MULTICRITERIA ANALYSIS FOR IRRIGATION SUSTAINABLE DEVELOPMENT: DESIGN AND SELECTION OF IRRIGATION SYSTEMS

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

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ABSTRACT

This study aimed to select the most sustainable irrigation methods able to obtain high water productivity considering economic aspects and water saving criteria for wheat and cotton in NE Syria. The models used are PROASPER for sprinkler, SADREG for surface and MIRRIG for drip irrigation. Multicriteria analysis (MCA) was used to rank a set of design alternatives considering water saving and economic priorities. For wheat, surface and sprinkler systems were applied. For cotton surface, sprinkler and drip methods were compared. All combinations were analysed for full and deficit irrigation.

Results for cotton show that drip irrigation is better than graded furrows for water saving but not a good option for economic priority unless the yield price increases. Sprinkler systems for cotton are rarely advantageous. For wheat, sprinkler systems are better than borders from water savings perspectives, showing an increased water productivity, as well as in economic terms leading to higher farmer's income. MCA proved to be a very useful tool in a water scarce region to select the most appropriate irrigation systems considering the users preferences.

Keywords: Multicriteria analysis, irrigation methods, irrigation design, ranking for water saving, economic farmer's income

RESUMO

“Análise multicritério para o desenvolvimento sustentável do regadio: projeto e seleção de sistemas de rega”

Métodos de rega sustentáveis, considerando a produtividade de água, aspetos económicos e critérios de poupança de água foram estudados e aplicados para as culturas do trigo e algodão no NE da Síria. Assim, utilizaram-se os modelos PROASPER, SADREG e MIRRIG para, respectivamente, modelar a rega por aspersão, de superfície e a microrrega. A análise multicritério (MCA) foi aplicada para ordenar um conjunto de alternativas de projeto, considerando a poupança de água e a maximização dos rendimentos. As três alternativas de rega foram adotadas para o algodão. Para o trigo, apenas se compararam a rega de superfície e por aspersão. Foram analisados diferentes tratamentos (rega completa e deficitária).

Para o algodão a microrrega permite maior poupança de água, embora seja menos vantajosa do ponto de vista económico quando comparada com a rega de superfície, se o valor da produção não se alterar. A rega por aspersão para o algodão mostra-se desvantajosa. Para o trigo os sistemas por aspersão são preferíveis à rega por faixas no que toca à poupança da água e aos resultados económicos, levando a um aumento da produtividade da água. A MCA mostrou-se uma ferramenta útil para a escolha de sistemas de rega em regiões de escassez.

Palavras-chave: Análise multicritério, métodos de rega, projetos de rega, ordenação para a poupança de água, rendimento da empresa agrícola

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List of abbreviations and symbols

BWU	beneficial water use (mm)
BWUF	beneficial water use fraction (ratio)
CU	Christiansen uniformity coefficient (%)
D	average water depth applied to the irrigated area (mm)
DI	deficit irrigation
dn	nozzle diameter (mm)
DP	deep percolation (mm, m^3 ha^{-1})
DRL	double rows per lateral
DSS	decision support system
DU	distribution uniformity (%)
D_w	wetted diameter (m)
ELP	economic land productivity (€ ha^{-1})
E_{pa_target}	target system efficiency (%)
ES	emitter spacing
ET_a	actual evapotranspiration (mm d^{-1}, mm $season^{-1}$)
ET_c	crop evapotranspiration (mm d^{-1}, mm $season^{-1}$)
ET_{max}	maximum evapotranspiration (mm d^{-1}, mm $season^{-1}$)
ET_o	references evapotranspiration (mm d^{-1}, mm $season^{-1}$)
EU	emitter emission uniformity (%)
EWP	economic water productivity (€ m^{-3})
EWPR	economic water productivity ratio (ratio)
f	infiltration rate (mm h^{-1})
f_0	empirical base infiltration rate, (m^3 min^{-1} m^{-1})
FC	field capacity
FI	full irrigation
FIC	fixed irrigation costs (€ ha^{-1})
G1,…G5	code for sprinklers and lateral spacing
GB	graded borders
GB_{LL}	graded borders of lasered land
GB_{NLL}	graded borders of non-lasered land
GF	graded furrows
GF_{LL}	graded furrows of lasered land
GF_{NLL}	graded furrows of non-lasered land
GIR	gross irrigation requirement (mm)
GW	ground water contribution (mm)
H	upstream operating pressure (kpa)
H_0	sprinkler's operation pressure (m)
i_a	target application rate (mm h^{-1})
I_n	net irrigation depth (mm)
IDP	irrigation deep percolation (mm, m^3 ha^{-1})
IRO	irrigation tail-end runoff (mm, m^3 ha^{-1})

IWU	irrigation water use (mm, m^3 ha^{-1})
k	empirical coefficient, (m^3 m^{-1} $min^{-\alpha}$)
K	potassium fertilizer, K_2O (%)
K_c	crop coefficient
Ks	hydraulic conductivity (mm h^{-1})
L_C	spacing between plants in line (m)
L_{EC}	major spacing between plant rows (m)
L_{em}	spacing between emitters in line (m)
L_{mec}	minor spacing between plant rows (m)
L1, … L6	layout' types base 1, …, 6
LL	land leveling (lasered land)
LF	leaching fraction (%)
LWS	linear weighted sum
MAD	management allowed deficit (%)
MCA	multicriteria analysis
NIR	net irrigation requirement (mm)
N	nitrogen fertilizer, NH_4NO_3 (%)
n	number of observations
NC	non-compensate emitter
Nc	number of attributes
NLL	non-land leveling (non-lasered land)
N_{irr}	number of irrigation event
NBWU	non-beneficial water use (mm)
Oe	effective fraction of water discharged (0.9 - 1.0)
p	depletion fraction (%)
P	phosphorus fertilizer, as (superphosphate) P_2O_5 (%)
pa	adequately irrigated area (%)
PE_{hd}	high density polyethylene
Pr	effective precipitation (mm $season^{-1}$)
PVC	polyvinyl chloride
PWP	permanent wilting point
q_n	sprinkler's flow rate (m^{-3} h^{-1})
RO	tail-end runoff (mm, m^3 ha^{-1})
Rw	throw range of sprinkler (m)
Z_r	effective root zone (m)
S1	solid-set system (fixed)
S2	semi-permanent system (gridded-pipe)
S3	portable system (hand-moved)
SC	self-compensate emitter
SI	supplemental irrigation
SRL	single row per lateral
sp1,...sp5	sprinkler types

STV	sensitivity of emitters to temperature variation
TAW	total available water (mm m^{-1})
TI	traditional irrigation
t_{i_target}	target irrigation duration (h $event^{-1}$)
(tr, sq)	sprinkler distribution pattern, (triangular or square)
TWU	total water use (mm, m^3 ha^{-1})
U	global utility
$U_j(x_j)$	utility for criteria's attribute, x_j
VIC	variable irrigation costs (€ ha^{-1})
W1,...W9	weighing scenarios
W_a	actual water applied (mm)
W_{max}	maximum water required (mm)
WP	water productivity (kg m^{-3})
WP_{irri}	irrigation water productivity (kg m^{-3})
W_c	water cost (€ m^{-3})
x_i	criteria's attribute
Y_a	actual yield (kg. ha^{-1})
Y_c	yield cost (€ kg^{-1})
Y_p	potential yield with no water deficit (kg ha^{-1})
Z	cumulative infiltration (m^3 m^{-1})

Greek symbols

ɑ	empirical exponent, dimensionless
α	graph slope
β	utility value, $U_j(x_j)$ for a null value of the attribute
λ_j	weight of criteria
τ	infiltration opportunity time (min)
θ_{FC}	soil water content at FC, (m^3 m^{-3}, mm mm^{-1})
θ_i	soil water content in day i, (m^3 m^{-3}, mm mm^{-1})
θ_{MAD}	soil water content at MAD, (m^3 m^{-3}, mm mm^{-1})
θ_P	soil water content at p, (m^3 m^{-3}, mm mm^{-1})
θ_{PWP}	soil water content at PWP, (m^3 m^{-3}, mm mm^{-1})

Chapter 1

Introduction

1.1. Introduction and the main current problem

The Syrian Arab Republic is a country that depends on agriculture, which is the second main sector in economy after oil industry; however, the governmental strategies for the agricultural production do not favour sustainability of the farming systems. The agriculture sector is the main water consumer, with about 80% of total water use in Syria. This study refers to Ras-El-Ain area, Northeast of Syria, in Al-Khabour basin, an ancient fertile region where wheat and cotton are grown under surface irrigation, predominantly traditional basin and furrows irrigation. The study area is heavily affected by water scarcity and the drawdown of the ground water table due to several factors related to climate aridity, increased needs for irrigation with heavy use of available water resources and, mainly, due to the enormous decrease of the Al-Khabour River flow. A necessary agreement between Turkey and Syria relative to the use of the large international aquifer whose sources feed the Al-Khabour River is required to avoid its depletion; unfortunately, it is difficult to be signed in the present international context.

This study aims to shed some light on the efficiency of water use for wheat and cotton and contribute to the current debate on utilization of scarce water resources in that area using decision support systems. The increasing water scarcity forced the Syrian government in 2005 to adopt a national irrigation modernization project, aiming to a more sustainable water use. This project encourages farmers to change the traditional irrigation methods and adopt modernized alternatives, mainly drip and sprinkler systems, by providing technical support and low-interest loans for investment. The farmers have a traditional knowledge or experience, using economic and social considerations that lead them to cultivate certain crops using given methods rather than assessing which would be the best solution for their farms and crops considering market prices and subsidies.

Irrigation methods in study area vary according to factors like water availability, irrigation system establishment, running cost, available fuel, soil properties and investment size. Traditional basin irrigation system is the major application method, which is highly labor demanding and has low application performance. Only a limited area is using pressurized methods, drip and sprinklers. A sustainable irrigated agriculture system requires the adoption of appropriate irrigation scheduling technologies, including the modernization of surface, sprinkler and drip irrigation, focusing on water savings to cope with the regional severe water scarcity, soil conservation, preventing problems related with salinity, and aimed to increase farmer’s economical incomes and to contribute to the economic and social rural development. Focusing on farmer’s preferences and on the irrigation methods that can be improved and applied, the study evaluates and optimises surface, drip and sprinkler from the hydraulics and economic point of view for wheat and cotton, and applies multicriteria analysis to select the best solutions for different farmers prioritizations.

Furthermore, for cotton, the study explores the use of furrows and borders irrigation and both drip and surface irrigation decision support systems analysing multiple point of views namely: investment, energy, water and labour costs, the water use and consume, the requirements of technology and its adequacy to local conditions, and the financial and socio-cultural issues that influence farmers' priorities. Then, to select among furrows, borders and drip irrigation systems for cotton water saving and economic priorities are considered. Furrows and borders irrigation alternatives were designed and ranked with the SADREG model considering lasered and non-lasered land levelling, field lengths of 50 to 200 m and various inflow discharges. Simulation of drip irrigation was performed with MIRRIG model for various alternatives: double and single crop row per lateral, emitters spacing of 0.5 and 0.7 m, six alternative pipe layouts and five self-compensating and non-compensating emitters. The performance of surface irrigation systems highly depends upon the design process, which is related with the appropriateness and precision of land leveling, field shape and dimensions, inflow discharges and soil infiltration characteristics. Improving surface irrigation needs to find alternative solutions that provide for both water saving and farm economic benefits in a context of small and family farms. For drip, the major drawback is the high initial investment that shows sensitivity to cotton price. The decision for shifting to drip irrigation also depends upon other factors related with location and size of plots, costs of cultivation, productivity, cost of produce, electricity charges, depth of groundwater, and irrigation requirement.

It was necessary to search for solutions that achieve adequate compatibility among irrigation performance, water saving and economic viability for farmers, which represent conditions for sustainable irrigation. Therefore, it becomes evident that decision support systems (DSS) using multicriteria analysis (MCA) are useful tools to evaluate and rank a set of furrows, borders and drip irrigation alternatives based upon contradictory economic and water saving's criteria. DSS is a powerful tool that integrates data and design and selection models, which allows easy creation and screening of management and design alternatives. The selection of an irrigation method requires the consideration of multiple criteria that may be supported by MCA.

A comparison for wheat application was analysed for sprinkler and surface (graded borders) irrigation using PROASPER model to design and evaluate sprinkler's alternatives. The design was created for three types of sprinkler; permanent (solid-set); semi-permanent (gridded-pipe); and portable system (hand-moved) for two layouts, five distribution grid of spacing between sprinkler and laterals, two sprinkler distribution patterns (square and triangular) and five impact sprinklers. The main question when selecting sprinkler or modernized surface irrigation for wheat refers to making compatible two central but contradictory objectives: water saving and farm economic results. Simulation models like SADREG for surface irrigation and PROASPER for sprinkler irrigation, combined with MCA modules, are used to compare different irrigation alternatives. Both models proved to be useful tools for both design and management. Starting with the appropriate design, focusing on the wheat producing area where the field data were collected, both models have been adopted to create, evaluate and rank different alternatives for graded furrows and borders (using SADREG) and for sprinkler systems (using an improved version of PROASPER).

Aiming at analysing possible decisions by farmers that produce both wheat and cotton, the MCA was applied to results of the three referred models for cotton as outlined in Figure 1.1.

1.2. Objectives

The main objective of this thesis is to develop tools to find the most sustainable irrigation methods for wheat and cotton and optimizing the systems' design of sprinkler, drip and surface based on adopting MCA relative to these irrigation systems and crops.

The specific objectives are:

1- To analyse and evaluate the potential of modernizing of surface irrigation of cotton, particularly with furrows and borders irrigation methods, for sustainable irrigated agriculture focusing on the compatibility between water saving and economic viability and then

2- To develop appropriate sets of design alternatives for surface and drip irrigation;

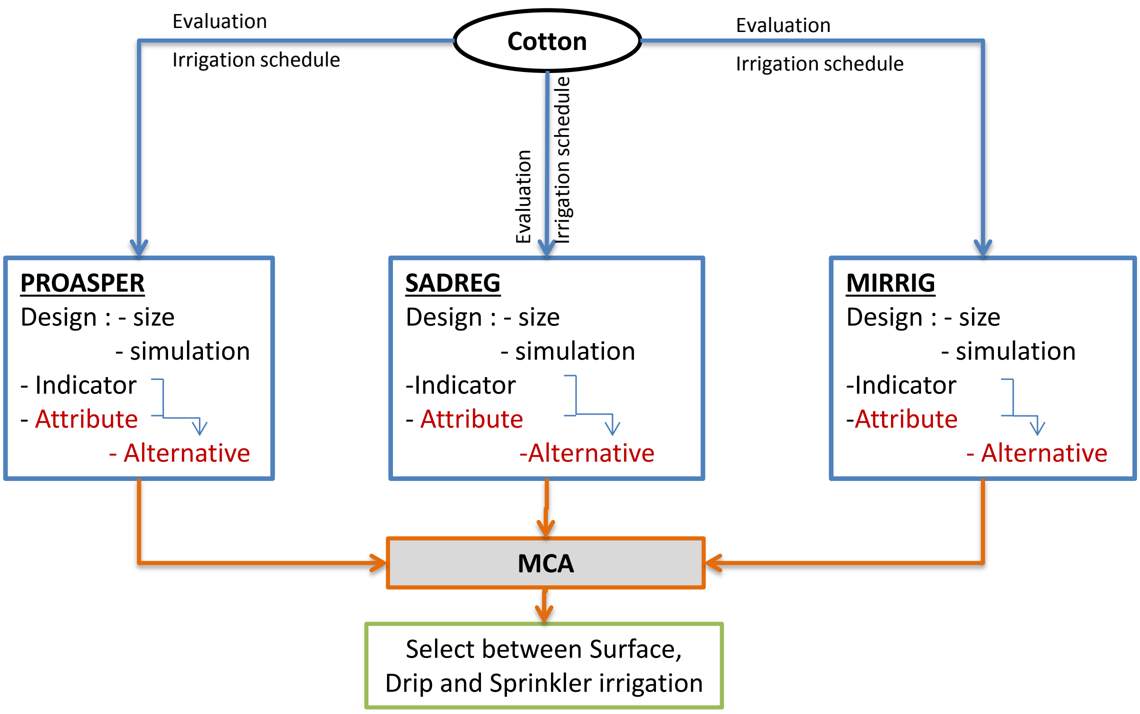


Figure 1. 1 Approach to compare three different irrigation systems for cotton

3- To apply both SADREG and PROASPER models for surface and sprinkler irrigation to create and rank appropriate sets of design alternatives for wheat.

4- To apply MCA through the use of the models SADREG, PROASPER and MIRRIG for various sets of surface, sprinkler and drip alternatives and rank and select alternatives for each systems and comparing surface and drip for cotton and sprinkler and surface for wheat, by considering decision criteria relative to irrigation performances, water saving and economic impacts (Figure 1.1).

5- To analyse the impacts of deficit irrigation over the different surface and drip irrigation for cotton, and surface and sprinkler irrigation for wheat.

6- To compare sprinkler, drip and surface irrigation systems for cotton for the same combination parameters and apply MCA for selection of the appropriate and sustainable methods.

7- To analyse results in terms of possible surface and sprinkler solutions for wheat and surface, drip and sprinkler solutions for cotton irrigation modernization in Northeast of Syria.

1.3. Outline of the thesis

This thesis is organized as follows:

- The state of art relative to the irrigation methods and related modelling is presented in Chapter 2,
- The study area, problem and constraints, historical and experimental data, and related methodology description is presented in Chapter 3,
- The application to cotton of surface irrigation, furrows and borders, using the model SADREG and related use of MCA is presented in Chapter 4,
- The comparison between surface irrigation borders and furrows with drip irrigation for cotton is analysed in Chapter 5.
- The PROASPER model for sprinkler irrigation systems integrating hydraulic sprinkler design with MCA and its use comparative to surface irrigation (graded border) to select the best solution for is presented in Chapter 6.
- The application of MCA for cotton, comparing all previous analysed irrigation systems and their selection is presented in chapter 7.
- Finally, Chapter 8 consists of conclusions and recommendations

Chapter 2

State-of-the-art on wheat and cotton irrigation

2.1. Crop water requirements and irrigation scheduling

2.1.1. Wheat crop water requirements, yields and water productivity

The crop evapotranspiration (ET_c) of wheat planted in December and harvested in middle of June ranges between 300 to 400 mm, and 450 to 650 mm when respectively rain-fed and irrigated (Eberbach and Pala, 2005; Somme et al., 2005; Karam et al., 2009; Oweis et al., 2011). The unfavourable distribution of rain, which was recorded in spring, from mid-March to mid-May, affects wheat growth and yield. This makes necessary to apply supplemental irrigation (SI) to control crop water stress and to guarantee the yields, usually with a significant economic benefit (Oweis et al., 1998, 2000; Somme et al., 2005; Oweis and Hachum, 2006; Karam et al., 2009; Yigezu et al., 2011, 2013; Rosa et al., 2012b).

The average yield of irrigated wheat is ranging from 3.0 to 4.5×10^3 kg ha^{-1}, while for the rain-fed crop is from 0.5 to 1.7×10^3 kg ha^{-1} for a dry or a wet year, respectively (Kahlown et al., 2007; Karam et al., 2009; Sadiddin and Atiya, 2009; Yigezu et al., 2011, 2013). Oweis (1997) showed that the difference of ET between a dry and a wet region is of 234-504 mm, the corresponding yield ranging from 0.74 to 5.0×10^3 kg ha^{-1}, with a water productivity (WP) of 0.33-0.99 kg m^{-3}, respectively. The maximum yield could be 5.5 - 6.3×10^3 kg ha^{-1} for some wheat genotypes (Rihane-3 and cham-6) (Oweis and Hachum, 2006; Kanshaw et al., 2007; Rajaram and Braun, 2008; Yigezu et al., 2013). The relationships between crop yield and water use have been a major focus of agricultural research in the arid and semi-arid regions and have been reviewed previously by Hanks (1983), Vaux and Pruitt (1983), Howell (1990), Oweis et al. (1999) and Sun et al. (2006). Yields are affected by several factors, as sowing's date, fertilization, planting pattern and density, irrigation methods and water applied. Delaying the sowing reduce the yield and has negative impact on water productivity (Oweis et al., 1999; Somme, 2005; Sun et al., 2006). Sun et al. (2006) reported that WP ranged from 0.97 to 1.83 kg m^{-3}, with a yield of 3.3-5.6×10^3 kg ha^{-1}. The fertilization shows significant impact on yield if nitrogen (N) is more than 100 kg ha^{-1} (Oweis et al., 1999; Karam et al., 2009) and phosphorus (P) about 40-50 kg ha^{-1} (Zhang and Oweis, 1999). The optimal planting pattern corresponds to a major/minor spacing of 40-20cm (Li et al., 2008).

Several studies relative to wheat yield response to applied water concluded that deficit irrigation (DI) was sustainable in many situations (Oweis et al., 1999; Zhang and Oweis, 1999; El Amami el al., 2001; Oweis et al., 2003; Li et al., 2008; Rodrigues and Pereira, 2009). Zhang and Oweis (1999) have shown that applying only 50% of SI requirements causes a yield reduction of about 10-15%, Oweis et al. (1999) reported a small difference in yield among full irrigation (FI) and 2/3 SI, respectively 5.8 and 5.4×10^{3} kg ha^{-1}. Schneider and Howell (1997) found that yield increases 1.0×10^{3} kg ha^{-1} when the water applied increases 33% in the first two irrigation events. Ilbeyi et al. (2006) found that one cubic meter of SI on wheat results in an additional gain of 2.0 to 3.5 kg over rain-fed. Oweis and Hachum (2009) reported that WP under rainfed and SI conditions ranges from 0.35 to 1.0 kg m^{-3}, respectively. Another study of Tavakkoli and Oweis (2004) concluded that deficit irrigation of 1/3 FI increased WP for about 0.6-0.7 kg m^{-3}.

DI increased the benefit by over 50% compared with the farmer's usual practice of over-irrigation, which water productivity is between 0.8-0.9 kg m^{-3} (Kahlown et al., 2007; Oweis and Hachum, 2009). However, DI is not recommended in areas with salinity problems, as an irrigation reduction may lead to 60% increase of salinity and reduce yield (Xu et al., 2013). Sun et al. (2006) demonstrated that the excessive irrigation might not produce greater yield or optimal economic benefit. The water stress in some growth development stage highly affects yield (Zhang and Oweis, 1999; Rodrigues and Pereira, 2009). El Amami el al. (2001) reported that adopting DI requires appropriate irrigation schedule and high irrigation performance; its feasibility highly depends upon the water price (Rodrigues and Pereira, 2009). Zairi et al. (2003) concluded about the feasibility of DI when the water price was higher than a local threshold, 0.13 € m^{-3} in the Tunisian case. Zhang (2003) concluded that WP is sensitive to the irrigation schedule strategy, with an increase from 0.93 and 1.19 kg m^{-3} when applying FI and 2/3 FI, respectively.

2.1.2. Cotton crop water requirements, yields and water productivity

Cotton is a fully irrigated crop with high water consumption. The water use and yield relationship were studied by Wanjura et al. (2002), Howell et al. (2004), Karam et al. (2006), Cholpankulov et al. (2008), DeTar (2008), Dağdelen et al. (2009), Farahani et al. (2009), Pereira et al. (2009), Oweis et al. (2011), Rosa et al. (2012b) and Akhtar at al.

(2013). Akhtar at al. (2013) concluded that 40% of water reduction decrease yield by 14-29%. On the other hand, Awan (2010) showed that 50% reduced water supply would bring a 22-30% yield reduction, with a higher risk in the early growing stage. Akhtar et al. (2013) reported that reducing water supply by 40, 50 and 60% resulted in 14-29, 30-45 and 48-59% yield reduction, respectively.

In NE Syria, the crop seasonal evapotranspiration (ET) is about 790-927 mm (Oweis et al., 2011), and the target irrigation water use (IWU) is about 760-816 mm, with 8 irrigation events when surface irrigation system is adopted (Farahani et al., 2009; Oweis et al., 2011; Akhtar et al., 2013). However, the traditional season IWU is about 1500 mm (Farahani et al., 2008). For Central Asia, seasonal ET was 670 up to 933 mm (Cholpankulov et al., 2008 and Pereira et al., 2009). Cotton is planted in late April and harvested in middle October with a crop season duration of 160-170 days (Chapagain et al., 2006; Pereira et al., 2009). Some studies concluded a significant groundwater contribution by capillary rise (Cholpankulov et al., 2008; Rosa et al., 2012b; Akhtar et al., 2013). The present yield achieved is 4.6×10^3 kg ha^{-1} and the optimal is about 5.0×10^3 kg ha^{-1} when the irrigation and crop practices are improved (Hussein et al., 2011; Oweis et al., 2011; Akhtar at al., 2013). The effect of water and nitrogen on yields is highly significant, with nitrogen doses of 200 kg N ha^{-1} (Janat, 2008; Oweis et al., 2011).

Comparing cotton productivity, the yield of 2.7×10^3 kg ha^{-1} was observed in Uzbekistan, for similar climate to Syria (Akhtar et al., 2013), and 4×10^3 kg ha^{-1} in Syria (Janat, 2008; Galli et al., 2010). The cotton water productivity when traditional methods are applied is about 0.20-0.25 kg m^{-3} of seed, and 0.07-0.09 kg m^{-3} for lint, and with recommend management practices this value can reach 0.48 kg m^{-3} of seed (Oweis et al., 2011). Other studies concluded that, the irrigation water productivity (WP_{irrig}) is from 0.56-0.85 kg m^{-3} (Ibragimov et al., 2007; Dağdelen et al., 2009; Dilbaugh et al., 2011; Hussein et al., 2011; MAAR, 2011; Sankaranarayanan et al., 2011). Lower WP_{irrig} 0.33-0.38 kg m^{-3} concluded by Norton and Silvertooth (2001), Cetin and Bilgel (2002), MunlaHasan (2007), Cholpankulov et al. (2008) and Pereira et al. (2009).

2.1.3. Irrigation scheduling modelling

Several irrigation scheduling models have been developed during the past two decades, applied to design or manage irrigation systems (Liu et al., 2000; Shang and Mao, 2006; Li et al., 2011), to assess impacts and feasibility of deficit irrigation (Zhang, 2003), or to evaluate water saving practices (Pereira et al., 2003; Zhang, 2003; Zhang et al., 2006; Fang et al., 2010). Generally, these models are based on the soil water balance and frequently they include yield-water functions. Examples are CROPWAT (Smith, 1992), ISM (George et al., 2000), ISAREG (Pereira et al., 2003), BUDGET (Raes et al., 2006), OSIRI (Chopart et al., 2007), PILOTE (Khaledian et al., 2009), SIMDualKc (Rosa et al., 2012a) and AquaCrop (Akhtar et al., 2013).

The ISAREG model has been extensively calibrated/validated for various crops and regions using soil water observations (Cancela et al., 2006; Popova et al., 2006; Popova and Pereira, 2011). It was applied for wheat in Syria by Oweis et al. (2003) and by Zairi et al. (2003) in Tunisia, Liu et al. (1998) and Cai et al. (2009) in China. It was applied for cotton by Cholpankulov et al. (2005), (2008) and Pereira et al. (2007) in Central Asia. SIMDualKc model was applied for wheat in China (Zhao et al., 2013) and in Syria (Rosa et al., 2012b), and for cotton in Central Asia (Rosa et al., 2012b). 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. The application of dual crop coefficient to estimate ET using soil water observations have been reported in the literature (Bodner et al., 2007; Greenwood et al., 2009; Descheemaeker et al., 2011; Martins et al., 2013; Zhang et al., 2013B).

The ISAREG model performs the soil water balance using different options to define and evaluate the irrigation schedules (Pereira et al., 2003). The water balance is performed for a multi soil's layers. Input data include precipitation, reference evapotranspiration (ET_o), total and readily available soil water, soil water content at planting, parameters characterizing conditions for groundwater contribution, crop coefficients and soil water depletion fractions for no stress, root depths and the water-yield response factor. Depending on weather data availability, various time step computations can be used. The model computes crop evapotranspiration (ET_c) using the methodology proposed by Allen et al. (1998), thus ET_c is calculated from the ET_o (mm) and the crop coefficients (Kc) (Eq. 2.1).

$$ET_c = K_c \times ET_o \qquad [2.1]$$

ET_a is estimated through the soil water balance as a function of the available soil water in the root zone when depletion exceeds the depletion fraction for no stress (p). The ISAREG model computes the irrigation water requirements throughout the soil water balance that is calculated for the effective root depth as:

$$\theta_i = \theta_i + \frac{(Pr_i - RO_i) + I_{ni} - ET_{ai} - DP_i + GW_i}{1000 Z_{ri}} \quad [2.2]$$

where θ_i and θ_{i-1} are soil water content in the root zone ($m^3\ m^{-3}$, or mm mm^{-1}) in the days i and i-1, Pr is the precipitation (mm), RO is the runoff (mm), I_n is the net irrigation depth (mm) that infiltrates in the soil, DP is deep percolation (mm), GW is the groundwater contribution (mm), and Z_r is the effective rooting depth (m). Irrigation depths and dates are selected in accordance with different objectives, which are computed according to water depths limits and soil water thresholds defined by the user.

2.2. Irrigation methods and modelling

2.2.1. Surface irrigation

2.2.1.1. Irrigation practice and methods

Surface irrigation systems are widely used in Mesopotamia, after centuries (McCorriston and Weisberg, 2002; Kamash, 2012). In NE Syria, the traditional surface irrigation methods are borders and basins applied for wheat, and zigzag furrowed basins and graded furrows for cotton, usually with a low water application efficiency. This low performance is due to poor irrigation management and several other problems i.e. levelling problems and the lower permeability of the soil (Mailhol et al., 2004; Farahani et al., 2009; Yigezu et al., 2013). High water reduction is in the distributed channel beside the high labour requirement with beneficial water use fraction, (BWUF) for cotton (Pereira et al., 2012) of about 0.5. This system would have high potential for modernization and achieving good performance including for cotton (Hunsaker et al., 1998; Pereira et al., 2002; Smith et al., 2005; Horst et al., 2007; Subramani and Martin, 2012). The irrigation systems performance has shown that raising water productivity implies the improvement of the performance of the irrigation systems and improved crop irrigation management (Smith et al., 2005; Rodrigues and Pereira, 2009; Rodrigues et al., 2010a). The sustainable irrigated agriculture requires the adoption of appropriate technologies including the modernization of traditional irrigation systems focusing water savings and economic water productivity enhancement (Oweis et al., 2011; Pereira et al., 2012).

The performance of surface irrigation systems highly depends upon the design process and management variable (Pereira, 1999; Gonçalves et al., 2011b), which is related with the appropriateness and precision of land levelling, field shape and dimensions, and inflow discharge. In addition, the soil infiltration characteristics that are spatially and seasonally variable significantly influence the system performance. Improving these systems requires low level technology with low investment and energy costs to manage the time duration of every irrigation event (Pereira et al., 2002). The efficiency of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice (Gonçalves et al., 2011b). Santos (1998) pointed out that, managing the cutback type and return-flow to recover the runoff flows helps to improve the surface efficiency, while land levelling increase the uniformity of distribution. However, the complexity of the parameter interactions within each of these main influences makes it difficult for irrigators to identify optimal design or management practices.

2.2.1.2. Surface irrigation modelling

The surface irrigation modernization is a basic condition to obtain sustainable agriculture targeting for water saving to cope with the regional severe water scarcity, soil conservation to prevent the problems related with salinity, and the increase of farmer's economical income to contribute to the economic and social rural development (Oweis et al., 2011; Kang et al., 2012; Pereira et al., 2012). A software SIPAR_ID (Rodríguez and Martos, 2010) developed to estimate infiltration and roughness parameters of a surface irrigation event. The complexity of surface irrigation design was mimicked by numbers or software for sole basins, borders or furrows, BASCAD (Boonstra and Jurriens, 1988), BICADM (Maheshwari and McMahon, 1991), FISDEV (Zerihun and Feyen, 1992), BASIN (Clemmens et al., 1995), BORDER (Strelkoff et al., 1996) and SURDEV (Jurriens, 2001). The obtained simulation allows irrigators and water managers to rapidly experiment with design and management variables the irrigation performance. Some models like SIRMOD model (Walker, 1998) and SRFR/WinSRFR (Bautista et al., 2009) provides an opportunity to identify practices that are more efficient and to assess the benefits for a fraction of the time and cost of field trials (Raine and Walker, 1998). These two models SIRMOD and SRFR are the most comprehensive software developed to design three types of surface irrigation systems (furrows, borders and basins). Adamala et al. (2014) develops software SIDES for the design and evaluation of surface irrigation systems (furrows, borders and basins) along with the design of water conveyance systems. These design models have been tested in many countries for modelling furrows, basins, and borders irrigation (Horst et al., 2005, 2007; Bakker et al., 2006; Pereira et al., 2007; Gonçalves and Pereira, 2009). They are useful tools to investigate the performance of surface irrigation at the field scale, which well adapted for supporting the decision process (Hornbuckle et al., 2005).

The DSS SADREG is adopted in this study; it includes a database, simulation models and a multicriteria analysis model. The database concerns field sizes and topography, soil, crop and irrigation management data, which are created through interactive simulations with the ISAREG model, and economic data. The simulation tools include a land leveling module and the SIRMOD simulation and design model (Gonçalves and Pereira, 2009; Gonçalves et al., 2011b). The model applications indicated the need for model parameterization, mainly regarding infiltration, labour requirements and irrigation costs, which makes clear that without appropriate basic information, it is not possible to produce adequate design alternatives. The Model showed useful adoption in Uzbekistan (Gonçalves et al., 2011b) and in Syria (Darouich et al., 2007, 2012). The Model is further described in Chapter 4.

2.2.2. Drip irrigation

2.2.2.1. Irrigation practice and methods

The main objective of the drip irrigation design is the uniform distribution of water delivered through the emitters. Several studies indicate that a uniformity indicator should be considered including the effects of manufacturer's discharge variation and the variation due to head loss and elevation differences in irrigated areas (Zhu et al., 2010). In drip irrigation for cotton, the spacing between laterals usually is 0.75-0.8 m and 0.3-0.35 m between emitters, with one lateral per each plant row with emitter discharge of 1.5-4.0 l h^{-1} depending on the soil types (Devasirvatham, 2009; DeTar et al., 2010; Dilbaugh et al., 2011; Hussein et al., 2011). Danierhan et al. (2013) found that the selection of emitter discharge rates is considerably important in arid silt loam, where the ideal emitter discharge rate is 2.4-3.0 l h^{-1} for soil desalinization due to favourable salt leaching. If one lateral is used to irrigate two paired rows of cotton, the spacing (major/minor x emitter spacing) is equal to 1.2/0.6 x 0.6 m (Sankaranarayanan et al., 2011). Ozbahce and Tari (2010) studied the effect of emitter spacing between 0.5 and 0.7 m and reported that WP for 0.5 m is larger than for 0.7 m due to higher yields but irrigation water applied is slight higher for spacing of 0.5 m. Another study on effects of emitter spacing did not show statistical differences in yields and WP (Grabow et al., 2006). Aujla et al. (2008) reported that paired double row laterals achieved water saving and less direct evaporation, thus saving 50% of the cost relative to single row per lateral.

Significant reduction of costs were reported in relation to layout (Sankaranarayanan et al., 2011). The germination time with drip could be managed through the emitter discharge and spacing or the irrigation frequency or amount (Devasirvatham, 2009) when using pressure-compensating emitters and higher irrigation uniformity.

The difference of irrigation water use, IWU among self-compensating (SC) and non-compensating (NC) emitters refers to uniformity and irrigation application efficiency (Schwankl and Hanson, 2007). Yohannes and Tadesse (1998) showed that the irrigation application efficiency was 71-98% and 68-76% for SC and NC emitters respectively, with high WP for SC. However, self-compensating drip lines have higher costs.

Design of drip systems is complex because it comprises the selection of emitters, pipes and respective layout, and decisions on pressure head and its variation along the system, as well as pressure and discharge regulators and filters (Keller and Bliesner, 1990; ASAE, 2006). Moreover, the uniform distribution is one of the main objectives in the trickle irrigation design, which is affected by design parameters like pressure, discharge variation and emitter characteristics (Pereira, 1999; Pereira et al., 2002; Zhu et al., 2010; Carrión et al., 2013). Nevertheless, uniformity alone is not sufficient to achieve the goal of irrigation. The irrigation schedule is equally important in microirrigation practice (Pereira, 1999; Barragan et al., 2010). A variety of criteria and calculation procedures may be used to size the pipe system and limit pressure and discharge variations in the system (Wu and Barragan, 2000; Demir et al., 2007). Advances in design are proposed aimed at attaining targets on emission uniformity or economic objectives (Barragan et al., 2006; Valiantzas et al., 2007). Adopting drip irrigation shows advantages for water saving concept comparing with others methods when application losses are minimized (Pereira, 1999).

2.2.2.2. Drip irrigation modelling

The information of water distribution in soil under a point source is essential for drip design, the wetted pattern are function of soil physical properties, soil initial conditions and emitter discharge rate, irrigation management, crop root characteristics and evapotranspiration (Revol et al., 1997a, 1997b; Thorburn et al., 2003; Malek and Peters, 2010; Naglič et al., 2012). Analytical empirical and numerical models help to predict the soil water movement for varied design parameters: Drip-Irriwater by Arbat et al. (2013), WetUp model by Cook et al. (2003), (2006). A variety of models have been developed to support and facilitate the hydraulic design, such as for the pump/filtration station (Haghighi et al., 1989), for assessing emitter uniformity (Barragan et al., 2006), for pipe sizing (Kang and Nishiyama, 1996; Valiantzas, 1998, 2002; Demir et al., 2007), for economic optimization of systems (Saad and Mariňo, 2002; Valiantzas et al., 2007) and for optimization deign based hydraulic and economic criteria, DESIGNER model is developed (Bralts et al., 1993). The optimal design is based on finding the sizes of lateral and manifold pipes that ensure optimal emission uniformity (EU) and inlet pressure head in the emitters. A model PRESUD (Pressurized Subunit Design) (Carrión et al., 2013) was developed to identify the optimum drip design considering the total investment and variable cost. Narayanan et al. (2002) develops a model that can assist an irrigation designer determining and selecting components for small-scale drip irrigation systems while optimizing costs. A nonlinear optimization model developed for design and management perspectives to optimize the best design scenarios considering the operation hydraulic performance and economic aspect rely on pipes' price, pumping, and all corresponding parameters (Holzapfel et al., 1990; Dandy and Hassanli, 1996; Kandelous et al., 2010; Wu et al., 2010). Another model, *Irrisystem* that works as a system designer, estimating the ideal dimensions in order to optimize the hydraulics of the irrigation system and its division into irrigation sectors Barradas et al. (2012). Moreover, with technologies' development some researches (Molina-Martínez and Ruiz-Canales, 2009) developed a software for smartphone and PC-pocket to enable engineers and installers to evaluate the sensibility to changing demands (water needs, emitters, spacing, etc.) in all commercial diameters of drip lines.

MIRRIG model is adopted in this study, which developed to support the design of microirrigation systems and to advise farmers because of field evaluations (Pedras et al., 2009). The model provides the means to design, analyse, compare and rank numerous design alternatives taking into account the complex and interacting factors involved in the design of microirrigation systems and multiple objectives of technical, economic and environmental nature. (The model is described in Chapter 5)

2.2.3. Sprinkler irrigation

2.2.3.1. Irrigation practice and methods

Sprinkler irrigation systems are often replacing traditional surface systems and it is one of the most commonly used agricultural irrigation methods. The system aims to have high uniform distribution with appropriate overlapping of several sprinklers by adjusting the spacing between sprinklers and laterals. There are several kinds of sprinkler systems developed to suit the economic situation, labour, land topography, water requirement and the availability of water: 1) solid-set, 2) semi-permanent, 3) portable, 4) side roll or wheel-line, 5) mobile rain-gun and 6) movable lateral system (Keller and Bliesner, 1990). The uniformity of applied water by sprinkler irrigation systems depends on the layout and spacing between sprinklers, wind speed and direction, pressure change, which directly affect sprinkler discharge, and the water distribution pattern of the sprinkler. Thus, -water distribution pattern- depends on sprinkler type, nozzle type, rotation rate, crop interference, malfunctioning sprinkler heads, and non-vertical risers (Keller and Bliesner, 1990; Pereira, 1999; Tarjuelo et al., 1999; Pereira et al., 2002; Hanson et al., 2011). Pressure variation can occur because of both elevation differences and friction losses in the pipelines, valves, bends, elbows, etc. The uniformity of hand-move sprinklers, wheel-line systems, and solid set sprinkler systems is strongly affected by wind, as well as center-pivot and linear-move sprinkler machines (Keller and Bliesner, 1990, Dalton et al., 2002).

The comparison between some of the sprinkler types' characteristics regarding the investment cost, ability to protect against frost damage, management requirement, seasonal labour needs, and expansion ability is shown in Table 2.1. The moveable (hand-line) systems require higher labour consume. Patterson et al. (1996) has estimated that each irrigation for portable system can require up to 110 minutes per ha of labour for set up and remove, where for permanent set systems require six minutes per ha per irrigation. Permanent system using buried PVC produced the lowest annual water application cost per unit area, that includes investment (pumping, pipes and sprinklers), energy, labour, maintenance, and water costs. Consequently, permanent solid-set systems usually have a higher uniformity and efficiency than portable systems where the laterals are dispersed in the plot (Dalton et al., 2002; Van der Gulik, 2003; Ortega et al., 2004; Ortiz et al., 2006).

Table 2.1 Irrigation system characteristics (Dalton et al., 2002)

Irrigation system	*Investment capital requirement*	*Frost protection*	*Management input*	*Labour requirement*	*Expandable*
Handline Moveable (Large Gun)	Low	No	Moderate to High	High	Yes[1]
Hose Reel (Large Gun)	Low	No	Low	Low	Yes[1]
Handline Small Sprinkler	Medium	Limited	Moderate to High	High	Yes[1]
Permanent Set Small Sprinkler	High	Yes	Low	Low	Not consider

[1]Limited by pump capacity.

Sprinkler irrigation with high performance requires sufficient pressure, replacing malfunctioning or leaking sprinklers and keeping sprinklers above the plant canopy to prevent crop interference on the spray pattern. For sprinkler systems, water application uniformity often does not exceed 90% and the average application efficiency of solid set impact sprinkler is about 83-92% (Tarjuelo et al., 1999), the Christiansen's uniformity coefficient (CU) varies 76-90% and distribution uniformity varies 62-80%. These variations depend on wind speed (Musick et al., 1988; Tarjuelo et al., 1999). The sprinkler irrigation is commonly used to irrigate wheat, allowing more frequent irrigation with smaller quantities of water, thus helping to reduce crop stress (Trout et al., 1994; Karam et al., 2009; Sadiddin and Atiya, 2009). The converting from the traditional surface irrigation to modern irrigation methods, particularly sprinklers, leads to 9 and 19% higher output of water efficiency and yield respectively (Allan, 1999; Yigezu et al., 2013).

Cost-benefit analyses have been studied looking for optimal water use with different systems and considering the farmer's objectives (Khanjani and Busch, 1982; Dalton et al., 2002; Ortega et al., 2004). Several factors affect the sprinkler system cost: climate, topography and field shape, technical constraints, equipment, layout design, soil and water characteristics, labour requirements (Dalton et al., 2002). The most influential factor on the annual cost was the spacing between laterals and sprinklers, following by water, investment and energy costs (Ortiz et al., 2006). Relatively to the laterals spacing, a significant decrease in the cost is achieved by optimizing the selection of the irrigation subunit size and shape, e.g., for sprinkler spacings of (12m×12m), (12m×18m), and (18m×18m) the last one concluded as the more economical design. When the application rate is larger than 6 mm h^{-1}, the total water application cost increases for large spacing, such as (18m×18m), due to the need for larger pipe diameters (Ortiz et al., 2006). Liu and

Kang (2007) applied this option with sprinkler flow rate of 3 m^3 h^{-1} with a pressure of 300 kPa. It was recommended to avoid a pressure greater than 400 kPa as the high pressure implies high energy cost (Tarjuelo et al., 1999). Liu and Kang (2007) reported a small yield improvement (0.3 to 0.5×10^{-3} kg ha^{-1}) when sprinkler irrigation replaced traditional practices. Regarding to energy, Rodrigues et al. (2010a) concluded that, contrasting with WP, improving irrigation systems performance has little impact on energy performance, but full irrigation requires higher energy performance than deficit irrigation.

2.2.3.2. Sprinkler irrigation modelling

Keller and Bliesner, (1990) demonstrated that the selection of economical pipe sizes is an important engineering decision. On the other hand, several analytical techniques (Dercas and Valiantzas, 2012) have been proposed, which focus on the optimization of single diameter pipeline networks. These methods are usually based on hydraulic criteria, not considering the economic one (Dercas and Valiantzas, 2012). In addition, many studies show factors affecting uniformity and performance of sprinkler irrigation (Dukes et al., 2006) which include sprinkler head and nozzle, distribution system hydraulics, weather conditions, and management practices (Zhang et al., 2013L). Uniformity is considered as a central design and performance goal (Pereira, 1999; Keller and Bliesner, 2000). Some of simulation models for sprinkler irrigation have been developed during the last few decades. Like a water application rate (WAR) (Fukui et al., 1980), SPRINKMOD (Andrade et al., 1999), SIRIAS (Carrión et al., 2001; Montero et al., 2001), Catch3D (Merkley, 2004), a ballistic simulation model by Playán et al. (2006), DEPIVOT (Valín and Pereira, 2006; Valín et al., 2012) and DSSIPM (Flores et al., 2010).

PROASPER model is adopted in this study, which includes a design and simulation module and performance analysis to optimize the design (Rodrigues et al., 2010b). The model was improved integrating hydraulic sprinkler design, databases, and simulation with multicriteria approach as described in Chapter 6.

2.3. Selecting irrigation systems based on multicriteria analysis

2.3.1. Introduction to the multicriteria analysis

The multicriteria analysis allows to aid decision-makers to integrate the different options, reflecting the opinions of the actors concerned, into a prospective or retrospective framework. Participation of the decision-makers in the process is a central part of the approach. This approach enables us to enhance the degree of conformity and coherence between the evaluation of the decision-making process, systems value and objectives of those involved in this process (Keen and Morton, 1978, Zeleny, 1982; Carlos, 1990; Korhonen at al., 1992; Pokharel and Chandrashekar, 1998; Tiwari et al., 1999; Munda, 2004). Further, the purpose of this methodology is to structure and combine the different assessments considered by decision-maker to have the final decision based on multiple choices (Keen and Morton, 1978; Linkov et al., 2006).

In irrigation application, MCA supports a better understanding of the irrigation impacts, enabling to achieve a satisfactory compromise between adversative decision-maker objectives (Pomerol and Romero, 2000; Huang and Chen, 2005; Hajkowicz and Collins, 2007; Montazar and Behbahani, 2007; Ishizaka and Nemery, 2013). It has been applied in agriculture for irrigation scheduling and design and management of on-farm irrigation systems to find the appropriate solution for a given environmental condition (Abdullah and Munir, 2003; Thysen and Detlefsen, 2006; Montazar and Behbahani, 2007; Bautista et al., 2009; Gonçalves et al., 2009; Pedras and Pereira, 2009). Bartolini et al. (2010) evaluated expected outcomes of different water policy scenarios from the point of view of different stakeholders, Rodrigues et al. (2013) compared and ranked various drip and sprinkler systems, Gonçalves et al. (2011b) and Darouich et al. (2012) selected surface irrigation alternative systems for cotton in Central Asia and Syria, respectively.

A functional diagram of MCA is presented in Figure 2.1, which starts by defining the criteria based on the user's objectives, where a utility function corresponds to each criterion, and the level of satisfaction depends on the user preference. A matrix is built among alternatives *vs.* utilities and ranks the effective alternatives after eliminate the unsatisfactory ones using multicriteria methods.

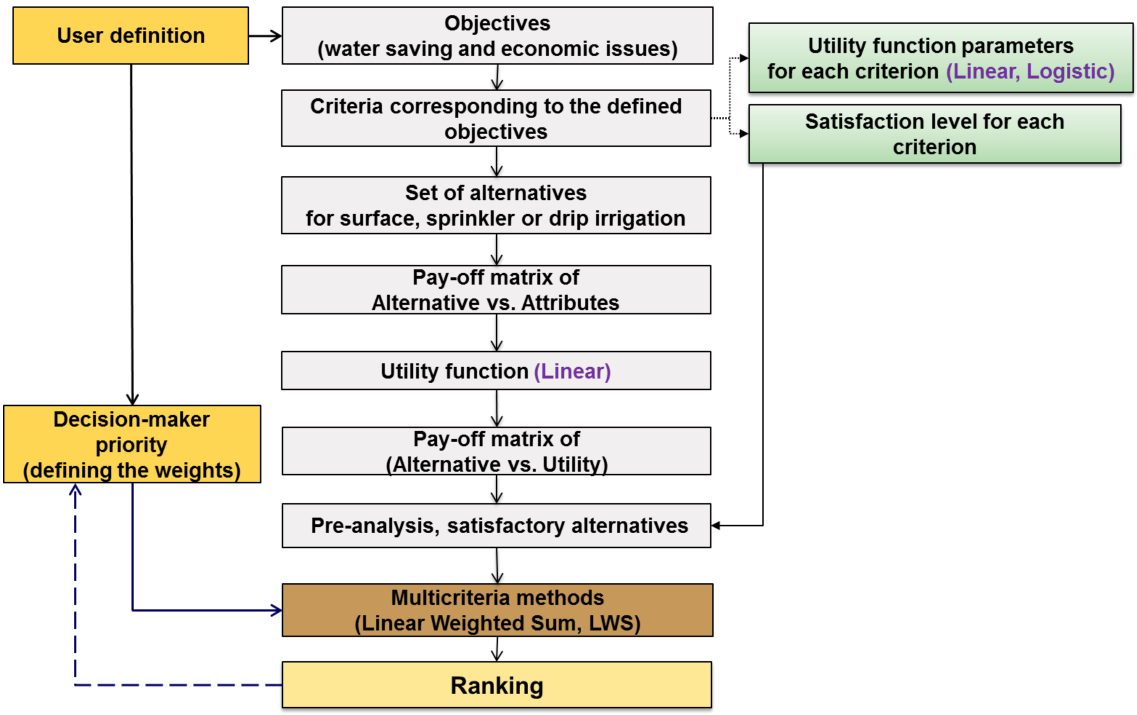


Figure 2. 1 Functional diagram of MCA model

The outranking methods are based on multiple comparisons of the type: "*does Measure A outrank Measure B from the point of view of the environment criterion?*", "*does Measure A outrank Measure B from the point of view of the benefit criterion?*", (e.g., Roy and Vincke, 1981; Vetschera, 1986; Vincke, 1992; Simpson, 1996). ELECTRA is widely applied (Raju et al., 2000; Mousseau et al., 2001; Huang and Chen, 2005; Wang and Triantaphyllou, 2008; Pedras et al., 2009; Alexopoulos et al., 2012). The evaluation method recognized with a strong performance record of accomplishment that can be employed to facilitate decision-making activities, which incorporate both qualitative and quantitative criteria (Huang and Chen, 2005). Evaluation methods are required to establish preference relations, i.e. outranking relations, and then make consistent exploration and analysis in support of decision-making. The major purpose of the evaluation methods is to select a desirable alternative that meets both the demands of concordance preference above many evaluation benchmarks and of discordance preference under any optional benchmark. The ELECTRE I and II evaluation methods generally included these concepts; namely the concordance index, discordance index and threshold value (Huang and Chen, 2005; Lee and Yeh, 2006). Following Pedras et al. (2009), the ELECTRE II is an outranking MCA method (Roy, 1996) aimed at supporting decisions by ranking alternative solutions for a multi objectives problem. It is based on a pair wise comparison of alternatives and evaluates the degree to which scores in the criteria and their associated weights confirm or contradict the dominance in the pair wise relationships. The final ranking is based on the strong and weak outranking relations calculated with the use of concordance and discordance thresholds (Pedras et al., 2009).

Others outranking methods, like PROMETHEE, I and II (Brans and Vincke, 1985) are other methods where the weights can be seen more as trade-offs between the criteria and not as coefficients of importance (Munda, 2004). The distance-based outranking technique is designed to identify non-dominated solutions, which are closest to an ideal solution using a quasi-distance measure (Zeleny, 1982). The distance-based methods consider subjective and objective weights, which are relatively unstable where these weights are sensitive to the changes in both the feasible set of alternatives and criteria.

2.3.2. Application to irrigation selection using Linear Weighted Sum

This study applied Linear Weighted Sum (LWS) (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, The high simplicity of this method is its major advantage as it has been successful in ranking surface irrigation alternatives (Gonçalves et al., 2011). For each alternative, the method allows the calculation of a global utility that represents its integrative score performance. A global utility value, U of each alternative used to rank alternatives is calculated according to criteria's weight referring the user priority (Saaty, 1977; Gonçalves et al., 2011a, 2011b; Darouich et al., 2012).

$$U = \sum_{j=1}^{n} (U_j(x_j)\ \lambda_j + U_{j+1}(x_{j+1})\ \lambda_{j+1} + \ ... \ + U_n(x_n)\ \lambda_n) \quad [2.3]$$

where $U_j(x_j)$ is the utility for criteria's attribute, x_j, λ_j is the corresponding weight for this attributes and n is the number of attributes. The utilities U_j relating to any adopted criterion j were normalized into the (0-1) interval with zero for the more adverse and 1 for the most advantageous result (Figure 2.2) (Saaty, 1977; Gonçalves et al., 2011b; Darouich et al., 2012). Linear utility functions are commonly applied:

$$U_j(x_j) = \alpha . x_j + \beta \quad [2.4]$$

where x_j is the attribute, α is the graph slope and β is the utility value of $U_j(x_j)$ for a null value of the attribute. The slope α is negative for criteria like costs and water use, and positive for other criteria like benefits and water productivity

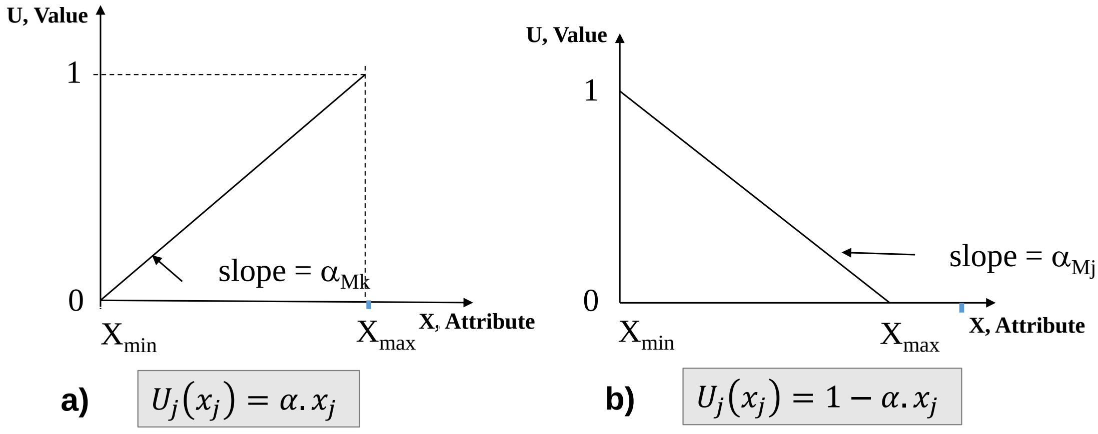


Figure 2. 2 Linear utility functions relating two points of type a) "*more is better*" and b) "*more is worst*"

The decision criteria for selecting irrigation systems are: 1) economic criteria relative to the yield value, the initial investment cost, and operation and maintenance costs, and 2) environmental criteria relative to the reduction of non-beneficial water uses relative to tail-end runoff and deep percolation and water saving in addition to the productivity of water unit. The criteria are common for all irrigation methods considered. The adopted criteria were represented by attributes and scaled according to the utility functions. The adopted criteria corresponding to surface, sprinkler and drip refer to two main objectives; water saving and environment, and economic productivity and costs (Gonçalves and Pereira, 2009; Gonçalves et al., 2011b; Darouich et al., 2012; Pereira et al., 2012)

2.3.3. Decision Support Systems

DSS are powerful tools for user decision aid because they integrate data and design and selection models, which allow easy creation and screening of management and design alternatives, therefore their ranking and selection following a variety of criteria. Their application in farm irrigation is useful because it allows associating hydraulics, irrigation performance, environmental and economic criteria in irrigation scheduling (Thysen and Detlefsen, 2006; Richards et al., 2008; Chen et al., 2012) and irrigation systems design (Hornbuckle et al., 2005; Gonçalves et al., 2007, 2011b; Pedras et al., 2009; Gonçalves and Pereira, 2009).

With the advent of the internet new possibilities opened for the use of DSS in agriculture with its strong advantages in remote maintenance of programs and, from the users' point of view, automatic update of dynamic data required by the DSS. The Web-DSS is the medium linking the client computer with the server and the Web-based data warehouse system which requires the interactive coordination among user, service and application server (Terol, 2008; Fang, 2009; Yu-Hui, 2009; Xiuquan et al., 2009). For crop production, weather data are important for many purposes covered by DSS applications, including DSS for irrigation (Thysen et al., 2006; Car et al., 2007). The DSS applications for irrigation are extensively studied in the literature, which refer the usefulness of these tools for the sustainability of agricultural production considering the rational use of the available water as a central variable. Thus variable depends on the crop, soil and climate, as well as the irrigation system, application rates and the scheduling mechanism (Lilburne et al., 1998; Raine and Walker, 1998; Abdullah and Munir, 2003; Bazzani, 2005; Montazar and Behbahani, 2007; Gonçalves and Pereira, 2009; Le Grusse et al., 2009; Zhong-Xiao and Yimit, 2009; Flores et al., 2010; Majumdar et al., 2010). However, only few operational decision support systems have been reported (Mateos et al., 2002). Of these, only a limited number is web-based like SAgMIS model and IRRINET (Thysen and Detlefsen, 2006), which produce output in terms of water balances. A study (Barradas et al., 2012) that applies DSS by integrating three modelling systems *Irrimanager,* which computes the crop water requirements and *Irrisystem*, which improve and help to optimal the design of drip or sprinkler systems and *Fertigation* aiming to increasing the sustainability of environmental irrigation systems. Another model Web DSS SADREG, which based on client-server architecture, comprises a Web module that creates the user interface; data fluxes numerical and graphical data, and the simulation model of SADREG (Gonçalves et al., 2011a).

Chapter 3

Case study area and characteristics

3.1. Case study area and water scarcity in northeast Syria

Increasing population and limited water resource and climate change in Syria will threat the food security for future generations. Therefore, priority decisions at government level should be taken to improve the water management in agriculture sector, which corresponds to about 80% of total water use. The total irrigated land is Syria has been more than doubled in 20 years from 0.65 Mha in 1985 to 1.4 Mha in 2005 while it has shown a 13% reduction between 2005 and 2009 (ASA, 2005; FAO, 2012).

This study refers to Ras-El-Ain area, in the Northeast of Syria, located in the Al-Khabour basin (Figure 3.1). The basin catchment of Al-Khabour River is divided between the Turkey, Syria and Iraq countries (Figure 3.2). In Syria the river covers an area of 19,200 km^2 , representing 60% from the total basin catchment land shared with tributaries Jagh-Jagh, Aawaj, Zarquan and Jerjeb (Kattan, 2001, 2008). The river is largely fed by 18 karstic springs (5 in southern Turkey, and 13 in northern Syria), which are recharged by precipitation in the adjacent Turkish mountains. The total discharge of these springs was around 43 $m^3\ s^{-1}$ (Öztan and Axelrod, 2011). This discharge had fallen to 14 $m^3\ s^{-1}$ in 1998 and to 7.38 $m^3\ s^{-1}$ in 2003 (Hole, 2009). Unsustainable water use in this region was identified earlier (Beaumont, 1996; Hole, 2009). A necessary agreement between both countries relative to the use of the large international aquifer whose sources feed the Al-Khabour River is required to avoid its depletion; unfortunately, it is difficult to be signed in the present international context.

This region is an ancient fertile area where wheat and cotton are irrigated, predominantly by traditional basins and furrows irrigation. This area is heavily affected by water scarcity influenced by climate aridity, enormous decrease of the Al-Khabour river flow and groundwater and heavy use of water available in irrigation (Öztan and Axelrod, 2011). Studies and reports indicate a severe water shortage in Al-Khabour basin as surface and groundwater sources, accompanied by degradation of the environment related to the deterioration of the water quality and intensive erroneous human activities. The current practice involves increasing intensification of irrigated agriculture by deep underground pumping, heavy use of fertilizers, and elimination of fallowing cycles (Beaumont, 1996; Kattan, 2001, 2008; Hole, 2009; Öztan and Axelrod, 2011; Kamash, 2012).

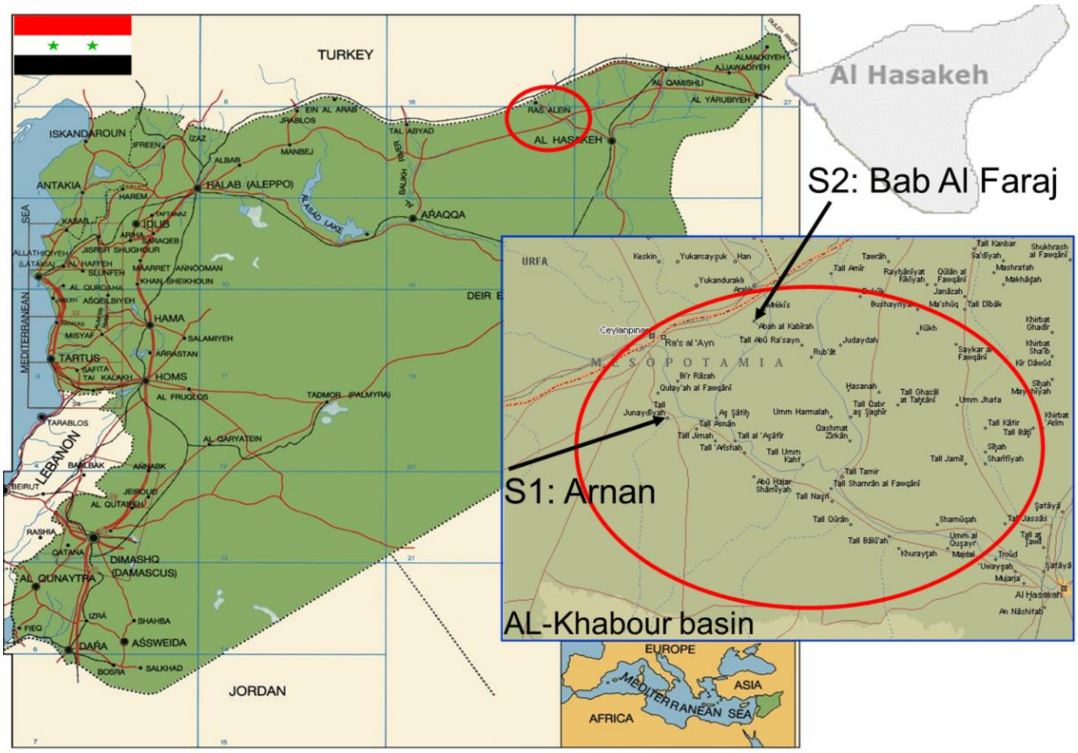


Figure 3. 1 Syrian map, location of Al-Khabour basin and Ras-El-Ain district.

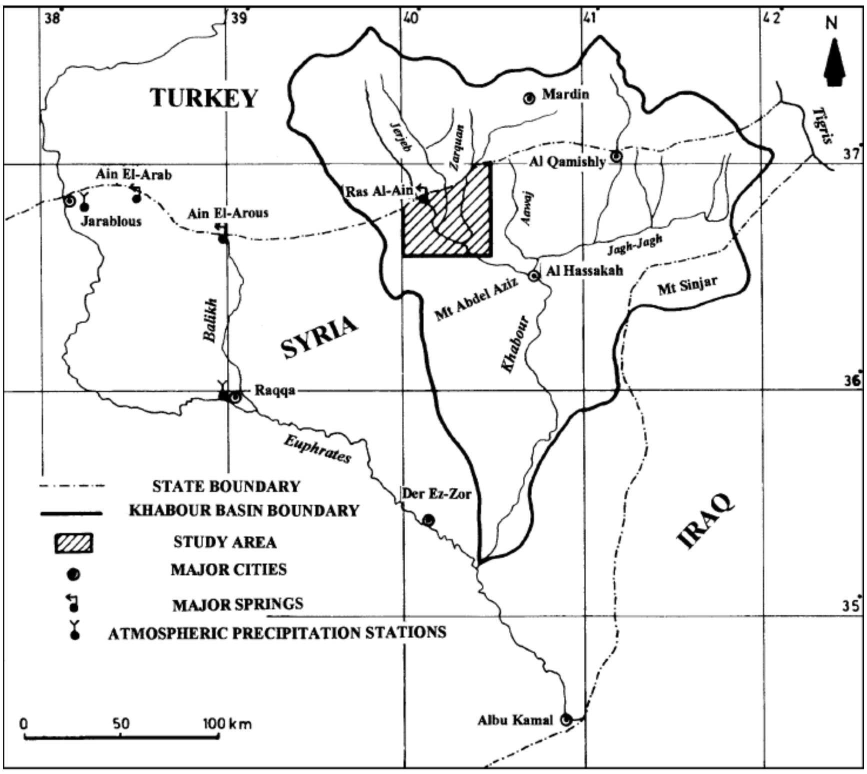


Figure 3. 2 Boundary of Al-Khabour Basin in north-east of Syria

The excessive pumping and the increase demand for irrigation is leading to rapid depletion of the groundwater resource, which decrease about 2 to 6 m of the piezometric levels in many parts of the Syria (ACSAD and BGR, 2003). However, a national irrigation modernization project in 2005 adopted by the Syrian government to cope the water scarcity problem and to aim for more sustainable water use since the agriculture sectors is the highest water consumer (Ortega and Sagardoy, 2001; Yassin et al., 2004; Sadiddin, 2013). The project provided technical support and low-interest loans to farmers to replace traditional systems by modern irrigation methods, mainly drip and sprinkler irrigation (MAAR, 2011; Yigezu et al., 2013). Moreover, what is produced in the field is strongly affected by social, economic, and institutional conditions. The farmers traditional knowledge, plus the economic and social considerations lead them to conserve the traditional practices, but they are sensitive to the market prices and subsidies which are given by government to various crops (Hole, 2009; Karam et al., 2009).

3.2. Land use, main crops and irrigation

The agricultural land in Al Hassakeh area is almost flat with smooth topography, with soil distribution of 45% cennamonic, 31% gypsiferous, 19% grumusol and 5% alluvial soil (MAAR, 2002). The land use considers cultivable, non-cultivable and pasture and forest, irrigated and rainfed or fallow land. The irrigated land is supplied from groundwater wells, or surface water through public projects. The irrigation methods are predominantly traditional surface one (furrows, zigzag basins and graded borders), having the modern systems a small application (MAAR, 2011) (Figure 3.3).

The main groundwater wells are artesian with an average depth of 188 m and a water level depth of 60 m, with discharges from 20 to 45 $l\ s^{-1}$. Almost 37% of the farmers have wells that are more recent (up to 20 years); 52% of farmers have fresh groundwater and 37% have water with a high content of sulfur. Almost 75% of wells use diesel for operating and the remaining use electricity (Ortega and Sagardoy, 2001). When the water has a high salt content (usual values are between 1.24 and 5.4 $dS\ m^{-1}$), the sprinkler systems could not be feasible, while drip irrigation often causes soil salinization (Yigezu et al., 2011).

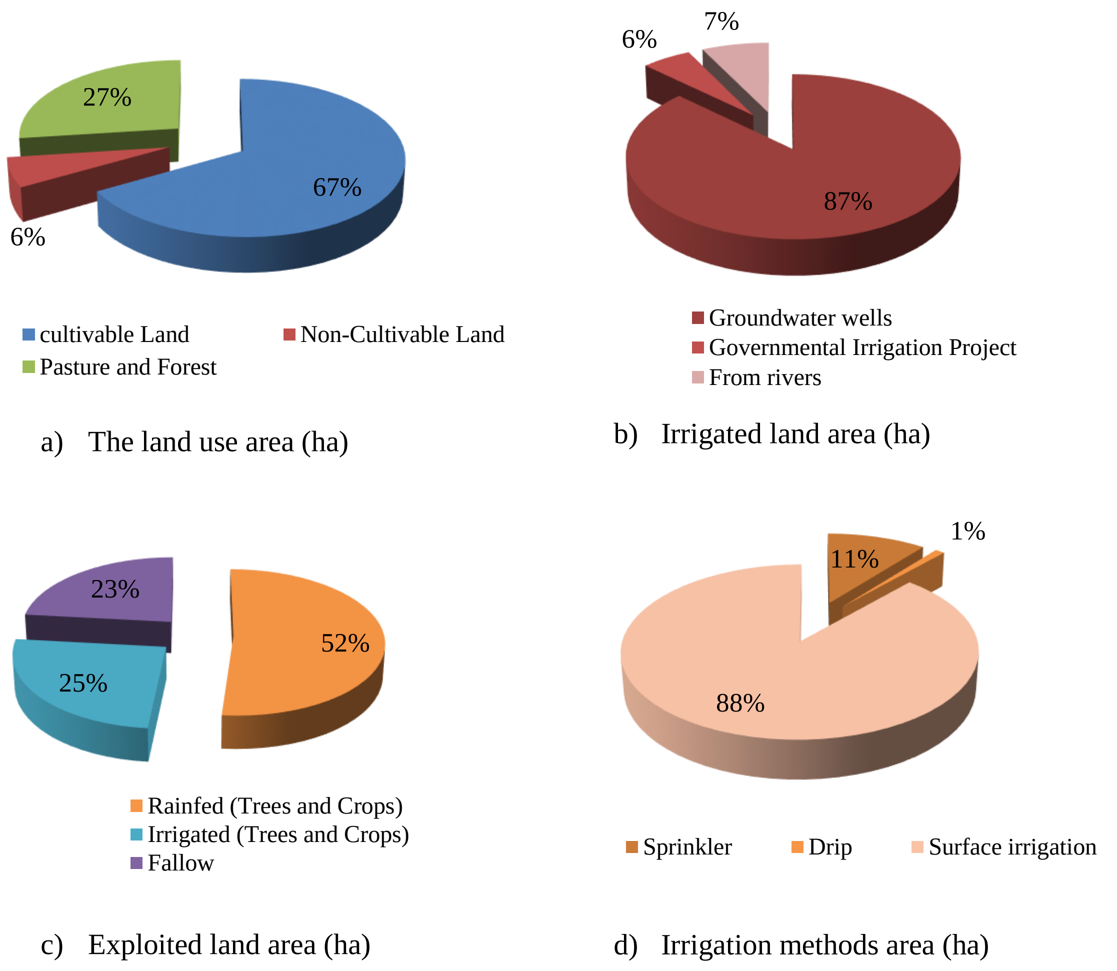


Figure 3. 3 Land use, Irrigated land, exploited and irrigation methods in Al-Hassakeh district, Year 2008

The main cultivated crops are cotton rotated with wheat. Wheat (*Triticum turgidum* L. var. *durum*) is the largest cultivated area in Al-Hassakeh Governorate, corresponding to 39% of the production from the whole country (Somme et al., 2005; Sadiddin and Atiya, 2009; Karrou et al., 2011, Yigezu et al., 2011). The irregular rain distribution during the crop season makes it necessary for farmers to apply supplemental irrigation to provide sufficient water in order to improve and guarantee the yield (Oweis et al., 1998, 2000; Oweis and Hachum, 2006; Karam et al., 2009). The rainfed crop has a net income 165 € ha^{-1} in case the wheat price is 0.35 € kg^{-1} while the irrigated crop arrives to 429 € ha^{-1} (MAAR, 2011). Zhang and Oweis (1999) reported that the total cost of agriculture and irrigation of rainfed crop is 191 € ha^{-1} while for irrigated crop it is 284 € ha^{-1}.

The dominant applied method is traditional surface irrigation by graded borders, 92-85%, being the sprinkler systems applied in 8-15% of the irrigated area (Karam et al., 2009;

Sadiddin and Atiya, 2009; Karrou et al., 2011). In addition, the wheat production accounts as a negative rate of -0.3%, with high fluctuations across years (FAO, 2012). Labour is not an important production factor because wheat is highly mechanised (Sadiddin and Atiya, 2009). Syrian policy makers were aware that applying traditional technology may not increase production and by merely increasing land area under cultivation. Instead, there was a need for technologies that improve productivity and stabilize yield and policies that encourage wheat production (Yigezu et al., 2011).

Cotton (*Gossypium Hirsutum* L.) is one of most important summer crop in Syria in terms of economic value and social impact. More than 20% of labour depends on this crop, through the cultivation, manufacturing, marketing, and other services (MAAR, 2002; Oweis et al., 2011). It is an irrigated crop with a high water demand, tolerant to salinity with a cultivated area of 56,100 ha, thus about 20% of the irrigated area (Chapagain et al., 2006; Shweih, 2006; Al Ashkar, 2009; Sadiddin and Atiya, 2009; MAAR, 2011). The seasonal irrigation water use by traditional cotton production systems is close to 1600 mm, with an average yield of 4.6×10^3 kg ha^{-1} (Janat, 2008; Farahani et al., 2009; MAAR, 2011; Oweis et al., 2011). A yield increase to about 5.0×10^3 kg ha^{-1} is expected if irrigation and crop practices are improved (Janat, 2008; Oweis et al., 2011).

The major cotton irrigation methods are surface irrigation, applied in 88.5% of the area and the traditional systems are prevailing; drip irrigation is the major pressurized systems applied. The sustainability of this crop in areas with severe water shortages, like in the Northeast of Syria, is a major priority (Sadiddin, 2009; Sadiddin and Atiya, 2009; Janat and Khalout, 2011; MAAR, 2011). Cotton irrigation is traditionally applied through furrowed zigzag basins, typical of the small family farms in the region. Few farmers adopt improvements in furrows and borders irrigation. Zigzag basins adapt well to existing field conditions without land levelling but there are labour consuming, impose limitations to mechanization, result in relatively low distribution uniformity, and often show a low beneficial water use ratio of about 50% (Darouich et al., 2007, 2012; Janat, 2008). The traditional system has a lower performance due to the non-levelness land, high labour consumption, and poor irrigation management (Farahani et al., 2009).

3.3. Experimental sites, climate and soils data

The experimental sites located in Ras-El-Ain, latitude 36° 50’ N, longitude 40° 4’ E, and altitude ranges 350 to 370 m a.s.l. were located in two farms, Arnan (Site 1) and Bab-Al-Faraj (Site 2), cultivated with wheat and cotton. Arnan farm is managed by the Syrian Ministry of Agriculture and the Cooperative Italian project by the experimental years of 2005 - 2007, while Bab-Al-Faraj is a private extensive land holding managed by the owner. Climate is semi-arid, with annual rainfall ranging 160-350 mm and potential evapotranspiration between 1600 to 2800 mm. Air temperature often reaches 43°C in July and August and decreases to 4°C in winter months. The predominant wind blows from the west and wind speed averages 2.3 m s^{-1} during the summer (Galli et al., 2010). The historical average temperature, precipitation and evapotranspiration for last 15 years is presented in Figure 3.4 (MAAR, 2011).

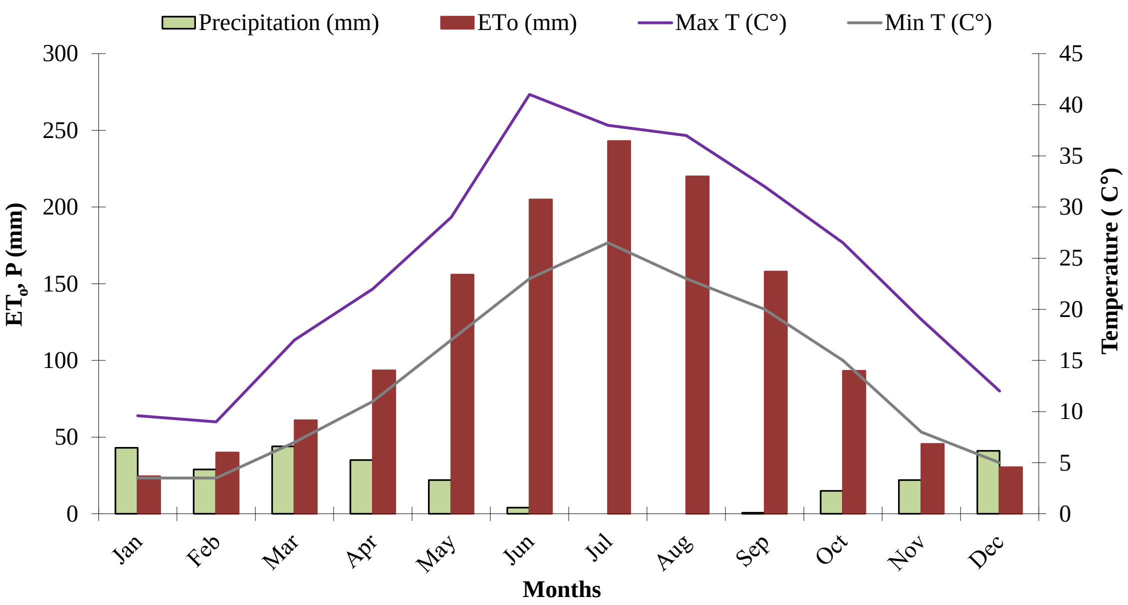


Figure 3. 4 Average climate data (1993-2008): precipitation, ET_o, minimum and maximum temperature

The total cultivated area of Arnan is 32.62 ha, which is divided into many fields cultivated with cotton, wheat and maize, with different irrigation systems, like the traditional, pressurized and improved surface systems. The main water resources are from two wells with discharges of 25 and 40 l s^{-1}. The test field was 300 m of length, and 50 m of width and was divided into three parts with 100 m length each; some sub-fields were divided to test furrows length 150m and 50m. The average longitudinal slope was about 0.8-1.0%, with slight cross slope. A topographic survey and a land smoothing operation were done to provide a uniform slope (Figure 3.5).

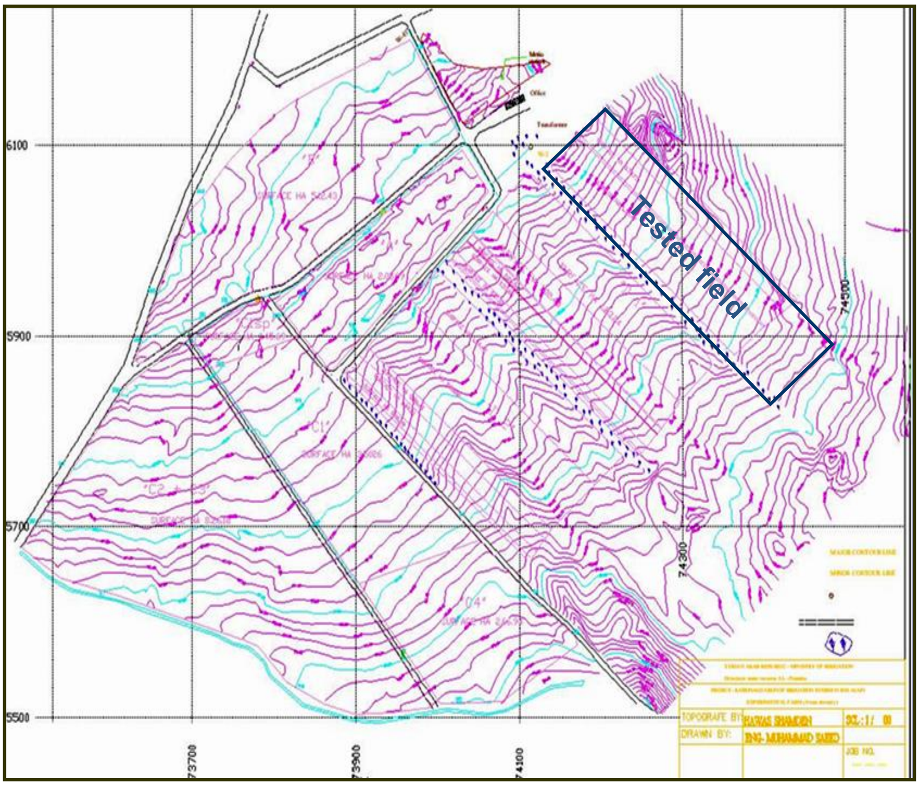


Figure 3. 5 Experimental farm in Arnan and the land topographic survey

A soil survey characterized the soil properties, mainly water contents at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), and soil texture. Table 3.1 shows soil properties in the two plots for three layers of 0.30 m depth each. The average total available water (TAW) is 139 mm m^{-1} (Darouich et al., 2007, 2012); the hydraulic conductivity Ks was about 3 to 4 mm h^{-1}. The groundwater salinity was 3.8 and 4.4 dS m^{-1}, in Site1 and Site 2, respectively (Yigezu et al., 2011). Field evaluation and treatments were carried out for different irrigation systems: graded furrows, graded borders, and traditional zigzag basins, for different lengths, slopes, discharges and the tail water management.

Table 3. 1 Physical soil properties of Arnan site

Plots	**Depth cm**	**Texture**			**Soil water content**		
		%	**%**	**%**	**% (weight)***		
		Clay	**Silt**	**Sand**	**FC**	**PWP**	**TAW**
1	00-30	29.0	35.6	35.4	24.6	14.5	10.1
	30-60	48.9	29.9	21.2	27.5	17.5	10.0
	60-90	45.9	27.0	27.0	26.4	16.6	9.8
2	00-30	45.1	31.8	23.0	27.4	17.2	10.2
	30-60	40.2	32.2	27.7	26.1	15.8	10.3
	60-90	49.9	30.5	19.5	25.7	17.1	8.6

* The bulk density is 1.3 -1.4 g cm^{-3}

The experimental applications in Site 2 adopted an improved surface irrigation system for cotton with long graded furrows, with medium and large slopes. The water was distributed through a ditch with small pipes across the ditch wall, being the discharge controlled by the water head in the supply ditch. The field experimentation was carried out in two plots to evaluate the current system application for lengths between 220 and 90 m and longitudinal slopes between 0.1 and 1.9%.

The improvement of irrigation systems requires that appropriate field data be collected to characterize the farm systems and the respective performance. Field evaluations of actual irrigation events were performed following the methodology described by Walker and Skogerboe (1987), ASAE (2003) and Horst et al. (2005), including for deriving infiltration and roughness parameters. Therefore, the field evaluation to define the soil and infiltration characteristic were done for several treatments for different furrows lengths of 50-220 m, open and diked tail-end management, and inflow rates between 0.35 and 1.31 l s^{-1}.

The modified Kostiakov infiltration equation was adopted:

$$Z = k.\tau^{a} + f_0.\tau \quad [3.1]$$

where Z is cumulative infiltration (m^3 m^{-1}), τ is infiltration opportunity time (min), k is an empirical coefficient (m^3 m^{-1} min^{-a}), a is an empirical exponent (dimensionless), and f_0 is the empirical base infiltration rate (m^3 min^{-1} m^{-1}). The methods used to get the infiltration characteristics were: 1) the double ring infiltrometer, 2) the volumetric water balance applied during the irrigation advance phase to get an approximation of parameters k and a, and 3) the furrows inflow-outflow balance applied after infiltration was stabilized to obtain the parameter f_0 (Walker and Skogerboe, 1987; ASAE, 2003; Horst et al., 2005). The inverse mode simulation with SIRMOD model was used with observed advance and recession data to optimize the k and a parameters and grouping the infiltration curves as defined in Table 3.2 and Figure 3.6.

Table 3. 2 Identification of infiltration curves in Figure 3.6

Site	Field Plots	α	k	f_0
Arnan	F1	0.207919	0.013406	0.000241
	F2	0.3223	0.011797	0.000167
	F3	0.071329	0.028607	0.000226
	F4	0.038148	0.023916	0.000151
	F5	0.278599	0.005862	0.000187
	F6	0.278599	0.005862	0.000187
	F7	0.3302	0.017	0.00021
	F8	0.3302	0.017	0.00021
	F9	0.3223	0.011797	0.000167
	F10	0.155612	0.01082	0.000336
	F11	0.161285	0.023259	0.000104
	F12	0.307782	0.004598	0.000243
	F13	0.149025	0.018178	0.000204
Bab-El -Faraj	F14	0.328568	0.00631	0.000324
	F15	0.243684	0.015012	0.000261
	F16	0.044037	0.020492	0.000198
	F17	0.211195	0.012616	0.00013

The typical infiltration parameters obtained from field observations are given in Table 3.3 and Figure 3.6. High infiltration rate soils are rare in the area and the medium values were applied in all simulations.

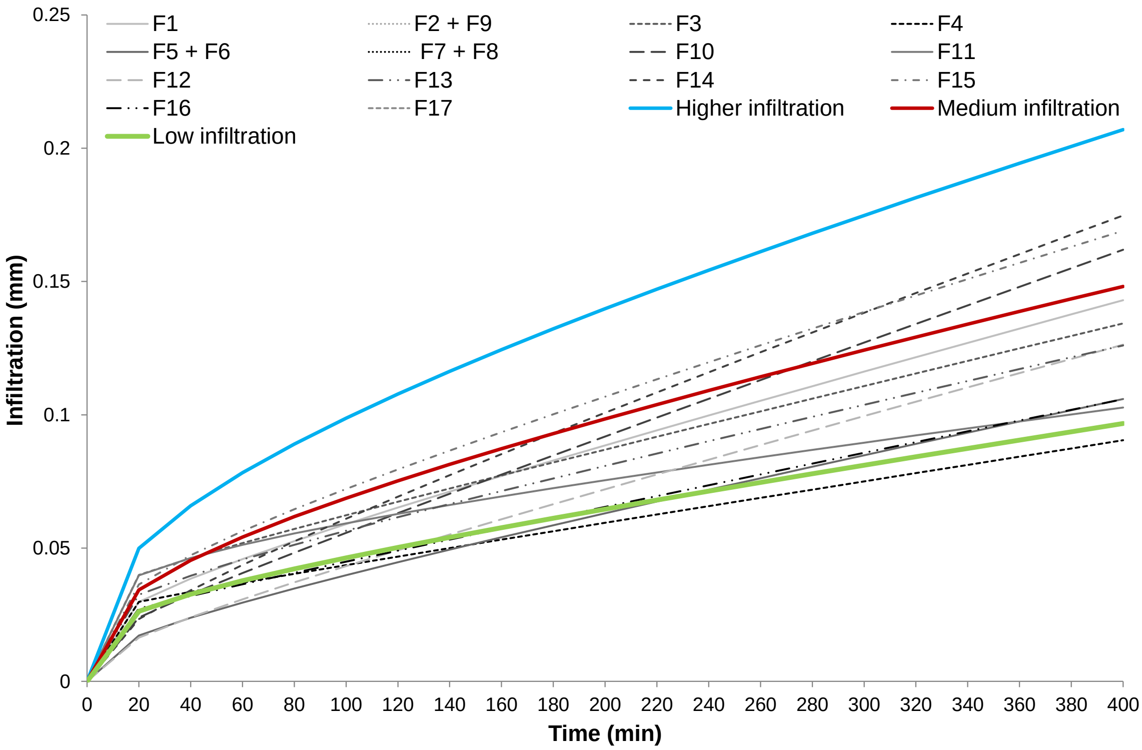


Figure 3. 6 Cumulative Infiltration curves for Ras-El-Ain

Table 3. 3 Parameters of the Kostiakov infiltration curves typical for Ras-El-Ain

Infiltration curves	k (m^3 m^{-1} $min^{-α}$)	α (-)	f_0 (m^3 m^{-1} min^{-1})
Lower infiltration	0.0126	0.2110	0.000130
Medium infiltration	0.0118	0.3227	0.000167
Higher infiltration	0.0170	0.3302	0.000210

3.4. Crop characterization and irrigation strategies

The wheat was cultivated during 165 days with an average yield of 5 kg ha^{-1}, which could increase to $5.25×10^3$ kg ha^{-1} for the wheat variety "Cham-6" adopting a modernized schedule (Kanshaw et al., 2007) with nitrogen fertigation of 150 kg ha^{-1} (Karam et al., 2009). The fertilizer was applied in traditional systems by machine before cultivation and later by hand. The average water applied for traditional systems in the year 2006 was 553 mm for total seasonal precipitation of 289 mm, the irregularity of the precipitation allowed only 149 mm as an effective water depth meet the crop water requirement and the obtained yield is $4.20 × 10^3$ kg ha^{-1} (Galli et al., 2010).

The cotton is planted in late April or early May and harvested by the middle of October, with a density of 71400 plants ha^{-1}. The seasonal water use by the traditional irrigation systems is about 1450-1620 mm, with an average yield of 3.75 to $4.6×10^3$ kg ha^{-1} (Darouich et al., 2007; Janat, 2008; Farahani et al., 2009; MAAR, 2011; Oweis et al., 2011). However, the potential yield is $5×10^3$ kg ha^{-1} when improving the irrigation methods and crop practices (Janat, 2008; Hussein el., 2011). Drip irrigation allows high fertigation efficiency, with the fertigation amount of N-P-K of 120-25-45 kg ha^{-1}, respectively. Moreover, the cost of production factors, like seeds, fertilizers, harvesting, and transportation, is around 26 to 21% of the total farmer income, considering for surface and drip irrigation systems, respectively (MAAR, 2011).

The irrigation schedule procedure was applied with the ISAREG model (Pereira et al., 2003). The methodology follows that described by Oweis et al. (2003) for wheat in Aleppo, Syria, and by Cholpankulov et al. (2005) for cotton in Central Asia, where the climate and the cultivation conditions are similar to those in Ras-El-Ain. The crop coefficients methodology proposed by Allen et al. (1998) was adopted. The soil hydraulic properties were averaged for one single layer of 100 cm, with a total available water TAW of 139 mm m^{-1}. The phenological stages of the wheat and cotton observed during 2005-2006 and other crop parameters are presented in Table 3.4.

Table 3. 4 Crop development stages and parameters for wheat and cotton in S1 (Darouich, 2006; Darouich et al., 2007)

Crop	Parameters	Crop development stages			
		Initial	Development	Mid-season	End- season
Cotton	Date: day/month	07/5 - 6/6	7/6 - 7/7	8/7 - 8/9	8/9 - 11/10
	Kc	0.30	0.30 – 1.13	1.13	1.13 - 0.61
	Depletion fraction, p	0.75 - 0.59	0.59 - 0.50	0.50 - 0.62	0.62 - 0.74
	Root depth (m)	1.00	1.00	1.00	1.00
Wheat	Date: day/month	1/1 - 1/2	2/2 - 30/4	30/4- 26/5	27/5 - 15/6
	Kc	0.54	0.54 – 1.10	1.10	1.10 - 0.32
	Depletion fraction, p	0.72 - 0.70	0.70 - 0.60	0.60 - 0.59	0.59 - 0.62
	Root depth (m)	0.75	0.75	0.75	0.75

The irrigation strategies adopted for both crops were:

a) Full irrigation (FI): irrigations applied when $\theta_{MAD} = \theta_p$ and for this strategy a constant irrigation depth (D) applied to refill the soil moisture to the field capacity. No irrigation was applied during the last 30 days before harvest, for wheat and cotton.

b) Deficit irrigation (DI): irrigation schedules were simulated by progressively lowering the threshold $\theta_{MAD} < \theta_p$ along the growing season, as referred by Pereira et al. (2003), for $\theta_{MAD} = 70\%\theta_p$. The percentage of deficit irrigation can be tested for various values along the growing season, given high deficit during the insensitive growing period for each of cotton and wheat, but this issue needs deep study and filed observations for that it is not considered. In this study, the simulations are made for fixed deficit percentage along the growing season like others studies Oweis et al. (2011) for cotton and Jalota et al. (2006) for wheat.

c) Current irrigation schedule (TI).

Chapter 4

Improving cotton surface irrigation. An application of SADREG model and multicriteria analysis

4.1. Introduction[1]

The study refers to Ras-El-Ain area, NE Syria, in the Euphrates basin, an ancient fertile region where wheat and cotton are grown under surface irrigation, predominantly traditional basins and furrows irrigation. This area is described in Chapter 3. Cotton cropland is about 20% of the irrigated area; cotton is the main cash crop in the region and has a very strategic value (Shweih, 2006). However, cotton is a high water demand crop (Chapagain et al., 2006) that seriously impacts the reduced water availability of Syria, particularly in Mesopotamia (Sadiddin, 2009; Sadiddin and Atiya, 2009). More about cotton characteristic and yield is described in Chapter 3. A sustainable irrigated agriculture requires the adoption of appropriate technologies including the modernization of traditional irrigation systems focusing water savings and economic water productivity enhancement (Oweis et al. 2011; Pereira et al., 2012).

Surface irrigation systems are used in the area, which is part of Mesopotamia, after centuries or millennia (Kamash, 2012). Commonly, farmers apply traditional irrigation methods, which are highly labor demanding and whose performance is often low, with a beneficial water use fraction (BWUF, Pereira et al., 2012) of about 0.5, and irrigation water productivity (WP_{irrig}) of 0.28 to 0.32 kg m^{-3} of cotton. However, surface irrigation has a high potential for modernization and achieving good performance including for cotton. The performance of surface irrigation systems highly depends upon the design process (Gonçalves et al., 2011b), which is related with the appropriateness and precision of land leveling, field shape and dimensions, and inflow discharge. (More details about surface irrigation for cotton is described in Chapter 2). Moreover, the irrigation performance also depends on farmer irrigation decisions, mainly in relation to land leveling maintenance, timeliness and time duration of every irrigation event, and on farmer's ability to overcome difficulties in water supply, such as uncertainty or scheduling constraints (Pereira et al., 2002). However, it is necessary to search for

[1] This chapter bases upon a paper entitled "Water saving vs. farm economics in cotton surface irrigation: An application of multicriteria analysis" authored by Darouich, H., Gonçalves, J.M., Muga, A., Pereira, L.S. and published in Agricultural Water Management 115, 223-231, (2012)

solutions that achieve adequate compatibility among irrigation performance, water saving and economic viability for farmers, which represent conditions for sustainable irrigation. This subject is well discussed by Wichelns and Oster (2006), who conclude that achieving the desirable sustainability implies direct costs and environmental impacts. The use of DSS based upon MCA could be appropriate to find related solutions, particularly when dealing with various and contradictory criteria (Roy and Bouyssou, 1993), such as in surface irrigation design (Gonçalves and Pereira, 2009). Both DSS and MCA are described in Chapter 2.

The objective of this study is to analyse and evaluate the potential of modernizing surface irrigation of cotton, particularly with furrows and borders irrigation methods for sustainable irrigated agriculture focusing the compatibility between water saving and economic viability. Aiming at this objective, the study applies MCA through the use of the DSS model SADREG to rank and select a set of design alternatives considering various decision criteria relative to irrigation performances, water saving and economic impacts.

4.2. SADREG

SADREG is a DSS model developed to assist designers and managers in the process of designing and planning improvements in farm surface irrigation systems (Gonçalves and Pereira, 2009; Gonçalves et al., 2011a; 2011b). It comprises two components: design and selection (Figure 4.1), the design includes a database, simulation models, user friendly interfaces, and the selection includes set of alternatives, user knowledge and multicriteria analysis models which allowed to rank alternative according to user criteria (Gonçalves and Pereira, 2009; Gonçalves et al., 2011a, 2011b). The simulation model used is SIRMOD (Walker, 1998). These alternatives are characterized by various hydraulic, economic and environmental indicators. The alternatives having main characteristics in common are grouped in *projects* as described by Gonçalves and Pereira (2009). The ranking and selection component is based on MCA.

The on-farm distribution systems refer to continuous and surge-flow (automatic or manual controlled) with layflat tubing with gates, gated pipes, concrete canals with lateral holes, and unlined canals with or without siphons.

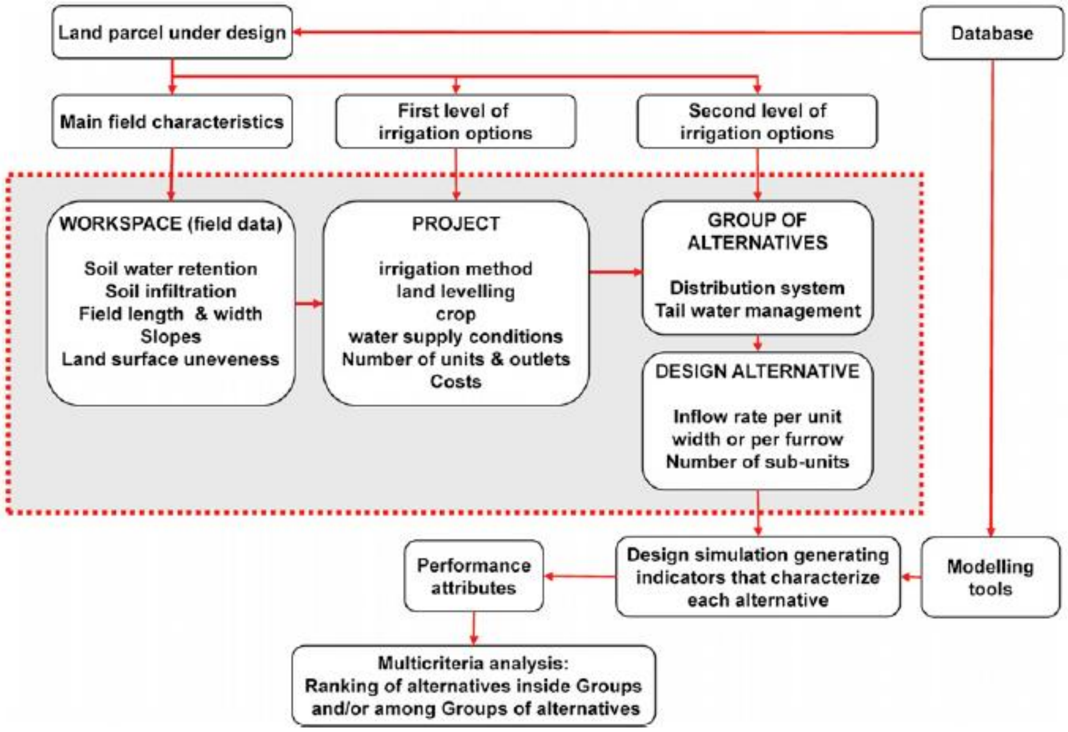


Figure 4. 1 Schematic flow-chart for the creation of field design alternatives using a multilevel approach for design and application of multicriteria ranking and selection (Gonçalves and Pereira, 2009).

The design alternatives are clustered into *groups* included in a *project* and relative to the upstream distribution system, and the tail-end management system, which both depends on the selected irrigation method and equipment available. The alternatives constitute complete design solutions. Within a group, they are differentiated by the operative parameters: the inflow rate per unit width of land being irrigated or per furrow, and the number of subunits.

The main steps on a SADREG application are:

1) Identification of field characteristics of a rectangular shape field;

2) Data input to characterize water supply and distribution equipment;

3) Data input referring to crop, soil data, mainly the infiltration parameters and costs and other financial parameters included manpower and land levelling;

4) Crop irrigation scheduling, created through interactive simulations with the ISAREG model (Pereira et al., 2003);

5) Design options to create the alternatives, using the SIRMOD hydraulics simulation tool (Walker, 1998); and

6) Ranking and selection of alternatives with MCA, the global utility value is computed for each alternative and linear weighted sum method (LWS) is adopted for multicriteria method (see Chapter 2) and weights are defined according to the user priorities.

4.3. SADREG application and parameterization

4.3.1. Case study

Ras-El-Ain was known for its important karst springs (Burdon and Safadi, 1963), which have been over-exploited, causing that piezometric heads continuously fall down, some sources dried out and land subsidence has occurred (see Chapter 2). The traditional irrigation systems are the furrowed zigzag basins and borders irrigation. These systems are typical of small and family farms in the region. The furrowed zigzag basin irrigation is practiced in long stripes of land, normally with 2-5 m wide and 30-150 m long, where the available discharge is divided into several strips that are irrigated simultaneously. Despite it is quite well adapted to existing field conditions without land leveling, it is labor consuming, and imposes limitations to mechanization. The resulting distribution uniformity is low (Darouich et al., 2007; Janat, 2008).

Cotton is the main cash crop in Al-Hassakeh governorate. A yield increase to about 5000 kg ha^{-1} is expected if irrigation and crop practices are improved (Janat, 2008; Oweis et al., 2011) (Field experiments, climate, soil characteristic and crop parameters are described in Chapter 3). The typical infiltration parameters obtained from field observations are given in Table 3.3; the medium infiltration curve is applied in all applications and simulations.

4.3.2. SADREG parameterization

The projects considered refer to graded furrows (GF) and graded borders (GB), using the options presented in Table 4.1. Simulations were performed assuming two scenarios: (1) without land leveling operation (identified GF_{NLL} and GB_{NLL}), which corresponds to reduced costs and less good irrigation performance; (2) considering precise land leveling and upgraded water use and irrigation performance. The reference situation corresponds to the traditional zigzag furrowed basins system, whose attributes correspond to average field observations.

Table 4. 1 Projects for simulating improved graded furrows (GF) and graded borders (GB) systems

Project	Irrigation method	Tail end condition	Soil surface condition	Number of irrigations	Target irrigation depth (mm)	Distribution system
GF	Graded furrow	Open	Furrowed with 0.70 m spacing	10	80	Gated layflat tubing
GB	Graded border	Open	Flat soil surface	10	80	Gated layflat tubing

The crop cycle duration is 170 days, with planting by May 1st and planting density of 71,400 plants ha^{-1}. The maximum yield achievable is 5000 kg ha^{-1}. The average net water irrigation requirements corresponds to 10 irrigation events, each one with 80 mm depth (Table 4.2). The total amount of irrigation is in agreement with results reported by Faharani et al. (2009) and Oweis et al. (2011) for Syria, Karam et al. (2006) for Near East, Cholpankulov et al. (2008) and Pereira et al. (2009) for Central Asia, and Chapagain et al. (2006) for other producing areas having a similar climate. For this typical field, full and deficit irrigation were considered, with net irrigation of 800 and 640 mm respectively (Table 4.2).

Table 4. 2 Irrigation scheduling considering the irrigation method and full and deficit irrigation

Irrigation method	Irrigation strategy	Evapotranspiration (ETa) (mm)	Number of irrigation events	Net irrigation depth, per event (mm)	Net irrigation water use (mm)
Traditional	-	881	10	150-220*	1620*
Surface	Full (FI)	886	10	80	800
Surface	Deficit (DI)	752	8	80	640

* The gross irrigation depth

A water-yield function was used to estimate crop yields as a function of the total water use during the irrigation season following the methodology proposed by Solomon (1984) and using regional data (Yazar et al., 2002; Dağdelen et al., 2009). This function $Y_a/Y_{max} = f(W_a/W_{max})$ relates the relative yield with the relative net water availability and refers to both deficit and excess irrigation. Y_a and Y_{max} are the actual and the maximum yield, that are achieved when the net applied water are, respectively, W_a and W_{max} (Table 4.3).

Table 4. 3 Water-yield function table parameters

W_a/W_{max}	0.25	0.5	0.75	1.0	1.5	2.0	2.5
Y_a/Y_{max}	0.10	0.56	0.85	1.0	0.97	0.9	0.73

The reference field used to represent the majority of fields in Ras-El-Ain area is 100 m long and 50 m wide, with 0.8% longitudinal slope, zero cross slope and medium infiltration characteristics (Table 3.3). The available discharge is 40 l s^{-1}. Hydraulics simulations were performed assuming a Manning roughness coefficient of 0.04 $m^{1/3}$ s^{-1} for furrows, and 0.16 $m^{1/3}$ s^{-1} for graded borders. The economic and labor input data applied presented in Table 4.4.

Table 4. 4 Economic and labour data

Description		Unitary costs
Land levelling	Hourly cost	220 € h^{-1}
	Operation time per area	3.0 h ha^{-1}
	Frequency of operation for graded borders	3 years
	Frequency of operation for graded furrows	4 years
PE layflat tubing	5” diameter	0.15 € m^{-1}
	9” diameter	0.22 € m^{-1}
	12” diameter	0.3 € m^{-1}
	Layflat valve	0.23 € per valve
Financial data	Analysis period	10 years
	Annual interest rate	4%
Effective lifetime of equipment	PE layflat tubing	1 year
	Layflat valve	1 year
Prices	Water price	0.022 € m^{-3}
	Labour cost	0.8 € h^{-1}
	Yield price	0.43 € kg^{-1}
Labour requirements	for equipment operation	40 min/100m
	for installing equipment	60 min/100m
	for removing equipment	50 min/100m

4.4. Multicriteria analysis application

The characterization of the design alternatives was performed with the performance indicators defined by Gonçalves and Pereira (2009) and Gonçalves et al. (2011b), listed in Table 4.5. In this study, two other indicators defined by Pereira et al. (2012) were added: (1) the beneficial water use fraction (BWUF), relating the beneficial fraction of applied irrigation water to the total irrigation water, and (2) the economic water productivity ratio (EWPR), that relates the yield value with the total costs for mobilizing and applying water to achieve that yield. The adopted criteria to be considered in ranking with MCA refer to the attributes and utility functions described in Table 4.5, which enable comparing variables having different units. The utilities U_j relative 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 (see Chapter 2). The slope, α, is negative for criteria like costs and water use, whose highest values are the worse, and positive for other criteria like benefits ELP, EWP and WP_{Irrig}, whose higher values are the best. The utility parameters were determined according to the full set of alternatives including the reference present condition. The decision maker priorities are modeled by the criterion weights (λ_j), which represent the relative importance of each criterion j as viewed by the decision maker. Criterion weights depend upon several factors, including socio-cultural, economic and environmental ones. Weights applied to the various attributes are listed in Table 4.5 in relation to water saving and environmental criteria (water saving), and to economic results at farm level (farm economics).

Table 4. 5 Criteria attributes utility functions and criteria weights

Criteria attributes (x)	Symbol	Units	Utility functions	Weights (%) assigned to attributes when considering	
				Water saving	**Farm economics**
Economic productivity and costs				**20**	**80**
Economic land productivity	ELP	€ ha^{-1}	U(x)= $0.280\times10^{-3}\,x$	2.5	15
Economic water productivity	EWP	€ m^{-3}	U(x)= $4.3\,x$	2.5	10
Economic water productivity ratio	EWPR	Ratio	U(x)= $0.25\,x$	5	20
Fixed irrigation costs	FIC	€ ha^{-1}	U(x)= $1 - 0.001\,x$	5	20
Variable irrigation costs	VIC	€ ha^{-1}	U(x)= $1 - 0.001\,x$	5	15
Water saving and environment				**80**	**20**
Total irrigation water use	IWU	$m^3\,ha^{-1}$	U(x)= $2.22 - 0.106\times10^{-3}\,x$	15	5
Beneficial water use fraction	BWUF	Ratio	U(x)= $1.429\,x$	20	5
Irrigation water productivity	WP_{Irrig}	kg m^{-3}	U(x)= $2.22\,x$	15	5
Irrigation tail-end runoff	RO	$m^3\,ha^{-1}$	U(x)= $1 - 0.100\times10^{-3}\,x$	15	2.5
Irrigation deep percolation	DP	$m^3\,ha^{-1}$	U(x)= $1 - 0.100\times10^{-3}\,x$	15	2.5

In this study, differently from a common design study, weights relative to farm economics and water saving criteria were progressively varied from a scenario where 90% of weights were assigned to farm economic criteria to a last scenario where 90% of weights were assigned to water saving. Analysing the rankings corresponding to these 9 weighing scenarios, W1 to W9, it could be possible to assess how alternatives respond to farm economics and water saving criteria.

4.5. Results and discussion

4.5.1. Water use performance, water saving, and farm economics

SADREG simulations created a set of 62 alternatives for the reference field, including scenarios with and without improved land leveling. This set was screened by removing the non-satisfactory ones, where the total irrigation water use, IWU was larger than the average value observed in field, 16,200 m^3 ha^{-1}. The characteristics of traditional irrigation method of furrowed zigzag basin were obtained from field observations in Ras-El-Ain area.

Results for IWU, irrigation tail-end runoff (RO) and deep percolation (DP) are presented in Figure 4.2a for the traditional and the satisfactory alternatives relative to both project types, GF and GB. Results show that the improved alternatives retained allow a significant decrease of IWU due to reduced deep percolation and runoff. Lower IWU correspond to GF(0.4) and GB(1.1) – numbers inside brackets refer to the unit inflow rate, $l\ s^{-1}$ per furrow or $l\ s^{-1}$ per m width of a border - but non-lasered leveling solutions $GF_{NLL}(0.4)$ and $GB_{NLL}(1.1)$ show not very different results relative to the lasered ones because reducing RO and DP mainly depends on the ability to control unit inflow rates applied. In other words, IWU and RO are very sensitive to the unit inflow rate, thus indicating that an improved performance requires appropriate control of inflow rates by farmers, i.e., that adequate equipment, such as gated layflat tubing, is available for that purpose. Replacing the traditional zigzag furrowed basins by graded furrows or borders increases the risk of producing high tail-end runoff if farmers do not have appropriate equipment and conditions to achieve a good control of the inflow discharges and cutoff time. This implies both investment and know-how. Meanwhile, results for RO (Figure 4.2) show that a potential exists for runoff reuse in irrigation, although these techniques increase the fixed and operative irrigation costs, as well as the operational complexity of the systems.

As expected, the beneficial water use fraction varies contrarily to IWU since its increase represents the ability to control RO and DP (Figures. 4.2a and b). The best alternatives, GF(0.4) and GB(1.1), led to IWU of 1150 and 1170 mm, respectively, which represent a reduction of 21-28% relative to the observed values, 1450-1620 mm. This reduction corresponds to an increase of the BWUF from observed 0.49 – 0.55 to 0.69 and 0.68, respectively, for GF(0.4) and GB(1.1) although $GF_{NLL}(0.4)$ produced BWUF = 0.65 and $GB_{NLL}(1.1)$ led to BWUF = 0.62. This result for $GF_{NLL}(0.4)$ a non-lasered field is in agreement with the adoption of graded furrows with small discharges by best farmers in the region. Results in Figure 4.2c for WP_{Irrig} vary in agreement with BWUF because crop yields change little among alternatives. The best performing alternatives, GF(0.4) and GB(1.1), had WP_{Irrig} of 0.44 and 0.43 kg m^{-3}, respectively, much above that of the reference, 0.31 kg m^{-3}, and similar to those predicted by Oweis et al. (2011). However, $GF_{NLL}(0.4)$ and $GB_{NLL}(1.1)$ produced WP_{Irrig} of 0.40 and 0.39 kg m^{-3}, respectively, thus representing a reasonable improvement relative to present and not requiring investment in precision laser leveling.

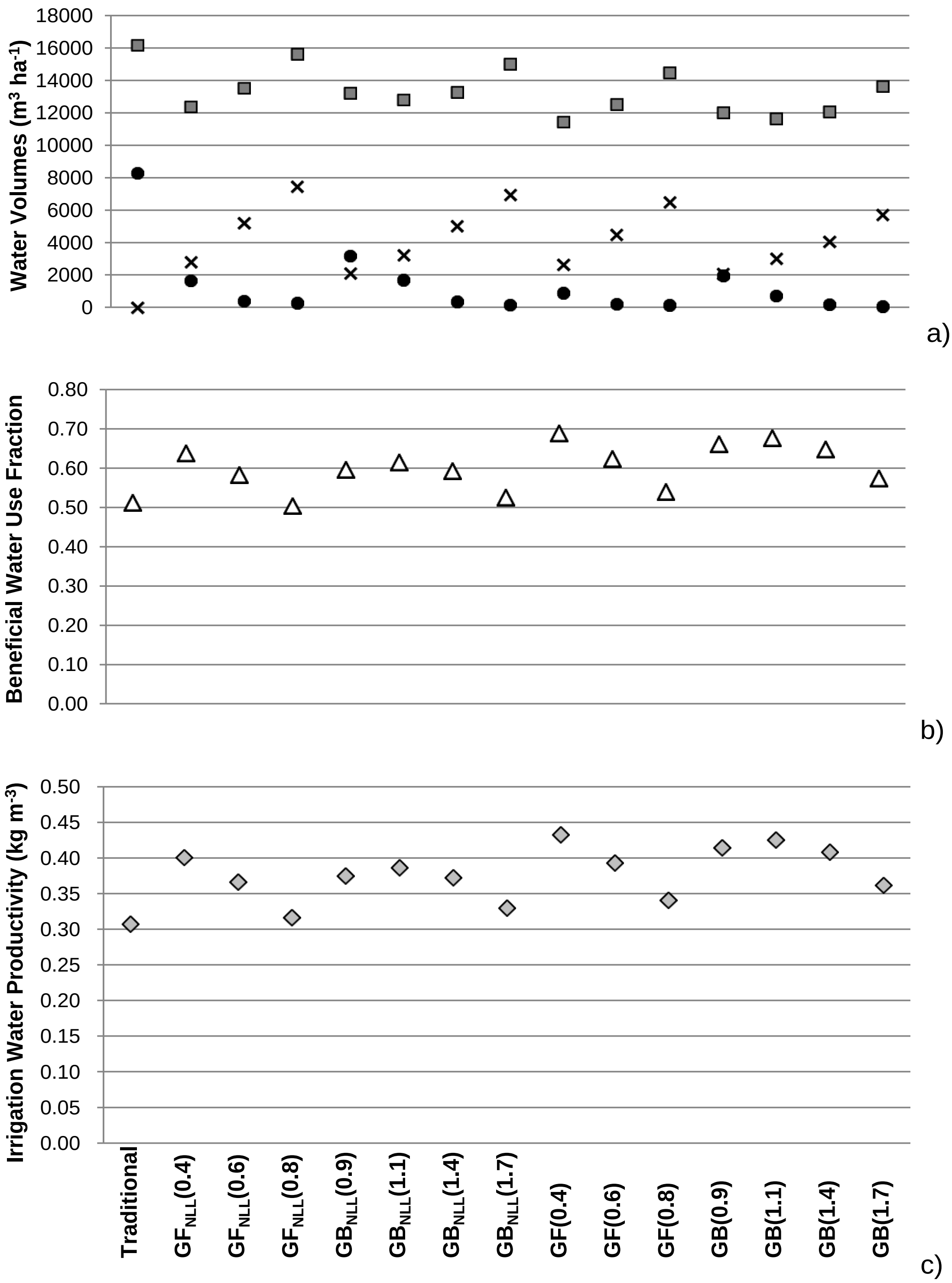


Figure 4. 2 Comparing alternatives for: (a) Irrigation water use (■), tail-end runoff (×) and deep percolation (●) all in m^3 ha^{-1}; (b) beneficial water use fraction (△); and (c) irrigation water productivity (◇) (kg m^{-3}), Alternatives GF and GB refer to graded furrows and borders, the index NLL identifies alternatives without land levelling, the number in brackets is the unit inflow rate (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1})

Results from comparing costs are presented in Figure 4.3a. It shows that the improved solutions require a higher cost than the traditional one, with a difference of 200-280 € ha^{-1} or 40-100 € ha^{-1} is for the solutions with or without land leveling, respectively. The fixed costs represented a small fraction of the total costs and concern the investments for the acquisition of the gated layflat tubing distribution system. Because land leveling requires periodic maintenance, related costs were all included in the variable costs.

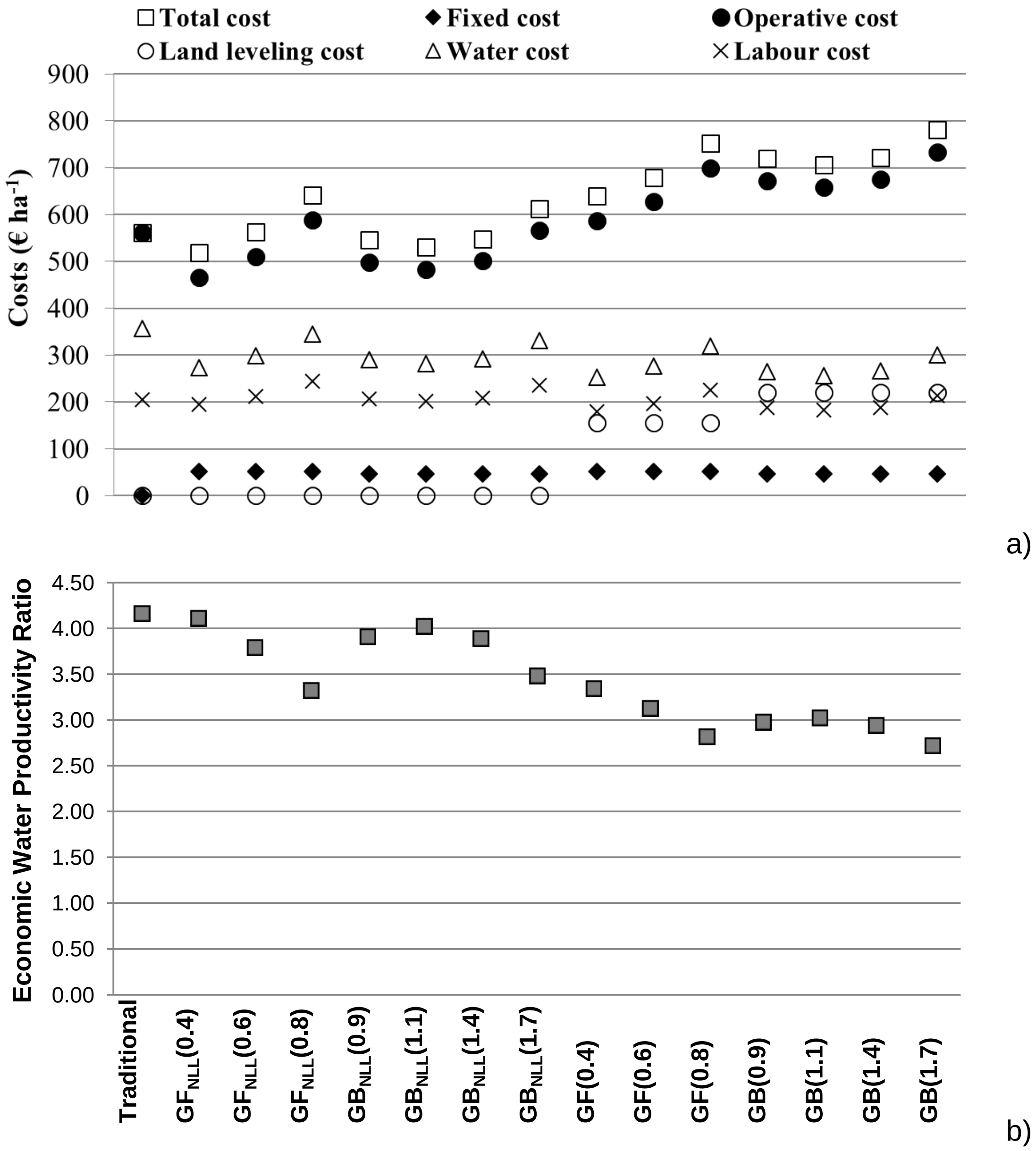


Figure 4. 3 Comparing alternatives for: (a) irrigation costs (all in € ha^{-1}); and (b) the economic water productivity ratio (■). Alternatives GF and GB refer to graded furrows and borders, the index NLL identifies alternatives without land levelling, the number in brackets is the unit inflow rate (l s^{-1} furrow^{-1} or l s^{-1} m^{-1})

The operation costs vary among alternatives because they refer to land leveling, and, mainly, to water and labor costs, which depend upon the amount of water use; thus, operation costs are higher for the alternatives using larger inflow rates that lead to higher tail-end runoff. Differences between GF_{NLL} and GB_{NLL} were small (Figure 4.3a). EWPR is highest for the traditional system (Figure 4.3b). This indicates that the currently adopted system is the one that better relates the achieved yield value with the irrigation and water costs. EWPR is higher for the alternatives with lower costs, when laser leveling is not considered and is lower when irrigation costs increase with land leveling. This means that farmers need some incentives or compensation if they should select alternatives requiring higher costs in order to achieve water saving. Results indicate that the economic value of the water saved due to land leveling does not compensate for the related costs. In addition, results show that equipment that may control discharges and cutoff time play a major role in water saving when compared to land leveling.

4.5.2. Water saving *vs*. farm economic issues

Figure 4.4 presents the global utilities (U) characterizing the traditional and the satisfactory alternatives for the priority scenarios defined through the criteria weights in Table 4.5. Results show that U values for the economics priority are larger than those for water saving only for the traditional reference case and for some non-lasered GF and GB. The reference traditional system has the lowest utility value associated with water saving. Contrarily, the alternatives relative with adoption of laser leveling, have higher U values associated with water saving. Results also show that there are no disagreements on ranking among the best alternatives for GF and GB with or without land leveling. This could be expected considering the results relative to water use (Figure 4.2) and costs (Figure 4.3).

To analyse the compatibility between water saving and economic issues the alternatives were ranked following various weighing approaches, W1 to W9. W1 is a weighing scenario where 90% of the weights are assigned to the economic criteria and 10% to the water saving criteria (Table 4.5). W2 corresponds to changing weights to, respectively, 80 and 20%, then W3 through W9 are scenarios where weights progressively inter-changed with W9 having 10% of weights assigned to economic criteria and 90% assigned to water saving criteria. It results that the sum of U(x) values relative to farm economic criteria decreases from W1 to W9 contrarily to the sum of U(x) relative to water saving (Figure 4.5).

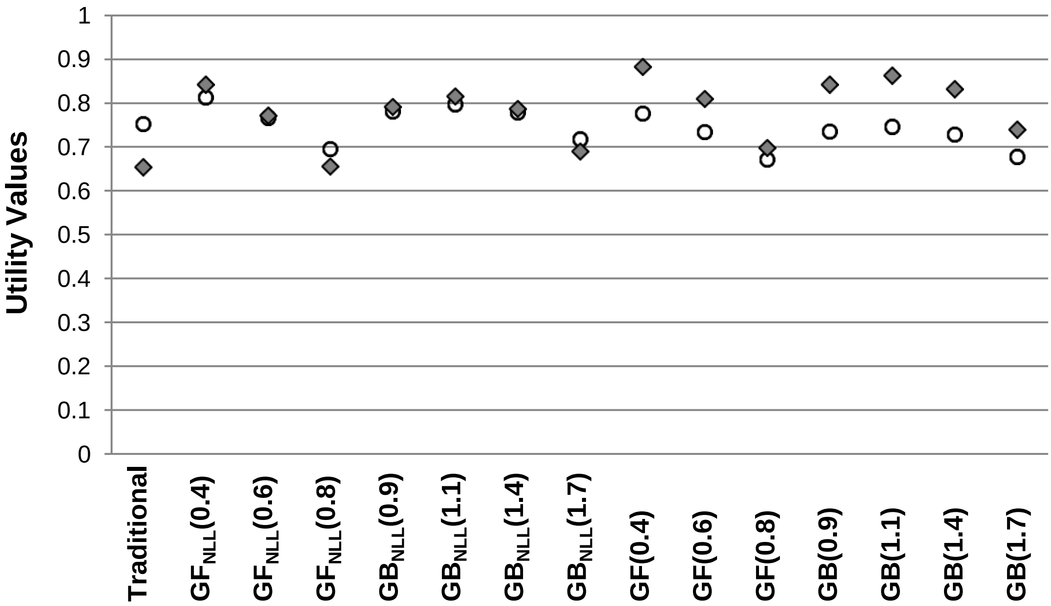


Figure 4. 4 Global utility value when the priority is assigned to economic issues (○) or to water saving (◆). Alternatives GF and GB refer to graded furrows and borders, the index NLL identifies alternatives without land levelling, the number in brackets is the unit inflow rate (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1})

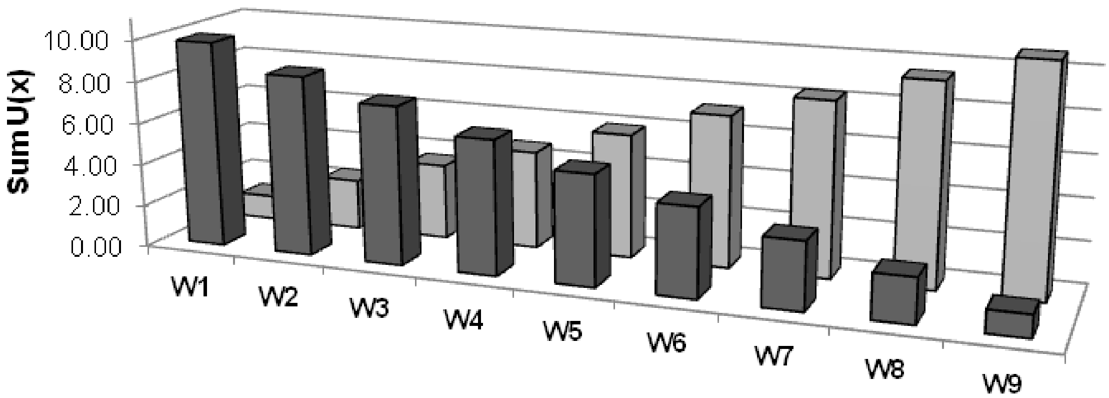


Figure 4. 5 Change in the sum of utility values U(x) associated with economic (□) and water saving (■) criteria for various weighting scenarios W1 to W9

The ranking of alternative solutions for the scenarios W1 to W9 are shown in Table 4.6 with identification of the solutions that ranked 1 to 15. For W1, a scenario where high weights are assigned to economic issues and low ones to water saving, the first four ranked alternatives refer to GF and GB without laser leveling, with GF_{NLL}(0.4) ranking first, and the fifth is the traditional system. The latter disappear for W2 and GF(0.4), a land leveling alternative, is ranked third. GF_{NLL}(0.4) ranks first also for scenarios W2 and W3, and keeps being an option until the scenario W9, where very high priority is assigned to water saving. The alternative GB_{NLL}(1.1) is second ranked for W1 and W2, and is kept among the first five until scenario W6. The first ranked for W4 is GF(0.4), that remains first ranked for all successive scenarios, while GB(1.1) is generally second ranked after scenario W5. For scenario W9, three GB alternatives are ranked among the first five. These ranking results indicate that for fields 100 m long, 0.8% slope and medium infiltration characteristics the best solutions are graded furrows with or without land leveling when it is possible to control the inflow rate at 0.4 l s^{-1} per furrow, as already tested in farmers' fields using locally developed equipment (Galli et al., 2010). Graded borders look to be good options when land leveling is adopted and results show that these alternatives are less dependent upon inflow rates than GF. The fact that the traditional zigzag furrowed basins rank fifth for scenario 1 indicates that the farmers option for this system is adequate when farmers have not the economic and technological means to adopt upgraded systems and equipment.

Table 4. 6 Ranking of the alternative solutions for the various weighing scenarios W1 (highest weights to economic issues) through W9 (highest weights to water saving).

	Weighing scenarios, with progressively decreasing weights to economic issues and increasing weights to water saving								
Rank	W1 (90-10)	W2 (80-20)	W3 (70-30)	W4 (60-40)	W5 (50-50)	W6 (40-60)	W7 (30-70)	W8 (20-80)	W9 (10-90)
1	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GF_{NLL}(0.4))	GF(0.4)	GF(0.4)	GF(0.4)	GF(0.4)	GF(0.4)	GF(0.4)
2	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GF(0.4)	GF_{NLL}(0.4)	GB(1.1)	GF_{NLL}(0.4)	GB(1.1)	GB(1.1)	GB(1.1)
3	GB_{NLL}(0.9)	GF(0.4)	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GF_{NLL}(0.4)	GB(1.1)	GF_{NLL}(0.4)	GB(0.9)	GB(0.9)
4	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB(1.1)	GB(1.1)	GB(0.9)	GB_{NLL}(1.1)	GB(0.9)	GF_{NLL}(0.4)	GB(1.4)
5	Traditional	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB_{NLL}(0.9)	GB_{NLL}(1.1)	GB(1.4)	GB(1.4)	GB(1.4)	GF_{NLL}(0.4)
6	GF(0.4)	GF_{NLL}(0.6)	GB_{NLL}(1.4)	GB(0.9)	GB(1.4)	GB(0.9)	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GF(0.6)
7	GF_{NLL}(0.6)	GB(1.1)	GB(0.9)	GB_{NLL}(1.4)	GF(0.6)	GF(0.6)	GF(0.6)	GF(0.6)	GB_{NLL}(1.1)
8	GB(1.1)	GB(0.9)	GF_{NLL}(0.6)	GB(1.4)	GB_{NLL}(0.9)	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB_{NLL}(0.9)	GB_{NLL}(0.9)
9	GF(0.6)	Traditional	GB(1.4)	GF(0.6)	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB_{NLL}(1.4)	GB_{NLL}(1.4)	GB_{NLL}(1.4)
10	GB(0.9)	GF(0.6)	GF(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)
11	GB_{NLL}(1.7)	GB(1.4)	Traditional	Traditional	GB(1.7)	GB(1.7)	GB(1.7)	GB(1.7)	GB(1.7)
12	GB(1.4)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GB(1.7)	GF(0.8)	GB_{NLL}(1.7)	GF(0.8)	GF(0.8)	GF(0.8)
13	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GB(1.7)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GF(0.8)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GB_{NLL}(1.7)
14	GF(0.8)	GB(1.7)	GF(0.8)	GF(0.8)	Traditional	GF_{NLL}(0.8)	Traditional	GF_{NLL}(0.8)	GF_{NLL}(0.8)
15	GB(1.7)	GF(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	Traditional	GF_{NLL}(0.8)	Traditional	Traditional

The alternative GF_{NLL}(0.4) ranked first for the scenarios W1 to W3 (Table 4.6) because it shows a very high utility U(x) relative to EWPR and the highest U(x) among the non-laser leveled alternatives relative to water saving indicators BWUF, IWU and EWP (Figure 4.6), i.e., showing to be the best when farm economic issues are the priority and performing reasonably well in terms of water saving. GB_{NLL}(1.1), that ranked second for the scenarios W1 and W2, has also a very high utility relative to EWPR but smaller ones for the other indicators which relate to water saving. Figure 4.6 shows that both GF(0.4) and GB(1.1), mainly the first one, have much better utilities relative to water saving, i.e., IWU, BWUF and EWP, which overall compensate for the lower utilities values relative to EWPR. Results in Figure 4.6 explain well why these 2 alternatives rank better than the ones without land leveling.

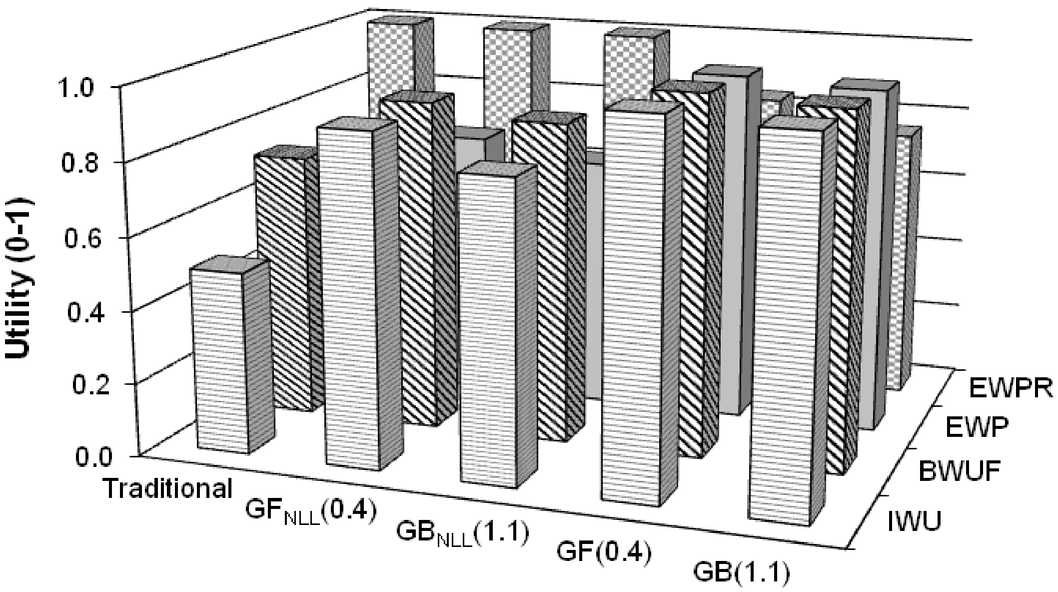


Figure 4. 6 Comparing the utilities of the best ranked alternatives and the traditional one for the IWU (▤), BWUF(▧), EWP(□) and EWPR(▨)

4.5.3. Deficit irrigation

The ranking of alternatives when deficit irrigation is adopted, 640 mm instead of 800 mm, are shown in (Table 4.7). Rankings changed relative to those for full irrigation given in (Table 4.6). Because yields and yield values are reduced with deficit irrigation (Table 4.8), the scenarios W1 to W6 have more alternatives requiring less irrigation costs ranked among the top five than alternatives requiring land leveling. The first rank for scenarios W1 to W5 is for GF_{NLL}(0.4), and for W6 to W9 is for GF(0.4), i.e., furrow irrigation with controlled inflow rates without and with land leveling is selected as the best. That ranking above GB_{NLL}(1.1) and, for land leveling alternatives, above GB(1.1) results from the fact that graded furrows with a small inflow rate are able to produce less non-beneficial water use and thus have better EWP and EWPR than graded borders as shown in (Figure 4.6). It can be concluded that alternatives more able to produce water saving are not the best ranked for deficit irrigation contrarily to the alternatives that better respond to farm economics criteria.

Table 4. 7 Ranking of the alternative solutions for the various weighing scenarios W1 (highest weights to economic issues) through W9 (highest weights to water saving) when deficit irrigation is adopted.

Rank	Weighing scenarios, with progressively decreasing weights to economic issues and increasing weights to water saving								
	W1 (90-10)	W2 (80-20)	W3 (70-30)	W4 (60-40)	W5 (50-50)	W6 (40-60)	W7 (30-70)	W8 (20-80)	W9 (10-90)
1	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GF(0.4)	GF(0.4)	GF(0.4)	GF(0.4)
2	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GF(0.4)	GF_{NLL}(0.4)	GF_{NLL}(0.4)	GB(1.1)	GB(1.1)
3	GB_{NLL}(0.9)	GB_{NLL}(0.9)	GB_{NLL}(0.9)	GF(0.4)	GB_{NLL}(1.1)	GB_{NLL}(1.1)	GB(1.1)	GF_{NLL}(0.4)	GB(0.9)
4	GB_{NLL}(1.4)	GB_{NLL}(1.4)	GF(0.4)	GB_{NLL}(0.9)	GB(1.1)	GB(1.1)	GB_{NLL}(1.1)	GB(0.9)	GB(1.4)
5	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GB_{NLL}(1.4)	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB_{NLL}(1.4)	GB(0.9)	GB(1.4)	GF_{NLL}(0.4)
6	GF(0.4)	GF(0.4)	GF_{NLL}(0.6)	GB(1.1)	GB(0.9)	GB(0.9)	GB(1.4)	GB_{NLL}(1.1)	GF(0.6)
7	GB_{NLL}(1.7)	GB(1.1)	GB(1.1)	GF_{NLL}(0.6)	GB_{NLL}(1.4)	GB(1.4)	GB_{NLL}(0.9)	GF(0.6)	GB_{NLL}(1.1)
8	GF(0.6)	GF(0.6)	GB(0.9)	GB(0.9)	GB(1.4)	GB_{NLL}(0.9)	GB_{NLL}(1.4)	GB_{NLL}(0.9)	GB_{NLL}(0.9)
9	GF_{NLL}(0.8)	GB_{NLL}(1.7)	GF(0.6)	GB(1.4)	GF_{NLL}(0.6)	GF(0.6)	GF(0.6)	GB_{NLL}(1.4)	GB_{NLL}(1.4)
10	GB(1.1)	GB(0.9)	GB(1.4)	GF(0.6)	GF(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)	GF_{NLL}(0.6)
11	GB(0.9)	GB(1.4)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GB_{NLL}(1.7)	GB(1.7)	GB(1.7)	GB(1.7)
12	GB(1.4)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GB(1.7)	GB(1.7)	GB_{NLL}(1.7)	GF(0.8)	GF(0.8)
13	GF(0.8)	GB(1.7)	GB(1.7)	GB(1.7)	GF(0.8)	GF(0.8)	GF(0.8)	GB_{NLL}(1.7)	GB_{NLL}(1.7)
14	GB(1.7)	GF(0.8)	GF(0.8)	GF(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)	GF_{NLL}(0.8)

W1, .. W9: weighing scenarios

Table 4. 8 Comparing indicators relative to main alternatives for full and deficit irrigation

	IWU (m^3 ha^{-1})	BWUF (ratio)	ELP (€ ha^{-1})	WP_{irrig} (kg m^{-3})	EWP (€ m^{-3})	EWPR (ratio)
Full irrigation						
GF_{NLL}(0.4)	12384.79	0.64	2135.48	0.401	0.172	4.12
GB_{NLL}(1.1)	12822.26	0.62	2133.73	0.387	0.166	4.02
GF(0.4)	11467.40	0.69	2135.89	0.433	0.225	3.34
GB(1.1)	11656.60	0.68	2134.66	0.426	0.221	3.03
Deficit irrigation						
GF_{NLL}(0.4)	9907.82	0.64	1880.39	0.441	0.190	4.42
GB_{NLL}(1.1)	10257.78	0.62	1878.98	0.426	0.183	4.33
GF(0.4)	9173.91	0.69	1880.71	0.477	0.205	3.40
GB(1.1)	9325.25	0.68	1879.72	0.469	0.202	3.04

To understand these results, selected indicators relative to main alternatives are compared in Table 4.8 for both full and deficit irrigation. It may be observed that decreasing 20% of irrigation water use causes a decrease of ELP of only 12% because cotton responds well to a sustained deficit irrigation (Fereres and Soriano, 2007; Pereira et al., 2009). Because the decrease in water use is larger than that for yield, both WP_{irrig} and EWP increase about 10%; however, for the land leveling alternatives, EWP increases less. Due to higher irrigation costs, EWPR increases only 1.5% for the alternatives requiring land leveling while for those not adopting it the increase is around 7%. These results explain why alternatives designed for water saving but more costly respond less well to deficit irrigation. Nevertheless, these results do not allow concluding when deficit irrigation is feasible or not because full production costs were not considered, hence it was not possible to assess when yield values are sufficient to cover the production costs. Anyway, adopting innovation requires appropriate financial incentives and capacity building, as well as an innovative institutional framework that provides the means for farmers to adopt water saving practices.

4.6. Conclusions

Using multicriteria analysis allowed to assess the changes in ranking of various alternatives for improvement of irrigation systems when priorities were assigned to farm economics or to water saving criteria. Both full and deficit irrigation were considered. The application refers to various sets of graded furrow and border irrigation alternatives, with and without precise land leveling, that were created and analysed with the decision support system SADREG.

Results show that both graded furrow and border alternatives are acceptable, with a slight advantage for graded furrows. Alternatives without land leveling are likely more appropriate when farm economic results are aimed, while alternatives including land leveling were highly ranked when priorities were assigned to water saving. This is due to higher costs of alternatives that consider land leveling. However, equipment for appropriate control of inflow rates was considered for all alternatives since performance highly depends upon the appropriateness of discharges and cutoff time control. The improved alternatives may lead to save up to 28% of irrigation water and to increase the irrigation water productivity from present 0.31 to 0.44 kg m^{-3}.

Ranks changed when the same alternatives were considered for a sustained deficit irrigation of 20%. Because yields and yield values are reduced with deficit irrigation it becomes less favorable to select the advanced alternatives since they are more costly. Hence, rankings changed and alternatives with land leveling could only be selected when very high priorities were assigned to water saving. Less costly alternatives were selected when farm economics was prioritized.

Results made evident that farm economics and water saving criteria are contradictory since the value of water saved when more advanced systems are used does not provide for recovering the additional costs relative to these alternatives. This study, in a context of small and family farms, shows that adopting more advanced but more costly irrigation technologies aimed at water saving requires appropriate economic incentives, training of farmers and an institutional framework able to support the sustainable use of water in irrigation.

Chapter 5

Drip *vs.* surface irrigation: a comparison focusing on water saving and economic returns using multicriteria analysis applied to cotton

5.1. Introduction[2]

Cotton (*Gossypium hirsutum* L.) is a main summer crop in Syria, both in economic and social terms and required high water demand crop. The irrigation is mainly performed by traditional zigzag furrowed basin irrigation. This study applies to Ras-El-Ain area, (see Chapter 3). Modernizing cotton irrigation includes achieving water saving, coping with the severe water scarcity, soil and water conservation, prevention against salinity, and the increase of farmers' economic incomes, thus contributing to the economic and social rural development (Sadiddin and Atiya, 2009). Irrigation modernization needs identification of the most recommended solutions for increased yields and incomes as well as for water saving and water productivity, e.g., knowing when drip irrigation may be in advantage relative to surface irrigation. Several studies demonstrated the appropriateness of using drip irrigation for cotton, namely in water stressed regions, which have shown a high potential for water saving and yield increase, particularly when adequate fertilization is adopted, and other studies show contradictory results in terms of deficit irrigation (DI) (more in Chapter 2). For this reason, despite numerous studies show advantages of drip over surface irrigation, related categorical conclusions are often not drawn. Howell et al. (1987) reported that drip reduced soil evaporation in narrow rows but did not lead to significant differences from furrows irrigation when soil water was not limiting. Hodgson et al. (1990) found higher water productivity under drip and that results for furrows irrigation could achieve high performance when furrows irrigation management would be improved through reduced "transmission losses between pump and field, by reducing runoff losses from the field, by recirculating runoff water, and by reducing waterlogging". Similarly, Bhattarai et al. (2006) found that advantages of drip over furrow irrigation could be obviated with improved furrows management producing faster irrigation

[2] This chapter bases upon the manuscript entitled "Drip vs. surface irrigation: a comparison focusing water saving and economic returns using multicriteria analysis applied to cotton", authored by Darouich, H., Pedras, C.M.G., Gonçalves, J.M., Pereira, L.S. Biosystems Engineering 122, 74-90 (2014)

advance and reduction of tail water. However, drip has advantages over furrows irrigation relative to off-site movement of sediments, nutrients and pesticides (Mchugh et al., 2008).

When comparing drip with furrows irrigation main questions refer to the performance of the irrigation systems and to irrigation scheduling (Barragan et al., 2010) that were the main factors considered in previous surface irrigation studies (Gonçalves et al., 2011b; Darouich et al., 2012). These aspects were evidenced in the study of Hunsaker et al. (1998), who reported excellent results for high frequency surface irrigation with precise level basins. Horst et al. (2007) reported the benefits of using appropriate control of furrows' inflows and surge flow, and Pereira et al. (2009) referred positive impacts of improved schedules applied to furrow systems. However, the difficulties inherent to modernize surface irrigation, mainly referring to investments in equipment, land levelling costs, insufficient training facilities and lack of support to farmers, make it relatively difficult to improve surface irrigation (Gonçalves et al., 2011b; Darouich et al., 2012).

Many studies in various regions of the world show the advantage of replacing surface by drip irrigation of cotton. For Spain, Mateos et al. (1991) reported both higher and lower yields from drip systems, with less water use in drip systems. Norton and Silvertooth (2001) referred advantages for drip in terms of water use, yield and consequently water productivity in Arizona. Janat and Somi (2001) found higher yields associated with water savings of 35-55% for Syrian conditions. For Turkey, Cetin and Bilgel (2002) reported yields about 20% higher with drip irrigation than for furrows as well as higher WP (0.49 and 0.39 kg m^{-3} for drip and furrows respectively). Bhattarai et al. (2006) and Sampathkumar et al (2012) found that drip was advantageous when deficit irrigation was applied from water use efficiency point of view. Ibragimov et al. (2007) reported 18-42% of irrigation water saving associated with higher yields in Central Asia. DeTar et al. (2010) found no differences in yield but 1/3 less water use by drip in a sandy soil. Sankaranarayanan et al. (2011) reported advantages in water use, yield and quality of the produced cotton in favour of drip; however, they found difficult to overcome the economic advantages of furrows irrigation, which led them to develop a low-cost drip system. Rajak et al. (2006) have also shown that though the gross income was more with drip than furrows irrigation, the net profit per unit of applied water was higher with furrows irrigation. Furthermore, in Syria, the drip obtained 26% profit/cost compare with improved furrows irrigation for cotton, this value decreases gradually with increasing the groundwater table's depth (MunlaHasan, 2007). In some studies, it was found that drip save 8-53 %, with water economic productivity (0.36-0.55) € m^{-3} and (0.49-0.82) € m^{-3} for improved furrows and drip, respectively. Dağdelen et al., 2009 conclude that drip irrigation is not economic solution when deficit irrigation is adopted.

The review presented above shows that a main question when selecting drip or modern surface irrigation for cotton refers to making compatible two central but contradictory objectives: water saving and farm economic results. If for a water scarce region like NE Syria it is essential to find irrigation solutions that lead to a reduced demand of irrigation water, it is also true that farmers would only adopt new technological solutions if these were economically viable. This type of decision problem considering contradictory criteria is appropriate to be handled with MCA aiming at supporting the decision maker to select the best compromise solution. (MCA more described in Chapter 2).

Adopting MCA and appropriate irrigation design focusing the cotton producing area of Ras-El-Ain, NE Syria, where field data were collected, it is possible to evaluate and rank alternatives for graded furrows and borders using SADREG model (Gonçalves and Pereira, 2009) as well as for drip systems using the MIRRIG model (Pedras et al., 2009). Thus, the objectives of this study are: (a) to develop appropriate sets of design alternatives for surface and drip irrigation; (b) ranking and selecting the best alternatives for both types of systems; (c) considering water saving and economic criteria, to use MCA to compare and rank those selected solutions assuming various weights for the diverse attributes; and (d) analyse results in terms of possible identification of surface and drip solutions for cotton irrigation modernization in NE Syria.

5.2. MIRRIG

MIRRIG is a decision support system aiming at design of microirrigation systems, i.e., drip and microsprinkling set systems, as well as performance analysis of field evaluated systems (Pedras et al., 2009 and Pedras and Pereira, 2009). Design and simulation models, a multicriteria analysis model and a database (Figure 5.1) compose MIRRIG. The database contains updated information on emitters and pipes available in the market, as well as on crops, soils and other field data collected from systems under operation. Keller and Bliesner (1990) describe the information of emitters' characteristics. The spacing between emitters estimated from the respective wetted radius (Schwartzmass and Zur, 1985) that is included in the emitters' database. The model does not support the selection of filters but considers the respective pressure requirements when computing the system head losses. Relative to valves and controllers, the model considers localized head losses and the requirements for pressure controllers when the variation of pressure within a given pipe network is excessive. These requirements are expressed in terms of pressure and discharge at the nodes where equipment should be located. The pumping requirements are expressed in terms of upstream pressure and discharge (Pedras and Pereira, 2009).

The field database is created when the design is executed and stores data relative to all design alternatives created for that field refer to the layout of the pipe system, the pipe characteristics and the emitters (drippers or microsprinklers). Each alternative contains the layout description of the mainline, submains, manifolds, laterals and emitters. Each system may be constituted by one or several sectors and subsectors depending upon the number of outlets of the main and submain pipes. The model's structure has four components:

1) A design module to iteratively size the pipe and emitters system for various design alternatives; 2) A performance analysis module that simulates the functioning of the system and computes the indicators depends on design criteria;

3) A Multicriteria module using ELECTRE II method (Roy, 1996) to rank the alternative design options based on the user priority (ELECTRE II described in Chapter 2);

4) an evaluation module that supports the analysis of data collected through field evaluations (ASAE, 2006) that can be used by designers and irrigation advisers when interactively working with farmers to evaluate possible improvements (Pedras et al., 2009; Pedras and Pereira, 2009). The model performs analysis module that simulates the functioning of the system and computes various indicators. These are used as attributes of the alternatives relative to the design criteria adopted for MCA. In addition, the emitters' characteristics relative to sensitivity to clogging and sensitivity of emitters to temperature variation (STV) are also used as attributes. sensitivity to clogging refers to the diameter of the emitter passageway and the emitter capability of flushing, and STV is related to the material and the flow regime of the emitter (Rodríguez-Sinobas et al., 1999).

The Multicriteria approach in MIRRIG used for some criteria exclusive for drip irrigation for that in this study, the applications were run and simulated for different design systems. The obtained alternatives were tested using another Multicriteria tool by creating common criteria among surface and drip irrigation. The alternatives of drip systems are designed taking into consideration user defined targets for the distribution uniformity.

The importance of distribution uniformity on cotton yields is analysed by Guan et al. (2013). All alternatives could be compared and ranked through multicriteria analysis with user defined weights relative to the adopted water saving and economic criteria.

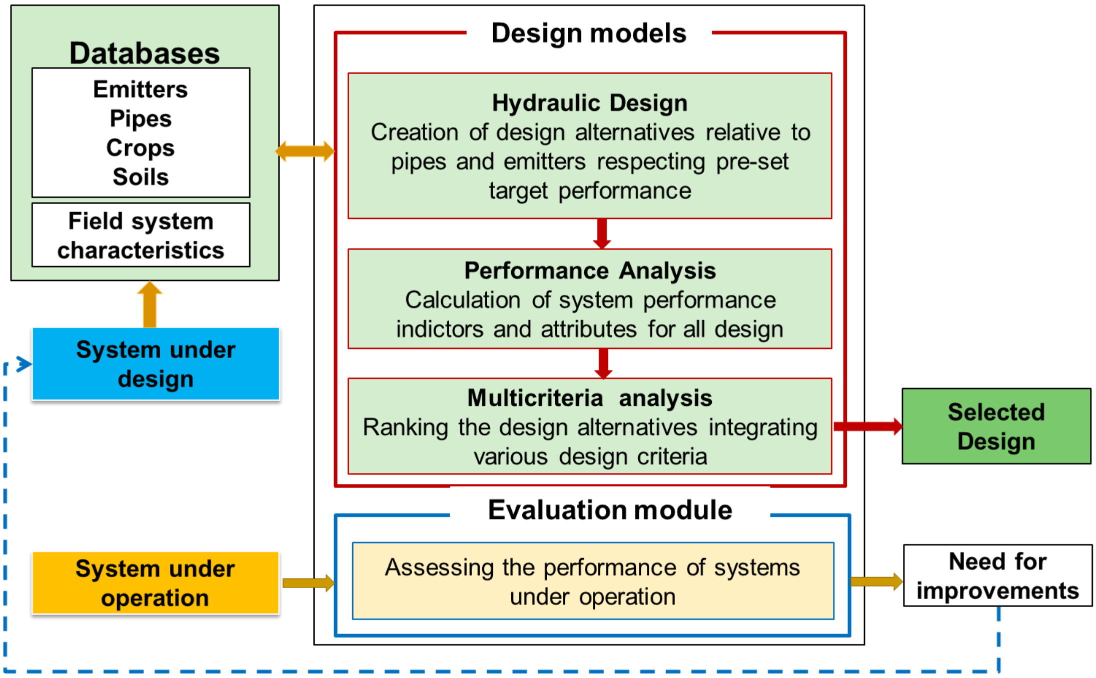


Figure 5. 1 Conceptual design and evaluation structure of the DSS MIRRIG

5.3. MIRRIG application and parameterization

5.3.1. The study area and field characteristics

The study area is located in Ras-El-Ain district, Al Hassakeh governorate, NE of Syria. (The study area, climate, soil and cotton crop characteristic are described in Chapter 3). The recent increase of water scarcity turned traditional systems less sustainable because, it is not able to provide for water saving. Modernized surface irrigation and drip systems have been tested in various cotton fields. However, for the majority of farmers, having limited financial resources, technology investments are limited while they aim at maximizing economic incomes for family sustainability.

Typical field sizes in Ras-El-Ain are 200 m long and 100 m wide, a longitudinal slope of 0.8% and a zero cross slope. The water is supplied from the highest part of the field and the maximum flow rate available is 40 l s^{-1}. Surface irrigation trials considered graded furrows and borders and adopted locally developed gated pipelines for farm distribution systems (Galli et al., 2010). Drip irrigation systems used locally consist of a single plant row per lateral, spaced 0.75-0.80 m, emitters spacing of 0.30-0.60 m, and emitter discharges of 1.5-4.0 l h^{-1}. When paired double row per lateral are used, lateral spacing then increase to 1.40 m. In surface irrigation systems, a conventional fertilization scheme is adopted, whereas fertigation is often used with drip irrigation. Darouich et al. (2007 and 2012) provide further information. The seasonal crop evapotranspiration (ET_c) and net irrigation requirements (NIR) were assessed with the ISAREG model (Pereira et al., 2003). The maximum ET is 934 mm and the irrigation scheduling results for full and deficit irrigation are presented in Table 5.1 and (see Table 4.2). The water-yield function is in Table 4.3.

Table 5. 1 Irrigation scheduling considering the irrigation method and full (FI) and deficit irrigation (DI)

Irrigation method	Irrigation strategy	ET_a (mm)	Number of irrigation events	Net irrigation depth, per event (mm)	Net irrigation water use (mm)
Surface	(FI)	886	10	80	800
Drip	(FI)	890	32	25	800
Surface	(DI)	752	8	80	640
Drip	(DI)	760	26	25	640

The determination of infiltration characteristics present in (Chapter 3 and in Table 3.3) where medium infiltration curve is adopted. In the present case study, the yield price was 0.74 € kg^{-1} (the yield price which presents in Chapter 4 was for the years 2006 and 2007, while in this application it is updated for 2010). The water, labour and energy cost, a period of investment years and the interest rate is the same as in Chapter 4 (qualified labour required for drip was 1.28 € h^{-1}).

5.3.2. MIRRIG application and parameterization

The characteristics of the simulated drip irrigation alternatives are:

- Six different layouts (L1, …, L6) whose differences refer to the number of manifolds, position of the supply inlet in the manifold and pipe lengths. Polyethylene of low density was selected for the pipe laterals, of high density for the manifolds and submains, and PVC for the mainline (Table 5.2).

Table 5. 2 Layout characteristics of the alternatives

Project	Length (m)					Location of manifold supply inlet	Number of manifolds per sector
	Mainline	Submain	Manifold	Lateral on left	Lateral on right		
L1	110	None	50	200	None	Middle	1
L2	110	100	50	100	None	Edge	2
L3	210	None	50	100	100	Edge	1
L4	160	100	50	50	50	Edge	2
L5	210	None	100	100	None	Middle	1
L6	210	None	100	50	50	Edge	1

- Two alternatives of lateral layouts: single row per lateral (SRL), and paired double row per lateral (DRL). DRL reduce investments relative to SRL (Figure 5.2);

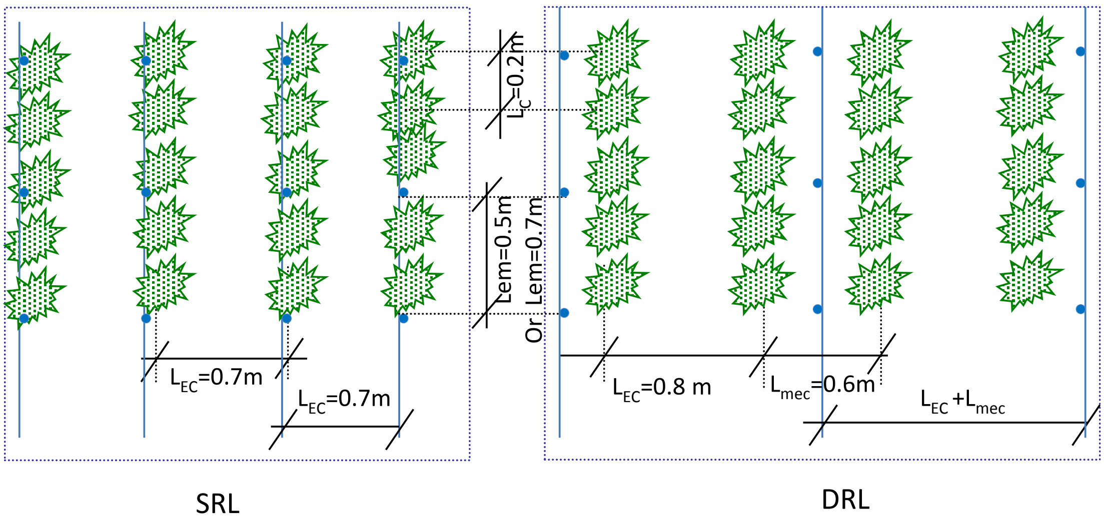


Figure 5. 2 Spacing of crop row and laterals, SRL single row per one lateral, DRL double rows per one lateral.

- Spacings between laterals were: 0.7 m for SRL, thus equal to row spacing, and 1.4 m for DRL, i.e., 0.8 m between paired rows and 0.6 m between rows in each pair (Figure 5.2);
- Two types of emitters were considered: non-compensating (NC) and self-compensating (SC) emitters having various discharges (1.5, 1.6, 2.7, 3.5 and 4.0 l h^{-1}): NC1.5, NC2.7, NC4.0, SC1.6 and SC3.5;
- Two emitter spacing (ES) of 0.5 and 0.7 m were considered (ES0.5 and ES0.7).

From the various combinations of these features described above, a set of 120 alternatives were built with MIRRIG to be analysed and ranked; only the high ranked alternatives were compared with the surface irrigation high ranked satisfactory solutions.

The fixed cost comprises the following components of the irrigation system: pipes, emitters, pump, chemical tank and injector pump, disk filter, control and management devices, and pipe layout accessories. Accessories were considered in the range 18-22% of the fixed cost; their costs of accessories vary with the pipe layout, being higher for layouts L2 and L4 and lower for L1 (Table 5.2). The variable costs include the water cost and the maintenance and operation cost which includes the energy and labour cost. Considering that the main source for water is groundwater, the well pumping cost was included in the base water cost (€ m^{-3}), which was the same value for drip and surface irrigation.

5.4. Multicriteria Analysis (MCA)

The evaluation and selection of the best irrigation method is performed with multicriteria analysis. The comparison between surface and drip irrigation makes evident contrasting criteria relative to economic farm returns and water saving. It is assumed that there is not a unique optimal alternative but, because MCA integrates different types of attributes on a trade-off analysis, it is possible to find the solutions that are closer to the wishes of the user (Chapter 2).

The MCA procedure starts with the definition of the design objectives and related criteria attributes (Table 5.3). Attributes refer to:

1. Economic productivity and costs related to farmer economic perspectives, including economic land productivity, economic water productivity, economic water productivity ratio, fixed irrigation costs and variable irrigation costs;
2. Water saving, relative to the irrigation environmental performance including total irrigation water use, beneficial water use fraction, irrigation water productivity and non-beneficial water uses.

The criteria attributes were calculated according to the water use and productivity indicators defined by Pereira et al. (2012), which were incorporated in MIRRIG and SADREG models (The SADREG applications are described in Chapter 4). These attributes are handled through appropriate linear utility functions, and for ranking the Linear Weighted Summation method was applied (see Chapter 2). The application of this method requires assigning priorities by selecting the weights λj that represent the relative importance of each criterion j from the perspective of the decision maker. Criterion weights depend on several factors including socio-cultural values, and economic and/or environmental perspectives. In this study, two priority scenarios were considered, one aimed at achieving the best water saving and the other aimed at attaining the highest farm incomes (see Table 5.3). The weight values among attributes for each of water saving and economic perspectives are based on the range variation between drip and surface, i.e. lower value is given for FIC comparing with one given in Table 4.5, as drip has very high FIC than surface.

Table 5. 3 Criteria attributes, utility functions and attribute weights

Criteria attributes (x)		**Symbol**	**Units**	**Utility functions**	**Weights (%) assigned to attributes when considering**	
					Water saving	Economic
Economic					**20**	**80**
Economic land productivity		ELP	€ ha^{-1}	$U(\boldsymbol{x}) = 0.27\times10^{-3}\,\boldsymbol{x}$	5	15
Economic water productivity		EWP	€ m^{-3}	$U(\boldsymbol{x}) = 1.73\,\boldsymbol{x}$	4	15
Economic water productivity ratio		EWPR	ratio	$U(\boldsymbol{x}) = 0.133\,\boldsymbol{x}$	5	20
Fixed irrigation costs		FIC	€ ha^{-1}	$U(\boldsymbol{x}) = 1 - 0.17\times10^{-3}\,\boldsymbol{x}$	3	15
Variable irrigation costs		VIC	€ ha^{-1}		3	15
Water saving					**80**	**20**
Total irrigation water use		IWU	mm	$U(\boldsymbol{x}) = 1.67 - 1.031\times10^{-3}\,\boldsymbol{x}$	20	5
Beneficial water use fraction		BWUF	ratio	$U(x)= 1.0\,\boldsymbol{x}$	15	4
Irrigation water productivity		WP_{Irrig}	kg m^{-3}	$U(\boldsymbol{x}) = 1.27\,\boldsymbol{x}$	15	5
Non-beneficial water use (NBWU)	Irrigation runoff	IRO	mm	$U(\boldsymbol{x}) = 1 - 0.118\times10^{-2}\,\boldsymbol{x}$	15	3
	Irrigation deep percolation	IDP	mm		15	3

SADREG and MIRRIG produced a large set of alternatives, which were clustered in groups after the respective ranking and selection analysis. A further application of MCA to the selected drip and surface irrigation alternatives allowed the required comparison between these different systems and considering the referred criteria. The analysis of rankings was carried out by varying progressively the weights relative to farm economics and water saving criteria, i.e., starting with a scenario where 90% of weights were assigned to farm economic criteria to end with a last scenario where 90% of weights were assigned to water saving. The same analysis was performed for deficit irrigation.

5.5. Results

5.5.1. Comparison of drip irrigation alternatives

MIRRIG simulated a set of 120 alternatives for drip irrigation resulting from different combination of six system layouts (L1, … L6), two lateral layouts (SRL and DRL), five emitters (SC1.6, SC3.5, NC1.5, NC2.7, NC4.0) and two emitters spacing of 0.5 and 0.7 m, as described in Section 2.2. Results (Figure 5.3a) relative to total irrigation water use (IWU) show that lower IWU values (825-832 mm) refer to self-compensating (SC) emitters contrarily to non-compensating (NC) emitters (837 to 977 mm) (Figure 5.3a), with the highest IWU for NC with discharge of 4.0 l h^{-1} installed in layout L1, SRL and spacing ES0.5. The difference of IWU between the two types of emitter SC and NC results from higher emitter and distribution uniformity (DU) when using SC emitters. With SC emitters, DU ranged 96-97%, while with NC emitters DU varied from 81 to 95%. Other researchers, e.g., Yohannes and Tadesse (1998), obtained similar results.

IWU was slightly smaller for DRL than for SRL (Figure 5.3a) with 89–96 % BWUF. Aujla et al. (2008) also reported higher water saving when using double rows per lateral comparatively to single rows. Relative to emitter spacing along the lateral, it was observed that the smaller spacing of 0.5 m leads to slightly higher IWU for most of the layouts, which is in agreement with results reported by Ozbahce and Tari, (2010). Grabow et al. (2006) reported that spacing varying from 0.91 to 1.82 m do not show significant differences in yield but only a very small differences in terms of WP_{irrig}, which is in agreement with our results. The variation of IWU and WP_{Irrig} values relative to the NC emitters adopted is higher for layout L1 when compared with L6 (Figure 5.3) because L1 has longer laterals that favour higher head losses and lower DU for non-compensating emitters. That variation is higher for ES0.5 because head losses tend to increase when increasing the number of outlets.

As expected, WP_{Irrig} behaves contrarily to IWU, i.e., WP_{Irrig} is larger when IWU is smaller (Figure 5.3b). Thus, WP_{Irrig} values are higher for SC emitters (0.61 kg m^{-3}) and lower for NC emitters, particularly for larger discharges and smaller spacing (0.51 kg m^{-3}). Dağdelen et al. (2009), Hussein et al. (2011), Ibragimov et al. (2007) and Sankaranarayanan et al. (2011) reported WP_{Irrig} similar values (0.56 to 0.85 kg m^{-3}). In agreement with the discussion above, differences in IWU and WP_{Irrig} values due to emitters spacing (0.5 *vs.* 0.7 m) are smaller for SC emitters than for NC and are also smaller for DRL lateral layouts comparatively to SRL (Figure 5.3).

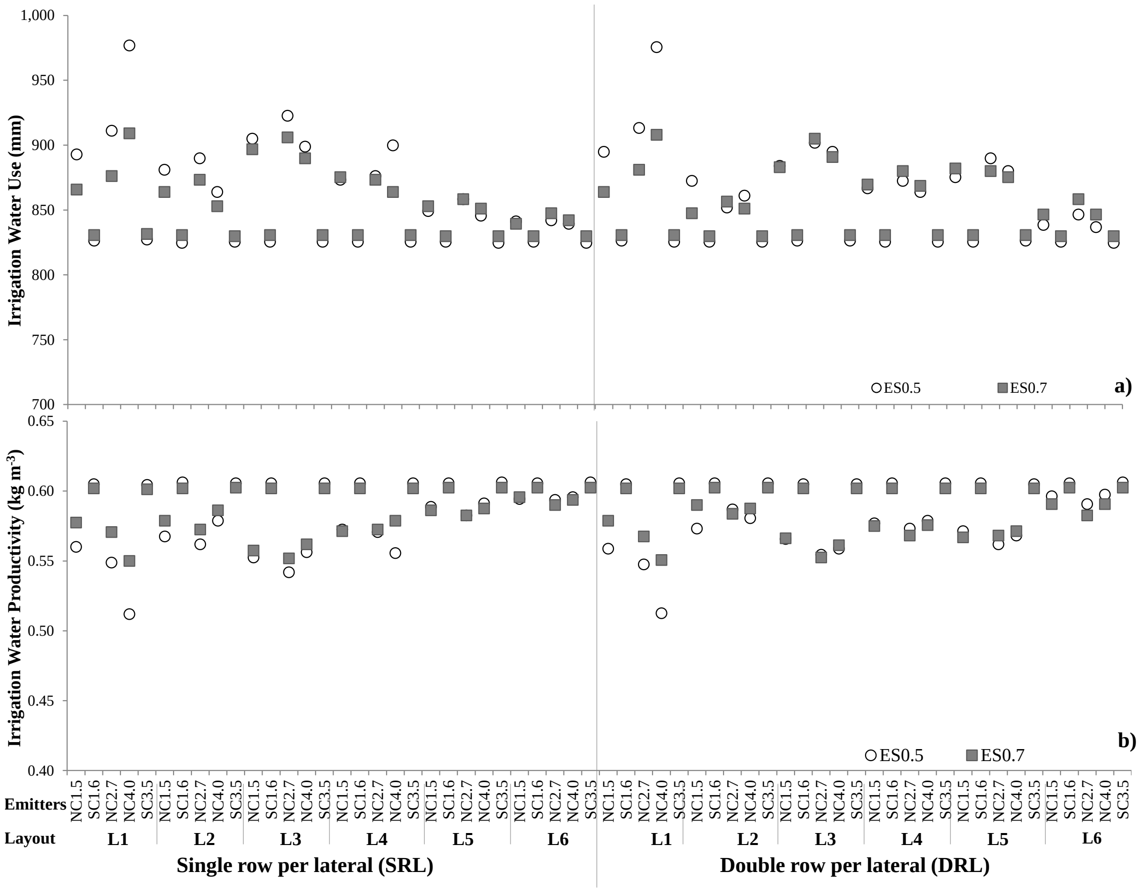


Figure 5. 3 Comparing: (a) irrigation water use, IWU and (b) irrigation water productivity, WP_{Irrig} for single and double rows per lateral (SRL and DRL) considering various system layouts (L1 to L6), self-compensating (SC1.6 and SC3.5) and non-compensating emitters (NC1.5, NC2.7 and NC4.0), and emitters spacing (ES) 0.5m (○) and 0.7m (■)

The economic water productivity (EWP) shows the same trend as WP_{Irrig} (Figure 5.4a), with higher values (0.45 € m^{-3}) for both SC1.6 and SC3.5 emitters, and for DRL lateral layouts. The lowest EWP is for L1, NC4.0, SRL and ES0.5. Main influences of the emitter spacing and lateral layouts refer to the fixed investment cost (FIC). DRL with 0.7 m emitter spacing have values for FIC 11-16 % lower than SRL for the same emitter spacing and layout (Figure 5.4b). Aujla et al. (2008) reported that double rows per lateral led to a reduction in costs of up to 50 % due to a smaller number of laterals required. FIC is also higher for SC emitters, more expensive than NC ones'. The highest FIC (> 3150 € ha^{-1}) was for NC4.0 and SC3.5 for SRL and ES0.5, while the lowest FIC (< 1450 € ha^{-1}) was for NC2.7 for DRL and ES0.7.

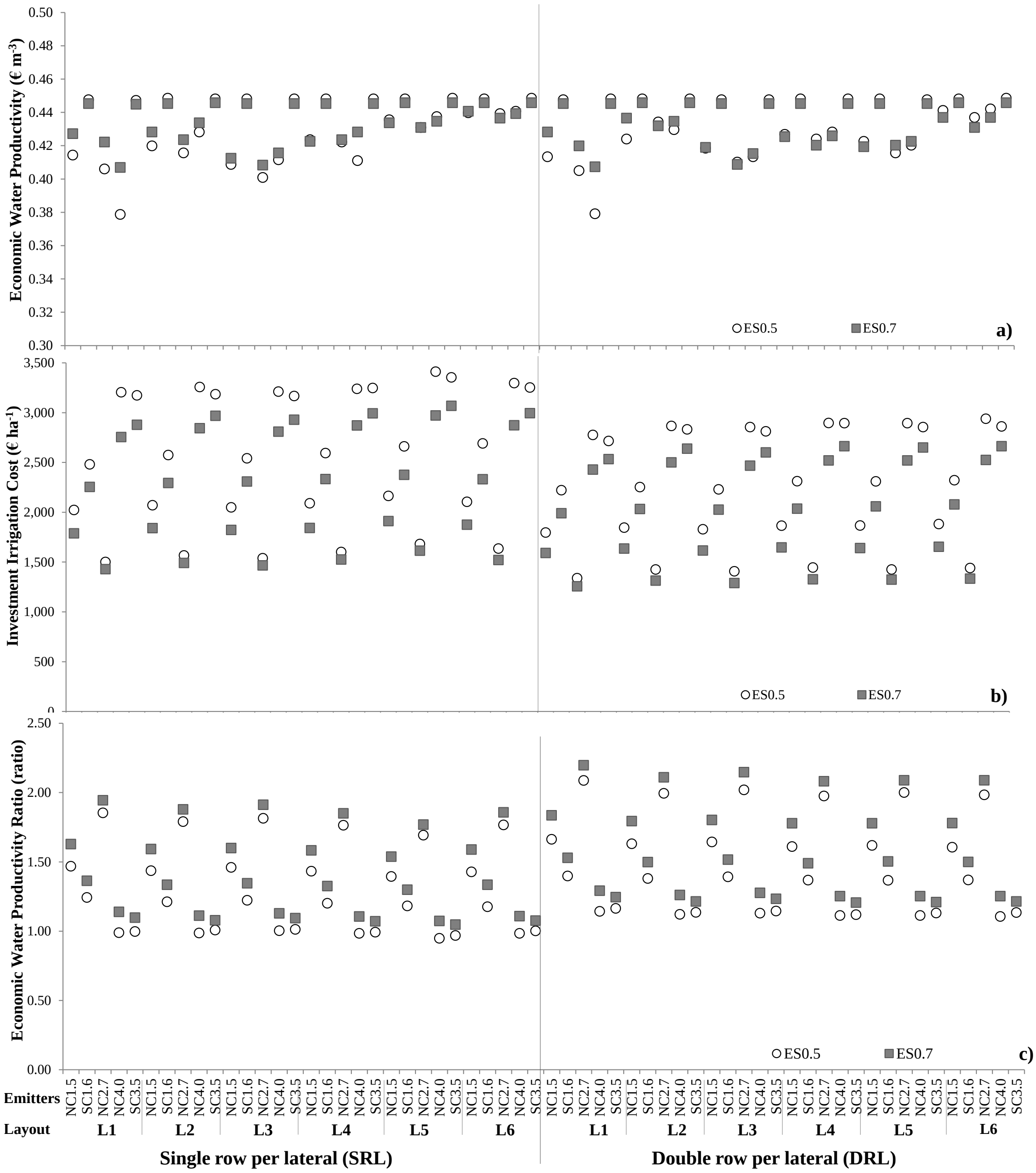


Figure 5. 4 Comparing (a) economic water productivity, (b) investment costs, and (c) economic water productivity ratios for single and double rows per lateral, various layouts (L1 to L6), self-compensating (SC1.6 and SC3.5) and non-compensating emitters (NC1.5, NC2.7 and NC4.0), and emitters spacing of 0.5 m (○) and 0.7 m (■)

The economic water productivity ratio EWPR, representing the yield value per unit cost of production varies contrarily to FIC (Figure 5.4c). Results show that economic results highly relate to the emitter type (SC emitters having larger costs than NC ones'), emitter spacing (with high costs for the smaller spacing), and lateral layout (with lower costs for the paired double rows per lateral). Apparently, the design layouts have less influence. However, the emitter type plays an important role in irrigation performance: self-compensating emitters, mainly the SC1.6, appear as the best solutions in terms of water saving; contrasting, the non-compensating emitters, particularly the NC2.7, show to be the best under an economic perspective. The emitter spacing of 0.5 m is more costly than that of 0.7 m and favour higher IWU, thus lower WP. Relative to the lateral layouts, DRL shows to be better than SRL in terms of costs and water use as also reported by Grabow et al. (2006) and Aujla et al. (2008). The layouts for lateral zero slope (L5, L6) produce lower pressure variation and higher DU. The layouts where laterals are in agreement with slope favour longer pipes and smaller head losses, while other layouts require higher pressure head and result more costly. Thus, the best layouts in terms of water saving and economic results are L2 and L6, while the worst is L1.

5.5.2. Comparison of surface irrigation alternatives

SADREG simulated 64 design alternatives of surface irrigation, mainly borders vs. furrows systems with and without precise laser land levelling (LL and NLL). The alternatives with higher performance are presented in Figure 5.5, where they are compared using the utilities relative to the indicators IWU, EWP, BWUF and EWPR. Results show that land levelling has a direct impact on irrigation performance, mainly the irrigation uniformity, thus with LL leading to high utility values for IWU, EWP and BWUF, i.e., land levelling favours a reduced IWU and higher EWP and BWUF. Similar conclusion was reported by Gonçalves et al. (2011)b and Darouich et al. (2012) who explained that land levelling improves irrigation performance and favours water saving but associated costs lead to less good economic results. Thus, land levelling leads to higher production costs and to reducing EWPR (Figure 5.5b). Therefore, a compromise between these two adversative effects of LL has to be searched depending upon the field topography and unevenness, the impacts on the distribution uniformity and the respective costs. The relatively high cost of land levelling implies that the NLL alternatives are likely to be more appropriate when a priority is assigned to economic results, whereas a high utility would correspond to LL alternatives when the priority is assigned to water saving.

Results for graded furrows have shown to be slightly better than those for graded borders when comparing the utilities for EWP and EWPR (Figure 5.5). Global utilities are higher for small discharges with furrows and for larger discharges with borders (Figure 5.6) as already reported by Darouich et al. (2012). In fact, the irrigation performance highly depends upon the appropriateness of discharges and cut-off time. Considering this fact, to avoid biasing the comparison among alternatives, the equipment for control of inflow rates was similar for all alternatives.

Differences are small when comparing field lengths of 100 and 200 m, which indicate adequate adaptability to predominant local conditions. However, the soil type and field slope influence this selection. Horst et al. (2007) reported that the best results were achieved for long furrows with 320 m, an inflow rate of 2.4 l s^{-1} and a furrow spacing of 0.9 m. However, for different slopes and infiltration characteristics of soils, lengths and discharges need to be different (Walker and Skogerboe, 1987, Hunsaker et al., 1998 and Gonçalves and Pereira, 2009).

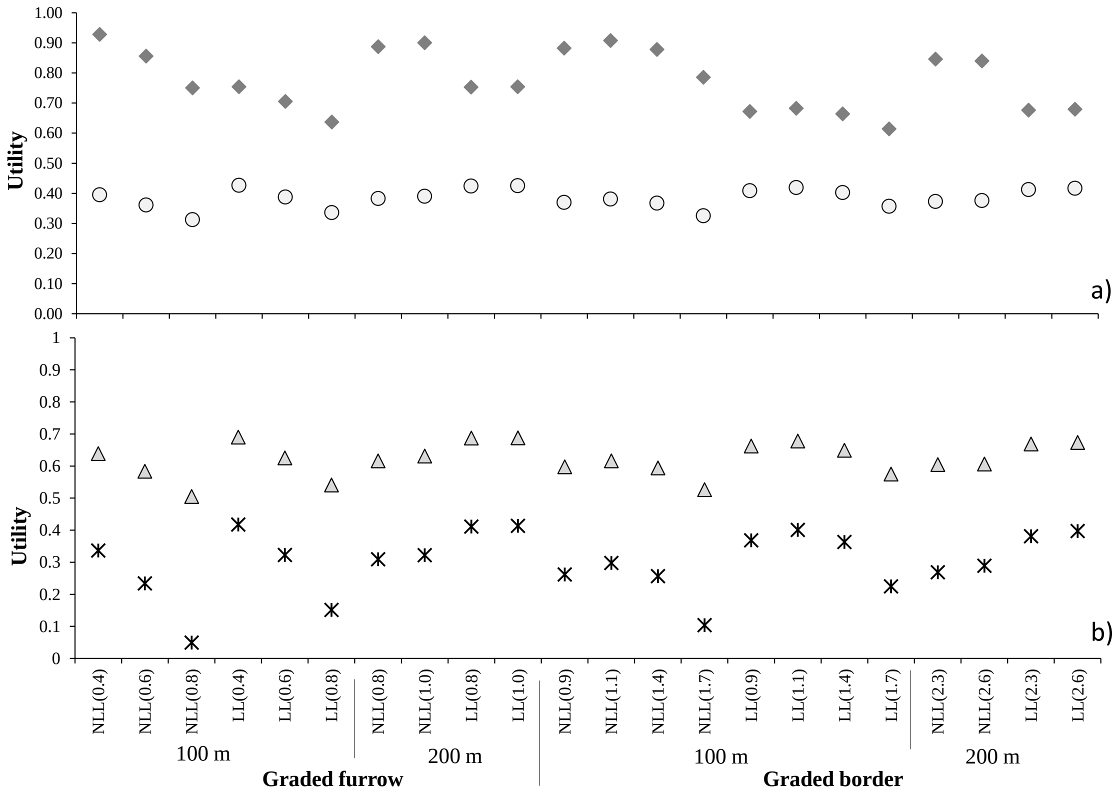


Figure 5. 5 Comparing the utilities of graded furrows and graded borders alternatives in terms of: (a) economic attributes (economic water productivity (○) and economic water productivity ratio, EWPR (◆)), and (b) water saving attributes (irrigation water use, IWU (⁎) and beneficial water use fraction, BWUF (△)), considering field lengths of 100 and 200 m, lasered and non-lasered land levelling (LL and NLL) and various inflow rates (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1})

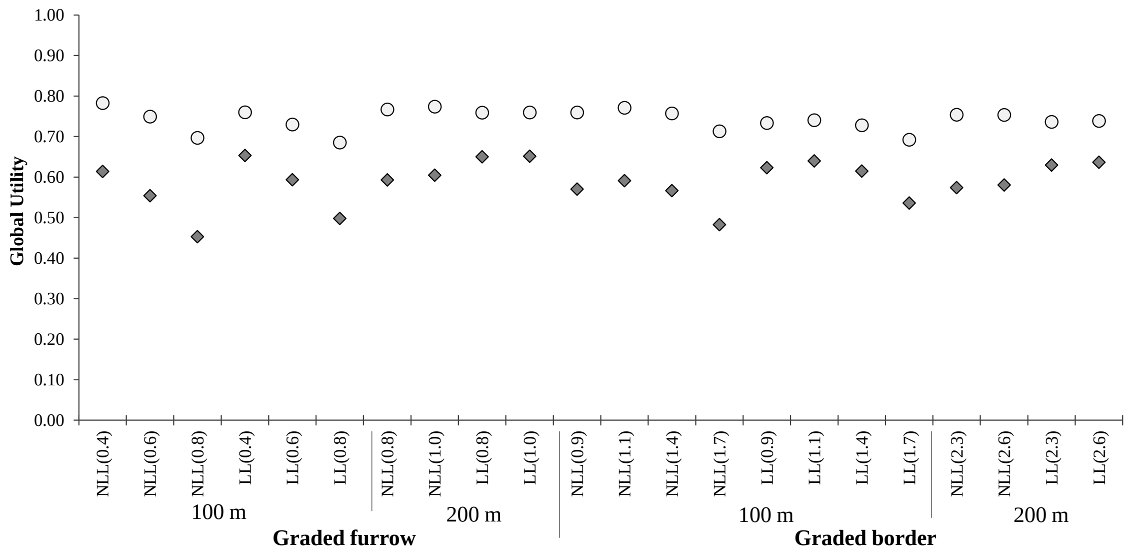


Figure 5. 6 Comparing the global utilities when the priority is assigned to economic results (○) or to water saving (◆) considering graded furrows and borders, field lengths of 100 and 200 m, lasered and non-lasered levelling (LL and NLL) and various inflow rates (l s^{-1} $furrow^{-1}$ or l $s^{-1}m^{-1}$)

5.5.3. Comparing and ranking drip *vs*. surface irrigation alternatives

The comparison and ranking of drip *vs.* surface irrigation alternatives was performed after ranking and then selecting the best alternatives for both systems as analysed in the previous Sections. The traditional surface irrigation system was considered as reference. The attributes for comparison include IWU, NBWU, and WP_{Irrig} as described in Table 5.3. IWU and WP_{Irrig} show contrasting results when comparing drip with surface irrigation (Figure 5.7). Drip irrigation requires less water use, about 350 to 700 mm less than surface irrigation, thus providing for higher water productivity, which exceeds that of surface irrigation by 0.13-0.29 kg m^{-3}. These results are similar to those presented by Cetin and Bilgel (2002), Ibragimov et al. (2007) and Sankaranarayanan et al. (2011), who reported differences of 0.11, 0.27 and 0.15 kg m^{-3} respectively. Non-beneficial water use (NBWU) in surface irrigation is much higher than for drip, respectively 450 and 50 mm for surface and drip. A large part of NBWU in surface irrigation consists of runoff, that can be reused but with additional costs. Deep percolation may also not be lost if not degraded and available for later reuse after reaching the groundwater. Moreover, deep percolation has a beneficial "service" of salt leaching, favouring the utility of surface irrigation in areas where salinity control is necessary (Pereira et al., 2012). Nevertheless, when the available water for irrigation is very limited, the water saving achieved by drip irrigation favours the selection of this method aiming at water saving and considering leaching requirements. Differences in NBWU between surface and drip irrigation are the main causes for the respective differences in IWU and WP_{Irrig}. All selected solutions for graded borders imply land levelling. Contrarily, various solutions for graded furrows did not include LL, when LL is considered then NBWU and IWU decrease. Apparently, the length of the fields has a smaller influence on IWU, NBWU and WP_{Irrig}. Differently from the varied responses of these indicators to various surface irrigation characteristics, the variation of these attributes for the various selected drip alternatives are very small. Summarizing, Figure 5.7 shows that drip irrigation provides for lower IWU and NBWU than surface irrigation and to higher water productivity.

Economic attributes - fixed irrigation investment costs (FIC), variable irrigation costs (VIC) and EWPR - are analysed in Figure 5.8 when comparing drip and surface irrigation systems. The investment costs are much higher for drip than for surface irrigation, however depending on various design factors analysed in Section 3.1. The investment cost for drip systems varies from 1313 to 2320 € ha^{-1}, with higher values when selecting SC emitters, resulting in FIC is much higher than for surface irrigation. The annuity relative to investment costs represents 24-53 % of the average farmers' gross income of 3700 € ha^{-1}, which is quite high and explains why farmers kept surface irrigation until present. These results are in line with those reported by MunlaHasan (2007) who have shown that furrow irrigation has the lowest cost and highest farmers return, with drip irrigation providing for economic results 25-45 % smaller than surface irrigation. Contrarily, differences in annual maintenance and operation costs are not very different when comparing drip with NLL systems; however, investment annuity and maintenance costs for laser levelling are relatively important and related VIC exceed those costs for drip; moreover VIC for LL systems exceed those for NLL systems by about 120 to 165 € ha^{-1}. The EWPR ratio (see Figure 5.8) expresses an enormous disparity between economic results obtained for these two irrigation methods, with EWPR ranging from 1.3 to 2.2 for drip systems, and from 4.9 to 7.1 for surface irrigation. Rajak et al. (2006) reported similar results when these authors reported that the gross benefit-cost ratio was lower for drip irrigation than for furrows irrigation due to higher initial cost incurred in drip irrigation. Results in Figure 5.8 show that decisions behind selecting drip systems to replace surface irrigation is mainly an investment decision, which is sensitive to the water cost and availability, labour cost and availability, yield commodity prices and credit facilities.

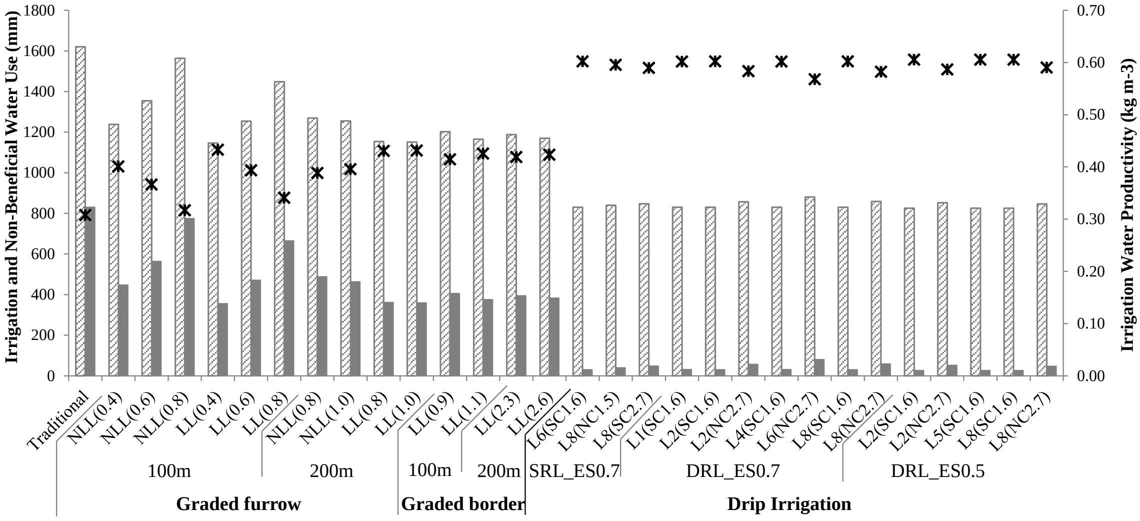


Figure 5. 7 Comparing surface and drip irrigation relative to irrigation water use (▨), non-beneficial water use (■) and irrigation water productivity, WP_{Irrig} (x). Surface irrigation alternatives refer to graded borders and furrows with field lengths of 100 and 200 m, adopting laser and non-laser land levelling (LL and NLL) and various inflow rates (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1}); drip irrigation refers single and double rows per lateral (SRL and DRL), various layouts (L1 to L6), self- and non-compensating emitters (NC1.5, SC1.6 and NC2.7) and emitters spacing (ES) of 0.5 and 0.7m

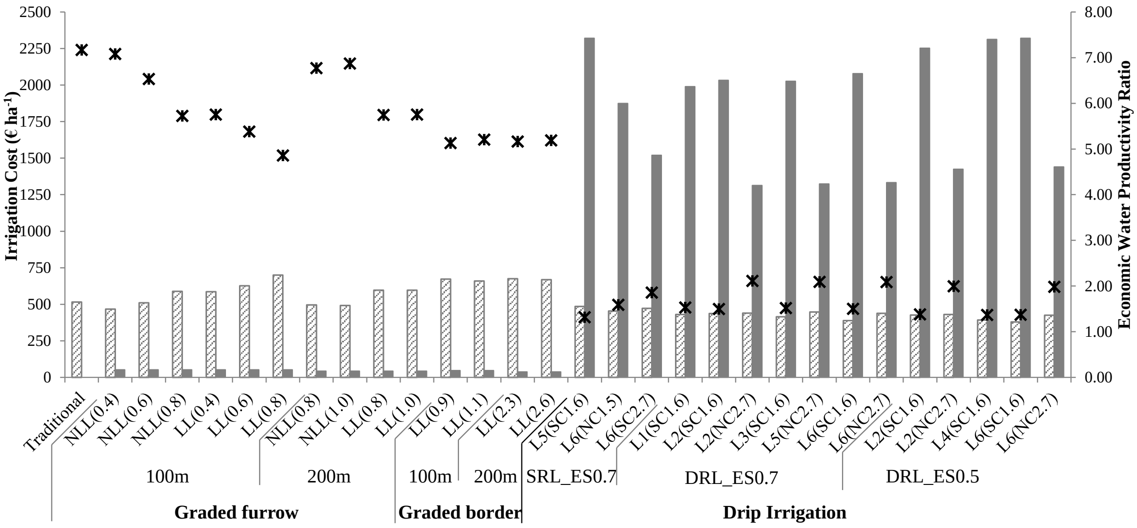


Figure 5. 8 Comparing surface and drip irrigation relative to irrigation investment costs, FIC (■), variable cost, VIC(▨) and the economic water productivity ratio, EWPR(x) Surface irrigation alternatives refer to graded borders and furrows with field lengths of 100 and 200 m, adopting laser and non-laser land levelling (LL and NLL) and various inflow rates (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1}); drip irrigation refers single and double rows per lateral (SRL and DRL), various layouts (L1 to L6), self- and non-compensating emitters (NC1.5, SC1.6 and NC2.7) and emitters spacing (ES) of 0.5 and 0.7m

Two prioritization schemes are considered following the disparity observed comparing surface and drip irrigation systems: to assign priority to water saving or to economic returns of irrigation (see Table 5.3). Therefore it is appropriate to compare the global utilities of the selected alternatives when assigning the priority to economic results or to water saving. Results show (Figure 5.9) that the global utility relative to the surface irrigation is above that for drip relative to economic results and vice-versa for water saving, which is consequent with the analysis performed above concerning (Figure 5.7 and 5.8). To be noted (Figure 5.9) that the traditional system has a utility similar to those of modernized systems when prioritizing economic results but quite low when the priority is water saving, i.e., the traditional system is not a feasible and sustainable solution to cope with water scarcity because it has very high water use (Figure 5.7). Summarizing, results in Figure 5.9 show that when prioritizing water saving the advantage is for drip systems while if economic results are prioritized the advantage goes to surface irrigation.

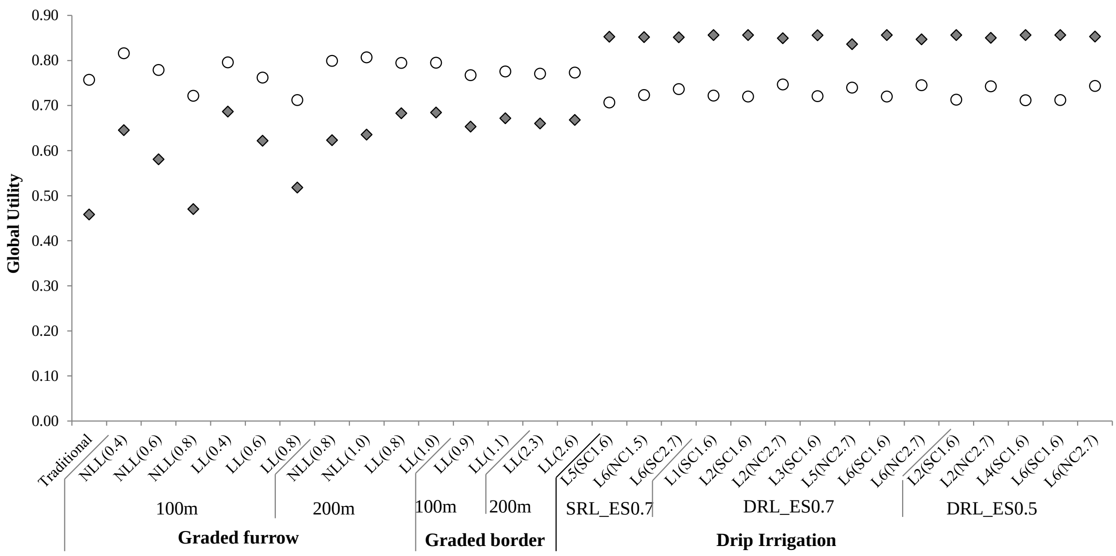


Figure 5. 9 Comparing global utilities when the priority is assigned to economic results (○) or to water saving (◆) referring to graded furrows and borders and to drip systems for various system characteristics as referred for Figs. 5 and 6.

Following the results analysed before, the retained drip and surface irrigation systems were ranked assuming various prioritization schemes, W1 to W6, with W1 corresponding to assign 90% of weights (see Table 5.3) to economic results and 10% to water saving while for W6 only 10% of weights were assigned to economic results and 90% to water saving. Results in Table 5.4 show that surface irrigation is dominantly selected until 40% of weights are assigned to economic returns to farmers (scenario W3) and that drip is selected when weights assigned to water saving represent 50% or more of total weights.

The first ranked for W1 through W3 are non-levelled graded furrows with controlled discharges while laser levelling has a lower preference. When drip is ranked first the paired double rows lateral layout is always selected. Non-compensating emitters are selected when drip starts to be first ranked (W4) but SC emitters become the choice when higher priority is assigned to water saving (W6). Overall, results in Table 5.4 represent an evolution in adoption of technologies, which are progressively more exigent mainly in terms of investment costs.

These results must be interpreted in a policy and decision making perspective: if policy and decision makers define water saving as the priority then they have to create technical and financial solutions that support farmers adoption of improved systems because the farmers economic perspectives favour the adoption of improved surface irrigation without laser levelling i.e., just adopting low cost technology. However, farmers also need technical support to successfully adopt such improvements (Galli et al., 2010).

Table 5. 4 Ranking of drip and surface irrigation alternatives for various weighing scenarios W1 (highest weights to economic issues) through W6 (highest weights to water saving)

	Weighing scenarios (progressively decreasing weights to economic issues and increasing weights to water saving)					
Rank	**W1(10-90)**	**W2(30-70)**	**W3(40-60)**	**W4(50-50)**	**W5(70-30)**	**W6(90-10)**
1	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)	DRL0.5L6(NC2.7)	DRL0.7L6(SC1.6)	DRL0.5L2(SC1.6)
2	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L6(SC1.6)
3	GF_{NLL}200(0.8)	GF_{LL}100(0.4)	GF_{LL}100(0.4)	DRL0.7L6(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L6(SC1.6)
4	GF_{LL}100(0.4)	GF_{LL}200(1.0)	GF_{LL}200(1.0)	DRL0.7L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.7L2(SC1.6)
5	GF_{LL}200(1.0)	GF_{LL}200(0.8)	DRL0.5L6(NC2.7)	DRL0.5L2(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(NC2.7)
6	GF_{LL}200(0.8)	GF_{NLL}200(0.8)	GF_{LL}200(0.8)	DRL0.5L6(SC1.6)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)
7	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	GF_{NLL}200(1.0)	GF_{LL}100(0.4)	GF_{LL}100(0.4)	GF_{LL}100(0.4)
8	DRL0.5L6(NC2.7)	DRL0.5L6NC2.7)	GF_{NLL}200(0.8)	GF_{LL}200(1.0)	GF_{LL}200(1.0)	GF_{LL}200(1.0)
9	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	GF_{LL}200(0.8)	GF_{LL}200(0.8)	GF_{LL}200(0.8)
10	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)
11	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)
12	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)

5.5.4. Deficit irrigation impact on ranking the alternatives

The comparison between the 12 selected drip and surface irrigation alternatives when adopting deficit irrigation was performed considering an irrigation depth of 640 mm, i.e., a reduction of 20% relative to full irrigation (800 mm). This decrease in water availability influences the actual evapotranspiration and yield (Table 5.1). Selected results are presented in Figure 5.10 where yields and water use are compared for full and deficit irrigation (FI and DI). A yield reduction of 11 to 12% was estimated for both surface and drip systems when adopting DI. Ünlü et al. (2011) reported that reducing irrigation by 22% produced a yield loss of 11%, which is a result similar to ours. Akhtar et al. (2013)

reported a lower impact on yields, with reducing the yield by 14% when the water supply is decreased by 40%. Dağdelen et al. (2009) reported also lower yield impacts of DI. Results in Figure 5.10 show that DI has lower impacts on yields when drip irrigation is adopted. This relates to the lower non-beneficial water use with drip and to the better placement of the irrigation water in the root zone.

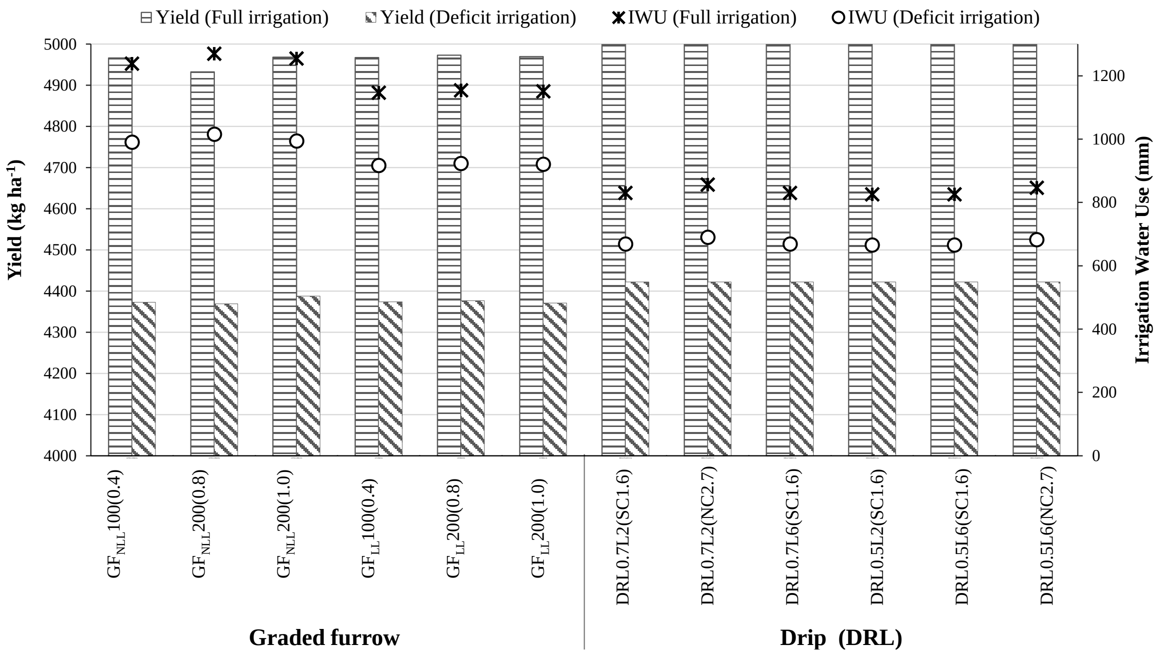


Figure 5. 10 Comparing irrigation water use for full (x) and deficit irrigation (O) and yields for full (⊟) and deficit irrigation (▧) for graded furrows and drip systems with double rows per lateral

Figure 5.11 presents the difference in IWU, BWUF, WP_{Irrig} and ELP utility values relative to the 12 retained surface and drip irrigation systems when changing from FI to DI. All utility values increase except the economic land productivity, which decreases due to yield reduction. IWU and BWUF increase because they reflect a decrease in water use, and WP_{Irrig} also increases because the yield decrease is proportionally smaller than the water use decrease. Drip and surface irrigation behave differently as shown in Figure 5.11 and as analysed before. It is noticeable that the increase of the utility of IWU and BWUF are higher for GF than for drip systems, which are explained by a better use of soil water when less irrigation is applied. DI could be advantageous if the decrease of farmer income is smaller than the decrease in production costs. However, DI implies an additional risk that leads farmers to adopt DI only as a response to water availability constraints.

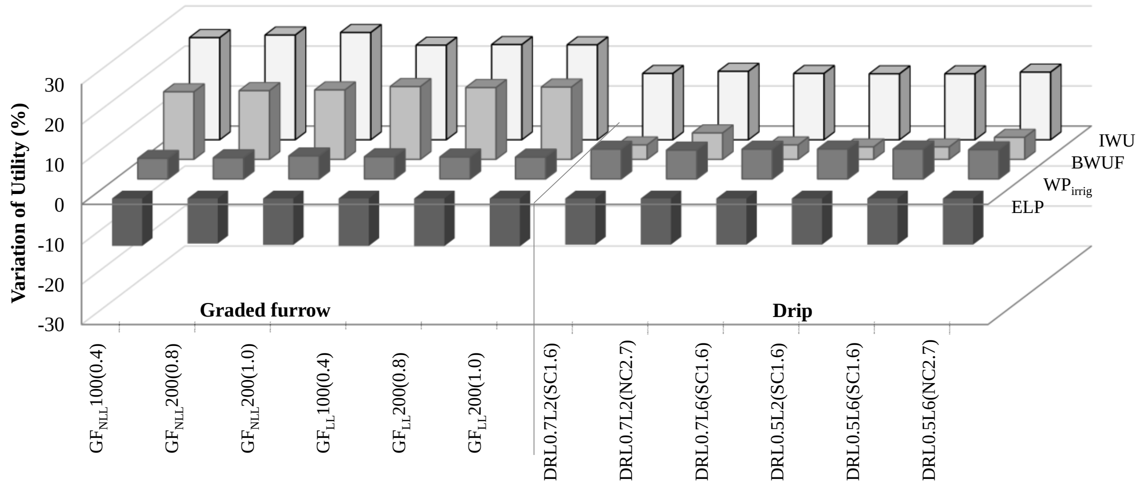


Figure 5. 11 Variation in the utility values relative to economic land productivity (ELP), irrigation water productivity (WP_{Irrig}), beneficial water use fraction (BWUF) and irrigation water use (IWU) when changing from full to deficit irrigation in graded furrows and drip irrigation systems

A ranking analysis similar to that in Table 5.4 is presented in Table 5.5 for the same 12 drip and graded furrows systems. Results show with evidence that if economic results are prioritized (W1 to W3), the first 6 ranked solutions refer to non-levelled graded furrows with appropriate control of inflow rates; differently, if priorities are assigned to water saving (W4 to W6) then drip systems are selected adopting paired double rows per lateral.

Table 5. 5 Ranking of drip and surface irrigation alternatives for various weighing scenarios W1 (highest weights to economic issues) through W6 (highest weights to water saving) when deficit irrigation is adopted

	Weighing scenarios (progressively decreasing weights to economic issues and increasing weights to water saving)					
Rank	**W1(10-90)**	**W2(30-70)**	**W3(40-60)**	**W4(50-50)**	**W5(70-30)**	**W6(90-10)**
1	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)	GF_{NLL}100(0.4)	DRL0.7L2(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L2(SC1.6)
2	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)	DRL0.5L6(NC2.7)	DRL0.7L2(NC2.7)	DRL0.5L6(SC1.6)
3	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)
4	GF_{LL}100(0.4)	GF_{LL}100(0.4)	GF_{LL}100(0.4)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)
5	GF_{LL}200(1.0)	GF_{LL}200(1.0)	GF_{LL}200(1.0)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L6(NC2.7)
6	GF_{LL}200(0.8)	GF_{LL}200(0.8)	GF_{LL}200(0.8)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.7L2(NC2.7)
7	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	GF_{LL}100(0.4)	GF_{LL}100(0.4)	GF_{LL}100(0.4)
8	DRL0.5L6(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L6(NC2.7)	GF_{LL}200(1.0)	GF_{LL}200(1.0)	GF_{LL}200(1.0)
9	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	GF_{LL}200(0.8)	GF_{LL}200(0.8)	GF_{LL}200(0.8)
10	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	GF_{NLL}100(0.4)	GFN_{LL}100(0.4)	GF_{NLL}100(0.4)
11	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)	GF_{NLL}200(1.0)
12	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)	GF_{NLL}200(0.8)

Self-compensating emitters are selected when weights assigned to water saving increase replacing the non-compensating ones, which are less expensive. Results for DI confirm that if policy and decision makers define water saving as a priority, then it is required to create technical and financial solutions that support farmer's adoption of improved systems since economic results favour the adoption of improved surface irrigation without precision land levelling.

5.6. Conclusions

This study aimed at developing, comparing and ranking various alternatives for cotton irrigation using modern surface and drip systems in Ras-El-Ain, Northeast of Syria. Two main criteria were considered: water saving and economic return to farmers. Design solutions for surface irrigation were developed and selected with the DSS model SADREG, and those for drip with the DSS model MIRRIG. Multicriteria analysis was used adopting the same attributes for both types of systems.

Data analysis have shown that drip irrigation uses less water than surface irrigation, thus the irrigation water productivity is larger for drip systems by 0.13-0.29 kg m^{-3} depending on various systems characteristics. The economical attributes revealed an investment cost for the drip systems of 1313-2320 € ha^{-1}, which is much higher than investments in equipment for surface systems and represents 24-53% of the total annual income. Variable costs are not very different among irrigation methods. The economic water productivity ratio ranges from 1.3-2.1 for drip systems and up to 4.9-7.1 for surface irrigation, thus indicating an enormous economic gap between both types of systems.

When ranking the best design solutions relative to drip and surface irrigation, it resulted that when the priority is assigned to economic results, the high ranked solutions refer to non-levelled graded furrows, while if the priority is assigned to water saving the first ranked solutions are for drip systems adopting double rows per lateral. Results for deficit irrigation do not change main rankings but evidence that drip may be more adequate for water saving, because it is able to reduce negative impacts on yields. Results indicate that if decision and policy makers desire to implement water saving policies and practices, it is required to adopt financial and technical support to farmers because related solutions are contrary to those providing good economic returns to farmers.

Chapter 6

Sprinkler *vs* borders irrigation of wheat in the semi-arid Northeast Syria: an application of multicriteria analysis

6.1. Introduction

The main cultivated crop in NE Syria is wheat, often rotated with cotton. Wheat (*Triticum durum and aestivurm L.*) was originated in the Fertile Crescent of Mesopotamia around 10,000 B.C. (Moragues et al., 2006; Araus et al., 2007). The largest wheat cultivated area, representing 39% of the total country production (45% irrigated and 55% rainfed), is located in Al-Hassakeh Governorate, NE Syria, Euphrates basin (Sadiddin and Atiya, 2009). Water scarcity has gradually increased in the last few years, mainly in the study area (Ras-El-Ain), which is located in the Al-Khabour basin (Mourad and Berndtsson, 2012). (More about study area and the current irrigation methods is described in Chapter 3).

The dominant irrigation method for wheat is traditional surface irrigation, both graded borders and basins (92%), with sprinkler systems representing only 8% (Sadiddin and Atiya, 2009). The traditional surface systems show low irrigation performance due to several problems mainly non-levelled land, high labour costs, and poor irrigation management. This system performance could be improved by adopting well designed and managed surface system, which may lead to improved land and water productivity, while meeting the farmer's preferences as demonstrated in Chapter 4 for cotton. As discussed in Chapter 5 (Darouich et al., 2014), drip irrigation could be an alternative to replace cotton surface irrigation, but water use and related economic issues are critical for decision-making. Pereira et al. (2007) indicated that for China the improvement of basin surface irrigation, in terms of flow, land levelling and irrigation scheduling, may lead to water savings by 33% relative to the actual demand, while reducing deep percolation and salinity. In recent years, farmers are starting to adopt sprinkler irrigation in the region, allowing more frequent irrigation with smaller depths, which helps to reduce crop stress (Sadiddin and Atiya, 2009). (More about sprinkler performance described in Sub_Chapter 2.2.3.1)

In the region, wheat is seeded in December and harvested in mid-June. The evapotranspiration, ET of rainfed wheat ranges 300 to 400 mm, while for irrigated wheat seasonal ET ranges 450 to 650 mm (see Chapter 2). The unfavourable rainfall distribution along the growing season makes it necessary to apply supplemental irrigation to avoid crop water stress and to stabilize yields. Wheat is sensitive to water stress, especially during the development stage (Oweis et al., 1999; Karam et al., 2009). Higher WP obtained when supplemental irrigation is applied (see Chapter 2). The average irrigated crop yield ranges from 3.0 to 4.5×10^3 kg ha^{-1} and higher yield could be attained (5.5-6.3×10^3 kg ha^{-1}) for some wheat genotypes (Kanshaw et al., 2007; Rajaram and Braun, 2008; Oweis and Hachum, 2009; Yigezu et al., 2013). Deficit irrigation (DI) of wheat increased significantly WP, reaching 0.77 - 0.92 kg m^{-3} for 2/3 of FI (Oweis et al., 2000).

Beside irrigation, the crop yield is affected by the sowing's date, fertilization and planting pattern (Li et al., 2008). Several studies analysed the yield impacts by the water depths applied; studies agree about the feasibility of some deficits being applied (Oweis et al., 1999, 2003; Zhang and Oweis, 1999; El Amami el al., 2001; Li et al., 2008; Rodrigues and Pereira, 2009). Zhang and Oweis (1999) have shown that applying only 50% of the crop water requirements may lead to a yield reduction of only 10-15%. However, adopting deficit irrigation should be avoided in areas where salinity may be a problem (Xu et al., 2013). El Amami el al. (2001) demonstrated that for some deficit irrigation strategies, sprinkler is not an acceptable system, while surface irrigation is always feasible. (more about the influence of deficit irrigation on WP described in Chapter 2)

Irrigation for wheat may be scheduled using soil water balance models, as ISAREG (Teixeira and Pereira, 1992) and SIMDulaKc (Rosa et al., 2012a). The latter as recently been applied for wheat in China (Zhao et al., 2013; Zhang et al., 2013B) and in Syria (Rosa et al., 2012b). ISAREG – which was used in this study – was applied for wheat in Syria (Oweis et al., 2003), in Tunisa (Zairi et al., 2003), and in China (Liu et al., 1998; Pereira et al., 2007; Cai et al., 2009).

In terms of economic assessment, cost/benefit analysis have been often applied. Several factors affect the economic returns as the irrigation system investment cost, climate, topography and field shape, equipment, layout design, soil characteristics and labour requirements (Dalton et al., 2002). The most influential factor on the annual costs in sprinkler systems was the spacing between laterals and sprinklers, followed by the water costs and by the investment and energy costs (Ortiz Romero et al., 2006). Regarding the energy balance, Rodrigues et al. (2010a) indicates that improving irrigation systems performance has little impact on energy performance, which contrasts with water productivity, with full irrigation leading to higher energy performance than deficit irrigation. The economic advantages of sprinkler irrigation include higher gross income and reduced risk due to higher water use efficiency (Trout et al., 1994). Kahlown et al. (2007) concluded that for a farm with large area, rain-gun systems are a better economical solution than surface irrigation.

The main question when selecting sprinkler or modernized surface irrigation for wheat refers to making compatible two central but contradictory objectives: water saving and farm economic results. The variation of farmer's preference based on economic priorities for farmers who have high water investment cost and on water saving when having limited water availability. This type of decision problem considering contradictory criteria is appropriate to be handled with MCA aiming at supporting the decision maker to select the best compromise solution. MCA approach has been applied in agriculture for improving irrigation schedule methods, on-farm systems design and management, and to optimize the appropriate solutions and methods under different environment conditions (Thysen and Detlefsen, 2006; Bautista et al., 2009; Gonçalves and Pereira, 2009; Pedras and Pereira, 2009). Le Grusse et al. (2009) proposed an approach applied to economic, hydraulic and agricultural performance with emphasis at the farm level, through the creation of synthetic indicators that require the formulation of global multi-criteria indicators, allowing the interaction between the farming-system components. Rodrigues et al. (2013) used a MCA approach to compare and rank various drip and sprinkler systems. Gonçalves et al. (2011)b and Darouich et al. (2012) performed a MCA to select surface irrigation alternative systems for cotton in Central Asia and Syria, respectively. MCA is more often incorporated into DSS models that integrate data, design and selection models. This integration has been adopted for surface irrigation design as reported by Gonçalves and Pereira (2009).

For sprinkler, various simulation models for sprinkler irrigation have been developed during the last few decades (see Chapter 2). PROASPER (Rodrigues et al., 2010b) for sprinkler irrigation may be used combined with MCA modules to compare different irrigation system alternatives. Both models prove to be useful tools at both design and management levels. Starting with the appropriate design, focusing on the wheat producing area where the field data were collected, both models have been adopted to create, evaluate and rank different alternatives for graded furrows and borders (using SADREG) and for sprinkler systems (using an improved version of PROASPER). Thus, the main objectives of this study are: a) to apply both SADREG and PROASPER models for surface and sprinkler irrigation respectively, to create appropriate sets of design alternatives for wheat; b) to rank and select the best alternatives for both system types considering water saving and economic criteria using MCA; and c) to analyse the impacts for deficit irrigation over the surface and sprinkler irrigation solutions.

6.2. Material and Methods

6.2.1. Experimental site and field data

The study area, Ras-El-Ain, which is characterized in Chapter 3. The main source of water in the region is from the artesian wells. Due to the low cost of irrigation from wells, the shift from traditional irrigation to sprinklers does not lead to enough water savings that encourage farmers to use more modernized methods, despite low-interest credit provided by the government to enhance the adoption of sprinkler systems (Yigezu et al., 2013). The currently most adopted traditional irrigation system is graded border; the farmers tend to divide the land into many plots, with each plot having many borders that can be irrigated simultaneously. The water is supplied by a main-canal and submain-canal. The average seasonal water depths applied using traditional systems in 2006 was 553 mm with harvested yield 4.2×10^3 kg ha^{-1}. (see Sub-Chapter 3.4)

The field experiments were conducted using surface graded borders irrigation, with three different lengths: 200, 100 and 50 m. The water source was a well with a discharge of 40 l s^{-1}. A soil survey was conducted by ICARDA to characterize the soil properties, mainly field capacity (θ_{FC}), permanent wilting point (θ_{PWP}), and soil texture, resulting in an average total available water (TAW) of 139 mm m^{-1}; the average saturated hydraulic conductivity (K_s) was 3-4 mm h^{-1} (Darouich et al., 2007, 2012). The experimental field had a dimension of x = 200 m and y = 100 m, with slope of 0.8 and 0.0%. A topographic survey and land smoothing were done to provide a uniform slope. The irrigated wheat was cultivated during 165 days, with the seedling occurring in 1st January; the average yield is 5×10^3 kg ha^{-1}, which could be optimized to 5.25×10^3 kg ha^{-1} with good nitrogen fertigation 150 kg ha^{-1}. The crop characteristics related to the development stages and the adopted irrigation schedule are presented in Chapter 3 and by Darouich et al. (2007).

Rainfall distribution plays an important role to define the irrigation schedule where the total precipitation is 289 mm; the non-effective rainfall is presented in Table 6.1. The irrigation schedule for full irrigation was applied based upon a management allowed deficit (MAD) equal to the depletion fraction (p), while deficit irrigation bases on MAD<p. The actual evapotranspiration (ET_a) was estimated using ISAREG. Values for rainfed, and full and deficit irrigation scenarios are presented in Table 6.1, where the maximum ET was 523 mm. ET values are in agreement with the ones presented by Somme et al. (2005) and Oweis et al. (2000). The soil water contents were 60 and 20%, respectively at seedling and harvest (Darouich et al., 2007).

Table 6. 1 Irrigation scheduling considering the irrigation method and full and deficit irrigation

Irrigation method	Irrigation strategy	Number of irrigation events	Net irrigation depth, per event (mm)	ET_a (mm)	Effective rainfall (mm)
Traditional	-	3	65-87	413	156
Border	Full (FI)	4	60	439	134
Sprinkler	Full (FI)	8	30	450	156
Border	Deficit (DI)	3	60	409.8	164
Sprinkler	Deficit (DI)	6	30	409	163

The yield response function to the water applied described by Solomon (1984) was adopted: $Y_a/Y_{max} = f(W_a/W_{max})$, where Y_a and Y_{max} are the actual and the maximum yield, both in kg ha^{-1}, and W_a is the actual water applied and W_{max} is maximum water required, both in mm. These parameters are presented in Table 6.2.

Table 6. 2 Water-Yield function table parameters (source: Kanshaw et al. (2007))

W_a/W_{max}	0.25	0.5	0.75	1.0	1.5	2.0	2.5
Y_a/Y_{max}	0.064	0.36	0.65	1.0	1	0.95	0.8

The determination of soil infiltration characteristics was performed as described in Chapter 3. The main model input data of the crop, soil and climate for the study area is presented in Table 6.3.

Table 6. 3 Input data of wheat crop, soil and climate of Ras-El-Ain

Crop		Soil		Climate data	
Max. daily water requirement (mm)	7.3	Field capacity (m^{-3} m^{-3})	0.37	Average wind speed, ($m\ s^{-1}$)	2.3
Max. Seasonal water requirement (mm)	446	Permanent wilting point (m^{-3} m^{-3})	0.23	Average daily ET, ($mm\ d^{-1}$)	4.1
Effective root zone (m)	0.75	Total water available ($mm\ m^{-1}$)	139	Effective precipitation (mm)	156*
Depletion fraction (%)	67	Infiltration rate ($mm\ h^{-1}$)	4.1		
Leaching requirement (%)	0				
Yield ($kg\ ha^{-1}$)	5250				
Yield value (€ kg^{-1})	0.21				

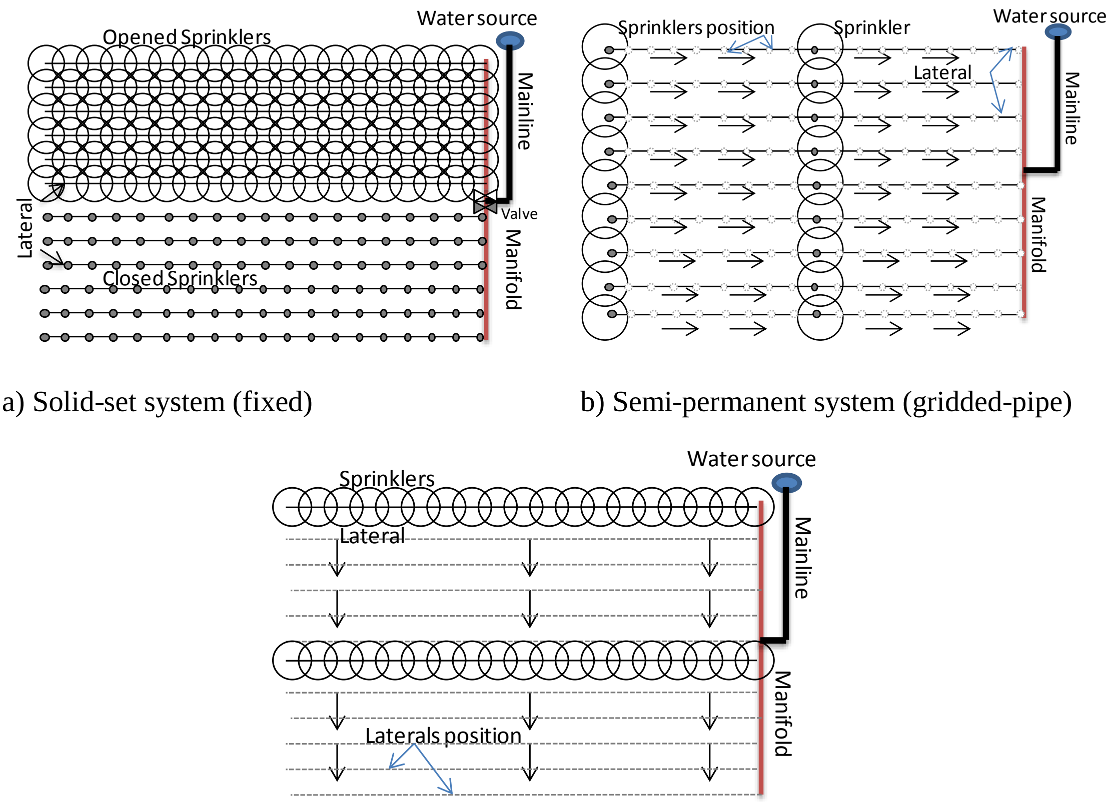
*the values change according to each irrigation methods (see Table 6. 1)

6.2.2. SADREG model

SADREG is a DSS model designed to assist designers and managers in the process of design and planning improvements in farm surface irrigation systems, mainly furrows, basins, and borders irrigation. It includes a database, user-friendly interface, and simulation and multicriteria analysis modules. (Gonçalves and Pereira, 2009; Gonçalves et al., 2011b) as described in Chapter 4. It integrates databases, design and simulation models, and user knowledge that allow generating and ranking alternatives. Thus, alternatives are characterized by various hydraulic, economic and environmental indicators. The alternatives sharing the main characteristics are grouped in "*projects*" such as graded borders (GB) in the present application. The ranking and selection component is based on MCA. Details about the model procedure and application steps are presented by Gonçalves and Pereira (2009), and the model application for the study area are discussed in Chapter 4.

6.2.3. PROASPER model

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). The model was redeveloped, enlarging the capability of the model to compare several designs from hydraulic, water saving and economic perspectives and integrated user knowledge in friendly interface to optimize the appropriate solution for different environment and economic conditions. The model was also improved in order to integrate hydraulic sprinkler design using a multicriteria approach. It allows to create three types of sprinkler irrigation systems following the methodology proposed by Keller and Bliesner (1990): Solid set (permanent and seasonal-move); semi-permanent (gridded-pipe); and portable system (hand-moved or sprinkler-hop) (Figure 6.1)



a) Solid-set system (fixed)

b) Semi-permanent system (gridded-pipe)

c) Portable system (hand-moved)

Figure 6. 1 Schematic system types of layout and laterals/sprinkler position and movements

The model can be used to assess the performance of sprinkler systems in operation aiming at improving their design and management, identifying appropriate modernization and rehabilitation measures, as well as to provide information that supports design. The model objectives can be described as: 1) design and simulate different irrigation systems alternatives; 2) evaluate their hydraulic system performance, economic and beneficial water use; 3) apply MCA modules to optimize the appropriate solution considering different design and management criteria among several alternatives. The model integrates a database, a user-friendly interface, and design and simulation modules that based on user knowledge, allow to generate and rank the different alternatives according to selected criteria. The conceptual structure of the model is shown in Figure 6.2.

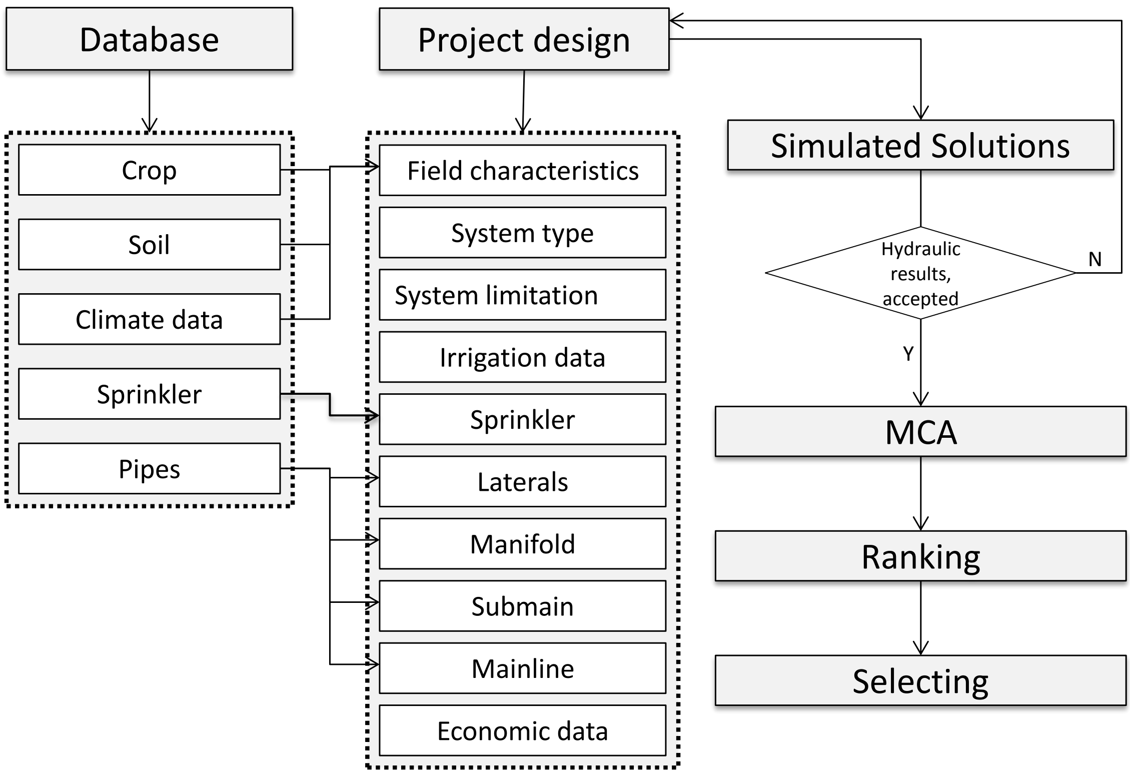


Figure 6. 2 Functional diagram of PROASPER model

The development of PROASPER is based on some criteria generally accepted as standards for the design of irrigation systems: 1) the variation in pressure head between sprinklers operating simultaneously along a lateral should not exceed 20% (Christiansen, 1942); 2) the variation in pressure head in mainline should not exceed 10%, while in manifold and submain not more than 5%; 3) the application rate should always be less than the rate of infiltration to avoid runoff and/or erosion (Pereira and Trout, 1999); 4) the choice of sprinklers should take into account the impact of wind speed and direction; 5) the velocity of water flow in pipes should be less than 1.5 m s^{-1}; and 6) the irrigation system should be able to provide the required irrigation schedule. The latter can be computed using a soil water balance simulation model, e.g., ISAREG (Teixeira and Pereira, 1992).

PROASPER requires the use of:

1) Database: the database includes all data including soil, crop, climate and system design, as presented in Table 6.4.

2) Project design: The design starts by defining: a) field characteristics, b) system type, and c) system limitation (see Table 6.4).The design is based on the assumption that the field is rectangular where the laterals have an equal length along the field. In addition, the field could be considered as only one sector or be divided into more than one sector. The hydraulic design is computed for each sector. The user can choose different combinations of pipes and sprinklers to simulate and test. Each lateral and sprinkler combination may be simulated for a rectangular and triangular sprinkler distribution grid and layout considering the position of the first sprinkler (equal or half spacing among sprinklers).

3) Irrigation data: Some of the required irrigation data can be obtained from a soil water balance simulation model (e.g. ISAREG). This simulation will allow to estimate the required net irrigation requirement (NIR, mm), number of irrigation events and the interval between events (days). Using this information, PROASPER will calculate the maximum interval between irrigation events depending on the total available water. Using the user defined target irrigation system efficiency (E_{pa_target}, %), the model estimates the gross irrigation requirement (GIR, mm) based on NIR using Eq. 6.1, while taking into account the leaching fraction (LF, %). The target application rate, i_a (Eq. 6.2), expressed in mm h^{-1}, is then calculated from the model using GIR and the target irrigation event duration (t_{i_target}, h).

$$GIR = \frac{NIR}{E_{pa\_target}(1-LF)} 100 \quad [6.1]$$

$$i_a = \frac{GIR}{t_{i\_target}} \quad [6.2]$$

Table 6. 4 Variables required for the database, project preliminary design and layout design.

Database				
Crop	**Soil**	**Climate data**	**Sprinkler**	**Pipes**
Maximum seasonal ET, ET_{max} (mm)	Field capacity, θ_{FC} (m^3 m^{-3})	Average wind speed (m s^{-1})	1º nozzle diameter, dn (mm)	Material
Potential seasonal water requirement, NIR (mm)	Permanent wilting point θ_{PWP} ($m^3 m^{-3}$)	Average ET (mm d^{-1})	Flow rate, qn (m^3 h^{-1})	Nominal pressure (m)
Effective root zone, Z_r (m)	Total available water, TAW (mm)	Effective precipitation, Pr (mm)	Pressure head, H_0 (m)	Internal diameter (mm)
Depletion fraction, p (%)	Infiltration rate (mm h^{-1})		Throw, Rw (m)	Price (€ m^{-1})
Leaching fraction, LF (%)			Price (€ $unit^{-1}$)	Life time (Year)
Yield, Yp (kg ha^{-1})			Life time (Year)	
Yield value, Yc (€ kg^{-1})			Distribution pattern	
Water-Yield function (table)				

Project preliminary design			
Field characteristics	**System type**	**System limitations**	**Irrigation data**
Climate	Solid set (permanent)	Maximum velocity allowed in pipes (m s^{-1})	Net irrigation requirement, NIR (mm)
Crop	Solid set (seasonal-move)	Pressure head variation in main line (%)	Target system efficiency, E_{pa_target} (%)
Soil	Semi-permanent (gridded-pipe)	Pressure head variation in submain (%)	Gross irrigation requirement, GIR (mm)
Width (X) m	Portable system (hand-moved)	Pressure head variation in the manifold (%)	Maximum interval between events, T_{max} (d)
Length (Y) m	N° of irrigated sectors, N_{se}	Pressure head variation in laterals (%)	Target duration, t_{i_target} (h)
Slope X %	N° Laterals/ sectors	Water losses in pipes, Oe (%)	Target application rate, i_a (mm h^{-1})
Slope Y %	N° Sprinkler/ Laterals	Pressure head at upstream (m)	Adequately irrigated area, pa (%)
		Flow rate at upstream (m^3 h^{-1})	N° irrigation events, N_{irr}

Layout design				
Sprinklers	**Laterals**	**Manifold**	**Submain**	**Mainline**
Sprinklers code	Pipe code	Pipe code	Pipe code	Pipe code
Height of riser (m)	Laterals spacing (m)	Slope (%)	Length (m)	Length (m)
Sprinklers spacing (m)	N° Lats/Manifold	Inlet position (edge or middle)	Upstream land elevation (m)	Upstream land elevation (m)
N° Sp/Lateral left	L. left slope (%)		Downstream land elevation (m)	Accessories cost (%)
N° Sp/Lateral right	L. right slope (%)		Distance between outlets(m)	
	Pressure regulator Head losses (m)			

4) Layout design: The design starts by choosing the suitable sprinkler that helps to find the combination of sprinkler spacing, operating pressure, and nozzle size that provides the desired application rate with the best distribution uniformity. The basic components of sprinkler irrigation systems are pumping station, pressure regulators, valves, filter, pipe couplers for the hand-move laterals, and sprinklers; the main layout system consists of the mainline, submain, manifold and laterals. The user chooses the sprinkler layout with the appropriate spacing between sprinklers and laterals, taking into account the effect of the wind speed. The number of sprinklers and laterals according to the pipe length should be defined, as well as the corresponding slope. If the user chooses to use pressure regulators in order to provide equal pressure and discharge along the system, the model estimates the required extra pressure to compensate the added pressure losses. The accessories costs are considered as a percentage of the total investment cost. The user can choose to simulate several layouts at the same time, in order to compare different alternatives.

5) Economic data: The economic inputs include fixed and variable costs and are presented in Table 6.5. The fixed economic data include the number of the analysed years, interesting rate, and water, labour and energy cost. The variable parameters include labour time for installation, repair, replacement, removing and operation of each irrigation sector, and the machinery operation time. The values change according to the type of irrigation system and to the size of each sector.

Table 6. 5 Economic required input data

Variable data	Fixed data
Installation (hour ha^{-1})	N° of analysed year (year)
Repair and replacement (hour ha^{-1})	Interest rate (%)
Removing (hour ha^{-1})	Water price (€ m^{-3})
Labour operation (hour ha^{-1} $irrigation^{-1}$)	Labour cost (€ h^{-1})
Machinery (hour ha^{-1})	Machinery cost (€ h^{-1})
	Energy cost electricity (€ kWh^{-1})

The performance indicators estimated by the model, described by Rodrigues et al. (2010b), which are affected by the wind speed and operating pressure relying on the sprinkler water-distribution pattern and spacing (Pereira, 1999; Dalton et al., 2002; Pereira et al., 2002; Van der Gulik, 2003; Ortega et al., 2004; Ortiz Romero et al., 2006; Rodrigues et al., 2010a). Indicative spacing recommendations for the most common water distribution profiles, based on the wetted diameter (D_w), are given and adjusted according to Keller and Bliesner (1990). The sprinkler pattern, either rectangular or triangular, determines the spacing between sprinklers and laterals. The calculation of the water distribution is computed for the overlapping middle square area of 16 sprinklers, for a rectangular distribution grid, and 12 sprinklers, for a triangular distribution grid. The water application pattern of a single sprinkler follows the single-leg distribution, as defined by Heermann et al. (1980). Higher distribution uniformities and efficiencies can be achieved when the design is optimized in order to achieve the required head pressure for the selected sprinkler discharge through the selection of the best combination of sprinkler spacing, discharge, nozzle size and operating pressure (Keller and Bliesner, 1990; Pereira, 1999; Tarjuelo et al., 1999; Pereira et al., 2002)

6.2.4. SADREG and PROASPER applications and MCA

6.2.4.1. Surface irrigation system scenarios

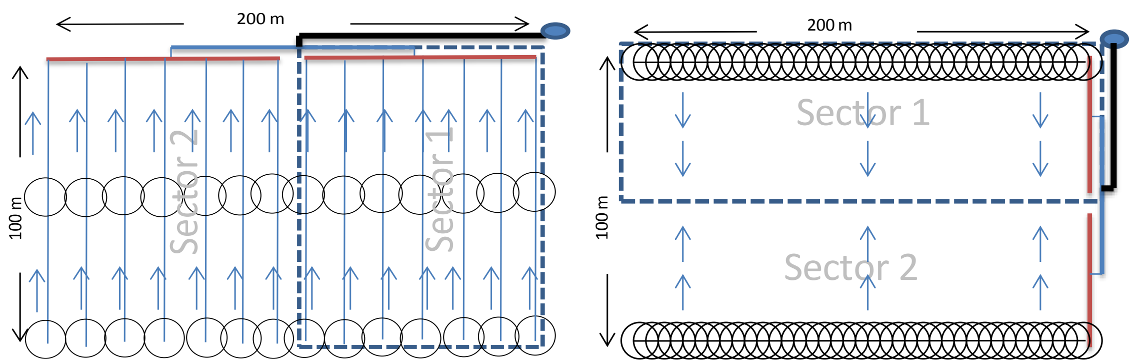
The project considered is graded borders (GB) which were developed adopting an open tail end condition, layflat gated tubing for in-field water distribution, flat soil surface for borders. Simulations were performed assuming two land levelling scenarios: with (GB_{LL}) and without (GB_{NLL}) land levelling operation. GB_{NLL} implies the reduction of investment costs but does not allows optimizing the water distribution and the irrigation performance; GB_{LL} aims to optimize the water use and irrigation performance with precise land levelling, thus with higher investment and operation costs, and with higher irrigation uniformity. Hydraulic simulations were performed assuming a manning roughness coefficient of 0.16 $m^{1/3}$ s^{-1} for borders (Walker and Skogerboe, 1987). The alternatives were simulated for different borders length 200, 100 and 50 m, for inflow rate 0.3-3.7 l s^{-1} m^{-1}. The field was subdivided into several sub-sectors according to the applied inflow rate. Labour and equipment costs of surface irrigation are presented in Table 6.6.

Table 6. 6 Labour and equipment economic data

Description		Unitary costs
Land levelling	Hourly cost	220 € h^{-1}
	Operation time per area	3.0 h ha^{-1}
	Frequency of operation for graded borders	3 years
Layflat gated pipe	5” diameter	0.15 € m^{-1}
	9” diameter	0.22 € m^{-1}
	12” diameter	0.3 € m^{-1}
	Layflat valve	0.23 € per valve
Financial data	Analysis period	10 years
	Annual interest rate	4 %
Effective lifetime	Layflat tubing	1 year
	Layflat valve	1 year
Prices	Water price	0.022 € m^{-3}
	Labour cost	0.8 € h^{-1}
	Yield price	0.21 € kg^{-1}
Labour requirements	for equipment operation	40 min/100m
	for installing equipment	60 min/100m
	for removing equipment	50 min/100m

6.2.4.2. Sprinkler irrigation systems scenarios

In order to build the different sprinkler system alternatives, three alternative systems were considered (Figure 6.1): solid-set (fixed) system (S1); semi-permanent using a gridded-pipe (S2); and portable, hand-moved (S3. For all analysed system types, two different layouts were also considered, L1 and L2 referring to two different pipes position, lengths and to inlet location of the manifold. Figure 6.3 shows, as an example, the schematic drawing of L1/S3 and L2/S2. The field was divided into two sectors, with the water being supplied from the highest part of the field where the well is located. The pipes adopted were high density polyethylene (PE_{hd}) and PVC: PE_{hd} was used for the laterals and manifold for system types S1 and S2, and PVC was used for laterals and manifold in S3 and for the buried mainlines of all systems.



Semi-permanent, gridded-pipe (S2/L2) Portable system, hand-moved (S3/L1)

Figure 6. 3 Irrigation systems types, gridded-pipe, (S2) of (L2) and portable, hand-moved (S3) for layout (L1).

Five impact sprinklers were tested - sp1, sp2, sp3, sp4 and sp5 - which have different characteristics, operating pressure, inflow rate and throw range, with distinctive distribution pattern, triangular or elliptic. The characteristics of each alternative sprinkler are presented in Table 6.7. Five distribution grids of spacing between sprinkler and laterals were also tested, G1 to G5, choosing the sprinkler based on its throw (Table 6.8). Table 6.9 presents number of sprinklers, laterals and pipe's diameters for each sector. The three types of systems were designed using the same hydraulic design, differing only from an economic perspective; the pipes used are the available in the Syrian market that are more economic. The number of sprinklers used in S2 is two sprinklers per lateral (placed in middle and end of lateral), and in S3, one lateral is used per manifold (see Figure 6.1b and c and Figure 6.3).

Table 6. 7 Sprinklers input data of characteristic and configuration

Sprinkler	sp1	sp2	sp3	sp4	sp5
1º Nozzle diameter (mm)	2.78	12.7	5	5	19.05
2º Nozzle diameter (mm)	0	0	2.5	2.5	8.9
Flow rate (m^3 h^{-1})	0.48	0.74	1.21	1.45	1.19
Pressure head (m)	40	25	35	40	40
Throw range (m)	12.8	13.4	18	20.19	28.2
Price (€)	0.42	8.5	1.11	1.11	11.3
Life time (year)	1	6	3	3	6
Distribution pattern	Triangular	Triangular	Elliptic	Elliptic	Triangular

Table 6. 8 Adopted distance between sprinkler and between laterals for all system types

System Types	G1 (12×12)*	G2 (12×16)	G3 (16×16)	G4 (16×20)	G5(25×25)
Solid set **(S1)**	(sp1- sp2)	(sp2)	(sp3)	(sp3 - sp4)	(sp5)
Gridded-pipe **(S2)**	(sp1- sp2)	(sp2)	(sp3)	(sp3 - sp4)	(sp5)
Portable system **(S3)**	(sp1- sp2)	(sp2)	(sp3)	(sp3 - sp4)	(sp5)

* (Sprinkler's spacing × lateral's spacing)

Table 6. 9 Alternatives for system S1, including the number of sprinklers and laterals and pipes diameters

S1	Sprinklers	Number of sprinklers	Number of laterals	Lateral diameter	Manifold diameter	Mainline diameter
L1.G1	sp1	17	4	PE.6/50*	PE.6/75	PVC.6/110
L1.G1	sp2	17	4	PE.6/63	PE.6/90	PVC.6/125
L1.G2	sp2	13	4	PE.6/50	PE.6/75	PVC.6/110
L1.G3	sp3	13	3	PE.6/63	PE.6/75	PVC.6/110
L1.G4	sp3	10	3	PE.6/75	PE.6/75	PVC.6/110
L1.G4	sp4	10	3	PE.6/75	PE.6/75	PVC.6/110
L1.G5	sp5	9	2	PE.6/50	PE.6/63	PVC.6/75
L2.G1	sp1	9	9	PE.6/50	PE.6/90	PVC.4/125
L2.G1	sp2	9	9	PE.6/50	PE.6/90	PVC.4/125
L2.G2	sp2	7	9	PE.6/50	PE.6/90	PVC.4/110
L2.G3	sp3	7	7	PE.6/50	PE.6/90	PVC.6/125
L2.G4	sp3	5	7	PE.6/63	PE.6/90	PVC.4/110
L2.G4	sp4	5	7	PE.6/63	PE.6/90	PVC.4/125
L2.G5	sp5	4	4	PE.6/50	PE.6/63	PVC.6/75

* Polyethylene, PE. pressure (bar)/internal diameter (mm)

The economic data for fixed and variable costs is presented in Table 6.10. Machinery operation costs are only considered for the portable system, and higher labour is required to move the laterals for field S3 (Patterson et al., 1996); labour for operation is higher for S2 and S3. The economic data that concerns water price, labour costs and commodity price is same for surface (see Table 6.6). Additionally, the energy cost is 0.08 € kWh^{-1}.

Table 6. 10 Variable economic data costs

Costs	S1-solid-set	S2-gridded	S3-portable
System Installation (h ha^{-1})	22	20	15
System Repair/replacement (h ha^{-1})	2	2	10
System Removing (h ha^{-1})	9	9	5
Labour for system operation (h ha^{-1} event^{-1})	0.5	5	5
Machinery operation (h ha^{-1})	0	0	3

6.2.4.3. Performance indicators and multicriteria analysis

The adopted criteria aims for two main objectives: 1) water saving, including indicators as the total irrigation water use, beneficial water use fraction, irrigation water productivity and non-beneficial water uses, and economic productivity; and 2) economic productivity and costs, including economic land productivity, economic water productivity, economic water productivity ratio, fixed irrigation costs and variable irrigation costs. The criteria attributes were calculated according to the water use and productivity indicators defined by Pereira et al. (2012), which were incorporated into PROASPER and SADREG models. These attributes are handled through appropriate linear utility functions (more details about the used MCA method is in Chapter 2). The utility functions adopted are listed in Table 6.11. With this procedure, the utilities U_j for any criterion j are normalized into the [0-1] interval (zero for the more adverse and 1 for the most advantageous result). The Linear Weighted Summation multicriteria method was applied (see Chapter 2). Criterion weights depend on several factors including socio-cultural values, and economic and/or environmental perspectives. In this study, two priority scenarios were considered, one aimed at achieving the best water saving and the other aimed at attaining the highest farm incomes (Table 6.11).

SADREG and PROASPER produced a large set of alternatives, which were clustered in groups after the respective ranking and selection analysis. A further application of MCA to the selected sprinkler and surface irrigation alternatives allowed the comparison between these different systems and considering the referred criteria. Further analysis of rankings was carried out by varying progressively the weights relative to farm economics and water saving criteria, i.e., starting with a scenario where 90% of weights were assigned to farm economic criteria and 10% to water saving to end with a last scenario where 90% of weights were assigned to water saving. The weights were the same as presented in Chapter 5, because the surface alternatives are the same, so changing the weights would lead to a different ranking for surface irrigation. The same analysis was performed for deficit irrigation.

Table 6. 11 Criteria attributes utility functions and criteria weights

Criteria attributes (x)		Symbol	Units	Utility functions	Weights (%) assigned to attributes when prioritizing	
					Water saving	Economics
Economic productivity and costs					**20**	**80**
Economic land productivity		ELP	€ ha^{-1}	$U(\boldsymbol{x}) = 0.907\times10^{-3}\,\boldsymbol{x}$	5	15
Economic water productivity		EWP	€ m^{-3}	$U(\boldsymbol{x}) = 4.0\,\boldsymbol{x}$	4	15
Economic water productivity ratio		EWPR	ratio	$U(\boldsymbol{x}) = 0.1667\,\boldsymbol{x}$	5	20
Fixed irrigation costs		FIC	€ ha^{-1}	$U(\boldsymbol{x}) = 1 - 1.67\times10^{-3}\,\boldsymbol{x}$	3	15
Variable irrigation costs		VIC	€ ha^{-1}	$U(\boldsymbol{x}) = 1 - 1.67\times10^{-3}\,\boldsymbol{x}$	3	15
Water saving and environment					**80**	**20**
Total irrigation water use		IWU	mm	$U(\boldsymbol{x}) = 1 - 1.8\times10^{-3}\,\boldsymbol{x}$	20	3
Beneficial water use fraction		BWUF	ratio	$U(x) = 1.0\,\boldsymbol{x}$	15	5
Water productivity		WP	kg m^{-3}	$U(\boldsymbol{x}) = 0.833\,\boldsymbol{x}$	15	4
Non-beneficial water use (NBWU)	Runoff	RO	mm	$U(\boldsymbol{x}) = 1 - 3.57\times10^{-2}\,\boldsymbol{x}$	15	4
	Deep percolation	DP	mm	$U(\boldsymbol{x}) = 1 - 3.57\times10^{-2}\,\boldsymbol{x}$	15	4

6.3. Result and discussion

6.3.1. Surface irrigation alternatives

Using SADREG, 44 alternatives were created according to the input variable parameters. The highest total irrigation depth applied with the traditional system was 553 mm for crop season of 2006-2007. The set of 38 satisfactory alternatives were built aiming to an irrigation water use, IWU lower than 553 mm. The results for these 38 alternatives, including IWU and non-beneficial water use (NBWU), as well as runoff (RO) and deep percolation (DP), are presented in Figure 6.4. These alternatives included different combinations of lasered and non-lasered land, different length and discharge, when compared with the traditional method. Results show that the improved alternatives allowed a feasible decrease of IWU due to the reduction of deep percolation and runoff.

The lowest IWU values obtained for the lasered land alternatives varied from 352 to 449 mm while for non-lasered land ranged from 386 to 507 mm. For 100 m length the best water saving alternatives were L100_GB(1.4), L100_GB(1.7) and L100_GB(2.0) and for 50 m length the lowest IWU values were achieved with L50_GB(0.6) and L50_GB(0.9) (Figure 6.4a). DP and RO present an opposite behaviour. DP decreases gradually with the increase of the inflow rate; contrarily, RO increases with the increase of this parameter. IWU and BWUF show to be very sensitive to the inflow rate, thus indicating that an improved performance requires appropriate control of this parameter by farmers. The highest BWUF (0.80) was obtained for L100_GB(1.7) with the lowest being achieved with the traditional system (0.54) (Figure 6.4b). The WP is higher for lasered land, varying from 0.78 to 0.93 kg m^{-3}, than for non-laser land, which varies from 0.71 to 0.86 kg m^{-3} (Figure 6.4c). The alternatives that lead to the highest WP values are the ones with lower IWU. These WP values are in agreement with the ones proposed by Oweis and Hachum (2009).

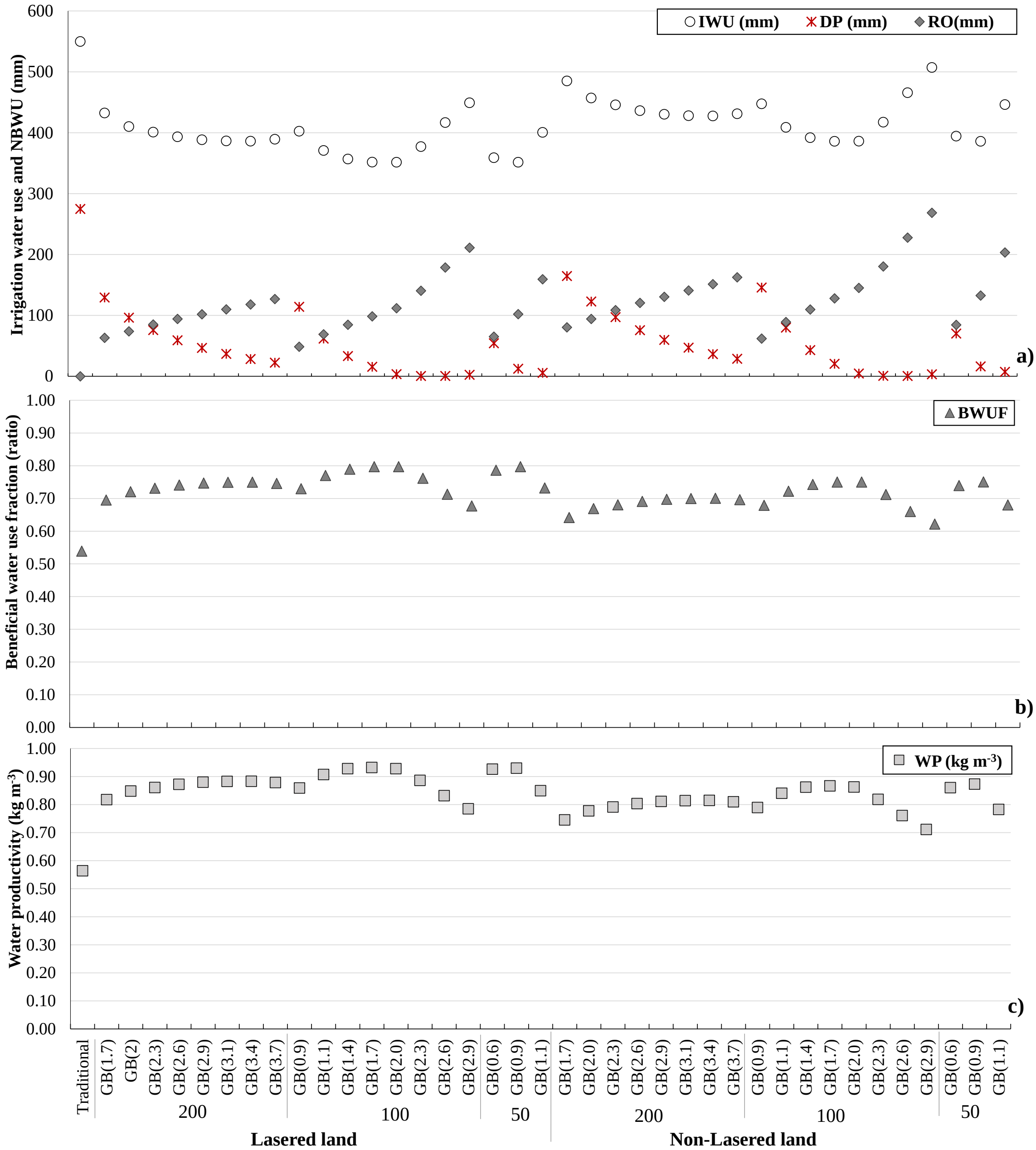


Figure 6. 4 Comparing alternatives for: a) Irrigation water use, tail-end irrigation runoff and irrigation deep percolation, all in (mm); b) beneficial water use fraction; and c) water productivity (kg m^{-3}), Alternatives consist of lasered and non-lasered graded borders (GB), and traditional irrigation (numbers in brackets refer to inflow rates (l s^{-1} m^{-1}))

In terms of economic results, Figure 6.5 shows that the investment cost is affected by the land levelling costs, which were relative high, and by the borders length, with the length of 50 m being the most expensive alternative. The labour cost also has an influence in terms of application time and number of sectors, varying according to the different inflow rate (Gonçalves and Pereira, 2009).

Figure 6.5 presents some variation of labour cost being affected by the inflow rate, border length and land levelling factors; the highest value was obtained for flow rate lower than 2.6 l s^{-1} and for 100 m border length. The non-lasered land requires more labour due to the required application time; however, the low labour cost leads to small differences when comparing these alternatives with lasered land scenarios. The EWP is higher for lasered alternatives than for the non lasered scenarios; the alternatives that led to the highest values are L100_GB(1.7) and L50_GB(0.9). EWPR is higher for the alternatives with lower costs > 4, when laser levelling is not considered; contrarily, this indicator tends to decrease when the irrigation costs increase mainly due to land levelling. These results indicate that the water savings due to land levelling does not compensate the related investment. The traditional system shows a EWPR value (3) higher than lasered land alternatives (2.08-2.34). Further, better results of graded borders in terms of water use and economic water productivity are obtained for 100 and 50 m length.

Figure 6.6 presents the global utilities (U) characterizing different alternatives for both priority scenarios – water saving and economic results – as defined in Table 6.11. Results show that, when priority is given to economic results, the non-lasered land's alternatives appear as better solutions than the lasered land ones. For most of the alternatives, the global utility values indicate a higher feasibility for economic results than for water savings'; exception is made for the traditional system and for the 200 m lasered land alternatives. Also, the variation in the utilities of water saving and economic priority is very small for lasered alternatives. As expected, the reference traditional system presents the lowest global utility value in terms of water savings.

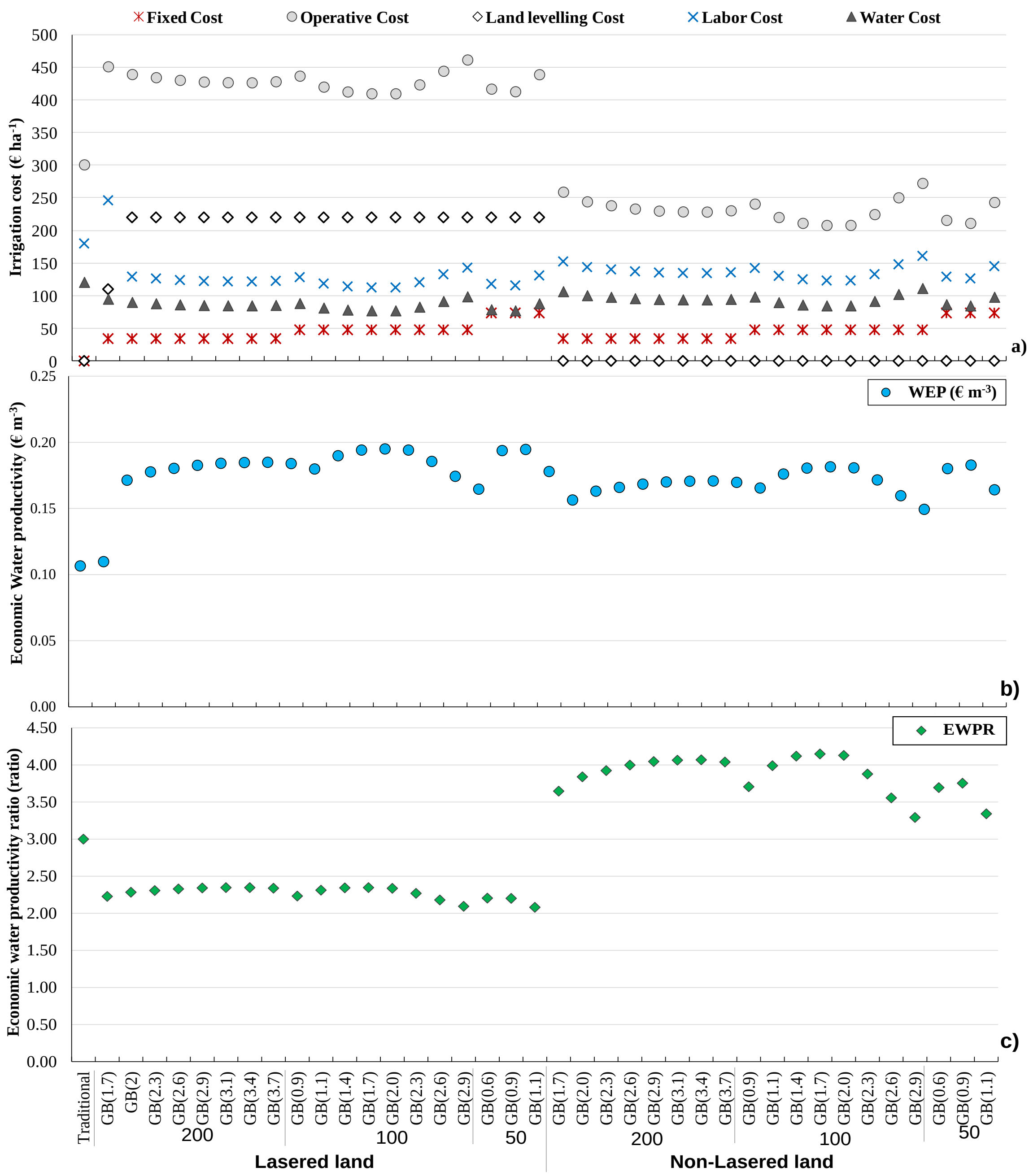


Figure 6. 5 Comparing alternatives for: a) irrigation costs, b) economic water productivity and c) the economic water productivity ratio. Alternatives consist of graded borders (GB), for lasered and non-lasered land (numbers in brackets are for inflow rates, l s^{-1} m^{-1}) and traditional option.

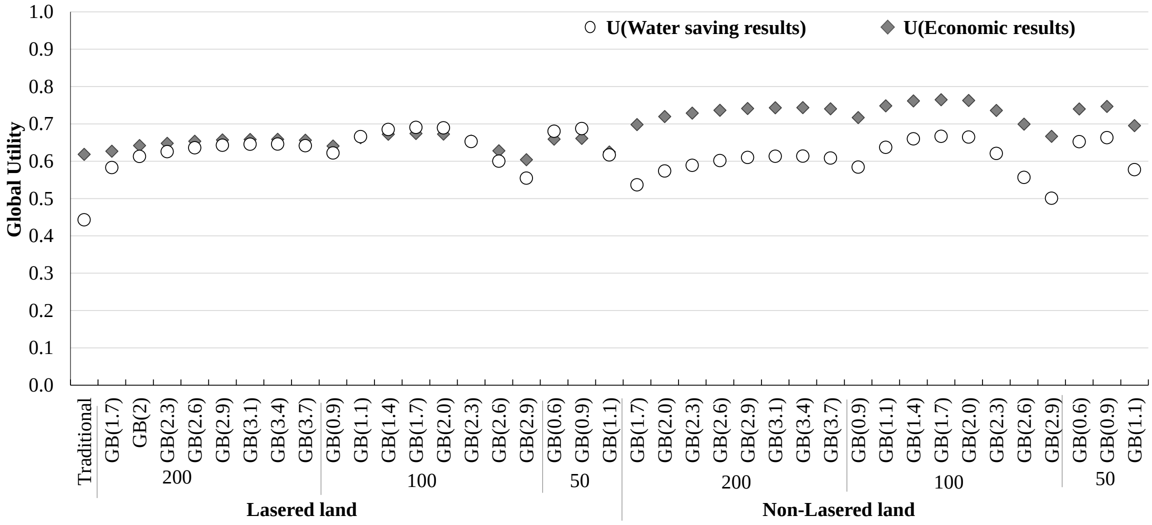


Figure 6. 6 Global utility value when the priority is assigned to economic results (◆) or to water saving (○). Alternatives refer to graded borders (GB) and traditional irrigation, (the number in brackets is the unit inflow rate, l s^{-1} m^{-1}).

6.3.2. Economic and water saving performance of sprinkler irrigation alternatives

PROASPER allowed to simulate a set of 84 different alternatives, resulting from the combinations of three system types (S1, S2 and S3), two layouts (L1 and L2), five distribution grid of spacing between sprinkler and laterals (G1 to G5), two sprinkler distribution patterns - square (sq) and triangular (tr) - and five impact sprinklers (sp1 to sp5) (see. Section 2.4.2). The difference between the three system types is purely economic thus only the water related indicators are presented in Figure 6.7. Results of IWU (Figure 6.7a) show that the lowest values are for combinations G1_sp1, G2_sp2 and G5_sp5 for both layouts, varying from 257 to 269 mm. Runoff, RO and deep percolation, DP are low for the different alternatives since the design is made in order to select the most appropriate sprinklers and spacing between sprinklers and laterals. The highest RO (55 mm) was obtained for G1_sp2 due to higher water distribution rate (5 m^3 h^{-1}). The highest DP (40 mm) was attained for G4_sp3, due to inappropriate spacing between laterals and lower coefficient uniformity (Figure 6.7a). Figure 6.7b shows a contrary behaviour of BWUF when compared with IWU, i.e., BWUF is higher when IWU is lower. The value of WP is ranged from 0.96 to 1.10 kg m^{-3} with the highest value being obtained for the alternative G5_sp5(sq), for both layouts. BWUF presents the same behaviour as WP, ranging from 0.83 to 0.94%. Results also show that the difference between layouts, in terms of water saving indicators, was not noticeable; also, the impact of the distribution pattern - square (sq) or triangular (tr) - was small due to the small differences of the application uniformity. The coefficient of uniformity (CU) ranges from

0.86-0.97 (Figure 6.7a); these results are in agreement with Liu and Kang (2007) for soil-set sprinkler and moving laterals. For G4, the results show that sp4 is more appropriate than sp3, which has low CU (Figure 6.7).

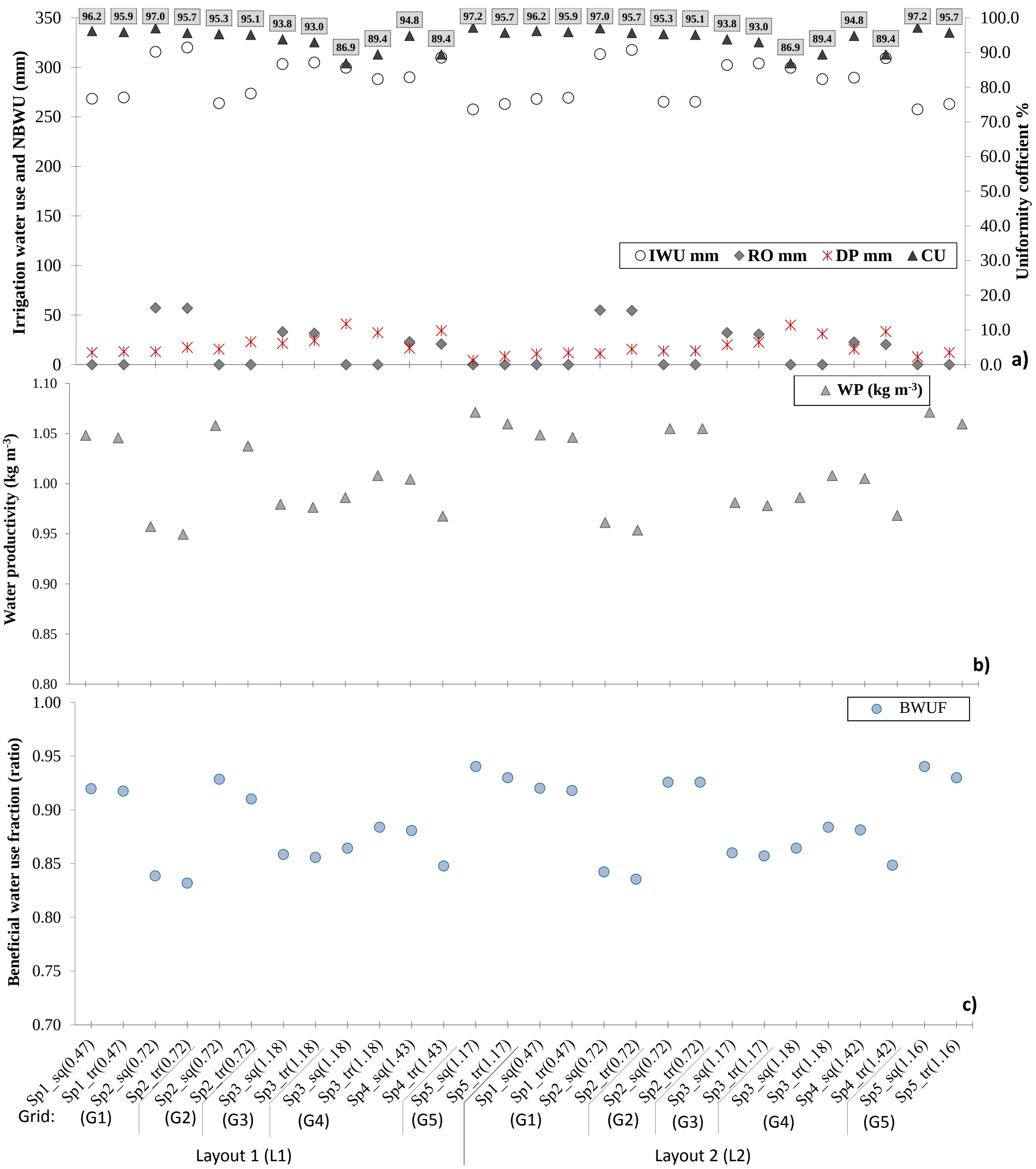


Figure 6. 7 Comparing sprinkler irrigation alternatives for: a) Irrigation water use, irrigation runoff and irrigation deep percolation, all in (mm), as well as the coefficient of uniformity, CU; b) water productivity (kg m^{-3}); and c) beneficial water use fraction. Alternatives refer to three systems types with two layouts, five spacing grids and five types of sprinkler (sp1 ..., sp5) for square (sq) and triangular (tr) distribution form (numbers in brackets refer to flow rates, m^3 h^{-1})

When assessing the economic results, Figure 6.8a shows that, the differences between the three system types are mainly due to the investment and variable costs. The highest investment costs was for solid-set system (S1), followed by the semi-permanent system (S2), with the portable hand-moved system (S3) being the lowest.

Results also show a higher investment cost for S1 than for S2 when sp2 is adopted mainly due to its higher price; however, this difference is smaller for cheaper sprinklers (sp3 and sp4). The cost of laterals (in PVC) in S3 includes the coupler price and it is higher than the laterals' cost for S1 and S2 (in PE_{hd}); thus, the FIC for S1 and S3 is similar when the number of laterals is minimized in S1, i.e. L1_G5. L2 presents a higher investment, varying from 250 to 540 € ha^{-1}, than L1 that ranges from 220 to 460 € ha^{-1}, mainly due to a higher number of sprinkler being required to adequately irrigate the same area. Concerning the distribution grids, the lowest FIC was obtained for the largest sprinkler and laterals spacing (G5) varying from 220 to 250 € ha^{-1}. Ortiz Romero et al. (2006) obtained similar results, reporting a more economical design when a large spacing (18 × 18 m) is adopted, but only if an appropriate application rate is implemented. Contrarily to FIC, the variable cost (VIC) was higher for S3 (ranging from 216 to 263 € ha^{-1}) since more labour and machinery operation are required (Figure 6.8b). The variation of VIC between layouts, sprinkler type and grids' spacing is highly related with IWU, i.e. low IWU leads to low VIC. Figure 6.9 presents a more detailed analysis of VIC including water, energy, labour and machinery operation cost, where S3 requires four times the operation cost when compared with S1 (29.6 and 119 € ha^{-1} for S1 and S3, respectively).

Figure 6.8c presents the results for EWPR, showing a higher value for L1, varying from 1.74 to 3.14, than for L2, ranging 1.55 – 2.91, with the combination G5_sp5 for both S1 and S2 leading to the highest EWPR (3.12). These results are in agreement with the ones proposed by Kahlown et al. (2007) for rain-gun sprinkler system. For smaller laterals spacing and higher sprinkler price, S3 appears as the best feasible economic solution in L2 for sp1 and sp2, and for the G1 and G2. EWPR is higher for L1 than for L2 and for G5 when sp5 is adopted. EWPR presents lower value for S1 than for S2 and S3 when sp2 is adopted. S3 appears to be feasible in L2 if the number of laterals is minimized, i.e. if G1 and G2 are adopted.

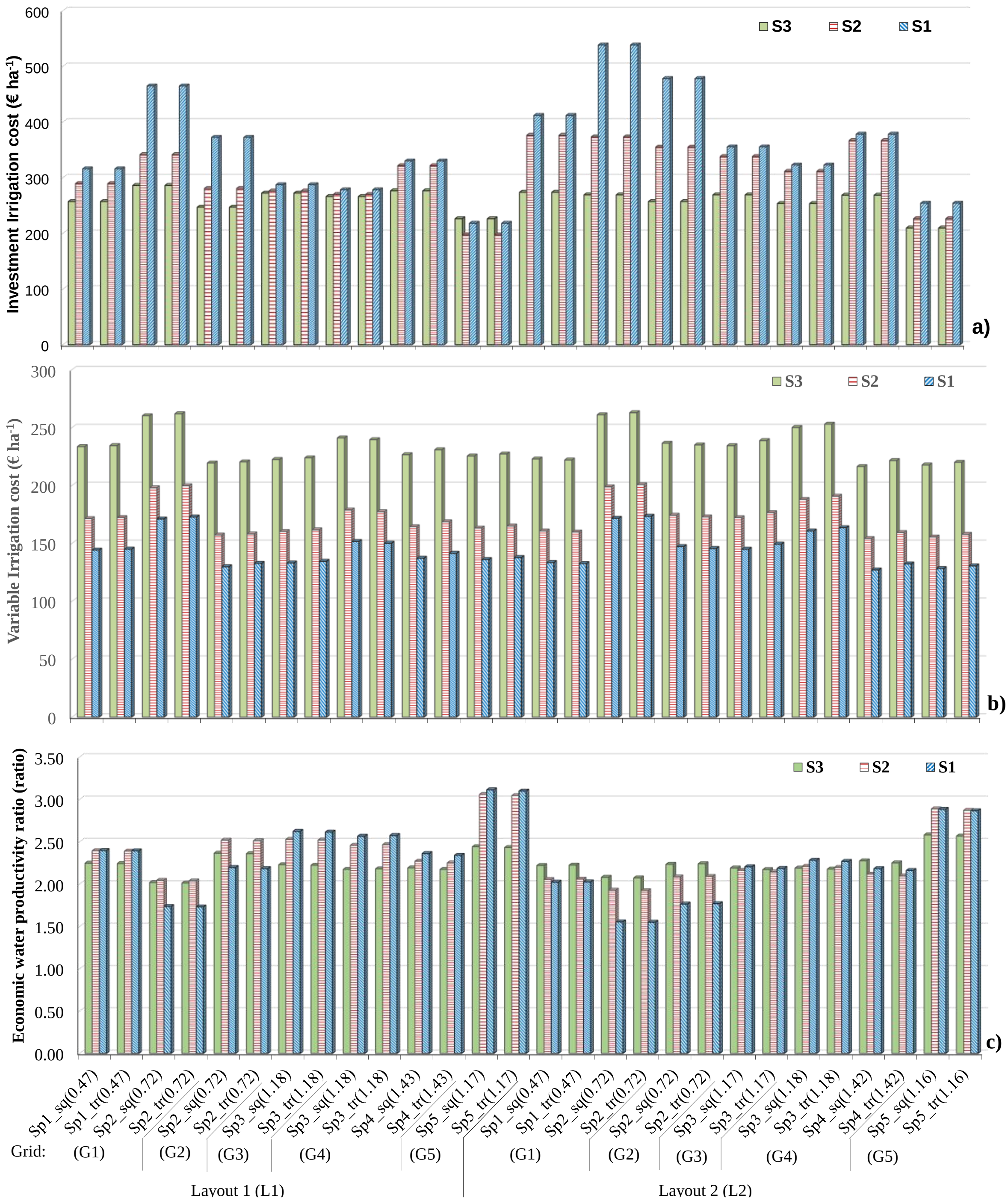


Figure 6. 8 Comparing sprinkler alternatives for: a) investment costs, b) variable costs (€ ha^{-1}) and c) economic water productivity ratio. Alternatives refer to three systems types with two layouts, five spacing grids and five types of sprinkler (sp1, ..., sp5) in square (sq) and triangular (tr) patterns (the numbers in brackets are flow rates, m^3 h^{-1})

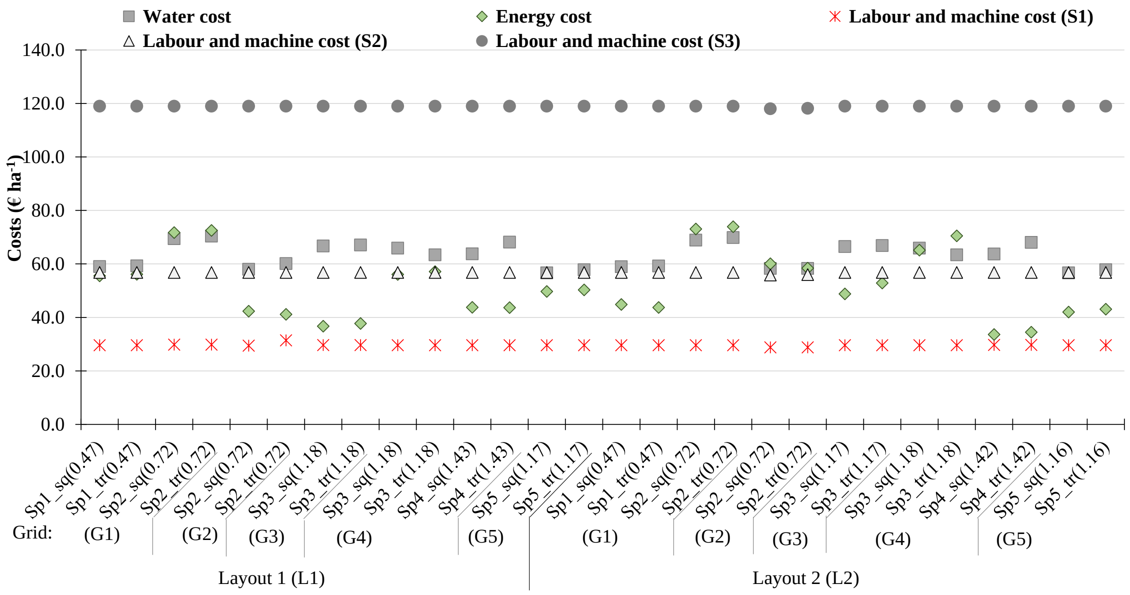


Figure 6. 9 Comparing sprinkler alternatives in terms of variable costs; water, energy, labour and machine cost (€ ha^{-1}). Alternatives refer to three systems types with two layouts, five spacing grids and five types of sprinkler (sp1, ..., sp5) in square (sq) and triangular (tr) patterns (the numbers in brackets are flow rates, m^3 h^{-1})

Figure 6.10 presents the global utility for both layouts, for all sprinkler's types and spacing, and for the three system types, in terms of economic results and water savings. Overall, results are similar for both L1 and L2. Combinations G1_sp1, G2_sp2 and G5_sp5 present the best water saving outcome, due to its irrigation performance. In terms of economic results, the best ranking is for the alternatives with larger spacing G5_sp5 for both S1 and S2. The global utility variation between S1 and S2 is higher with the sprinkler price increase, i.e. sp2, and S3 becomes the most feasible choice when G5 and L2 are adopted. The less feasible alternative is the combination of S1_G1_sp2 for both layouts.

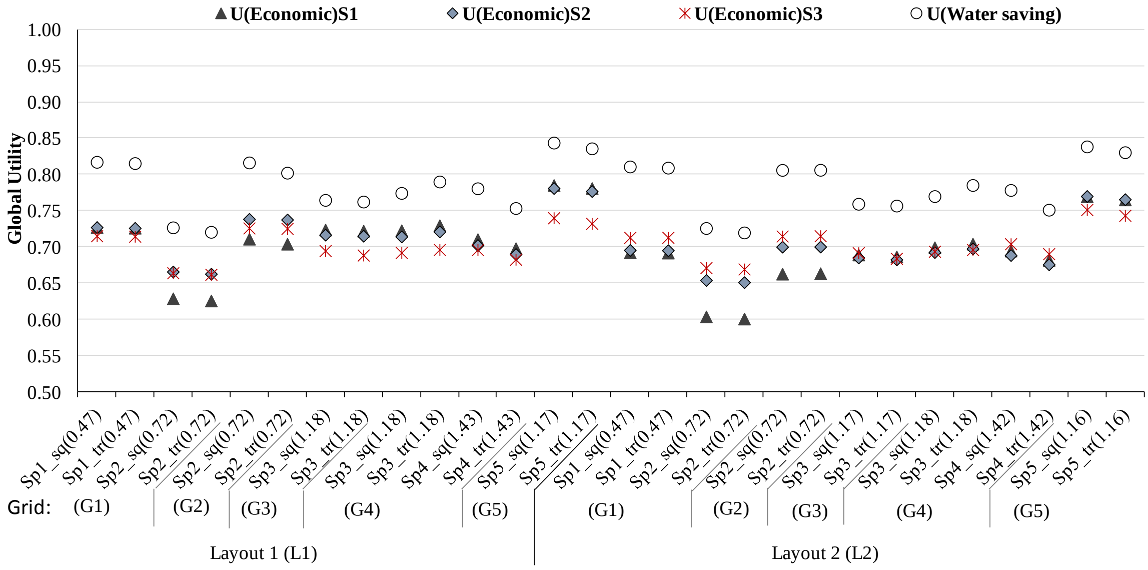


Figure 6. 10 Global utility value of sprinkler systems when the priority is assigned to water saving or to economic issues for three systems types. Alternatives refer to three systems types with two layouts, five spacing grids and five types of sprinkler (sp1, ..., sp5) in square (sq) and triangular (tr) patterns (the numbers in brackets are flow rates, $m^3\ h^{-1}$)

6.3.3. Comparing and ranking sprinkler and surface irrigation alternatives

The comparison among borders and sprinkler irrigation systems is accomplished by selecting a group of the best alternatives for both systems. When comparing IWU (Figure 6.11), the sprinkler alternatives led to seasonal irrigation depths varying from 257 to 269 mm, while surface irrigation leads to IWU ranging 352-387 mm and 386-428 mm for lasered and non-lasered land, respectively. Thus, sprinkler irrigation can lead to water savings varying from 26 to 37% when compared with surface irrigation, mainly due to its higher application efficiency. These results are in line with the ones proposed by Kahlown et al. (2007), who reported that irrigation requirements for sprinkler could be as low as 26% of the water used in basin irrigation. This low IWU leads to a WP of 1.10 kg m^{-3} for sprinkler irrigation, contrasting with a WP of 0.93 kg m^{-3} for border.

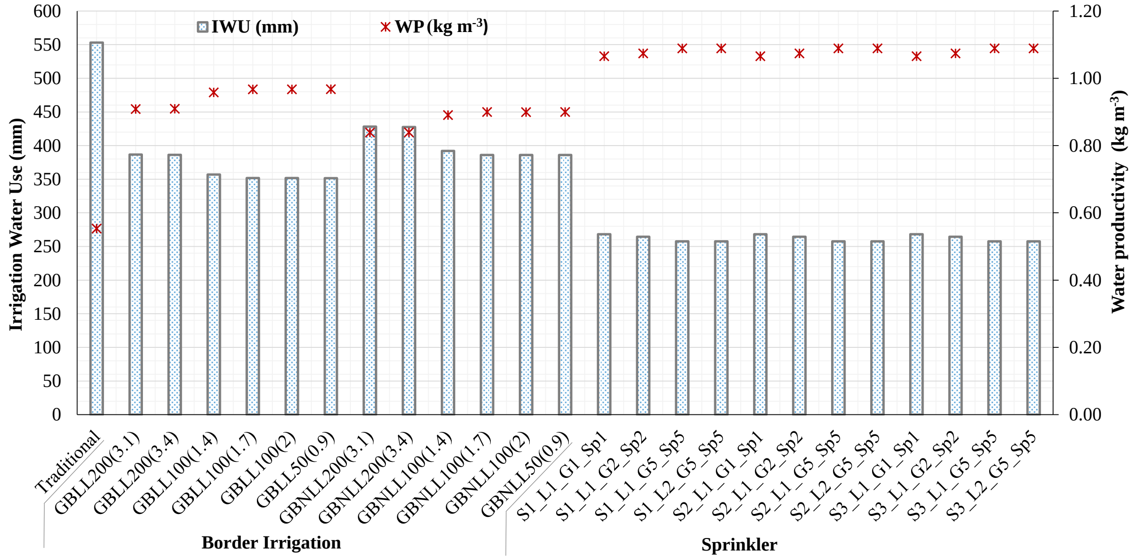


Figure 6. 11 Comparing irrigation water use, IWU and water productivity, WP for sprinkler of system types; solid-set permanent (S1), grid-pipe (S2) and hand-move (S3), two layouts and three distribution grids (G1, G2 and G5) for 2 sprinklers sp1, sp2 and sp5 and borders irrigation 200, 100 and 50 m length, lasered and non-lasered land (LL and NLL) and various inflow rate (l s^{-1} m^{-1}) and traditional and non-irrigated crop

Figure 6.12 presents a comparison between the FIC, VIC and EWPR of both irrigation systems. Results show that the sprinkler systems require higher FIC (varying from 200 to 370 € ha^{-1}) than surface irrigation (ranging 34 to 74 € ha^{-1}). VIC presents a contrasting behaviour with sprinkler irrigation showing higher economic feasibility than surface irrigation, especially for the lasered land alternatives. Concerning the sprinkler alternatives, S1 presents the highest investment cost with G5 presenting the lowest of all system types. The best alternatives of sprinkler are for S1, which can operate with lower VIC than that required for border. Higher EWPR (4.15) can be obtained for non-lasered land borders irrigation, while best ratio for sprinkler irrigation (3.14) can be attained for the combination S1_L1_G5_sp5. Both hand-moved sprinkler system (S3) and lasered land surface irrigation alternatives present similar EWPR due to high operation demand. However, the economic advantages of sprinkler systems include higher gross income since it is designed by minimizing the piping cost. This in agreement with Trout et al. (1994).

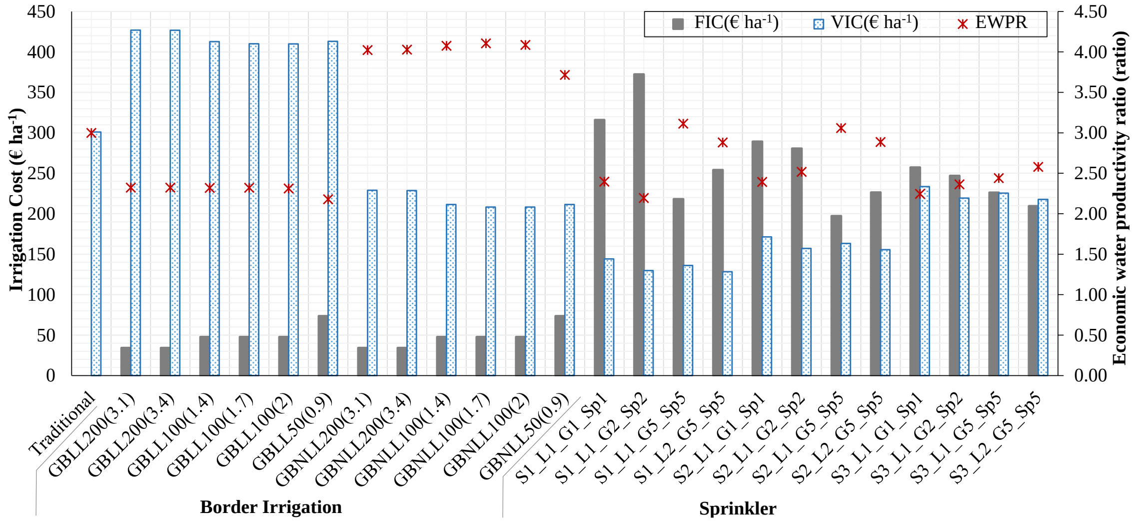


Figure 6. 12 Comparing fixed irrigation costs, FIC, variable irrigation costs, VIC and EWPR for sprinkler solid-set (S1), grid-pipe (S2) and hand-move (S3) systems for two layouts and three distribution grids (G1, G2 and G5) for sprinklers sp1, sp2 and sp5 and for lasered and non-lasered (LL and NLL) borders with 200, 100 and 50 m length and various inflow rates ($l\ s^{-1}\ m^{-1}$) and traditional and non-irrigated crop

When analysing the global utility of all alternatives (Figure 6.13), if the priority is given to the economic results, sprinkler irrigation shows a slight advantage when compared with the surface irrigation alternatives. Results support the adoption of sprinkler irrigation, especially if a large spacing between laterals is adopted, over surface irrigation. This is in agreement with the results presented by Kahlown et al. (2007). El Amami et al. (2001) concluded that the gross margins associated with sprinkler irrigation are higher than those relative to surface irrigation, because labour costs are higher for surface irrigation, being is in line with the present study. Furthermore, the water saving priority scenario strongly differentiate the utility of the two irrigation methods, prevailing the sprinkler over the borders systems. Albaji et al. (2010) presented similar results, concluding that significant water savings can be achieved when adopting sprinkler irrigation, being the recommended method over surface irrigation for a semi-arid area.

Following the results analysed above, different sprinkler and surface irrigation alternatives were ranked assuming various prioritization schemes, W1 to W5, with W1 being assigned with 90% of weights for economic results and water savings with only 10% (see Table 6.11); W5 presents the opposite where only 10% of weights were assigned to economic results and 90% to water saving. Results in Table 6.12 shows that sprinkler irrigation is dominantly selected for most weight scenarios, with surface system of non-lasered land and with 100 m length borders appearing in first and fifths ranking order for

W1 and W2, respectively. The laser-levelled alternatives only appear on the last quarter for W4 and W5. Similar results by Mailhol et al. (2004) recommended sprinkler as solution over surface from an economic perspective.

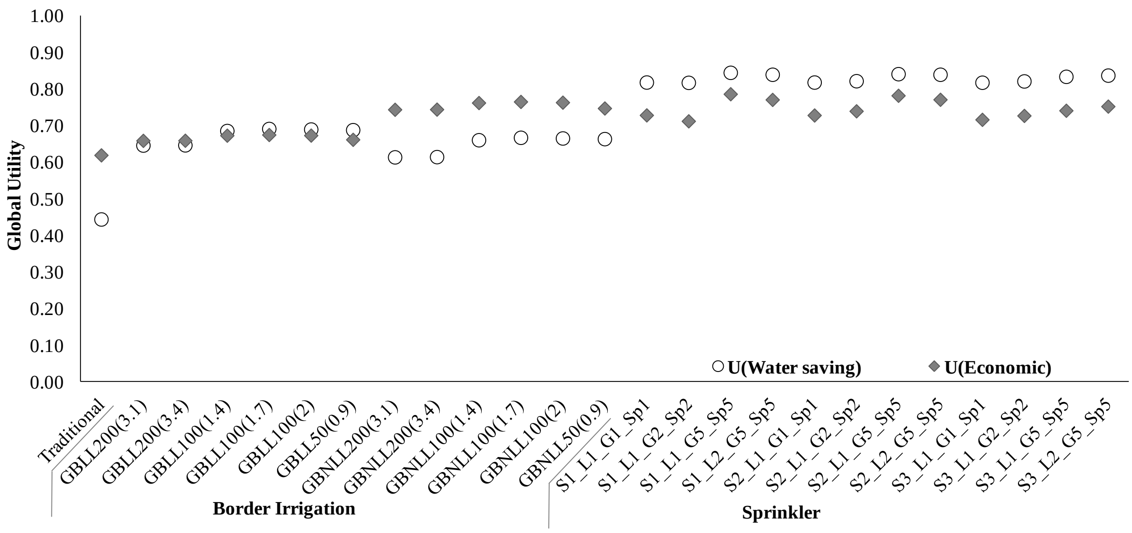


Figure 6. 13 Global utilities for sprinkler solid-set (S1), grid-pipe (S2) and hand-move sysrems (S3), two layouts, three distribution grids (G1, G2 and G5) and 3 sprinklers sp1, sp2 and sp5 which are compared with lasered and non-lasered (LL and NLL) borders with 200, 100 and 50 m length and various inflow rate (l s^{-1} m^{-1}) and traditional and non-irrigated crop

Table 6. 12 Ranking of the alternative solutions for various weighing scenarios W1 (highest weights to economic results) through W5 (highest weights to water savings) when full irrigation is adopted, the sprinkler *vs.* graded borders alternatives

	Weighing scenarios (progressively decreasing weights to economic issues and increasing weights to water saving)				
	W1 (10-90)	**W2 (30-70)**	**W3 (50-50)**	**W4 (70-30)**	**W5 (90-10)**
1	GB_{NLL}100(1.7)	S1_L1_G5_Sp5	S1_L1_G5_Sp5	S1_L1_G5_Sp5	S1_L2_G5_Sp5
2	GB_{NLL}100(2.0)	S2_L1_G5_Sp5	S2_L1_G5_Sp5	S1_L2_G5_Sp5	S2_L2_G5_Sp5
3	GB_{NLL}100(1.4)	S1_L2_G5_Sp5	S1_L2_G5_Sp5	S2_L2_G5_Sp5	S1_L1_G5_Sp5
4	S1_L1_G5_Sp5	S2_L2_G5_Sp5	S2_L2_G5_Sp5	S2_L1_G5_Sp5	S2_L1_G5_Sp5
5	S2_L1_G5_Sp5	GB_{NLL}100(1.7)	S2_L1_G2_Sp2	S2_L1_G2_Sp2	S2_L1_G2_Sp2
6	GB_{NLL}200(3.4)	GB_{NLL}100(2.0)	S1_L1_G1_Sp1	S1_L1_G1_Sp1	S1_L1_G2_Sp2
7	GB_{NLL}200(3.1)	GB_{NLL}100(1.4)	S2_L1_G1_Sp1	S2_L1_G1_Sp1	S1_L1_G1_Sp1
8	S1_L2_G5_Sp5	S2_L1_G2_Sp2	S1_L1_G2_Sp2	S1_L1_G2_Sp2	S2_L1_G1_Sp1
9	S2_L2_G5_Sp5	GB_{NLL}50(0.9)	S2_L2_G2_Sp2	S2_L2_G2_Sp2	S2_L2_G2_Sp2
10	GB_{NLL}50(0.9)	S1_L1_G1_Sp1	S2_L2_G1_Sp1	S2_L2_G1_Sp1	S2_L2_G1_Sp1
11	S2_L1_G2_Sp2	S2_L1_G1_Sp1	S1_L2_G1_Sp1	S1_L2_G1_Sp1	S1_L2_G1_Sp1
12	S1_L1_G1_Sp1	GB_{NLL}200(3.4)	S1_L2_G2_Sp2	S1_L2_G2_Sp2	S1_L2_G2_Sp2
13	S2_L1_G1_Sp1	GB_{NLL}200(3.1)	GB_{NLL}100(2.0)	GB_{LL}100(1.7)	GB_{LL}100(1.7)
14	S1_L1_G2_Sp2	S1_L1_G2_Sp2	GB_{NLL}100(1.7)	GB_{LL}100(2.0)	GB_{LL}100(2.0)
15	S2_L2_G2_Sp2	S2_L2_G2_Sp2	GB_{NLL}100(1.4)	GB_{NLL}100(2)	GB_{LL}50(0.9)
16	S2_L2_G1_Sp1	S2_L2_G1_Sp1	GB_{NLL}50(0.9)	GB_{NLL}100(1.7)	GB_{LL}100(1.4)

6.3.4. Deficit irrigation impact on alternatives selection

A comparison between the 24 selected sprinkler and surface irrigation alternatives when adopting deficit irrigation (for $\theta_{MAD} = 70\%\theta_p$) was performed considering a total irrigation depth 180 mm, i.e., a reduction of 25% relative to full irrigation (240 mm) (Table 6.1). This decrease in water availability influences the actual evapotranspiration as calculated by ISAREG and yield based on yield-water function (see Table 6.2). Nevertheless, the reduction in TWU was of 12 and 14% with corresponding yield reduction of 10 and 12% for graded borders and sprinkler, respectively. The variation of the reduction of TWU relies on different effective precipitation amounts (see Table 6.1). Small differences in yield are noticed between sprinkler and borders systems where it was negligible for deficit irrigation scenario (Table 6.13) this in close to results concluded by Lv et al. (2011). For better understand these results, some indicators relative to main six alternatives were selected, and compared in Table 6.13 for both full and deficit irrigation. Results show that graded furrows with a length of 100 m with inflow rate of 1.4 and 2.0 l s^{-1}, and the sprinkler system combination S1/S2, G5 and sp5 are able to produce less non-beneficial water use and thus have better EWP and EWPR for full irrigation than for the alternatives of deficit irrigation. It can be concluded that alternatives, which are more able to produce water saving are not the best ranked for deficit irrigation neither responding for farm economics criteria where EWPR is lower in deficit irrigation alternatives due to high yield reduction.

Table 6. 13 Comparing indicators relative to main alternatives for full and deficit irrigation

		TWU (mm)	Yield (kg ha^{-1})	BWUF (ratio)	WP (kg m^{-3})	EWP (€ m^{-3})	EWPR (ratio)
	Full irrigation						
Graded border	GB_{NLL}100(1.4)	591.0	5089	0.74	0.86	0.18	4.12
	GB_{NLL}100(1.7)	585.0	5063	0.75	0.87	0.18	4.15
	GB_{NLL}100(2.0)	585.1	5042	0.75	0.86	0.18	4.14
Sprinkler	S1_L1_G5_Sp5	478.6	5248	0.94	1.10	0.23	3.14
	S2_L1_G5_Sp5	478.6	5248	0.94	1.10	0.23	3.08
	S2_L2_G5_Sp5	478.6	5248	0.93	1.10	0.23	2.90
	Deficit irrigation						
Graded border	GB_{NLL}100(1.4)	523.0	4584	0.78	0.88	0.18	4.05
	GB_{NLL}100(1.7)	518.5	4564	0.79	0.88	0.18	4.09
	GB_{NLL}100(2.0)	518.6	4548	0.79	0.88	0.18	4.07
Sprinkler	S1_L1_G5_Sp5	422.2	4610	0.97	1.09	0.23	3.09
	S2_L1_G5_Sp5	422.2	4610	0.97	1.09	0.23	3.08
	S2_L2_G5_Sp5	422.2	4610	0.97	1.09	0.23	2.77

Moreover, by analysing the ranking for all alternatives for several weight scenarios from W1 to W5, Table 6.14 shows only a small difference occurs in the alternatives' ranking when deficit irrigation is adopted. The graded borders of non-lasered land with a length of 100 m shows to be the most feasible solution for the economic priorities W1 and W2. Additionally, the graded borders of lasered-land shows less advantage than sprinkler associated with water saving perspectives and appearing just in the last quarter of ranking order in W5. The very slight advantage is given to graded borders in W1, and W2 over sprinkler when compared with Table 6.12. On the other hand, the deficit irrigated sprinkler alternatives show better results for S2 than S1 when compared with the full irrigation scenarios, due to small variation in IWU when DI is adopted. The sprinkler alternatives could be a good economic solution when the yield is maximised.

Table 6. 14 Ranking of the alternative solutions for various weighing scenarios W1 (highest weights to economic results) through W5 (highest weights to water savings) when deficit irrigation is adopted for sprinkler *vs.* graded borders alternatives

	Weighing scenarios (progressively decreasing weights to economic issues and increasing weights to water saving)				
	W1 (10-90)	**W2 (30-70)**	**W3 (50-50)**	**W4 (70-30)**	**W5 (90-10)**
1	GB_{NLL}100(1.7)	S2_L1_G5_Sp5	S2_L1_G5_Sp5	S2_L1_G5_Sp5	S2_L1_G5_Sp5
2	GB_{NLL}100(2)	S1_L1_G5_Sp5	S1_L1_G5_Sp5	S1_L1_G5_Sp5	S1_L1_G5_Sp5
3	GB_{NLL}100(1.4)	S2_L2_G5_Sp5	S2_L2_G5_Sp5	S2_L2_G5_Sp5	S2_L2_G5_Sp5
4	S2_L1_G5_Sp5	GB_{NLL}100(1.7)	S1_L2_G5_Sp5	S1_L2_G5_Sp5	S1_L2_G5_Sp5
5	S1_L1_G5_Sp5	GB_{NLL}100(2)	S2_L1_G2_Sp2	S2_L1_G2_Sp2	S2_L1_G2_Sp2
6	GB_{NLL}200(3.4)	GB_{NLL}100(1.4)	S2_L1_G1_Sp1	S2_L1_G1_Sp1	S2_L2_G2_Sp2
7	GB_{NLL}200(3.1)	S1_L2_G5_Sp5	S1_L1_G1_Sp1	S1_L1_G1_Sp1	S1_L2_G1_Sp1
8	GB_{NLL}50(0.9)	GB_{NLL}200(3.4)	S1_L1_G2_Sp2	S1_L1_G2_Sp2	S1_L1_G2_Sp2
9	S2_L2_G5_Sp5	GB_{NLL}50(0.9)	S2_L2_G2_Sp2	S2_L2_G2_Sp2	S2_L1_G1_Sp1
10	S1_L2_G5_Sp5	GB_{NLL}200(3.1)	S1_L2_G1_Sp1	S1_L2_G1_Sp1	S1_L1_G1_Sp1
11	S2_L1_G2_Sp2	S2_L1_G2_Sp2	S2_L2_G1_Sp1	S2_L2_G1_Sp1	S2_L2_G1_Sp1
12	S2_L1_G1_Sp1	S2_L1_G1_Sp1	GB_{NLL}100(2)	S1_L2_G2_Sp2	S1_L2_G2_Sp2
13	S1_L1_G1_Sp1	S1_L1_G1_Sp1	GB_{NLL}100(1.7)	GB_{NLL}100(1.7)	GB_{LL}100(1.7)
14	S1_L1_G2_Sp2	S1_L1_G2_Sp2	S1_L2_G2_Sp2	GB_{NLL}100(2)	GB_{LL}100(2)
15	S2_L2_G2_Sp2	S2_L2_G2_Sp2	GB_{NLL}100(1.4)	GB_{NLL}100(1.4)	GB_{LL}50(0.9)
16	S1_L2_G1_Sp1	S1_L2_G1_Sp1	GB_{NLL}50(0.9)	GB_{LL}100(1.7)	GB_{LL}100(1.4)

6.4. Conclusion

Multicriteria analysis modules were applied for both graded borders (lasered land and non-lasered land) and sprinkler (solid-set, gridded-pipe and hand-moved) systems, considering different alternatives for both methods, when irrigating wheat in Northeast of Syria. The adoption of MCA modules aims to create improved alternatives to cope with water scarcity when considering different priorities – economic results and water saving. Two different models - SADREG and PROASPER - were used in order to create and rank a large set of alternatives. The results of graded borders indicate that, the alternatives of non-lasered land are more appropriate when the priority is given to economic results; contrarily, when the priority is given to water savings, the lasered land scenarios were better ranked. When ranking the sprinkler alternatives, designed to optimize the irrigation performance, the costs are minimized when adoption alternative G5. The solid-set and gridded-pipe systems prevail as the best economic alternatives mainly since the labour was minimized; these alternatives also lead to a high water productivity, reaching 1.10 kg m^{-3}, and a high economic water productivity ratio as high as 3.14.

The comparison between surface and sprinkler systems shows that, the sprinkler irrigation alternatives led to higher irrigation uniformity than surface systems. Additionally, the sprinkler alternatives dominate the ranking when priority is given to both water savings; if the priority is given to economic results, the borders alternatives with of non-lasered land becomes feasible, appearing in the top of the ranking. The labour required for moving the laterals, maintenance and operation of portable systems make these alternatives similar to borders systems with non-lasered land from an economic perspective. Thus, borders irrigation alternatives becomes unfeasible for both water saving and economic results priorities mainly due to the high cost required for maintenance.

When deficit irrigation is adopted, a yield reduction of 12% may occur, leading to a slight change in the analysed alternatives ranking, with sprinkler irrigation being predominant when assigning the priority to water savings. The graded borders of non-lasered land alternatives appear as a more feasible solution from an economic perspective for both full and deficit irrigation scenario. For sprinkler types, the gridded-pipe - semi-permanent – shows better or equal alternative to solid-set systems, due to very low different in farmer’s income.

Over all the results, applying MCA for on-farm application scale shows as a useful tool in the study area, to help user to select the adequate irrigation methods based on the user’s preference. It was founded that sprinkler for wheat is high recommended when the layout investment cost is minimized and the high operation cost for graded borders and portable sprinkler type limited their application. This issue should consider the effect of farm size, which might favours higher initial investment on sprinkler irrigation

Chapter 7

Comparing border, drip and sprinkler irrigation for cotton with multicriteria analysis

7.1. Introduction

The objective of this Chapter is to compare the three types of irrigation systems - border, drip and sprinkler irrigation - that are feasible for cotton in NE of Syria, considering design and management features. In Chapter 4 several surface irrigation systems were compared and best results were assumed for graded borders. In Chapter 5, surface and drip irrigation were compared and results have shown that the option depends upon the prioritization scheme, with MCA selecting surface irrigation alternatives if farm economics alternatives are prioritized, or drip systems if water saving is the first objective. In Chapter 6, surface and sprinkler systems were compared for wheat, with ranking first surface irrigation when prioritizing economic results and sprinkler for water saving. The use of sprinkler irrigation alternatives is now considered, allowing a complete evaluation of cotton irrigation.

The design of surface systems was achieved using model SADREG, described in Chapter 4, that of drip systems was performed with MIRRIG (Chapter 5) and that of set sprinkler systems was developed with the PROASPER model, (explained in Chapter 6). The systems designed in Chapters 4 and 5 are considered herein. For sprinkler irrigation, PROASPER considers three system types - solid-set (S1), semi-permanent (S2) and portable hand-move (S3), with two layout types (L1 and L2) and five sprinkler grid patterns with square and triangular positioning of sprinklers. The investment cost of the main equipments, and the operative input data are described in Chapter 6.

The comparison of the full set of alternatives was based on MCA methodology, explained in Sub-Chapter 2.3 and applied in Chapters 4 to 6. The selection and ranking of alternatives aimed at two main groups of objectives: 1) water saving, through reducing total irrigation water use and non-beneficial water uses, and increasing the beneficial water use fraction and the irrigation water productivity; and 2) farm economic results, including the improvement of economic land productivity, economic water productivity, economic water productivity ratio and controlling fixed and variable irrigation costs. The attributes were handled through appropriate linear utility functions, and the Linear Weighted Summation method was used to aggregate the multiple criteria.

The main aspect of the irrigation management refers to full irrigation (FI) and deficit irrigation (DI) as summarized in Table 7.1. The duality between these options was analysed in previous Chapters for drip and surface systems. The comparison of these systems with sprinkler alternatives introduces a wider view of this decision problem. Sprinkler irrigation should not be applied in the final phase of the crop, after the boll opening, to avoid a drop of the yield quality and crop diseases (Burke, 2003; Bange et al., 2010). For this reason, the FI strategy is not feasible with sprinkler systems (Sadiddin and Atiya, 2009; Jalota et al., 2006) and the DI strategy refers to cut-off irrigation at boll opening. It implies that the comparison of these three irrigation systems should consider together the aspects of the irrigation management and design. The irrigation scheduling data is presented in Table 7.1.

Table 7. 1 Cotton irrigation scheduling considering the irrigation method and full (FI) and deficit (DI) irrigation.

Irrigation methods	Irrigation strategies	Number of irrigation events	Net irrigation depth per event (mm)	ET_a (mm)	Effective rainfall (mm)
Traditional	FI	10	80-110	881	7.8
Surface	FI	10	80	886	7.8
Drip	FI	50	16	890	7.8
Sprinkler	DI(a)	19	30	647	7.8
Surface	DI(b)	8	80	752	7.8
Drip	DI(b)	40	16	725	7.8

(a) The deficit irrigation starts after boll opening
(b) The deficit irrigation applied for $\theta_{MAD} = 70\%\theta_p$ through the growing stages

7.2. Results and discussion

7.2.1. Performance indicators

The performance indicators of water use – total water use (TWU), beneficial water use fraction (BWUF) and the non-beneficial water use components runoff (RO) and deep percolation (DP) - of the selected alternatives relative to all irrigation methods, for both FI and DI management strategies, are presented in Figure 7.1. The TWU indicator shows the effectiveness of the modern systems with FI and its resulting improvement in comparison to the traditional practices. On the other hand, surface irrigation requires a higher water use depth when compared with drip and sprinkler irrigation. RO is particularly high in the surface systems, though, its reuse would significantly improve their performance. The set of DI alternatives shows, as expected, a significant decrease of TWU when compared with FI (FI values c.a. 900 mm for drip and 1200-1300 mm for surface, and DI values ranging 700-750 mm to drip and sprinkler and 1100 mm for surface). Note that the DI management is specific to the irrigation method. Moreover, for drip and surface systems, the irrigation timing is through the crop phenological stages at soil moisture $\theta_{MAD} = 70\%\theta_p$, and for sprinkler, the cancel of irrigation season is after the boll opening. The surface systems BWUF shows a high increase from traditional to improved surface systems with FI and from this to the DI. The BWUF for pressurized systems varies between 0.90-0.95 for sprinkler and 0.92-0.98 for drip. In practice, the BWUF can be lower for drip systems if the quality of drip equipment is not very good and for sprinkler if the irrigation is done during the periods of strong wind.

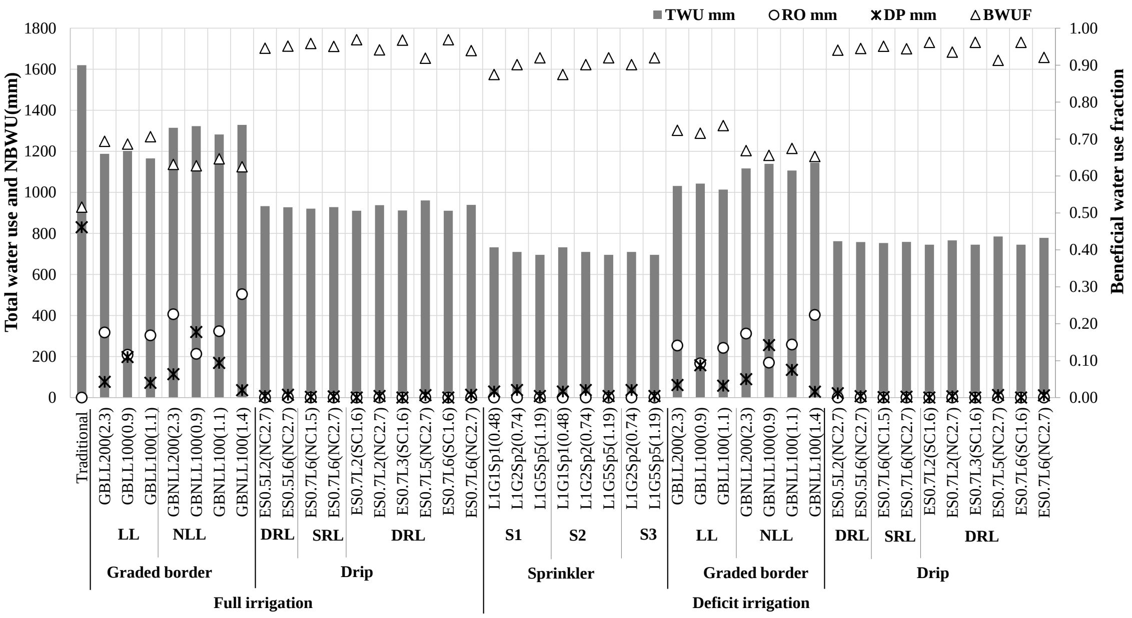


Figure 7. 1 Total water use, TWU, irrigation deep percolation, DP and irrigation runoff, RO, and beneficial water use fraction, BWUF, for selected FI and DI alternatives of cotton irrigation (the inflow rate in parentheses for graded borders is in l s^{-1} m^{-1}, for sprinkler is in m^3 h^{-1} and for drip is in l h^{-1}).

The impact of water use on yield evidences the duality between FI and DI. The yield is very close to maximum for FI, 5000 kg ha^{-1}, while for DI lower values are expected, varying between 4000 to 4250 kg ha^{-1}, thus with a yield decrease of 14-20%. The sprinkler systems allow a land productivity similar to DI strategies of drip and surface ones, although with a slightly more severe water deficit of the sprinkler systems (Figure 7.2).

The EWP of pressurized systems (0.45-0.50 € m^{-3}) are significantly higher than that for surface irrigation (0.28-0.33 € m^{-3}). On the other hand, the management strategy (FI vs.

DI) has no significant effect on EWP. This result has high practical relevance because it demonstrates that DI has high potential to cope with water scarcity in NE Syria. Its effectiveness will however depend on the feasibility of the water supply and distribution system to guarantee the appropriate irrigation scheduling plan. Therefore, the possibilities to select the sprinkler system are associated with the potential of DI, beyond the strong compatibility of this system with wheat irrigation, on field rotation.

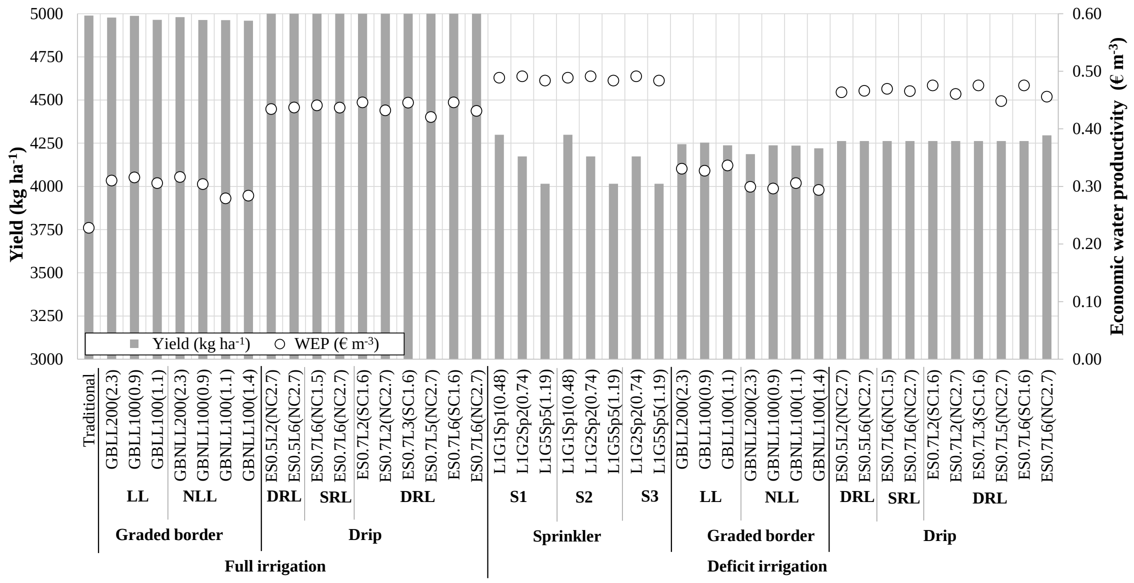


Figure 7. 2 Yield and economic water productivity, EWP, for selected FI and DI alternatives of cotton irrigation (the inflow rate in parentheses for graded borders is in l s^{-1} m^{-1}, for sprinkler is in m^3 h^{-1} and for drip is in l h^{-1}).

The economic indicators of the selected alternatives are summarised in Figures 7.3 and 7.4. Considering the investment cost, drip systems have a higher value than surface and sprinkler. This high fixed cost explains a very low EWPR, ranging from 1.4 to 2.3, which evidences that drip irrigation requires a good funding capacity of the farmers to support the investments and to accept the associated financial risk. Conversely, the variable costs have no significant variation when comparing among all the systems. The land levelling maintenance makes that, the corresponding surface systems have a higher cost value (Figure 7.4). Concerning the labour costs, the drip systems have a reduced value (about 40 € ha^{-1}) when compared with the surface and sprinkler (160-240 € ha^{-1}).

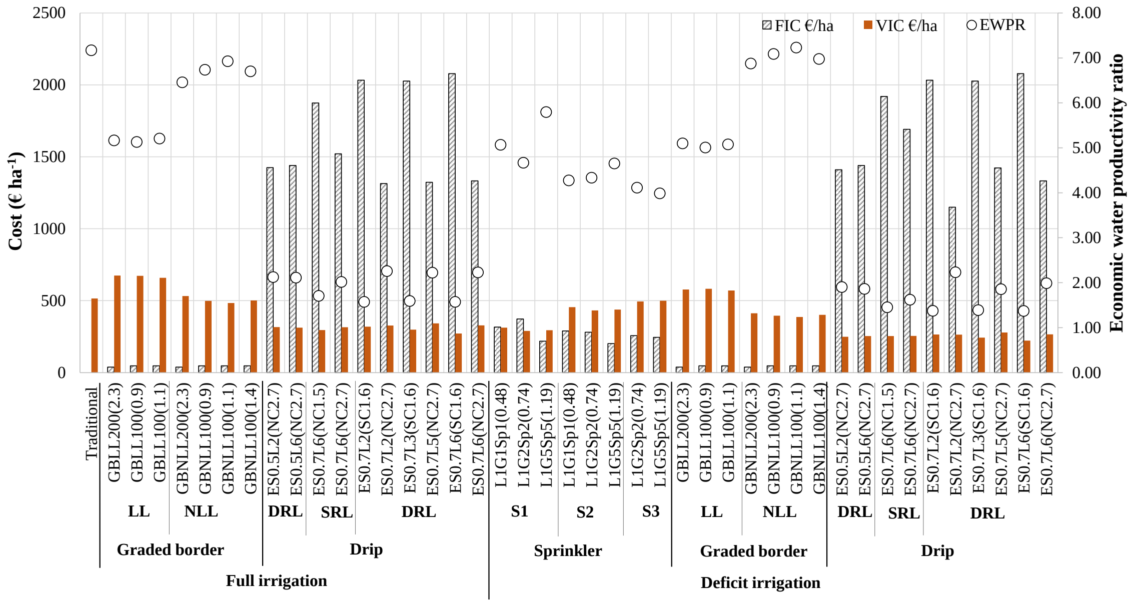


Figure 7. 3 Investment cost, FIC (■), variable cost, VIC (▨) and economic water productivity ratio, EWPR (○), for selected FI and DI alternatives of cotton irrigation (the inflow rate in parentheses for graded borders is in l s^{-1} m^{-1}, for sprinkler is in m^{3} hr^{-1} and for drip is in l h^{-1}).

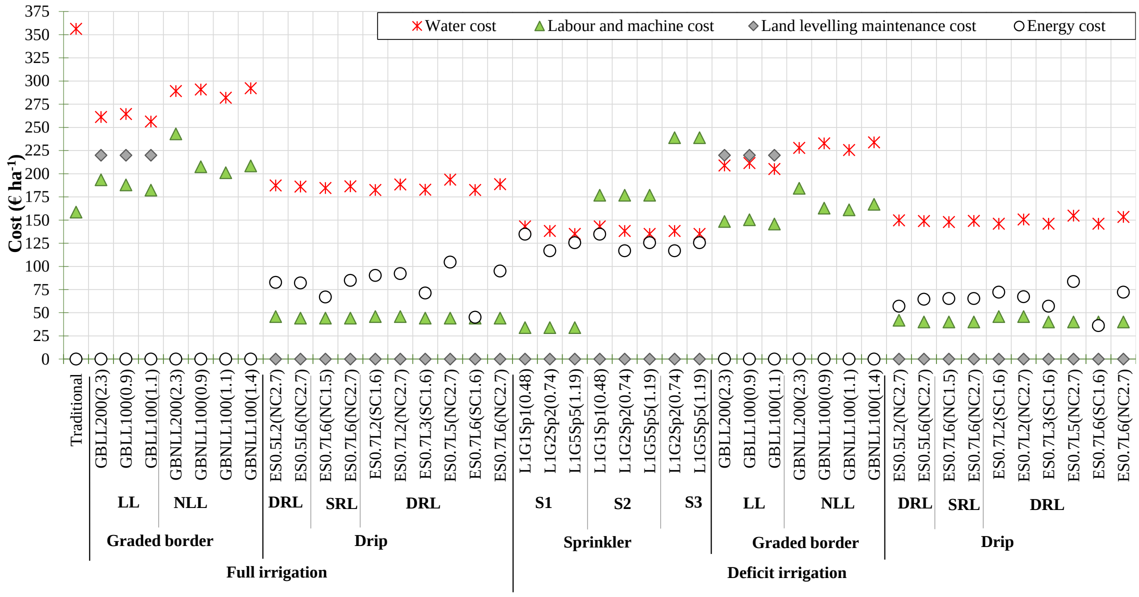


Figure 7. 4 Variable cost components, water, land levelling maintenance, energy and labour and machine for, for selected FI and DI alternatives of cotton irrigation (the inflow rate in parentheses for graded borders is in l s^{-1} m^{-1}, for sprinkler is in m^{3} hr^{-1} and for drip is in l h^{-1}).

The water cost follows the TWU values. It should be noted that usually in NE Syria the water has not a cost per unit of volume, being the cost calculated by a fixed rate related with the field area and the pumping cost. This practice might favour higher water consumption, but the trend is to calculate the water cost based on the volume of irrigation water used.

7.2.2. Multicriteria analysis

The global utilities of the selected alternatives according to the assessed economic and water saving priority scenarios are synthesized in Figure 7.5. Assuming the economic priority, the selected solutions are the sprinkler systems (with a utility of about 0.83-0.85), very close with surface NLL, both with FI and DI (0.80-0.82), followed by surface LL (0.78), and finally the drip systems (0.68-0.74). The main fragility about these results is the lack of flexibility of the sprinkler systems for cotton irrigation because it implies a DI management. This option lose preference if the price of cotton increases, or if the cost of water decreases (Shweih, 2006). However, on the other hand, the sprinkler system can be used without constraints in wheat irrigation.

Considering the water saving priority, the pressurized systems are highly ranked, with spotlight for sprinkler (0.90-0.93), followed by drip DI (0.88-0.90) and drip FI (0.86-0.88). The surface systems are the less preferred for water saving, having utilities of 0.65-0.73 for DI and 0.60-0.65 for FI. It is clear that drip systems are more flexible, allowing FI or DI.

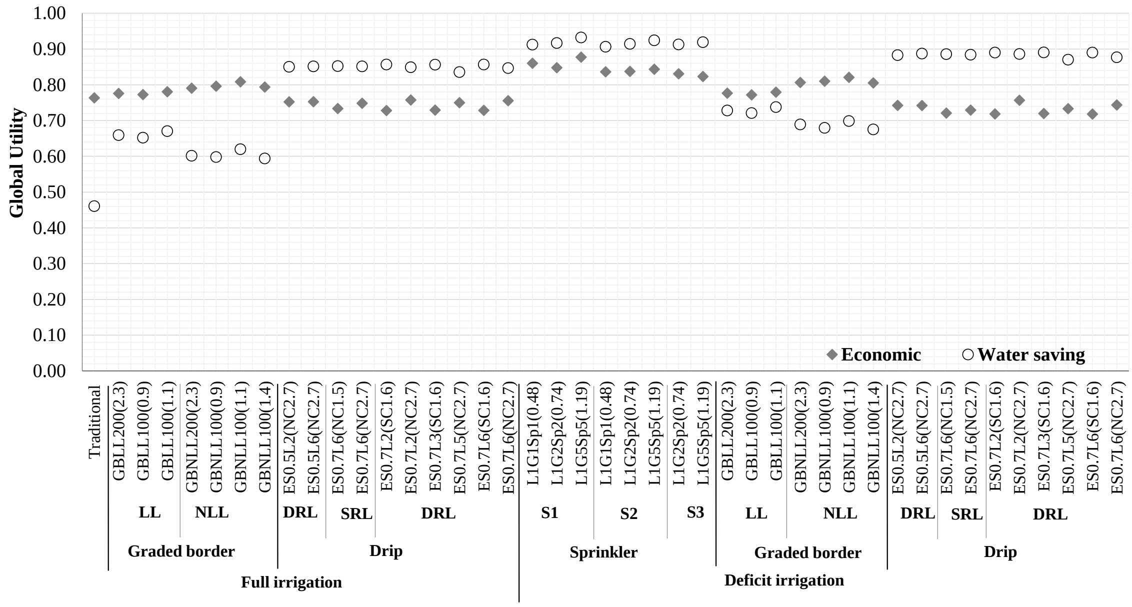


Figure 7. 5 Global utility value when the priority is assigned to water saving and to economic issues, for selected FI and DI alternatives of cotton irrigation (the inflow rate in parentheses for graded border is in l s^{-1} m^{-1}, for sprinkler is in m^3 h^{-1} and for drip is in l h^{-1}).

7.3. Conclusion

To bring competitiveness and sustainability to the cotton crop it is required knowledge on the locally available resources, the characteristics of irrigation methods and the farmers' preferences. The balance between environmental and economic impacts turns the irrigation system selection a complex decision problem, beyond the uncertainty of prices and water resources available for farmer irrigation. This study proved that surface, sprinkler, and drip systems are, in general, feasible solutions for cotton. However, using the MCA for supporting decision-making it results that the alternative selected is sensitive to the farmer priorities.

For small farmers, usually conditioned by economic priorities, the full-irrigated surface systems, LL or NLL are advisable solutions. However, if DI is economically accepted, the set sprinkler systems are a good alternative. For farmers with financial ability to make higher investments, the drip irrigation allows an acceptable compromise between economics and water saving, and a good flexibility between FI and DI. On the other hand, if the priority is for water saving, the best solutions are the sprinkler and the drip with DI or FI. However, a special attention should be taken on the quality of irrigation equipment, particularly with drip irrigation, because it affects significantly the irrigation performance.

This study also concluded that DI is very relevant when selecting a system given its potential to deal with water scarcity scenarios. The sprinkler systems only manage a DI strategy, with a yield decrease of about 14-20%, but its performance may be satisfactory. This capability is also feasible with the graded borders method, being the NLL option an advisable solution if economics becomes more relevant than the water-saving priority. However, the DI effectiveness depends on the feasibility of the water supply and distribution system to guarantee the appropriate irrigation-scheduling plan. Therefore, the possibilities to select the sprinkler system are associated with the potential of the DI, beyond the strong compatibility of this system with wheat irrigation on field rotation.

Chapter 8

Conclusions

MCA modules were applied for irrigation methods for wheat and cotton in a water scarcity area, Ras-Al-Ein, NE Syria. The study allowed comparing between sprinkler and graded borders for wheat and between drip, sprinkler, graded borders and graded furrows for cotton for full and deficit irrigation. One MCA method is used based on calculation of global utility for several of criteria's attributes using "Linear Weighted Sum" method to outrank the alternatives. Applying MCA aims to improve irrigation management and to overcome the water scarcity problem based on various farmer's decision and preference for economical or to water saving priorities.

The surface irrigation design; graded borders and graded furrows in lasered and non-lasered land was optimized using the DSS-SADREG model for different field lengths of 50, 100 and 200 m and a longitudinal slope of 0.8% with various inflow discharges. Both systems were applied for cotton while only graded borders were applied for wheat. Sprinkler systems were designed using PROASPER for wheat and cotton; solid-set, gridded-pipe and hand-moved systems with small and large spacing between laterals and sprinklers and two layout-bases were considered. Drip applications were analysed with MIRRIG model for only cotton, for different combination of six system layout-bases, two lateral layouts - number of plant rows per lateral - five emitters type; self-compensating and non- compensating, and two emitters spacing of 0.5 and 0.7 m.

The results of surface irrigation for wheat and cotton show that the alternatives without land leveling are likely more appropriate when farm economic results are aimed, while alternatives including land leveling were highly ranked when priorities were assigned to water saving due to higher costs of alternatives that considered land leveling. The equipment for appropriate control of inflow rates was considered for all alternatives since surface irrigation's performance highly depends upon the appropriateness of discharges and cutoff time control.

For cotton, the comparisons between graded furrows and graded borders of non-lasered and lasered land created a set of alternatives that were analysed with the decision support system SADREG. Results show a slight advantage for graded furrows but both systems are feasible. The improved alternatives may lead to save up to 28% of irrigation water and to increase the irrigation water productivity from present 0.31 to 0.44 kg m^{-3}. Ranks changed when the same alternatives were considered for a sustained deficit irrigation of 20%. Because yields and yield values are reduced with deficit irrigation, it becomes less favorable to select the advanced alternatives since they are more costly. Hence, rankings changed and alternatives with land leveling could only be selected when very high priorities were assigned to water saving. Less costly alternatives were selected when farm economics was prioritized.

Moreover, when the application was analysed for drip for cotton, results show that the most impact factor in drip irrigation was emitter's type, number of plant rows per lateral, spacing between emitter and inflow-rate; the layouts have lower influence among alternatives. Both emitter's types; self-compensating and non- compensating have visible and good results; it was obvious that emitters with high flow-rate >3.5 l h^{-1} have high investment cost and were completely out of the famers choice. The self-compensating emitter were not economic options for field crops like cotton, and the emitter NC2.7 is the best selection for farmers, as the variation of total water use among emitter types is not sufficient. The double plant row per laterals is the best solution for farmers for water saving and economic considerations due to lower cost with both emitter spacing 0.5 and 0.7 m.

The results when comparing between drip and surface irrigation; graded borders and graded furrows for 100 and 200 m filed length, lead to conclude that drip irrigation is obviously better solution than graded furrows for water saving with water saving 28-35% than graded furrows and 49% compared with traditional system. The sensitive point is the economic priorities. It was concluded that the drip would not be economical solution unless it obtained the maximum yield, the yield price increases, or the interesting rate decreases, which could help to recover the high-required cost. In additional that the investment cost of drip can change or be minimized for another variables related to spacing among laterals or use another equipment. However, by adopting deficit irrigation, the graded furrows become better solution for farmers due to an economic point of view.

In addition, further applications were analysed for sprinkler and compared with both drip and surface for cotton. This study proved that surface, sprinkler, and drip systems are, in general, feasible solutions. For small farm-size, usually conditioned by economic priorities, the full-irrigated surface systems, LL or NLL are advisable solutions. However, if DI is economically accepted, the set sprinkler systems are a good solution. For farmers with financial ability to make higher investments, the drip irrigation allows an acceptable compromise between economics and water saving, and a good flexibility between FI and DI. On the other hand, if the priority is for water saving, the best solutions are the sprinkler and the drip, with DI or FI. However, a special attention should be taken on the quality of irrigation equipment, particularly with drip irrigation, because it affects significantly the irrigation performance. In addition, it was concluded that DI effectiveness depends on the feasibility of the water supply and distribution system to guarantee the appropriate irrigation-scheduling plan; for cotton it is very relevant when selecting a system given its potential to deal with water scarcity scenarios. The sprinkler systems for cotton only manage a DI strategy, with a yield decrease of about 14-20%, but its performance may be satisfactory.

The results for wheat when sprinkler irrigation systems are applied indicate that the sprinkler alternatives hydraulically designed to optimize and minimize the cost from chosen pipe's diameters, adequate head pressure and enlarge the spacing of laterals and sprinklers. The solid-set and gridded-pipe systems' type dominated as the best economical design mainly as the labour was minimised and obtained high WP, 1.08 kg m^{-3}, and high gross income EWPR, 3.12.

The comparison between surface (graded borders) and sprinkler shows that, sprinkler irrigation systems provide better control on the amount of applied water and better irrigation uniformity than surface systems. In addition, sprinkler is dominated by borders systems associated with water saving and economical perspectives, except for high economic priority where borders of non-lasered land was feasible and appear in the first ranking. The high labour required for maintenance and moving the laterals and operation in portable systems make this option similar to borders for non-lasered land assessing with economic aspects. The borders system is not favourable for water saving and economic consideration because the high required cost of maintenance. When slight sustained deficit irrigation, 12-14% is adopted, a yield reduction of 17% obtained and this reduction change the ranking for the same considered alternatives and recession the sprinkler for later order associated for economic priorities where borders show feasibility and preceding over sprinkler.

The study, in a context of small and family farms, shows that adopting more advanced but more costly irrigation technologies aimed at water saving requires appropriate economic incentives, training of farmers and an institutional framework able to support the sustainable use of water in irrigation. The results made evident that farm economics and water saving criteria are contradictory since the value of water saved when more advanced systems are used does not provide for recovering the additional costs relative to these alternatives. The graded furrows could be improved to meet both framer's priorities; water saving and minimizing the cost by reuse the tail runoff.

The MCA tools proved very useful for selecting the more sustainable irrigation methods for wheat and cotton among different irrigation methods, considering possible farmer's preference and governmental perspectives like to solve the water scarcity problem in the study area. This approach can be used for irrigation at small and large scale (farm and basin level). For future study, other sprinkler types like center-pivot and rain-gun systems, which are feasible and applicable in different area - not in our study area - can be analysed. Criteria could be extended to include other environmental issues, e.g., attributes to consider salinity build-up in the soil or in irrigated water, or soil erosion. From economic point of view, further consideration can be done for total farmer's outcome including the agriculture service cost, which varied replying on adopted irrigation methods. In addition, developing the MCA model to include other methods like ELECTRE II and PROMETHE II is interesting to evaluate the results and to compare which method is more adequate to represent reality in irrigation management and in the agriculture sector.

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