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Capillary rise quantification improves irrigation performance in pear orchards

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Abstract

The shallow water table in Río Negro and Neuquén valley causes a capillary rise (CR) that modifies the water content in soil profile. Therefore, irrigation performance is expected to be affected by the capillary water input into the root zone. The aim of this study was to evaluate the effect of CR on surface irrigation performance during 2020-2021 growing season in a pear orchard. In a Bartlett pear orchard planted in 2003, three irrigation moments were evaluated, and irrigation sheets were calculated to obtain efficiency. Water table level (WTL) was measured monthly in an open aquifer piezometer. CR was calculated with the software UPFLOW. Soil water content was measured with a Frequency Domain Reflectometry (FDR) sensor at: 0.20 m, 0.40 m, and 0.60 m. Water use efficiency (WUE) and water productivity were calculated using pear crop yield and the irrigation sheets applied and the crop water demand, respectively. WTL was shallower in spring than in the rest of the season. The mean depth fluctuated between 0.70-1.20 m during spring, affecting irrigation performance. Data of FDR deepest sensor showed an increase of soil moisture due to CR. Capillary contribution negatively affects irrigation efficiency if it is not included in the water balance. Irrigation schedules can be re-arranged considering soil moisture and CR. In this way, the necessary water sheets could be applied in each crop development stage adjusted to water demand. Improving irrigation performance and WUE enables a sustainable water management strategy in pear production.

Keywords: water use efficiency, water productivity, water table level

Cuantificar el aporte capilar mejora el desempeño del riego gravitacional en perales

Resumen

La napa freática superficial del Alto Valle causa un ascenso capilar (AC) que en primavera y otoño modifica el balance hídrico del suelo. El objetivo es evaluar el efecto del AC sobre el desempeño del riego superficial durante una temporada de crecimiento en perales Bartlett. Se evaluaron tres momentos de riego, de septiembre a abril (temporada 2020-2021) y se calcularon las láminas de riego para obtener las eficiencias. El nivel freático (NF) se midió mensualmente en un freatímetro. El AC se calculó con el software UPFLOW. El contenido de agua del suelo se midió con sensores de reflectometría de dominio de frecuencia (FDR) a: 0,20 m, 0,40 m y 0,60 m. La eficiencia del uso del agua (EUA) y la productividad del agua (PA) se calcularon utilizando el rendimiento del cultivo, las láminas de riego aplicadas y la demanda de agua del cultivo. El NF fue más superficial en primavera que durante el resto de la temporada. La profundidad media fluctuó entre 0,70-1,20 m a inicio de la primavera. Los datos del sensor FDR más profundo mostraron un aumento de la humedad del suelo debido al AC, que afecta negativamente al desempeño del riego si no se incluye como componente del balance hídrico. Programar el riego considerando la humedad del suelo y el AC permite aplicar láminas de agua según sean necesarias en cada etapa de desarrollo del cultivo. Mejorar el desempeño del riego y la EUA resulta en una estrategia de gestión sostenible del agua en la producción de peras.

Palabras clave: eficiencia en el uso del agua, productividad del agua, nivel freático

Quantificar a contribuição capilar melhora o desempenho da irrigação gravitacional em pereiras

Resumo

O lençol freático superficial do Vale Superior provoca uma ascensão capilar (AC) que na primavera e no outono modifica o equilíbrio hídrico do solo. Objetivo: avaliar o efeito da AC no desempenho da irrigação superficial durante o período vegetativo em peras 'Bartlett'. Foram avaliados três momentos de irrigação, de setembro a abril (safra 2020-2021) e calculadas as folhas de irrigação para obtenção das eficiências. O lençol freático (NF) foi medido mensalmente em freatímetro. A AC foi calculada com o software UPFLOW. O conteúdo de água no solo foi medido com sensores de reflectometria no domínio da frequência (FDR) em: 0,20 m, 0,40 m e 0,60 m. A eficiência do uso da água (EUA) e a produtividade da água (AP) foram calculadas usando o rendimento das culturas, as taxas de irrigação aplicadas e a demanda de água das culturas. O NF foi mais raso na primavera do que durante o resto da temporada. A profundidade média oscilou entre 0,70-1,20 m no início da primavera. Os dados do sensor FDR mais profundo mostraram um aumento na umidade do solo devido à AC, o que afeta negativamente o desempenho da irrigação se não for incluído como um componente do balanço hídrico. Programar a irrigação considerando a umidade do solo e a AC permite a aplicação de lâminas de água conforme necessário em cada etapa do desenvolvimento da cultura. A melhoria do desempenho da irrigação e da WUE resulta numa estratégia sustentável de gestão da água na produção de peras.

Palavras-chave: eficiência no uso da água, produtividade da água, nível do lençol freático

1. Introduction

Surface water sources such as lakes, rivers and reservoirs are showing fast changes all around the world, and one in five river basins show considerable fluctuations in surface water levels in the last 5 years. Extreme climatic events cause water to be more scarce and more unpredictable. Among the 2030 Agenda for Sustainable Development, the Sustainable Development Goal (SDG) 6 seeks to support countries in monitoring water- and sanitation-related issues to assure water availability, integrated management, and sanitation[(1)].

Climate change events have reached Alto Valle of Río Negro and Neuquén (AVRNyN) as climatic variability, extreme climatic events occurrence, and water scarcity[(2)(3)(4)(5)]. Extreme climatic events include the diminution of rainfall and snowfall in the high mountains, causing a decrease in the river flows of the basin that provides irrigation water to the area. Water scarcity has reached a 13-year period between 2010 and 2023, affecting the basin water balance. Irrigation water management in arid regions is a relevant aspect for the development and maintenance of sustainable agro-ecosystems and water resources preservation.

Irrigation performance improvement is one of the challenges of integrated water resource management. The agriculture sector had the highest increase in water resources efficiency use (20%) since 2015, compared to the industry (13%) and service sectors (0.3%)[(6)]. Irrigation efficiency has been the most used approach to assess irrigation performance. The traditional methodology to evaluate field irrigation efficiency considers aspects of the field, the soil, and the irrigation practice, focused on a field scale[7]. However, irrigation efficiency assessment is a better indicator when it considers a basin perspective and regional characteristics of the environment[8].

AVRNyN is a 100,000 ha irrigated region located in the Argentinian arid diagonal. Most of the area is surface irrigated and the main crops are pip and stone fruits, with 37,837 ha planted[9]. Water table raise is a consequence of the irrigation system operation in AVRNyN. It is mainly caused by the losses of the distribution channels and by the low field irrigation efficiency, and occasionally affected by river flows[10][11][12]. In AVRNyN, capillary rise as a consequence of the shallow water table negatively affects irrigation efficiency performance. Additionally, according to the previous evaluations developed, irrigation efficiency can be improved by modifying some management aspects such as irrigation extent and frequency[13][14].

Although irrigation efficiency standards have been largely developed and studied in different locations and conditions, simulation models do not consider capillary rise as a relevant factor[15][16][17]. In AVRNyN the existence of a shallow water table modifies the soil water balance. As the water table has a seasonal variation, the capillary rise contribution to the soil water balance is not uniform throughout the year.

The aim of this study was to evaluate the effect of capillary rise on surface irrigation performance during a growing season in a pear orchard, and to calculate water use efficiency and water productivity for local conditions.

2. Materials and methods

Capillary rise was estimated between September 2020 and April 2021. Irrigation sheets were calculated considering capillary rise. Water use efficiency and water productivity were obtained.

2.1 Experimental plot

This is a case study and was carried out in a pear orchard located at INTA Experimental Station (39°01’40” S; 67°44’35” W, mean elevation 240 m, General Roca, Argentina). The 1.8 ha study plot was planted in 2003 with Bartlett (*Pyrus communis* Williams Bon Chretien) pears on seedling rootstock. The orchard rows have West-East orientation and less than 0.05% slope in the same direction, suitable for surface irrigation. Soil profile is heterogeneous, medium-fine textured with low organic matter, slightly alkaline and non-saline or sodic. Tall fescue (*Festuca arundinacea* Schreber) and other spontaneous vegetation cover the alleys. To the west of the plot, there is a poplar windbreak; to the east and south side, there are other pear plots. Between-row spacing is 4 m and the intra-row tree spacing is 2 m. Trees are trained as modified trellis (palmette).

2.2 Irrigation performance

Field work was carried out to obtain infiltration, soil moisture, flow capacity inflow, irrigation extent, size of the irrigated plot (length, width, and number of simultaneously irrigated rows), and longitudinal slope of the plot. Seven irrigations were performed during the season; three of them were fully evaluated with the following methodology. For the rest of the irrigation performances an average gross sheet was estimated. Field irrigation efficiency was evaluated according to the standards of the American Society of Agricultural Engineering[18] and Walker and Skogerboe[15], adapted and described by Morabito and Schilardi[19].

Performance indicators were obtained from irrigation sheets and water volumes. Application efficiency (AE) is defined as the quotient between the volume of water stored in the soil profile explored by the roots of the pear trees and the volume of water entered into the irrigated plot. Storage efficiency (SE) is represented by the sheet stored in the soil profile after an irrigation event with respect to the sheet that needs to be stored. Deep percolation (DP) is the ratio between percolated water sheet and applied irrigation sheet. A summary of irrigation sheets and irrigation standards is presented in Table 1.

Table 1. Irrigation sheets and irrigation standards summary

Irrigation sheets			***References***
Replacement Sheet (I)	dr	(Wc-Wa)/100*D*1000	Wc: field capacity (% $m^3.m^{-3}$) Wa: soil moisture before irrigation (% $m^3.m^{-3}$)) Wai: soil moisture after irrigation (% $m^3.m^{-3}$) D: root exploration depth (m) V: volume of water entered into the plot (m^3) S: irrigation area (m^2)
Gross Sheet	db	(V)/S	
Infiltrated Sheet (I)	dinf	(Wc-Wa)/100*D*1000	
Stored Sheet	ds	(Wai-Wa)/100*D*1000	
Percolates Sheet	dper	dinf-ds	
Irrigation standards			
Application Efficiency	AE	db/dr*100	
Storage Efficiency	SE	dinf/dr*100	
Deep Percolation	DP	dper/db*100	

(I)dr and dinf are equivalent when there is no foot drain.

2.3 Capillary rise and deficit aeration

Capillary rise (CR) and Deficit aeration (DA) were estimated with UPFLOW software[(20)]. The information used was environmental conditions, water table level (WTL), volumetric water content (VWC) in the topsoil, crop evapotranspiration (ETc), and soil texture, among others. To estimate crop water demand, ETo was obtained from the weather station located in the experimental station with Penman-Monteith methodology and local crop coefficients (kc) were used[(21)(22)(23)]. A steady state condition was assumed, so that the calculated flux was in equilibrium with the crop (ETc) demand and the soil water conditions in the topsoil[(20)]. WTL was measured weekly with an acoustic probe in an opened piezometer in accordance with the methodology described by Mañueco[(13)]. Frequency domain reflectometry (FDR) soil moisture sensors (ECH2O EC-5, METER Group, Inc., USA) were installed at 0.20, 0.40, and 0.60 m depth to measure volumetric water content of the soil profile. All sensors recorded hourly to a data logger, and data was presented as daily and 10-day media.

Soil water content at field capacity was determined by the soil moisture sensors records. With the hourly data, water outflow curves were made starting with the irrigation day and observing the point in which the excess water was drained, determined by the inflection point and the rate of downward movement decreased, within the 48-72 h[(22)]. Water content at field capacity (θFC) was thus determined and water content at wilting point (θWP) was estimated using texture reference tables[(24)]. Readily available water (RAW) was calculated considering a p factor of 0.5[(24)]. The active roots of the pear trees were located between 0.2 and 1 m soil depth and irrigation sheets were calculated using Z=0.8 m.

2.4 Water use efficiency and water productivity

Water use efficiency (WUE) and water productivity (WP) were calculated using yield and irrigation sheets applied and crop water demand, respectively, as considered by Caviglia and others[(25)], Van Halsema and Vincent[(7)], and Neffen[(26)]. To obtain yield, trees were harvested from the last week of January to the first week of February to collect all the fruits that reached commercial size (>65 mm of fruit diameter).

Water productivity is the ratio between the product or accumulated biomass and the water consumed. This approach supposes that sub-optimal yields are due to lack of irrigation, and considers water as any other input for the crop and can be transformed into an increasing yield. In terms of the pear production process, it can be obtained as:

$$WP\ (kg\ mm^{-1}) = \frac{fruit\ yield\ (kg)}{crop\ evapotranspiration\ (mm)}$$

Water use efficiency considers a water management perspective. It can be calculated as the ratio between the product or accumulated biomass and the water available or applied (db=gross sheet). It can be calculated as:

$$WUE\ (kg\ mm^{-1}) = \frac{fruit\ yield\ (kg)}{groos\ sheet\ (mm)}$$

3. Results

Volumetric water content (VWC) of the soil profile was graphed from the records of the soil moisture sensors at 0.20, 0.40, and 0.6 m depth. The difference between Field capacity (FC) and Wilting point (WP) is the Total available water (TAW) of the soil profile. Readily available water (RAW) was set as 50% of the TAW. The records from the sensors threw back the pattern of the irrigation scheme behavior (**Figure 1**).

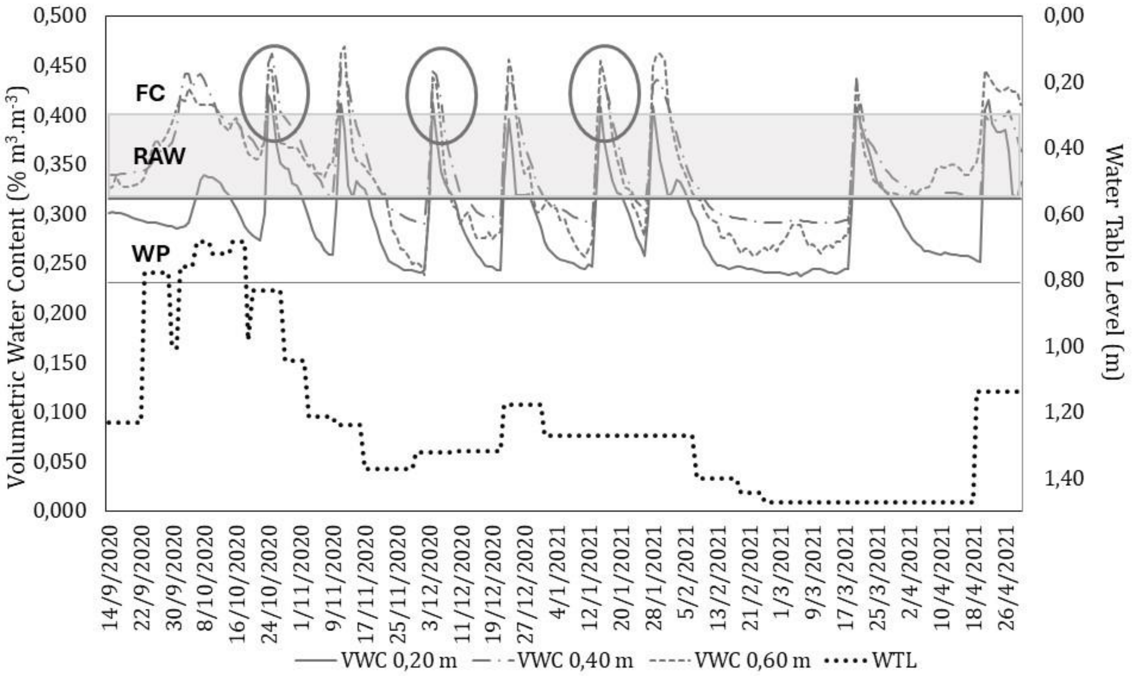

Figure 1. Volumetric water content of the soil and water table level. The circles indicate the irrigation efficiency evaluation moments in October, December, and January

Water table level (WTL) was shallower in spring than in the rest of the season. Average depth in early spring fluctuated between 0.70-1.20 m. Soil water content of the deeper sensors (0.4 and 0.6 m) was higher than soil water content at 0.2 m, especially during the early spring when WTL was shallower. During that period, soil water content was over the Field capacity (FC) threshold, indicating a waterlogged condition due to capillary rise (**Figure 1**).

Soil water balance for a pear crop is presented in **Table 2**. Estimating irrigation needs based on daily or monthly average values is insufficient to adjust the surface irrigation schedule. Therefore, the average of 10-day periods, 3 periods each month, was used. The water demand for the growing season expressed as crop evapotranspiration (ETc) was 1036 mm. According to the capillary rise estimation, the water table contribution was 436 mm, which represents 42% of the ETc. However, as WTL has a seasonal pattern, CR is proportionally higher in spring, when compared to ETc. In this period, the poor aeration values (86 and 74%) calculated with the Upflow software (**Table 2**) and the soil moisture values recorded by FDR sensors (**Figure 1**) show a waterlogged condition.

Table 2. Soil-crop water balance and Capillary rise quantification for 2020-2021 seasons. Months were divided into three equal periods to schedule surface irrigation. VWC and ETc are the average of each period. Capillary rise and Deficient aeration were the results of the Upflow simulation software

Year	*10-day period*	*VWC 0.20 m (m^3 m^{-3})*	*ETc (mm day $^{-1}$)*	*Capillary rise q (mm day $^{-1}$)*	*Deficient aeration (%)*
2020	Sep-03	0.291	2.2	2.2	16
	Oct-01	0.312	1.8	1.8	86
	Oct-02	0.307	2.5	2.5	74
	Oct-03	0.341	2.5	2.4	12
	Nov-01	0.284	3.2	2.1	4
	Nov-02	0.332	3.3	1.8	0
	Nov-03	0.250	4.0	1.9	0
	Dec-01	0.320	7.0	2.0	1
	Dec-02	0.261	6.6	2.0	1
	Dec-03	0.319	7.9	2.1	5
2021	Jan-01	0.255	8.5	2.1	4
	Jan-02	0.318	8.4	2.0	4
	Jan-03	0.316	7.8	2.0	4
	Feb-01	0.308	6.3	1.8	0
	Feb-02	0.249	6.5	1.8	0
	Feb-03	0.242	6.5	1.8	0
	Mar-01	0.240	3.9	1.8	0
	Mar-02	0.268	4.0	1.8	0
	Mar-03	0.335	3.7	1.7	0
	Apr-01	0.268	2.6	1.8	0
	Apr-02	0.257	2.5	2.3	7
	Apr-03	0.369	1.9	1.9	8
			1036	**436**	

Irrigation performance intends to evaluate the water application practices in terms of well-timing and sufficiency. To standardize that evaluation, irrigation sheets and irrigation standards were obtained. Seven irrigations were done during the growing season, and three of them were evaluated with the complete evaluation efficiency methodology (**Figure 1** and **Table 3**). The gross sheet estimated for the rest of the irrigation performances was 150 mm each. Further, the gross sheet for the season was 1164 mm.

Table 3. Irrigation sheets (mm) and irrigation standards (%) of the three irrigations evaluated in October, December, and January in a surface irrigated pear crop

Irrigation Sheets mm				
		October	*December*	*January*
Replacement sheet	dr	62	129	101
Gross Sheet	db	120	150	293
Infiltrated Sheet	dinf	120	150	293
Stored Sheet	ds	85	140	113
Percolates Sheet	dper	58	21	193
Irrigation Standards %				
		October	*December*	*January*
Application Efficiency	AE	52	86	34
Storage Efficiency	SE	100	100	100
Deep Percolation	DP	48	14	68

Thresholds defined by Roscher[27] were used to assess irrigation performance for surface irrigation (see **Table S1** in Supplementary material). Application efficiency (AE) compares gross sheet and replacement sheet. Irrigation events of October, December and January reached an application efficiency of 52%, 86% and 34%, respectively (**Table 3**). The difference between the gross sheet and the replacement sheet resulted in the bad managed performance observed in October and January. Thus, AE calculated for irrigation events of December can be qualified as “good managed”, whereas the October and January irrigation performances were “bad managed”[27].

Storage efficiency (SE) obtained in all three cases exceeded 100%, suggesting that the irrigation practices were sufficient to replenish the necessary water in the soil profile to reach the state of field capacity. Deep percolation (DP) was 48%, 14% and 68% in October, December, and January, respectively, showing an excess of applied water (**Table 3**).

In October, irrigation sheets turned out to be higher than needed, as shown in **Figure 1**, with the waterlogged soil water content. Capillary contribution negatively affected irrigation efficiency, pointing out a badly-timed irrigation, not needed yet, or needed but with a lower sheet. In January, the percolation sheet was twice the replacement sheet, indicating that irrigation time was too long, and a large amount of water was lost by percolation.

Water productivity (WP) was calculated using the yield of the pear crop and the crop evapotranspiration of the season (WP=38000 kg/1036 mm), resulting in 37 kg.mm^{-1}. Water use efficiency (WUE) was calculated with the sum of the sheets (db) of the seven irrigations applied during the season (WUEdb=38000 kg/1164 mm). The result of this theoretical approach is WUEdb=32 kg.mm $^{-1}$. When CR during October´s irrigation was quantified, irrigation schedule could be improved and WUE increased up to 38.8 kg.mm^{-1}.

4. Discussion

The result of this study shows that capillary rise significantly increases soil moisture, especially in spring, covering the pear crop water needs during that period. Therefore, it might be possible to decrease gross sheets or even dispose of spring irrigation. Additionally, WUEdb might also be enhanced by improving irrigation performance. This is in accordance with other regional results[13][22][28].

Water table contribution represents 42% of the total ETc, but it represents the whole ETc of the early spring (September and October). This situation caused a waterlogged condition in the soil profile, confirmed by soil moisture sensors and deficient aeration percentage. The same situation was reported by Galeazzi and Aruani[28], where 36% of the crop water demand was complemented by groundwater[8]. Moreover, the influence of CR in the root zone was previously estimated in one season in a pear orchard[22] and during three seasons in a cherry orchard[13].

According to Roscher[27], the irrigation event of December can be qualified as “good managed” as the threshold was above 75%. The irrigation performances of October and January were “bad managed”, as thresholds were below 60%. Application efficiency depends on different factors; in this study, “bad managed” irrigation in October occurred because the soil was waterlogged. Whereas “bad managed” irrigation in January can be explained by the gross sheet that was three times higher than the replacement sheet needed. Low irrigation performance is usually associated with the irrigation method and management[7][8]. Long irrigations are related to low efficiency performances and can be easily improved by adjusting plot irrigation management[29][30]. However, adjusting irrigation schedules according to soil water content is an appropriate tool to improve irrigation efficiency.

Generally, an improvement of WUE is associated to deficit irrigation and yield reduction[31][32][33][34]. Similar values of WUE (28.6 and 31.9 $kg.mm^{-1}$) were calculated in two consecutive years in pear trees without deficit irrigation, and they improve WUE by different levels of deficit irrigation[35]. In this study, WUE was 32 $kg.mm^{-1}$ and the possibility of improving WUE (38.8 $kg.mm^{-1}$) is associated with the supply of water due to capillary rise in the root zone. This supports the idea that crop water requirement is satisfied not only by irrigation, but also by groundwater contribution[8][22][27], allowing to space irrigations in spring without diminishing yield. WUE can be improved even over WP, as the gross sheet needed to be provided by irrigation if CR is quantified and considered into the water balance could be lower than ETc.

5. Conclusions

Irrigation efficiency assessments enabled to review structural issues as drainage systems and irrigation domain. The adjustment of the irrigation frequency in spring would positively impact irrigation performance, considering the water table capillary impute. In this study, the influence of the capillary rise in soil moisture and consequently in irrigation efficiency was quantified and analyzed. Considering a field scale, irrigation schedules can be re-arranged to consider soil moisture and capillary rise and apply the necessary water sheets for each crop development stage and water demand. From a basin perspective, irrigation water requirements are not only the water needed for a specific crop, but also a contribution from the irrigation system to the landscape.

Irrigation planning aims to ensure that irrigation is sufficient, well-timed, and uniform. However, a field perspective is insufficient, and a basin perspective is needed to obtain integral and long-lasting improvements. Thus, improving irrigation performance and water use efficiency enables a sustainable water management strategy in pear production. This plays a significant role in ensuring sustainable water use and maintaining productivity of crops.

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Transparency of data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author contribution statement

Mañueco M. L.: Conceptualization; Investigation; Writing–original draft

Guiñazu, M.: Investigation; Writing–review & editing

Muñoz, A.: Data curation

Del Brío, D.: Data curation; Writing–review & editing

Curetti, M.: Writing–review & editing

Raffo, M. D.: Conceptualization; Methodology; Writing–review & editing

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Supplementary material

Table S1. Qualification of application, storage and distribution efficiencies on the field scale for surface irrigation methods(27)

Parameter	Bad	Satisfactory	Good
EAP	≤ 60%	60-75%	≥ 75%
EAL	≤ 80%	80-90%	≥ 90%
EDI	< 80%	80-90%	> 90%