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Modernizing Surface Irrigation and Land Levelling in Hetao with Application of the Decision Support Systems SADREG

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Abstract

Water resources allocated to the agricultural sector in the Yellow River basin are being reduced due to severe water scarcity and an increasing demand by the non-agricultural sectors, which imply surface irrigation modernization and the adopting water-saving technologies. The Hetao irrigation district has 0,570 Mha of irrigated land; traditional basin irrigation is the most common irrigation method. Its general conditions are adequate for surface irrigation due to the high charge of sediments on irrigation water and, among other factors, due to its appropriateness to leach salts. The new technologies of surface irrigation, including the modernized furrowed and flat basin irrigation systems, require the adoption of effective precise land leveling to reach the best performance standards. In this context, the development of high quality land leveling operation is a main condition for irrigation modernization. The laser land leveling technology provides for high land leveling quality, with significant benefits on water saving, salinity control and crop productivity. The irrigation modernization also requires adopting adequate irrigation scheduling, control of inflow discharges and of related application times. The DSS methodology may contribute to improved design and management. The DSS SADREG aims to support design and selection of farm surface irrigation alternatives; it ranks those alternatives relative to irrigation performance and environmental and economic impacts using Multicriteria analysis. The DSS application bases on three years field work to evaluate the traditional practices and for the parameterization of design models from field irrigation systems evaluation. This paper presents the following SADREG application results: (i) evaluation of land leveling operation based on field observations and the comparison between laser and common practices; (ii) land parcels description, namely its size, slopes and water supply conditions; (iii) SADREG base models parameterization, including crop irrigation scheduling, infiltration, SIRMOD hydraulic simulation and economics; and (iv) presentation and comparison of alternatives of field irrigation modernization.

Keywords: Basin irrigation; Surface irrigation modeling; Precise land leveling; Irrigation design; Decision support systems (DSS); Yellow River basin

Introduction

The Hetao irrigation district is located in the upper reaches of the Yellow River and is among the three largest irrigation districts of China, with 0,570 Mha of irrigated land, with 250 km long and more than 50 km wide. The average annual rainfall is near 200 mm, so only irrigated agriculture is feasible. The canal network, supplied directly from the Yellow river, has five irrigation canal levels: main, branch, lateral, sub-lateral, and distributor, with low slopes of 1/3000 to 1/5000. Most of the system is by gravity, with only a small area irrigated with groundwater. Hetao traditionally uses $5{,}0 \times 10^9$ m^3 $year^{-1}$ of water derived from the Yellow River. However, due to increased demand for non-agricultural sectors, the Yellow River Commission aims to reduce the Hetao supply to $4{,}0 \times 10^9$ m^3 $year^{-1}$. To manage the irrigated agriculture with less available water is challenging and requires the adoption of modern technologies that enable water saving, optimising water productivity and improving farmers' incomes.

Hetao consists of 361 divisions in relation with the canal networks structure. Each division comprises several sectors, each one supplied by a unique branch, so having independent operation. Each division has a Water Users Association (WUA), which administration is elected by farmers; the main task is the operation and maintenance of the hydraulic structures following water distribution rules.

Traditional basin irrigation is the most representative irrigation method [1]. Conditions are appropriate for surface irrigation due to the high charge of sediments of the irrigation water, flat land, and farmer's knowledge, high compatibility with the canal conveyance and distribution network, and appropriateness to leach salts. New technologies of surface irrigation - modernized furrowed and flat basin systems, land levelling and improved water use management - together with the cropping pattern adjustment, offer feasible solutions for irrigation modernization well adapt to local conditions [2,3]. To control soil salinization, that is a common and serious problem, farmers usually over irrigate as a guarantee to leach soil salts and having a good soil water refill.

Land levelling (LL) plays a determinant role in the performance of surface irrigation and is normally the first step in a system design process particularly relevant in basin irrigation [2,4-7]. Applications were studied for the North China Plain [8], and the Yellow River basin [2,9]. Laser land levelling is particularly accurate to overcome land surface unevenness, providing for significant reduction of the irrigation advance time and water required, promoting uniform infiltration distribution, thus leading to more uniform and favourable conditions for crop growth. Limitations of laser levelling operation include its higher cost and the need for skilled operators. Laser land levelling benefits are not always tangible in terms of farm profitability, which explains that many times farmers prefer the simpler and cheaper common traditional land smoothing [10]. Traditionally, in Hetao, land levelling uses rudimentary equipment's and practices, with very low quality and performance. Poor LL leads to irregular advance and recession phases, over irrigation, low infiltration uniformity and uncontrolled deep

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percolation. Contrarily, laser land levelling technology creates new opportunities to overcome these problems, with significant benefits on water saving, salinity control and crop productivity. The relevance of LL levelling for Hetao explains why field research developed there during three years, 2011-2013. This research aims to evaluate the traditional practices, the feasibility and the performance of precise operation with laser technology and to determine the main operative and economical parameters contributing to surface irrigation modernization in Hetao.

The DSS methodology exploring the capabilities of irrigation modelling may contribute to improve design and management procedures [11], namely the DSS SADREG aiming at designing and selection of farm surface irrigation systems [12]. Through several simulation and computational tools, it produces a set of design alternatives based upon the user options, and ranks those alternatives relative to irrigation performance and environmental and economic impacts using Multicriteria analysis. This paper presents SADREG applications to: (i) evaluation of land levelling operation based on field observations comparing laser and common practices; (ii) assessing land parcels characteristics; (iii) SADREG base models parameterization, including crop irrigation scheduling, infiltration, hydraulic simulation and economics; and (iv) comparison/ranking alternatives for field irrigation modernization.

Material and Methods

Hetao experimental site

An experimental study was carried out in Dengkou, in a typical sector with 33.4 ha and supplied by the Dongfeng canal. The fields are clustered according to a rotational delivery scheme managed by the WUA. For each irrigation event, fields are supplied with a nearly constant discharge during the irrigation time established by the water management authority according to the farmer's demand and water availability. The number of land parcels is 394 with an average area of 750 m^2. The Dongfeng canal supplies 480 sectors with a total of 16 × 10^3 ha. The traditional basin irrigation method is applied to basins whose typical length is 50 m, and widths vary between 7 and 50 m. A field basin irrigation assessment was developed allowing the models parameterization [1]. The field topography is flat but irregular, not well adjusted to the requirements of good infiltration uniformity. The soil is silt loamy with average total available water (TAW) of 200-260 mm m^{-1}. The most common crops are maize, wheat and sunflower whose irrigation requirements were studied by Miao et al. [13]. A set of eight field plots were selected for the land levelling study having a length of 50 m and widths from 15 to 50 m. A micro-topography survey was applied to all these fields; an electronic station device with an elevation accuracy of 1 mm was used. A 5 × 5 m grid was used before and after land levelling operations [14]. The land levelling operations consisted of: i) the common traditional practice of land smoothing, with tractor or animal power, which applies small graders, scarifies or disc harrows, coupled with a scraper; ii) Laser land levelling, with the objective to reshape the soil surface with a precise zero slope in all field directions, applying a Spectra System equipment from a local private specialised enterprise. The operation is usually performed by October, after ploughing, aiming at soil surface smoothing and preparation for seedling.

Land levelling computation

The land levelling computation was made by the LEVEL program, a component of SADREG simulation engine model [11]. It applies the plane method to calculate the earth volumes, the operation time and the optimal slopes using the elevation data obtained in the field topographic survey. The land levelling operation aims to adjust the shape of the soil surface to a specific design surface plane. Assuming the coordinates in the x and y-direction, the surface plane is represented by the equation:

$$Z(x,y) = z_0 + S_x \cdot (x - x_0) + S_y \cdot (y - y_0) \quad (1)$$

With Z(x,y)=elevation of the plane surface at the point with coordinates (x,y); x=coordinates in the x-direction measured in the grid spacing; y=coordinates in the y-direction; (x_0, y_0, z_0) the coordinates of field centre of gravity; S_x=slope on x-direction; S_y=slope on y-direction. A field topographic survey provides the elevation data of a set of points of soil surface, usually from the nodes of a rectangular grid. The coordinates of the field centre of gravity (x_0, y_0, z_0) are calculated by the area weighted sum of the coordinates of these nodes. The target cross and longitudinal slopes can be selected according to the irrigation method, or are obtained by minimizing the volume of earth to be moved, so corresponding to the natural field slopes. The surface elevation difference (E), also known as depth of earth work, is the vertical distance between the original ground elevation H(x,y) and the elevation for a given point on the design surface plane Z(x,y) with the coordinates (x,y), is given by:

$$E(x,y) = H(x,y) - Z(x,y) \quad (2)$$

A positive E value indicates an excavation area, and a negative value indicates a landfill one. The quality of a field land levelling may be characterized by the standard deviation (Sd, cm) of E, calculated from a set of field surface points H(x,y).

The program LEVEL calculates the amount of land involved in the leveling operation based on the surface elevation difference and identifies the areas of excavation and landfill. The ratio of excavation and fill volumes required to balance of earth moved is calculated through an iterative process aimed to find the position of the plane for the specified ratio. The program also determines the slope that optimizes the levelling operation based on least-squares best fit and on the criterion of minimization of the volume of earth move required to obtain a desirable smooth surface, which optimizes the operation cost and the negative soil impacts. LEVEL allows the evaluation of field land levelling scenarios with a random generation of elevation data depending upon the actual slopes and the sd of surface elevation differences. The accurate determination of the cost of the operation considering the machine time is a relatively complex problem because it depends on a wide range of factors such as the type and power of land leveling machine, the horizontal distances between the cut and fill sites within the field, their volumes and soil characteristics. Thus, LEVEL applies a simplified procedure to compute the operating time based on excavation volume with the following equation [15,16]:

$$t_{LL=} t_{unit\text{-}volume} \cdot V_{excav.} \quad (3)$$

Where t_{LL}=machinery time required to field land levelling (h); $t_{unit\text{-}volume}$=machinery required for a unit of cut volume (h/m^3); V_{excav}=volume of excavation (m^3). The operation time calculated from this equation should not be less than the time required for its current land levelling maintenance, which depends mainly on the field area because it requires only a soft land smoothing; it is given by:

$$t_{LL=} t_{unit\text{-}area} . A. \quad (4)$$

Where $t_{unit\text{-}area}$=machinery time required to land levelling a unit area (h/ha); A=field area (ha). The land levelling cost $C_{LL\text{-}total}$ (€) considers a fixed ($C_{LL\text{-}fixed}$) and a variable ($C_{LL\text{-}variable}$) component:

$$C_{LL\text{-}total} = C_{LL\text{-}fixed} + C_{LL\text{-}variable} \quad (5)$$

The fixed one refers to the cost required to have the equipment in the field. The variable component depends of the operation time t_{LL}, calculated by the equation:

$$C_{LL\text{-}variable} = c_{unit\text{-}machine} \cdot t_{LL} \quad (6)$$

With $c_{unit\text{-}equipm}$=unit cost of operation land levelling equipment (€ h^{-1}).

The economic and technical input parameters considered in this study are presented in Table 1. On the other hand, the output includes the volume of excavation and landfill and its spatial visualization, the maximum depths of cuts and fills, the time of operation and its cost.

The program LEVEL was applied to calculate the cost and the land levelling operation required for several irrigation design modernization scenarios. This study considers fields with lengths of 50 m, 100 m and 200 m, with an actual zero slope but poor land levelling conditions, and scenarios of precision land levelling without change of the slope, or with a longitudinal slope of 0.05%, to verify the impact of this topographic change in the irrigation performance. The change of slope requires an initial laser land levelling operation. For the maintenance of land levelling, alternatively to the laser option the traditional practice of land smoothing is tested. This study should provide the parameters and guidelines to plan land leveling operation in the irrigation design process, as presented in 4.3 (Tables 2 and 3).

DSS modelling

Model parameterization: SADREG is a DSS model developed to assist designers and managers in the process of designing and planning improvements in farm surface irrigation systems [1,2]. The design component applies database information and produces a set of alternatives in agreement with the user options. 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 Pereira et al. [2]. The main steps of a DSS application are:

a) Identification of field characteristics of a rectangular shape field.

b) Data input to characterize water supply and distribution equipment.

c) Data input referring to crop and soil data, mainly the infiltration parameters.

d) Crop irrigation scheduling, created through interactive simulations with the ISAREG model [17].

e) Design options to create the alternatives, using the SIRMOD hydraulics simulation tool [18].

f) Ranking and selection of alternatives with Multicriteria analysis, whose weights are defined according to the user priorities.

Parameter	Symbol	Value	Comments
Time of laser land leveling operation per a cubic meter of cut volume	$t_{unit\text{-}volume}$	0.03-0.08 h/m^3	This value depends of the distances between cut and fill sites, from the power of the equipment, the experience of the operator and the soil conditions
Time of maintenance laser land leveling operation per hectare of field area	$t_{unit\text{-}area}$	4-6 h/ha	This value depends mainly of the power of the equipment, the experience of the operator and the soil conditions
Fixed land leveling cost per operation	$C_{LL\text{-}fixed}$	0	Usually, an operator does a significant work time for several farmers, implying that he neglects the fixed cost, being all cost include in the variable component
Land leveling operation cost per hour	$c_{unit\text{-}machine}$	25-35 € h^{-1}	This value depends mainly of the equipment power and size

Table 1: Economical and technical input parameters for laser land levelling calculation.

Type	Description	Value
Field distribution equipment	Non-lined canal cost, including field gate	1.0 € m^{-1}
Land levelling	Fixed cost per operation	0
	Hourly cost (laser/traditional)	30/15 € h^{-1}
	Operation time (laser/traditional)	4.0/3.0 h ha^{-1}
	Frequency	1 year
Irrigation water	Volumetric price	0.006 € m^{-3}
	Fixed cost per unit area (WUA irrigation fixed cost)	100 € ha^{-1}
Yield: maize	Yield price	0.30 € kg^{-1}
	Maximum yield	12000 kg ha^{-1}
	Production cost (excluding irrigation and land levelling cost)	775 € ha^{-1}
Labour	Cost	0.5 € h^{-1}
Effective life-time of equipment	Non-lined canal	1 year
Labour requirements	Operating the non-lined canal	Equal to the application time
	Installing the non-lined canal	40 min/100 m

Table 2: Economic and labour DSS input data.

Irrigation scheduling	Full /Deficit irrigation (FI/DI) [a]	Number of irrigations	Target irrigation depth (mm)	Season net irrigation requirement (mm)	Season non-irrigation supply[b] (mm)	Yield (kg/ha)	Relative yield losses (%)
Present	Present (DI)	4	105	420	346	11400	5.0
Improved	FI	5	90	450	340	12000	0.0
Improved	DI	4	90	360	389	11160	7.0

[a]FI=full irrigation, DI=deficit irrigation.

[b]It refers to the net contribution to crop ET of precipitation, soil water reserve and capillary rise.

Table 3: aize irrigation scheduling scenarios (from Miao et al. 2014a).

The representative land parcel considered in this study is a 0.15 ha field, with 50 m length and 30 m width, levelled to zero slopes and served by one outlet with discharge of 15 l s^{-1}. To analyse the effect of the field length, also lengths of 100 and 200 m with 50 m width were considered. It was assumed a maximum maize yield of 12000 kg ha^{-1}. The medium infiltration for a silt loamy soil is given by Miao [1]. Several projects were defined with laser land levelling: flat level basin and furrowed level basin with furrow spacing of 75 cm. The Manning roughness coefficients were 0.14 and 0.04 s $m^{-1/3}$, respectively (Table 4). The projects considered full or deficit irrigation scheduling (Table 3) as reported by Miao [13]. The field distribution system was a non-lined canal. The economic and labour data input are presented in Table 2. At present, the farmer's irrigation fees in Hetao are calculated from the field area, and vary from 135 to 190 €/ha including all water cost components and the maintenance of collective infrastructures. The water price established by the Yellow River Commission at sector level is 0.005 to 0.006 €/m^3. It means that 25-45% of farmer's water fees correspond to the strict payment of water and 55-75% corresponds to the payment of other WUA costs. In this study a partition of the irrigation cost is considered: a fixed cost corresponding approximately to 60%, based on a cost of 100 € ha^{-1}, and a variable cost proportional to the water used, based on a water price of 0.006 € m^{-3}.

Projects: A project corresponds to a development scenario to build-up alternatives according to a set of input factors. It considers the land levelling data, namely the field slope, the irrigation method, the crop and its irrigation scheduling (Table 4). The projects are applied to the actual typical field (50 m × 30 m) and to fields that should be implemented in the modernization process, 100 m × 50 m and 200 m × 50 m.

The Project P0 represents the present situation of flat basins with traditional land levelling and a slight longitudinal slope, with the present irrigation scheduling (Table 3). The effect of laser land levelling, compared with the traditional practices, corresponds to an increase of distribution uniformity between 10 and 20%, averaged to 15% according field observations. Project P1 corresponds to the present situation after improving land levelling. The projects P2 to P9 represent a greater improvement in addition to laser land levelling (Table 4).

Results and Discussion

Field land levelling

Table 5 presents the natural slopes of four experimental fields. These results show the usual low quality of actual land topography, namely the existence of excessive cross slopes that reaches 0.43%, a slight longitudinal slope of about 0.05%, and an average Sd of 7 to 8 cm of surface elevation differences.

Table 6 presents the laser land levelling operation time and the observed Sd of surface elevation differences before and after laser levelling operation. Comparing these two conditions, it shows the beneficial effect of this operation by the decrease of Sd to 2-3 cm. The observed land levelling operation characteristics, correspondent to a longitudinal slope between zero and 0.05% and a null cross slope, are summarized in Table 7. The operation time per hectare depends of the levelling equipment power and the field size and the values in Table 7 represent actual practices in Hetao.

Laser land levelling impacts on irrigation performance

The effect of land levelling (LL) on basin irrigation is evaluated through the comparison of the alternatives of P0 (traditional LL) and P1 (laser LL) projects. Figure 1 presents irrigation water use (IWU) and deep percolation (DP) values, according the applied unit inflow rate (Table 8). Traditional LL implies a higher IWU and DP than laser LL, a direct consequence of lower distribution uniformity on traditional LL, about 15% (vd. 2.3.3).

Figure 2a presents the economics of the alternative with an inflow rate of 2 l s^{-1} m^{-1} for both P0 and P1 projects. The economic benefit is identical for both projects, about 3405 € ha^{-1}. The laser LL cost is 150 € ha^{-1}, whereas the traditional one is 75 € ha^{-1}, corresponding to 24% and 13% of total irrigation cost (TIC), respectively. Water cost is 130 and 103 € ha^{-1}, respectively for P0 and P1 corresponding to 22% and 17% of TIC. On the other hand, the labour cost is 47 and 42 € ha^{-1}, 10% and 8% of TIC, respectively for P0 and P1.

Figure 2b presents the economical irrigation water productivity (EWP), showing that it is sensitive with LL practice, increasing from

Projects	Land levelling	Irrigation method (b)	Slope (%)	Field length	Crop	Irrigation scheduling(a)
P0	traditional	Flat basin	0.05	50	Maize	Present
P1	Laser	Flat basin	0.05	50	Maize	Present
P2	Laser	Level Flat basin	0	50/100/200	Maize	FI
P3	Laser	Level Flat basin	0	50	Maize	DI
P4	Laser	Level Furrowed basin	0	50	Maize	FI
P5	Laser	Level Furrowed basin	0	50	Maize	DI
P6	Laser	Graded Flat basin	0.05	50/100/200	Maize	FI
P7	Laser	Graded Flat basin	0.05	50	Maize	DI
P8	Laser	Graded Furrowed basin	0.05	50/100/200	Maize	FI
P9	Laser	Graded Furrowed basin	0.05	50	Maize	DI

(a)FI (full irrigation), DI (deficit irrigation).

(b)Furrow spacing of 0.75 m.

Table 4: Summary of DSS irrigation projects.

Length × Width (m)	Before land levelling		
	Sx (%)	Sy (%)	Sd (cm)
50 × 15	0.433	0.020	5.8
50 × 50	0.001	0.054	6.7
50 × 30	0.116	0.053	8.2
50 × 20	-0.243	0.053	8.6

Table 5: Actual field longitudinal (Sy) cross slope (Sx) and standard deviation of Sd.

Length × Width (m)	Area (ha)	Before laser Land Levelling Sd (cm)	After laser Land Levelling Sd (cm)	Observed LL operation time (h/ha)	Notes
50 × 15	0.08	5.8	3.4	5.56	(a)
		10.6	3.8	4.44	
50 × 20	0.10	8.6	3.2	2.83	(a)
		6.17	1.8	6.70	(a,b)
		11.3	3.5	4.33	
50 × 30	0.15	8.2	3.1	1.67	(a)
		2.93	1.6	6.30	(a,b)
		4.13	1.5	8.30	(a,b)
		14.1	3.6	4.33	
50 × 40	0.2	14.9	3.4	4.17	
50 × 50	0.25	11.1	3.1	4.20	(a)
		6.7	2.6	1.67	
50 × 60	0.30	3.73	2.8	5.00	(a,b)
		6.92	2.8	5.80	(a,b)

(a) Laser land levelling was preceded by a soil disking operation; (b) Data adapted from Xu (2012).

Table 6: Field laser land levelling data before and after laser land levelling and operation time.

	Operation time (h/ha)	Cost (€ha^{-1} year^{-1})	Sd (cm)
Traditional land smoothing	5-8	5-75	5.8-8.6
Laser land leveling	3-5	90-150	1.5-3.0

Table 7: Land levelling maintenance operation characteristics (yearly operation).

Length × Width (m)	Area (ha)	Cut volume (m³/ha)	Operation time (h/ha)	Cost (€/ha)
50 × 30	0.15	46-76	4-6	120-180
100 × 50	0.50	46-84	4-7	120-210
200 × 50	1.00	46-146	4-8	120-240

Table 8: Laser land levelling for slope adjustment (0-0.05%) for several field sizes.

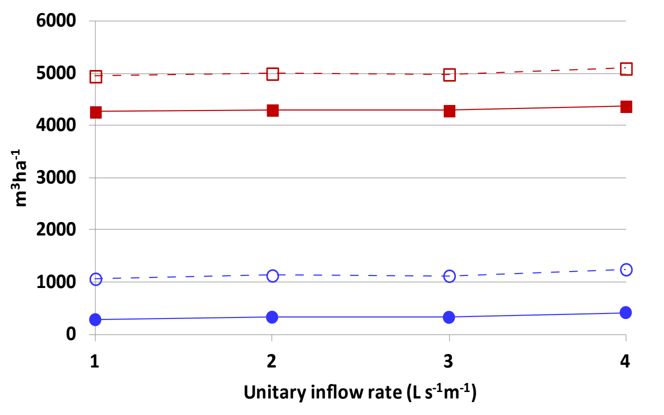

Figure 1: Traditional land levelling (project P0) irrigation water use (–⊟–) and deep percolation (–⊖–) and laser land levelling (project P1) irrigation water use (–■–) and deep percolation (–●–), according the unit inflow rate.

0.68 € m^{-3}, for traditional LL, to 0.79 € m^{-3}, for laser LL. On the other hand, TIC/IWU and LLC/IWU increase from 0.11 to 0.14 € m^{-3} and 0.01 to 0.03 € m^{-3}, concluding that laser LL favours an economic benefit of 0.06 € m^{-3}. Laser LL, although do not have an evident direct effect on farmer economic return, allows a better irrigation water management with a significant increase of economical water productivity, being recommended to cope the irrigation system with water scarcity.

DSS simulation of improved alternatives

Field basin with 50 m length: SIRMOD was applied to create a data base to be uploaded by SADREG, assuming a precise land levelling and an adequate cut-off time. It was observed that the irrigation performance in a basin with 50 m length is very high when the inflow rate is higher than 1 l s^{-1} m^{-1} (beneficial water use fraction, BWUF>90%), and that the irrigation performance is not sensitive with the unit inflow rate within the range 1 to 4 l s^{-1} m^{-1}. This result is explained by the short basin length and the medium soil infiltration, which allow a fast advance even with a moderate unit inflow rate.

The various projects (P0 to P9) will be represented by the alternative of a unit inflow rate of about 2 l s^{-1} m^{-1} or 2.6 l s^{-1} furrow^{-1} which corresponds approximately to the optimal performance. Figure 3 presents several indicators of all projects, grouped according the irrigation scheduling strategy: the present one and the improved full (FI) and deficit irrigation (DI) (vd. Table 3).

Figure 3a presents IWU and DP values, showing that the present scenario (P0) has the worst performance (higher IWU and DP), with a BWUF of 77%, consequence of the negative effect of an inadequate land levelling. Obviously, FI projects have a higher IWU than DI ones. For the improved alternatives, BWUF is very high, 92% for P1 and graded flat basin (P6 and P7), and 97% for other projects (P2, P3, P4, P5, P8 and P9). Figure 3b shows economic benefits, total irrigation cost and non-irrigation production costs. The economic benefits depend directly from the crop yield, which highly depends from the irrigation scheduling. FI projects have the highest benefit. TIC varies from 452 € ha^{-1} for present scenario P0 (37% of total cost), an average of 520 € ha^{-1} for FI projects (40% of total cost) and 507 € ha^{-1} for DI one (39% of total cost). It should be highlighted that traditional and laser LL represent 7% and 13% of the TIC, respectively. Figure 3c shows that EWP is very sensitive to irrigation scheduling, with 0.68 € m^{-3} for P0, 0.78 € m^{-3} for FI and 0.91 € m^{-3} for DI. TIC/IWU has a value between 0.04-0.05 € m^{-3}, and LLC/IWU a value of 0.015 for P0, and between 0.030-0.042 €

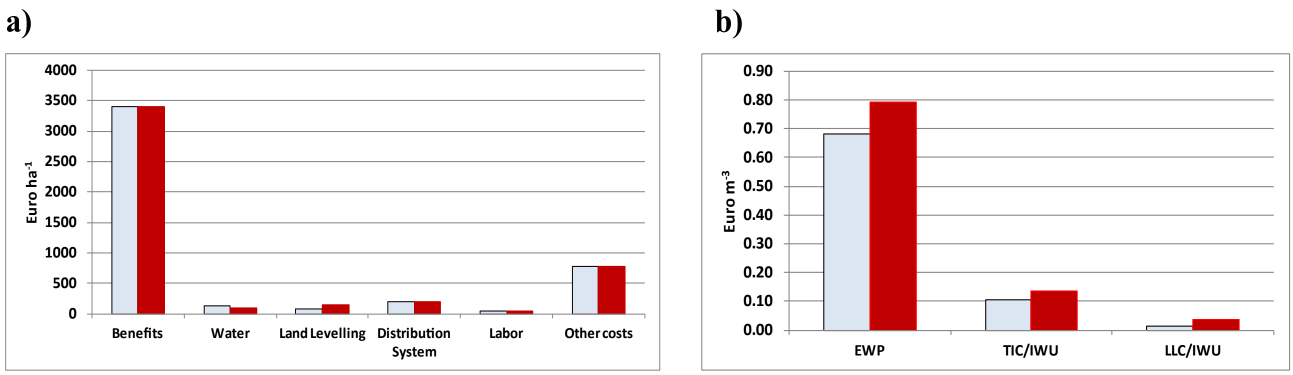

Figure 2: Comparison between traditional land levelling (□) with laser land levelling (■): a) Economic benefits, and cost components: water, land levelling, distribution system, labor, other production costs; b) EWP=economical water productivity, TIC/IWU=total irrigation cost per irrigation water use, LLC/IWU=Land levelling cost per irrigation water use.

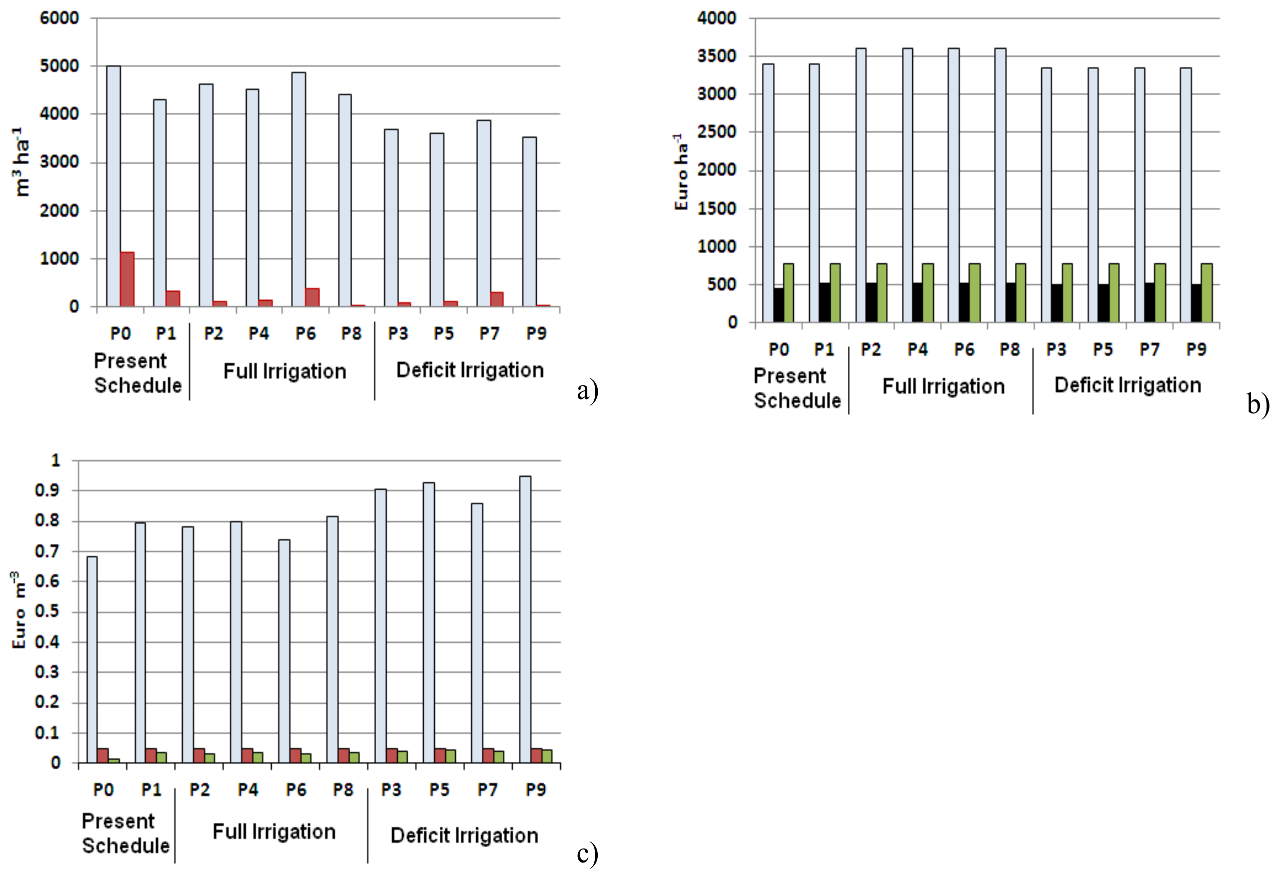

Figure 3: Comparison among several projects, represented by the alternative with an unit inflow rate of 2 l s^{-1}, based on: a) irrigation water use (□) and deep percolation (■); b) Economical benefits (□), total irrigation costs (■), and other production costs; c) (■) economical water productivity (□), total irrigation cost per irrigation water use (■), land levelling per irrigation water use (■).

m^{-3} for FI and DI improved systems. A significant result relative to the irrigation method itself is that the design options flat vs. furrowed, or level vs. graded basin, have identical economic performance. It allows concluding that these options should be considered mainly according crop cultivation aspects.

Impacts of basin lengths: The analyse of the field basin length effect on irrigation performance was based on projects with flat basins (P2), graded flat basins (P6) and graded furrowed basins (P8) considering fields with 100 m and 200 m length (vd. Table 4). Figure 4 shows IWU and DP of these projects for several unit inflow rates. It shows that, for flat basins (P2 and P6), IWU increases with the field length due to the significant increase of the advance time with the length; BWUF has a value of 97-92% for 50 m length, 90-85% for 100 m, and 69-72 for 200 m. The unit inflow rate has a low influence on irrigation performance, except that the inflow rate of 1 l s^{-1} m^{-1} for 200 m length has a low

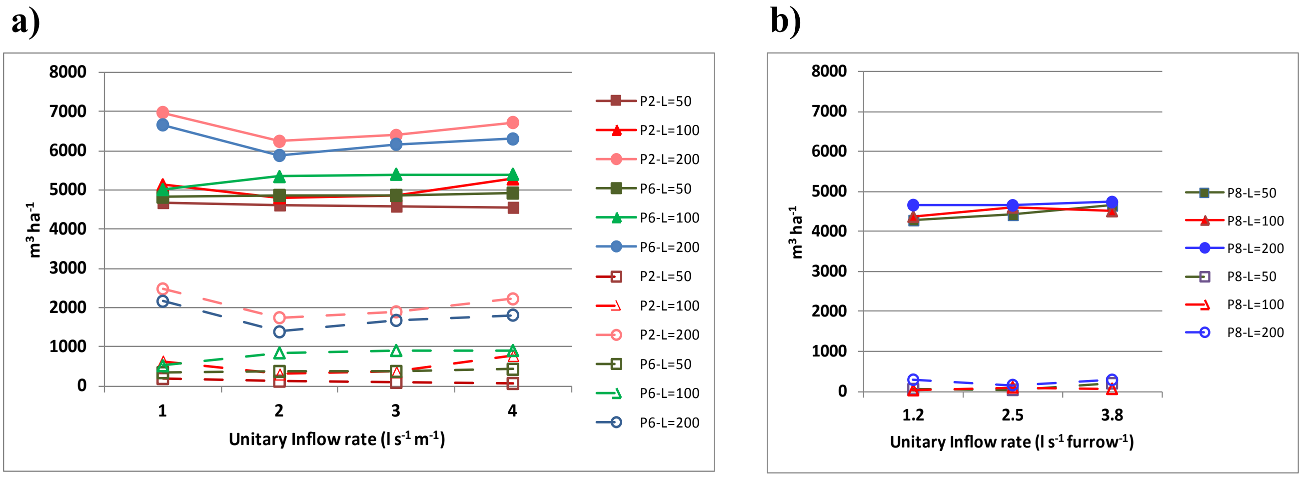

Figure 4: IWU (continuous line) and DP (dashed line) for: a) level flat basin (P2) and graded flat basin (P6); and b) graded furrowed basin (P8), with several lengths: 50 m, 100 m and 200 m.

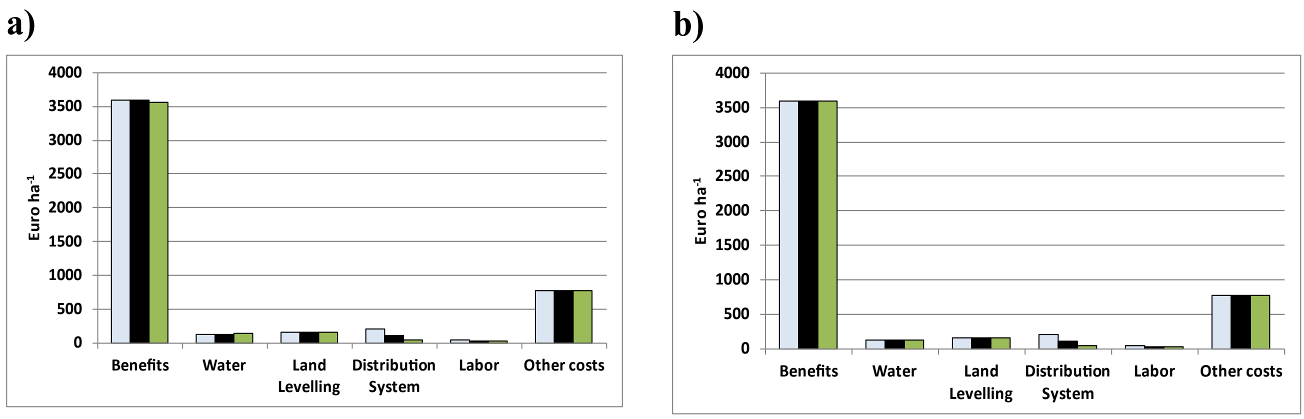

Figure 5: Economic indicators relative to different flat level basin (P2) (a) and graded furrowed basin (P8) (b) with several lengths: 50 m (□), 100 m (■), and 200 m (■).

BWUF of 65%. For furrowed basins, the field length has no influence on irrigation performance, with BWUF values within 95-98% range [19].

Figure 5 shows economic indicators for several projects and lengths relative to the unit inflow rate of 2 l s^{-1} m^{-1} (flat basins) or 2.5 l s^{-1} $furrow^{-1}$ (furrowed basins). For flat basins, the economic benefit is 3600 € ha^{-1} for 50 m and 100 m length, and a value of 3560 € ha^{-1} for 200 m length. For furrowed basins the benefit is 3600 € ha^{-1} for all lengths. The LL and water costs have identical values for the three projects, with a distribution system and operative labour costs decreasing slightly with the basin length. It can be concluded that the development of the surface irrigation through the field reshaping creating longer field parcels has capability to achieve high BWUF when using furrowed basins of 200 m length. The economical results are favourable, with possibilities to reduce the labour irrigation costs due to a larger application time, added with the increased efficiency of the cultivation machinery when the field length is longer.

Conclusions

The experimental study analysed the field land parcels, soil characteristics, crops, and field irrigation practices. Based on a field topographic survey, a traditional and a laser land levelling were evaluated, concluding that the LL operation is crucial for irrigation modernization, for achieving high irrigation infiltration uniformity. The economical irrigation water productivity increases from 0.68 € m^{-3} for traditional LL, to 0.79 € m^{-3}, only applying laser LL and using the present irrigation scheduling, and 0.90 € m^{-3} for improved alternatives with laser LL and DI. It was concluded that laser LL do not have a significant cost impact (approximately 7% of TIC) and allows a better irrigation water management with a significant increase of economical water productivity (approximately 16% and 30% for improved systems FI and DI, respectively).

The results obtained for a flat level basin with 50 m length show that the irrigation performance was almost independent of the unit inflow rate between 1 and 4 l s^{-1} m^{-1}, with potential to have a BWUF close to 95%. If the furrowed level basin is applied (feasible for row crops like maize, tomato, or sunflower), the results are identical, with a more favourable performance of lower inflow rates on furrowed basin. In practice, the cut-off control by the farmer plays an important role on irrigation performance. The modernization of the surface irrigation should focus these problems, with particular attention to the quality of the distribution system.

The development of the surface irrigation through the field reshaping creating longer field parcels (100 to 200 m) has potential to achieve high BWUF (approximately 90%), particularly with the use of furrowed basin for longer lengths. The performance is almost independent of the unit inflow rate within the interval 1 and 4 $l\ s^{-1}\ m^{-1}$, and the total irrigation cost varies between 28 and 33% of the economic benefit. The economical results are favourable, showing possibilities to reduce the labour irrigation costs due to a larger application time, added with the increased efficiency of the cultivation machinery when the field length is longer.

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