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A Case Study from the Arid Mediterranean Highlands

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DOI
10.1007/s41101-025-00393-w

Publication date
2025

Document Version
Final published version

Published in
Water Conservation Science and Engineering

Citation (APA)
Amdar, N., Anwar, A., Elmahdi, A., Al-Bakri, J., Jewitt, G., & Mul, M. (2025). Insights into the Potential of Water Conservation in Irrigated Agriculture: A Case Study from the Arid Mediterranean Highlands. *Water Conservation Science and Engineering*, *10*(2), Article 81. https://doi.org/10.1007/s41101-025-00393-w

Water Conservation Science and Engineering (2025) 10:81
https://doi.org/10.1007/s41101-025-00393-w

RESEARCH

Insights into the Potential of Water Conservation in Irrigated Agriculture: A Case Study from the Arid Mediterranean Highlands

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Received: 4 March 2025 / Revised: 8 June 2025 / Accepted: 17 June 2025

Abstract

Jordan's Amman-Zarqa (AZ) basin faces increasing water scarcity due to increasing demands and persistent groundwater over-abstractions for irrigation. To address this issue, water conservation has been set as a national strategy, and several initiatives aiming to conserve water in irrigated agriculture have been implemented in the basin's highlands. This study evaluates the impact of water conservation technologies (WCTs) on irrigation water savings in the AZ basin highlands. Monthly data on irrigation application were collected from 22 farms over three crop seasons (2019–2022) for four dominant orchards. Farm-scale water savings were calculated and projected to the basin scale under two scenarios: a sustainability scenario aligning groundwater abstraction with irrigation needs under WCTs and an economic scenario expanding irrigated areas using the saved water. Results show that irrigation efficiency before the influence of WCTs was below 55%, with farmers applying an average of 1277 mm/year. After implementing WCTs and farmers fine-tuning their irrigation practices, irrigation application decreased to an average of 795 mm/year, resulting in 38% water savings. Projecting these savings basin-wide, WCTs could conserve 44 Mm^3/year of water under the sustainability scenario. The results provide a solid basis for informing water conservation targets in this region. However, successful water conservation using WCTs depends on farmer-led testing to ensure reduced irrigation does not compromise crop yields. Pilot programs supported by trusted technical advice through farmer field schools and appropriate incentives can achieve sustainable water conservation in this region. Concurrently, monitoring is required to regulate irrigation expansion as it could undermine water savings.

Keywords Drip irrigation · Irrigation technologies · Water savings · Irrigation efficiency

Introduction

Irrigation plays a crucial role in global food production, particularly in regions where rainfall is insufficient to meet crop water demands. Globally, irrigation accounts for 70% of freshwater withdrawals [12]. With the growth of population and increasing water scarcity, particularly in water-stressed regions, the efficient use of water in irrigation has become critical to meeting the growing food demand while conserving the limited freshwater resources for long-term food and water security [9, 17].

Jordan, one of the most water-scarce countries in the world, faces severe challenges in water management due to

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Published online: 18 July 2025

its naturally limited water resources and increasing demands. Official records show that irrigation consumes more than 50% of the country's available freshwater resources [23]. However, remote sensing studies, corroborated by ground surveys, suggest that actual irrigation abstractions might be twice as high as the official figures, indicating widespread unauthorized irrigation [3, 4].

The highlands of the Amman-Zarqa (AZ) basin are one of the important irrigated areas that supply high-quality fruits and vegetables to local and international markets [6]. However, over the last two decades, excessive groundwater abstraction for irrigation has led to a severe decline in groundwater levels, approaching – 2.95 m/year and causing wells to dry up [24, 28]. As a result, farmers have resorted to deepening existing wells or illegally drilling unauthorized new wells to meet their irrigation needs, further exacerbating the existing water scarcity crisis [2, 7].

In response to over-abstraction, the government introduced several regulatory measures, such as raising water tariffs and closing illegal wells [2, 18]. However, political pressure compelled the Ministry of Water and Irrigation to allow farmers to deepen existing wells. Concerns over increasing unemployment from well closures have further hindered policy enforcement [18].

Given the persistent over-abstraction and challenges in enforcing corrective policies, the focus has shifted towards demand management in irrigated agriculture. This approach has been highlighted in Jordan's National Water Strategies for 2016–2023 and 2023–2040 [22, 23]. Various initiatives have promoted water conservation technologies (WCTs), such as advanced drip irrigation systems, to improve water use efficiency at the field scale (e.g. Mercy [21, 32]).

Irrigation efficiency (IE) is defined as the ratio of crop water use to the total water applied and expressed as a percentage [14]. WCTs aim to increase IE by minimizing water distribution losses and delivering water more effectively to plant roots [10, 27, 31].

However, previous research suggests that improving IE through WCTs does not always reduce overall water use and may sometimes increase water "consumption", particularly in arid regions. This phenomenon, known as the "IE paradox", occurs when water saved at the field level is actually used by farmers to expand irrigated areas or intensify crop production, ultimately increasing total water use [11, 19, 25, 26]. Additionally, while improving IE reduces water losses at the farm level, it can decrease return flows, water that would otherwise contribute to downstream availability [11].

Previous studies often assess the impact of WCTs by predicting farmers' responses to improved farm water availability, driven by farmers' economic ambitions, prioritizing economic efficiency and correlating higher productivity with greater water consumption [11, 19, 25, 26]. These studies focus on subsidized WCTs, which reduce perceived irrigation costs, making irrigation more economically attractive to farmers, without necessarily promoting broader shifts in water management practices. This approach overlooks the varying effects of improved IE on water flows across different contexts and spatial–temporal scales, potentially leading to oversimplified conclusions [17].

Therefore, evaluating the impact of WCTs requires empirical research using observational data to assess their effectiveness in achieving their intended outcomes while avoiding unintended consequences [8, 13]. This exploration is especially relevant in the context of the United Nations' Sustainable Development Goal (SDG) 6.4, which promotes improving water use efficiency, including in irrigation, to address water scarcity [8].

Given the critical importance of water conservation and the limited research on the impact of WCTs in Jordan's context, this study aims to empirically assess the impact of implementing WCTs in irrigated agriculture in the Mafraq highlands of Jordan, located within the Amman-Zarqa basin, and provide recommendations for water conservation initiatives by addressing the following questions:

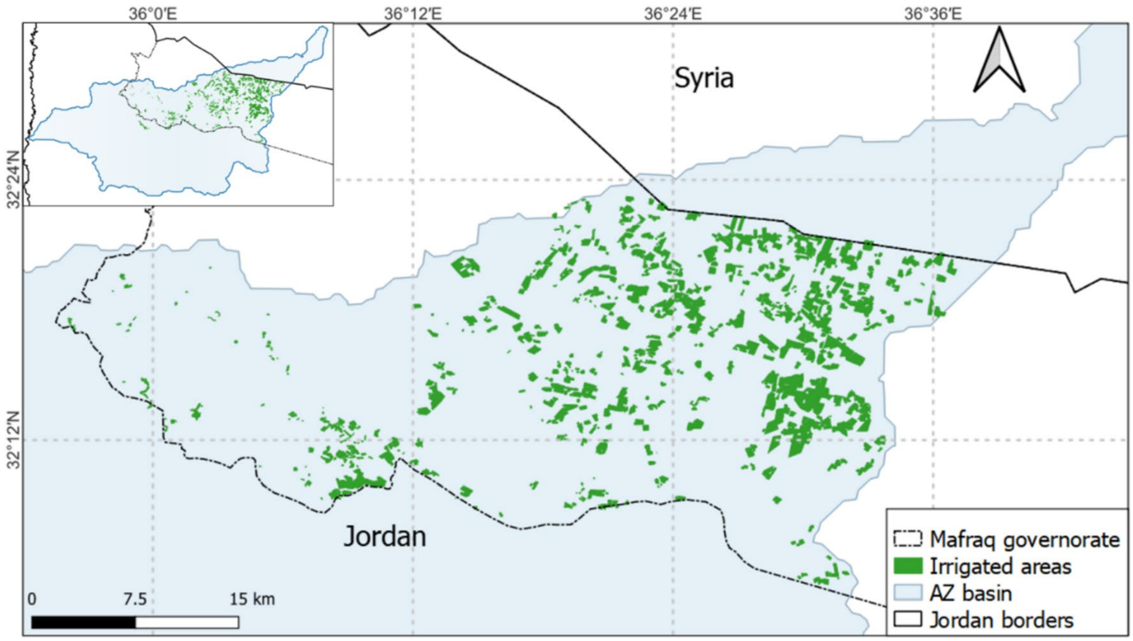
- How much water can be saved at the field scale through the application of WCTs in the Mafraq Highlands?
- What is the potential for water savings in the Amman-Zarqa basin if WCTs are adopted across key crops in the basin?
- What recommendations can be derived from this study to support water conservation initiatives that promote the adoption of WCTs in the Mafraq highlands?

Materials and Methods

This study employs a bottom-up approach to evaluate the impact of WCTs at the field scale and extrapolates the result to the basin scale. An irrigation monitoring system was established to directly measure changes in irrigation application across various crop types following the implementation of WCTs. The data collected were used to calculate water savings and improvements in irrigation efficiency at a field scale. This field data was then used to develop scenarios that examine the potential impact of WCTs on groundwater use at the basin scale.

Study Area

This study focuses on irrigated areas in the Mafraq governorate, located within the Amman-Zarqa (AZ) basin in Jordan (Fig. 1). This highland region experiences an arid to semi-arid climate, with hot summers beginning in April (average highs of 29 °C) and mild winters starting in November (average lows around 7 °C). Annual precipitation



Irrigated farms file was sourced from Al-Bakri et al. [4]

Fig. 1 Mafraq governorate location map and its irrigated areas

is approximately 107 mm/year [33]. The irrigated area spans about 10,617 hectares (ha), with orchards comprising 83% and vegetables 17% of the land [6]. Stone fruits (44%) and olives (37%) dominate the orchards, while pomegranates and grapes each cover 1% of the irrigated area. The main irrigation season extends from March to November and a brief off-season from December to February. Irrigation in this region relies on groundwater sourced from registered farmer-owned wells, which establish formal water rights for these farmers [16], as well as unauthorized wells drilled by farmers [4].

A sample of 22 large farms, each ranging between 20 and 60 ha, was selected for this study based on farmers' willingness to participate in field-scale irrigation monitoring. These farms, which primarily cultivate grapes, stone fruits, pomegranates, and olives, represent the main crops of the region [4, 6]. The irrigation systems typically used in this region are as follows:

- **Glass-reinforced (GR) drip system**: This system uses laterals with cylindrical emitters attached to the inner wall, each with four inline holes releasing 4–8 l/h. Emitters are spaced 20–30 cm apart, and two irrigation laterals are placed along each tree line, delivering a flow of 16–20 l/h per 20–30 cm of pipe length. It is primarily used for irrigating grapes, pomegranates, and olives.
- **Mini sprinklers**: This system employs one or two online emitters per tree, with a flow rate of 100–200 l/h, and is predominantly used for stone fruits and olives.

WCTs were introduced on subsections of these farms, replacing the existing irrigation systems with two types of WCTs:

- **Improved GR system**: Featuring a single lateral with inline emitters spaced at 30–40-cm intervals. The improved GR system reduces water flow by using fewer emitters and one lateral per tree line, making it a more efficient alternative to the commonly used GR drip system in this region.
- **Pressure-compensating (PC) drip systems**: Designed to improve irrigation uniformity, this system features a standard flow of 24 l/h with two to four emitters per tree.

Table 1 provides an overview of the areas equipped with WCTs across the sampled farms, including crop types and the specific WCT applied. The total area where WCTs were installed is 307 ha, with 83.2% equipped with PC systems

Table 1 Overview of areas under WCTs within the sampled farms

Crop type	Area under WCTs (ha)		Total area (ha)
	PC	Improved GR	
Grape	63.2 (80%)	15.8 (20%)	79 (26%)
Stone fruits	79.5 (82%)	17.5 (18%)	97 (31%)
Pomegranate	51.7 (94%)	3.3 (6%)	55 (18%)
Olive	60.8 (80%)	15.2 (20%)	76 (25%)
Total area (ha)	255.2 (83.2%)	51.8 (16.8%)	307

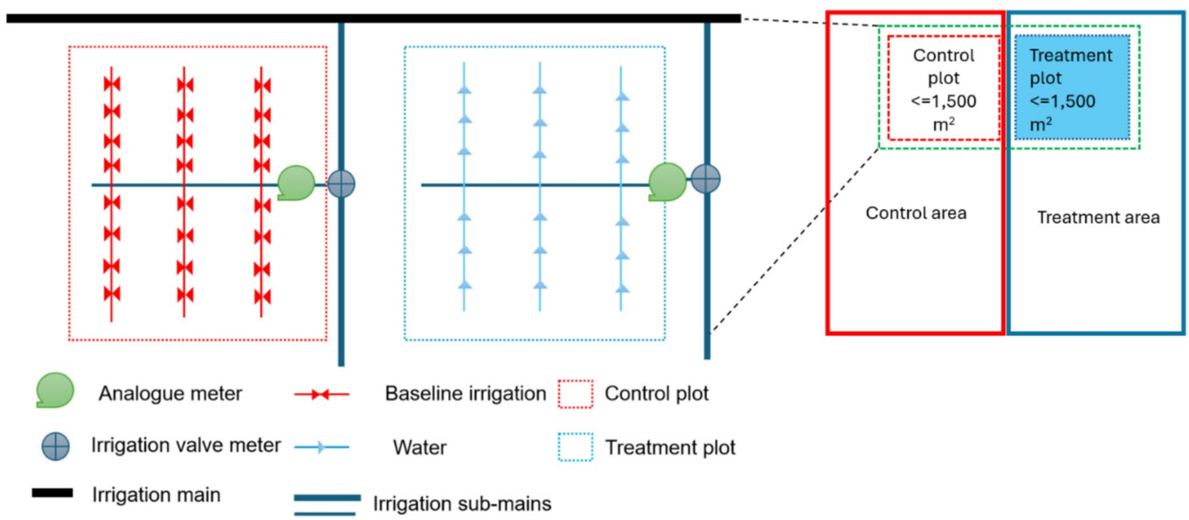


Fig. 2 Schematization of the setup of the field irrigation monitoring system

Table 2 Composition of monitored control and treatment plots

Crop type	Control plots			Treatment plots		
	Mini sprinklers	**GR**	**Total**	**Improved GR**	**PC**	**Total**
Grape	3	4	7	3	6	9
Stone fruits	4	8	12	3	9	12
Pomegranate	2	6	8	3	5	8
Olive	3	2	5	2	3	5
Total	12	20	**32**	11	23	**34**

and 16.8% with improved GR systems. The crop composition across these sites was 26% grapes, 31% stone fruits, 18% pomegranates, and 25% olives.

It is important to note that the crop-type composition in our study area (approximately 10,617 ha) was derived from a remote sensing classification conducted by Al-Bakri et al. [4]. According to that study, grapes and pomegranates each account for about 1% of the total irrigated area (roughly 106 ha per crop). However, due to intercropping (e.g. olives mixed with grapes or stone fruits), these figures should be viewed as approximate rather than exact. While grapes and pomegranates represent a relatively small share of the overall landscape, they are high-value crops at the field scale. They are also important in other agricultural regions of Jordan. Field selection for our monitoring campaign was based on the farmer's willingness to participate rather than achieving a representative sample of crop types. As a result, a large share of the grape and pomegranate area was included in the trial though this occurred by coincidence rather than by design. We consider this extensive coverage beneficial, as the irrigation insights gained may support improved practices both among participating farmers and, more broadly, through extension services working with these crops.

Field Monitoring and Data Collection

A simple monitoring system was established across the 22 farms. This system involved installing two analogue meters on comparable plots (< 1500 m^2) within each farm to measure the volume of water applied at the field scale.[1] The choice to install the meters on small plots was to address farmers' concerns about water use tracking and data privacy. One plot served as the control with the existing irrigation technology (either GR or mini sprinklers), while the other was a treatment plot representing areas under WCTs. Both plots were identical in crop type, age, and variety but differed in their irrigation systems.

Figure 2 illustrates the monitoring system setup, showing meters installed on both the control and treatment plots. The plots were located close to each other to ensure they were within the same irrigation pressure zone but on different laterals. This arrangement allowed farmers to adjust irrigation scheduling for each plot according to the irrigation technology used.

[1] Field scale is defined here by the size of treatment and control plots—not exceeding 1500 m^2.

A total of 66 plots were monitored across the 22 farms (Table 2). Each farm had a monitoring system installed for two paired plots, one control and one treatment, for each crop type. However, two farmers opted to test two different WCTs on their grape crops. As a result, these farms had two separate treatment plots for grapes with a shared control plot for comparison.

The control and treatment plots were monitored for monthly water application over three cropping seasons (2019/2020, 2020/2021, and 2021/2022), each running from March to the following February, with data collected at the end of each month. A total of 1152 monthly readings were recorded for the control plots and 1224 for the treatment plots.

Monthly irrigation depths on all plots were calculated as follows:

$$I_{d(i,k,m,s)} = \frac{r_{(i,k,m,s)} - r_{(i,k,m-1,s)}}{a_{(i,k)}} \times 1000 \quad (1)$$

where:

$I_{d(i,k,m,s)}$—is the monthly irrigation depth on plot i of type k (treatment $k=1$ or control $k=2$) in month m of season s (mm/month).

$r_{(i,k,m,s)}$—is the meter reading at plot i of type k in month m of season s (m^3).

$r_{(i,k,m-1,s)}$—is the meter reading at plot i of type k in the previous month $m-1$ of season s (m^3).

$a_{(i,k)}$—is the area of monitored plot i of type k (m^2).

1000—the conversion factor from irrigation volume (m^3/m^2/month) to irrigation depth (mm/month).

Irrigation depths were documented for the paired control and treatment plots along with their meta data including the following:

- Crop type ($j=1,2,3,4$)
- Type of irrigation technology used on the control plot
- Type of WCT used on the treatment plot

Irrigation Depths Analysis

Estimation of Average Monthly and Seasonal Irrigation Depths

Average monthly irrigation depths were calculated using two classifications:

- **Crop type-plot type:** Average monthly irrigation depths were calculated for each crop type (grapes, stone fruits, pomegranates, and olives) based on the plot type (control or treatment).
- **Plot-type irrigation technology:** Average monthly irrigation depths were calculated based on the irrigation technologies used on the control plots (GR, mini sprinklers) and the treatment plots (PC, improved GR), regardless of crop type.

The average monthly irrigation depths under these two classifications were calculated as follows:

$$I_{d(k,m,s)} = \frac{\sum_{i=1}^{n} I_{d(i,k,m,s)}}{n_k} \quad (2)$$

where:

$I_{d(k,m,s)}$—is the average monthly irrigation depth for plots of type k in month m of season s (mm/month), calculated first per crop type and then per irrigation technology regardless of crop type.

$\sum_{i=1}^{n} I_{d(i,k,m,s)}$—is the sum of monthly irrigation depths for plots ($i=1$ to n) of type k in month m of season s (mm/month). The aggregation was first done by crop type and then by irrigation technology regardless of crop type.

n_k—is the number of monitored plots of type k. The number of plots was calculated first per crop type and second per technology type regardless of crop type.

Seasonal average irrigation depths were derived by aggregating the monthly values by crop and plot type and by plot type and irrigation technology. This provided the seasonal average irrigation depths for each of the four crop types on control and treatment plots and the seasonal averages for the different irrigation technologies on the control and treatment plots.

Estimation of Irrigation Efficiency

IE is a key metric used to assess the impact of WCTs [17, 20]. In this study, we calculate IE by comparing irrigation depth with the net crop water requirement (CWR_{net}).

The CWR for the four orchard types was sourced from previous studies [3, 6], which developed monthly CWR values for this region using the FAO Penman–Monteith method based on regional weather data [5].

To account for the influence of rainfall on crop growth, monthly effective rainfall was calculated using precipitation data derived from the *C*limate *H*azards Center *I*nfra*R*ed *P*recipitation with *S*tation data (CHIRPS), accessed through the FAO's portal to monitor *WA*ter *P*roductivity through *O*pen access of *R*emotely sensed derived data (WaPOR[2]). CHIRPS data were used due to the limited availability of ground observations within the study area. A previous study confirmed the accuracy of CHIRPS data in comparison with ground observations in the AZ basin [1]. Given the arid to

[2] WaPOR data can be accessed here: FAO WaPOR.

semi-arid climate of the region, effective rainfall was calculated using the following equation [30]:

$$P_{e(m)} = P_m \times f_r \quad (3)$$

where:

$P_{e(m)}$—is the average monthly effective rainfall in the study area in month m (mm/month).

P_m—is the average monthly rainfall in the study area for month m (mm/month).

f_r—is a reduction factor derived from Stamm [30] (U.S. Bureau of Reclamation Method).[3]

The monthly CWR_{net} was calculated as follows:

$$CWR_{net(m)} = max\left\{CWR_m - P_{e(m)}, 0\right\} \quad (4)$$

where:

$CWR_{net(m)}$—is the net monthly CWR for each of the four crops in month m (mm/month).

CWR_m—is the total monthly CWR for each of the four crops in month m (mm/month).

$P_{e(m)}$—is the effective rainfall in month m (mm/month).

The net seasonal CWR for each crop type was derived by aggregating the monthly CWR_{net} for each cropping season.

IE was computed for both control and treatment plots of each crop type using the following equation:

$$IE_{(k,s)} = \frac{CWR_{net(s)}}{I_{d(k,s)}} \quad (5)$$

where:

$IE_{(k,s)}$—is the average IE in season s for plot of type k for each of the four crop types and expressed as percentage (%).

$CWR_{net(s)}$—is the net crop water requirement for each of the four crops in season s (mm/year).

$I_{d(k,s)}$—is the average seasonal irrigation depth in season s observed on plots of type k for each of the four crop types (mm/year).

IE was calculated for each of the four crop types across both control and treatment plots over the three cropping seasons.

Estimation of Plot-Level Water Savings

Plot-level water savings were calculated using the following equation:

$$S_{(i1,m,s)} = I_{d(i2,m,s)} - I_{d(i1,m,s)} \quad (6)$$

where:

$S_{(i,m,s)}$—is the average monthly water savings due to the adoption of WCTs on treatment plot *i1* in month m of season s (mm/month).

$I_{d(i2,m,s)}$—is the average monthly irrigation depth observed on control plot *i2* in month m of season s (mm/month).

$I_{d(i1,m,s)}$—is the average monthly irrigation depth observed on treatment plots *i1* in month m of season s (mm/month).

Average monthly water savings were calculated for all crop types. These monthly savings were aggregated to derive the *average seasonal water savings* using two classifications:

- **By crop type:** to determine the average annual water savings per crop type
- **By irrigation technology:** to determine the average annual water savings for each combination of baseline technologies and WCTs used on control and treatment plots

The *total seasonal water savings* achieved from applying WCTs across the 22 farms were calculated as follows:

$$S_s = \sum_{j=1}^{4} \left(S_{(j,s)} \times A_j \times 10\right) \quad (7)$$

where:

S_s—is the seasonal water savings achieved on sites treated with WCTs for the four crop types in the 22 farms in season s (m^3/year).

$S_{(j,s)}$—is the average annual water savings due to the adoption of WCTs on crop j in season s (mm/year).

A_j—is the total area under WCTs for crop type j (ha), derived from Table 1.

10—is a conversion factor from mm/year to m^3/year.

The annual water savings were then aggregated to derive the total water savings achieved over three seasons across a total area of 307 ha within the 22 farms.

Scenarios Development

To evaluate the potential impact of on-farm WCTs on basin-scale water availability, we developed two scenarios to explore the potential outcomes of scaling water savings across all orchard farms in the Mafraq highlands, considering two distinct futures: (1) no expansion of irrigated areas, where water savings are retained (sustainability scenario), and (2) using the saved water to expand irrigation (economic scenario).

- **The sustainability scenario:** this scenario envisions a future where all farmers in the Mafraq highlands, cultivating grapes, stone fruits, pomegranates, and olives, adopt WCTs. This scenario assumes that farmers are driven by a heightened awareness of local water scar-

[3] The reduction factor values are provided on this webpage: Chapter II. Measurement of effective rainfall (fao.org)—Table 5.

city and the substantial costs of depleting groundwater resources and the rising energy expenses required to pump water from significant depths, ranging from over 200 m to as much as 500 m in certain locations (MWI and BGR 2017).

In this scenario, the primary objective is to sustain current areas of irrigated agriculture while reducing water abstraction through the effective use of WCTs. Under these assumptions, farmers are expected to reduce their water abstraction by the amount saved through implementing WCTs (Eq. 8).

$$\Delta W_s = S_s \tag{8}$$

where:

ΔW_s—is the change in groundwater withdrawals due to the use of WCTs on the four crops in the Mafraq highlands in season s (m^3/year).

Areas cultivated with the four crops in the Mafraq highlands were sourced from Al-Raggad and Belhaj [6] based on a field survey conducted in 2019 as shown in Table 3.

- **The economic scenario:** this scenario assumes that farmers in the Mafraq highlands cultivating grapes, stone fruits, pomegranates, and olives adopt WCTs to enhance profitability. Their strategy involves utilizing the saved water using WCTs to expand the total irrigated area. This expansion includes investing in new agricultural lands and irrigation infrastructure while continuing the use of WCTs to optimize irrigation efficiency across the newly irrigated areas.

The potential increase in irrigated areas resulting from the adoption of WCTs is estimated using the following calculation:

$$A_{new} = \frac{S_s}{I_{d(avg)} \times 10} \tag{9}$$

where:

A_{new}—is the expansion in irrigated area due to the adoption of WCTs on the four crops in the Mafraq highlands (ha).

Table 3 Area of the four main orchards in Mafraq highlands (2019)

Crop type	Total area (ha)
Grape	132
Stone fruits	4635
Pomegranate	54
Olive	3968
Total	8789

S_s—is the total water savings achieved from adopting WCTs across the four crop types in season s (m^3/year) (derived from the sustainability scenario).

$I_{d(avg)}$—is the average seasonal irrigation depth for the four crop types over the three monitoring seasons under WCTs (mm/year), derived from the treatment plots.

10—is a conversion factor of the area from m^3/mm to ha.

Results

Irrigation Depth on Control and Treatment Plots

Figure 3 presents the average monthly and seasonal irrigation application on control plots for grapes, stone fruits, pomegranates, and olives over three seasons. During the first season, irrigation depths were notably higher across all crops compared to subsequent seasons. Grapes received the highest irrigation, reaching 300–350 mm/month from May to July. Stone fruits followed closely, with a maximum irrigation application of 250–300 mm/month in May and June. Pomegranates peaked at around 200 mm/month from June to August, while olives reached just above 200 mm/month in June. Irrigation application then gradually decreased in the second and third seasons. By the third season, the highest monthly irrigation depths were significantly lower, with grapes reaching approximately 170 mm/month in June and July, pomegranates at 199 mm/month in August, stone fruits at 125 mm/month in June, and olives at 82 mm/month in August.

Overall, irrigation depths on control plots declined substantially over the three seasons, with reductions ranging from about 40% to over 50% for most crops. Grapes and stone fruits showed the most pronounced reductions, indicating a marked shift towards more water-conservative practices over time.

Seasonal irrigation trends mirrored the monthly irrigation patterns. In the first season, grapes received the highest irrigation at 1560 mm/year, followed by stone fruits (1269 mm/year), pomegranates (1212 mm/year), and olives (1038 mm/year). However, by the third season, these values decreased to 836 mm/year for grapes, 521 mm/year for stone fruits, 965 mm/year for pomegranates, and 520 mm/year for olives.

On the other hand, the average irrigation depths on the treatment plots, as shown in Fig. 4, varied depending on the crops and seasons. Grapes received the highest monthly irrigation, peaking at 218 mm/month in July during the second season. Stone fruits received a maximum of 125 mm/month in May of the third season, while pomegranates received 247 mm/month in August of the first season. Olives received the highest monthly irrigation of 121 mm/month in July of the second season. Overall, the maximum monthly irrigation

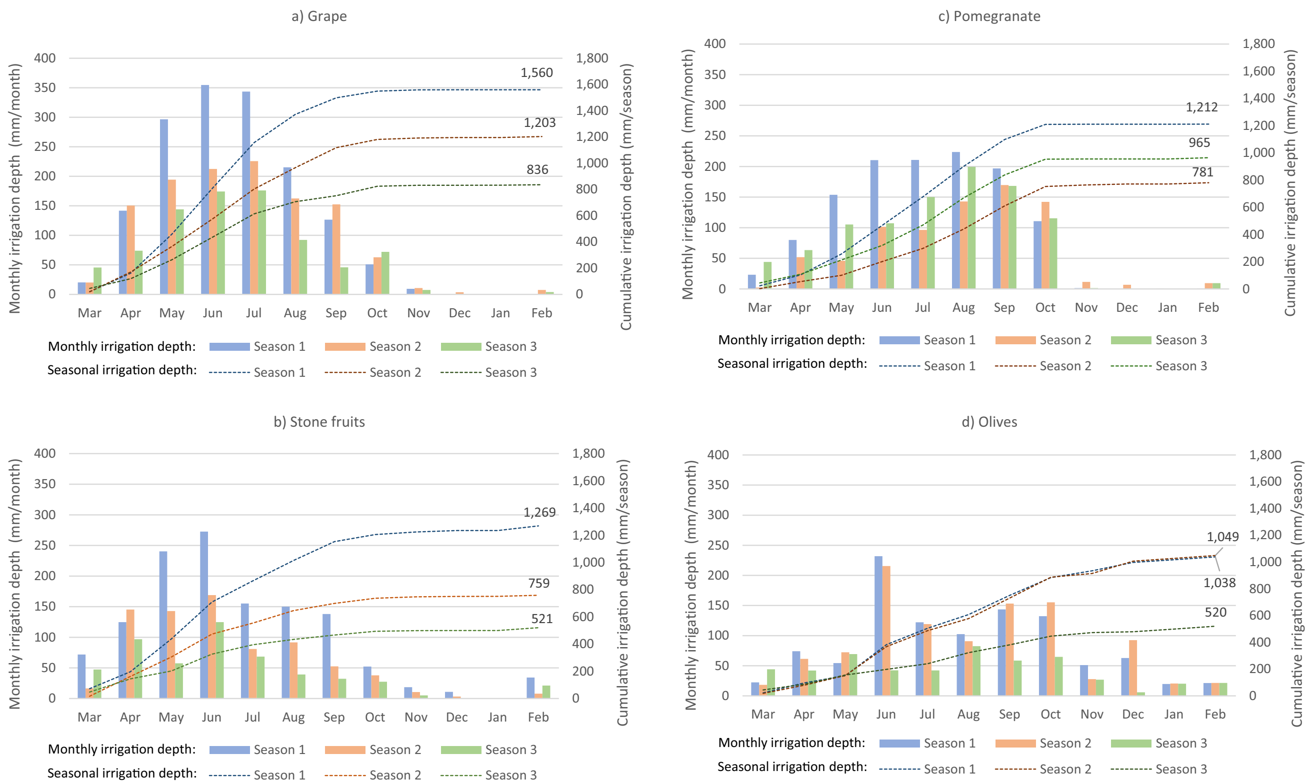


Fig. 3 The average monthly and seasonal irrigation depths on the control plots of grape, stone fruits, pomegranate, and olive in Mafraq highlands for three crop seasons

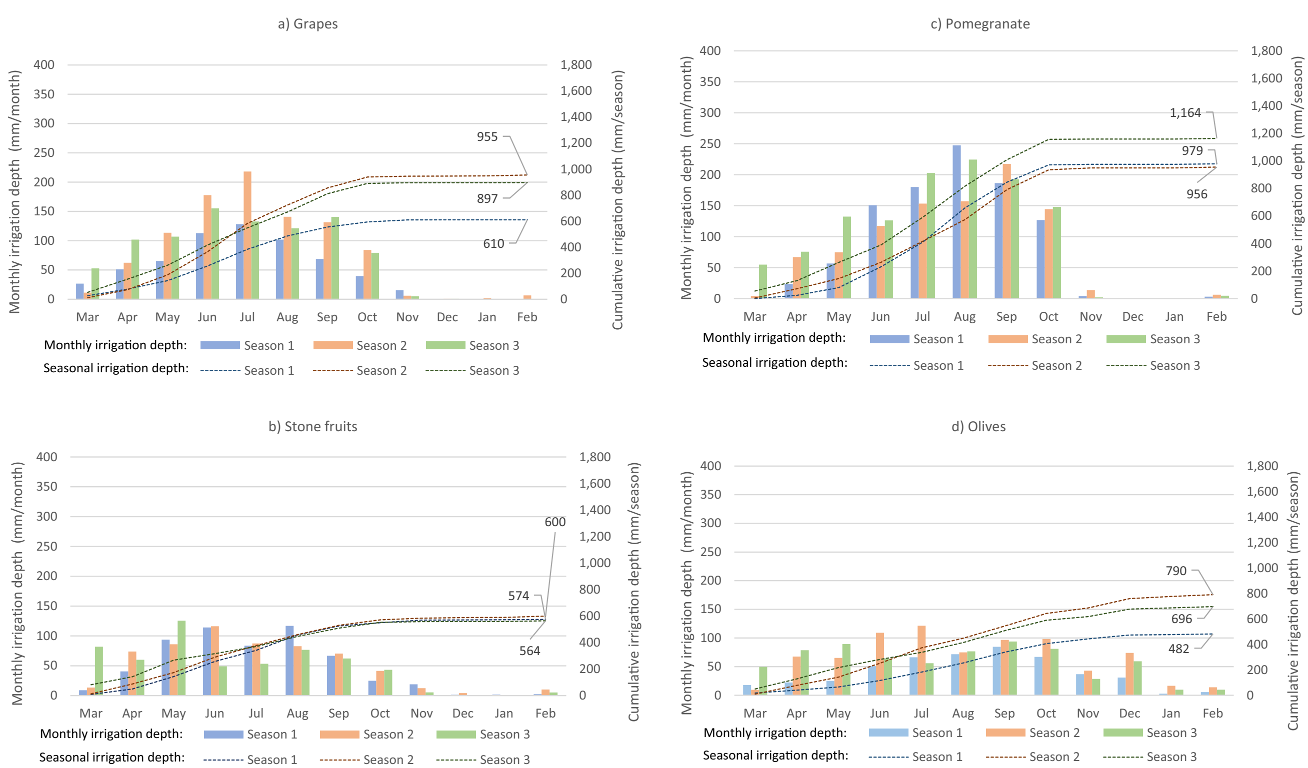


Fig. 4 The average monthly and annual irrigation depths on the treatment plots of grape, stone fruits, pomegranate, and olive in Mafraq highlands for three crop seasons

depths on treatment plots were lower than those observed on control plots in the first season, except for pomegranates.

The seasonal average irrigation for grapes ranged from 610 mm/year in the first season to 955 mm/year in the second season. Irrigation application on stone fruit plots consistently averaged around 579 mm/year across the three seasons. Irrigation on olive plots increased from 482 mm/year in the first season to 696 mm/year in the third season. Irrigation on pomegranate plots increased from 979 mm/year in the first season to 1164 mm/year in the third.

In summary, while grapes and stone fruits under treatment generally received less water than in the control plots, olives and pomegranates showed modest increases in irrigation over time. These differences likely reflect crop-specific water requirements and adaptive irrigation practices by farmers using WCTs.

The average seasonal irrigation application on control plots gradually decreased over time. By the third season, irrigation on grape plots decreased to 836 mm/year and to 520 mm/year for stone fruits and olives. These seasonal irrigation amounts were comparable to those observed on the treatment plots, which were 896 mm/year for grapes, 564 mm/year for stone fruits, and 696 mm/year for olives by the third season.

For pomegranates, the seasonal irrigation application was higher than that observed for other crops. Treatment plots received between 955 and 1163 mm/year, while control plots received between 780 and 1212 mm/year. During our field visits, farmers explained that they irrigate pomegranates more generously during the harvest season to prevent fruit cracking and maintain marketability. This practice contributed to the minimal change in irrigation application with WCTs for pomegranates.

The results suggest that farmers growing grapes, stone fruits, and olives may have gradually adjusted irrigation schedules on control plots to mirror the more efficient water use observed on treatment plots using WCTs. However, these changes typically occurred only after the first season, once farmers were confident that reduced water use with WCTs did not negatively impact crop production. To avoid introducing bias from these adjustments, only irrigation data from the first season, when control plot practices had not yet been influenced by the treatment, were used as the baseline for estimating water savings. This ensures that our comparisons reflect water use prior to any indirect effects from the adoption of WCTs.

Irrigation Efficiencies

The average seasonal CWR for fruit orchards, including grapes, pomegranates, and stone fruits in the study area, was estimated at 746 mm/year [6]. As shown in Fig. 5, approximately 50% of the CWR for fruit trees was needed during June, July, and August, ranging from 114 to 139 mm/month. However, CWR for these orchards was negligible between December and January due to dormancy. On the other hand, the CWR of olive trees was slightly less, averaging 689 mm/year, with peak CWR occurring from June to August, between 81 and 95 mm/month, accounting for nearly 40% of their seasonal CWR.

Rainfall occurred in the study area during October–May, averaging 208, 197, and 150 mm/year over the three cropping seasons, respectively. Effective rainfall, on the other hand, totalled 190, 179, and 137 mm/year in the first, second, and third seasons, respectively. The contribution of effective rainfall to meeting the crop needs was observed in October, November, and March, bringing the seasonal net CWR of fruit orchards to between 670 and 711 mm/year over the monitoring duration. However, the effective rainfall contribution to meeting the CWR of olives was more significant than that of the other orchards, as olives are irrigated all year round in this region. Hence, the net CWR for olives was between 536 and 596 mm/year over the monitoring period.

Irrigation efficiencies, calculated for the four crop types under baseline conditions and WCTs over the three monitoring, are illustrated in Fig. 6. Under baseline conditions, irrigation efficiencies ranged from 43% for grapes to 55% for pomegranates, suggesting over-irrigation likely due to extended schedules or operational inefficiencies. This is expected among commercial farms in the region, where growers aim to increase fruit weight by over-irrigating, a practice colloquially referred to as "selling water within the fruits".

Following the introduction of WCTs, irrigation efficiencies initially exceeded 100% for all crops except pomegranates during the first season. This anomaly was likely due to mismanagement of WCTs, resulting from fixed monthly irrigation schedules rather than adjusting to CWR, leading to slight under-irrigation.

In the following two seasons, adjustments in irrigation depths, reflecting improved scheduling and adaptation to WCTs, brought irrigation efficiencies to acceptable levels for drip irrigation. In the second and third seasons, efficiencies were 71% to 79% for grapes, 68% to 61% for pomegranates, and 68% to 86% for olives, respectively.

In contrast, irrigation efficiencies for stone fruits consistently exceeded 100% across the three seasons. This could be due to the sample including young (3–5 years) and mature (over 10 years) orchards. Young orchards require less water and are therefore irrigated less than mature orchards. Additionally, peak irrigation was observed in May and June, earlier than the estimated CWR peak in July, suggesting that farmers grow early varieties of stone fruits (Fig. 5). These growers typically start irrigation in February, earlier than the usual March or April, to align with May harvest. Rainfall in February and March may have also contributed to

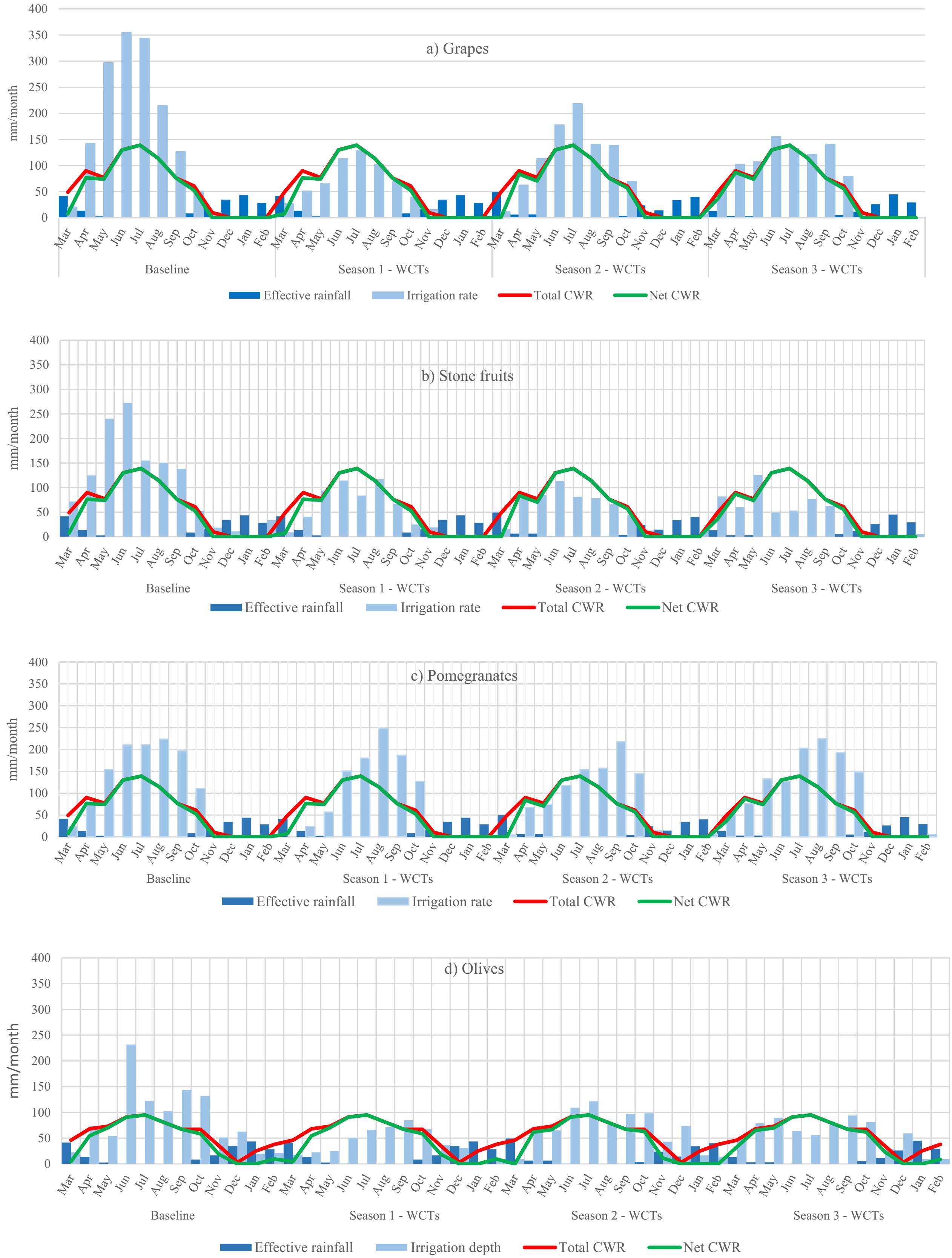


Fig. 5 Comparison between the average monthly irrigation depths, total, and net CWR under baseline conditions and WCTs on the main orchards in Mafraq highlands (grapes, stone fruits, pomegranates, and olives) over the three monitoring seasons

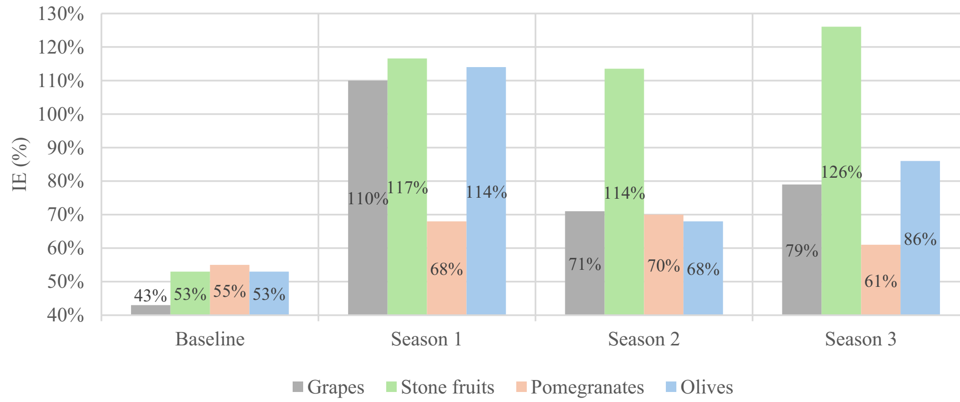


Fig. 6 Irrigation efficiency across crop types and monitoring seasons

crop growth, reducing irrigation needs. Additionally, commercial farmers in this region typically harvest stone fruits before they fully ripen, as the fruits undergo a freezing stage before being distributed to local or international markets. This freezing process allows the fruits to ripen later, which may also explain the lower irrigation application compared to the estimated net CWR. Furthermore, the sustained lower irrigation application compared to the net CWR over 3 years implies a possible overestimation of actual CWR, as farmers would typically increase water use to protect crops. With stone fruits covering 44% of irrigated areas in the Mafraq highlands, accurately determining CWRs for different varieties considering agricultural practices is essential.

Overall, adopting WCTs significantly improved irrigation efficiencies for grapes, olives, and stone fruits by the third season. However, pomegranates saw only a modest increase in efficiency, rising by 6% to reach 61% in the third season.

Plot-Level Water Savings

Figure 7 represents the average plot-level water savings for the four crops. Water savings were the most consistent on stone fruit plots ($n = 12$), averaging 694 mm/year, 669 mm/year, and 704 mm/year for the first, second, and third seasons, respectively. These results suggest that WCTs led to steady and reliable reductions in irrigation for stone fruits, equivalent to saving nearly 7000 m^3/year on a typical 1-hectare plot.

On grape plots ($n = 9$), water savings averaged 950 mm/year in the first season, 605 mm/year in the second, and 663 mm/year in the third. This reflects a strong initial reduction in water use, with less but substantial savings in the following two seasons, potentially due to farmers learning on how to manage WCTs.

Water savings on pomegranates plots ($n = 8$) ranged between 256 mm/year in the second season and 48 mm/year in the third, indicating that WCTs had a smaller impact on irrigation efficiency for this crop, likely due to the need to maintain crop marketability.

On olives plots ($n = 5$), savings decreased from 557 mm/year in the first season to 248 mm/year in the second and to 342 in the third. While initial reductions were significant, the variability in the following two seasons suggests that some adjustments in irrigation application on treatment plots or changes in rainfall timing may have influenced ongoing efficiency.

Figure 8 shows the average seasonal water savings classified by technologies utilized under baseline conditions and WCTs used on treatment plots.

Converting from mini sprinklers to PC, observed on ($n = 11$) plots, led to the highest water savings ranging

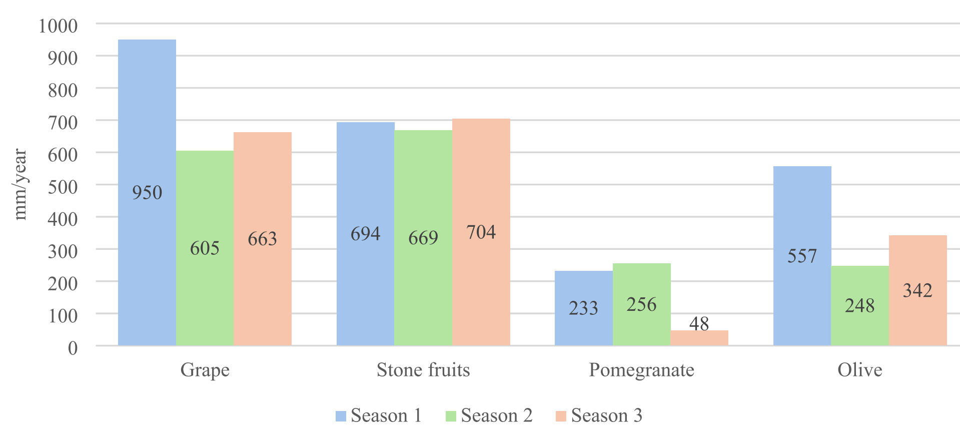


Fig. 7 The average water savings achieved on treatment plots in Mafraq highlands over three seasons

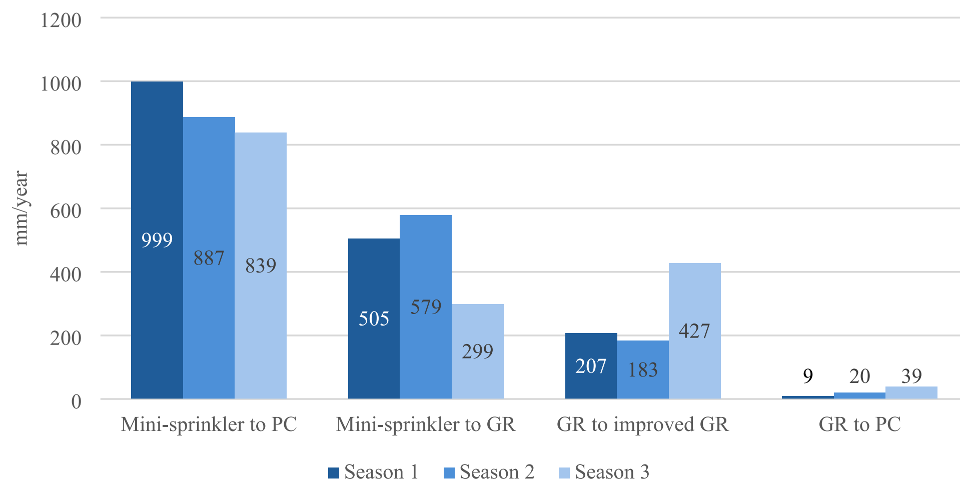


Fig. 8 The average water savings classified per combination of technologies used on treatment and control plots regardless of the crop type over three seasons

between 839 and 999 mm/year. This translates to annual water reductions of roughly 8000 to 10,000 m^3/ha. Savings were consistently high for all crop types across all seasons. Switching from mini sprinklers to improved GR, observed on ($n=3$) plots, resulted in an average seasonal savings of between 299 and 579 mm/year. Switching from GR to improved GR, observed on ($n=7$) plots, resulted in average seasonal water savings of between 183 and 427 mm/year. However, converting from GR to PC, observed on ($n=13$) plots, yielded the least savings of between 9 and 39 mm/year. In this group of plots where GR was replaced by PC, increased water application on some treatment plots was observed compared to the baseline conditions. This suggests that PC systems are not universally more efficient when replacing GR, possibly due to mismanagement, system incompatibilities, or crop-specific needs.

The use of WCTs across the 307 ha within the 22 farms resulted in a total water savings of 4.9 Mm^3 during the monitoring period. The highest savings occurred in the first season, amounting to 1.9 Mm^3/year in irrigation application relative to the baseline. In the subsequent second and third seasons, savings decreased to 1.4 Mm^3/year (Table 4). These findings suggest realistic sustainable annual water savings of 1.4 Mm^3/year for the sampled farms. Based on this pattern, the sustainable long-term savings of approximately 1.4 Mm^3/year for these farms can supply the annual water needs of about 5109 households (based on an average demand per person of 150 L per day (MWI, 2023), and an average household size of 5 persons, equivalent to household demand of 274 M^3/year). Based on these results, and with reference to Fig. 7, the average water savings that are considered realistic and sustainable in the study area are 634 mm/year for grapes, 687 mm/year for stone fruits, 152 mm/year for pomegranates, and 295 mm/year for olives.

Scenarios

The Sustainability Scenario

Adopting WCTs across all farms cultivating grapes, stone fruits, pomegranates, and olives in the Mafraq highlands within the AZ basin, which occupy an area of 8789 ha, could lead to reducing irrigation water abstractions by 44 Mm^3/year (Table 5). This reduction equates to 50% of the AZ basin aquifers' annual safe yield of 88 Mm^3/year (MWI 2016). This figure aligns with the previously reported over-irrigation in this region, determined following remote sensing techniques and estimated at 40 Mm^3/year [3]. It is important to mention again that this scenario assumes that WCTs would lead to reducing abstractions by an amount equivalent to the water saved on farms. Further elaboration on this assumption is provided in the discussion.

Table 4 Water savings due to the use of WCTs in the selected farms over the three monitoring seasons

Season water savings	Grapes Mm^3/season	Stone fruits	Pomegranates	Olives	Total per season
Season 1	750,349	673,583	127,960	422,988	1,974,881
Season 2	478,081	649,030	140,740	188,703	1,456,555
Season 3	524,053	683,263	26,240	259,966	1,493,522
Total water savings per crop type over the study period (Mm^3)	1,752,483	2,005,876	294,940	871,658	4,924,958

Table 5 Potential water savings from adopting WCTs on main orchards in the Mafraq highlands

Crop type	Total area (ha)	Average water savings (mm/year[a])	Potential reduction in irrigation abstractions (Mm^3/year)
Grapes	132	634	0.84
Stone fruits	4,635	687	31.83
Pomegranates	54	152	0.08
Olives	3,968	295	11.71
Total	8789	506[b]	44.46

[a]This average is calculated from the savings in the second and third seasons

[b]Weighted average calculated by multiplying the average water savings of each crop by its respective cultivated area, summing these values across all crops and then dividing by the total orchard area

Table 6 calculations of potential expansion in irrigated areas due to the adoption of WCTs under the economic scenario

Variables	The sample 22 farms	The Mafraq highlands
Total average water savings (Mm^3/year)	1.48	44.46
Average irrigation depth using WCTs (mm/year)	795[a]	795
Initial irrigated area (ha)	307	8789
Irrigated area expansion (ha)	186	5592
Irrigation expansion percentage (percentage of initial areas equipped with WCTs)	61%	64%

[a]This figure is the 2-year average of observed weighted average irrigation depth across sample crops

The Economic Scenario

Under the economic scenario, adopting WCTs on the selected sites with an area of 307 ha, within the 22 sample farms, could expand irrigated areas by 186 ha, increasing the total to 493 ha, a 61% growth (Table 6). If all growers of grapes, stone fruits, pomegranates, and olives in the Mafraq highlands adopt WCTs, the irrigated area could expand by 5592 ha, reaching 14,381 ha, a 64% increase. This scenario assumes optimal WCT application on initial and newly expanded lands, with an average irrigation depth of 795 mm/year. Consequently, water savings from WCT adoption would be fully utilized for new cultivation, negating conservation efforts and reverting water use to pre-adoption levels.

Discussion

Impact of WCTs on Irrigation Application and Water Savings in the Sampled Farms

The findings of this research provide valuable insights into water savings achievable at the farm scale through WCTs in the Mafraq highlands of Jordan. Prior to the introduction of WCTs, irrigation applications on the four orchards (grapes, stone fruits, pomegranates, and olives) were 1560 mm/year, 1269 mm/year, 1212 mm/year, and 1048 mm/year, respectively. These figures corresponded to irrigation efficiencies ranging from 43 to 55%, indicating significant over-irrigation.

The implementation of WCTs resulted in observed water savings of 1.9 Mm^3/year across the sampled farms in the first season. However, the savings decreased in the subsequent two seasons to 1.4 Mm^3/year, suggesting that the sustainable water savings achievable across the sampled sites are approximately 1.4 Mm^3/year. These savings corresponded to increases in irrigation efficiency of 36% for grapes, 6% for pomegranates, and 33% for olives, resulting in final efficiencies of 79% for grapes, 61% for pomegranate, and 86% for olives in the third season. The average irrigation depths sustained by farmers, as observed in the second and third seasons on treatment plots, were 922 mm/year for grapes, 1160 mm/year for pomegranates, and 743 mm/year for olives.

As water savings were the highest in the first year of adopting WCTs, our analysis indicates that this observation is due the slight reduction in irrigation application on treatment plots, with depths of 610 mm/year, 574 mm/year, 979 mm/year, and 482 mm/year on grapes, stone fruits, pomegranates, and olives, respectively, compared to the following seasons. In the second and third seasons, farmers adjusted their irrigation practices, increasing irrigation depth with WCTs. This adjustment suggests that farmers have calibrated irrigation application based on experimenting with WCTs, gradually aligning water use with crop needs for this region. This hands-on experience contributes to the sustainable adoption of WCTs as farmers continue to improve their irrigation practices over time.

However, stone fruit plots exhibited a different behaviour compared to other crops. During the three monitoring seasons, irrigation efficiency on treatment plots exceeded 100%. This observation initially suggests under-irrigation due to the use of WCTs. However, this interpretation is likely inaccurate because the net CWR used to calculate irrigation efficiency in our case study is based on average values for stone fruits in the Mafraq highlands, derived from FAO 56 guidelines [6]. These estimates do not consider specific stone fruit varieties, age, or the impact of agricultural practices such as early harvesting on crop needs. As far as we know, no more accurate CWR for stone fruits is available for this region. Therefore, the consistent average irrigation depth of 576 mm/year observed over the three seasons on stone fruits represents the realistic irrigation needs for the sampled plots. This finding indicates the need to improve CWR estimates for this region, taking into account the different stone fruit varieties and local agricultural practices. Such information is important for improving irrigation advisory services in this region.

To further assess the sustainability of reduced irrigation application using WCTs, we compared the weighted average of observed irrigation application to a recent remote sensing study conducted in the study region during the same period [4]. That study estimated irrigation water needs for the region's total irrigated area of 18,243 ha, of which 10,617 ha are cultivated with orchard trees, while the remaining area is planted with vegetables, cereals, and fodder. The estimates were based on an assumed irrigation efficiency of 70%. The study concluded that the gross irrigation needs for the region ranged between 101.5 and 118.2 Mm^3/year from 2017 to 2019, corresponding to areal irrigation depths of 556–648 mm/year over the same period [4]. In comparison, our calculated irrigation depths, sustained by farmers following the introduction of WCTs, were 795 mm/year, suggesting that the irrigation depths observed using WCTs align more closely with the region's estimated average irrigation needs to maintain crop production. This indicates the effectiveness of WCTs and farmers' success in optimizing irrigation application using these technologies in the sampled farms.

Reflecting on seasonal irrigation patterns observed in the control plots, our findings show a decreasing trend towards the third season. Although the control plots were established to monitor irrigation application under baseline conditions, our observation shows that farmers reduced irrigation even on these plots, attempting to replicate the more efficient water use observed on treatment plots using WCTs. This behaviour emphasizes our recommendation on the importance of farmer-led testing and evaluation of WCTs. Water conservation initiatives should prioritize pilot programs that enable farmers to experiment with WCTs on a small scale. This approach allows farmers to directly observe the impact on crop yields and helps alleviate concerns about potential risks. Once farmers are confident that reduced water use does not negatively affect production, larger-scale adoption can follow. Providing ongoing support and technical advice from trusted sources such as farmer field schools during the early stages of WCTs adoption can further encourage farmers to optimize their irrigation practices.

In terms of technologies and their impact on irrigation application, our findings indicate that the type of irrigation system affects farmers' irrigation applications. This is evident with the observed high irrigation application on plots irrigated with mini sprinklers (high flow emitters) across all monitored orchards. Therefore, changing mini sprinklers to improved GR or PC yielded the most significant reduction in irrigation application. Notably, farmers successfully maintained these lower irrigation levels in the second and third growing seasons, suggesting that system inefficiencies were the primary drivers of over-irrigation in the sampled farms.

A previous study conducted in this region found that farmers who perceived a decline in physical water availability and faced agricultural losses tended to irrigate more frequently, often relying on self-judgment to determine their irrigation needs [15]. This reactive behaviour, driven by concerns about water scarcity and potential crop loss, can lead to inefficient water use. Our findings further highlight the role of irrigation technologies in influencing irrigation practices as observed with mini sprinklers. However, when provided with appropriate and tested technologies, farmers can improve the precision of their irrigation decisions.

The Potential Impact of WCTs on the Amman-Zarqa Basin

Extrapolating findings from the sampled farms to all farms cultivating the grapes, stone fruits, pomegranates, and olives within the AZ basin shows that the potential for water savings under the sustainability scenario could reach 44 Mm^3/year, reducing the pressure on the groundwater aquifers by 50%. This scenario assumes that farmers would reduce their irrigation abstractions by an amount equivalent to the total on-farm water savings achieved through WCTs. However, translating this scenario into practice via restrictive groundwater abstraction policies presents a significant challenge due to the widespread presence of unauthorized wells and the difficulty of enforcing such policies.

Given these challenges, water conservation efforts should prioritize incentivizing farmers to voluntarily reduce groundwater use once WCTs are implemented. An example of potential incentives is the energy cost savings associated with matching irrigation abstractions with the total farm irrigation needs under WCTs. In the Mafraq highlands, high energy costs result from pumping groundwater from high depths, making irrigation increasingly costly for farmers. Presenting financial savings of reduced groundwater pumping as part of a business case could motivate farmers to conserve water. Farmers could be shown how much money in USD they could save for every cubic meter of water saved using WCTs instead of extraction from rapidly depleting aquifers. This approach aligns the use of WCTs with economic incentives, encouraging farmers to implement these technologies while promoting water conservation.

Conversely, under the economic scenario, our results indicate that if farmers use all saved water to increase profits through irrigation expansion, the irrigated area could increase by 64%. This would jeopardize water conservation efforts and exacerbate over-abstraction of the basin's aquifers. The rapid decline in groundwater levels in this region between 2000 and 2017 has already been linked to the expansion of irrigated areas [29]. Therefore, water conservation initiatives should monitor and regulate irrigation expansion alongside the implementation of WCTs. Remote sensing–based crop mapping studies have proven the effectiveness of remote sensing techniques in detecting and monitoring changes in irrigated areas [3, 4]. By leveraging these techniques, water authorities can ensure the saved water is not diverted to more irrigation development in this region.

Conclusions

This study investigates the water conservation potential in irrigated agriculture in the Mafraq highlands of Jordan using two WCTs: PC drip systems and improved GR systems. The study focused on a sample of 22 farms representative of the region's crops. Irrigation application was monitored on 32 control plots representing baseline irrigation technologies and practices and 34 treatment plots where WCTs were implemented.

The findings reveal a substantial water savings potential of approximately 44 Mm^3/year using WCTs. The most significant and consistent water savings were observed on plots transitioning from mini sprinklers to WCTs, particularly in grape and stone fruit orchards.

The successful implementation of WCTs in this region depends on farmers' ability to test and monitor the impact of WCTs to ensure they can sustain their crops. Given that, farmers can gradually optimize their irrigation application under WCTs and achieve water savings. However, incentivizing farmers to voluntarily reduce their water abstractions in line with the actual irrigation needs through WCTs is crucial for the success of water conservation efforts. In parallel, monitoring and regulating irrigated area expansion is essential to avoid unintended consequences of water conservation initiatives.

This research did not include crop production data to assess the impact of WCTs on water productivity, due to the lack of detailed plot-level yield records. Farmers typically maintain records of average yields, which limits the ability to directly measure water productivity. Remote sensing offers a promising method for analysing biomass production. Combining remote sensing with irrigation application observations could enhance future assessments of WCTs' effectiveness in improving water productivity while sustaining crop yields.

Acknowledgements We would like to thank Professor Stefan Uhlenbrook, Director of Hydrology, Water and Cryosphere at the World Meteorological Organization for supporting the first author's funding application to Schlumberger Faculty for the Future.

Author Contribution NA, MM, AA, AE and GJ conceptualized the methods; NA collected the data and conducted the analysis; NA wrote the first draft; all authors reviewed and edited the paper; MM, AA, AE, JA and GJ supervised the research activities; all authors acquired the funding from the stated sources.

Funding This publication was partly made possible by the support of the American people through the United States Agency for International Development (USAID), under the terms of Award No. AID-ME-IO-15–003. Additional support came from Mercy Corps Jordan, through their USAID-funded program "Water Innovations Technologies" (Cooperative Agreement #AID-278-A-17–00002, CFDA # 98.001 between USAID and Mercy Corps Jordan), from the CGIAR Research Program on Water, Land and Ecosystems, and from the Schlumberger Faculty for the Future Stitching Fund, a foundation organized under the laws of the Netherlands, with its registered address at Parkstraat 83–89, 2514JG, The Hague, The Netherlands ("SSF"), through a PhD grant, granted to the first author in 2021.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Ethical Approval and Consent to Participate Field monitoring of irrigation depths was conducted only after obtaining informed consent from the participating farmers. The consent form clearly stated that individual irrigation data would remain confidential and not be shared with any external entity. It was also specified that only aggregated data, representing average values across all monitored farms, would be utilized in the study. Upon agreeing to these terms, the farmers granted permission for the research team to establish monitoring systems and collect the data throughout the study period.

Competing interests The authors declare no competing interests.

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