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Effect of Pulse Drip Irrigation Duration on Water Distribution Uniformity

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Abstract: Developing an appropriate irrigation schedule is essential in order to save water while at the same time maintaining high crop yields. The standard procedures of the field evaluation of distribution uniformity do not take into account the effects of the filling and emptying phases of the irrigation system. We hypothesized that, in sloping sandy soils, when short drip irrigation pulses are applied it is important to take into account the total water applied from the beginning of irrigation until the emptying of the irrigation system. To compute distribution uniformity, we sought to characterize the filling, stable pressure, and emptying phases of a standard strawberry irrigation system. We found that the shorter the time of the irrigation pulse, the worse the distribution uniformity and the potential application efficiency or zero deficit are. This effect occurs because as the volume of water applied during filling and emptying phases increases, the values of the irrigation performance indicators decrease. Including filling and emptying phases as causes of non-uniformity has practical implications for the management of drip irrigation systems in sloping sandy soils.

Keywords: filling; emptying; water saving; sloping field; sandy soil

1. Introduction

The relentless growth of the human population, the rise in general living standards, and the need for water to maintain the long-term sustainability of the environment and ecosystems are straining water resources all over the world [1]. There is a growing trend in water withdrawal for agriculture, which has a critical importance in semi-arid Mediterranean environments, such as Spain [2].

In Spain, horticultural crops with a high added value are highly dependent on irrigation. Berries from the province of Huelva are a clear example of this case. The annual export of berries is around one billion euros, which generates approximately 80,000 work positions. Seventy-five percent of the berry production in Huelva is situated near the Doñana National Park, which is catalogued as a UNESCO World Heritage site [3]. The main source of water for berry fields and for the Doñana National Park system is the same, the "Almonte-Marismas" aquifer, which has been declared to be in a "poor" state by water authorities [4]. Due to this, berry production in Huelva is criticized for negatively affecting the Doñana National Park because of poor irrigation management.

Berry production in Huelva has some specific drawbacks that hinder efficient irrigation management. One of the main irrigation drawbacks is having very sandy soils (more than 90% sand) in most of the berry production area [5]. Sandy soils not only have a lower water-holding capacity but also significant downward water movement [6,7]. Farmers seek to maximize berry production,

which requires an irrigation strategy without water deficient crops. This approach may result in water and nutrient losses and groundwater pollution due to over irrigation in sandy soils [8,9]. In fact, irrigation frequency was found to affect nitrate leaching beneath the root zone [10–12].

A significant number of farmers in Huelva apply irrigation pulses of 30–40 min. [13] recommended different irrigation pulse durations for the strawberry producers of Huelva depending on the time of the season. During the first part of the season (October to January), [13] suggested that the pulse duration should range from 10 to 20 min. In the second half of the season, from February to June, irrigation pulses should be increased from 20 up to 60 min, depending on the root depth and water needs. On the other hand, some works revealed that pulse drip irrigation can improve strawberry production and marketable yields relative to the no pulse irrigation [14,15]. Therefore, developing appropriate irrigation pulse scheduling is essential to reduce current irrigation doses and reach high quantitative and qualitative production levels.

An additional drawback in high-frequency irrigation (short pulses) is water distribution on sloping plots. The effect of the slope on irrigation uniformity has also been addressed. [16] developed a method to design microirrigation laterals in uniformly and non-uniformly sloped fields. [17] developed analytical expressions relating water distribution indices to design variables that define trapezoidal drip irrigation plots. [18] evaluated the effect of hydraulic head and slope on water distribution uniformity. [19] analyzed the influence of the slopes on the water distribution of a single pipe during the stable pressure phase of irrigation. [20] developed an analytical method to design evenly sloped drip irrigation systems. It must be noted that all these studies assume stable pressures throughout the irrigation pulse, which may not be entirely true for short irrigation pulses on sloped fields.

On sloping plots, an uneven discharge of the irrigation tapes considering filling, stable pressure, and the emptying of the pipe flow process have been described by some authors [21,22]. In fact, these studies have analyzed the effects of the slope on the water emitter application at lateral levels according to the emitter position. Their results have been a starting point in understanding the effect of filling and emptying in a single tape in short pulses. However, these effects have not been studied at the irrigation unit scale for commercial fields.

The most popular methodologies for the field evaluation of distribution uniformity were proposed by [23–25]. These three methodologies differ in the number and location of the emitters selected to represent the entire irrigation unit.

Merriam and Keller's methodology (adopted by FAO) is based on the measurements of the water discharge located in 16 locations. These 16 locations are selected from four laterals and four emitters per lateral located at the inlet, at a third and at two thirds of the distance to the end of the manifold and the lateral, and also at the end of the manifold and the lateral.

ASAE's method is based on the works [26–28]. These works presented a statistical approach that uses water measured at 18 locations. The locations are selected randomly to measure both the discharge and pressure.

Burt's method indicated that discharge and pressure should be measured from a total of 66 locations: 16 locations close to the water source, 16 locations near the middle of the field, and 28 locations at the end of the lateral most distantly to the manifold.

Merriam and Keller's, ASAE's, and Burt's methodologies calculate the emitter's discharges assuming that the pressures of the irrigation system are stable throughout the irrigation pulse. Merriam and Keller's and Burt's methods record water flow for an integer number of minutes (from 3 to 6 min). Merriam and Keller's method uses a water volume between 100 and 250 mL for each emission point tested. On the other hand, ASAE's method records the time required to fill a 100 mL container. Therefore, in these methods the distribution uniformity value is only representative of the stable pressure of the pipe flow process.

Burt's methodology includes the emptying phase of the irrigation system as another component of the distribution uniformity, but indicates that a longer data collection time is not guaranteed

because of the relatively small impact of the emptying phase of the distribution system on the overall distribution uniformity.

Standard irrigation units without anti-drain emitters have three pipe flow phases per irrigation pulse. The first phase is the filling phase. This starts at the beginning of the irrigation pulse and ends when the entire irrigation unit has stable pressure in all the emitters. The stable pressure phase starts once there is stable pressure and ends at the end of the irrigation pulse. The emptying phase starts at the end of the irrigation pulse and ends after complete water emptying of the irrigation system.

Our hypothesis is that, in high-frequency and short-duration irrigation and sloped fields, it is important to compute the water volume applied during the filling, stable pressure, and emptying phase of the pipe flow process to know the real water distribution uniformity. To the best of our knowledge, there are no studies that characterize the different phases of the pipe flow process in a drip irrigation unit of a real field.

The authors are aware that the use of different tapes or emitters could change the quantitative response of the filling, stable pressure, and emptying phase of the pipe flow process. This manuscript shows the influence of these three pipe flow phases on short-term irrigation in a specific case study. In this way, the authors understand the limitations of this work. However, we understand that this manuscript provides a step forward to manage short irrigation pulses on drip irrigation systems under more arbitrary irrigation material, soil, and slope conditions.

Therefore, the objectives of this work are: (i) to characterize the filling, stable pressure, and emptying phases of the pipe flow process in high-frequency and short-duration irrigation on a sloping field, and (ii) to evaluate the effect of duration of irrigation pulses on the water distribution uniformity and the application efficiency of a drip irrigation unit.

2. Materials and Methods

2.1. Description of the Study Irrigation Unit

The study was carried out during the 2015–2016 irrigation season in a commercial strawberry production farm located near Lepe, Huelva, Spain. The climate in Huelva is subhumid Mediterranean, classified as warm temperate with a maritime influence. Huelva has more than 3000 light hours per year and temperatures that only exceptionally fall below 0 °C. Therefore, frosts are unusual. In Huelva, the annual average rainfall is 553 mm, and the average, maximum and minimum temperatures are 17.4, 28.8, and 8 °C, respectively. The soils of berry farms located in Huelva are sandy (quite a few soils are more than 90% sand).

The study irrigation unit was composed of 12 strawberry greenhouses. Each greenhouse has an area of 290.42 m^2 and consists of six rows 1.1 m separated. The area of the irrigation unit was 3485 m^2 (79.2 m wide and 44 m long). The irrigation unit has an average ascending transverse slope of 0.3% and an average descending longitudinal slope of 3% (Figure 1). The slopes of the irrigation units were obtained by a topographic survey.

The irrigation unit had a manifold polyethylene pipe and 72 built in emitter laterals. The manifold pipe and built in emitter laterals are new every season. Thus, the operating conditions are similar throughout the entire irrigation season in the case study of this work. The manifold polyethylene pipe was 63 mm in diameter and 79.2 m in length. A total of 72 laterals (irrigation tapes) were inserted into the manifold pipe. Each lateral had a 16.2 mm inner diameter and a 44 m length. The laterals used were Netafim StreamlineTM 16,080, with a nominal flow and pressure of 5.25 l h^{-1} m^{-1} and 1 bar, respectively. The drip emitter separation was 0.2 m. The total number of drip emitters in the irrigation unit was 15,912.

The water applied and pressure at the head of the unit were measured rigorously and controlled during this study. The volume of irrigation applied was measured through a flow-meter located at the head of the irrigation unit. The inlet water pressure was regulated at the entrance of the irrigation unit using a pressure regulator. The pressure regulator was located after the flow-meter to avoid the

head loss caused by the flow-meter. The inlet water pressure was fixed to 1 bar, which is the nominal pressure of the drip emitters.
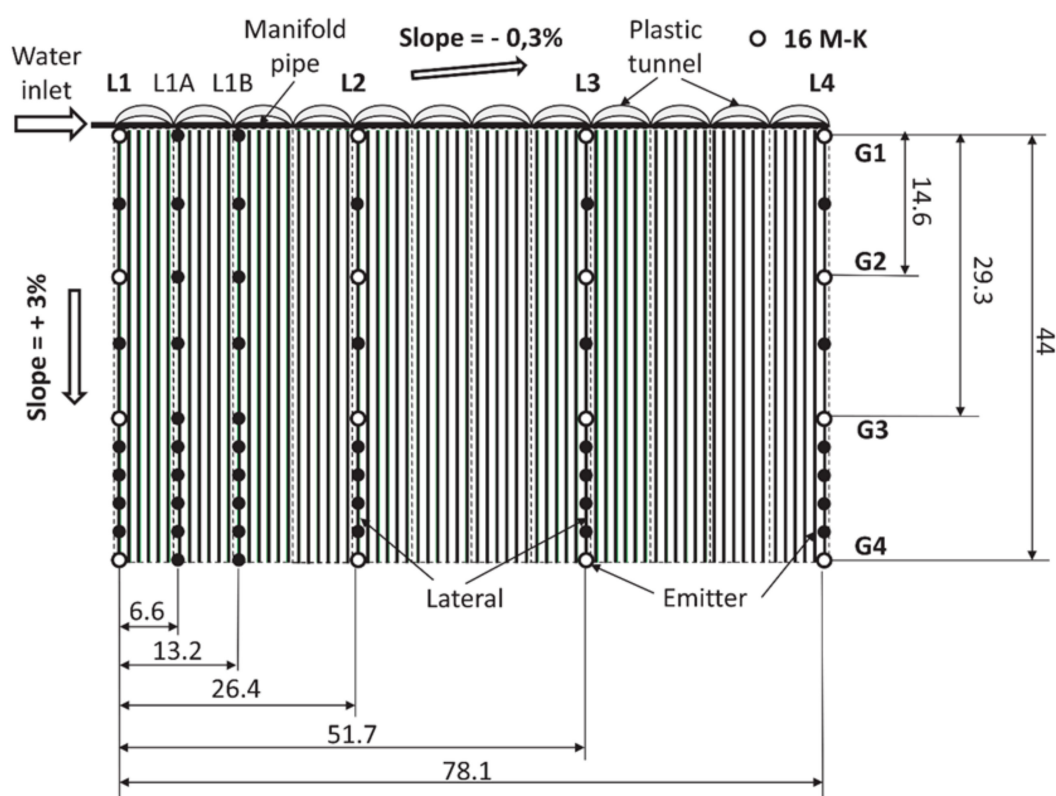

Figure 1. Scheme of the irrigation unit evaluated. Measurements were made at 60 points, including locations that correspond to Merriam and Keller's measuring points (16 Merriam and Keller (MK) locations).

2.2. Location of Measuring Points

Six laterals were selected for the irrigation unit studied (Figure 1). Four of them (L1, L2, L3, L4) correspond to the criteria proposed by Merriam and Keller's methodology: Laterals L1, L2, L3, and L4 are located at the beginning, at a third, at two thirds of the distance to the end of the manifold pipe, and at the end of the manifold pipe, respectively. The location of the other two irrigation points was at a quarter (L1A) and at a half (L1B) of the L1 to L2 distance. This decision was based on a total applied volume gradient that was studied previously for a single pipe [21].

Sixty measuring points were used for studying the water distribution in the study irrigation unit. Ten emitters were used for each lateral. The location of the emitters was also based on a previous study of water distribution in a single sloped lateral [21]. From the 60 volume measuring points selected, 16 correspond to the criteria proposed by Merriam and Keller's methodology. From now on, these 16 locations will be referred to as the 16 MK locations (Figure 1).

The pressure was measured at the 16 MK locations. To measure the water pressure, 16 manometer intakes were installed in the laterals. Sixteen glycerine manometers were located inside the manometer intakes close to the 16 MK selected locations. The manometers had a measuring range from 0 to 2.5 bar and a 0.05 bar accuracy (EN 837-1/6, weinmann-schanz©).

2.3. Characterization of the Pipe Flow Process

We characterized the three phases of the pipe flow process (filling, stable pressure, and emptying) in the irrigation unit studied. The water distribution uniformity of the study irrigation unit was evaluated at the beginning of the season (November). Firstly, the water distribution uniformity was

evaluated by measuring the pressure during the stable pressure process and transforming it into volume at each of the 16 MK measuring points. Therefore, through this form of calculation, the water distribution uniformity is independent of the irrigation duration. Secondly, four different irrigation pulses of 5, 10, 15, and 20 min were evaluated considering the volume applied by the tested emitters from the beginning of the irrigation to the emptying of the pipe. In this work, we do not evaluate the effect of the same total irrigation time with a different number of irrigation pulses. The objective was to evaluate each irrigation pulse duration independently. For that purpose, each irrigation pulse (5, 10, 15, 20 min) was evaluated on different days to assure the same initial conditions.

2.3.1. Filling Phase

The filling phase was characterized by measuring the continuous evolution of the pressure at 16 MK locations. The 5 min and 10 min irrigation pulses were used to measure the evolution of pressure. Five minutes of irrigation pulses was enough to characterize the entire filling phase. To measure the pressure, we used 16 manometers simultaneously (with a measuring range from 0 to 2.5 bar). The manometer accuracy was 0.05 bar. The evolution of the pressure in each of the 16 manometers was recorded with 16 Gopro© video cameras operating simultaneously. The pressure was measured every 10 s and recorded. The pressure values used each 10 s for the characterization of the filling phase were the average values of the 5 min and 10 min irrigation pulses.

The emitter flow rate during the filling phase was calculated using the equation supplied by the drip emitter manufacturer. The manufacturer's equation was tested before use (data not shown). The manufacturer's equation was used in each one of the 16 MK points:

$$Qf_{ej} = 0.3824 Pf_{ej}{}^{0.4384} \tag{1}$$

where Qf_{ej} ($l\,h^{-1}$) is the flow rate (liters per hour) of the emitter e at the instant j during the filling phase. Pf_{ej} is the pressure (meter's water column) measured in the manometer intake e at the instant j during the filling phase. In this equation, the values of e range from 1 to 16, corresponding to the 16 MK measuring points (Figure 1). The values of j range from 1 to 30 because there are six pressure values per minute (1 each 10 s), and because the duration of the pressure recording of the irrigation pulse was 5 min.

During the filling phase, the volume of water applied to each of the 16 MK emitters was estimated using the following equation:

$$Vf_e = \sum_{j=1}^{j=T_f} Qf_{ej}\Delta T_f \tag{2}$$

where Vf_e (l) is the water volume applied by the emitter e (1 to 16 MK) during the filling phase. ΔT_f (h) is the time interval of the pressure recorded (10 s). T_f is the number of the first time interval measured once the pressure is stable in the 16 MK emitters.

From the water volume estimated during the filling phase ($Vf_1, \ldots Vf_{16}$), an interpolation was performed to assign the volumes applied during the filling phase to the 15,912 emitters of the irrigation unit. Third degree polynomial equations were obtained based on the applied volume by 16 MK emitters during the emptying phase.

2.3.2. Stable Pressure Phase

The stable pressure phase was characterized by measuring the pressure twice at each of the 16 MK measuring points for each irrigation pulse (5, 10, 15, and 20 min). The pressure at the entrance of the irrigation unit was set at 1 bar for all the irrigation pulses. At each of the 16 MK points, the pressure was measured twice for each irrigation pulse. The value of the pressure assigned to each measurement point was the average of the two values. To measure the pressure, intake manometers were installed

on the 16 MK measuring points (Figure 1). The flow rate was calculated using the equation proposed by the drip emitter manufacturer:

$$Qsp_e = 0.3824 Psp_{eavg}{}^{0.4384} \qquad (3)$$

where Qsp_e (l h^{-1}) is the flow rate of the emitter e during the stable pressure phase, and *Psp*$_{eavg}$ is the average pressure measured (meter's water column) in the intake manometer e during the stable pressure phase in the four irrigation pulses.

The volume of water applied during the stable pressure phase in each of the 16 MK emitters was estimated using the following equation:

$$Vsp_e = Qsp_e T_{sp}, \qquad (4)$$

where Vsp_e (l) is the water volume applied by the emitter *e* (1 to 16 MK) during the stable pressure phase, and T_{sp} (h) is the duration of the stable pressure phase.

2.3.3. Emptying Phase

The emptying phase was characterized by measuring the water volume applied by 60 selected drip emitters (Figure 1) after the end of the irrigation pulse duration. Based on the experience of the authors, to ensure the complete emptying of the laterals the emptying phase was considered to be 2 h. After 2 h, the authors can guarantee that no dripper emits water. The data of the emptying volume was the average value of four independent irrigations on different days. The water of 60 drip emitters was stored in 0.7 l plastic containers. These plastic containers were placed under the 60 drip emitters after the end of the irrigation pulse. The emptying water volumes were measured using a graduated cylinder of 0.5 l capacity with a 5 mL accuracy. Third degree polynomial equations were developed based on the relationships between the volume applied by 60 emitters that were controlled during the emptying phase and the distance from the beginning of laterals.

2.4. Validation of the Water Distribution Model

An empirical water distribution model was developed to simulate the flow emitted by each one of the 15,912 emitters for the study irrigation unit. The model was based on the previous characterization of the filling, stable pressure, and emptying phases of the pipe flow process. To validate the water distribution model, four irrigation pulses were applied on four different days in May. The duration of the irrigation pulses was 5, 10, 15, and 20 min. The pressure at the entrance of the irrigation unit was also set at 1 bar in all the irrigation pulses.

To validate the model during the three irrigation phases (filling, stable pressure, and emptying), the water applied by the 60 selected emitters (Figure 1) was measured. The filling and stable pressure volumes were measured together as a unique stage called the volume of irrigation pulses. The water volumes at the emptying phase were measured separately. The pressure measurement methodology to validate the stable pressure phase was the same used during the characterization stage in the 16 MK measuring points. The values measured were compared to the values predicted by the model.

The water applied by emitters was stored in plastic containers, both from the beginning until the end of the irrigation pulse and from the end of the irrigation pulse until 2 h after the end of the irrigation pulse. Subsequently, the irrigation pulse water volumes were measured using a graduated cylinder of 0.5 l capacity with a 5 mL accuracy.

In the validation stage, 120 plastic containers of 0.7 l were used; 60 of them were used for measuring the volume of irrigation pulse (filling + stable pressure phases), and 60 were used for measuring the water volume of the emptying phase. The water volume was measured using a graduated cylinder of 0.5 l capacity with a 5 mL accuracy.

2.5. Irrigation Performance Indicators

2.5.1. Distribution Uniformity

Distribution uniformity is usually defined as the ratio of the smallest accumulated discharges in the irrigation water distribution to the average discharges of the whole distribution [29]. The distribution uniformity of the low quarter (UD_{lq}) is an irrigation performance indicator developed by the United States Department of Agriculture–Natural Resources Conservation Service (USDA-NRCS). UD_{lq} has been widely accepted by the international irrigation research community for decades [30,31], and there is a high correlation between distribution uniformity and other water distribution indicators [32,33]. UD_{lq} is calculated using Equation (5):

$$UD_{lq} = 100\frac{Q_{25\%}}{Q_{avg}} = 100\frac{V_{25\%}}{V_{avg}}$$

(5)

where $Q_{25\%}$ is a 25% average flow ($l\,h^{-1}$) with a lower flow of water, Q_{avg} is the average flow ($l\,h^{-1}$), $V_{25\%}$ is the 25% average water applied volume (l) with a lower volume of water, and V_{avg} is the average water applied volume (l).

The performance indicator UD_{lq} was calculated both with values measured in the validation stage or with values predicted using the water distribution model generated in this study.

- Standard distribution uniformity:

Distribution uniformity in the stable pressure phase (UD_{lq_sp}) is the water distribution uniformity indicator obtained using classical evaluation methodologies (i.e., Merriam and Keller's, ASAE's, and Burt's). It is important to highlight that UD_{lq_sp} is independent of the duration of the irrigation pulse. UD_{lq_sp} was calculated using Equation (3), and Merriam and Keller's methodology using the following equation:

$$UD_{lq_{sp}} = 100\frac{Q_{25\%_{sp}}}{Q_{avg_{sp}}}$$

(6)

where $Q_{25\%\_sp}$ ($l\,h^{-1}$) is the average flow of 4 MK emitters with a lower water flow during the stable pressure phase, and Q_{avg_sp} ($l\,h^{-1}$) is the average of the flow of the 16 MK emitters during the stable pressure phase.

- Distribution uniformity of the total water applied in the irrigation unit studied:

The distribution uniformity of the total water applied in the field ($UD_{lq\_field\_3phases}$) depends on the filling, stable pressure, and emptying phases of drip irrigation. $UD_{lq\_field\_3phases}$ was calculated for the water volume measured in irrigation pulses of 5, 10, 15, and 20 min in the validation stage. The volume of water applied during these three drip irrigation phases was measured in the 16 MK emitters from the beginning of the irrigation pulse until the emptying of the irrigation system. The duration of the irrigation tests was 2 h of the emptying phase plus the time of the irrigation pulses (5, 10, 15, and 20 min). The $UD_{lq\_field\_3phases}$ was calculated using the following equation:

$$UD_{lq_{field\_3phases}} = 100\frac{V_{25\%_{field\_3phases}}}{V_{avg_{field\_3phases}}}$$

(7)

where $V_{25\%\_field\_3phases}$ (l) is the average of 4 MK emitters with a lower volume of total water applied by the 16 MK emitters from the beginning of the irrigation pulse until the emptying of the irrigation system, and $V_{avg\_field\_3phases}$ (l) is the average volume of the 16 MK water volumes measured from the beginning of the irrigation pulse until the emptying of the irrigation system.

- Distribution uniformity of the total water applied by each emitter:

The distribution uniformity obtained with the empiric model (UD_{lq_model}) was calculated for seven simulations of irrigation pulses. Simulations were made every 5 min, from 5 to 30 min, plus an additional simulation of 60 min. The UD_{lq_model} was calculated using the following equation:

$$UD_{lq_{model}} = 100 \frac{V_{25\%_{model}}}{V_{avg_{model}}}$$ (8)

where $V_{25\%\_model}$ (l) is the average of 25% with a lower volume of total water applied (including three phases) by 15,912 drip emitters of the irrigation unit, and V_{avg_model} (l) is the average of the total water applied by the 15,912 drip emitters of the irrigation unit during the three drip irrigation phases.

2.5.2. Potential Application Efficiency for Zero Deficit

Application efficiency provides a general indication of how well an irrigation system performs in delivering water from the irrigation system to the crop. Therefore, application efficiency is a measure of the ratio between the crop water requirements (ET_c) and the total volume of water delivered to the field by the irrigation system ($V_{water\ delivered}$). ET_c was calculated based on FAO methodology, using the measured reference evapotranspiration (ET_o) and local crop coefficients (K_c). ET_o was obtained from a meteorological station belonging to the Agrometeorological Network of Andalusia [34]. K_c was calculated based on crop coverage using the relationship obtained by [35].

Potential application efficiency without deficit irrigation at any location ($PAE_{zerodeficit}$) occurs when there is no irrigation deficit, and no over-irrigation, at the point where the irrigation water applied was at a minimum. This irrigation performance indicator is especially important for the irrigation strategies of horticultural crops of high added value, such as berries. For these kinds of crops, the farmer's production strategy is to maximize yield [14,35], which requires the absence of water deficit throughout the plot. $PAE_{zerodeficit}$ can be defined as:

$$PAE_{zerodeficit} = 100 \frac{neV_{ETc}}{V_{waterdelivered}}$$ (9)

where ne is the number of emitters of the irrigation unit evaluated and V_{ETc} is the minimum irrigation volume applied by one emitter in the irrigation unit, assuming that the minimum irrigation volume is equal to the crop water requirements.

2.6. Statistical Methods Used to Compare the Model and Data Fit

In order to carry out the subsequent statistical analysis for validating the irrigation distribution model, the following parameters were calculated.

2.6.1. Coefficient of Determination

The coefficient of determination (R^2) is a key output of regression analysis. R^2 is interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable. An R^2 between 0 and 1 indicates the extent to which the dependent variable is predictable.

2.6.2. Theil's Inequality Coefficient

Theil's inequality coefficient (U) was calculated as [36]:

$$U = \sqrt{\frac{\sum_{i=1}^{n}(Ob_i - Pr_i)^2}{\sum_{i=1}^{n} Ob_i^2}}$$ (10)

where Ob_i and Pr_i are the observed (measured) and predicted values and n is the number of data pairs. Parameter U could be 0 or greater. U = 0 means a perfect fit between the model results and observations. A larger U value means a poorer model performance [36].

2.6.3. Modeling Efficiency

Modeling efficiency (ME) was calculated as [37]:

$$ME = 1 - \frac{\sum_{i=1}^{n}(Ob_i - Pr_i)^2}{\sum_{i=1}^{n}\left(Ob_i - Pr_{avg}\right)^2} \tag{11}$$

where Pr_{avg} is the average of predicted values. ME = 1 indicates a perfect fit. ME = 0 reveals that the model is no better than a simple average, and negative values indicate a poor performance.

2.6.4. Standardized Residual

Residual methods calculate the difference between the observed and modelled data points. In our case, the residual plot was a plot of the Standardized Residual (SR) as the dependent variable and the location of the measured points as the descriptor variable [38]. The standardized residual was calculated as:

$$SR_i = \frac{Ob_i - Pr_i}{Ob_i} \tag{12}$$

3. Results

3.1. Modelling of the Filling Phase

The evolution of pressure measured during the filling phase depended on the location of the emitters. One hundred and forty seconds was the time it took for the entire system to fill and pressurize. The transition from zero pressure to the value of stable pressure is sharper as the distance of the pressure locations increases relative to the water entrance of the irrigation unit (Figure 2a). In this sense, 20 s was the amount of time it took to fully pressurize the system's most distant extremities. In this regard, the pressure stabilized 160 s after the beginning of irrigation. Therefore, the duration of the filling phase in the irrigation unit in our study was 160 s. In the case of the farthest emitter (L4-G4), there was no pressure in the first 140 s, which implies that the application of different water volumes during the filling phase depended on the location of the emitters in the irrigation unit (Figure 2b).
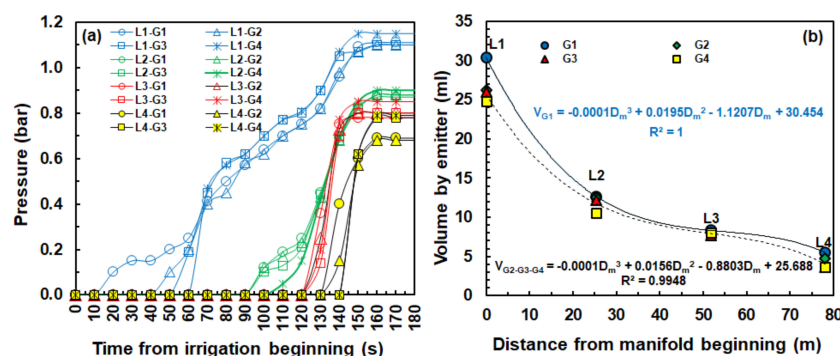

Figure 2. Modelling of the filling phase (160 s) in the 16 MK locations (L1-G1, ... , L4-G4) using (**a**) the evolution of pressure from the beginning of irrigation or (**b**) the volume of water applied by emitters as a function of the distance from the beginning of the manifold (D_m).

3.2. Modelling of the Stable Pressure Phase

The decrease in ground level in the direction of the laterals (positive slope, Figure 1) caused a positive gradient of pressure. This positive gradient occurs because the decrease in ground level is higher than the head loss in the laterals. In contrast, in the manifold pipe there was a negative gradient of pressure, which was caused by the increment in ground level (negative slope, Figure 1) and the head loss in the manifold pipe (Table 1).

Table 1. Calibration data set of average pressure (bar) measured during the stable pressure phase on each 16 MK location for 4 different irrigation pulses (5, 10, 15, and 20 min) in November.

Irrigation Pulse Duration	L1-G1	L2-G1	L3-G1	L4-G1	L1-G2	L2-G2	L3-G2	L4-G2
	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)
5 min	0.99	0.88	0.80	0.72	1.02	0.90	0.80	0.70
10 min	0.93	0.81	0.72	0.66	0.95	0.84	0.70	0.65
15 min	0.93	0.77	0.67	0.67	0.96	0.77	0.70	0.69
20 min	0.90	0.70	0.65	0.66	0.85	0.72	0.67	0.67
Average	0.94	0.79	0.71	0.68	0.95	0.81	0.72	0.68
SD	0.03	0.07	0.06	0.02	0.06	0.07	0.05	0.02
	L1-G3	L2-G3	L3-G3	L4-G3	L1-G4	L2-G4	L3-G4	L4-G4
	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)
5 min	1.00	0.88	0.82	0.68	1.03	0.82	0.82	0.80
10 min	1.02	0.85	0.70	0.7	1.07	0.87	0.73	0.75
15 min	0.99	0.83	0.74	0.73	1.07	0.88	0.76	0.77
20 min	0.91	0.76	0.7	0.71	0.95	0.82	0.75	0.77
Average	0.98	0.83	0.74	0.71	1.03	0.85	0.77	0.77
SD	0.04	0.04	0.05	0.02	0.05	0.03	0.03	0.02

The increases and decreases in pressure were adjusted to second-degree equations in the laterals (Figure 3a) and in the manifold (Figure 3b). Second-degree equations were used to assign a predicted pressure to each of the 15,912 emitters of the irrigation unit during the stable pressure phase.
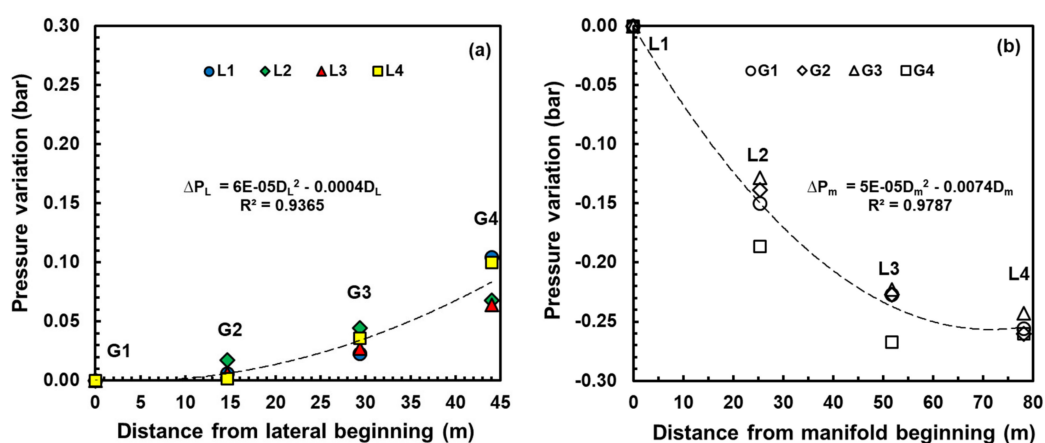

Figure 3. Pressure variation (ΔP) with respect to the point closest to the water inlet of the irrigation unit (L1-G1) during the stable pressure phase (**a**) from the lateral beginning (D_L) and (**b**) from the manifold beginning (D_m).

3.3. Modelling of the Emptying Phase

The effect of the emptying phase on sloped fields was much higher in the last third of the laterals (Figure 4). The analysis of the water volume measured during the emptying phase of the calibration stage showed that lower elevation laterals are more affected by the emptying phase of the manifold pipe (Table 2). To address the effect of emptying the manifold pipe, the study irrigation unit was divided into two areas: the irrigation area of lower elevation from L1 to L1B (see Figure 1), and the irrigation area of higher elevation from L1B to L4 (see Figure 1). In both areas, the third degree polynomial equations of water volume measured during the emptying phase versus the distance from the lateral beginning were obtained (Figure 4). The two equations shown in Figure 4 allow the simulation of the volume of water applied by the 159,212 emitters of the irrigation unit during the emptying phase.
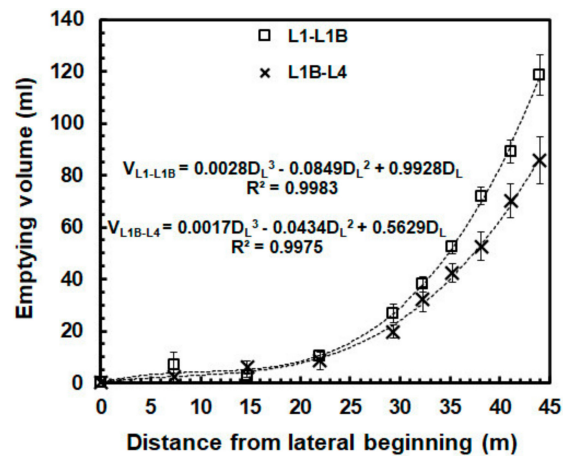
Figure 4. Average and standard deviation of the volume of water applied by the emitters in the emptying phases in four irrigation pulses (5, 10, 15, and 20 min) from the lateral beginning (D_L). The two equations were adjusted for the areas between the laterals L1 and L1-B (L1-L1B) and L1-B and L4 (L1B-L4) using the calibration data set.

Table 2. Calibration data set of the applied water volume (mL) during the emptying phase of the irrigation pulse in 60 selected locations for 4 different irrigation pulses (5, 10, 15, and 20 min) in November.

Dm (m)	L1	L1A	L1B	L2	L3	L4	L1L1B	L1BL4	L1	L1A	L1B	L2	L3	L4	L1L1B	L1BL4
	Average Volume (m)								Standard Deviation (ml)							
0.0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.3	9	5	5	2	2	1	7	2	5.59	4.42	6.02	2.92	2.05	0.50	5.00	2.87
14.7	6	0	11	4	5	4	3	6	1.50	0.00	8.01	0.00	0.71	0.50	0.75	2.30
22.0	16	5	11	9	11	4	10	9	1.64	0.87	2.87	2.59	5.72	3.27	1.25	3.61
29.3	29	25	26	14	19	20	27	20	0.87	6.12	5.36	2.38	0.87	1.09	3.49	2.42
32.3	41	35	40	27	27	34	38	32	2.49	3.27	3.96	6.30	4.66	4.44	2.88	4.84
35.2	53	51	51	36	44	38	52	42	2.28	2.86	2.35	6.70	2.12	3.39	2.57	3.64
38.1	78	67	63	46	48	53	72	53	1.80	5.02	2.45	8.73	3.27	7.35	3.41	5.45
41.1	92	86	80	61	66	73	89	70	1.79	7.12	5.43	7.95	7.01	6.16	4.45	6.64
44.0	126	111	111	69	70	93	119	86	3.46	11.80	19.73	5.89	5.39	5.10	7.63	9.03

3.4. Validation of the Water Distribution Model of the Study Irrigation Unit

3.4.1. Filling Phase

The results obtained in the validation phase show that the model is a good predictor of the filling phase. There was an excellent correlation ($R^2 = 0.9953$) between the measured volume ($V_{fmeasured}$) and the emptying volumes predicted by the model (V_{fmodel}) during the emptying phase (Figure 5).
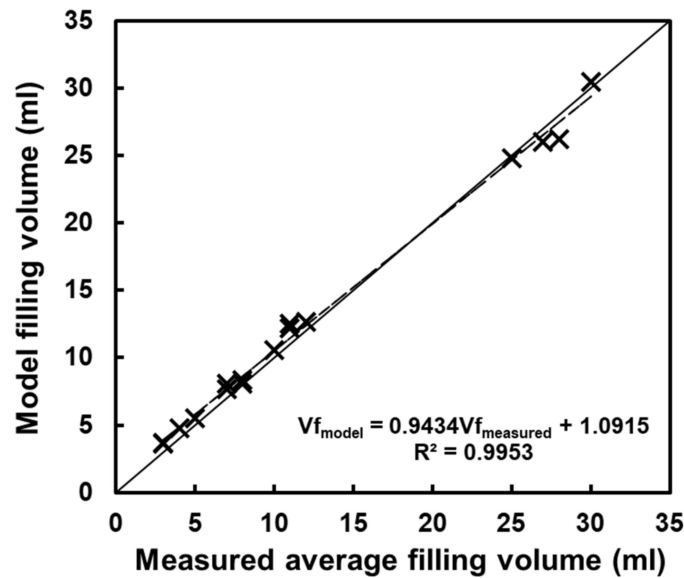
Figure 5. Evolution of the measured volume and the volume estimated by the irrigation distribution model during the filling phase (160 s) in 16 MK locations during 5 min irrigation pulses in May.

3.4.2. Stable Pressure Phase

The validation data set of the average measured pressure during the stable pressure phase on each of the 16 MK locations shows a clear negative trend in the pressure values of the manifold pipe and a slightly positive trend in the laterals (Table 3).

Table 3. Validation data set of the average pressure (bar) measured during the stable pressure phase on each 16 MK location for 4 different irrigation pulses (5, 10, 15, and 20 min) in May.

Irrigation Pulse Duration	L1-G1	L2-G1	L3-G1	L4-G1	L1-G2	L2-G2	L3-G2	L4-G2
	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)
5 min	1.00	0.89	0.80	0.71	1.00	0.91	0.80	0.72
10 min	0.98	0.83	0.75	0.71	1.00	0.85	0.75	0.72
15 min	0.99	0.83	0.70	0.65	1.00	0.84	0.70	0.68
20 min	1.01	0.81	0.70	0.68	1.02	0.81	0.70	0.68
Average	1.00	0.84	0.74	0.69	1.01	0.85	0.74	0.70
SD	0.01	0.03	0.04	0.02	0.01	0.04	0.04	0.02
	L1-G3	L2-G3	L3-G3	L4-G3	L1-G4	L2-G4	L3-G4	L4-G4
	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)
5 min	1.02	0.90	0.80	0.70	1.05	0.88	0.85	0.80
10 min	1.02	0.88	0.80	0.70	1.09	0.88	0.85	0.89
15 min	1.00	0.83	0.77	0.70	1.03	0.86	0.80	0.74
20 min	1.04	0.86	0.74	0.70	1.08	0.85	0.80	0.72
Average	1.02	0.87	0.78	0.70	1.06	0.87	0.83	0.79
SD	0.01	0.03	0.02	0.00	0.02	0.01	0.03	0.07

There was also a very good correlation ($R^2 = 0.9658$) between the measured average pressure ($Psp_{avg\ measured}$) and the pressure predicted by the model (Psp_{model}) (Figure 6).
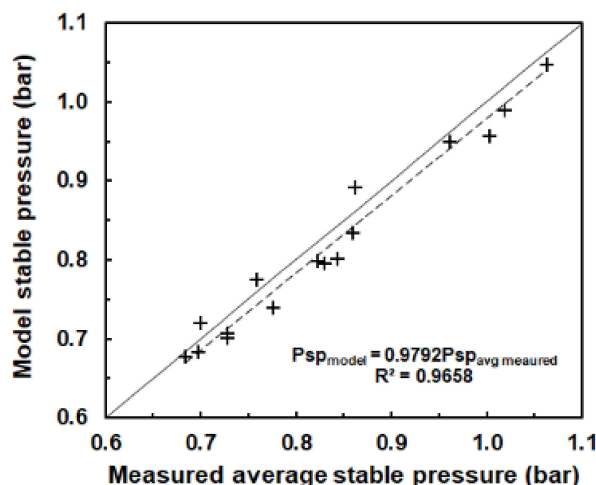
Figure 6. Correlation between the stable pressure phase from the validation data set ($Psp_{avg\,measured}$) and the stable pressure phase predicted by the irrigation distribution model (Psp_{model}) using the calibration data set.

3.4.3. Emptying Phase

The validation data set of the average measured volume during the emptying phase on each 16 MK location shows a clear increase in the emptying volume values applied as the distance to the lateral origin increases. This increasing volume trend along the lateral in the validation stage (Table 4) is similar to the one we found with the calibration data set (Table 3).

Table 4. Validation data set of the applied water volume (ml) during the emptying phase of the irrigation pulse in 60 selected locations for 4 different irrigation pulses (5, 10, 15, and 20 min) in May.

	L1	L1A	L1B	L2	L3	L4	L1L1B	L1BL4	L1	L1A	L1B	L2	L3	L4	L1L1B	L1BL4
Dm (m)	**Average Volume (ml)**								**Standard Deviation (ml)**							
0.0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.3	11	6	6	3	0	0	9	2	4.15	2.59	4.33	0.00	0.00	4.15	4.53	1.73
14.7	4	0	11	1	2	0	2	3	0.00	2.87	1.00	0.87	0.43	0.00	0.65	1.29
22.0	19	12	18	9	10	4	15	10	11.26	3.03	7.53	3.56	3.77	11.26	6.28	4.47
29.3	26	28	26	16	20	19	27	20	3.46	2.87	1.92	0.50	1.92	3.46	2.67	1.80
32.3	43	34	43	32	28	28	38	33	4.39	3.46	7.36	2.12	2.05	4.39	3.22	3.75
35.2	50	50	51	23	47	38	50	40	0.87	2.17	7.71	3.42	2.12	0.87	0.98	3.85
38.1	93	71	65	45	53	58	82	55	2.87	3.27	8.41	7.38	13.99	2.87	5.55	8.26
41.1	107	100	78	60	73	70	103	70	6.38	5.72	6.38	8.07	14.67	6.38	5.24	8.71
44.0	123	129	96	78	87	107	126	92	14.72	14.97	7.50	8.95	4.95	14.72	12.40	9.09

There was an excellent correlation ($R^2 = 0.9942$) between the measured average volume and the emptying volumes predicted by the irrigation distribution model in both L1-L1B and L1B-L4 (Figure 7).
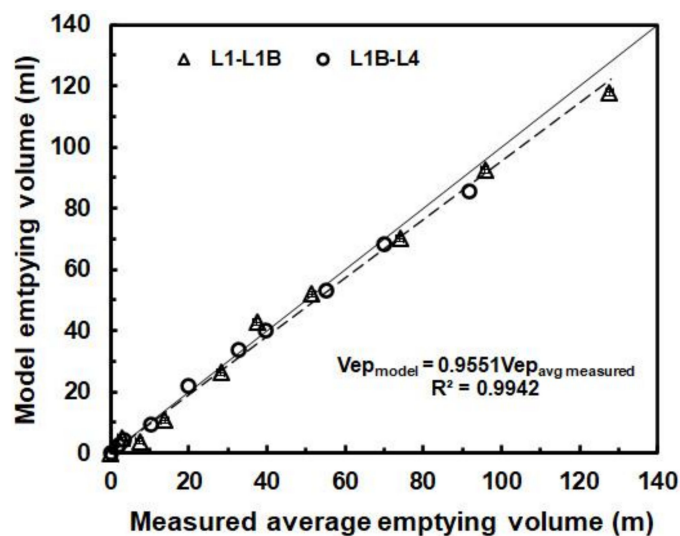
Figure 7. Correlation between the volumes measured during the emptying phase from the validation data set (Vep$_{avg\ measured}$) and the volume predicted by the irrigation distribution model during the emptying phase (Vep$_{model}$).

3.4.4. Model Performance Evaluation

The performance of the irrigation distribution model developed in this study was evaluated by four criteria: the coefficient of determination (R^2), the Theil's index (U), the modelling efficiency (ME), and the standardized residuals (SR). The values of the first three indices are shown in Table 5. The fourth index were plotted against the location of measuring points (Figure 8).

The coefficient of determination (R^2) was higher than 0.965 for all the irrigation phases, which implies an excellent goodness of fit. The values of U near to zero for the filling and stable pressure phases indicated an excellent performance in simulating the volume of water applied and the pressure. The emptying phase has a very good performance, but it was worse than the other two irrigation phases. In the case of modelling efficiencies, the ME values were near to 1, which means that the model performed very well in simulating volumes and pressures. Although different indices showed slightly different results, the irrigation distribution model is argued to be reliable in simulating the applied water volume by the emitter in the filling, stable pressure, and emptying phases.

Table 5. Statistical comparison of the overall fit of the irrigation distribution model outputs against the measured data.

Irrigation Phases/Indices	R^2	U	ME
Filling phase	0.9953	0.057	0.99
Stable pressure phase	0.9658	0.040	0.92
Emptying phase	0.9942	0.141	0.96

Note: R^2, coefficient of determination; U, Theil's coefficient; ME, modelling efficiency.

A sensitivity analysis for quantifying the model behavior by the three drip irrigation phases according to the location of the measuring points was carried out. For that purpose, we used a standardized residual plot using the standardized residual (SR, Equation (12)) as the dependent variable and the location of the measuring point as the descriptor variable (Figure 8).

Analyzing the standardized residuals by the drip irrigation phases (Figure 8), the stable pressure phase has the closest values to zero, and therefore the best model fit. The filling phase has similar values to the pressure phase in the first 10 emitter locations (Lateral L1, Figure 1). However, on lateral L3 and especially on lateral L4, the values are worse. In the case of L4, the values of the volumes applied are

less than 5 mL, which causes greater experimental errors in volume collection and measurement. The emptying phase shows worse values than the other two phases. The area between L1 and L2, the first third of the study unit (Figure 1), shows the worst values (Figure 8). In this area, there was a transition of equations used in the empirical model to predict the volumes of the emptying phase (Figure 4), which seems to generate greater standardized residuals.
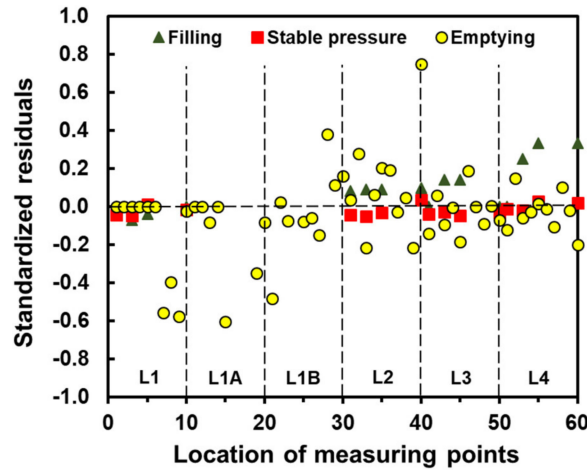

Figure 8. Standardized residuals plot regarding the location of the measuring points for the filling, stable pressure, and emptying phases.

3.5. Influence of the Drip Irrigation Phases on Water Applied According to the Irrigation Distribution Model

We found that, as the duration of the irrigation pulse increased, the influence of the filling and emptying phases decreased (Figure 9). The water volumes applied at each irrigation phase by each of the 15,912 emitters of the irrigation unit, were simulated using the empirical distribution model. The emptying phase had a greater influence than the filling phase on the irrigation water distribution. In any case, the phase of stable pressure had a greater influence than the filling and emptying phases together; however, the volume of water applied during the filling and emptying phases at an irrigation pulse of 5 min could reach half of the total. For irrigation pulses exceeding 20 and 60 min, the filling and emptying phases represent less than 10% and 4% of the total volume of water applied, respectively.
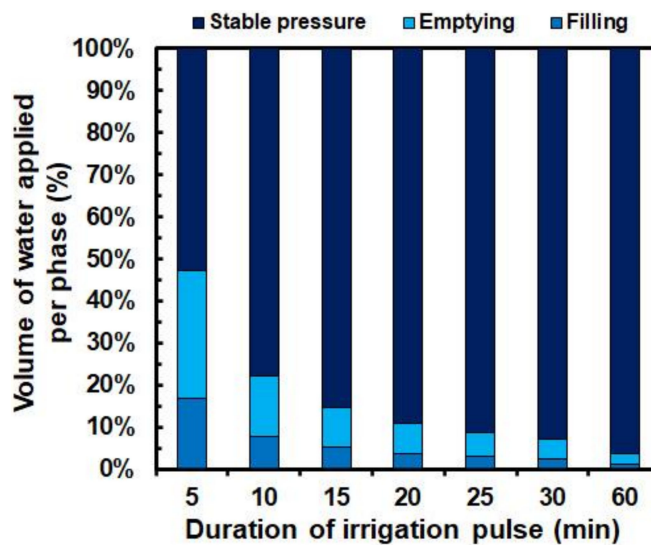

Figure 9. Percentage of water applied per irrigation phase using the irrigation distribution model.

3.6. Sensitive Analyisis of Irrigation Performance Indicators Regarding the Duration of the Irrigation Pulse

UD_{lq_sp} overestimated the distribution uniformity values in comparison with the methodologies that include the three phases of the pipe flow process. According to the duration of the irrigation pulse, the UD_{lq} values change depending on the drip irrigation phases that are included in the calculation of the UD_{lq}. The shorter the irrigation pulse, the greater the difference between the different UD_{lq} was. UD_{lq_sp} not only had the highest value but also was independent of the duration of the irrigation pulse. Both $UD_{lq\_field\_3phases}$ and UD_{lq_model} had lower values than UD_{lq_sp}. Except for UD_{lq_sp}, the other two UD_{lq} values ($UD_{lq\_field\_3phases}$ and UD_{lq_model}) varied with the duration of the irrigation pulse. $UD_{lq\_field\_3phases}$ and UD_{lq_model} had a similar distribution uniformity evolution depending on the duration of the irrigation pulse, even if $UD_{lq\_field\_3phases}$ had lower values than UD_{lq_model}. The discrepancy between $UD_{lq\_field\_3phases}$ and UD_{lq_model} was due to the difference in the size of the sample of emitters—16 and 15,912, respectively. Furthermore, the difference between the UD_{lq} values of the field and model, both including three phases, were less than 3% when the duration of irrigation pulse exceeded 10 min. Therefore, the selection of the 16 MK emitters may be sufficient to obtain a good approximation of the water distribution uniformity for practical purposes.

The $PAE_{zerodeficit}$ value increased with the duration of the irrigation pulse (Figure 10). The value of the $PAE_{zerodeficit}$ indicator was 91%, assuming a potential UD_{lq_sp} of 93%. However, in irrigation pulses below 20 min, the $PAE_{zerodeficit}$ was under 85%, while in the 5 min irrigation pulses the $PAE_{zerodeficit}$ was 57%. This deviation from the application efficiency to obtain a zero deficit in the irrigation schedule can have serious repercussions in terms of yield and economic performance.
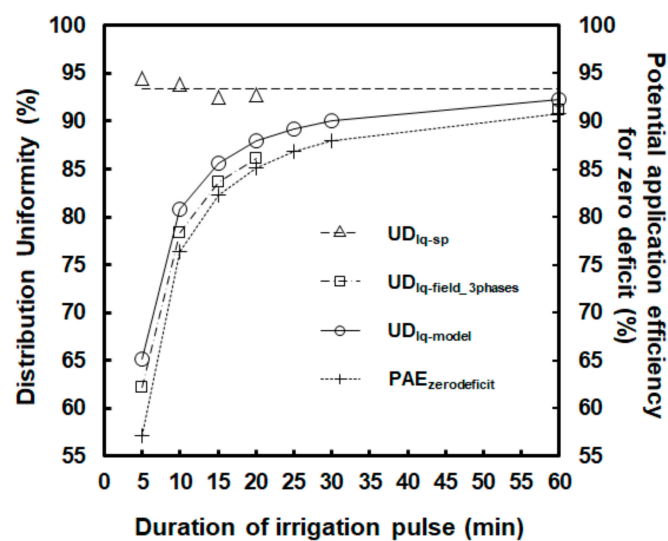

Figure 10. Distribution uniformity (%) according to the duration of the irrigation pulse taking into account the average pressure at 16 MK from the validation data set (UD_{lq_sp}), the total water applied by the 16 MK from the beginning of the irrigation pulse until the end of the emptying phase from the validation data set ($UD_{lq\_field\_3phases}$), and the volume of water applied by the 15,912 emitters of the irrigation unit using the irrigation distribution model (UD_{lq_model}). Potential application efficiency for zero deficit ($PAE_{zerodeficit}$) using the irrigation distribution model.

4. Discussion

We wanted to know how important it was to include the volume applied during the filling and emptying phases of the pipe flow process on the water distribution and application efficiency without water deficit. Typically, distribution uniformity and application efficiency are calculated assuming constant pressures throughout the irrigation pulse [23–25,39,40]; however, we hypothesized that it was important to compute the water volume applied during the filling and emptying phases of the pipe flow process for short-duration irrigation pulses, particularly in sloping fields. The study found

that the water distribution uniformity and potential application efficiency for zero deficit were greatly affected by the duration of the irrigation pulse for irrigation pulses shorter than 20 min (Figure 10). The distribution of the volume of water applied during the filling and emptying phases of the pipe flow process contributed decisively to this effect (Figure 9).

Moreover, the duration of the irrigation pulse has great relevance in sandy soils. In general, short-duration irrigation pulses are associated with lower water loss [41,42]. Even in a field experiment, high irrigation frequency led to an equivalent or improved yield and increased water productivity [8,43]. Previous studies also indicated the positive role of pulse drip irrigation with increasing the irrigation application efficiency. However, the irrigation events were between 15 and 25 min [44,45], which is consistent with the conclusions of this study.

However, it is important to take into account that the quantitative results obtained in this work are conditioned by the type of tapes and emitters of the studied irrigation unit. The used emitter constitutes a particular case of microirrigation systems. In fact, [46] concluded that the use of pressure-compensating emitters instead of built-in emitters changed the discharge results. In addition, laterals are thin-walled, collapsible polyethylene tapes with built-in emitters. The use of more rigid polyethylene tubes could also change the response of each phase. Despite this constraint, we think the conclusions are sufficiently robust and valid for the purpose of this work. Based on these results, new steps must be taken to generalize the results in any irrigation unit with any kind of irrigation system. Including a rational model in a decision-support tool will help to manage short irrigation pulses under more arbitrary irrigation material, soil, and slope conditions.

The distribution uniformity and potential application efficiency for zero deficit were overestimated for the short irrigation duration if some causes of non-uniformity are ignored. The greater the percentage of volume of water applied during the filling and emptying phases, the worse the performance of the water distribution uniformity and potential application efficiency for zero deficit are (Figures 9 and 10). The distribution uniformity value was 93%, which is classified as "excellent" according to Merrian and Keller's classification, using only stable pressure phase in a 5 min irrigation pulse. However, the value estimated by the water distribution model was 65% when the filling and emptying phases are included, which is classified as "poor" (Figure 10). Therefore, including the filling and emptying phases has profound practical implications for optimal irrigation scheduling in sloping sandy soils with very short irrigation durations. Optimal irrigation schedules are especially important in sandy soil because sandy soils require a balance in water application efficiency and deep percolation to save water without reducing yields.

5. Conclusions

The filling and emptying phases of drip irrigation both have an impact on accurately calculating water distribution uniformity and potential application efficiency with zero deficit. The influence of the filling and emptying phases varies according to the duration of the irrigation pulse. The shorter the duration of the irrigation pulse, the greater the influence of the filling and emptying phases on the irrigation performance indicators. For the better design and management of the drip irrigation system, it is necessary to know the upper threshold values of the real distribution uniformity and potential application efficiency for zero deficit depending on the duration of the irrigation pulse.

The irrigation performance indicators of very high frequency drip irrigation in sloping fields must include the total volume applied by the drip emitters. In order to include the total volume applied by the drip emitters, it is necessary to characterize the filling and emptying phases of the irrigation unit. This characterization can contribute significantly to improve irrigation scheduling, especially in sloping fields, which constitutes a significant breakthrough. The next step should be to make a rational model that allows a generalized quantitative analysis of any drip irrigation unit. Even so, we believe that the identification of this issue in drip irrigation systems in order to calculate irrigation performance indicators more accurately is an original contribution.

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

Abbreviations

4 MK	4 emitters with a lower water volume measured during the three phases (filling, stable pressures and emptying) using the Merriam and Keller's methodology
16 MK	16 emitters selected by the Merriam and Keller's methodology to calculate water distribution uniformity in a drip irrigation system
ΔT_f	Time interval of pressure recorded (10 s)
ΔP_L	Pressure variation depending on lateral distance (bar)
ΔP_m	Pressure variation depending on manifold distance (bar)
D_L	Distance from lateral beginning (m)
D_m	Distance from manifold beginning (m)
e:	emitter. Range from 1 to 16, corresponding to 16 MK (Figure 1), during the filling and the pressure stable phases. Range from 1 to 60 during the emptying phase
ETo	Reference evapotranspiration
ETc	Crop water requirements
G1	Measuring points at the beginning of the laterals
G2	Measuring points at a third of the distance to the end of the laterals
G3	Measuring points at two third of the distance to the end of the laterals
G4	Measuring points at the end of the laterals
i	Index of data pairs of observed and predicted values. 1 to 16 for emptying and stable pressure phases. 1 to 60 for irrigation pulse stage and emptying phase
j	Time interval for measuring pressure. Range from 1 to 30. One value each 10 s during 5 min
Kc	Crop coefficient
L1	Irrigation lateral located at the beginning of the manifold pipe
L1A	Irrigation lateral at a quarter of the L1 to L2 distance
L1B	Irrigation lateral at a half of the L1 to L2 distance
L2	Irrigation lateral located at a third of the distance to the end of the manifold pipe
L3	Irrigation lateral located at two third of the distance to the end of the manifold pipe
L4	Irrigation lateral located at the end of the manifold pipe
ME	Modelling efficiency
n	Number of measuring points. 16 for filling and stable pressure phases and 60 for emptying phase
ne	Total number of emitters of the irrigation unit evaluated
Ob_i	Observed (measured) values
Pf_{ej}	Pressure measured in the manometer intake e at the instant j during the filling phase (meter water column)
Pr_{avg}	Average of predicted values
Pr_i	Predicted values by a model

$Psp_{avg\ measured}$	Average stable phase pressure measured from the validation data set (bar)
Psp_{model}	Stable phase pressure predicted by the irrigation distribution model (bar)
Psp_{avg}	Average pressure measured in the manometer intakes e during the stable pressure phase (metre water column)
$PAE_{zerodeficit}$	Potential application efficiency without deficit irrigation at any location
$Q_{25\%}$	25% average flow with a lower water flow ($l\,h^{-1}$)
$Q_{25\%\text{-}sp}$	25% average flow of 16 MK emitters with a lower water flow during the stable pressure phase ($l\,h^{-1}$)
Q_{avg}	Average flow ($l\,h^{-1}$)
$Q_{avg\text{-}sp}$	Average flow of 16 MK emitters during the stable pressure phase ($l\,h^{-1}$)
Qf_{ej}	Flow rate of the emitter e at the instant j during the filling phase ($l\,h^{-1}$)
Qsp_{e}	Flow rate of the emitter e during the stable pressure phase ($l\,h^{-1}$)
SR	Standardized residual
SD	Standard deviation
T_{f}	Number of the first time interval measured once the pressure is stable
T_{sp}	Duration of the stable pressure phase (h)
U	Theil's inequality coefficient
UD_{lq}	Distribution uniformity of the low quarter (%)
$UD_{lq\_field\_3phases}$	Distribution uniformity of the low quarter during filling, stable pressures and emptying phases measuring in 16 MK emitters
UD_{lq_model}	Distribution uniformity of the low quarter during the three irrigation phases (filling, pressure stables and emptying) calculated with the irrigation distribution model for the 15,912 drip emitters of the study unit
UD_{lq_sp}	Distribution uniformity of the low quarter on stable pressure phase measuring in the 16 MK emitters (%)
$V_{25\%}$	25% average water applied volume with a lower volume of water (l)
$V_{25\%\_model}$	25% average of a lower volume of total water applied by the 15,9212 drip emitters of the study irrigation unit calculated with the empirical model
$V_{25\%\_field\_3phases}$	Average of 4 MK emitters with a lower water volume measured during the three irrigation phases (filling, stable pressures and emptying)
V_{avg}	Average water applied volume (l)
$V_{avg\_field\_3phases}$	Average measured volume of 16 MK emitters during the three irrigation phases (filling, stable pressures and emptying)
V_{avg_model}	Average of total water applied by the 15,912 drip emitters of the study irrigation unit calculated with the empirical model
$Vep_{avg\ measured}$	Average water volume measured during the emptying phase from validation data set (ml)
Vep_{model}	Water volume predicted by the irrigation distribution model during the emptying phase (ml)
V_{ETc}	Volume of crop water requirements (l)
Vf_{e}	Water volume applied by the emitter e during the filling phase (l)
Vf_{model}	Predicted water volume applied by emitters during the filling phase using the irrigation distribution model (ml)
$Vf_{measured}$	Measured water volume applied by emitters during the filling phase (ml)
V_{G1}	Water volume applied by emitters in position G1 (Figure 1) during the filling phase (ml)
V_{G2G3G4}	Water volume applied by emitters in position G2, G3 and G4 (Figure 1) during the filling phase (ml)
$V_{L1\text{-}L1B}$	Water volume applied by emitters between the laterals L1 and L1B during the emptying phase (m)
$V_{L1B\text{-}L4}$	Water volume applied by emitters between the laterals L1B and L4 during the emptying phase (m)
Vsp_{e}	Water volume applied by the emitter e during the stable pressure phase (l)
$V_{water\ delivered}$	Total volume of water delivered to the field by the irrigation system

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