irrigation water use imposes the need to systematically optimise the soil and water management practices and the irrigation equipment (Knox et al., 2012).

The optimization of water use and productivity, whose indicators are defined by Pereira et al. (2012), may be achieved through the adoption of deficit irrigation (DI). DI consists of deliberately applying irrigation depths smaller than those required to fully satisfy the crop water requirements but keeping a positive economic return. Many authors assessed the impacts of DI on maize yields (Cabelguenne et al., 1999; Farré and Faci, 2009; Popova and Pereira, 2011; Ma et al., 2012), water productivity (Payero et al., 2009; Katerji et al., 2010) and economic returns (Rodrigues and Pereira, 2009; Abd El-Wahed and Ali, 2012; Dominguez et al., 2012). Consequently, authors searched irrigation schedules that could achieve the feasibility of DI because this technique highly depends upon the adopted management, i.e., when those deficits are applied (Bergez et al., 2004), as well as on irrigation and water costs (Kampas et al., 2012; Montero et al., 2012). Modelling can play a main role in determining rational deficit irrigation schedules (Mailhol et al., 2011; DeJonge et al., 2012; Ma et al., 2012).

Higher WP may be achieved by adopting high performance irrigation systems, having high distribution uniformity (Pereira et al., 2002; 2009). Numerous studies show that there is great potential to achieve a more efficient water use, mainly through an enhanced distribution uniformity when improving surface irrigation (Raghuwanshi and Wallender, 1998; Horst et al., 2007; Gonçalves et al., 2011) or pressurized sprinkler and drip irrigation (Namara et al., 2007; Pedras et al., 2009; López-Mata et al., 2010; Ørum et al., 2010; Mailhol et al., 2011; Abd El-Wahed and Ali, 2012; van Donk et al., 2012). Choosing the most suitable irrigation

system involves numerous factors, such as irrigation scheduling, soils, system performance, irrigation costs, and the performance of the off farm systems. The latter are particularly important because adopting an optimized irrigation scheduling in collective irrigation systems requires that off farm systems are dependable and reliable in terms of discharges and time of deliveries in surface irrigation systems (Gonçalves et al., 2007; Zaccaria et al., 2010), and in terms of timing, discharge and pressure in case of pressurized systems (Lamaddalena and Pereira, 2007; Lamaddalena et al., 2007; Calejo et al., 2008). The adoption of more uniform systems involves a trade off between increased capital expenditure on equipment and the benefits associated with reduced water application when it is uniformly distributed (Bernnan, 2007).

When modelling to rank the best irrigation management alternatives, simulation outputs may be difficult to handle and the selection of the most feasible alternatives may be hard to achieve. However, a variety of design and management alternatives can be created and then ranked by adopting multicriteria analysis (MCA) (Roy and Bouyssou, 1993; Pomerol and Romero, 2000), multi-attribute modelling (Bartolini et al., 2007), or multi-objective optimization (Groot et al., 2012). When aiming at combining different actors in decision-making, e.g., farmers and stakeholders, instead of ranking solutions, fuzzy cognitive mapping may be used; however, few studies have been applied to irrigation (Giordano et al., 2007; Mouratiadoua and Moranb, 2007; Kafetzis et al., 2010). MCA proves to be a useful approach that can incorporate a mixture of quantitative and qualitative information and take into account the preferences of users. Various applications of MCA to irrigation are reported in the literature (Teclé and Yitayew, 1990; Bazzani, 2005; Manos et al., 2006; Riesgo and Gómez-Limón, 2006; Bartolini et al., 2010) and are applied to irrigation systems design (Gonçalves et al., 2007, 2011; Pedras et al., 2009; Darouich et al., 2012).

Considering the aspects analysed above and previous developments by Rodrigues and Pereira (2009), the main goal of this study is to assess the economic impacts of water deficits, commodity prices and enhanced irrigation systems performance on the physical and economic water productivity of irrigated maize in the Vigia Irrigation District, Southern Portugal. Multicriteria analysis is adopted to rank alternative solutions and help understanding contradictory results due to assigning priorities to water saving vs. farm economic results.

## 9.2. MATERIAL AND METHODS

### 9.2.1. Yield responses to irrigation

The maize yield response to water was derived using several field treatments that were designed to determine the impacts of deficit irrigation in different stages of the maize crop season on yield. These experiments were performed at the António Teixeira Experimental Station, located in the Sorraia Valley, near Coruche, Portugal. A description of the experiments is given by Alves et al. (1991). The SIMDualKc model adopted in this study was calibrated/validated for maize in the same area, with the description of the experimental area, soils and climate being given by Rosa et al. (2012b).

Field experiments were performed with maize (*Zea mays* L.) var. LG18 (FAO 300) with a plant density of around 90,000 plants ha<sup>-1</sup> during 1989 (Alves et al., 1991). Maize was sown by 10 May and maturation, depending on the irrigation treatment, was reached during the period 29 August to 5 September. Harvest was performed for all treatments by 5 September. Using a line-source system, seven different irrigation schedules, with various replications, were adopted, including full and deficit irrigation treatments and considering three crop development stages: vegetative, flowering and maturation (Alves et al., 1991).

Due to heavy yield losses associated with stress at the mid season stage, from flowering to maturation, imposing stress during that period have been shown to be economically unfeasible as observed by several authors (Stewart and Hagan, 1973; Stewart et al., 1977; NeSmith and Ritchie, 1992; Karam et al., 2003; Farré and Faci, 2009); thus the corresponding treatments are not considered in the present study. The four treatments analysed herein differ in the timing that the stress was implemented:

- A – full irrigation with application of the required irrigation water depth in all the selected crop development stages;
- B – stress imposed during the vegetative stage;
- C – stress imposed during maturation and;
- D – stress imposed during the vegetative and maturation stages.

The irrigation timing was assessed using infra-red thermometers (Jackson, 1982; Alves and Pereira, 2000). This experiment allowed verifying that the transpiration rate did not decrease

during the 5 to 6 days following an irrigation event, with this irrigation interval being adopted thereafter to meet evapotranspiration demand (Alves et al., 1991).

The actual yield was assessed by harvesting 7 plants for each replication treatment. The yield was evaluated at 13% grain moisture (Popova et al., 2006; Popova and Pereira, 2011).

To estimate the impacts of water on yield the Stewart et al. (1977) single (S1) and multiphasic (S2) models were used. The model S1 gives an average yield reduction factor for the entire crop growth season ( $K_y$ ), with

$$Y_a = Y_m - Y_m K_y (T_d/T_m), \quad (9.1)$$

where  $Y_m$  and  $Y_a$  are, respectively, the maximum (expected) yield of the crop in absence of environmental or water stresses and the actual yield obtained under stress conditions, both expressed in  $\text{kg ha}^{-1}$ ;  $T_d$  is the transpiration deficit defined as the difference between maximal ( $T_m$ ) and adjusted transpiration ( $T_{adj}$ ), all expressed in mm. In the field studies described above, Alves et al. (1991) obtained  $K_y = 1.35$  when  $Y_m$  was the highest yield achieved in the full irrigation Treatment A, where no stress was observed.

Since the maize crop exhibits different sensitivities to water stress throughout the growing cycle, the experiments allowed to use and parameterize the S2 model

$$Y_a = Y_m - Y_m (\beta_v T_{d,v} + \beta_f T_{d,f} + \beta_m T_{d,m})/T_m, \quad (9.2)$$

where  $\beta_v$ ,  $\beta_f$  and  $\beta_m$  are the yield reduction factors for each crop growth stage (vegetative, flowering and maturation) and  $T_{d,v}$ ,  $T_{d,f}$  and  $T_{d,m}$  are the transpiration deficits for the same crop stages. The yield response factors for the S2 model were  $\beta_v = 1.2$  and  $\beta_m = 2.1$ ;  $\beta_f$ , was not considered in the current study.

### 9.2.2. Water Productivity and Water Use Indicators

The water productivity concepts used are those defined by Pereira et al. (2012). The total water productivity (WP,  $\text{kg m}^{-3}$ ) is:

$$WP = \frac{Y_a}{TWU} \quad (9.3)$$

where  $Y_a$  is the adjusted (actual) yield achieved (kg) and TWU is the total water use ( $\text{m}^3$ ).  $Y_a$  varied with the DI management adopted and TWU varied with the performance of the irrigation systems (referred in the next Section) and with the DI management considered.

Replacing the numerator of equation (9.3) by the monetary value of the achieved yield, it results the economic water productivity (EWP, € m<sup>-3</sup>):

$$\text{EWP} = \frac{\text{Value}(Y_a)}{\text{TWU}} \quad (9.4)$$

In addition, to better consider the economics of production, a ratio expressing both the numerator and the denominator in monetary terms is used. This ratio is named economic water productivity ratio (EWPR) and relates the yield value with the full farming costs when TWU is the amount of water used to achieve  $Y_a$ , i.e., also depending on the farm irrigation system considered:

$$\text{EWPR}_{\text{full-cost}} = \frac{\text{Value}(Y_a)}{\text{Cost}(\text{TWU})} \quad (9.5)$$

Pereira et al. (2012) also proposed new water use indicators aimed at distinguishing between beneficial and non-beneficial water use, which is important from the water economy perspective. The beneficial water use fraction (BWUF) is defined as the fraction of total water use that is used to produce the actual yield, i.e., it corresponds to the ratio between the actual crop ET and the TWU as computed with the SIMDualKc model as described in Section 9.2.4.

### 9.2.3. Scenario characterization

Two different approaches were conducted in this study to assess the feasibility of full and deficit irrigated maize. The first consists in comparing the results relative to selected irrigation treatments when considering different scenarios on DI management and commodity prices. The second compares different well-designed and managed pressurized irrigation systems – center pivot and set sprinkler systems and drip tape systems - when used with base data relative to various full and deficit irrigation treatments. Two field sizes are considered, 5 and 32 ha, representing small to medium and large to medium size farms at Vigia Irrigation System, southern Portugal. Vigia has been object of previous studies (Calejo, 2003; Rodrigues and Pereira, 2009; Rodrigues et al., 2010a).

Two commodity prices scenarios were considered to assess the feasibility of farming maize under different deficit irrigation management. The commodity prices refer to the grain yield prices of 154 and 264 € t<sup>-1</sup>, referred herein as “low” and “high” prices, respectively. The low

price corresponds to a pessimist scenario that occurred in 2008. Contrarily, the second price refers to 2011, which is the reference year for all costs and prices.

#### *Weather and soils data*

Meteorological data for Vigia are those relative to the nearby station of Évora (38.77°N, 7.71°W, and 472 m elevation), which are reported in Table 9.1, both for the last decade and the maize season of 2011 used for simulation. Data refers to the reference evapotranspiration ( $ET_o$ ), the climatic variables used to compute  $ET_o$ , and rainfall.  $ET_o$  was computed daily with the FAO-PM method (Allen et al., 1998).

**Table 9.1.** Monthly average climatic data, Évora, maize season of 2011 and average for 2002-2012

	May		Jun		Jul		Aug		Sep	
	2002-12	2011	2002-12	2011	2002-12	2011	2002-12	2011	2002-12	2011
<b>Max air temperature, °C</b>	25.4	27.7	30.5	30.2	32.7	32.0	33.9	32.3	30.4	30.9
<b>Min air temperature, °C</b>	10.1	12.7	13.3	12.3	14.4	13.7	15.0	14.7	13.4	12.9
<b>Minimum Relative Humidity, %</b>	37.2	40.1	32.9	32.5	28.5	29.6	27.8	30.6	33.5	31.9
<b>Maximum Relative Humidity, %</b>	93.7	94.6	91.4	91.2	89.1	89.7	88.3	90.5	90.6	91.8
<b>Wind Speed, m s<sup>-1</sup></b>	2.2	1.5	2.2	2.1	2.5	2.9	2.2	2.2	1.9	1.7
<b>Solar radiation, MJ m<sup>-2</sup> d<sup>-1</sup></b>	22.0	21.7	24.6	25.7	25.9	26.2	22.5	21.7	17.3	17.9
<b>ET<sub>o</sub>, mm d<sup>-1</sup></b>	4.2	4.1	5.3	5.3	5.9	6.0	5.4	5.1	3.8	3.8
<b>Precipitation, mm</b>	38.2	26.8	15.1	15.8	0.9	0.6	3.1	7.6	40.6	33.2

Note: All climatic variables were obtained averaging daily data except for precipitation that represents the monthly accumulation

Soil data are summarized in Table 9.2. They consist of textural and basic soil hydraulic properties of the Vigia fields. The total available soil water (TAW, mm) was computed from field capacity  $\theta_{FC}$  ( $m^3 m^{-3}$ ) and wilting point  $\theta_{WP}$  ( $m^3 m^{-3}$ ) as defined by Allen et al. (1998). Following the model test by Rosa et al. (2012b) and the soil properties in Table 9.2, the following soil evaporation characteristics were adopted: total evaporable water TEW = 38 mm, readily evaporable water REW = 9 mm, and thickness of the evaporation soil layer  $Z_e$  = 0.15 m. The definitions proposed by Allen et al. (1998) were adopted for all soil variables.

**Table 9.2.** Soil physical and hydraulic properties and total available water (TAW)

Soil layer depth (m)	Coarse sand (%)	Fine sand (%)	Loam (%)	Clay (%)	$\theta_{FC}$ ( $m^3 m^{-3}$ )	$\theta_{WP}$ ( $m^3 m^{-3}$ )	TAW (mm)
0.00-0.20	38.4	39.4	12.2	10.0	0.33	0.11	44.0
0.20-0.50	23.0	33.0	15.8	28.2	0.34	0.18	48.0
0.50-1.00	34.4	40.9	10.3	14.4	0.33	0.15	90.0

$\theta_{FC}$  is for field capacity,  $\theta_{WP}$  for wilting point and TAW for total available soil water

### Crop data

A FAO 600 maize variety (NK Famoso) with a planting density of approximately 90,000 plants  $ha^{-1}$  was used in the simulations.  $Y_m$  was obtained using the modified approach of the 'Wageningen' method (Doorenbos and Kassam, 1979) and taking into account the average yield values observed in the Vigia area;  $Y_m$  was set at 16,860  $kg ha^{-1}$ . The dates of crop growth stages, basal crop coefficients ( $K_{cb}$ ), soil water depletion fractions for no stress ( $p$ ), root depths ( $Z_r$ , m), crop heights ( $h$ , m), and fractions of soil cover by vegetation ( $f_c$ ) are given in Table 9.3.  $h$  and  $f_c$  vary with treatments and management. The fraction wetted by rain and sprinkler irrigation was  $f_w = 1.0$ ; for drip irrigation  $f_w$  was 0.6.  $K_{cb}$  values were obtained from the SIMDualKc model when using observations of the soil water balance (Alves et al., 1991), whose global results are shown in Section 9.3.1. The adjusted crop evapotranspiration ( $ET_c$  adj) was then obtained from SIMDualKc simulations.

**Table 9.3.** Crop growth stages and related crop parameters for maize

	Treatments	Initial	Crop development	Mid season	End season
Period lengths	A	10 May – 16 Jun	17 Jun – 15 Jul	16 Jul – 28 Aug	28 Aug – 20 Sep
	B	10 May – 16 Jun	17 Jun – 22 Jul	23 Jul – 30 Aug	01 Sep – 20 Sep
	C	10 May – 16 Jun	17 Jun – 16 Jul	17 Jul – 28 Aug	29 Aug – 20 Sep
	D	10 May – 16 Jun	17 Jun – 19 Jul	20 Jul – 02 Sep	03 Sep – 20 Sep
$K_{cb}$		0.15	0.15 - 1.15	1.15	1.15 – 0.40
$p$		0.65	0.65	0.65	0.65
$Z_r$ (m)		0.20	0.40	1.00	1.00
$h$ (m)	A	0.10	0.50 - 1.00	2.85	
	B	0.10	0.50 - 1.00	2.50	2.50
	C	0.10	0.50 - 1.00	2.50	2.50
	D	0.10	0.50 - 1.00	2.00	2.00
$f_c$	A	0.1	0.59	0.97	0.92
	B	0.1	0.45	0.91	0.88
	C	0.1	0.45	0.95	0.80
	D	0.1	0.45	0.91	0.79

$K_{cb}$  = basal crop coefficients;  $p$  = depletion fraction for non-stress;  $Z_r$  = root depth;  $h$  = crop height;  $f_c$  = fraction of ground cover by the canopy

#### 9.2.4. Models

The simulation scenarios relative to the various farm irrigation systems were developed considering the actual characteristics of systems operating in Vigia. The considered farm irrigation systems were designed with the support of three different models: DEPIVOT (Valín et al., 2012) for center-pivot irrigation, MIRRIG (Pedras et al., 2009) for drip irrigation, and PROASPER (Rodrigues et al., 2010b) for set sprinkler systems. The irrigation management scenarios were simulated with the SIMDualKc model (Rosa et al., 2012a).

DEPIVOT consists of a simulation model allowing the development and evaluation of sprinkler packages for center-pivots. The model performs various computations including: (1) sizing of the lateral pipe spans; (2) selection of the sprinklers package; (3) estimation of potential runoff; and (4) estimation of the expected performance indicators when in operation, mainly the distribution uniformity. To size the lateral pipes, both the friction losses and the effects of topography are considered. This allows estimating the pressure and discharge at each outlet, recognizing when pressure regulators are required. Once the sprinkler package is known, the model compares the application and infiltration rates at various locations along the lateral to estimate the runoff potential. The computations can be reinitiated as many times as necessary until the user verifies that the expected performance is within target values (Valín et al., 2012). Main input data consisted of: net applied depth,  $D = 12$  mm; percentage of area adequately irrigated,  $p_a = 95\%$ ; system pressure not exceeding 150 and 300 kPa for the 5 ha and 32 ha fields, respectively; sprayers on drop to limit wind and interception losses. The infiltration rate curve applied was

$$I = k_p t^a \quad (9.6)$$

where  $I$  is the infiltration rate ( $\text{mm h}^{-1}$ ),  $t$  is time (h),  $k_p$  and  $a$  are empirical parameters. For the Vigia soil and after a field experiment,  $k_p = 6.070 \text{ mm h}^{-a}$  and  $a = -0.891$ . Main characteristics of the center-pivot systems are included in Table 9.4. The terrain is nearly flat with a slope ranging from 0.5 to 2%; runoff was null for the small field and about 9% of  $D$  for the 32 ha field. As discussed by Pereira et al. (2002) and previously adopted by Rodrigues and Pereira (2009), it was assumed that the potential application efficiency relative to the lower quarter (PELQ) could be estimated by the distribution uniformity (DU); actual efficiency may be lower depending upon farmer's management.

The PROASPER model was developed to support farmers in decision-making on set sprinkler systems design and evaluation. The model includes modules for design, simulation and performance analysis. Design is performed either through indirect control by the user (optimized simulation) or direct interactive calculations as selected by the user. Opting for indirect control, the simulation is performed to optimize the design, with automatic search in the database of the characteristics of the pipes and sprinklers that meet the user's previous choices in terms of spacing, length and performance. When the user directly controls the simulation, messages are displayed that indicate if design conditions are not being met prompting the user to search for appropriate solutions. The model allows obtaining a set of results related to pipes' system sizes, hydraulic pressure and discharge of each sprinkler and their variation across the system, as well as performance indicators (Rodrigues et al., 2010b). Main input data were  $D = 12$  mm;  $pa = 95\%$ ; system pressure limited to 250 kPa; infiltration rate given by Equation 9.6. PELQ was assumed equal to DU as in a former application to Vigia (Rodrigues and Pereira, 2009). Main characteristics of the set system are also in Table 9.4.

MIRRIG is aimed at designing microirrigation systems, i.e., drip and microsprinkling set systems. MIRRIG is composed by design and simulation models, a multicriteria analysis model and a database. Various alternative design solutions are created and then ranked based upon an integration of technical, economic and environmental criteria. Design alternatives refer to the layout of the pipe system, the pipe characteristics and the emitters, either drippers or microsprinklers. The model components include: (1) a design module to iteratively size the pipe and emitters system; and (2) a performance analysis module that simulates the functioning of the system and computes various indicators used as attributes of the alternatives relative to the design criteria adopted for MCA (Pedras et al., 2009). Main input data consisted of: drip tape on the surface and double row irrigation;  $D = 8$  mm;  $fw = 0.6$ ; pressure not exceeding 120 kPa; target DU  $>90\%$ ; infiltration as for other cases. Relevant system characteristics are included in Table 9.4 with PELQ also assumed equal to DU following field observations (Pereira, 2007).

**Table 9.4.** Main characteristics and costs of farm irrigation systems

System scenario	Irrigated area (ha)	Discharge (l h <sup>-1</sup> )	System pressure (kPa)	Emitter spacing (m)	DU (%)	Potential application efficiency (%)	Investment annuity (€ ha <sup>-1</sup> )	Maintenance annual cost (€ ha <sup>-1</sup> )
<b>Center-Pivot</b>	5	80 to 270	150	variable	83.5	83.5	345	35
	32	80 to 750	290		90.8	87.3	152	21
<b>Set Sprinkler</b>	5	890	214	14 x 14	84.1	84.1	289	75
	32						270	70
<b>Drip</b>	5	1.10	118	0.2 x 1.4	93.8	93.8	867	120
	32						815	112

The model SIMDualKc adopts the dual crop coefficient approach as proposed by Allen et al. (1998, 2005) to calculate  $ET_c$  considering the E and T components separately. The model is described in detail by Rosa et al. (2012a) and its test with field data on maize is presented by Rosa et al. (2012b). Weather, soils, crop and irrigation data used in this application are described above (Tables 9.1, 9.2 and 9.3). Simulations with SIMDualKc were performed for various scenarios relative to the allowed soil water depletion (ASWD) thresholds as described in Table 9.5, which are defined in relation to the soil water depletion fractions for no stress (p). Treatments are those defined in Section 9.2.1.

**Table 9.5.** Allowed soil water depletion fractions (ASWD) relative to each treatment and crop stage.

Treatments	Imposed stress during maize development stages			
	Initial	Development	Mid	End
<b>A</b>	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW
<b>B</b>	ASWD=1.2p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW
<b>C</b>	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=1.2p × TAW
<b>D</b>	ASWD=1.2p × TAW	ASWD=1.05p × TAW	ASWD=p × TAW	ASWD=1.2p × TAW

### 9.2.5. Investment, operation and production costs

Data for labour, machinery, seeds, fertilizers and irrigation costs were obtained from regional data for 2008. These data were adjusted to 2011 considering the average annual inflation rate, resulting in the values presented in Table 9.6.

**Table 9.6.** Production costs

Category	Cost
Seeds (€ ha <sup>-1</sup> )	243.5
Labour (€ ha <sup>-1</sup> )	
Farm	101.0
Irrigation	25.8
Fertilizers (€ ha <sup>-1</sup> )	1013.7
Machinery (€ ha <sup>-1</sup> )	527.2
Grain Drying (€ t <sup>-1</sup> )	15.6
Electricity (€ kWh <sup>-1</sup> )	0.13
Water Cost	
Fixed (€ ha <sup>-1</sup> )	52.0
Variable (€ m <sup>-3</sup> )	0.03

Investment costs ( $C_{inv}$ , €) were computed for each system scenario. They comprise the pump, the pipe system, and the chosen emitter package for all irrigation system scenarios defined in Table 9.4. The investment annuity  $A_{inv}$  (€ year<sup>-1</sup>) relative to the investment cost  $C_{inv}$  is

$$A_{inv} = CRF C_{inv}, \quad (9.7)$$

where CRF is the capital recovery factor.  $A_{inv}$  was computed for center-pivot equipment (including pump, pump pipe, distribution pipe and center-pivot) considering a life-time of  $n = 24$  years and  $n = 12$  years for the sprinklers. For the set sprinkler irrigation system, the life-time for all system components was  $n = 15$  years. For the drip irrigation system, different life-times were considered:  $n = 15$  years for the PVC pipes,  $n = 10$  years for the PE pipes, and  $n = 2$  years for the drip tape. Computations were performed assuming an interest rate  $i = 5\%$ . CRF was then calculated from the life-time  $n$  (years) and the interest rate  $i$  as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (9.8)$$

The investment annuity per unit of irrigated area is  $C_a$  (€ ha<sup>-1</sup> year<sup>-1</sup>), which is the ratio of  $A_{inv}$  by the irrigated area.

The operation costs were obtained from the sum of the annual energy costs ( $C_{en}$ ), the energy demand tax ( $C_d$ ), and the annual maintenance costs ( $C_m$ ).  $C_{en}$  is calculated as:

$$C_{en} = P E_r T_i \quad (9.9)$$

where  $P$  is the power of the pumping station (kW),  $E_r$  is the energy rate (€ kWh<sup>-1</sup>), and  $T_i$  is the total operation time (h) of the pump required annually. The energy cost per unit irrigated area (€ year<sup>-1</sup> ha<sup>-1</sup>) is calculated by dividing  $C_{en}$  by the irrigated area. Calculations are based in energy prices presented in Table 9.6. The annual maintenance costs ( $C_m$ ) are considered to be an additional 1%, 2.5% and 5% of the investment cost for center-pivot, set sprinkler and drip irrigation systems, respectively.

The scenarios considered for the irrigation systems designed through application of the above referred models are characterized in Table 9.4, which includes the chosen emitter package-discharge, system working pressure, spacing, distribution uniformity (DU) and seasonal application efficiency, as well as the investment annuity and annual maintenance costs for each farm irrigation system scenario.

### 9.2.6. Criteria, attributes and priorities

In order to characterize the irrigation system scenarios, performance indicators were defined including the economic land productivity, irrigation costs, total production costs, BWUF, TWU, WP and EWPR. The adopted criteria to perform MCA were represented by attributes and scaled according to measures of utility using utility functions that enable variables having different units to be compared. The utilities  $U_j$  relating to any criterion  $j$  were normalized into the [0-1] interval, with zero for the more adverse and 1 for the most advantageous result. Linear utility functions were applied:

$$U_j(x_j) = \alpha \cdot x_j + \beta \quad (9.10)$$

where  $x_j$  is the attribute,  $\alpha$  is the graph slope and  $\beta$  is the utility value  $U_j(x_j)$  for a null value of the attribute. The slope,  $\alpha$ , is negative for criteria like costs and water use, whose highest values are the worst, and positive for other criteria like WP and EWPR, where higher values are the best. Criteria attributes and utility functions are presented in Table 9.7. This approach is similar to the one described by Gonçalves et al. (2011) and Darouich et al. (2012).

The MCA method applied is the linear weighted summation (Pomerol and Romero, 2000), a full compensatory and aggregative method, which has the major advantage of its high simplicity, allowing an easier understanding of the procedure and results. However, this method has the disadvantage of full compensatory assumption, which means that any criterion with lower result can be compensated by another one with a better result, which is a trade-off

that may not be well accepted by the decision makers. For each alternative, adopting user defined weights ( $\lambda_j$ ) for every criterion  $j$ , a global utility  $U$ , that represents its integrative score performance, was computed as:

$$U = \sum_{j=1}^7 \lambda_j \times U_j \quad (9.11)$$

The different irrigation systems scenarios were ranked according to the global utility values. In this study, different sets of weights were adopted to characterize assigning priorities to water saving, economic results and a balance between the former (Table 9.7).

**Table 9.7.** Criteria attributes, utility functions and criteria weights.

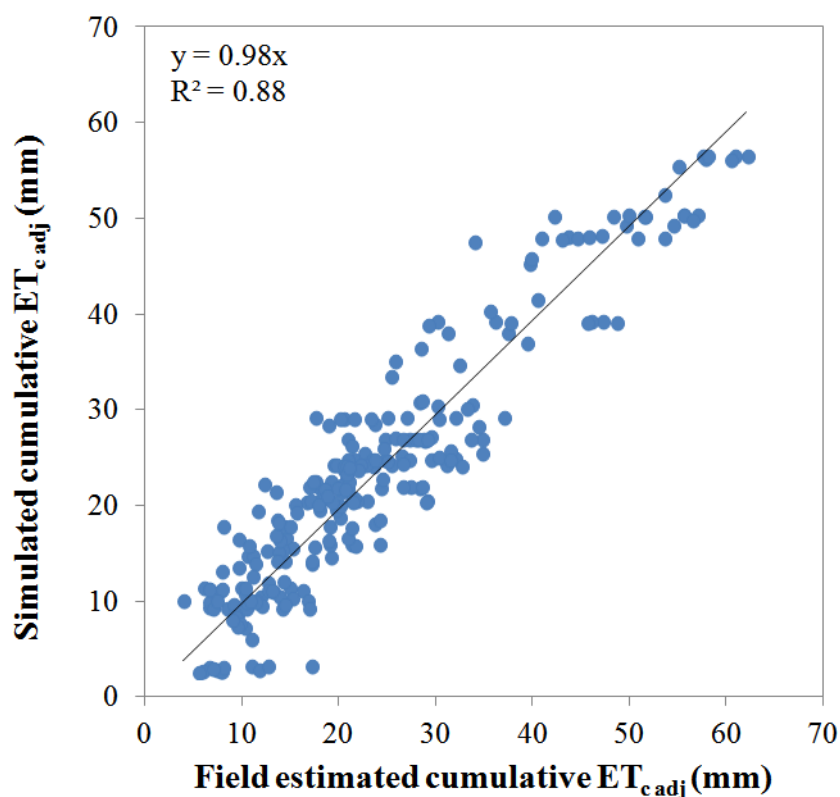
Attributes (x)	Units	Utility function	Weights (%) for the attributes in condition of		
			Balance among water saving	Priority to water saving	Priority to economic results
<b>Economic</b>					
Economic land productivity	€ ha <sup>-1</sup>	$U(x) = 0.22 \times 10^{-3} x$	14	5	22
Irrigation costs	€ m <sup>-3</sup>	$U(x) = 1 - 1.47x$	14	6	22
Total production costs	€ m <sup>-3</sup>		14	6	22
Economic water productivity ratio	–	$U(x) = 0.60x$	14	5	22
<b>Water Saving</b>					
Beneficial water use fraction	–	$U(x) = 1.02x$	14	26	4
Total water use	m <sup>3</sup> ha <sup>-1</sup>	$U(x) = 5.41 - 0.82 \times 10^{-3} x$	15	26	4
Water productivity	kg m <sup>-3</sup>	$U(x) = 0.35x$	15	26	4

## 9.3. RESULTS

### 9.3.1. Irrigation treatments and yield

The SIMDualKc model was validated for the various treatments referred in Section 9.2.1 (4 treatments and a total of 16 replications). Results are shown in Fig. 9.1 comparing field measured and simulated ET values cumulated for the periods between successive irrigation events. The regression coefficient is 0.98, indicating a good model fit, and  $R^2$  is 0.86 showing that most of the variance is explained by the model. The estimated RMSE is 4.8 mm, *i.e.*, 7.7% of maximum cumulated ET observed. Results of using ET computed from observations of the soil water balance for model calibration/validation in maize are reported by Cameira et

al. (2005), Popova et al. (2006) and Hong et al. (2013). The respective indicators of model fit are similar to those presented above.



**Figure 9.1.** Comparison between field estimated and simulated adjusted crop evapotranspiration ( $ET_{c\_adj}$ ) cumulated between successive irrigation events for all treatments and replications.

The referred four irrigation treatments (A, B, C and D) were adopted in this study, applied to the Vigia Irrigation System. The irrigation management scenarios simulated were built adopting different ASWD thresholds at various crop stages as given in Table 9.5. The exception was the flowering stage because maize is particularly sensitive to water stress at midseason (Alves et al., 1991; Çakir, 2004; Farré and Faci, 2009).

Table 9.8 presents the net irrigation depths, adjusted crop evapotranspiration ( $ET_{c\_adj}$ ), adjusted transpiration ( $T_{adj}$ ), transpiration deficit ( $T_d$ ), and simulated actual yield ( $Y_a$ ) for all treatments obtained with the SIMDualKc model for the Vigia fields in 2011 considering sprinkler and drip irrigation methods. Results refer to the S2 model (Eq. 9.2). The maximum transpiration for the entire season was 480 mm for a non-stressed drip Treatment A.

**Table 9.8.** Adjusted crop evapotranspiration ( $ET_{c\ adj}$ ), adjusted transpiration ( $T_{adj}$ ), transpiration deficit ( $T_d$ ), net irrigation and simulated actual grain yield ( $Y_a$ ) relative to each treatment

<b>Irrigation method</b>	<b>Treatments</b>	<b><math>ET_{c\ adj}</math> (mm)</b>	<b><math>T_{adj}</math> (mm)</b>	<b><math>T_d</math> (mm)</b>	<b>Net irrigation (mm)</b>	<b><math>Y_a</math> (kg ha<sup>-1</sup>)</b>
Sprinkler	A	568	471	4	372	16554
	B	521	438	19	360	16074
	C	569	441	28	336	14784
	D	492	413	47	300	14279
Drip	A	579	480	0	432	16858
	B	579	434	17	440	16161
	C	536	429	17	320	15614
	D	546	409	41	384	14468

Results in Table 9.8 show that greater DI (Treatment D) leads to considerable yield losses due to a reduction of  $ET_{c\ adj}$ , mainly transpiration,  $T_{adj}$ , and thus an increase of the transpiration deficit, with  $T_d = 47$  and 41 mm respectively for sprinkler and drip irrigation methods. The drip irrigation Treatment C presents a lower yield than Treatment B despite having the same  $T_d$  due to stress imposed during the late season, which produces an increased yield impact.

Yields for drip irrigation are higher than for sprinkler because when adopting smaller and more frequent irrigation events stress is more easily avoided. This is apparent in transpiration deficits reported in Table 9.8, which are higher for the sprinkler irrigation systems. However, the net irrigation depths are greater than for sprinkler systems due to higher soil evaporation that results from the higher frequency of soil wettings. As for sprinkler, yield tends to decrease for the drip system when adopting a DI schedule. Contrarily to sprinkling, Treatment C under drip irrigation has a lower  $T_{adj}$  and higher  $T_d$  when compared with Treatment B; this is due to differences in irrigation timing.

### 9.3.2. Water productivity as influenced by commodity prices and irrigation systems

Results comparing the beneficial water use fraction (BWUF) and physical and economic water productivity (WP and EWP) for all treatments and irrigation systems as well as for both field sizes of 5 and 32 ha and commodity prices of 154 and 264 € t<sup>-1</sup> are presented in Table 9.9. Results show that drip systems lead to higher BWUF than set sprinkler and center-pivot systems. This is due to lower soil evaporation since the wetted fraction of the soil is  $f_w = 0.6$ , less than for sprinkler irrigation, where all area is wetted; therefore, soil evaporation is less for

drip than for sprinkling. Adopting Treatments A and C lead to higher BWUF than Treatments B and D for all irrigation systems and all cases analyzed. Since BWUF is herein defined as the ratio of  $ET_{adj}$  to TWU, that situation is due to the fact that  $ET_{adj}$  is smaller for B and D, thus decreasing that ratio. Treatment B presents the lowest BWUF among all cases analyzed, which results from the decrease of  $ET_{adj}$  caused by the stress imposed during the vegetative stage. Comparing the small and the larger field, BWUF are similar for drip and set sprinkler systems but are smaller for the center-pivot systems in case of the 5 ha field comparatively to the 32 ha field.

When adopting full irrigation (Treatment A) a higher WP than for other treatments is generally obtained. Similar results are obtained for the C treatment, where stress is induced only during the late season. Because BWUF is also high for both treatments, yield losses are null or minimized. For B and D treatments TWU also decreases but proportionally less than for C, thus resulting in lower WP. The highest values for WP correspond to the non stressed Treatment A, varying between 2.60 to 2.80 kg m<sup>-3</sup> for all systems and management conditions. The lower WP values are obtained for Treatment D under drip irrigation and Treatment C for center-pivot. This occurs because the water savings that are attained with the stress imposed during the different crop stages are not enough to overcome the correspondent yield losses. WP does not change from the 5 ha to the 32 ha field in case of drip and set sprinkler systems but WP are larger for the 32 ha field under center-pivot due to higher BWUF. This is due to higher distribution uniformity for center-pivot in a larger field (Table 9.4), that leads to a lower TWU.

EWP varies in accordance with WP. Both indicators have a similar behaviour, with EWP depending only upon the commodity prices though this indicator varies linearly with them. The highest value is achieved when adopting Treatment A under a drip system. As for WP, Treatment C has the lowest EWP value among all sprinkler treatments, but the lowest value for drip refers to Treatment D. This different behaviour, also observed for WP, results from the fact that the smaller and frequent net irrigation depths applied with drip irrigation lead to overcome stress produced with Treatment C better than sprinkler irrigation. Various studies compared drip and sprinkler irrigation and found higher yields and WP for drip irrigation, e.g., Tognetti et al. (2003) for sugar beet, Colaizzi et al. (2004) for sorghum, and Almarshadi and Ismail (2011) for alfalfa. The greater advantage of drip systems was found when deficit irrigation was applied. However, Albaji et al. (2010) found contradictory results because the

relative advantages of drip or sprinkler systems depended upon various factors including soil characteristics, salinity and water quality.

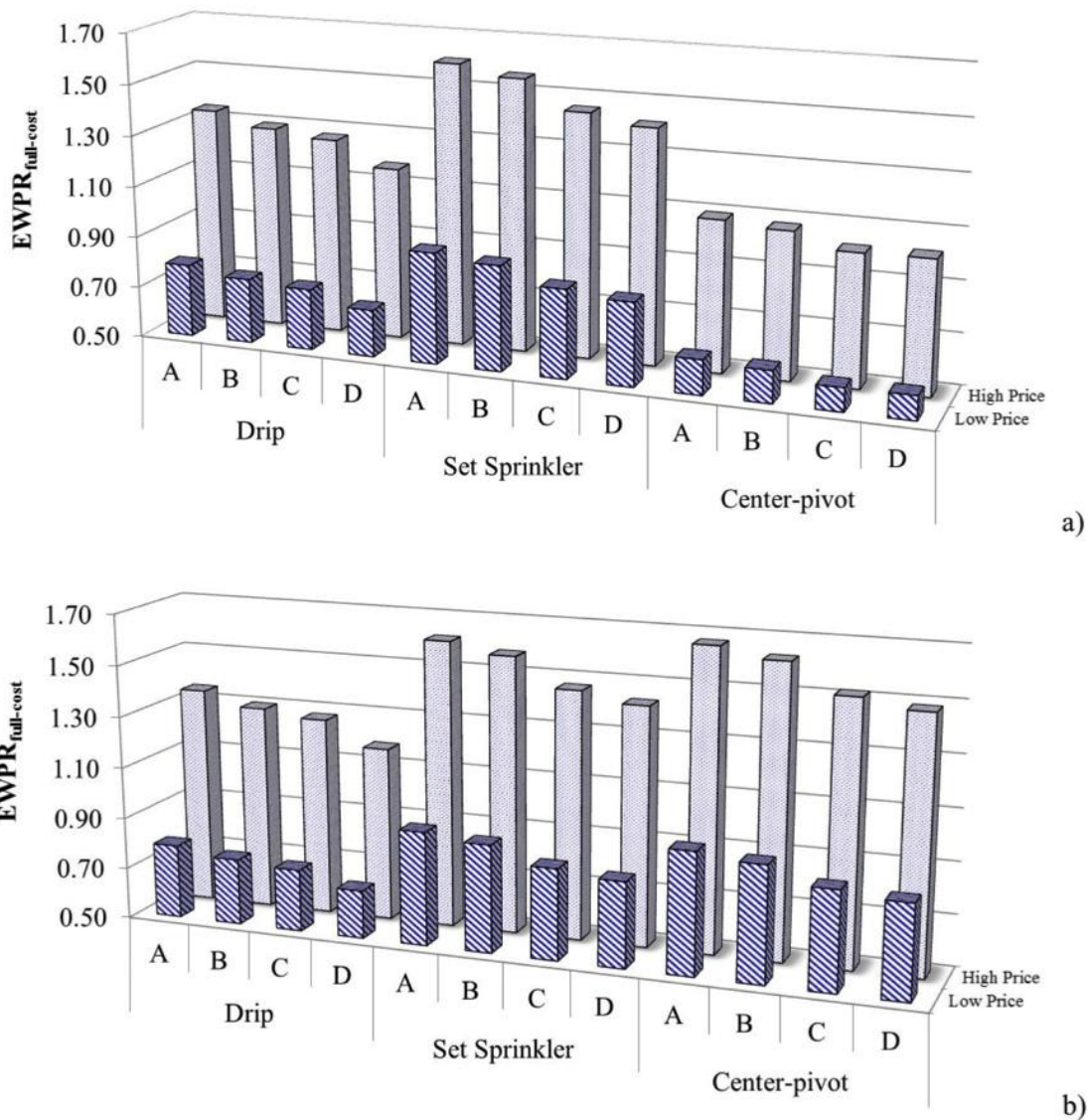
**Table 9.9.** Comparison of BWUF, WP and EWP for all treatments, irrigation systems and management precision, and field sizes.

Field	Irrigation system	Irrigation treatment	BWUF	WP (kg m <sup>-3</sup> )	EWP (€ m <sup>-3</sup> )	
					Low price	High price
5 ha	Drip	A	0.96	2.80	0.43	0.74
		B	0.88	2.47	0.38	0.65
		C	0.96	2.79	0.43	0.74
		D	0.90	2.37	0.37	0.63
	Set Sprinkler	A	0.90	2.62	0.40	0.69
		B	0.85	2.62	0.40	0.69
		C	0.91	2.36	0.36	0.62
		D	0.86	2.49	0.38	0.66
	Center-pivot	A	0.89	2.60	0.40	0.69
		B	0.85	2.61	0.40	0.69
		C	0.90	2.35	0.36	0.62
		D	0.86	2.48	0.38	0.66
32 ha	Drip	A	0.96	2.80	0.43	0.74
		B	0.88	2.47	0.38	0.65
		C	0.96	2.79	0.43	0.74
		D	0.90	2.37	0.37	0.63
	Set Sprinkler	A	0.90	2.62	0.40	0.69
		B	0.85	2.62	0.40	0.69
		C	0.91	2.36	0.36	0.62
		D	0.86	2.49	0.38	0.66
	Center-pivot	A	0.92	2.69	0.41	0.71
		B	0.87	2.69	0.41	0.71
		C	0.93	2.42	0.37	0.64
		D	0.88	2.55	0.39	0.67

BWUF = beneficial water use function; WP = water productivity; EWP = economic water productivity

EWPR was used to compare the yield values per unit of farming costs considering both scenarios of commodity prices. This approach allows assessing the feasibility of different irrigation treatments in order to define the economical return threshold for which farming becomes profitable. For this purpose, Fig. 9.2 shows the variation of EWPR for all the

irrigation treatments and both commodity prices. EWPR for all treatments, all irrigation systems and both field sizes ranged from 0.64 to 0.97, thus indicating that no treatment would be feasible with that low commodity price, irrespective of the adopted irrigation system. Treatment A, corresponding to full irrigation, was the one approaching feasibility for center-pivot in case of the large field, and set sprinkler for the small one. Drip systems were far from economic viability for low commodity prices, with EWPR values lower than 0.80 in all cases. Treatments C and D had EWPR smaller than Treatments A and B, thus indicating that stress imposed during the late season led to non-negligible impacts.



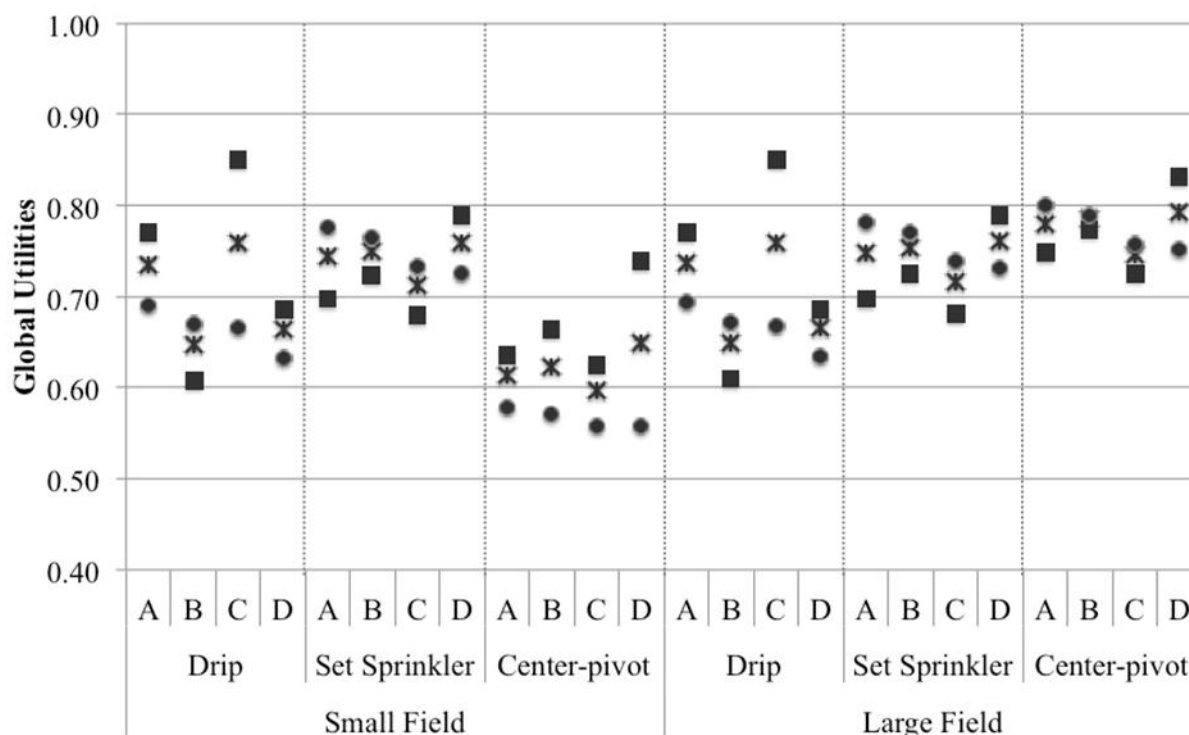
**Figure 9.2.** Economic water productivity ratio (EWPR) for all deficit irrigation treatments and irrigation systems applied to small (a) and large (b) farm sizes when adopting low (▨) and high (▣), commodity prices

For high commodity prices (Fig. 9.2), most scenarios lead to positive incomes, i.e.,  $EWPR > 1.0$ . A negative income was only observed when adopting Treatment D under a center-pivot system in a 5 ha field, thus confirming the non-appropriateness of this combination treatment/system in small fields. When farming maize in a 32 ha field, the adoption of deficit irrigation would lead to a positive income in all cases, with  $EWPR$  values ranging from 1.18 to 1.67. For this field size, irrigating with a center-pivot system would produce a farm income 1.40 to 1.67 times greater than the annual production costs. For 5 ha fields the best  $EWPR$  values correspond to a sprinkler set system, ranging from 1.42 to 1.61 (Fig. 9.2). Positive values were obtained for drip systems (1.18 to 1.35) but lower than for set or center-pivot sprinkler systems. However,  $EWPR$  values change with the prices of water as analyzed for Brazilian conditions (Rodrigues et al., 2013). One can conclude that the adoption of deficit irrigation is well supported for this high price scenario and that adopting drip irrigation for maize would not be selected by a farmer unless he would assign high priority for water saving, as analysed in the following chapter. Results by Heumesser et al. (2012) also found that sprinkler irrigation was more profitable than drip in case of maize. They also found that drip irrigation adoption would require subsidies for equipment investing.

### 9.3.3. Ranking of different alternatives

The global utilities of all the alternatives combining irrigation treatments and irrigation systems are shown in Fig. 9.3. Computations refer to the high commodity price only because when considering the low price scenario a negative farm income was obtained for all the alternatives as shown in Fig. 9.2. The three prioritization schemes defined in Table 9.7 are herein considered. Results show that the global utilities are very different for the various prioritization schemes considered, showing a disagreement between water saving and economic criteria. Changing the weights assigned to each criterion would change the utilities values. Using the weights referred in Table 9.7 it is noticeable that higher utility values correspond to the C treatment (water stress during the late season) under drip irrigation if water saving is prioritized. Differently, when the priority refers to the economic returns, the highest values of the utilities correspond to the A treatment (full irrigation) for set sprinkler systems in case of the small field and for center-pivot in case of the large field (Fig. 9.3). These results are largely explained by the costs associated with the irrigation systems, higher for drip than for sprinkler and, when considering the size of the field, because of the higher investment cost of center-pivot systems versus set systems for small fields. Differences

between small and larger fields were already referred by O'Brien et al. (1998) and Lamm (2002), reporting that center-pivot irrigation was more advantageous for large fields.



**Figure 9.3.** Global utilities relative to the prioritization schemes adopted: water saving (■), farm economic returns (●), or a balance between both (✱), when considering various deficit irrigation Treatments A through D, drip and sprinkler systems as well as small and large fields.

High utilities when prioritizing for water savings are also assigned to D treatments (DI during all stages except midseason) for center-pivot systems in the case of the large field, and set sprinkler systems for the small one. Differently, other high utility values when prioritizing for economic returns refer to the B treatment (stressed during the vegetative stage only) for set sprinklers and the small field or center-pivots in large fields. The advantage in using MCA for ranking is evidenced by these differences in results.

The top five alternatives relative to the three prioritization schemes defined in Table 9.7 are shown in Table 9.10 for both field sizes (5 and 32 ha). Rankings are definitely different when considering the various prioritization schemes. They also change with field sizes. For the 32 ha field, there are differences in rankings for all priority schemes but differences in utility values are small.

**Table 9.10.** The five best alternatives relatives to the considered prioritization scheme for both irrigation managements and field sizes.

Priorities	Rank	Treatment	Field size				
			5 ha		32 ha		
			Irrigation system	Utility	Treatment	Irrigation system	Utility
<b>Water Saving</b>	1	C	Drip	0.85	C	Drip	0.85
	2	D	Set Sprinkler	0.79	D	Center-pivot	0.83
	3	A	Drip	0.77	D	Set Sprinkler	0.79
	4	D	Center-pivot	0.74	B	Center-pivot	0.77
	5	B	Set Sprinkler	0.72	A	Drip	0.77
<b>Economic results</b>	1	A	Set Sprinkler	0.78	A	Center-pivot	0.80
	2	B	Set Sprinkler	0.77	B	Center-pivot	0.79
	3	C	Set Sprinkler	0.74	A	Set Sprinkler	0.78
	4	D	Set Sprinkler	0.73	B	Set Sprinkler	0.77
	5	A	Drip	0.69	C	Center-pivot	0.76
<b>Balance between water saving and economic results</b>	1	D	Set Sprinkler	0.76	D	Center-pivot	0.79
	2	C	Drip	0.76	B	Center-pivot	0.79
	3	B	Set Sprinkler	0.75	A	Center-pivot	0.78
	4	A	Set Sprinkler	0.75	D	Set Sprinkler	0.76
	5	A	Drip	0.74	C	Drip	0.76

For all cases and water saving priorities the first rank is assigned for drip irrigation and the C treatment (stressed during the late season only), given the water saving effects linked to the irrigation method and the adoption of DI. The second place goes to Treatment D (DI during all stages but midseason) with set or center pivot sprinklers for the small and large fields, respectively. Full irrigation (Treatment A) with drip is third for the 5 ha field but is fifth for the 32 ha field. Differently, when priority is given to economic returns, set sprinkler systems with scheduling Treatments A, B, C, D are in the first four ranks; in case of large fields, the center-pivot systems A, B and C rank first, second and fifth. These rankings clearly identify the impact of systems costs combined with yield values. In the case of balanced prioritization, drip C comes in second place while drip A comes in fifth place for the small field. The other ranking positions are given to the set sprinkling systems. For the 32 ha field, center-pivot systems comes in the first 3 ranking positions, while drip C comes in the fifth position.

These results clearly show the importance of investment costs in relation to the water saving potential. Comparisons were made for well designed and managed systems which are, all of them, able to produce high BWUF and support high WP. Therefore, the preferences

evidenced by the rankings identify the possible use of various alternatives, both in terms of water saving and economic returns depending upon the decision-maker preferences.

Results show that the variation of the production costs, mainly due to the investment annuity and the maintenance annual costs, largely interfere in the economic ranking of the best alternatives when comparing different farm sizes. For a larger area, a center-pivot system proves to be the most economically feasible; however, for a smaller field, the best option is the adoption of set sprinkler systems. One can also conclude that the investment and maintenance costs play an important role when comparing different field sizes, since it widely interferes in the choosing of the best alternatives to be adopted. Marques et al. (2005) and O'Brien et al. (2010) also referred that various factors influencing production and irrigation costs and yield level and value play a major role in determining which irrigation systems should be selected. Thus, rankings shown above may deeply change when these factors are modified.

Overall results show that the selection of the best design alternatives highly depends upon the decision maker, mainly on the prioritization scheme and weights adopted. The weights and priority given to criteria must therefore involve the end user in order to choose the scenario that suits him/her the best. Adopting a decision support system with MCA requires the definition of the main purpose, choosing the most appropriate prioritization schemes and related criteria weights. For supporting the definition of the adopted priorities and weights and the analysis of results by users, one needs to take into account some additional factors such as the water availability, which is more important in case of more water demanding alternatives, the commodity prices, which could have a greater impact on the alternatives having lower land productivity; or the production costs, that affect the alternatives that require higher investment. Results also show that it is necessary to search for solutions that assure compatibility among water saving, irrigation performance and economic viability for farmers, i.e., assuring conditions for sustainable irrigation, which is in agreement with findings by Wichelns and Oster (2006). Furthermore, adopting water saving approaches requires adequate measures to support farmers on the selection of the most appropriate irrigation systems and management options since just using a MCA decision support tool requires good knowledge of factors influencing rankings. Results also indicate that appropriate support must be given to farmers when adopting high performance irrigation systems, which represent a high

investment, as well as to adopt mild deficit irrigation management strategies that allow for sustainable crop profitability.

#### **9.4. CONCLUSIONS**

This study shows that economic water productivity indicators may be an appropriate approach for assessing the impacts of deficit irrigation, mainly considering commodity prices. Comparing different scenarios of economic water productivities may help to assess when deficit irrigation is or is not feasible. The economic water productivity ratio EWPR, relating the yield values per unit of farming costs, reveals to be adequate to assess the feasibility of deficit irrigation as influenced by commodity prices and irrigation systems. Results show that viability of deficit irrigation strategies is extremely dependent on the commodity prices. If low commodity prices are considered all the treatments for all the irrigation systems and field sizes lead to a negative income. Contrarily, for higher commodity prices, most scenarios lead to positive incomes.

Drip irrigation systems were found to lead to higher water use performance in terms of beneficial water use and water productivity when compared with sprinkler systems. However, the EWPR were lower for drip than for both set and center-pivot sprinkler systems due to respective investment costs. Results were also different when comparing a 5 ha with a 32 ha field: best results for all treatments were for set sprinkler in case of the smaller field and for center-pivot in case of the large one, thus evidencing the influence of higher costs of center-pivot systems when a small field is considered. This study demonstrates that the adoption of well designed and managed irrigation systems may lead to contradictory results when the achieved water saving does not allow the desired recovery of the investment costs, also depending on the farm size. This may help policy makers to understand the contradictions between water saving and farm economic results.

Ranking irrigation system alternatives for water saving leads to the selection of drip and deficit irrigation for both types of fields. Contrarily, relative to economic results, sprinkler and full irrigation treatments are first ranked. Center-pivot rank above set sprinklers when a large field is considered. First ranking positions for water saving are not common to those obtained when the priority is assigned to farm economic results. Nevertheless, when adopting a prioritization scheme that balances water saving and economic results, it is possible to have a

ranking that represents a trade-off between water saving and economic returns. This study shows the need to appropriately selecting the weights to be assigned to each criterion, which requires appropriate support to farmers when they want to select a new irrigation system allowing sustainable crop profitability. Results of this research may be useful for farmers, managers and policy makers when aiming at improving water management at field scale, particularly for understanding the economic limits of deficit irrigation, as well as economic and water saving issues when comparing drip and sprinkler systems.

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# **Capítulo 10**

## **Conclusões**



## 10. CONCLUSÕES

O principal objectivo desta tese foi a modelação económica aplicada ao uso e produtividade da água em regadio, pretendendo-se determinar o potencial dos sistemas de rega à escala da parcela para se atingir um uso eficiente da água. Neste processo foi dada particular atenção à maximização dos usos benéficos da água e da produtividade física e económica da mesma. O Capítulo 1 justifica a motivação da análise. O trabalho central desta tese é apresentado nos Capítulos 2 a 9. As principais conclusões são aqui abordadas.

A análise do Capítulo 2 permitiu verificar que os indicadores de produtividade da água podem ser uma ferramenta apropriada para avaliar os impactos da rega deficitária e dos preços da água. Foi observado que as diferenças entre as produtividades da água, com e sem restrições hídricas, das culturas do milho e girassol, quando cultivadas no perímetro da rega da Vigia, não são suficientes para justificar se a adopção de técnicas de rega deficitária é ou não viável. Foi também demonstrado que a produtividade da água depende largamente do desempenho dos sistemas de rega, aumentando significativamente com a sua melhoria. A cultura do milho mostra-se uma cultura fortemente dependente do desempenho dos sistemas de rega e dos preços da água praticados no perímetro. O girassol revela-se uma cultura mais resistente à variação dos preços, desde que o desempenho dos sistemas de rega se mantenha alto. Já a rega de complemento do trigo mostra-se resistente às variações dos preços da água, desde que o preço da produção não atinja valores baixos.

Contudo, é necessário considerar os custos totais de produção, de forma a avaliar a sustentabilidade da rega deficitária (Capítulo 3). Considerando uma procura climática extrema, a razão da produtividade económica da água mostra que, no caso do milho, não existe viabilidade para a rega deficitária para os preços do produto praticados à data. Contudo, para um valor da produção de  $0.230 \text{ € kg}^{-1}$ , a rega completa da cultura levaria a retornos económicos positivos. Já a cultura do trigo em rega de complemento pode responder positivamente se o valor da produção for superior. Considerando a rega para conforto hídrico, i.e., sem restrições, verifica-se que a rega do milho só é viável para desempenhos melhorados relativamente aos atuais e para os preços da água à data. Diferentemente, a rega de complemento do trigo apresenta viabilidade sob este cenário de gestão.

Complementando o estudo abordado no Capítulo 2, o Capítulo 4 teve por objectivo avaliar a eficiência energética das culturas do milho, trigo e girassol sob influência de diferentes níveis

de desempenhos de sistemas de rega e disponibilidade hídrica, e proceder à sua comparação com a produtividade física e económica da água. Os resultados obtidos demonstram que o milho e girassol poderão ser culturas energeticamente eficientes, ao contrário do trigo, que se mostra desapropriada para a produção de bioenergia. Para conviver com situações de escassez hídrica, a rega deficitária mostra ser uma opção de gestão alternativa, levando a aumentos na produtividade da água e eficiência energética desde que as quebras de produção não sejam elevadas. A comparação entre a eficiência energética e a produtividade da água mostra uma fraca relação entre os indicadores, devido aos fatores que os influenciam. Os resultados mostram também que a melhoria do desempenho dos sistemas de rega tem menor impacto no desempenho energético do que na produtividade da água.

Os sistemas de rega por aspersão têm vindo a substituir os sistemas de rega de superfície tradicionais. Surge, assim, o modelo PROASPER, o qual é descrito no Capítulo 5. O modelo PROASPER procura responder à necessidade de produzir informação para agricultores e gestores que possa auxiliar na tomada de decisão no projeto dos sistemas de rega. A aplicação do modelo PROASPER a sistemas em operação, teve como objetivo a solução dos problemas identificados que levam a baixos desempenhos, produzindo resultados claramente melhorados para os mesmos. Concluiu-se que, se os gestores dos sistemas e os regantes dispuserem de ferramentas informáticas de projeto simples, podem encontrar soluções que levam a melhores desempenhos. Demonstrou-se que o modelo PROASPER pode ser aplicado com este objetivo quando integrado num sistema de informação para regantes, em conjunto com informação sobre a calendarização de rega.

No Capítulo 6 pretendeu-se identificar as necessidades de rega do milho em condições de seca severa e extrema em várias localidades de norte a sul de Portugal. As alternativas de rega foram avaliadas tendo em consideração a poupança de água de rega e o impacto nas produções, recorrendo a dados sobre o valor da produção e desempenho de sistemas. Verificou-se que, em condições de disponibilidade de água limitada, a seleção de uma estratégia de rega que optimize as disponibilidades de água em relação à menor quebra de produção possível depende não só da cultura e do local onde esta é praticada, mas ainda das condições de seca (severa e extrema) a que está sujeita. A análise das produtividades da água mostra que este indicador depende fortemente da região, tendendo a ser maior na região centro. Contudo, os valores de produção atuais poderão não cobrir os custos de produção se se mantivesse ao nível praticado, e se não se verificarem melhores desempenhos de rega. Assim, considera-se que em situação de seca severa e extrema a melhor opção será a adoção ou de

défices reduzidos ou da rega para satisfação das necessidades totais do milho mas reduzindo a área cultivada.

No Capítulo 7 trata-se da calibração e validação do modelo SIMDualKC para a cultura do milho regada por aspersão fixa e microrrega recorrendo a cobertura do solo por *mulch*. Os resultados estatísticos obtidos demonstram a capacidade do modelo simular a água disponível no solo, sem tender a sobre ou subestimar o teor de água no mesmo durante os diferentes períodos culturais. Os indicadores relativos aos erros mostram que estes são inferiores a 4% do total de água disponível no solo. O modelo permitiu ainda determinação dos coeficientes culturais basais, sendo estes comuns a ambos os sistemas de rega. Contudo, demonstrou-se neste Capítulo, a necessidade de estudar a viabilidade económica dos calendários de rega adotados de forma a aconselhar os agricultores de uma forma mais eficiente.

O estudo desenvolvido no Capítulo 8 mostra que os indicadores de uso e produtividade da água podem ser considerados como ferramentas apropriadas para a avaliação dos impactos da rega deficitária, principalmente ao considerar os preços e custos de produção. Os resultados demonstram que a rega deficitária é extremamente dependente do preço do produto, enquanto que os preços da água e da mão-de-obra apresentam um impacto reduzido nos resultados económicos. O investimento em sistemas de rega por rampa pivotante poderá levar a uma uniformidade de rega melhorada. Contudo, e apesar de uma melhoria significativa das produtividades física e económica, os resultados não permitem conclusões definitivas que apoiem a adopção destes sistemas em conjunto com técnicas de rega deficitária, principalmente tendo em consideração os impactos dos preços e custos da produção. Apenas se a precipitação for abundante e o défice adoptado for moderado é que a adopção destes sistemas de rega poderá ser viável para as condições brasileiras estudadas.

Através da aproximação adoptada no Capítulo 9, onde se procedeu à comparação de diferentes cenários de rega, completa e deficitária, ao adoptar diferentes sistemas de rega, foi demonstrado que a viabilidade da rega deficitária no Perímetro de Rega da Vigia é extremamente dependente do preço do produto. Este estudo demonstrou que a adopção de um determinado sistema de rega leva a resultados contraditórios quando a poupança de água obtida não produz a recuperação dos custos de investimento desejada, dependendo da área regada. A classificação das diferentes alternativas em termos de poupança de água demonstrou a superioridade dos sistemas de microrrega e da rega deficitária. Contrariamente, ao dar prioridade aos resultados económicos, os sistemas de rega por aspersão prevalecem, sendo as rampas pivotantes superiores para área regadas de maior dimensão. Os resultados demonstram

a importância da escolha das prioridades a adoptar pelo agricultor aquando da escolha do sistema de rega, de forma a alcançar a sustentabilidade da empresa agrícola.

Considera-se que o desenvolvimento deste modelo económico, associado a módulos de análise multicritério, se apresenta como uma excelente ferramenta para o apoio à decisão na empresa agrícola. Assim, é recomendável a extensão da sua aplicação às principais culturas hortícolas e arvenses nas várias regiões de Portugal, de forma a determinar a viabilidade de práticas que apontem à poupança de água. Tais aplicações conduzirão a novos aperfeiçoamentos do modelo, que poderão passar pela inclusão de indicadores inovadores, como as pegadas hídrica e do carbono, e indicadores que traduzam o impacto das novas políticas agrícolas europeias, como os apoios à produção.

A melhoria do modelo aqui apresentado poderá passar pela sua integração com outros modelos de gestão, de forma a contribuir para um sistema de apoio à decisão mais eficiente, quer para o projeto, quer na gestão da rega pelos agricultores. Este aperfeiçoamento deverá passar principalmente pela sua integração num modelo de água-produção, em conjunto com o modelo SIMDualKc, permitindo avaliar os impactos económicos resultantes da alteração na gestão da cultura, nomeadamente as alterações nos níveis de produção, na calendarização da rega e nos factores de produção.

A aplicação de técnicas de “upscaling”, nomeadamente com recurso a SIG, representam ferramentas inovadoras que trarão benefícios a este modelo económico. Estas medidas permitirão passar da análise à escala da parcela para a escala do perímetro regado, possibilitando ao gestor do perímetro a determinação dos impactos da gestão do mesmo.