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Assessment of Precise Land Levelling on Surface Irrigation Development. Impacts on Maize Water Productivity and Economics

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Abstract: The new technologies of surface irrigation require the adoption of effective Laser-controlled precision land levelling (PLL) to reach the high irrigation performance standards, with significant benefits on water saving, salinity control, crop productivity, and farmer's income. This study aimed to assess the performance and the impacts of PLL on surface irrigation systems, focusing the maize crop on the irrigation districts Hetao (China) and Lower-Mondego (Portugal). The experimental study at field scale assessed the PLL and evaluated the on-farm irrigation under precise levelled fields and well management practices. PLL operators have been inquired to improve the knowledge about hiring services. The design of surface irrigation scenarios allowed to explain the effects of field size and slope on irrigation and land levelling performance. The best practice to manage the PLL maintenance is an important issue to guarantee a high effectiveness of irrigation performance. The optimization of PLL appeals the application of best soil tillage practices and the monitoring of soil surface elevations with newest information technologies. Efficient operational guidelines to support the PLL planning, schedule, and operation, well trained operators and carefully adjusted equipment, are key factors to the improvement.

Keywords: surface irrigation; water saving; precise land levelling; irrigation modernization; hetao irrigation district; lower mondego irrigation district

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1. Introduction

Surface irrigation systems have undergone a modernization path in several countries in the second half of the 20th century, together with the progressive development of mechanized agriculture. Innovations were triggered by the need to reduce labor, decrease irrigation costs, improve the irrigation water use and water saving, and control the environmental impacts of cropping practices and irrigation. The factors influencing the performance of these modern systems are multiple and refer to the design process, which in turn are related with the appropriateness of land levelling, field shape and dimensions, and inflow discharge. Moreover, they also depend on the farmer operative decisions, mainly regarding the land levelling maintenance, timeliness and time duration of every irrigation event, and the water supply uncertainties. Improving the irrigation performance requires a variety of measures and practices, acting together on the design and operation of the systems. To consider the conjunction of these development actions of surface irrigation systems, is a hallmark of methodology for analyzing these problems. In this context, the land levelling operation plays a determinant role in the pragmatic performance of these systems, namely on the reduction of water use and on the increasing of land and water productivity [1–5].

Land levelling is used in agriculture to change the land topography to create a desired terrain surface, with selected field slopes, affecting the water movement on soil surface, improving irrigation and drainage, and the effectiveness of cultivation operations [6]. The laser-controlled precision land levelling (PLL) is a technology adaptable to levelling tools, like drag scrapers or levelling blades, allowing a very accurate levelling of soil surface [4]. It was introduced in the 1970′s with a significant impact on surface irrigation since then [7]. The PLL accuracy can be very high, with an average deviation of land elevation lower than 20 mm, even in large fields, performed with a reduced number of passages of the levelling machine in the same place, saving time and soil compacting. The main benefits of PLL include the improvement of: i) the water control in surface irrigation systems due to the reduction of the advance time and the volume of water needed to complete the advance, thus providing a uniform distribution and water savings, a higher adoption of deficit irrigation and a better control of the leaching fraction [8,9]; ii) the surface drainage, controlling the waterlogging, and salinity and the erosion risks; iii) crop and soil productivity conditions like germination, growth uniformity and soil cultivation, the use of fertilizers [10], increasing yields [11], and the reduction in weeding, labor and energy costs [3,12,13].

The initial land levelling operation could have negative impacts on soil conservation [13,14]. On one hand, when significant depths of topsoil are removed from some locations and deposited on others, thereby removing the primary source of nutrients for the crop, it may adversely affect soil fertility, at least in the early years after exposure to the low fertile soil layers, requiring additional soil amendments and fertilizers. On the other hand, areas where levelling equipment passes repeatedly can become so compacted affecting root growth and water infiltration, thereby reducing yields [15]. Nevertheless, laser-control equipment allows to reduce the operation time, comparing with traditional tools, implying lower compaction risks. The maintenance land levelling, also called land smoothing, compared with the initial one, is usually faster and involves reduced soil cuts, with not so significant damages. In less developed regions, PLL equipment's and inherent services could be unavailable, too expensive to farmers, or restricted by the small size of the field parcels, which explains why many times farmers are unwilling to adopt these technologies, preferring the simpler and cheaper common traditional land levelling, using rudimentary equipments and practices, with very low performance [16]. Nowadays, PLL equipment's are becoming increasingly available all over the world, allowing a fast and efficient operation, implying that this technology has potential to overcome the referred obstacles, increasing the quality of the land levelling.

As mentioned, the PLL plays a determinant role in the performance of surface irrigation. It is normally the first step in a system design process, which is planned according to the drainage design [4]. The PLL is particularly relevant on flat lands, on graded border or furrows with a mild slope and basin irrigation systems, and on rice paddies, to reach the high irrigation performance standards [17,18]. There are numerous studies reporting the relevance of PLL on surface irrigation development, namely in China [17,19–21], Portugal [22,23], India [21,24], and USA [25].

The PLL planning and design process is highly dependent on changes to the layout of the plots and the amount of the earthworks required. It is more complex in the initial adaptation to irrigation or the field reshaping, or reparceling, and lighter in the maintenance operations over the years. The acquisition of topographic data can be accomplished by conventional topography equipments, aerial mapping, laser-GPS systems, GPS surveying systems, or using UAV's [26], being represented by digital elevation models (DEM) or digital terrain models (DTM). The establishment of the system layout must meet the drainage criteria, in addition to the irrigation ones. The selection of the parcel slopes is addressed according to the following approaches [27]: (i) selecting the natural field slopes to minimize the earth movement, and, in consequence, undertaking the design of the irrigation system to make the system as efficient as possible with the improved field topography; or (ii) selecting the slopes that optimize the effectiveness of the planned irrigation system, even if this solution involves a relatively high effort of land levelling.

The numerical methods applied in data analysis are based on the choice of the desired surface for the terrain: simple linear regression fit of field elevations of a two-dimensional plane through the plan method [28–30], or non-linear methods [31]; on the procedures to best fit [32]; on the earthwork calculation (e.g., assuming a tetrahedron or a prismoidal form [4], and on the optimization of the plot earthmoving [33]). The plan method is the most common, with several options in the criteria of optimization and calculation of volumes and working times. The cut and fill areas and their depths and volumes can be identified and used to plan the field operation and assess costs and soil and energy impacts [34]. The study of the soil profile should evaluate the maximum cut that can be made without permanently effecting agricultural production.

The rationalization of PLL requires evaluating the agronomic practices used by farmers, in order to establish the best procedures, minimizing energy consumption and cost, and choosing the most appropriate equipment and its use. In this sense, PLL field evaluations and the analysis of its impacts on crop productivity and economy are important at regional scale to allow iterative improvements based on these specific assessments.

The objective of the study here reported was to assess the water productivity and economics impact of precise land levelling practice by typical farmers on surface irrigation systems cropped with maize. It was carried out in the Hetao Irrigation District, China, and in the Lower Mondego Irrigation District, Portugal, sites, where irrigated maize by surface methods is dominant, with high economic relevance. This proximity to contexts of water saving requirement and the typology of irrigation problems has led the research teams of both countries to have worked together on projects and scientific cooperation, sharing knowledge and methodologies. The following topics are included: (i) The evaluation of land levelling operation based on field observations, allowing its technical characterization at local conditions; (ii) The land levelling computation using the LEVEL tool, based on the plane method and using the elevation data from field topographic survey, to calculate the earth volumes moved, the operation time, and the optimal slopes; (iii) The analysis of the impact of PLL on water productivity and economics, based on the observed data and the design of modern projects scenarios of surface irrigation. This study aims to improve the PLL planning and practical outcomes, increasing its effectiveness on water productivity and rural development.

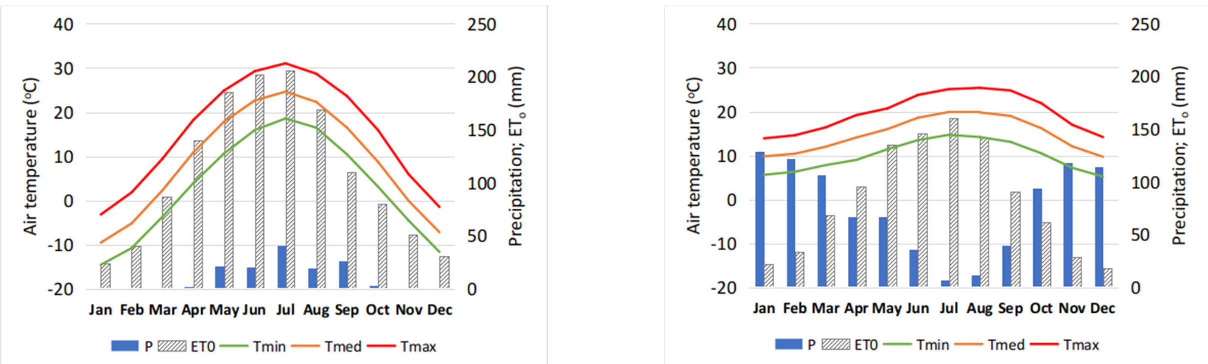
2. Materials and Methods

2.1. Study Sites

This study focused on two distinct geographic sites, Hetao Irrigation District, China (Hetao) and Lower-Mondego Irrigation District, Portugal (Lower-Mondego) (Figure 1). These areas have in common the fact that the maize crop irrigated by surface methods is the most representative, with high economic and social regional relevance.

Hetao is located in Inner Mongolia, in the upper reaches of the Yellow River, with an irrigation area of about 676,000 ha. Water resources management in the Yellow River basin is facing a paradigmatic change in consequence of an unbalanced supply and demand, due to an increased demand for water from non-agricultural sectors and a reduced supply, due to climate change that is causing a reduced precipitation and an increased climatic demand [35–37]. The problem is aggravated by low equity of spatial water allocation within the basin [38]. A supply reduction in the upstream basin area aims to control the water scarcity conditions occurring in the middle and lower reaches of the basin. Forecasted scenarios on water resources allocation and usage for agriculture in the upper reaches of the Yellow River basin point out the need of reducing irrigation water withdrawal and increasing land and water productivity [39]. Hetao has an arid continental monsoon climate, BWk of Köppen climate classification, with an average annual rainfall range from 140 to 200 mm, with hot and dry summers and long, dry, and severely cold winters, which extend from November to March (Figure 2). Agriculture is only feasible during the spring-summer crop season and when irrigated. Sustainable water saving irrigation, applying technologies and practices guaranteeing land productivity, soil conservation and farmers' income, is being implemented in response to the referred global changes occurring in the Yellow River basin [40]. This implementation requires a technological adaption regarding the modernization of the canal water conveyance and delivery system. At field level, modern irrigation technologies adapted to local conditions are under implementation, being PLL a determinant technology to achieve the high performance of on-farm irrigation systems [41]. The experimental site is located at the Dengkou area, supplied by the Dongfeng canal, in the upstream part of Hetao. The soil is a siltic irragric Anthrosol, originated from sediments deposited by the Yellow River. The soil texture is generally silt loamy in the upper layers, until a 0.60 m depth, and silt clay, below that depth. Typical field lengths vary between 50 m and 70 m and widths vary from 7 to 50 m. A set of six field parcels (H_1 to H_6), regional representative, were used to be assessed for the impacts of PLL and the improved irrigation practices (Table 1). The Hetao irrigation practice includes, in addition to the summer irrigation, an out of season autumn irrigation, which is performed after the crop season and applies a high irrigation depth, usually close to or greater than 250 mm, particularly when the soil salinity is high, being assumed as adequate an irrigation depth of 230 mm to leach the salts out of the root zone.

Figure 1. Location map of study case (Hetao; Lower-Mondego) (Map Data © 2020 Google, INEGI).



(**a**) (**b**)

Figure 2. Average monthly climatic data, maximum, medium and minimum air temperature, precipitation and reference evapotranspiration: (**a**) Hetao (Linhe county, period 1981–2012, source: Linhe Weather Station); (**b**) Lower-Mondego (Montemor-o-Velho county, period 1971–2000; source: www.ipma.pt).

Table 1. Characteristics of experimental field parcels of Hetao and Lower-Mondego.

Irrigation District	Field Code	L (m)	W (m)	A (ha)	S (%)	IM	Soil Texture	Irrigation District Sector
Hetao	H1	50	15	0.08	0.06	GB	silty loam	Dengkou
	H2	50	20	0.10	0.02	GB	silty loam	Dengkou
	H3	50	30	0.15	0.02	GB	silty loam	Dengkou
	H4	50	40	0.20	0.05	GB	silty loam	Dengkou
	H5	50	50	0.25	0.05	GB	silty loam	Dengkou
	H6	50	60	0.30	0.08	GB	silty loam	Dengkou
Lower—Mondego	M1	200	120	2.4	0.23	GF	sandy loam	Margem Esquerda
	M2	160	100	1.6	0.14	GF	sandy loam	Margem Esquerda
	M3	100	160	1.6	0	LB	loamy	Tentúgal
	M4	180	80	1.4	0.10	GF	silty loam	Montemor-o-Velho

L—length, m; W—width, m; A—area, ha; S—Longitudinal slope, %. IM—irrigation method: LB—Level Basin; GB—Graded Basin; GF—Graded Furrows. Field codes: H1 to H6—Hetao experimental fields; M1 to M4—Lower-Mondego experimental fields.

The Lower-Mondego is located on the center region of Portugal, has an irrigation area of about 12,000 ha with alluvial soils, and has a Mediterranean climate, Csb and Csa of Köppen classification, with an annual average precipitation of 900 mm. It has temperate and mild summers, with virtually no rainfall, and rainy winters with mild temperatures (Figure 2). Maize is the major irrigated crop, intensively produced. The traditional irrigation systems are the graded furrows and the furrowed level basin, selected according to the land slope and the drainage conditions. The common problems that these systems have to deal with include: the low quality of the land levelling, very erodible furrows due to tillage practices, implying its low flowrate capacity, and inadequate practices to control the inflow and cutoff time. These situations result in frequent waterlogging, water waste, fertilizers leaching, and yield losses. The priority to improve these systems is to reduce water use, while keep favoring higher yields, through the application of distribution equipment that allows a better control of the inflow rate, in order to save labor and to increase the distribution uniformity. These improvements should be linked with better practices of irrigation scheduling. This study was carried out on four research fields (M_1 to M_4) located at upstream and the medium part of Lower-Mondego Valley (Table 1), being the water diverted and conveyed by gravity from the Mondego River.

2.2. Land Levelling Assessment and Computation

To assess the actual conditions of PLL in Hetao and Lower-Mondego, inquires have been carried out to the personnel of the PLL enterprises. The questionnaire presented to machine operators included the tractor power, the levelling blade width, the total cost of service per hour, the usual operation time per hectare, the usual operation frequency in years between consecutive operations in the same field, and the range of field area were the operator usually provides the PLL service. These inquiries were posed to the operators active in each of the sites, having obtained answers from seven operators in Hetao, and from nine operators in Lower-Mondego, who answered by referring to the most common field parcels recently operated.

The experimental fields referred in Table 1 were assessed relative to the microtopography, being the observations performed before and after the PLL operations. In Hetao it was performed using a 5 m square grid, using an electronic level sensor (KGU9901, Chongqing Shanlan, Chongqing, China), with an elevation accuracy of 1 mm; in Lower-Mondego it was applied a square grid of 10 m, using an optical automatic surveyor level (NA1, Wild, Heerbrugg, Switzerland), with an elevation accuracy of 2 mm. In Hetao, the PLL operations used a grading blade controlled by a spectra precision laser (AG401, Trimble, Sunnyvale, USA). This operation was performed during October, after field ploughing and before the autumn irrigation. In Lower-Mondego, the PLL was performed in April, before maize sowing.

To assess the quality of land levelling, the root mean of squared deviations between observed and target land elevations ($RMSD_{EL}$) was used:

$$RMSD_{EL} = \sqrt{\frac{\sum_{i=1}^{N}(Obs_i - Tag_i)^2}{N}}, \quad (1)$$

where Obs_i and Tag_i (i = 1, 2, . . . , N) are respectively the observed and the target land elevations.

The land levelling computation was made by the LEVEL program, that 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:

$$Z(x, y) = z_0 + S_x \cdot (x - x_0) + S_y \cdot (y - y_0), \quad (2)$$

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 be obtained by minimizing the volume of earth to be moved, 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:

$$E(x, y) = H(x, y) - Z(x, y), \quad (3)$$

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 levelling 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. It allows the evaluation of field land levelling scenarios with a random generation of elevation data depending on the actual slopes and the standard deviation 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 levelling 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 [29,42]:

$$t_{LL} = t_{ue} \cdot V_e, \quad (4)$$

where t_{LL} = machinery time required to field land levelling (h); t_{ue} = machinery required for a unit of cut volume (h m^{-3}); Ve = 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:

$$t_{LL} = t_{ua} \cdot A, \quad (5)$$

where t_{ua} = machinery time required to land levelling a unit area (h ha^{-1}); A = field area (ha). The land levelling cost depends on the operation time t_{LL}, and the c_u = unit cost of operation land levelling equipment (€ h^{-1}), calculated by the equation:

$$C_{LL} = c_u \cdot t_{LL}, \quad (6)$$

The economic and technical land levelling input parameters applied to design irrigation systems were established according to the field data obtained from inquires to the operators and field assessment in the experimental plots, presented in Section 3.1. 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, allowing practical support to the field operation. When starting a project, the user must select the irrigation method, and carry out a land levelling simulation adopting cross and longitudinal field slopes appropriate to the considered irrigation method and the actual field slopes. LEVEL computes the cut and fill volumes required to change from the actual elevations Z(x, y) into the target elevations. The plan position (value of Z_0 of Equation (2)) is iteratively changed until the cut to fill ratio becomes >1.0 and <1.2 (Figure 3). Results include the cut and fill depths and volumes, and related costs.

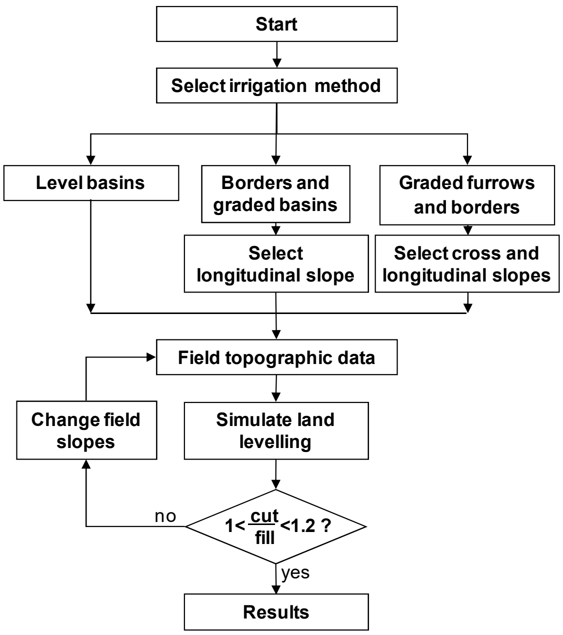


Figure 3. LEVEL flowchart, the land levelling calculation tool.

2.3. Irrigation Performance Assessment

The field evaluation includes the measurement of inflow rates, cut-off, advance and recession times, soil moisture prior and after the irrigation and crop development [27]. Field infiltration tests were performed, providing a first estimation of the Kostiakov infiltration equation parameters (Equation (7)):

$$I(\tau) = K \cdot \tau^a + f_0 \cdot \tau, \quad (7)$$

being I (m^3 m^{-2}) the cumulative infiltration, K (m^3 m^{-1} min^{-a}), a (dimensionless), and f_0 (m^3 m^{-1} min^{-1}) empirical parameters, which ones were later optimized using field advance and recession observations through the inverse method with the model SIRMOD [43,44]. Irrigation scheduling was determined for the full irrigation practice of maize, applying the water balance method, according to the methodology (Table 2) by Allen et al. [45]. Hetao irrigation scheduling refers to low salinity soil, with silty loam texture [46], and Lower-Mondego one refers to loamy soil [22].

Table 2. Average data of maize full irrigation scheduling and crop cycle in the experimental areas.

Study Site	NIE	NTI (mm)	SNI (mm)	SNIS (mm)	Yield (Mg ha^{-1})	AI (mm)	ER (mm)	ETc Act (mm)	CC (days)
Hetao	5	90	450	303	12.00	230	103	753	154
Lower—Mondego	7	56	392	140	12.00	0	130	535	140

NIE—Number irrigation events; NTI—Net target irrigation (mm); SNI—Season net irrigation (mm); SNIS—Season non-irrigation supply (mm); AI—Autumn irrigation (mm); ER—Effective rainfall (mm); ETc act—Actual crop evapotranspiration (mm); CC—crop cycle (days). Hetao data refers to a silty loam on Dengkou; Mondego data refers to a loamy soil.

The design of irrigation systems was modeled by the decision support system SADREG, developed to assist the process of designing and planning improvements in farm surface irrigation systems. The hydraulic simulations are performed with the model SIRMOD, which is incorporated in SADREG. The procedure for creating the required design alternatives and for their evaluation and ranking, follows various steps, as described by Gonçalves and Pereira [22]. Applications include several countries [18,47,48], namely in Hetao, for wheat irrigation [40]. It allows to determine the performance indicators of design alternatives (Equations (7)–(10)), useful to assess and compare alternatives for decision-aid. The input data refers to the crop data (Table 3), infiltration parameters and Manning's hydraulic roughness (Table 3), and other technical and economic parameters (Table 4).

Table 3. Infiltration and hydraulic roughness parameters used for irrigation systems design.

	Irrigation Event	K (m^3 m^{-1} min^{-a})	a (−)	f_0 (m^3 m^{-1} min^{-1})	n ($m^{-1/3}$ s)
Hetao	First	0.0049	0.526	0	0.04
	Later	0.0045	0.510	0	0.04
Lower—Mondego	First	0.0042	0.625	0.00020	0.04
	Later	0.0032	0.563	0.00017	0.04

K—coefficient of infiltration function (m^3 m^{-1} min^{-a}); a—exponent of infiltration function (dimensionless); f_0—basic infiltration rate (m^3 m^{-1} min^{-1}); n—Manning's hydraulic roughness ($m^{-1/3}$ s); Hetao data refers to a silty loam on Dengkou; Lower-Mondego data refers to a loamy soil.

Table 4. Technical and economic parameters used for irrigation systems design (2020 prices).

Parameter		Hetao	Lower-Mondego
Water distribution equipment	type of equipment	Non-lined canal	Layflat tubing
	aquisition cost	0.125 € m^{-1}	1.0 € m^{-1}
	effective life-time	1 year	1 year
Water cost	price per volume	0.010 € m^{-3}	0.025 € m^{-3}
	fixed per area	100 € ha^{-1}	100 € ha^{-1}
Crop price	yield price	0.30 € kg^{-1}	0.30 € kg^{-1}
Labour cost	unit cost	4.0 € h^{-1}	5.0 € h^{-1}

Currency exchange: 1 Euro = 8.0 Yuan.

A set of 16 irrigation projects were considered in this study, through a simulation process, being selected based on the authors experience, applying the irrigation methods and the on-farm distribution systems with more potential and feasibility for each one of the study sites (Table 5): For Hetao, the furrowed level basin (LB) were designed with 50 m, 100 m and 200 m length, and the furrowed graded basin (GB) with the longitudinal slopes of 0.05% and 0.10%, for 100 m and 200 m length. For Lower-Mondego, furrowed level basin (LB) were designed with 100 m and 200 m length, and the graded furrows with a longitudinal slope of 0.05% and 0.10% (GF), with 100 m, 200 m and 265 m length. A medium value of inflow rate per furrow was defined in relation to the furrows or basin length. The on-farm water distribution system considered was: i) for Hetao, the non-lined canal equipped with modern field gates, well-adjusted to the high charge of sediments of irrigation water which does not allow a pipe distribution system, a low cost solution, well practiced by farmers; ii) for Lower-Mondego, the lay-flat tubing with manual valves to adjust each single gate, the most usual solution, with a reduced cost and well managed by farmers.

Table 5. Surface irrigation projects for PLL assessment.

Study Site	L (m)	S (%)	IM	W (m)	A (ha)	Project Identifier
Hetao	50	0	LB	30	0.15	H-LB-50-null
	50	0.05	GB	30	0.15	H-GB-50-0.05
	100	0	LB	50	0.50	H-LB-100-null
	100	0.05	GB	50	0.50	H-GB-100-0.05
	100	0.10	GB	50	0.50	H-GB-100-0.10
	200	0	LB	50	1.0	H-LB-200-null
	200	0.05	GB	50	1.0	H-GB-200-0.05
	200	0.10	GB	50	1.0	H-GB-200-0.10
Lower--Mondego	100	0	LB	75	0.75	M-LB-100-null
	100	0.05	GF	75	0.75	M-GF-100-0.05
	100	0.10	GF	75	0.75	M-GF-100-0.10
	200	0	LB	75	1.5	M-LB-200-null
	200	0.05	GF	75	1.5	M-GF-200-0.05
	200	0.10	GF	75	1.5	M-GF-200-0.10
	265	0.05	GF	75	2.0	M-GF-265-0.05
	265	0.10	GF	75	2.0	M-GF-265-0.10

L—Field length (m); S—Slope (%); IM—Irrigation method: LB—Level Basin; GB—Graded Basin; GF—Graded Furrows; W—Field width (m); A—Field area (ha).

The irrigation performance indicators adopted are described below [49] (Pereira et al. 2012):

(a) Beneficial water use fraction (BWUF, %), expressing the efficiency of water application on field, is defined as:

$$\text{BWUF} = \begin{cases} \frac{Z_{avg}}{D} \times 100;\ Z_{lq} > Z_{req} \\ \frac{Z_{lq}}{D} \times 100;\ Z_{lq} < Z_{r} \end{cases}, \quad (8)$$

where Z_{avg} is the average depth of water infiltrated in the whole irrigated field (mm), Z_{lq} is the average low quarter depth of water infiltrated (mm), and D is the average water depth (mm) applied to the field. The two equations are used to distinguish the cases of over-irrigation ($Z_{lq} > Z_{req}$) and under-irrigation ($Z_{lq} < Z_{req}$).

(b) Distribution uniformity (DU, %), expressing the quality of the irrigation system to uniformly infiltrate the water spatially, is defined as:

$$\text{DU} = \frac{Z_{lq}}{Z_{avg}} \times 100, \quad (9)$$

(c) Irrigation Water Productivity (IWP, kg m^{-3}), expressing the amount of physical production obtained per unit of irrigation water applied, is defined as:

$$\text{IWP} = \frac{Y_a}{\text{IWU}}, \quad (10)$$

where Ya is the actual crop yield, and IWU the irrigation water use.

(d) Economic Water Productivity Ratio (EWPR, ratio), expressing the economical production obtained per unit of cost relative to the irrigation water applied, is defined as:

$$\text{EWPR} = \frac{\text{Value(Yield)}}{\text{TIC}}, \tag{11}$$

where Value (Yield) is the monetary value of yield, and TIC is the total irrigation cost.

(e) Total Irrigation Cost (TIC, € ha^{-1}) is defined as:

$$\text{TIC} = \text{PLLC} + \text{IWC} + \text{ILC} + \text{DSC}, \tag{12}$$

where PLLC is the precise land levelling cost, IWC is the irrigation water cost, ILC is the irrigation labor cost, and DSC is the distribution system cost.

3. Results

3.1. Land Levelling Assessment

The results of the survey answered by the operators of land levelling equipment (Table 6) show that there are well-differentiated conditions for the PLL service in the two irrigation districts. In Lower-Mondego, the PLL is intensively used in the paddy rice fields, and the field parcels are larger than those in Hetao, justifying the use of powerful and wider equipment (195 HP, 5.0 m, and 4-wheel-drive tractors). In Hetao, the small sized field parcels and the traditional levelling practice explains that the requirements for PLL service is relatively reduced and carried out with machines with lower power and width (150 HP, 3.2 m, and 4-wheel-drive tractors).

Table 6. Characteristics of precise land levelling equipment used in maize fields on study sites.

Study Site	TP (HP)	LBW (m)	HC (€ h^{-1})	LR (h ha^{-1})	OF (Year)	RFA (ha)
Hetao	100	3.0	30	5–7	1–3	0.1–0.4
	120	3.0	30	5–6	2–3	0.2–0.4
	120	3.2	30	4–6	2–3	0.2–0.4
	150	3.2	33	3–5	2–4	0.2–0.4
	200	3.2	38	3–4	2–4	0.2–0.4
	150	3.5	35	3–4	2–4	0.4–1.0
	200	3.5	38	2–4	2–4	0.4–1.0
Lower—Mondego	140	4.5	65	2.5	3	0.3–5
	145	4.5	60	2.5	5	0.6–6
	240	6.0	80	2.0	5	0.3–7
	360	6.0	100	1.5	5	1.2–20
	155	4.5	60	2.0	8	0.3–5
	210	6.0	85	2.0	6	1.2–15
	200	5.0	80	2.0	10	0.5–13
	165	4.5	60	2.5	8	0.3–16
	140	4.0	60	2.5	8	0.35–10

TP—Tractor power (HP); LBW—levelling blade width (m); HC—Hour cost (€ h^{-1}); LR—Levelling rate (h ha^{-1}); OF—Operation frequency (years); RFA—Range of field area (ha).

The operation frequency of the land levelling maintenance of maize field parcels is a decision variable with a significant impact on system performance. In Lower-Mondego, the practice has been showing a low accuracy of this operation, adopting long frequencies, many times exceeding 5 years. General explanation of farmers for this practice included: (i) difficulties in reconciling the PLL operation with other sowing preparation tasks in March and April; (ii) the relative abundance and low cost of irrigation water, not inducing water saving practices and leading to the devaluation of land levelling; (iii) the significant cost of PLL; and iv) the difficulty in making the equipment available in the period when the operation is most recommended, generally after the ploughing. In Hetao, due to the reduced quality of the operation by traditional processes and its affordability to growers, this operation is more frequently performed, every 2 to 4 years, to overcome the problems due to ploughing and harrowing, which significantly deteriorate the land levelling in very small plots.

The average excavated volume was higher in Hetao (401 m^3/h) than in Lower-Mondego (167 m^3/ha). These differences are directly related with the initial low quality of the land form on both irrigation districts, according to the values of $RMSD_{EL}$, therefore dependent on the previous land levelling practices. The levelling rate of PLL operations achieved values of 4.7 ± 1.0 h/ha in Hetao, and 2.7 ± 0.24 h/ha in Lower-Mondego. This rate depends on the length of the paths to be covered within the field parcel, between the excavation points and the landfill points; however, the longer field parcels are favoured as they enable fast equipment and fewer turns. The PLL operation cost, referring to one single operation, was 151 ± 40 €/ha in Hetao and 176 ± 1.9 €/ha in Lower-Mondego.

The results obtained from inquires to the PLL operators and from field assessment, allowed to determine the PLL parameters: levelling rate (h/ha), hour cost (€/h), and operation frequency (years), presented in Table 6. These results jointly with data from the field parcels (Table 7) were used as the input for the simulation of design projects, according to their description on Table 5. The levelling rates in Hetao were 3.0 and 3.5 h/ha for graded and level basins; in Lower-Mondego these values were 2.5 and 3.0 h/ha for level furrows with 200 m and 100 m, respectively, and 2.0 h/ha for graded furrows. The differences between irrigation methods are explained by the major requirements of accuracy of level basins, compared with graded fields. The differences between the irrigation districts are explained by the short length of the 50 m parcels and the lower power of the equipment of Hetao. The unitary cost of the PLL was 38 €/h in Hetao, and 70 €/h in Lower-Mondego. The frequency of the PLL operation in Hetao was a yearly operation on fields lower than 100 m length, and two years for longer fields, given the higher efficiency on longer field parcels. In Lower-Mondego the frequency of the PLL operation was two years for level basins and three years for graded fields, a solution significantly more frequent than the actual practice of land levelling maintenance, aiming to achieve a satisfactory accuracy.

Table 7. Precise land levelling data from the field parcels.

Field Parcel Code	TP (HP)	LBW (m)	HC (€/h)	$RMSD_{EL}$ (cm)		LR (h/ha)	EV [2] (m^3 ha^{-1})	EVH (m^3 h^{-1})	PLLC [3] (€/ha)
				Before PLL [1]	After PLL				
H1	100	3.0	30	8.3	3.5	4.3	374	87	129
H2	100	3.0	33	7.2	2.5	4.8	327	68	158
H3	100	3.0	35	9.1	2.6	6.3	414	66	221
H4	100	3.0	30	14.9	3.4	4.2	601	143	126
H5	120	3.2	33	10.9	3.0	3.3	442	134	109
H6	120	3.2	30	5.3	2.8	5.4	247	46	162
ave [4]	—	—	32	9.3	3.0	4.7	401	91	151
std [4]	—	—		3.3	0.41	1.0	120	39	40
M1	140	4.0	65	4.4	2.3	3.0	180	60	195
M2	140	4.0	60	4.2	2.6	2.5	175	79	150
M3	140	4.0	65	3.1	2.0	2.8	96	34	182
M4	145	4.5	70	4.3	2.4	2.5	215	86	175
ave [5]	—	—	65	4.0	2.3	2.7	167	65	176
std [5]	—	—		0.6	0.2	0.2	50	23	2

[1] Previous land levelling condition: Hetao, traditional practice; Lower-Mondego, medium quality. [2] Excavation volume calculated based on elevation data before and after land levelling. [3] PLLC—PLL operation cost (€ ha^{-1}) of a unique PLL operation. [4] ave—average, std—standard deviation of Hetao parcels (H1 to H6). [5] ave—average, std—standard deviation of Lower-Mondego parcels (M1 to M4). LR—Levelling rate (h ha^{-1}); EV—Excavation volume (m^3 ha^{-1}); EVH—Excavated volume per hour (m^3 h^{-1}).

3.2. Impacts on Irrigation Performance

The assessment of the irrigation performance, based on observations carried out in the experimental fields (Table 8), shows that the modernized systems allow a higher irrigation efficiency, with BWUF higher than 75%, achieving 86% on field M1 (Lower-Mondego) and 88% on field H3 (Hetao). It should be noted that these results combine the effects of PLL with adequate irrigation scheduling, inflow rates and cut-off control, it is not possible to differentiate the isolated effects of each of these factors.

Table 8. Summary of field observations on precise land levelling parcels.

Field Code	BWUF (%)	DU (%)	Zreq (mm)	DP (%)	q_0 ($l\ s^{-1}\ m^{-1}$)	t_{av} (min)	t_{co} (min)
H3 [1]	88	95	109	12	1.9	35	48
M1	86	91	56	14	2.5	47	56
M2	78	81	71	22	1.4	70	102
M3	76	80	57	24	1.9	37	60
M4	75	77	85	25	1.6	80	120

[1] The field H3 is the most representative and was used to show data of a 50 m length parcel. Notes: The previous operation was the common LL; Values calculated from observed field elevation data. BWUF—beneficial water use fraction (%); DU—distribution uniformity (%); DP—deep percolation (%); t_{adv}—advance time (min); t_{co}—cut-off time (min); q_0—unitary inflow rate ($l\ s^{-1}\ m^{-1}$).

The performance indicators of the designed projects (Table 9) allow to conclude that the BWUF is, in general, very high (higher than 80%). The lowest values were obtained on level basin fields with 200 m length (with 67%, in Hetao), on graded borders of 200 m in Hetao (71.4% and 76.8%, relative to the slopes of 0.05% and 0.10%), and on graded furrows with 265 m length and a slope of 0.10% in Lower-Mondego (80.6%). The values of the crop yield achieved, in Hetao, the maximum value in fields with 50 m and 100 m with null or 0.05% slopes. For longer fields, the uniformity of infiltration decreases, and, in consequence, there are negative effects of crop yield; however, in Lower-Mondego, the uniformity of infiltration had high values (higher than 95% in the majority of the design projects). The values of IWP varied from 2.40 and 1.92 kg m^{-3} in Hetao, on 100 m fields, decreasing to 1.74–1.85 kg m^{-3} on 200 m length fields. In Lower-Mondego the maximum value was 2.70 kg m^{-3}. The values of EWPR varied from 7.16 to 11.82 in Hetao, and 6.16 to 9.65 in Lower-Mondego, and, in both irrigation districts, it is evident the scale effect of field area: higher field parcel area imply lower PLL, labor and distribution system costs. The indicator IWP is not correlated with the field parcels area (Figure 4), showing that surface irrigation has flexible solutions on the several plot sizes to cope with the issues of optimizing water productivity and water saving.

3.3. Impacts on Economics

The results of the annual irrigation costs (Table 10) show that the PLL, in Hetao, has the highest value of 133 €/ha in level basins of 50 m and 100 m length, and the minimum value of 57 €/ha in graded basins. In Lower-Mondego, these costs vary between 105 €/ha in level fields with 100 m length, and 47 €/ha in graded fields. The water cost is directly related with the irrigation performance, through the BWUF (Table 9). To note that the values relative to Hetao only consider the summer irrigation events. In its turn, the labor costs are inversely related with the field length, facing higher application times. In Hetao, the value of labor cost varies from 195 €/ha in basin with 50 m length, to 58 €/ha in level basin with 200 m. In Lower-Mondego, a basin with 100 m length requires 140 €/ha and a graded furrow of 265 m the cost is 60 €/ha. These results show the positive impact on economics of the higher size of the field parcels. The relative PLL cost indicator (ratio to the total irrigation cost) in Hetao, varies between 0.18 (graded border of 200 m) and 0.26 (level basin of 50 m) with the lowest value on the 200 m field length. In Lower-Mondego, this indicator is more uniform, with 0.10–0.12 for graded furrows, and 0.19–0.21 for level basin, reflecting the additional PLL cost of these systems.

Table 9. Surface irrigation projects for PLL assessment.

Projects	Y (kg/ha)	RY (-)	ELP (€/ha)	BWUF (%)	IWU (m^3/ha)	IWP (kg m^{-3})	EWPR (-)
H-LB-50-null	11,992	0.999	3598	90.0	5000	2.40	7.16
H-GB-50-0.05	11,991	0.999	3597	90.0	5000	2.40	7.47
H-LB-100-null	11,994	1.000	3598	88.0	5114	2.35	8.73
H-GB-100-0.05	11,977	0.998	3593	84.3	5340	2.24	8.95
H-GB-100-0.10	11,090	0.924	3327	78.0	5767	1.92	7.44
H-LB-200-null	11,719	0.977	3516	67.0	6720	1.74	11.82
H-GB-200-0.05	11,628	0.969	3488	71.4	6300	1.85	11.73
H-GB-200-0.10	10,767	0.897	3230	76.8	5859	1.84	10.04
M-LB-100-null	11,483	0.957	3445	86.0	4557	2.52	6.16
M-GF-100-0.05	11,390	0.949	3417	87.2	4498	2.53	6.99
M-GF-100-0.10	11,202	0.934	3361	87.6	4476	2.50	6.88
M-LB-200-null	10,084	0.840	3025	78.5	4995	2.02	7.16
M-GF-200-0.05	11,315	0.943	3395	85.1	4605	2.46	8.89
M-GF-200-0.10	11,842	0.987	3553	89.4	4387	2.70	9.20
M-GF-265-0.05	11,250	0.938	3375	81.6	4806	2.34	9.26
M-GF-265-0.10	11,777	0.981	3533	80.6	4864	2.42	9.65

Y—Yield, kg/ha; RY—Relative yield (ratio); ELP—Economic Land Productivity, €/ha; BWUF—Beneficial Water Use Fraction (%); IWU—irrigation water use, m^3/ha; IWP—irrigation water productivity, kg m^{-3}; EWPR—Economic Water Productivity Ratio, dimensionless.

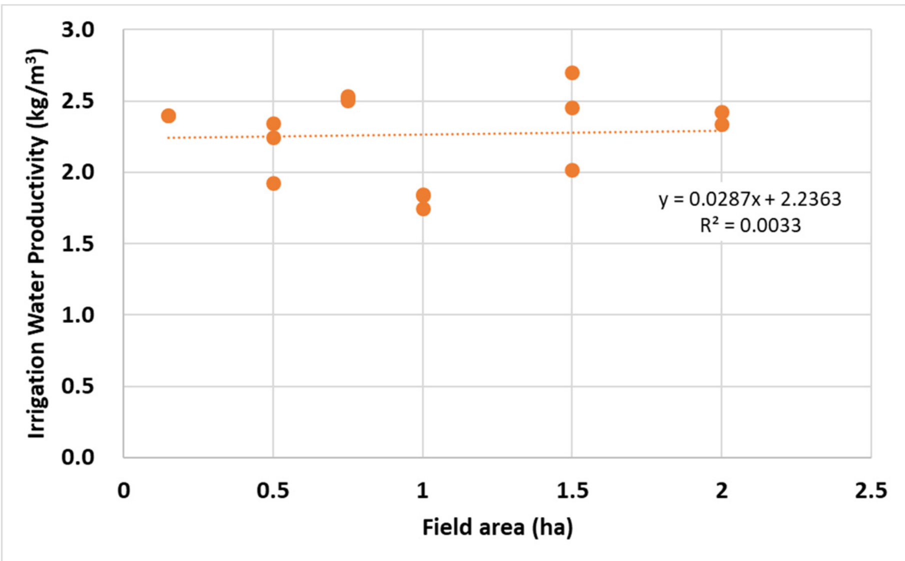


Figure 4. Relationship between field parcel area and irrigation water productivity.

Table 10. PLL parameters and components of irrigation cost of design projects.

Projects	PLL Parameters [1]			Costs [2] (€/ha)					Cost Ratio
	OT (h/ha)	HC (€/h)	OF (years)	PLLC	IWC	ILC	DSC	TIC	PLLC/TIC
H-LB-50-null	3.5	38	1	133	150	194	25	502	0.26
H-GB-50-0.05	3.0	38	1	114	150	193	25	482	0.24
H-LB-100-null	3.5	38	1	133	151	116	13	412	0.32
H-GB-100-0.05	3.0	38	1	114	153	121	13	401	0.28
H-GB-100-0.10	3.0	38	1	114	158	144	13	428	0.27
H-LB-200-null	3.5	38	2	67	167	58	6	297	0.22
H-GB-200-0.05	3.0	38	2	57	163	71	6	297	0.19
H-GB-200-0.10	3.0	38	2	57	159	100	6	322	0.18
M-LB-100-null	3.0	70	2	105	214	140	100	559	0.19
M-GF-100-0.05	2.0	70	3	47	212	130	100	489	0.10
M-GF-100-0.10	2.0	70	3	47	212	130	100	489	0.10
M-LB-200-null	2.5	70	2	88	225	60	50	422	0.21
M-GF-200-0.05	2.0	70	3	47	215	70	50	382	0.12
M-GF-200-0.10	2.0	70	3	47	210	80	50	386	0.12
M-GF-265-0.05	2.0	70	3	47	220	60	38	365	0.13
M-GF-265-0.10	2.0	70	3	47	222	60	38	366	0.13

[1] PLL parameters: OT—operation time (h/ha); HC—hour cost (€/h); OF—operation frequency (years). [2] Annual costs (€ ha^{-1} $year^{-1}$): PLLC—precise land levelling cost, annuity value; IWC—irrigation water cost; ILC—irrigation labor cost; DSC—distribution system cost, annuity value; TIC—Total irrigation cost; exchange rate: 1 Euro=8.0 Yuan.

The relationship between the field parcel area and a single PLL operation cost is presented in Figure 5, considering the data of field assessment (Table 6) and the data of design projects simulated. These results clearly show that these two variables are not correlated (R^2 = 0.076). The explanation for this result is that the type of equipment is adjusted to the size of the field parcels: the smaller ones in Hetao use lower and cheaper equipment, the opposite of what happened in Lower-Mondego. Note that this data does not show the lower quality of PLL on those smaller field parcels, as can be observed on Table 6.

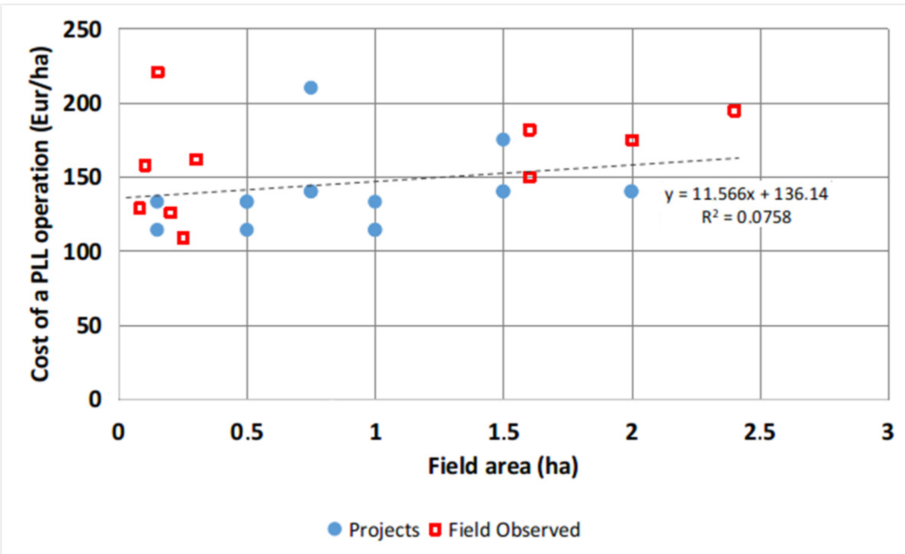


Figure 5. Relationship between field parcel area and the PLL operation cost, considering simulated projects and field observations.

The relationship between the field parcel area and the ratio between PLL operation cost and total irrigation cost (Figure 6), considering the data from the designed projects, shows a mild decrease trend of the relative cost of PLL with the area (slope of −0.0792), with a small correlation (R^2 = 0.391). It is explained by the higher economic effectiveness of land levelling in higher fields, compared with the water, labor and distribution system costs.

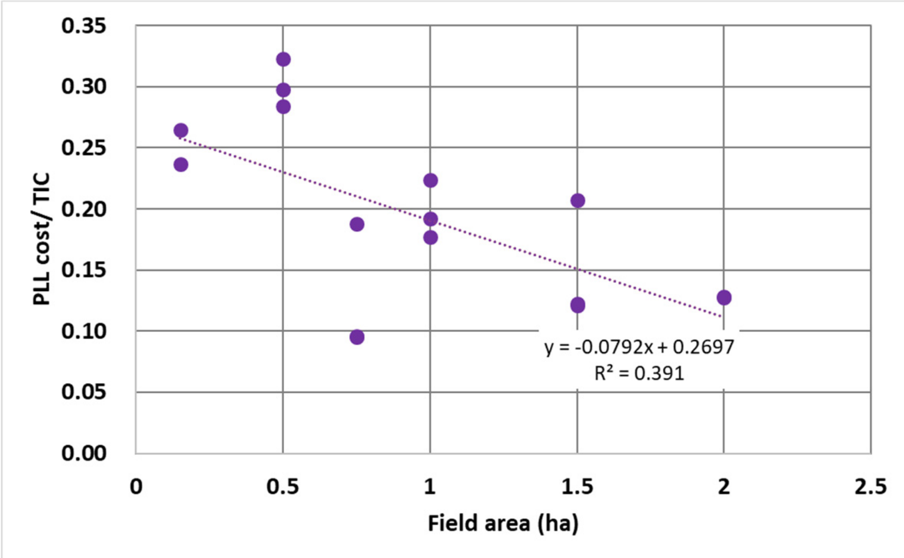


Figure 6. Relationship between field parcel area and the ratio of the precise land levelling cost and the total irrigation cost.

4. Discussion

Precision land levelling allowed a great development of surface irrigation, through a high performance on the use of water, land, labor, fertilizers and energy resources, when properly managed. This performance explains the significant economic productivity and sustainability of these irrigation systems, worldwide reported [3,9,11,13,21]. PLL complemented with surface irrigation improvements allows water savings on maize irrigation, when compared with the traditional practices. There are examples of water saving reported worldwide: in India, 22–33% [24], and 11.5–20.5% [11]; in the USA, Mississipi River Valley, 39.5% [50]. Therefore, the results of the present study confirm the success of surface irrigation, showing that PLL, combined with adequate irrigation scheduling and control of inflow rates and cut-off, had direct impact on maize water productivity and economics. Values of BWUF of 80–90%, IWP of 2.0–2.4 kg/m^3, and EWPR of 6–8, were observed on Hetao and Lower-Mondego, which are similar to the good ones achievable by sprinkler systems.

The expansion and improving of the PLL is a priority in several regions to overcome the increasing water scarcity and to meet the requirements to reduce labor and energy consumption. This issue implies the application of extensive programs to explain farmers the importance of PLL and its technical efficient application. An example of the perception of farmers to the PLL is reported by Hosseini [51] about an Iranian case study, being observed a positive relationship between farmer's knowledge, attitude, opinion and motivation factors, with the PLL appropriateness. The positive relationship between farmers' accession to PLL and the size of land holders is another aspect, (e.g., observed in India [12], and in Portugal [52]), concluding the major difficulties to apply PLL to be small plots and poor farmers. In fact, farm size matters for achieving operational efficiency of the laser leveler to manifest its full potential. Therefore, reparcelling of land is determinant in several regions to increase the plot size for better production efficiency. Another advantage of reparcelling and PLL in small land areas is the enhance of the cultivable area due to removal of extra bunds and channels in the field: Jat et al. [15] and Sidhu et al. [53] reported increased average areas of 3.2% and 9%, respectively. These changes of the rural environment should be carefully analysed to consider its impacts on landscape, livelihood, social, traditional culture and heritage [54].

The use of PLL equipment has become economically feasible and accessible through custom services, even to lower income farmers of South Asia, as reported by Jat et al. [15]. The development of PLL practice is the local availability of equipment suitable for the specific land levelling requirements. It is highly related with farmers' demand, the size of field parcels, and the usual time period for the execution of the operation. The cost of owning the equipment can be overcoming by using hiring services by smallholder farmers. The results of the survey of equipment available on both case studies (vd. Table 6) has shown that the local market offer is relatively limited, constraining the choice of equipment that should be used for each particular field parcel. This issue is challenging, with impacts on levelling quality and cost.

The levelling rate of the equipment (h/ha) shows the effectiveness of the operation; higher levelling rate imply a fast and accurate operation, with less soil compaction and executed at more right time, implying, however, that more powerful equipment is only well adapted to larger plots. Clemmens and Dedrick [55] reported levelling rates in the South West of the USA of about 1.0 h/ha to 2.0 h/ha (the lower value referring the maintenance of level basins previously PLL finishing), with large equipment (8–10 m^3 scrapers, tractor with 200 HP and 4-wheel drive tractor); on the other hand, Aryal et al. [56] in India, reported an average rate of 5 h/ha for the first PLL operation. The levelling rates observed in Hetao and Lower-Mondego with lower values than referred by Clemmens and Dedrick [55] were most likely caused by: (i) smaller equipment, (ii) improper matching or inappropriate selection of equipment, (iii) greater unlevelness occurring since last levelling and, thus, the need for moving more mass than in the USA.

The land levelling maintenance is an operation determinant to guarantee a high effectiveness of the irrigation performance in a long term period. It happens that, after a PLL operation, this precision needs to be maintained due to the soil mobilization, like mouldboard, ploughing, or disking, which tends to decrease the precision, unless proper equipment and operational procedures are used. This issue was addressed by several researchers, being used for level basins the standard deviation of the field surface elevation as an indicator to represent the lack of precision of the levelling: Clemmens and Dedrick [55] reported that, in the South West of the USA, the PLL on level basins has a typical Sd of 1.2 cm. Sousa et al. [8] reported, in Portugal, an Sd of 1.7 cm immediately after levelling; also that, after PLL on level basins, a reduction of the Sd from 3.0 cm to 1.7 cm, implies an increasing of 18% and 12% of DU, and maize yield, respectively. Observed practices on Hetao and Lower-Mondego have shown (vd. Table 6) that maintenance is not properly cared for, with frequencies between two and four years in Hetao, and higher than four years in Lower-Mondego, plus the fact that deep ploughing is carried out annually. These frequencies exceed the general recommendations of one or two years for level basins, and a maximum of three years for graded furrows [4]. However, similar situations of deficient levelling maintenance are reported by several authors [11,12,15,51].

The optimization of the PLL practice is a challenging issue, needed to save cost and increase benefits. Analysis of actual field data reveals that there are still cases of inefficient use, so monitoring, good practices and optimization should be priority tasks of farmers, water user's associations and rural extension services. It is urgent to have quantitative measures of soil topography to guide the land levelling operation, and to assist in determining the precision control requirements, associated with soil tillage practices. The accurate monitoring of soil surface topography is a basic element. The newest technologies based on UAV [26] open fast procedures to collect data to support decisions on the land levelling maintenance. Also, the impact analysis of PLL could be improved, as reported by Alzoubi et al. [34] that have applied the methodology of genetic algorithms to predict environmental indicators for PLL, such as labor, energy, and machinery cost, opening an innovative procedure to optimize the planning and practice of PLL. Well trained operators and carefully adjusted equipment, and informed farmers, is fundamental [12]. It is very important to design operational guidelines to support the PLL planning, schedule, and operation. The PLL operation should be executed under satisfactory field conditions, being timing, weather, and field condition the factors that must be considered, and annual maintenance should be highlighted as an important part of the farmer's operation to obtain the proper return on the land levelling investment [4].

5. Conclusions

This study aimed to assess the performance and the impacts of PLL on surface irrigation systems, focusing on maize crops on Hetao and Lower-Mondego case studies. The experimental study at field scale analyzed the laser-controlled land levelling, based on topographic surveys with the application of a calculation tool, and evaluated the on-farm irrigation under precise levelled fields and well management practices. PLL operators have been inquired to improve the knowledge about hiring services, and the design of surface irrigation scenarios allowed to explain the effects of field size and slope on irrigation and land levelling performance.

The PLL operation was shown to be crucial for surface irrigation modernization, and that the traditional practices have strong constraints on land forming. The PLL allowed values of $RMSD_{EL}$ of 2.5–3.5 cm in Hetao, and 2.0–2.6 cm in Lower-Mondego. The modernized systems that combine PLL with adequate irrigation scheduling, inflow rates and cut-off control have a BWUF from 75% to 86%, a IWP between 1.74–2.40 kg m^{-3} in Hetao and 2.0–2.7 kg m^{-3} in Lower-Mondego, and a EWPR between 7.16–11.82 in Hetao and 6.16–9.65 in Lower-Mondego, evidencing that higher field parcel area imply lower PLL labor and lower distribution system costs. The levelling rate of PLL operations achieved values of 4.7 $\pm$ 1.0 h/ha in Hetao and 2.7 $\pm$ 0.24 h/ha in Lower-Mondego, with a unitary cost of 38 €/h in Hetao, and 70 €/h in Lower-Mondego. The PLL annual cost, in Hetao, was 133 €/ha in level basins of 50 m and 100 m length, and 57 €/ha in graded basins, and in the Lower-Mondego was 105 €/ha in level fields with 100 m length and 47 €/ha in graded fields. The ratio of PLL cost to TIC varied between 0.18–0.26 in Hetao, with the lowest value on the 200 m field length, and in the Lower-Mondego was 0.10–0.12 for graded furrows, and 0.19–0.21 for level basin, reflecting the additional PLL cost of these systems. The PLL operation cost of a single operation was 151 $\pm$ 40 €/ha in Hetao and 176 $\pm$ 1.9 €/ha in Lower-Mondego.

The development of the surface irrigation through the field reshaping creating longer field parcels has potential to improve irrigation performance, with favourable economic results, showing possibilities to reduce the labour irrigation costs due to a larger application time, added with the increased efficiency of the cultivation and of the PLL machinery when the field length is longer.

Land levelling maintenance is an important issue to guarantee a high effectiveness of irrigation performance. It should be highlighted that the its effectiveness requires the adoption of other improvement measures, namely those related with the irrigation management, or with the agronomic inputs and practices. The optimization of PLL appeals the application of better soil tillage practices and the monitoring of soil surface elevations with newer information technology tools to support decisions about the land levelling maintenance. Efficient operational guidelines to support the PLL planning, schedule, and operation are key factor to its improvements, such as well trained operators, carefully adjusted equipment, and informed farmers. Appropriate extension and training services for farmers and equipment operators, as well as institutional and economic incentives, are also determinant.

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