Water saving techniques and practices for on-farm surface irrigation systems †

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Abstract: Water saving from irrigated agriculture is a world-wide priority facing the increasing water demand by multiple non-agricultural users and the variability in climate regimes affecting the availability of water resources. The challenges of water saving for surface irrigation systems are particularly important because these systems are the most used in the world. In turn, these systems are the ones that allow a greater margin for saving water, because they are often degraded, working with high water losses. Modern methods provide water and energy saving, control of environmental impacts, labor saving, and cropping economic success. The methodology applied in this study is based on the field experimentation of modern surface irrigation technologies and on its analysis by a decision support system. The results include alternative irrigating solutions by level basin, graded border and graded furrows, using precision land leveling, and their performance evaluation. The study’s conclusions prove the effectiveness of modern surface water systems and the need to adapt to local characteristics of plot size and slope, soil type and water supply. Also relevant on development, the issue that the local markets with equipments and consulting services should be available for farmers.

Keywords: Surface irrigation; agricultural water management; irrigation water productivity; water use indicators

1. Introduction

The increasing water demand by multiple non-agricultural users and the variability in climate regimes affecting the availability of water resources, have led to society urging for water saving from irrigated agriculture, particularly in water scarce areas [1]. How-ever, water savings in agriculture must be compatible with the farmers’ technical know-how and their farms’ economic sustainability. This task is often complex because the severe reduction of water supply for irrigation implies serious social, economic and environmental impacts, particularly for poor peasant farmers [2]. Consequently, the water use in agriculture requires an assessment of its value to fully understand the effects of any change. It is also necessary to find technical solutions related to agronomic and irrigation practices that can adapt these systems to cope with water scarcity and climate change [3].

Surface irrigation systems are characterized by the water application to one or more sites of the head of the plot, with a free flow over the soil surface and by gravity to the place where the infiltration into the root zone of the crop occurs [4]. These systems are adopted worldwide, representing more than 83% of the world’s irrigated area, mainly in Asia, for both rice paddies and field crops. The advantages to adopt surface irrigation include the simplicity of its application at farm in flat areas with low infiltration rates, namely when water conveyance and distribution are performed with canal, or low-pressure pipe systems, low capital investment, and low energy consumption. The most significant limitations include high soil infiltration and high variability of infiltration through-out the field, land leveling requirements, need for control of a constant inflow rate, difficul-
in matching irrigation time duration with soil water deficit at time of irrigation, and difficult access to equipment for mechanized and automated water application and distribution.

There is a high potential for surface irrigation development, as it is still used in various regions of the world in a precarious and inefficient way, which opens a significant margin for progress regarding water saving and water productivity improvement [5]. These traditional systems are often degraded, and their development and modernization represents a major technical, economical and social challenge. The systems located in water-scarce areas have great potential for water saving, because the technologies that allow an increase of water productivity can be quite effective. Even in modernized systems, there are several factors that can be adjusted to increase the efficiency.

Improving the irrigation performance requires a variety of measures and practices, acting on systems design and operation, which provide for reducing the water use, increasing land and water productivity, and enabling an higher farmer income. These main aspects are further developed below.

1. Precision land leveling - Laser-assisted precision land leveling control is a technology applied in modern surface irrigation systems, that allows a fast and efficient operation, being these equipments available worldwide [6]. The precise land levelling reduces the advance time and the volume of water needed to complete the advance, improving the infiltration uniformity and allowing higher yields, and prevents ponding and improves drainage.

2. Level basin - The adjustment of inflow control to the basin length and slope, allows a high distribution uniformity and labor savings [7]. The equipment to control the inflow enables a wide range of solutions. Irrigation performance can be improved through the shortening of the basin length, or the reducing of their width, allowing shorter advance time and higher distribution uniformity, when the inflow rate is small or variable.

3. Rice paddy - Irrigation water use can be reduced resorting to keeping shallow water depths in basins, for lower seepage and percolation losses, aiming higher yields and better conditions to store any storm rainfall [8]. Another technique uses the alternate wetting and drying method, decreasing percolation losses and methane emissions [9].

4. Graded border - The modernization follows the procedures of basin irrigation, namely adopting precise land-leveling, and analogous equipments for inflow rate control [10]. If the borders are open at the downstream end, outflow could be controlled by anticipated cutoff, and runoff may be reused. A recent trend is the conversion of border method to the basin irrigation, adopting a ridge-furrow system for row crops, when land slopes are small.

5. Graded furrows - The inflow rate control may be achieved with different types of equipments [11], namely: gated pipes, including lay-flat tubes, which supply water to each furrow under automated valves control, as well as different techniques, like surge-flow, irrigation with cutback, cablegation, and irrigation by alternate furrows.

6. Reuse of tail water runoff - Systems with tail end open, mainly graded border and furrows, can adopt a drainage reuse system of runoff, either through a pumping system to the parcel head side, or by gravity, to other fields. The reuse systems could be integrated in automatic on-farm distribution systems, allowing water and labor savings [12].

7. Irrigation systems design - Advances in design method are based on simulation modeling and computing, which provided good tools for new systems, as well as, for the
modernization of traditional ones. These design models integrate the hydraulics simulation modeling with irrigation scheduling, land leveling, water delivery and distribution systems [11], and cost and environmental analysis [13].

8. Irrigation systems real-time management - The real-time control of inflow rate and cutoff time is a big challenge to deal with soil infiltration variability in time and space. The use of sensors for water advancing monitoring in furrows or borders and using wireless transmission and controllers equipped with receivers and specific operational algorithms open perspectives for higher irrigation performance and systems automation [14, 15].

The objective of this article is to present the issue of the water saving of surface irrigation systems, focusing on the challenges of practical implementation of innovative measures, aiming economical and environmental sustainability. The research carried out in two case studies, illustrating the practical issues of modernizing irrigation, and its impacts on irrigation water use and farmer’s economics.

2. Materials and Methods

This study focused on two distinct geographic sites, Hetao Irrigation District, China (Hetao) and Lower-Mondego Irrigation District, Portugal (Lower-Mondego). 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. The description of these sites is presented by Miao et al. [16]. The field evaluation procedure considered measures of irrigation scheduling, soil texture and hydraulic properties, and advance and recession data during irrigation events. Field infiltration tests were performed, providing the infiltration equation parameters, later optimized using field advance and recession observations through the inverse method with the model SIRMOD [17]. The design of irrigation systems were modeled by a decision support system, as described by Gonçalves and Pereira [13], allowing to determine the performance indicators of several alternatives. Irrigation scheduling was determined for the full irrigation practice of maize, applying the water balance method, according to the methodology (Table 1) by Allen et al. [18]. Hetao irrigation scheduling refers to low salinity soil, with silty loam texture, and Lower-Mondego one refers to loamy soil. The irrigation systems options include the present practices, used as reference, and alternative modernized methods based on precise land leveling, chosen according to the type of crop and the local context.

Table 2. Maize full irrigation scheduling and crop data, in the study sites (source: [16]).

<table>
<thead>
<tr>
<th>Study site</th>
<th>NIE</th>
<th>NTI (mm)</th>
<th>SNI (mm)</th>
<th>SNIS (mm)</th>
<th>Yield (Mg ha⁻¹)</th>
<th>AI (mm)</th>
<th>ER (mm)</th>
<th>ETₐact (mm)</th>
<th>CC (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hetao</td>
<td>5</td>
<td>90</td>
<td>450</td>
<td>303</td>
<td>12.00</td>
<td>230</td>
<td>103</td>
<td>753</td>
<td>154</td>
</tr>
<tr>
<td>Lower—Mondego</td>
<td>7</td>
<td>56</td>
<td>392</td>
<td>140</td>
<td>12.00</td>
<td>0</td>
<td>130</td>
<td>535</td>
<td>140</td>
</tr>
</tbody>
</table>

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); ETₐact—Actual crop evapotranspiration (mm); CC—crop cycle (days). Hetao data refers to a silty loam on Dengkou; Lower-Mondego data refers to a loamy soil.

The methodological approach considered the field evaluation and the modeling of irrigation systems. The performance indicators adopted was the Beneficial water use fraction (BWUF, %), expressing the efficiency of water application on field, the Distribution uniformity (DU, %), expressing the quality of the irrigation system to uniformly infiltrate the water spatially, the Irrigation Water Productivity (IWP, kg m⁻³), expressing the amount of physical production obtained per unit of irrigation water applied, and the Economic Water Productivity Ratio (EWPR, ratio), expressing the economical production obtained per unit of cost relative to the irrigation water applied [19].
3. Results

3.1. Hetao study site

The modern irrigation methods considered are the flat level basin (LB) and the flat graded basin (GB) with a longitudinal slope of 0.5‰, with precise land levelling. Medium inflow rates were fixed according to the land parcel size, of 50 m, 100 m, and 200 m. The on-farm water distribution system was by non-lined canal equipped with modern field gates. The high charge of sediments of irrigation water does not allow a pipe distribution system.

The most relevant results achieved (vd. Figure 1) are the following:

1. The modern systems show a significant increase of performance in comparison with the traditional system, with a DU and BWUF about 60%, due to irregular land levelling and the practice of over-irrigation.
2. Precise land-levelled basins (LB) allows a very high DU (up to 91%), which in turn allow to achieve a high BWUF, for basin length from 50 m to 100 m (88-90%). GB with a slope of 0.5‰ is also an acceptable choice for length of 100 m and 200 m, with a BWUF of 84% to 71%. However, these results assume that farmers apply an appropriate irrigation scheduling and cutoff time.
3. Focusing on the increase of water productivity, the results point out that the modern LB systems with 50 m, and 100 m, allow the maximum IWP of 2.4 kg m\(^{-3}\); for LB-200 m, IWP is 1.7 kg m\(^{-3}\), although with the highest EWPR of 11.8. These values of water productivity for maize are in agreement with other published data [5,20,21].
4. The performance of these modern systems requires that farmers apply an appropriate irrigation scheduling and cutoff time.

![Figure 4](image)

**Figure 4.** Indicators of Hetao case study, for maize crop: (a) Beneficial water use fraction (BWUF), and Distribution Uniformity (DU); (b) Irrigation Water Productivity (IWP), and Economic Water Productivity Ratio (EWPR), relative to the traditional practice and five improved irrigation conditions using precise land levelling: LB-50, LB-100 and LB-200 – level basin method with field length of 50 m, 100 m, and 200 m, respectively; GB-0.5-100 and GB-0.5-200 – graded border method with a longitudinal slope of 0.5 % and a field length of 100 m, and 200 m, respectively.

3.2. Lower-Mondego study site

The modern irrigation methods analysed are the furrowed level basin (LB), with 100 m and 200 m length, and the graded furrows with a longitudinal slope of 1.0‰ (GF-1), with 100 m, 200 m and 265 m length. Precise land levelling was always carried out. A medium value of inflow rate per furrow was defined in relation to the furrows length. The
on-farm water distribution system considered the lay-flat tubing with manual valves to adjust each single gate. The results to highlight (vd. Figure 2) are the following:

1. Precise land-leveled basins (LB) is a good alternative for short fields, with a length of about 100 m, with DU of 88%; with basins of 200 m, the advance is not so fast and the DU is close to 80%, identical to the traditional systems (75%).
2. Graded furrows with 1.0‰ slope (GB-1) show the best performance, particularly for longer fields, with length of 200 m and 265 m, with DU about 90% and BWUF higher than 85%.
3. Traditional system, with a BWUF about 70% and a DU of 75%, should be replaced by the modernized systems, because these allow the increase of IWP and EWPR.

4. Focusing on the increase of water productivity, the results point out that the modern LB systems with 100 m, and GB-1 with 200 m or 265 m, allow the maximum IWP of 2.0 to 2.3 kg m⁻³, although the GB-1 with 200 m or 265 m allow the highest EWPR of 9.1-9.3, because with longer fields there are savings of irrigation costs, namely the distribution system and labor. These values of water productivity for maize are in agreement with other published data [5,20,21].

![Figure 5](image_url)

**Figure 5.** Indicators of Lower Mondego Irrigation District case study, for maize crop: (a) Beneficial water use fraction (BWUF), and Distribution Uniformity (DU); (b) Irrigation Water Productivity (IWP), and Economic Water Productivity Ratio (EWPR), relative to the traditional practice and five improved irrigation conditions using precise land levelling: LB- 100 and LB-200 – level basin method with length of 100 m, and 200 m, respectively; GF-1-100, GF-1-200 and GF-1-265 – graded furrows method with slope of 1.0 ‰ and a field of 100 m, 200 m and 265 m, respectively.

### 4. Conclusions

The two different case studies presented here, for arid continental monsoon and Mediterranean climate regions, illustrate the question of water saving and irrigated agriculture development, showing the significant positive impacts on water productivity when the traditional systems, which evidence design and operative problems, are replaced by the modern systems. In Hetao, replacing traditional system by level basin with 100 m length, the IWP increased 40% and the EWPR increased 23%. If it is replaced by the 200 m length, the IWP increased 3% and the EWPR increased 67%. The effect of longer basin of 200 m is the reduction of operative costs, with a mild increase on distribution uniformity. In its turn, in Lower Mondego, adopting graded furrows with 1.0 ‰ and 200 m length, the IWP increased 65% and the EWPR increased 82%.

Surface irrigation systems can be sustainable, if control of inflows is practiced, precise land-leveling is adopted, systems are properly designed, irrigation scheduling is appropriate, fertilizer management is adequate, and crop management, including the control of pests and weeds, is appropriate. There is a large variety of surface irrigation methods, revealing their adaptability to climate, crops, land forms, and cropping techniques, contributing to the resilience of agricultural systems to global change. Their very low energy demand and the low investment requirements also contribute to irrigation sustainability.
The local markets with equipments and consulting services available for farmers play an important role on development. However, adaptation to new water resources paradigm implies a great harmonized effort among farmers and technicians, as well as incentives for farmers and the support of extension services.

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