IECAG 2021

MDPI

Proceedings

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

José Manuel Gonçalves[1,*] and Qingfeng Miao [2]

[1] Instituto Politécnico de Coimbra, Escola Superior Agrária, Coimbra; LEAF - Linking Landscape, Environ- ment, Agriculture and Food, Institute of Agronomy, University of Lisbon, Portugal; jmmg@esac.pt
[2] College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China; imaumqf@imau.edu.cn
* Correspondence: jmmg@esac.pt; imaumqf@imau.edu.cn
† Presented at the 1st International Electronic Conference on Agronomy, 3–17 May 2021. Available online: https://iecag2021.sciforum.net/

Abstract: Water saving from irrigated agriculture is a world-wide priority facing the increasing wa- ter 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 environmen- tal 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 develop- ment, 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

Citation: Gonçalves, J.M..; Miao, Q.Water saving techniques and practices for on-farm surface irri- gation systems. Proceedings 2021, 68, x. https://doi.org/10.3390/xxxxx

Published: date

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 se- vere reduction of water supply for irrigation implies serious social, economic and envi- ronmental 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, diffi- culties 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 vari- ous 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 wa- ter-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, in- creasing 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 techiques, 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 sytems, 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 sim- ulation modeling with irrigation scheduling, land lev- eling, water delivery and dis- tribution systems [11], and cost and en- vironmental 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 opera- tional 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 irri- gation 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 im- pacts 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 site is presented by Miao et al. [16]. The field evaluation procedure considered measure- ments of irrigation scheduling, soil texture and hydraulic properties, and advance and recession data during irrigation events. Field infiltration tests were performed, providing the infiltra- tion 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], al- lowing 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 sched- uling refers to low salinity soil, with silty loam texture, and Lower- Mondego one refers to loamy soil. The irrigation systems options include the present prac- tices, used as reference, and alternative modernized methods based on precise land level- ling, 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]).

Study site	NIE	NTI (mm)	SNI (mm)	SNIS (mm)	Yield (Mg ha^{-1})	AI (mm)	ER (mm)	ET$_{cAct}$ (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- ir- rigation supply (mm); AI—Autumn irrigation (mm); ER—Effective rainfall (mm); ET$_{cAct}$—Actual crop evapotranspira- tion (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 irri- gation systems. The performance indicators adopted was the Beneficial water use frac- tion (BWUF, %), expressing the efficiency of water application on field, the Distribution uni- formity (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 level- ling and the practice of over-irrigation.
2. Precise land-leveled 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 appro- priate 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 appro- pri- ate irrigation scheduling and cutoff time.

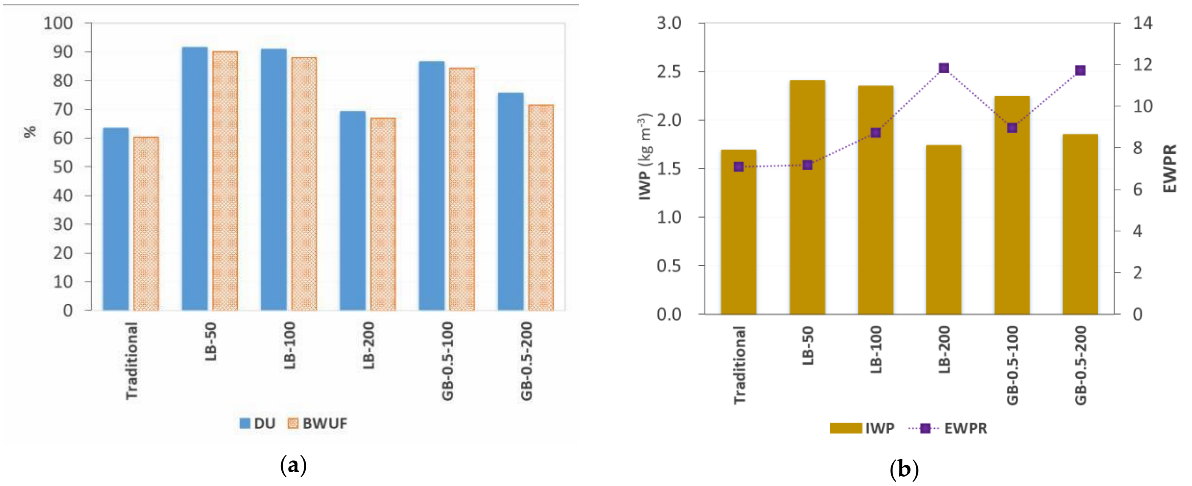
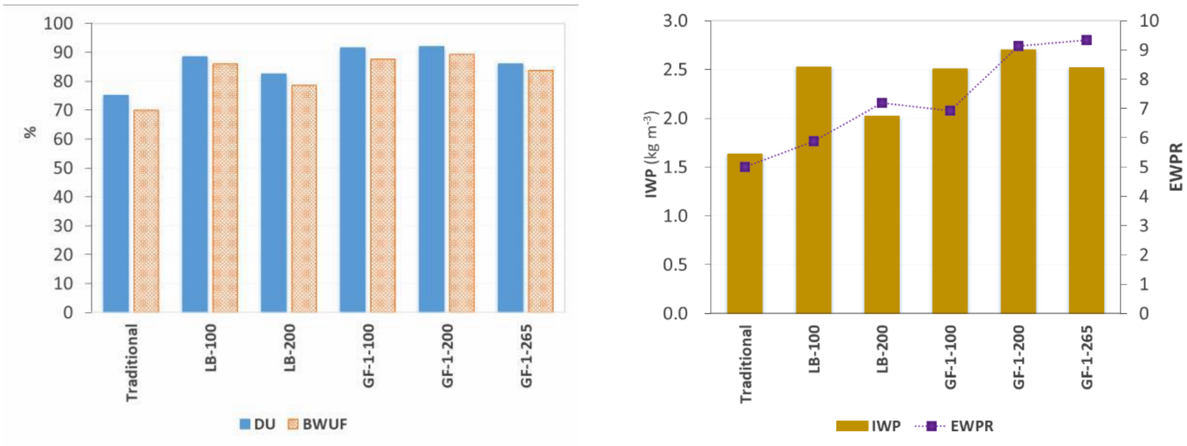


Figure 4. Indicators of Hetao case study, for maize crop: (**a**) Beneficial water use fraction (BWUF), and Distribution Uniformity (DU); (**b**) Irrigation Water Productivity (IWP), and Economic Water Productivity Ratio (EWPR), relative to the traditional practice and five improved irrigation conditions 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].



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

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.

Author Contributions: Conceptualization, J.M.G., Q.M.; methodology, J.M.G., Q.M.; Data analysis, J.M.G., Q.M.; writing–original draft preparation, J.M.G., Q.M..

Funding: This research was funded by National Natural Science Foundation, grant number 52009056, 51839006, 51539005; Inner Mongolia Natural Science Foundation grant number 2019BS05015, and projects of Inner Mongolia Agricultural University, grant number NDSC2018-11; 2017XQG-4, NDYB2016-23.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Clemmens, A.J.; Walker, W.R.; Fangmeier, D.D.; Hardy, L.A. Design of surface systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J.; Evans, R.G.; Jensen, M.E.; Martin, D.L.; Elliot, R.L. ASABE: St. Joseph, MI. 2007; pp. 499-530.
2. Lenton, R. Irrigation in the twenty-first century: reflections on science, policy and society. Irrig. and Drain. **2014**, 63,154–157.
3. Pereira, L.S.; Cordery, I.; Iacovides, I. *Coping with Water Scarcity, Addressing and Challenges.* Springer: 2009.
4. Pereira, L.S.; Gonçalves, J.M. Surface irrigation. In Oxford Encyclopedia of Agriculture and the Environment, Subject: Sustain- ability and Solutions, Agriculture and the Environment. Publisher: Oxford University Press: Oxford, UK, 2018.
5. Molden, D.; Oweis, T.; Steduto, P.; Bindraban, P.; Hanjra, M.A.; Kijne, J. Improving agricultural water productivity: Between optimism and caution. *Agric. Wat. Manag.* **2010**, 97, 528-535.
6. Dedrick, A.R.; Gaddis, R.J.; Clark, A.W.; Moore, A.W. Land forming for irrigation. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J.; Evans, R.G.; Jensen, M.E.; Martin, D.L.; Elliot, R.L. ASABE: St. Joseph, MI. 2007; pp. 320–346.
7. Reddy, J.M. Design of level basin irrigation systems for robust performance. *J. Irrig. and Drain. Engin.* **2013**, 139, 254-260.
8. Mao, Z.; Dong, B.; Pereira, L.S. Assessment and water saving issues for Ningxia paddies, upper Yellow River Basin. *Paddy and Wat. Environ.* **2004**, 2(2), 99–110.
9. Carrijo, D.R.; Lundy, M.E.; Linquist, B.A. Rice yields and water use under alternate wetting and drying irrigation: A meta- analysis. *Field Crops Res.* **2017**, 203, 173–180.
10. Morris, M.R.; Hussain, A.; Gillies, M.H.; O'Halloran, N.J. Inflow rate and border irrigation performance. *Agric. Water Manage.* **2015**, 155, 76–86.
11. Replogle, J.A., and Kruse, E.G. 2007. Delivery and distribution systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J.; Evans, R.G.; Jensen, M.E.; Martin, D.L.; Elliot, R.L. ASABE: St. Joseph, MI. 2007; pp. 499-531.
12. American Society of Agricultural and Biological Engineers (ASABE) *Surface Irrigation Runoff Reuse Systems*. ASAE: Standards EP408.3, St. Joseph, MI, 2014.
13. Gonçalves, J.M.; Pereira, L.S. A decision support system for surface irrigation design. *J. Irrig. and Drain. Engin.* 2009, 135 (3), 343- 356.
14. Koech, R.K.; Smith, R.J.; Gillies, M.H. A real-time optimisation system for automation of furrow irrigation. *Irrig. Science* 2014, 32(4),319–327.
15. Arnold, B.J.; Upadhyaya, S.K.; Wallender, W.W.; Grismer, M.E. Sensor-based cutoff strategy for border check–irrigated fields. *J. Irrig. and Drain. Engin.* 2015, 141(7), 04014081.
16. Miao, Q.; Gonçalves J.M.; Li, R.; Gonçalves, D.; Levita, T.; Shi, H. Assessment of Precise Land Levelling on Surface Irrigation Development. Impacts on Maize Water Productivity and Economics. *Sustainability* **2021**, 13, 1191.
17. Walker, W.R. *SIRMOD III: Surface irrigation simulation, evaluation and design - Guide and technical documentation*. Utah State Uni- versity: Depart. Biological and Irrigation Eng., Logan, USA 2003.
18. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*; FAO Irrigation and drainage paper 56; FAO: Rome, Italy, 1998; 300p.
19. Pereira, L.S.; Cordery, I.; Iacovides, I. Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agric. Water Manage.* **2012**, 108, 39–5.
20. 20Ali, M.H., Talukder, M.S.U. Increasing water productivity in crop production. A synthesis. *Agric. Water Manage.* **2008**, 95, 1201-1213.
21. Zwart, S.J.; Bastiaanssen, W.G.M. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manage.* **2004**, 69, 115-133.