Probe - Soil Science 2024, 6(1), 2243.
https://doi.org/10.18686/ss2243

Article

A short-term assessment of pulsed drip irrigation on blueberry production and soil-water behavior of Morocco's sandy soils

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CITATION

El Ghailassi A, Boularbah S, Choukr-Allah R, Dragonetti G. A short-term assessment of pulsed drip irrigation on blueberry production and soil-water behavior of Morocco's sandy soils. Probe - Soil Science. 2024; 6(1): 2243. https://doi.org/10.18686/ss2243

ARTICLE INFO

Received: 31 July 2024
Accepted: 18 October 2024
Available online: 2 November 2024

Abstract: Water scarcity poses serious threats to agriculture and efficient irrigation practices are essential to mitigating this impact. Such practices should not only optimize crop water consumption but also account for soil type, such as sandy soil cases with low water-holding capacity and fast water movement below the root zone. Endorsing short-duration and more frequent (pulsed) irrigation events thus becomes paramount to improving soil water distribution and efficient crop water uptake. Accordingly, a study on blueberries was carried out in a greenhouse in Morocco to assess the performance of short-term pulsed drip irrigation technique (PLS) on soil characteristics, soil water fluxes, and yield. Within a plastic tunnel (34 m × 30 m) 10 strips were selected: 5 strips operated under PLS and 5 under continuous drip irrigation practices (N-PLS) to measure soil water content, soil electrical conductivity (ECe) and pH. The results indicated that PLS drip irrigation, using on average 8 pulses/day, increased yield by 10%, fruit size by 8%, and water and nutrient use efficiency of blueberry by 9%, compared to N-PLS irrigation (one times/day). Flow pulses followed by breaks also improved water redistribution in the root zone, better-controlled soil ECe pattern, and maintained pH values within the optimal range for blueberries.

Keywords: blueberry production; sandy soils; soil monitoring; pulse irrigation; water use efficiency; salinity

1. Introduction

The Moroccan red berries sector, particularly blueberry cultivation, has seen significant development in the last decade, driven by the National Agriculture Strategy and the expanding international demand. Production in this sector passed from 60,570 to 124,000 tons between 2006 and 2023, reflecting a 51.2% growth. Notably, blueberry production achieved a monumental feat in 2020 producing 35,100 tons of blueberries, and 19 times more than the yield of 2005 [1].

In Morocco, high-value horticultural crops like blueberry cultivation are highly dependent on irrigation covering a dedicated area of 1200 Ha out of a total of 5700 hectares, overall [2]. Achieving high production levels on this cultivated land also requires effective irrigation management which plays a crucial role. Given that, also, the water uptake capacity of blueberries is restricted along the growth and production phases, especially because their root system is superficial, confined, and has a small number of root hairs [3–5]. Yet, these limitations are exacerbated under water deficit conditions, which reduce the potential yield and vegetative growth of the bushes, making it essential to meet appropriate irrigation requirements [6–8] Similarly, blueberry growth and production are closely linked to maintaining acceptable ranges of soil water content throughout the season. However, efficient irrigation management need is often hindered by several factors, especially the prevalence of very sandy soils (more than 90% sand) in many cultivated areas.

Sandy soils are characterized to have low water holding capacity leading to rapid water movement below the root zone and contributing to water and nutrient losses when irrigation is mismanaged [9,10]. To address these challenges, shorter-duration applications with high frequency (pulsed) irrigation events have been shown to improve plant water uptake by enhancing soil water distribution [11–13]. This method also created a favourable aerated environment contributing to enhanced photosynthesis activity.

Pulsating irrigation is altogether applied to any irrigation method, but it is largely used in drip irrigation systems since water supplied during each irrigation session drains out, and the waiting period allows the soil to absorb water, reducing drainage losses. Additionally, pulse irrigation is beneficial for most soil types, since alternating short irrigation periods with short waiting periods improves soil water distribution, and increases the wet zone. Especially for sandy soils, where the wetting area is small and water quickly percolates below the root zone, this irrigation mode helps mitigate water loss through drainage. In detail, the first pulse wets the soil allowing it to absorb subsequent pulses more effectively enhancing the soil's water retention capability. This provides optimal conditions for soil water movement and root uptake. For instance, pulsed drip irrigation also improved the wetting front and reached efficient water distribution in clay soil [14]. Similarly, in silt loam, using pulse irrigation for 30 minutes every 2 hours, up to eight times per day, improved soil water availability and water holding capacity [15].

On the whole, the pulsed irrigation technique has demonstrated positive effects on several crops grown in sandy soils, such as yields [16]. For example, strawberry yields increased by 40% under pulsed irrigation with four pulses, achieving a yield of 15.76 t/ha compared to 11.28 t/ha with continuous irrigation [16,17]. This management approach, compared to standard irrigation (continuous), resulted in a yield gain of 5.2 t/ha and an additional cumulative profit of up to 20,000 EUR/ha. Additionally, application efficiency (AE) increased to 94% under pulsed irrigation, compared to 89% with continuous irrigation.

Another crucial aspect of pulse irrigation management is to operate with highly-efficient irrigation systems. With this regard, the drip irrigation system is most suitable for combination with pulse irrigation management due to its capability to spread water both precisely and uniformly, consequently reducing drainage flux, controlling soil salinity, and increasing yield. Thus, combining pulse and drip irrigation techniques, it may achieve two key advantages: 1) high irrigation uniformity, and 2) well-distributed water in the root zone with minimal water and nutrient losses, thus improving soil physical characteristics.

As previously mentioned, a drip irrigation system saves water by wetting a large soil area and reducing water or nutrient loss beyond the root zone, but incorporating pulse irrigation can further enhance sandy soil characteristics, making it an effective strategy for improved water and nutrient management. The combination of pulse and drip irrigation can therefore contribute to proper irrigation management, allowing for adequate water rationalization in irrigated lands. Additionally, it can serve as an alternative technique to mitigate stress and climate change scenarios. In this regard, a study showed that using a pulsed drip irrigation type in sugarcane increased photosynthesis, water-use efficiency and leaf area. The fresh biomass production of the stem and leaves also increased, suggesting that this technique achieved the highest physiological indices and fresh biomass production in sugarcane [18].

Accordingly, this study aimed to propose an alternative irrigation practice to improve sandy soil processes, optimizing water interception through pulse-drip irrigation and enhancing blueberry production. Specifically, it compared pulsed (PLS) and continuous (N-PLS) irrigation techniques to assess the efficiency of PLS on blueberry yield and sandy soil water dynamics under mulched drip irrigation in a greenhouse in the Loukkos region of northwest Morocco.

2. Materials and methods

2.1. Study area

The study area is located in Loukkos region, near the city of Larache, in the north west of Morocco. The climate is oceanic Mediterranean, with annual rainfall between 500 and 800 mm, an average annual temperature ranging from 17 °C and 19 °C, with a minimum of 7 °C recorded in January and a maximum of 35 °C in July. The region enjoys approximately 3159 h of daylight per year.

The study was conducted in collaboration with a private farming company on a 1020 m^2 area (34 m × 30 m) dedicated to blueberry cultivation, including five tunnels (**Figure 1**). The variety of blueberry is CORRINA, planted in December 2020 and drip-irrigated under 6.8 m width tunnels.

Figure 1. An overview of blueberry cultivation in tunnels.

2.2. Experimental design and irrigation performance

The study area included two irrigation modes: pulsed (PLS) and continuous (N-PLS) irrigation management under greenhouse conditions in sandy soil. Each modality was set up to a cultivated blueberry considering only five drip lines (**Figure 2**). For each tunnel, two blueberry cultivation lines were set up with a density of 3.4 m by 1 m. Each blueberry strip has two driplines, providing uniform water irrigation around the crop. The drip lines, with a diameter of 16 mm, are equipped with emitters that use a nominal discharge of 2 L/h and are placed 30 cm apart. The flow rate of the drip irrigation system is 3.92 mm/h.

Both PLS and N-PLS modes stand out for supplying the same irrigation volume to the blueberries but differ in irrigation frequency. PLS was characterized by scheduling the irrigation volume three times per day, while N-PLS irrigation scheduled it once per day according to the farmer's irrigation. For instance, if irrigation events were scheduled once daily, the water amount was divided into three intervals for PLS. Conversely, if set twice daily, PLS was conducted six times (3 + 3). This PLS irrigation mode was adopted due to the characteristics of sandy soil. Sandy soil commonly tends to promote infiltration and drainage, but the break between two irrigation events in PLS helps soil better control the water distribution process. This pause allows the soil to retain water rather than quickly releasing it, slowing down downward fluxes beyond the root system. Preliminary tests on this sandy soil showed that the 3 + 3 interval effectively minimized drainage fluxes, ensuring more water remains available for the roots.

Since the study had to be adapted for only a small section compared to the vast irrigated area entirely managed by the farmer and used the existing drip irrigation system layout, assessing PLS performance often required adjusting the irrigation plan to meet the farmer's needs. This involved splitting the irrigation volume and adapting it twice during the season.

In detail, farm irrigation management is based on meeting 100% of crop evapotranspiration (ETc). Given that the existing drip irrigation system serves the entire farm sector, this study was only able to perform the analysis per strip line, resulting in the consideration of ten drip lines.

Each line was equipped with a manual valve to independently control the opening and closing times. Manual valves were installed at the inlet of each line to be irrigated according to pulse criteria, with 3 times and a 30-minute break between two applications.

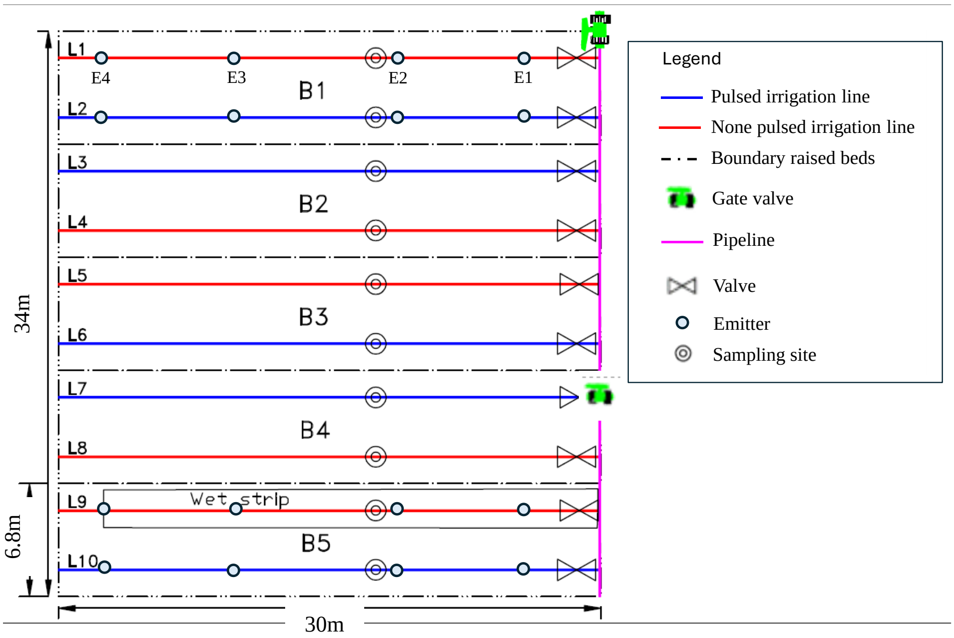


Figure 2. Experimental design and monitored sites selected in the case study.

To assess the performance of the pulse irrigation management, measurement campaigns were conducted, including the evaluation of blueberry growth parameters, soil water content, soil solution electrical conductivity, and pH. The yield of blueberry, water and nutrient efficiency, soil salinity (soil solution electrical conductivity ECe), and pH of investigated sandy soil were also estimated to compare the effects of PLS and N-PLS irrigation.

Additionally, to evaluate the uniformity of irrigation between pulsed and non-pulsed practice, the discharge was measured below such emitters by identifying four sites per drip line (E1, E2, E3 and E4), as shown in **Figure 2**.

Emission uniformity was determined as the ratio of the average flow emitted by the lowest 25% of the emitters to the mean flow emitted by all the control emitters [19]:

$$EU = \frac{\overline{q}_{25\%}}{\overline{q}_a} \times 100 \quad (1)$$

where: EU is emission uniformity (%), $\overline{q}_{25\%}$ is the average of 25% of the lowest values of flow rate (cm^3h^{-1}), $\overline{q}_a$ is the average flow rate (cm^3h^{-1}).

Overall, there was no significant difference in the emission uniformity coefficient between PLS and non-PLS modes, averaging 94% and 92% respectively. This is attributed to the identical irrigation system and its hydraulic characteristics. For the irrigation schedule, a crop-specific water use method was adopted, based on the evapotranspiration rate obtained from a reference crop (grass or alfalfa) and the crop coefficient (Kc). Reference evapotranspiration (ET0) was determined using the simplified Penman-Monteith equation, with climate parameters (air temperature, solar radiation, humidity, and wind) measured via a meteorological station and used as input data to obtain ET0 [20]. As mentioned earlier, farm irrigation management was carried out once per day for 20 or 30 minutes and split into 2 or 3 intervals per day for the pulse. During some vegetative periods, the duration was shortened to 15 or 20 minutes per interval.

2.3. Monitoring soil and blueberry parameters

2.3.1. Soil sampling

In six cultivated blueberry strips, soil samples were collected at three sites per strip (near the initial, medium and near the end) as shown in **Figure 2**, and at two-compartment depths: 0–20, 20–40 cm, to determine the soil water content, soil salinity and pH.

Each month starting from March, one tunnel was selected. For both PLS and N-PLS strips, three sites per cultivated line (near the inlet, at the middle and near the end) were dug to collect two samples per depth (0–20 cm and 20–40 cm) to account for soil variability along the strip, and three replicates assessed per treatment. In detail, disturbed soil samples were collected to determine soil water content using the thermo-gravimetric method. After sampling, the soil was weighed and placed in an oven at 105 °C until it reached a constant weight (24–48 hr).

To quantify water retained in the soil for the two treatments, a comparison of the water storage (W) results between the two irrigation treatments was conducted.

Specifically, W was calculated along the soil profile by integrating soil water content measurements across two compartments. Water content at each selected depth, θz, measured at three-compartment depths along the dripper lines, represents the water stored along the soil profile (0–40 cm) and per each drip line. Consequently, the water stored (W) in each drip line is obtained by multiplying the water content, θz_i (cm^3/cm^3), measured along the *i-th* monitored soil compartments, Δz_i, by the corresponding depth, z_i (z_1 = 20, z_2 = 40 cm), as follows: $W_{(0–40\ cm)} = \Sigma\theta i\ \Delta zi$ and integrated over time.

2.3.2. Fruit diameter and yield

Ten randomly selected fruits from each treatment were evaluated for diameter using a digital calliper. Both equatorial and polar diameters were taken, and the average diameter per berry was calculated.

On the contrary, to estimate the yield, six harvest events were randomly selected and observed. Overall, at each picking and for each cultivated line, the quantity of marketable blueberry harvested was weighted using a balance and recorded.

2.3.3. Water use efficiency (WUE)

To assess the efficiency of PLS irrigation mode, some indices were calculated for blueberry.

Water use efficiency (WUE) was determined to assess the irrigation water consumed by blueberries, as follows: WUE = $yield/W_{application}$, where WUE is water use efficiency (kg/m^3), *yield* is total grain yield (kg/Ha), and $W_{application}$ is total applied water (m^3/Ha). Similarly, Nutrient Use Efficiency for nitrogen N and phosphorous P taken up by blueberries was calculated as follows: NUE = *yield* (Kg/Ha)/N or P fertilizer (Kg/Ha).

3. Statistical analysis

Statistical analysis was performed using ANOVA to assess differences among factors between pulse and no pulse irrigation, with four replications. Adjusted sum of squares was used for tests, with a 95% confidence interval ($p = 0.05$).

Hydrus 2D simulations to describe soil water fluxes

As mentioned, soil water fluxes under drip irrigation were also simulated using the Hydrus-2D tool [21]. The core of the model is the Richards equation, which is solved numerically using an implicit finite element scheme.

The purpose was to simulate two scenarios to retrieve the distribution of the water content in the 2D domain: PLS and N-PLS modes. Due to the limited measurements, it was assumed that these simulations provided a comprehensive understanding of the entire evolution of soil water content over time and through the sandy soil profile.

Soil hydraulic parameters were estimated using a PTF function [22]. The parameters obtained for the 0–40 cm depth range to input into the model are as follows: $\theta s = 0.353$, $\theta r = 0.00$, $\alpha = 0.04$, $n = 1.38$ and $Ks = 86.7$ cm/day and $\tau = 0.5$, where θs is the saturated water content, θr is the residual water content, α and n are geometric parameters of water retention curve, and Ks is the saturated hydraulic conductivity, and τ is tortuosity coefficient. For the second layer 40–80 cm, the default parameters for sandy soil provided in the Hydrus library were used.

The simulation domain, 80 cm depth, was discretized into triangular meshes, with detailed meshing around the emitter to account for rapid soil water content variations during irrigation. To compare the simulated water content with measured values, the average of the measurements collected at the three sites along the strip drip line and in the middle of the experiment on 16 April was considered.

These two scenarios (PLS and N-PLS) allowed us to rebuild the soil water patterns and below the plastic mulch throughout the irrigation season.

4. Results and discussion

The data were obtained from three measure campaigns carried out on 21 March, 16 April and 1 June selecting three lines operating under PLS practice and three more under N-PLS. To each line of 30 m in length, three sites were sampled: near the initial, middle and near the end and two depths: 20 and 40 cm.

4.1. Blueberry irrigation water requirement

During the experimentation, the amount of water delivered to both: PLS and N-PLS irrigation was similar, differing only in frequency. **Table 1** lists the irrigation volumes by frequency.

Table 1. Irrigation volumes were supplied for both treatments during the trial.

Date	Non-Pulsed irrigation			Pulsed irrigation			Total Time (min/day)	Total Volume (m^3/ha/day)
	T/app (min)	V/ap (m^3/ha)	Fr (app/day)	T/app (min)	V/ap (m^3/ha)	Fr (app/day)		
05/02/22	15	8.62	2	5	2.87	6	30	17.24
06/02/22	20	11.49	1	7	3.83	3	20	11.49
07 to 13/02/22	15	8.62	2	5	2.87	6	30	17.24
14 to 20/02/22	20	11.49	2	7	3.83	6	40	22.99
21 to 22/02/22	20	11.49	3	7	3.83	9	60	34.48
23/2 to 04/3/22	20	11.49	2	7	3.83	6	40	22.99
05 to 06/03/22	15	8.62	2	5	2.87	6	30	17.24
07 to 08/03/22	20	11.49	2	7	3.83	6	40	22.99
09 to 15/03/22	15	8.62	2	5	2.87	6	30	17.24
16 to 22/03/22	20	11.49	2	7	3.83	6	40	22.99
23 to 26/03/22	(20) + (15)	(11.49) + (8.62)	2	(7) + (5)	(3.83) + (2.87)	6	35	20.11
27/3 to 25/4/22	15	8.62	3	5	2.87	9	45	25.86
26/04/22	15	8.62	2	5	2.87	6	30	17.24
27/4 to 12/5/22	15	8.62	3	5	2.87	9	45	25.86
13/05/22	10	5.75	3	5	2.87	6	30	17.24
14/5 to 02/6/22	15	8.62	3	5	2.87	9	45	25.86

Notes: T: time; app: application; Fr: frequency.

As mentioned above, the amount of water delivered was calculated based on estimated evapotranspiration $ET0$, using a simplified Penman-Monteith equation solution as follows:

$$ET0 = 0.006 \times Rg \quad (2)$$

Since the experiment was conducted in a greenhouse where conditions, differ from open field standards, the actual blueberry water requirement, AbWR, was thus calculated as follows:

$$\text{AbWR} = ET0 \times Kc \times Kr \quad (3)$$

where ETc is the estimated evapotranspiration in the greenhouse, *Rg* is global radiation, *Kc* is the blueberry crop coefficient, and *Kr* is the reduction coefficient accounting for low plantation density.

Overall, the estimated blueberry water requirement was slightly lower and by 13% than the water requirement based on planting density. Specifically, the applied seasonal blueberry water volume was 2430.46 compared to the estimated 2792.71 m^3/ha.

However, the estimated blueberry water requirement was smoothed to reflect actual water application (AbWR) accounting for the controlled conditions. By examining the daily volume data, it was observed that the trend of estimated (blue line) and applied (orange line) water amounts are quite similar throughout the irrigation season (5 February–1 June 2022). No significant difference was noted between the daily applied and estimated blueberry water amounts (**Figure 3**). However, the planting density coefficient used to estimate the water applied showed that values are higher than evapotranspiration at the beginning of the irrigation period. This behavior was observed in two periods: February–April and April–June, influenced by different incoming radiation and shade structures during the irrigation season. The plastic cover alters reflected solar radiation, enhances certain wavelengths, and controls heat and humidity in the greenhouse [23,24].

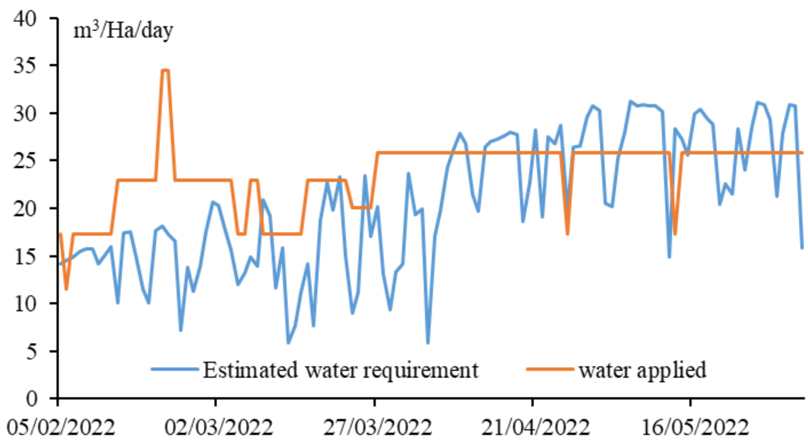


Figure 3. Comparison between estimated and applied daily blueberry water amount during the experiment.

4.2. Comparison between Pulse and non-pulse irrigation techniques

Table 1 illustrates the trend of the irrigation volumes supplied, focusing on three specific days: 21 March, 16 April and 1 June. These data correspond to three soil measurement campaigns conducted for both pulse (PLS) and non-pulse (N-PLS) modes, the data shows that the irrigation volumes delivered on these three days differ between the two treatments (PLS, N-PLS).

Although the total amount of water supplied to the blueberry plants was similar, the pulse irrigation mode PLS introduced breaks that allowed the soil to gradually absorb water. In other words, these breaks facilitated better water redistribution in the root zone and, along with the plastic mulch helped to further reduce evaporation.

In contrast, the N-PLS irrigation, which involved longer breaks, allowed water to move quickly through the soil without enough time to distribute in the root zone. By comparison, the PLS mode, with shorter breaks, allows water time to redistribute and be retained in the soil. This led to a higher likelihood of water loss through drainage with N-PLS, which is typical for sandy soil with high permeability [13,16].

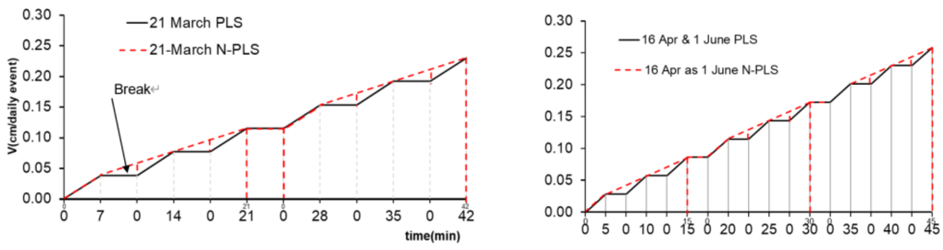
The PLS irrigation mode proved to be more efficient, conserving more water in the root zone, which was confirmed by the observed yield and water storage results.

In detail, the PLS irrigation mode induced a sequence of six breaks, while the N-PLS accounted for only two or three breaks, constrained by the farm management practices. Since the entire farm is served by an irrigation network and the irrigation volume is delivered in turn, it was not possible to keep N-PLS open continuously. However, this didn’t affect the overall aim, and the PLS showed better performance compared to N-PLS.

As an example, **Figure 4** shows a detailed sequence of breaks induced by PLS and N-PLS over three days, focusing on only one irrigation day. The trend of daily volume and frequencies of irrigation on 1st June is similar to that on 16 April.

Thoroughly, in **Figure 4a** the black broken straight line represents nine breaks under PLS, compared to two breaks under N-PLS, depicted with a red dashed line, with an equal daily water amount on 21 March. For two irrigation durations, 21 and 42 minutes, six partial volumes were delivered under PLS, influencing the soil water dynamics differently than N-PLS mode.

A similar behavior can be observed in **Figure 4b**, where nine breaks occurred under PLS irrigation compared to three breaks under N-PLS.



(a) **(b)**

Figure 4. The cumulative irrigation volumes for only one day to the three campaign dates: **(a)** 21 March, **(b)** 16 April and 1 June under both pulse (PLS) and non-pulse (N-PLS) irrigation (as an example of the irrigation schedule).

Overall, the daily breaks induced by PLS irrigation over a short period result in a different response from the sandy soil in terms of water distribution. In other words, PLS indirectly improved the soil’s ability to retain and release water, as illustrated subsequently.

4.3. Effects on soil water storage and water fluxes under pulse and non-pulse technique

Water storage, W, represents the amount of water retained along the soil profile and is obtained by integrating the soil water content, θ, at each soil compartment with the corresponding explored depth, z, as follows: $W = \Sigma\theta z$ (see materials and methods). In other words, W being a local measure, may also indicate water held in the soil at specific depths: 20 and 40 cm and on three specific dates: 21 March, 16 April and 1 June.

Soil water content data, used to estimate water storage, W, was obtained on these three dates in six strips, at three locations per treatment: near the initial, middle and near the end. As shown in **Figure 5**, the bars depict the value of the water storage for three drip lines and three dates for both PLS and N-PLS irrigation. The full and empty bars represent W calculated for three measurement campaigns, averaging three sites per line: near the initial, middle and near the end under N-PLS and PLS, respectively. W is similar, with a slight difference observed in the middle of the experiment on 16 April, with a value of 7.3 cm for N-PLS mode, higher than the 6.2 cm for PLS. This behaviour can be explained by observing the daily actual evapotranspiration acquired on that day, which was 4.3 mm compared to 2.2 mm on 21 March and 1.8 mm on 1 June. This means more water was supplied on 16 April, with three breaks in the N-PLS mode compared to nine in the PLS mode. In the first case, irrigation induced the incoming water to move swiftly along the profile, contributing to increased water storage, W, and a higher probability of inducing downward fluxes below the root zone compared to PLS. Conversely, under PLS, the nine scheduled breaks allowed for a more efficient redistribution of water in the root zone, promptly used by the blueberry crop, as confirmed by later water flux values. At the beginning of the experiment, water storage calculated using water content measured on 21 March under PLS irrigation mode was slightly higher than that of N-PLS. This occurs because shorter and more frequent irrigation pulses improve irrigation performance—a relevant factor in managing drip irrigation systems in sandy soils [25]. Considering the water volumes supplied on 21 March were lower than those estimated for the next irrigation period, 16 April to 1 June, due to low evapotranspiration demand, PLS enhanced however water productivity by minimizing water losses and increasing yields [26]. Overall, PLS influenced water movement in sandy soil, inducing horizontal redistribution more than vertical, benefiting the crop during the growing season, as shown by yield results. In the last campaign, when the blueberry entered the senescence phase, water storage remained somewhat higher due to reduced root uptake.

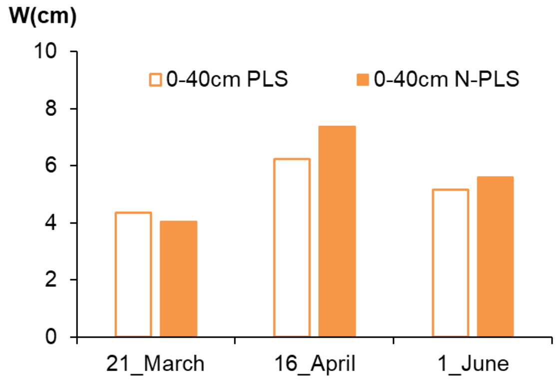


Figure 5. Water storage, *W*, calculated for three measurement campaigns: 21 March, 21 April and 1 June at three sites, for both PLS and N-PLS irrigation.

Based on only three samplings done across three strip-lines, water flux, *Jw*, was estimated, assuming a similar daily water storage across three intervals: 5 February to 21 March, 21 March to 16 April, and 16 April to 1 June, with the elapsed span being short between measurements. Water flux values were obtained by dividing the water storage estimated over the interval time: 2 February and 21 March.

Figure 6 shows the values of water fluxes, *Jw*, for the three measurement intervals at three locations: near the initial, middle and near the end along the strip-line and at a depth of 0–40 cm, depicted with bars. The symbols represent the average water storage at two depths: 0–20 and 20–40 cm and at three sites. The data revealed distinct patterns in water movement and retention for both irrigation modes, providing valuable insights into the efficiency and effectiveness of PLS compared to N-PLS. Assuming that the soil water fluxes depicted in **Figure 6** only represent the water loss by evapotranspiration, thus these fluxes results can be explained most in terms of upward water fluxes, as evapotranspiration. The black line indicates the trend of crop evaporation averaged over three intervals: 5 February to 21 March, 21 March to 16 April and 16 April to 1 June. The trend of crop evapotranspiration reflects the variation of soil water flux, *Jw*, estimated over the three intervals. Full bars, representing the estimated water fluxes under N-PLS mode, show a slight increase compared to PLS, represented by empty bars. This behavior can be explained by the different breaks set for the two treatments, as shown in **Figure 4a,b**. With the same supplied volume but discontinuities induced by PLS, it is observed that water delivery with N-PLS, illustrated with a red dashed line continued, while a delay in water supply with PLS, depicted with a black line, was observed. This contributed to an overall increase in water flux with N-PLS, while PLS allowed for more efficient water stored in the root zone, slightly decreasing water flux values. The step effect induced by PLS improved the capability of sandy soil to retain water because the off-schedule in PLS allowed for delayed vertical movement, reducing the likelihood of triggering downward fluxes. In this regard, a study demonstrated that pulsing played a significant role in irrigating raspberry crops in sandy or silty loam soils [15].

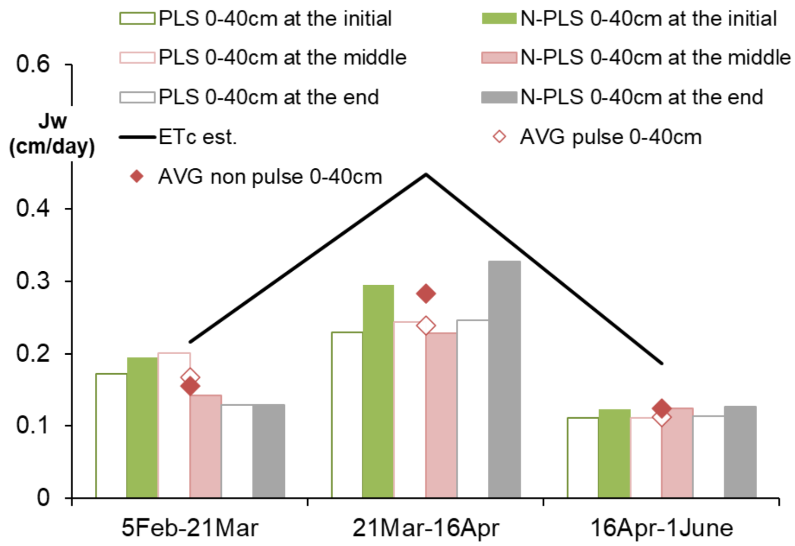


Figure 6. Soil water fluxes estimated at three places: near the initial, middle and near the end along three sampled strip-lines and at 0–40 cm under pulse (PLS) and non-pulse (N-PLS) irrigation schedules.

Overall, PLS irrigation significantly improved water efficiency in sandy soil. Thus, the irrigation pulses maintained sufficient water content, thereby ensuring the marketable quality of blueberries [27]. Overall, assessing soil water content in the root zone in various case studies showed that increasing the number of pulses and off-time duration, enhanced infiltration time, promoting soil moisture redistribution. This improvement in water distribution within the soil profile led to better crop yield and water productivity [28].

4.4. Effect of pulse irrigation on soil solution electrical conductivity and pH

As mentioned above, the scheduled breaks with the PLS technique influenced water fluxes in sandy soil, showing better efficiency in saving water in the root zone compared to N-PLS. This also led to a different salt pattern. The data provided insights into how these two irrigation modes influenced the soil's nutrient availability and salt patterns at different soil depths. Assuming that soil solution electrical conductivity, ECe, measured at three places: near the initial, middle and near the end of each of the three strip-lines and at three times: 21 March, 16 April and 1 June, represents nutrients in the soil, it is evident that ECe values observed under PLS can also indicate the soil nutrient availability to blueberries, showing better efficiency with PLS irrigation. After a sequence of breaks starting on 5 February and continuing through the middle of the experiment on 16 April, the salt value was 0.36 dS/m under PLS compared to 0.14 dS/cm at 20 cm under N-PLS, as shown in **Figure 7**. This could be due to an increase in horizontal water movement rather than vertical movement with the PLS irrigation, resulting in improved water distribution with a larger wet soil volume in root zone and better control of the salt pattern [11,13]. In other words, PLS treatment improved nutrients availability at 20 cm, as shown by the blue empty bars in **Figure 7**, especially in the middle of the irrigation season when roots activity was highest, thereby enhancing the yield. The contrasting results obtained at the beginning of the experiment can be explained by the brief period during which PLS irrigation was adopted for this case study.

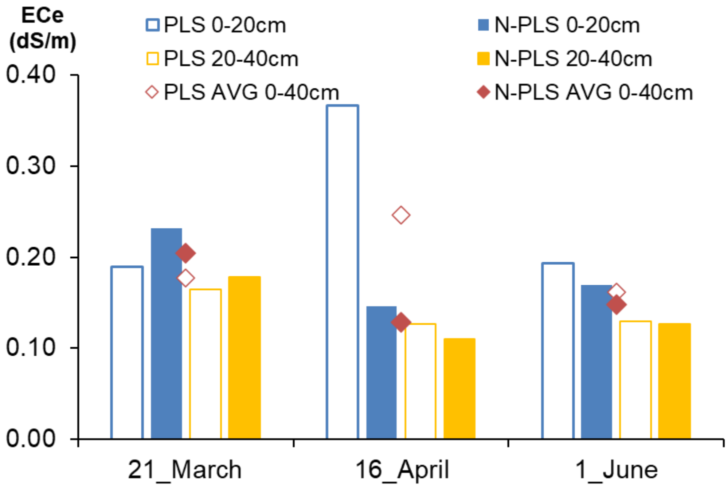


Figure 7. Soil solution electrical conductivity (ECe) measured on three dates: 21 March, 16 April and 1st June and at two depths: 0–20 and 20–40 cm across three samplings under pulse (PLS) and non-pulse (N-PLS) irrigation.

In the middle of the season, the difference in ECe average value observed on 16 April under PLS irrigation, depicted in **Figure 7** with a full symbol, is quite evident compared to the other two dates: 21 March and 1 June. Overall, the soil wetting pattern maintained higher nutrient availability in the root zone for the crop.

On the contrary, soil pH was measured at the last campaign on 1 June in one trail. It is well-known that pH and ECe parameters are important for monitoring the effects of agricultural management practices on nutrient interactions [29]. As shown in **Figure 8**, the pH values at two depths differ. The **Figure 8a** displays pH values measured along the line at three sites and at last campaign: near the initial, middle and near the end along the strip-line, and depicted with empty bars for values observed at 20 cm and full bars for values at 40 cm. The PLS irrigation decreased pH values compared to those observed under N-PLS at both depths: 20 and 40 cm. This implies that the PLS mode improved the effectiveness even if taking farmer practices into account, as demonstrated in this study where the PLS experiment was tailored to the existing drip irrigation system and pre-selected irrigation management. In detail, **Figure 8b** shows that pH values measured under PLS irrigation, illustrated with empty bars, were lower than those under N-PLS. Knowing also that blueberry cultivation requires acid soils, thus pH correction is commonly practised by farmers to keep values within 4–5.5, especially since Moroccan soils are mostly basic with values higher than 7 [30]. Therefore, PLS contributed to making this agronomic practice more efficient, maintaining optimal pH values at both depths: 20 and 40 cm.

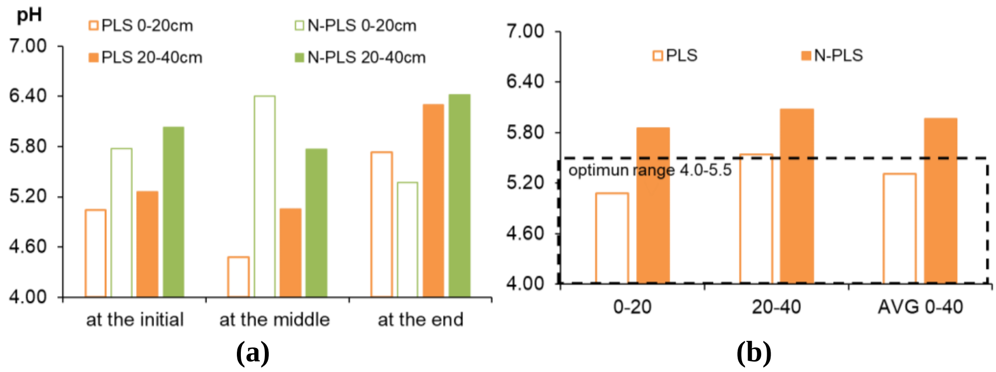


Figure 8. pH data collected during the last campaign on 1 June under pulsed (PLS) and non-pulse (N-PLS) irrigation management. **(a)** pH data at three sites: near the initial, middle and near the end; **(b)** pH values averaged over the three sites.

The time-off period performed with PLS irrigation improved the soil water pattern, enhancing nutrients availability and efficiency in the root zone.

4.5. Assessing water and nutrient use efficiency WUE and NUE

Because the trial was conducted over a short period, it did not allow for significant differences between PLS and N-PLS irrigation to be demonstrated, apart from yield and soil pH. Additionally, due to the non-linearity of soil water processes, the soil response was not immediate. However, the observed differences between PLS and N-PLS irrigation suggest that efficiency calculation in terms of water and nutrient use may be important indices to validate the results described above. In detail, water use efficiency, WUE, and nutrient use efficiency, NUE, were calculated.

Concerning WUE, obtained as the ratio between yield and evapotranspiration, a notable difference was observed between PLS and N-PLS techniques. **Figure 9** shows a comparison of WUE between PLS and N-PLS irrigation, depicted with orange and red bars, respectively. Two types of WUE were calculated to quantify the efficiency of the PLS technique: 1) partial WUE which represents WUE for each measurement interval: 5 February–21 March, 21 March–16 April and 16 April–1 June, accounting for the partial yield corresponding to the investigated line at only one specific data, 2) overall WUE which represents, on the other side, the efficiency obtained by considering the total yield collected from three PLS lines and three N-PLS lines, using both actual, ETa, and potential evapotranspiration, ETc, estimated for the entire irrigation season. These two evapotranspiration types were obtained as water storage and crop-specific water use calculations, respectively. ETa was also considered because it is representative of water root uptake, which is useful because of indicates the local amount of water consumed by the blueberry plants. Overall, it is clear that the PLS mode shows a higher WUE compared to the N-PLS mode. As previously discussed, at the beginning of the experiment, the effects of PLS are not very evident due to a delayed soil response. During this period, N-PLS irrigation showed a slight increase in WUE. However, as the experiment progressed, PLS irrigation distinguished itself from N-PLS, achieving a WUE of 1.25 Kg/mm compared to 1 Kg /mm when based on the ETa, and 1.15 compared to 1.05 Kg/mm when based on ETp.

The pulse irrigation practice increased the yield by 10%, which in turn improved water use efficiency WUE. This demonstrates that the PLS mode may be an effective alternative strategy to save water and increase yield, which is crucial in regions like Morocco where water shortage is a significant risk to agriculture.

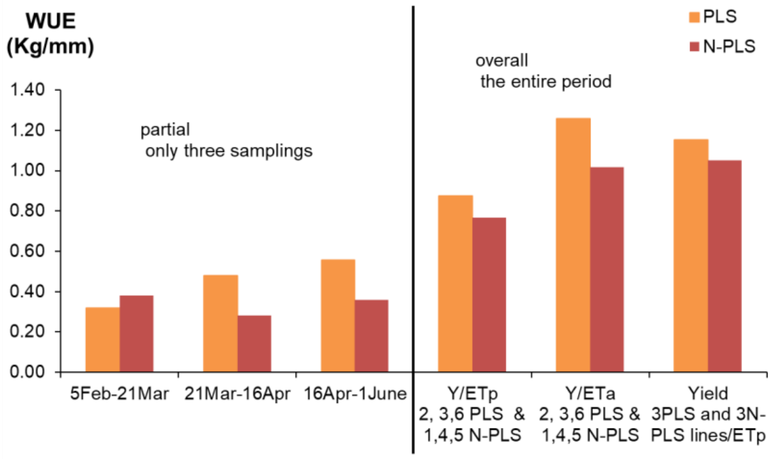


Figure 9. Comparison of water use efficiency (WUE) calculated for the three measurement intervals: 5 February–21 March, 21 March–16 April, and 16 April–1 June and for three strip-lines. Partial WUE (considering partial evapotranspiration for the three measurement intervals and the yield), and overall WUE (considering evapotranspiration over the whole irrigation season 2022 and the yield for each of the three strip-lines: 2, 3, 6 for PLS, and 1, 4, 5 for N-PLS) for both pulse PLS and pulse (PLS) and non-pulse N-PLS irrigation.

A similar pattern was observed in nutrient use efficiency. In this regard, **Figure 10** shows the values of nitrogen use efficiency, NUE, and potassium use efficiency, PUE. Nutrient use efficiency was calculated as the ratio between blueberry yield, *Y*, in kg, and kilograms of nitrogen *N* and potassium *P* fertilizer applied. PLS irrigation resulted in a slight increase in both NUE and PUE compared to N-PLS.

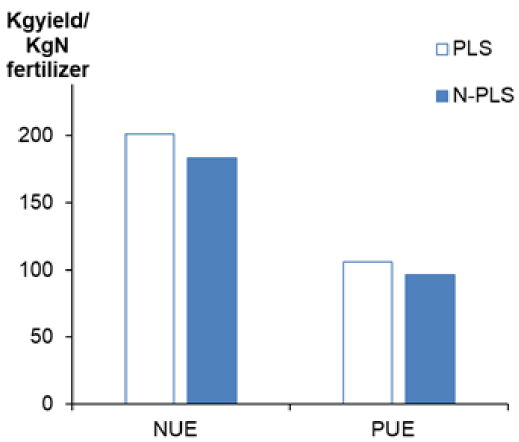


Figure 10. Comparison of water nutrient efficiency (NUE) for both pulse PLS and non-pulse N-PLS irrigation.

This demonstrates that the PLS irrigation facilitated horizontal water distribution rather than vertical, thereby making nutrients more available in the root zone and promoting growth. Increasing the number of pulses enhances water movement horizontally rather than vertically [17].

4.6. Effect on fruit size and the yield of the blueberry crop

Statistical analyses were conducted to assess the effect of irrigation management (pulse and non-pulse) on fruit size. The equatorial and polar diameters of 10 randomly selected fruits were measured and analyzed for both irrigation modes. A significant increase was observed in both fruit diameters. The pulse irrigation practice enhanced fruit size compared to continuous management. Specifically, the equatorial diameter increased by approximately 8%, from 14.7 to 15.85 mm, while the polar diameter increased by about 9%, from 12.6 to 13.7 mm.

Increasing fruit size is a crucial aspect of blueberry farming. It mainly boosts marketable yield compared to smaller fruits that do not meet market standards. Moreover, larger fruit size implies a higher yield, making the product more competitive in the market.

A *t*-student test was also performed to assess the statistical significance of yield obtained from 8 lines, with 4 lines for PLS and 4 for N-PLS, assuming a p-value < 0.05, with a 95% confidence interval. However, the yield did not show a statistically significant difference between pulse and non-pulse irrigation mode. Despite this, the PLS irrigation practice showed approximately a 10% yield increase compared to continuous N-PLS irrigation, with an overall 297.23 kg for N-PLS compared to 326.03 for PLS.

4.7. Effect on soil water behavior and ECe

Soil water and salinity patterns were retrieved using observational data from three lines and three dates. The Inverse distance weighting (IDW) method was applied to map the soil water storages, W, and soil solution electrical conductivity, ECe, data, to observe their evolution along the soil profile and across the entire strip.

On the contrary, to only describe the behavior of soil water content throughout the entire irrigation season, from 5 February to 1 June, a scenario was set up in Hydrus 2D model. The simulation was designed to assess the wet bulb shape evolution under PLS and N-PLS irrigation at the midpoint of the strip (30 m × 0.8 m). As mentioned in materials and methods, the simulation was based solely on soil water content data collected for two depths: 20 cm and 40 cm on 16 April.

According to the IDW method, the maps in **Figures 11–13** show the interpolated water content values along the 30 m strip up to a depth of 40 cm. Specifically, **Figures 11–13** show the water storage and water fluxes, as well as soil solution electrical conductivity, ECe data for 21 March, 16 April and 1 June. The water pattern (soil water content and water fluxes) in the middle section under PLS irrigation and for two strip lines is almost always different compared to N-PLS, where the water content swiftly dropped, as confirmed by Hydrus 2D simulations. While soil solution electrical conductivity, ECe, is quite evident near the initial section of the two strip lines under PLS, in contrast, most of the high ECe values are observed in the middle of the two strip lines as well, under N-PLS. This indicates that the pulse mode does not provide enough time for salts, intended as nutrients, to spread evenly in only one day. On the other hand, PLS allows nutrients to remain available for longer compared to non-PLS.

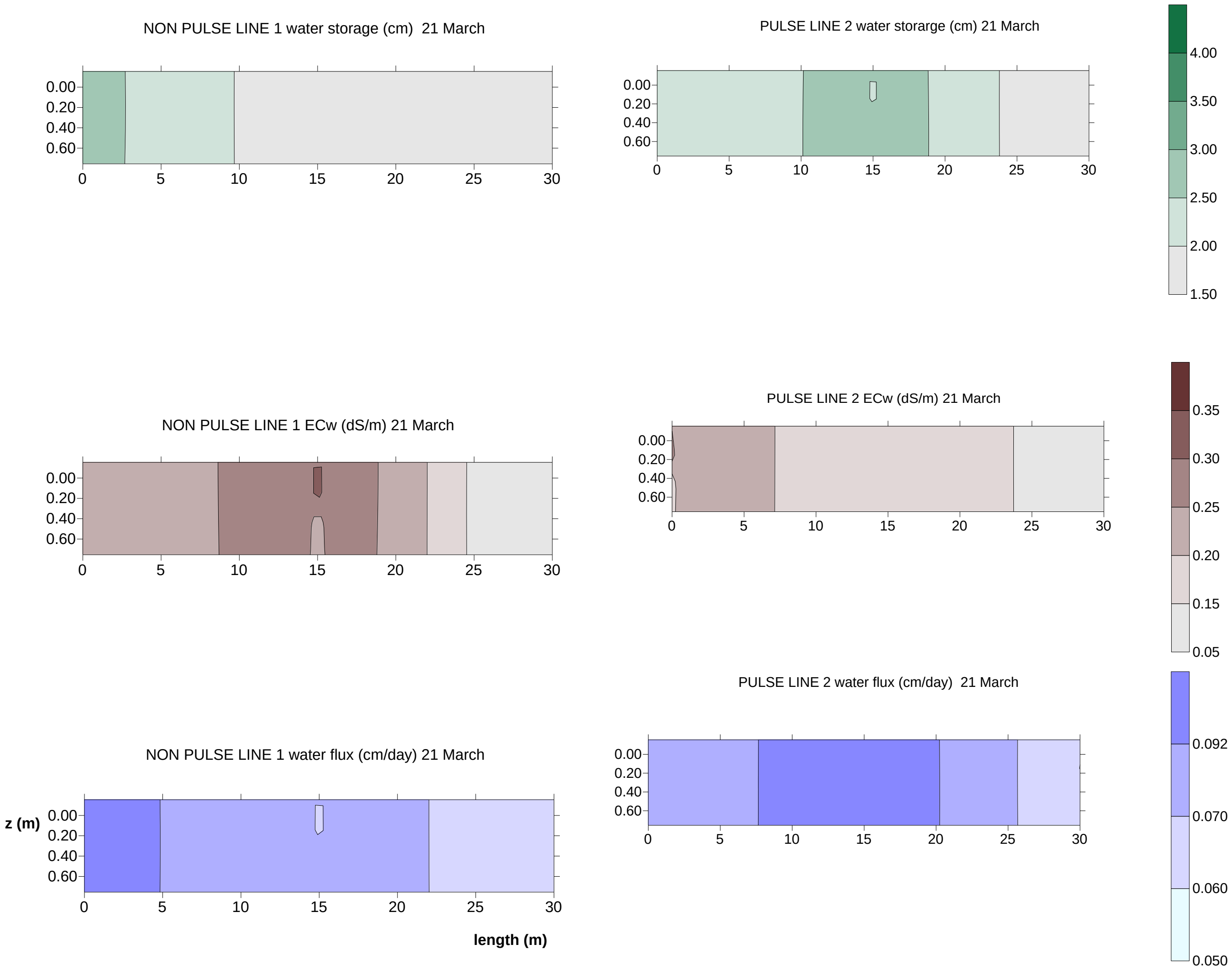


Figure 11. Map of water storage and fluxes and salt distribution in the soil under pulse (line 2) and non-pulse (line 1) irrigation management.

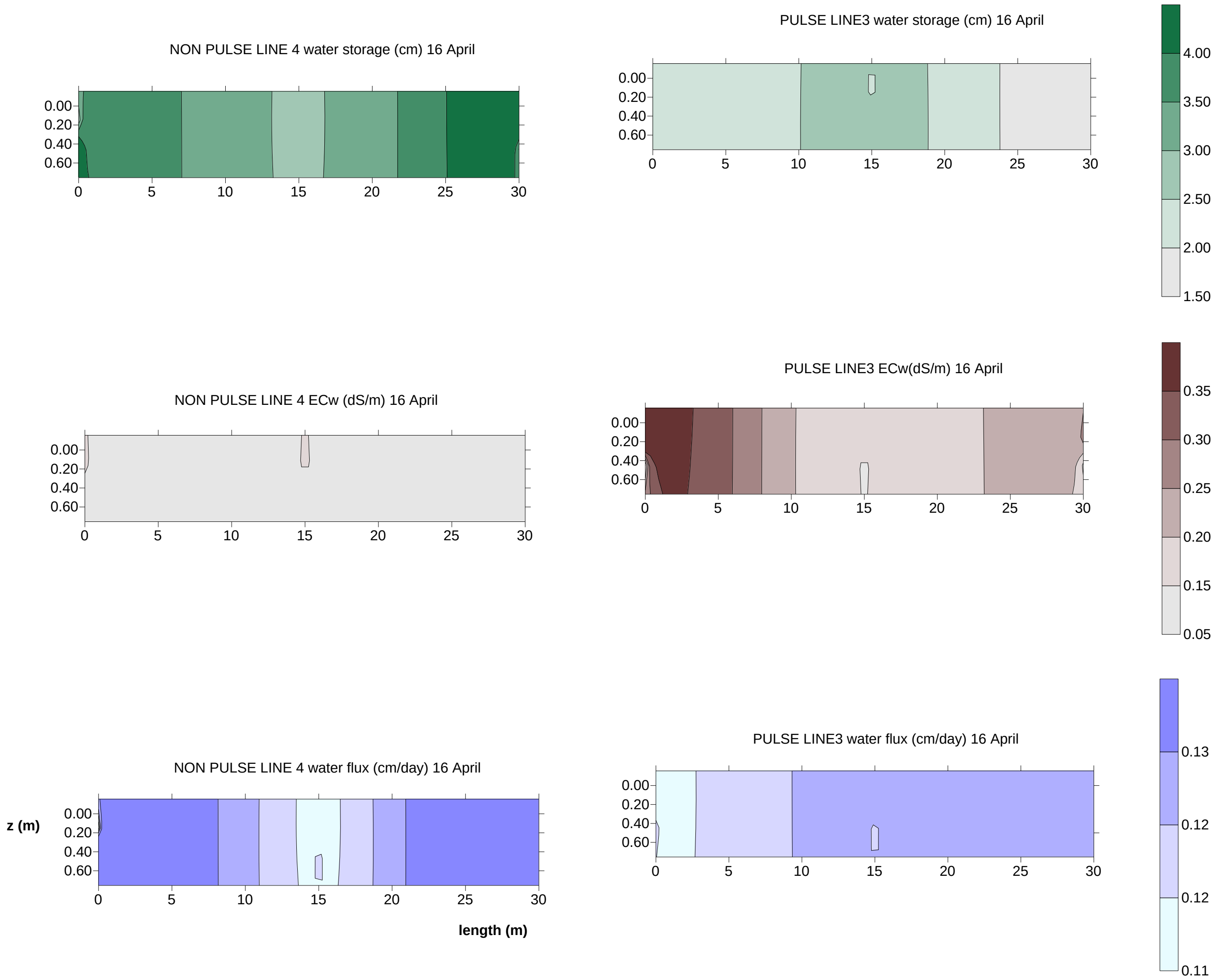


Figure 12. Map of water content and water fluxes, and soil solution electrical conductivity for two strip lines under pulse and non-pulse irrigation.

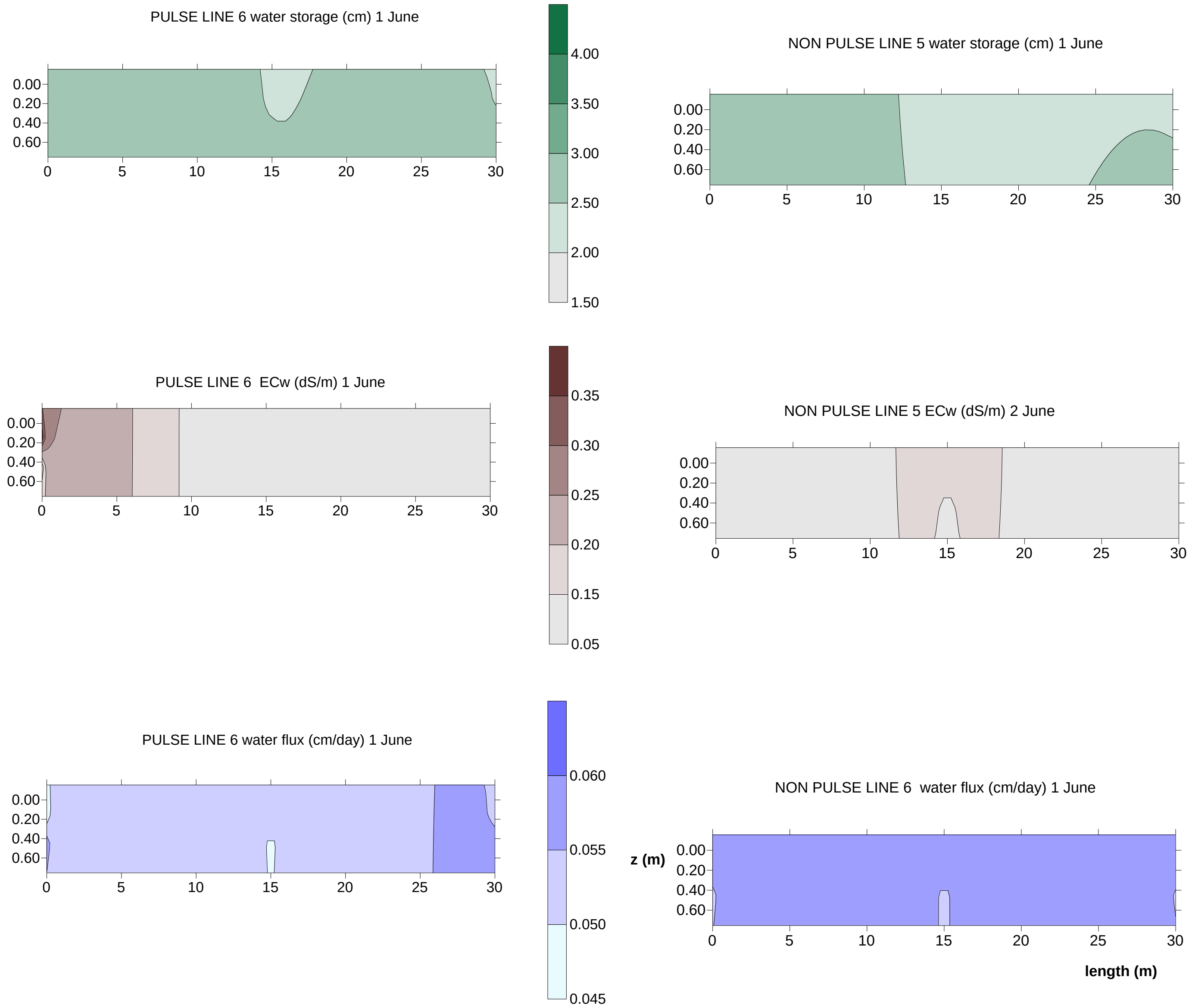


Figure 13. Map of water content and water fluxes, and soil solution electrical conductivity for two strip lines under pulse and non-pulse irrigation.

4.8. Water content under pulse and non-pulse irrigation simulated using Hydrus 2D

Hydrus 2D simulation was conducted to analyze soil water content behavior, as there were insufficient measurements collected during the experiment. Furthermore, due to the short duration of the experiment, the simulation is provided only in terms of soil water content behavior.

To monitor the soil water content evolution beneath the dripper during the irrigation period from 5 February to 1 June, two scenarios were simulated in Hydrus 2D: PLS and N-PLS modes for a single strip line. In detail, water content readings for 16 April served as reference points for the simulations, addressing the trend of water content values based on measured data, particularly in the middle of the strip line, assumed to represent the most soil water variability.

The geometry domain designed in Hydrus 2D included free drainage as the bottom condition, no flux to the top and lateral sides, while a constant flux surrounding the dripper, plus were inputted soil hydraulic parameters and obtained as illustrated in materials and methods. **Figure 14** shows different water content data collected on 16 April for two lines in both PLS and N-PLS. The observed data allowed the reproduction of the detected water content trends observed throughout the irrigation period during field monitoring for both irrigation techniques: PLS and N-PLS. It is evident different water contents for PLS compared to N-PLS, although water content measurements at 20 and 40 cm, taken only once, were similar for both techniques.

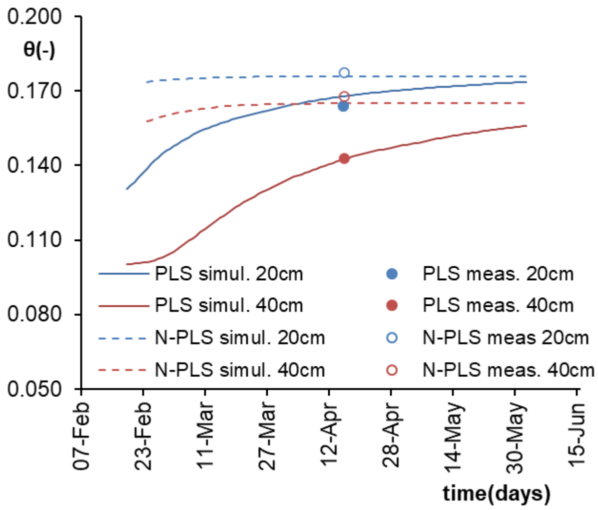


Figure 14. Comparison between measured (symbols) and simulated (line) soil Water contents under PLS and N-Pulse irrigation management.

In conclusion, Hydrus 2D simulations corroborated the observed form field measurements. In other words, the pulse irrigation technique appears to have improved soil water distribution thanks to the sequence time off set which enhanced water and nutrient uptake efficiency for blueberry.

5. Conclusions

The study was conducted in north-west Morocco on blueberries cultivated under mulched drip irrigation in sandy-loamy soil. The results indicated that with the same amount of water supplied in both pulse PLS and non-pulsed N-PLS modes, the high-frequency of pulse irrigation led to better water and nutrient efficiency.

On average, the PLS, applied eight pulses per day increased yield by 10% and fruit size by 8%, while the water and nutrient use efficiency of blueberry increased by 9% compared to N-PLS irrigation (applied once or twice per day). Irrigating with small applications (pulses) for a very short duration (5 to 7 min), followed by 30 min breaks between pulses, also improved water redistribution in the root zone, better controlled the soil electrical conductivity (ECe) pattern, and maintain pH values within the optimal range for blueberry (pH = 4.0–5.5).

Pulse drip irrigation can be an effective strategy to improve water behavior in sandy soil, increasing the horizontal spread of water in the soil. In other words, it can increase soil water content horizontally in the root zone rather than vertically, as shown by maps and Hydrus 2D model results.

The PLS strategy thus allowed for improved irrigation and fertilization management, resulting in better nutrient uptake efficiency in blueberries.

Pulse irrigation remains a strategy worth exploring further due to its significant role in crop production. It enables lower water application rates, distributed in cycles, with efficient distribution in the root zone. This can potentially increase yield and enhance water use efficiency, especially when used with mulching, as with blueberries. Additionally, it may reduce deep percolation of water, increasing horizontal spread, and resulting in particularly positive benefits for sandy soils.

Author contributions: Conceptualization, GD, SB and AEG; methodology, GD and SB; software, GD; validation, AEG, SB and GD; formal analysis, AEG, RCA and GD; investigation, AEG; resources, SB and AEG; data curation, GD and SB; writing—original draft preparation, AEG, GD, and SB; writing—review and editing, GD, RCA and SB; visualization, RCA and SB; supervision, RCA and SB; project administration, GD, SB and RCA; funding acquisition, GD and SB. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest

References

1. Fresh Fruit Portal. Morocco is conquering the global blueberry market and rising to meet demand in UK. Produce Business. 2024.
2. Céleyrette C. 2018 Berries in Morocco. FruiTROP n.255 Producer country file. 2018.
3. Gough RE. Root distribution of “Coville” and “Lateblue” highbush blueberry under sawdust mulch. Journal of American Society for Horticultural Science (USA). 1980; 105(4): 576–578.
4. Freeman B. Blueberry production. Agfact H3 1.4. Department of Agriculture. New South Wales. Australia. 1983.
5. Eck P. Blueberry Science. Rutgers University Press; 1988.
6. Austine ME, Draper AD. Brightwell Rabbiteye blueberries. HortScience. 1983; 18(2): 252.
7. Gough RE. Better management means more blueberries. Fruit Grower. 1982.
8. Holzapfel EA, Hepp RF, Jaureguiberry ME, Serri HE. Growth response of a highbush blueberry under trickle and microjet irrigation: first year after establishment. Acta Horticulturae. 1993; 346: 117–124. doi: 10.17660/ActaHortic.1993.346.16
9. Dukes MD, Scholberg JM. Soil moisture controlled subsurface drip irrigation on sandy soils. Applied Engineering in Agriculture. 2005; 21(1): 89–101.
10. Skaggs TH, Trout TJ, Rothfuss Y. Drip irrigation water distribution patterns: Effects of emitter rate, pulsing, and antecedent water. Soil Sci Soc Am J. 2010; 74: 1886–1896. doi: 10.2136/sssaj2009.0341
11. Assouline S, Möller M, Cohen S, et al. Soil-Plant System Response to Pulsed Drip Irrigation and Salinity. Soil Science Society of America Journal. 2006; 70(5): 1556–1568. doi: 10.2136/sssaj2005.0365
12. Coolong T, Susmitha S, Richard W. Evaluation of irrigation threshold and duration for tomato grown in a silt loam soil. HortTechnology. 2011; 21(4): 466–473.
13. Eid AR, Bakry AB, Moamen HT. Effect of pulse drip irrigation and mulching systems on yield, quality traits and irrigation water use efficiency of soybean under sandy soil conditions. Agricultural Sciences. 2013; 4: 249–261. doi: 10.4236/as.2013.45036
14. Okasha AM, El Metwally WF, Attaffey TM. Effect of different types of irrigation systems on soybean production under clayey soil conditions. Misr Journal of Agricultural Engineering. 2016; 33(1): 43–62.
15. Carroll JL, Orr ST, Benedict CA, et al. Feasibility of using pulse drip irrigation for increasing growth, yield, and water productivity of red raspberry. HortScience. 2024; 59(3): 332–339.
16. Gendron L, Letourneau G, Cormier J, et al. Using pulsed water applications and automation technology to improve irrigation

practices in strawberry production. HortTechnology. 2018; 28(5): 642–650. doi: 10.21273/HORTTECH04001-18
17. Ramadan A. Study the Performance of Pulse Drip Irrigation in Organic Agriculture for Potato Crop In Sandy Soils [PhD thesis]. Cairo University Egypt; 2009. doi: 10.13140/2.1.4753.4400
18. de Menezes SM, da Silva GF, da Silva MM, et al. Pulsed drip irrigation reduces sugarcane water consumption and improves growth, productivity, sugar and ethanol yields. BioEnergy Research. 2024; 17: 1413–1424.
19. ASAE. Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot, Corner Pivot, and Moving Lateral Irrigation Machines Equipped with Spray or Sprinkler Nozzles. ASAE; 1993.
20. Andales AA, Chavez JL, Bauder TA. Irrigation Scheduling: The Water Balance Approach. Colorado State University Extension. 2015; 4(707).
21. Simunek J, van Genuchten MT. Using the HYDRUS-1D and HYDRUS-2D codes for estimating unsaturated soil hydraulic and solute transport parameters. Characterization and measurement of the hydraulic properties of unsaturated porous media. 1999; 1: 523-1.
22. Schaap MG, Leij FJ, van Genuchten MT. Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology. 2001; 251(3–4): 163–176. doi: 10.1016/S0022-1694(01)00466-8
23. Sangpradit K. Study of the solar transmissivity of plastic cladding materials and influence of dust and dirt on greenhouse cultivations. Energy Procedia. 2014; 56: 566–573.
24. Kim DW, Kim MH, Lee DW. Economic and environmental analysis of solar thermal and seasonal thermal energy storage based on a renewable energy conversion system for greenhouses. Energies. 2022; 15(18): 6592.
25. Lozano D, Ruiz N, Baeza R, Contreras JI, Gavilán P. Effect of pulse drip irrigation duration on water distribution uniformity. Water, 2020, 12(8): 2276.
26. Ray LI, Swetha K, Singh AK, et al. Water productivity of major pulses—A review. Agricultural Water Management. 2023; 281: 108249.
27. ZamoraVRO, da Silva MM, da Silva GF, et al. Pulse drip irrigation and fertigation water depths in the water relations of coriander. Horticultura brasileira. 2019; 37, 22-28.
28. Mohammadi S, Mirlatifi SM, Homaee M, et al. Evaluation of silage maize production under pulsed drip irrigation in a semi-arid region. Irrigation Science. 2024; 42(2): 269–283.
29. Smith JL, Doran, JW. Measurement and use of pH and electrical conductivity for soil quality analysis. Methods for assessing soil quality. 1997; 49, 169-185.
30. Achkir A, Aouragh A, El Mahi M, et al. Effects of Different Rates of Liquid Sewage Sludge Amendment on Nutrient Content of the Soil in Rabat, Morocco. Environmental Sciences Proceedings. 2022; 16(1): 19.