Received: 3 February 2022 | Revised: 25 April 2023 | Accepted: 18 May 2023
DOI: 10.1002/ird.2850

RESEARCH ARTICLE

WILEY

Evaluation of new pivoting linear-move precision irrigation machine

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Funding information
European Union's Horizon 2020 'WATERAGRI Water retention and nutrient recycling in soils and steams for improved agricultural production', Grant/Award Number: 858375

Abstract

Due to population growth, freshwater resources around the world are becoming increasingly scarce, and the water supply in agriculture has emerged as one of the limitations of food production. Variable-rate irrigation (VRI), a type of precision irrigation, allows water-efficient irrigation techniques to ensure an optimal water supply. The University of Debrecen, in collaboration with Magtár Kft., was the first in Hungary to develop a new laterally mobile irrigation machine equipped with VRI. The subject of our study was the testing of this system. According to the research, high and homogeneous irrigation uniformity was achieved in practice, with a Christiansen uniformity coefficient (CUc%) of 93 ± 2, distribution uniformity (DU%) of 88 ± 2 and coefficient of variation (CV) of 9 ± 2. Irrigation accuracy was also found to be satisfactory (mean absolute error 0.6 ± 0.1, mean bias error 0.2 ± 0.2, normalized root mean square error 8.6 ± 2), and only 1.4% ± 2% was overirrigated and 0.4% ± 0.3% underirrigated. In addition, the uniformity and accuracy of irrigation in different management zones along the pipeline were also investigated, and significant differences ($p < 0.05$) were found between irrigation water depths. Based on the above, a new laterally mobile irrigation machine equipped with VRI can be used to develop more uniform and accurate irrigation schedules in the future in arable fields as this is critical for water-saving irrigation management.

KEYWORDS
irrigation accuracy, irrigation uniformity, linear irrigation system, variable rate irrigation

Résumé

En raison de l'augmentation de la population, les ressources en eau douce dans le monde deviennent de plus en plus rares et l'approvisionnement en eau dans l'agriculture est devenu l'une des limites de la production alimentaire. L'irrigation à taux variable (VRI), un type d'irrigation de précision, permet d'utiliser

Article title in French: Évaluation d'une nouvelle machine d'irrigation de precision a mouvement lineaire pivotant.

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des techniques d'irrigation économes en eau pour garantir un approvisionnement optimal en eau. L'Université de Debrecen, en collaboration avec Magtár Ltd, a été la première en Hongrie à développer une nouvelle machine d'irrigation latérale mobile équipée de la VRI. L'objet de notre étude était l'essai de ce système. Selon les recherches, une uniformité d'irrigation élevée et homogène a été atteinte dans la pratique, avec CUc% 93 ± 2, DU% 88 ± 2 et CV 9 ± 2. La précision de l'irrigation s'est également avérée satisfaisante (erreur absolue moyenne (MAE):0.6 ± 0.1, erreur moyenne de biais (MBE): 0.2 ± 0.2 et erreur quadratique moyenne normalisée (NRMSE): 8.6 ± 2, et seulement 1.4 ± 2% était sur-irrigué et 0.4 ± 0.3% était sous-irrigué. En outre, l'uniformité et la précision de l'irrigation dans différentes zones de gestion le long de la canalisation ont également été étudiées et des différences significatives ($p < 0.05$) ont été trouvées entre les profondeurs d'eau d'irrigation. Sur la base de ce qui précède, une nouvelle machine d'irrigation mobile latérale équipée de VRI peut être utilisée pour développer des programmes d'irrigation plus uniformes et plus précis à l'avenir dans les champs arables, car cela est essentiel pour la gestion de l'irrigation pour économiser l'eau.

MOTS CLÉS
irrigation à taux variable, Système d'irrigation linéaire, uniformité de l'irrigation, Précision de l'irrigation

1 | INTRODUCTION

In parallel with population growth, which is predicted to reach 9.5 billion by 2050, agricultural production, urbanization and industrialization raise the global demand for freshwater resources (Sharma & Irmak, 2021). Especially in arid and semi-arid regions, drought and water scarcity due to climate change will be one of the major limiting cropping factors in agriculture; therefore, adequate water supply and optimal management of the available water resources are crucial in food production and security. The climate in Hungary is classified into warm temperate dry (WTED) and cold temperate dry (CTED) climate zones (Hungarian Meteorological Service (HMS), 2019), where the annual precipitation is lower than the annual evapotranspiration (Huzsvai et al., 2020, 2022), resulting in the prevalence of drought, especially in July and August every 3 years. In recent decades, the intensity and frequency of droughts have increased from year to year in Hungary and also as at the experimental site of this study. Therefore, in Hungary, as well as in some regions of the world, efficient irrigation management systems must be established to prevent instances of water scarcity (Tsang & Jim, 2016). On the other hand, only 2% of agricultural land is irrigable in Hungary due to technical reasons. Laterally moving (linear) irrigation is the dominant irrigation method in the country (65%), 16% is irrigated by rain gun systems pulled by hose reels, and only 15% is irrigated with centre pivots (Demeter, 2022). Linear irrigation can save up to 50% more time than surface, side-roller or drum sprinkler irrigation. The large ratio of linear irrigation machines among irrigation machines is due to the high channel density of the Hungarian Great Plain. Another issue is that the linear irrigation machines are usually outdated and GPS is not available, which prevents variable-rate irrigation (VRI). In this way, farmers can irrigate at a constant irrigation rate without considering the spatial heterogeneity of the field, which leads to overirrigation or underirrigation of a field (Kumar et al., 2017). Irrigation technologies such as centre pivots and linear irrigation systems, as well as related management approaches, are continuously evolving to meet the current irrigation needs of efficient agricultural crop production (Raine et al., 2007). More effective control of irrigation water and fertilizer application (i.e. fertigation) to boost agricultural yields was a great challenge two decades ago (Zhang et al., 2002). In contrast to constant rate irrigation, precision irrigation techniques are more water efficient, reducing the amount of irrigation water and increasing agricultural production efficiency based on crop requirements (Smith et al., 2010). VRI and micro-irrigation systems are two examples of precision agriculture technologies that enable farmers to apply water and agrochemicals in a site-specific and variable manner

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within a field, depending on the needs of the crops (Evans & Sadler, 2008; Sharma & Irmak, 2020). Three different kinds of VRI can be suggested in practice: (i) basic, speed control plan of the machine; (ii) zone, where banks of sprinklers are controlled on the machine; and (iii) full, where individual sprinklers are controlled on the machine. The application of VRI focuses primarily on centrally rotating systems, but it can also be applied to systems with lateral movement and even some fixed systems. The VRI system can be retrofitted to current centre pivot systems integrating GPS positioning into the control system. The control system cycles through each sprinkler or set of sprinklers within each distinct treatment zone, turning them on and off and changing the pace of advance to obtain the proper application rates. Current crop data, soil characteristics (such as soil type and organic matter content) and a topographic map can all be entered into VRI (Boluwade et al., 2016; Colaizzi et al., 2017; Yari et al., 2017). The use of VRI on slopes and in valleys can also help reduce runoff and soil erosion and reduce sedimentation in low areas. In the case of constant-rate irrigation, to prevent underirrigation of any part of the field, producers typically plan irrigation according to the driest areas of the field or install soil water sensors in the places with the lowest available soil water retention (Daccache et al., 2014; Peters & Flury, 2017). VRI can improve overall crop yields by preventing overirrigation and underirrigation. Considering temporal and spatial variability in soil and crop characteristics of a field, Sui and Yan (2017) tested VRI techniques to analyse irrigation volumes in contrast to constant-rate irrigation and revealed that the VRI technology used 25% less water. Hedley and Yule (2009) found that VRI saved 23%–26% of irrigation water. Sadler et al. (2000) determined that the VRI is optimal to control the spatial distribution of applied irrigation water, improving water use efficiency and crop yield. The uniformity and accuracy of applied water depths are crucial for VRI systems from a water use efficiency point of view (Dukes & Perry, 2006; Hui et al., 2022; King et al., 2006; O'Shaughnessy et al., 2013; Perry & Pocknee, 2003; Sui & Fisher, 2015; Yari et al., 2017). According to ISO 11545-2009 (ISO Standards, 2009), GB/T 19797-2012 (Chinese National Standard GB/T, 1979–2012) and ASAE S436.1 (ASABE Standards, 2016), various testing techniques have been sequentially presented for uniformity measurements of both centre pivot and linear-move irrigation systems. However, these standards refer to constant-rate irrigation, and there are no contemporary standards that can be applied to VRI systems. To date, several worthwhile investigations on the uniformity and precision of centre pivot VRI systems have been carried out. Sui and Fisher (2015), Takács et al. (2018), Clark et al. (2003) and Dukes and Perry (2006) evaluated the Heermann and Hein uniformity coefficient (CUH), Christiansen uniformity coefficient (CUc%) and distribution uniformity coefficient (DU%).

The main aim of this investigation was to test the implementation of a unique pivoting linear irrigation system with VRI by assessing its irrigation uniformity and accuracy. In Hungary, there were no linear-move irrigation systems equipped with VRI until recent years, especially linear irrigation systems that can pivot at the end of fields and can operate in centre pivot mode. The first pivoting linear irrigation system with VRI was installed in 2020 for maize irrigation in the country, with test periods in 2020 and 2021 at an experimental site in the north-eastern part of Hungary. The uniformity and accuracy of irrigation water use and application of a linear pivot irrigation system with a VRI system were investigated, and the uniformity and accuracy of irrigation in different management zones along the pipeline (rectangular to the channel and to the travel direction of the irrigation machine) and the longitudinal (in the travel direction of the irrigation machine, parallel with the irrigation channel) zone transitions were also assessed at the test field.

2 | MATERIALS AND METHODS

2.1 | Experimental site

The experiment was carried out at a farm in the north-eastern region of Hungary. The experimental site was arable land (85 ha) with maize crops and an elevation of approximately 155 m above the Baltic Sea level. The average annual mean temperature is 9.5–9.7°C with 1900–2000 annual sunshine hours at the experimental site and 16.6°C in the growing season. The maximum temperature ranges between −17.0 and −18.0°C on the coldest winter days and can exceed 34°C on the hottest summer days. There is 570–600 mm of annual precipitation, with 350–360 mm during the vegetative season. North-east and south-east are the most typical wind directions, with an average speed of 2.5 m/s in the growing season (Szabó et al., 2022). In conclusion, this region has a climate that is ideal for growing maize, with an average sowing time in the middle of April and a harvest in late September. The geometry and geography of the site were analysed. Generally, there are only a few metres of difference in elevation throughout the area, mostly with north-east slope directions, and the slope is less than 5% at 97% of the site (Figure 1). The physical characteristic of the soil is sand, which makes it less sensitive to the intensity of

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FIGURE 1 Location and slope of the experimental site.

irrigation. A Davis Vantage Pro2 (Davis Instruments Corporation) automated weather station was used to monitor the weather conditions of the experiments at the site.

2.2 | Pivoting linear irrigation system

A unique pivoting laterally moving sprinkler irrigation machine was installed in the field. The total structural length of the irrigation machine was 209 m, including the end console. The irrigation system consisted of four 47.5-m long irrigation spans and an 18.6-m long overhang, with a total irrigation radius of approximately 235 m. The maximum water demand of the system was 180 m^3/h, and the minimum water demand depended on the aim of the VRI. The GPS control was located on the power tower consisting of two antennas and a receiver with steering electronics. There was a canal in the middle of the field coming from a reservoir and going in the southern direction (Figure 2). The canal fed the irrigation machine. The water was conveyed by gravity from the reservoir to the canal. The canal had a separate water level control that was connected back to the electric gate valve controlling the water flowing out from the reservoir. The first step for design was to determine the required daily irrigation rate (millimetre per day). This value depends on the type of crop and climatic conditions. The design minimum must at least meet or slightly exceed the maximum daily evapotranspiration of the grown crop to avoid the continuous operation of the irrigation unit. As the system was equipped with a VRI, the pump was controlled by a frequency driver. A pressure-reducing control valve was also required to keep the base of inlet pressure constant for the system. The irrigation system was controlled from the main control panel of the system.

Since the irrigation machine set at the Hungarian case study site should work in lateral and pivoting mode as well, the system was equipped with a double sprinkler package. A total of 118 nozzles were installed on the irrigation machine on drop hoses at a height of 2.2 m above the ground. Out of 118 nozzles, 62 nozzles worked only in lateral-move mode, 48 nozzles were used only in pivoting mode, and in the middle of the irrigation machine, 8 nozzles worked in both lateral and pivot modes. In total, 70 nozzles worked in linear-move mode, and the sprinkler spacing was 2.9 m. Solenoid valves were installed at the connection between each drop hose and the lateral pipe, and every four solenoid valves shared a valve controller. The 17 irrigation zones working in lateral-move mode were controlled by a pulse signal, with a 180-s cycle time (100%). For example, if a zone needed to be on 50% of the time, then that zone was on for 90 s and off for 90 s, with the amount of irrigation water needed being only half of the amount in the zones that were open the entire time (180 s). The type of sprinkler selected in this experiment was a common low-pressure sprinkler (Nelson O3030 Orbitor with a black plate nozzle). The Orbitor features technology that eliminates the struts of a sprinkler body to provide outstanding uniformity and optimal droplets at low operating pressures. With this innovative technique, the disc not only rotates in a circular pattern but also draws eccentric circles around the vertical axis of the nozzle, recognized as wobbler-type nozzles, to achieve a uniform sprinkler pattern. The uniformity characteristics of the pivoting linear-move irrigation system were provided by Reinke based on the simulated irrigation depth. The simulations

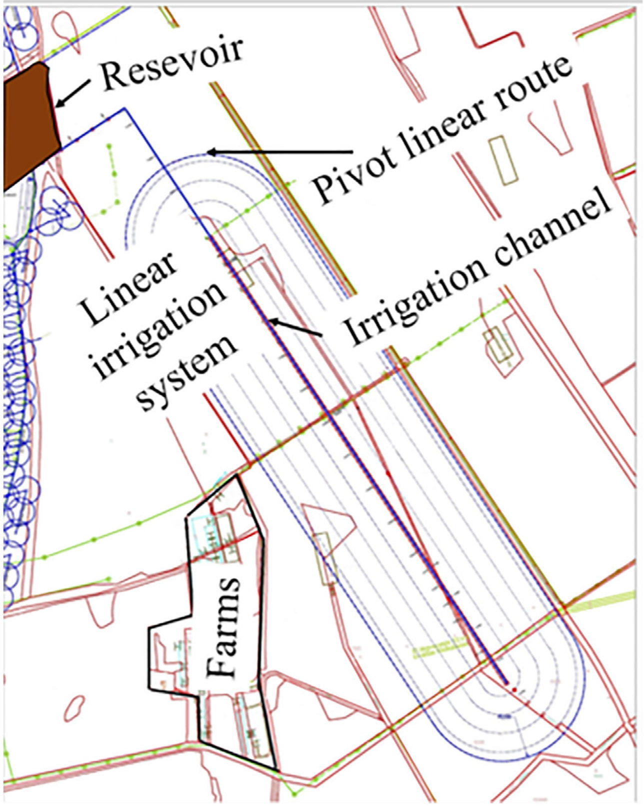

FIGURE 2 Blueprint of the irrigation system built in the test area.

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were performed for both pivot and linear-move modes under constant-rate irrigation (2.5 mm) considering the full length of the pipeline. The simulated Christiansen uniformity (CU) and DU were 98% and 96% for the linear-move mode and 96% and 93% for the pivot mode, respectively.

2.3 | Water distribution measurement

To assess the water distribution of the irrigation system working in linear-move mode, the VRI performance of the irrigation system was tested in grids, in the travel directions of the irrigation system, and along the lateral pipeline. Catch cans with a millimetre scale on their side were used for the measurements. The purpose of measurements in grids (grid measurement) was to model a management zone with a constant irrigation rate to evaluate the homogeneity of the irrigation and the accuracy of the water application contrary to the designed water depths as well as to analyse the rate and spatial distribution of the underirrigated and overirrigated areas. The design irrigation water application was 10 mm. Catch cans were placed at a height of 50 cm in a 6 × 4 grid with a distance of 5 m between the catch cans (Figure 3). The experiments were carried out in three repetitions, with the same parameters in the summers of 2020 and 2021.

An irrigation test in the travel direction of the irrigation machine was carried out to define the longitudinal transition of the water application between two irrigation zones and to assess the minimum length of a management zone. The design irrigation water depths of the zones were 5 and 10 mm. Forty catch cans were placed in a straight line at 1-m intervals, and the design border between the zones was at the 20th catch can. The longitudinal transition experiments were carried out in three repetitions.

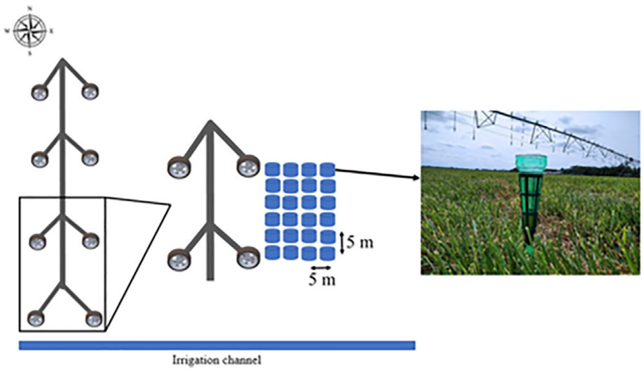

FIGURE 3 Scheme of water distribution measurements and layout of catch cans in the grid.

To analyse the accuracy of irrigation in different management zones, four zones were set transversally along the pipeline by pulse signal, adjusting cycle times to 25%, 50%, 75% and 100% with 10-mm maximum designed irrigation depths. Correspondingly, four irrigation depths of 2.5, 5, 7.5 and 10 mm were tested using 80 catch cans in a straight line at 1-m intervals (Figure 4). These experiments were carried out in two repetitions.

To provide precise measurements and eliminate the potential effect of evaporation in all measurements, water depths were read from the catch cans immediately after the tests were conducted and the sprinkler no longer emitted water to the catch cans. The wind speed was low, 1.5 m s^{-1} as an average with no rainfall, air temperatures varied between 10 and 24°C, and relative humidity ranged from 60% to 93%.

2.4 | Irrigation uniformity and accuracy calculation

The uniformity of the water distribution resulting from the water depth data of the catch cans was assessed using uniformity coefficients. In this study, the CUc%, the low-quarter DU and the coefficient of variation (CV) were used. A CUc% (Equation 1) was calculated to evaluate the water application uniformity of the pivoting linear-move irrigation system (Christiansen, 1941; Takács et al., 2018). In practice, to have an adequate standard deviation uniformity, the CUc% should reach a minimum of 84%. The computation method considers underirrigated and overirrigated areas in equal quantities (Maroufpoor et al., 2010).

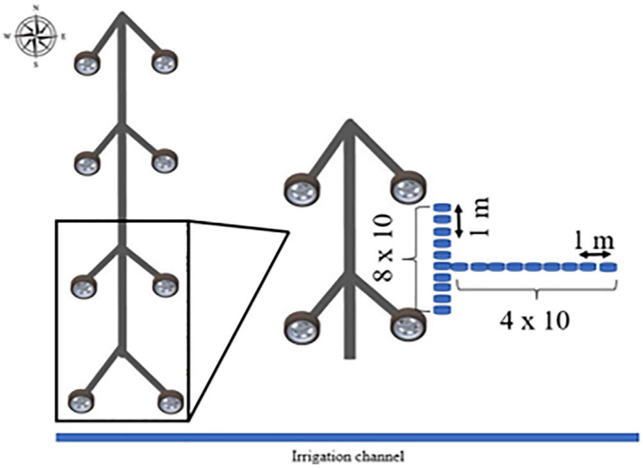

FIGURE 4 Scheme of water distribution measurements and layout of catch cans in straight lines for longitudinal transition and transverse measurements.

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$$\mathrm{CUc} = 100\left[1 - \frac{\sum_{i=1}^{n}\left|h_i - \overline{h}\right|}{\sum_{i=1}^{n} h_i}\right], \quad (1)$$

where $\sum\left|h_i - \overline{h}\right|$ is the sum of the absolute deviations of the individual measurements in relation to the mean; $\overline{h}$ is the average of measured water depths in all catch cans; h_i is the individual measurement data, measured water depth in the ith catch can; and n is the number of catch cans (24 catch cans in the grid experiment and 20 catch cans per zone in accuracy analyses of irrigation in different management zones).

The lower-quarter DU (Equation 2), which is highly sensitive to underirrigation (Kruse, 1978), was calculated to determine the uniformity of irrigation. The low-quarter irrigation DU is usually defined as the ratio of the smallest accumulated depths in the distribution and the average depths of the whole distribution. In practice, irrigation uniformity should reach at least 80% (Irmak et al., 2011).

$$\mathrm{DU} = 100\left(\frac{\overline{h_{i25\%}}}{\overline{h}}\right), \quad (2)$$

where $\overline{h_{i25\%}}$ is the average water depth of the 25% of the catch cans that collected the least amount of water.

Note that CU and DU give complementary information: Empirical evidence confirms that uniformity is increased when their values are closer (Ortiz et al., 2010). In addition, the CV (Equation 3) can be computed as the standard deviation (σ) of all catch can measurements divided by the average (Abd El-Wahed et al., 2016).

$$\mathrm{CV} = \frac{\sigma}{\overline{h}}100 \quad (3)$$

In addition to the calculation of the uniformity coefficients, the rate and the spatial distribution of the underirrigated and overirrigated areas were also assessed based on the results of grid measurement. The limit of underirrigation was calculated as the difference between the median and the minimum water depth value subtracted from the median (median − [median − minimum]). The limit of overirrigation was set as the difference between the maximum and median value added to the median (median + [maximum − median]). The distribution of applied irrigation water was plotted and calculated in Surfer 15 (Golden Software, Inc., Golden, Colorado).

The accuracy was assessed by the following methods. The mean absolute error (MAE) (Equation 4) was chosen to assess how close the measured water depths were to the designed depths in different management zones (O'Shaughnessy et al., 2013).

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{n}\left|P - h_i\right|, \quad (4)$$

where P is the designed water depth (mm).

The mean bias error (MBE) (Equation 5) was used to evaluate the estimation accuracy of water depths applied by the irrigation system. Positive values represent overirrigation, while negative values indicate underirrigation (Yari et al., 2017):

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{n}\left(P - h_i\right) \quad (5)$$

The normalized root mean square error (NRMSE) (Equation 6) (Wang et al., 2020) reflects the relative error between the designed and measured irrigation depths:

$$\mathrm{NRMSE} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(P - h_i\right)^2}}{\overline{h}}100 \quad (6)$$

Additionally, analysis of variance was applied to determine the differences among the water depths in the management zones using Tukey and Duncan tests in the case of irrigation accuracy measurements of different management zones along the pipeline.

3 | RESULTS AND DISCUSSION

3.1 | Water distribution and irrigation uniformity in a model management zone under constant irrigation rate

Table 1 describes the combined results of the irrigation test for CV, CUc and DU for water depths and for overirrigation and underirrigation characteristics in a model management zone under a constant irrigation rate. The average volume of irrigation water collected in the catch cans was 10 ± 0.6 mm, and the CUc, DU and CV were 95%, 91% and 6%, respectively, for the first measurement, indicating good irrigation homogeneity. The measured CUc and DU values were slightly less than the simulated ones, definitely due to the effect of the environment (evapotranspiration, temperature and relative humidity, etc.) in a real condition. The underirrigated area was 8.6 m^2, representing 4% of the total irrigated area, while the overirrigated area was only 0.007 m^2, representing 0.03% of the total area according to the spatial analysis of the measured water depths. In the next measurement,

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TABLE 1 Irrigation uniformity and accuracy results of grid experiment.

Measurements	*n*	Water depth (mm)	CUc %	DU %	CV %	Underirrigated area (m^2)	Underirrigation (%)	Overirrigated area (m^2)	Overirrigation (%)	MAE (mm)	MBE (mm)	NRMSE %
First	24	10 ± 0.6	95	91	6	8.6	3.8	0.007	0.03	0.5	−0.03	6
Second	24	9.7 ± 1.1	92	88	11	0.5	0.1	2.2	0.6	0.7	0.3	11
Third	24	9.6 ± 0.9	92	87	10	0.8	0.2	0.2	0.4	0.7	0.3	8

Abbreviations: CUc, Christiansen uniformity coefficient; CV, coefficient of variation; DU, distribution uniformity coefficient; MAE, mean absolute error; MBE, mean bias error; NRMSE, normalized root mean square error.

the average irrigation water depth was 9.7 ± 1.1 mm, and the uniformity coefficients were slightly lower compared to the first measurement but still indicated homogenous water distribution (CUc 92%, DU 88%, CV 11%). The ratio of underirrigation was only 0.1%, affecting 0.5 m^2 of the test area, while the overirrigated area was 2.2 m^2, representing 0.60%. In the third measurement, a water depth of 9.8 ± 0.9 mm was detected, and uniformity showed very similar characteristics to those in the previous measurement (CUc 92%, DU 87%, CV 10%). Underirrigation and overirrigation were also negligible: 0.2% (0.8 m^2) of the irrigated test area was underirrigated, and 0.4% (1.5 m^2) was overirrigated (Figure 5). To summarize the results, all tests proved that constant-rate irrigation was uniform and homogeneous in the modelled management zone, although the two additional measurements gave slightly lower CUc% and DU% and thus higher CV% values compared to the first measurement. This is probably due to the weather conditions. During the first measurement, the weather was completely calm at the site, and during the second and third measurements, wind gusts of 10–13 km/h were recorded from the north-east, which may explain the lower values of CUc and DU.

MAE, MBE and NRMSE% were calculated to assess the accuracy of irrigation. The obtained MAE values were low, ranging from 0.5 to 0.7 mm; MBE was also low, ranging from −0.03 to 0.3 mm; and NRMSE% ranged from 6% to 11%, which is appropriate for water application. In our first measurement, the indicators showed small irrigation deviations (MAE 0.5 mm, MBE −0.03, NRMSE% 6%). The negative MBE value indicated that the applied water volume was less than the applied irrigation water volume. Larger deviation rates were observed at the second and third measurements compared to the first, with the largest deviation at the second measurement date (MAE 0.7 mm, MBE 0.3 mm, NRMSE% 11%).

Faria et al. (2016) investigated a linear-move sprinkler irrigation system with a mechanical solution-moving sprinkler irrigation system in 16 field trials for rice irrigation. The catch cans were placed 70 cm above the soil in two rows with 5 m distances parallel to the linear-motion system. The CUc varied from 85% to 94% over the 16 field tests, and DU ranged from 76% to 89%, which gave similar or slightly worse results than in this study. Szabó et al. (2021) also performed tests on a conventional linear sprinkler system, where the irrigation uniformity of the sprinklers was much lower (CUc% 75% and DU% 74%). In this case, poor uniformity may be due to the lack of maintenance and clogging of the nozzles. Furthermore, the underirrigated area was 21% of the total irrigated area, and the overirrigated portion was 3% of the total area. In contrast, in the light of the present results, it is possible to decrease underirrigation and overirrigation

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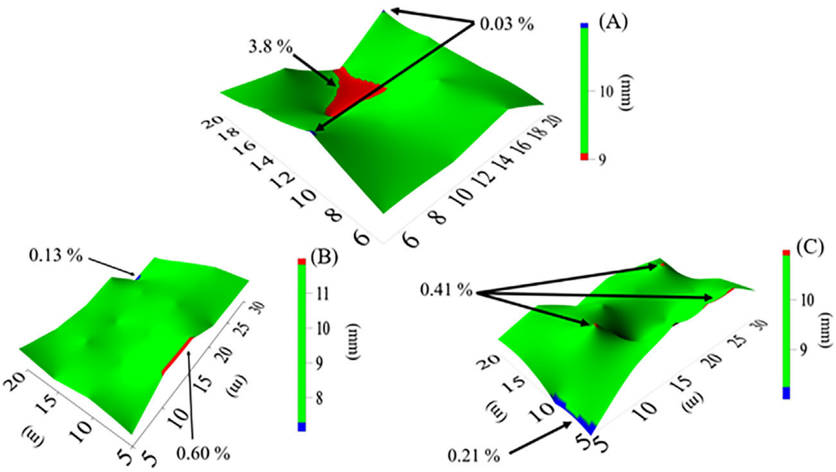

FIGURE 5 Distribution of underirrigated and overirrigated areas in the first (A), second (B) and third (C) measurement.

using VRI. Yari et al. (2017) tested a centre pivot system with three different water volume settings. The mean NRMSE values between the measured and prescribed depths were 21%, 38% and 34%, respectively, and the MBE values ranged from 1.1 to 9.6 mm for all water discharge treatments. In the present study, better NRMSE and lower MBE values were obtained in comparison, which is probably due to the weather conditions since the wind speed in their study was higher and ranged from 2.4 to 6.5 m/s during the test periods. In contrast, Hui et al. (2022) measured high accuracy values of 16.9%–32.7% NRMSE, 1.4–3.6 mm MBE and 2.4–5.3 mm MAE for constant-rate irrigation in the case of calm weather conditions. In this case, the higher values compared to this study may be explained mostly by the use of different sprinklers.

3.2 | Evaluation of longitudinal transition of water application between zones

Water application at the borders is likely to be affected by the differently designed irrigation levels of the management zones. Nevertheless, it was important to know how wide the borders between zones in the travel direction of the irrigation machine are since it determines what the minimum adjustable length of a management zone is for VRI. The longitudinal transition between zones was continuous and homogenous from the 14th to 26th catch cans, which is a 12-m wide border between the management zones in the travel direction of the irrigation machine (Figure 6). This is probably due to the application radius of the sprinklers, which was approximately 12 m. The defined borders between the measurement zones also highlight that the length of a management zone in the longitudinal direction should be larger than 12 m considering the transition effect of the borders between the zones.

Takács et al. (2018) used the two measurement lines perpendicular to the travel direction and measured the transitions from 0% to 100% and from 50% to 100%. In these two cases, both the 0%–100% and 50%–100% lines showed that the borders between management zones ceased within 9 m. Thus, on average, considering the width of the transition bands, it is necessary to calculate 9 m for the travel direction of the irrigation machine.

3.3 | Evaluation of uniformity of irrigation in different management zones along pipeline

The water distribution characteristics of VRI systems are a crucial indicator to evaluate the uniformity of irrigation in different management zones. The average volume of irrigation water collected in the catch cans was 2.4 ± 0.5 mm, and the CUc%, DU% and CV% calculated from the applied water data were 81%, 81% and 20%, respectively, for the first zone. In the next management zone, the average irrigation water was 4.8 ± 0.9 mm, resulting in a CUc% of 86%, a low DU% of 78% and a CV of 17%. In the third zone, the average irrigation water was 7.1 ± 0.7 mm, resulting in a CUc% of 93%, a DU% of 88% and a CV of 9%. In the fourth zone, set with a maximum water discharge, 9.2 ± 0.8 mm water was measured on average, with a CUc% of 93%, DU% of 91% and CV of 8% (Table 2). Most of the studies focusing on water distribution and irrigation uniformity evaluate centre pivot systems. For instance, O'Shaughnessy et al. (2013) conducted experiments with two centre pivot irrigation systems with VRI. The catch cans were positioned above the mown wheat. The collection cans were set in a linear grid and a curved orientation to evaluate the consistency with which the VRI system was applied. The average CUH and DU ranged from 86% to 90% and 76% to 83%, respectively. These average values compare well with the

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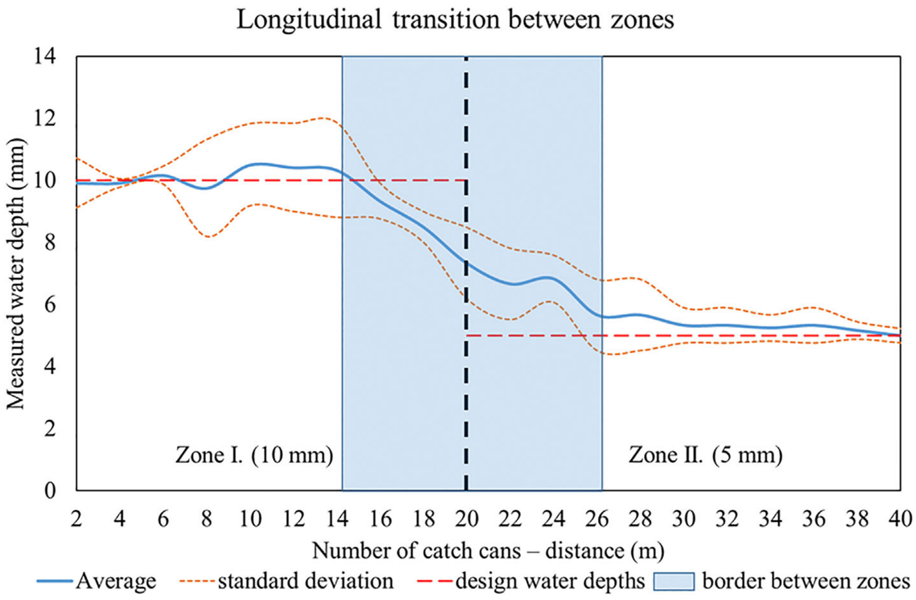

FIGURE 6 Evaluation of longitudinal transition between irrigation zones.

TABLE 2 Results of accuracy of irrigation in different management zones along pipeline.

Zone no.	*n*	Design water depths (mm)	Average measured water depths (mm)	CUc %	DU %	CV %	MAE (mm)	MBE (mm)	NRMSE %
1	20	2.5	2.4[a]	81	81	20	0.5	0.04	22
2	20	5	4.9[b]	86	78	17	0.6	0.1	12
3	20	7.5	7.1[c]	93	88	9	0.6	0.3	7
4	20	10	9.2[d]	93	91	8	0.8	0.6	6

Note: There is no significant difference between water depths marked with the same letter ($p > 0.05$).

Abbreviations: CUc, Christiansen uniformity coefficient; CV, coefficient of variation; DU, distribution uniformity; MAE, mean absolute error; MBE, mean bias error; NRMSE, normalized root mean square error.

uniform application results of Dukes and Perry (2006). They measured lower CUH and DU varying between 73% to 82% and 64% to 74%, respectively, for a linear-move system with VRI. In contrast, Clark et al. (2003) measured good uniformity performance (CUH 90%), corresponding with the results in this study. Other studies investigated linear-move systems at a constant rate. Chavez et al. (2010) investigated a linear-move VRI system with a rotating spreading plate, nozzles spaced 3 m apart and 1.2 m above the ground, moving over catch cans spaced 1.5 m apart in an 8 × 20 grid system. According to their results, the CUc% was 88%–97%. Although a smaller grid size was used in this present study for testing, similar uniformity results were found.

3.4 | Evaluation of accuracy of irrigation in different management zones along pipeline

The combined results for the average of measured water depths, NRMSE, MAE and MBE of the water applications of four VRI zones along the pipeline under various designed water applications are represented in Table 2. Significant differences in water depths were found between the management zones (Table 1), which means that the VRI system performed well, and the designed irrigation levels of management zones were found to be different in all cases. The departure from the specified level was analysed to evaluate the accuracy of the irrigation at each management zone. In the case of all management zones, the measured water depths in the catch cans were slightly less than the designed irrigation water depths. The 25% water application rate resulted in an MAE of 0.5 mm, an MBE of 0.04 mm and an NRMSE% of 22%. At 50% application, the MAE between the values of the amount of water to be applied and the amount of water absorbed was 0.7 mm and MBE 0.2 mm, higher than at 25% application. NRMSE%, on the other hand, was lower compared to the 25% application with a result of 12%. The 75% water application resulted in an MAE of 0.6 mm and MBE of 0.3 mm, which were almost the same as at the 25% application, and a slightly lower NRMSE% of 7%. For the 100% application, the MAE and MBE values were higher than for the other applications (0.8 and 0.6 mm, respectively), while the NRMSE% value

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was 6%. This enables optimal variations of management zones along a span to apply the required amount of water to specific locations (Table 2).

O'Shaughnessy et al. (2013) tested centre pivot systems and found that the MAE, MBE and root mean square error (RMSE) ranged from 1.9 to 2.6, −0.6 to 1.1 and 1.8 to 2.4 mm in span, respectively. On average, nozzles in stages 1 and 2 overirrigated by approximately 9%, while nozzles in stages 5 and 6 underirrigated by approximately 2%. For collectors in irrigation zones with pulsation rates between 30% and 100%, the MBE% and RMSE% ranged from −6% to 14% and 11% to 21%, respectively. Chavez et al. (2010), in their linear-motion VRI study, reported that MBE% and RMSE% for measured collector depths ranged from −0.6% to −12% and 3% to 9%, respectively, for target percent application rates between 20% and 100% when linear motion was applied upwards. Moving downwards, the MBE% and RMSE% ranged from −8.3% to 19% and from 4% to 12%, respectively. When their control was moved to a linear movement in North Dakota, MBE% and RMSE % were −8.8% ± 8.1% and −0.1% ± 6.7%, respectively. The results also suggest that the irrigation uniformity and accuracy were highly correlated and that the better uniformity of irrigation resulted in higher accuracy, and vice versa, in agreement with the findings of Yari et al. (2017).

4 | CONCLUSION

This study presents the results of water distribution characteristics, such as (i) irrigation uniformity and accuracy at a modelled irrigation zone, (ii) the evaluation of the borders of management zones and (iii) precision of the water application between different management zones of a VRI-equipped pivoting linear-move irrigation system. Homogeneous irrigation uniformity with considerable accuracy was achieved, resulting in negligibly low underirrigation and overirrigation in practice. The management zones in this paper were tested and divided transversally (i.e. along the lateral pipe) and divided longitudinally in the travel direction of the linear-move VRI system. As a result, not only was the minimum length of a zone defined in the travel direction of the VRI system but also the accuracy of irrigation under different design water depths. The outcomes recommend optimal design information for a linear-move VRI system. This supports the development of more accurate irrigation schedules considering field-scale spatial patterns and differences. However, this study has some shortcomings: The influence of different sprinkler types or sprinkler spacing, the pressure of the irrigation, etc. on application uniformity and accuracy of VRI have not been discussed in this paper; therefore, further research is expected.

ACKNOWLEDGEMENTS

The research was funded by the European Union's Horizon 2020 'WATERAGRI Water Retention and Nutrient Recycling in Soils and Streams for Improved Agricultural Production' research and innovation programme under grant agreement no. 858375.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available.

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How to cite this article: Szabó, A., Tamás, J., Kövesdi, Á. & Nagy, A. (2023) Evaluation of new pivoting linear-move precision irrigation machine. *Irrigation and Drainage*, 1–12. Available from: https://doi.org/10.1002/ird.2850

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