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PREDICTIVE MODELS OF WATER APPLICATION AND DISTRIBUTION EFFICIENCY IN CONVENTIONAL SPRINKLING

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KEYWORDS

uniformity coefficient, irrigation efficiency, evaporation and wind drift.

ABSTRACT

Correct determinations of distribution (E_d) and application (E_A) efficiencies allow adequate estimations of the gross irrigation depth. This study aimed: i) to determine the distribution efficiency using the Christiansen uniformity coefficient (CUC) in a sprinkler irrigation system under different weather conditions and working pressures; ii) to compare the mean, median, and cumulative CUC values; and iii) to evaluate the predictive capacity of four E_A estimation models. CUC values were determined from 80 assessments, as well as the mean, median, and cumulative. The precipitated water depth accumulated in each collector was considered for the accumulated CUC. More uniform evaluations were used for E_A (working pressure of 196 kPa), resulting in 20 samples. Besides being measured, E_A was estimated by Keller & Bliesner, Playán, Tarjuelo, and Beskow methods. Statistical indicators were the root mean square error, mean bias error, Willmott agreement index, mean absolute error, and Pearson correlation coefficient. CUC values ranged from 66.51 to 92.04%, and the accumulated CUC provided an improvement over the isolated evaluations. The Beskow model had the best E_A estimations in conventional spraying.

INTRODUCTION

Irrigated agriculture is essential in some regions of Brazil for maintaining high crop yields due to the irregular precipitation distribution. The conventional sprinkler irrigation system is widely used in Brazil (Alves et al., 2017). However, this system does not operate at its maximum efficiency under adverse weather conditions, such as high temperature, low air humidity, and high wind speed, wasting water, bad fertilizers solubilization, and instability in electrical network (Molle et al., 2012; Sheikhesmaeili et al., 2016).

For irrigation management, irrigation efficiency (E_i) is determined by application (E_A) and distribution (E_d) efficiencies and is calculated as the product of these two variables. Knowledge of E_i is of paramount importance for proper irrigation management because the gross water depth to be applied is adjusted from this variable (Kifle et al., 2017).

In sprinkler irrigation systems, part of the water depth applied by emitters does not reach the soil surface

and/or the shoot occupied by crops. This portion of water represents evaporation and wind drift (WDEL), which, in turn, are expressed as the percentage of the gross applied volume lost in a given irrigation event (Andrés & Cuchí, 2014). The ratio between the water depth that reached the irrigation target (collected water depth) and applied water depth is defined as application efficiency (E_A). WDEL is obtained by subtracting E_A by the unit value.

Evaporation losses depend on the relative humidity, wind speed, ambient temperature, emitter working pressure, emitter installation height from the soil surface, and droplet diameter. Wind drift, on the other hand, depend mainly on wind speed, droplet diameter, and the distance traveled by droplets until they reach the shoot of crops or soil surface (Maroufpoor et al., 2017).

The quantification of WDEL is considered of high relevance in both environmental and economic aspects. However, estimating these losses separately is a rather complicated task due to the difficulties of the methodologies required for their measurements (Beskow et al., 2011). Several studies have been conducted in different

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regions of the world with the purpose of modeling or evaluating some existing models for WDEL estimation in sprinkler irrigation systems (Colombo et al., 2015; Faria et al., 2012; Stambouli et al., 2013).

Another factor necessary to be considered in sprinkler irrigation systems assessments is the Ed. To calculate this, uniformity coefficients need to be used. Several methods can be found in the literature, but the Christiansen uniformity coefficient is the most widely used for conventional sprinkling (Cavero et al., 2016). Ed is also influenced by weather conditions and characteristics of the irrigation equipment.

According to Colombo et al. (2015), knowledge of the performance of an irrigation system, especially regarding the uniformity of distribution of the applied water depth, is essential for making decisions that allow the rational use of water, energy, and fertilizers. Thus, knowing the influence of weather variables is essential to predict or estimate irrigation uniformity, and even to identify the best time for the operation of a sprinkler irrigation system.

Therefore, this study aimed: i) to determine the distribution efficiency using the Christiansen uniformity coefficient (CUC) in a sprinkler irrigation system under different weather conditions and working pressures; ii) to compare the mean, median, and cumulative CUC values; and iii) to evaluate the predictive capacity of four application efficiency estimation models.

MATERIAL AND METHODS

Location and characterization of the area

The study was conducted in an experimental irrigation area of the Department of Agricultural Engineering of the Federal University of Viçosa, Viçosa, MG, Brazil, with geographical coordinates of 20°45' S and 42°51' W, and an altitude of 651 m. The local climate is Cwa, according to the Köppen-Geiger classification, i.e., a humid subtropical climate with dry winter and hot summer (Alvares et al., 2013).

This study consisted of the evaluation of an irrigation system with six midi-sectorial or 360° sprinklers with a 4 mm nozzle. Sprinklers were spaced at 11 × 8 m to suit the experimental area configuration, supported by a 1.7 m rod above the soil surface and recommended working pressure for system operation of 196.13 kPa.

Distribution uniformity evaluation

Collectors were arranged between six sprinklers operating simultaneously. Collectors were of the Fabrimar® brand and were installed equidistant at 2 m, resulting in 44 collectors (Figure 1). A rod was used to suspend the collector at the height of 70 cm from the soil surface, following the methodology proposed by Merriam & Keller (1978).

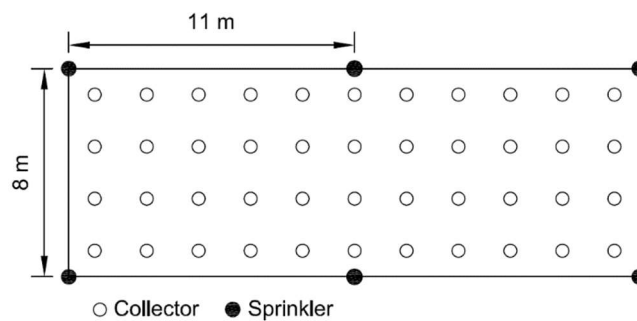


FIGURE 1. Sketch of the experimental area.

The data on mean air temperature, relative humidity, solar radiation, and wind speed were collected throughout the testing period using an Irriplus E5000® automatic weather station, located 30 m from the experimental area.

Eighty field tests with 60 minute durations were performed under different weather conditions (Figure 4) from April to July 2017. The reading of weather elements was performed every 20 minutes, and their mean was used to represent the weather conditions during irrigation.

Water depth was measured at the end of each test on each collector using a 15 mm Fabrimar® graduated beaker. The Christiansen uniformity coefficient (CUC) (Christiansen, 1942) was used to calculate the uniformity of distribution, according to [eq. (1)].

$$CUC = 100 \left(1 - \frac{\sum_{i=1}^N |D_i - D_m|}{ND_m} \right)$$

Where:

CUC is the Christiansen uniformity coefficient (%);

N is the number of observations;

D_i is the water depth applied at the i -th point on the soil surface (mm), and

D_m is the mean applied water depth (mm).

The mean and median CUC values were calculated after CUC has been determined for each evaluation. Cumulative CUC was also determined by summing the 80 values of water depth measured in each collector. The calculation was performed with these cumulative values, according to Equation (1).

The mean, median, and cumulative CUC were determined for every ten successive evaluations to verify the sensitivity of differences in a few numbers of evaluations, resulting in eight replications in a randomized block design. These data were analyzed by the Tukey test at a 0.05 significance level.

Evaporation and wind driftevaluation

Before starting the evaluations, the flow versus working pressure curve was determined for the sprinkler used in this study (Figure 2A). For this, pressures ranging from 78 to 333 kPa were used. Thus, a linear regression model was adjusted to predict the flow as a function of working pressure.

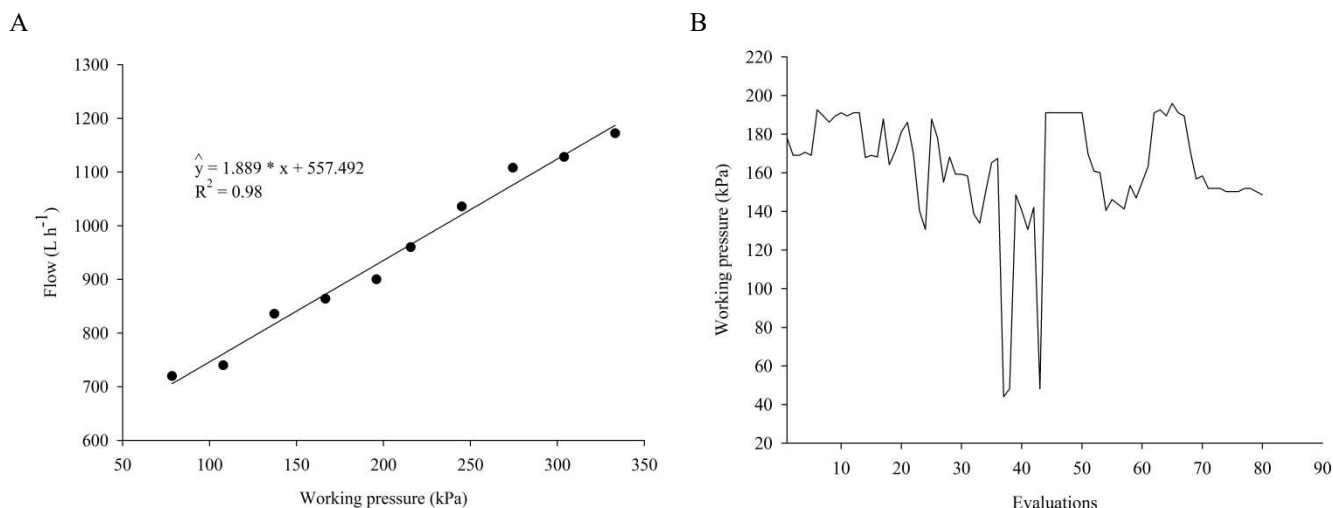


FIGURE 2. (A) Flow as a function of working pressure and (B) mean pressure variation of Fabrimar sprinklers (midi model with 4 mm nozzle) during the study period. Viçosa, MG, Brazil, DEA–UFV, 2017.

Working pressure readings of the six sprinklers were taken in all evaluations at the beginning, middle, and end of the irrigations. Schrader valves (coarse nozzle) were installed in the riser pipe at 5 cm below the sprinkler to facilitate working pressure readings. The flow rate and, thus, the water depth applied in each evaluation were obtained with the mean pressure using the regression equation shown in Figure 2A.

The evaluation of evaporation and wind drift (WDEL) or application efficiency (E_A) was carried out using twenty evaluations with working pressures closer to 196.13 kPa (pressure recommended by the manufacturer). This procedure was used to standardize the droplet size, as operating pressures of the irrigation system showed high variations during the evaluation period (Figure 2B). Thus, it was also possible to correlate them better with input variables based on weather conditions of prediction models.

Pressure variation is related to the instability of the electrical network and water quality used in irrigation, as it had suspended solids. These impurities caused disc filter clogging and, consequently, reduced the working pressure

during the test. Backwash was performed manually at the interval of each evaluation.

The arithmetic means water depth applied by sprinklers and the water depths measured in the collectors were used to calculate the evaporation and wind drift. Thus, WDEL was calculated using [eq.(2)].

$$WDEL = \left(\frac{D_{applied} - D_{collected}}{D_{applied}} \right) 100$$

Where:

WDEL is the evaporation and wind drift (%),

$D_{applied}$ is the applied water depth (mm), and

$D_{collected}$ is the collected water depth (mm).

However, data processing was based on E_A . For this, WDEL values were subtracted from 100.

In addition to measurements, E_A was estimated by different models as a function of weather conditions in the tests. The mathematical models used in the present study were proposed by Keller & Bliesner (1990), Playán et al. (2005), Tarjuelo et al. (2000), and Beskow et al. (2008), represented, respectively, by equations shown in Table 1.

TABLE 1. Equations for application efficiency modeling used in the study. Viçosa, MG, Brazil, DEA–UFV, 2017.

Author	Empirical equation
Keller & Bliesner (1990)	$E_A = 100 \times [(0.976 + 0.005ET_0 - 0.0001ET_0^2 + 0.0012U) - CI(0.00043ET_0 + 0.00018U + 0.000016ET_0U)]$, where CI is a function of the type of deflector plate
Tarjuelo et al. (2000)	$E_A = 100 - [0.007WP + 7.38(e_s - e_a)^{0.5} + 0.844U]$
Playán et al. (2005)	$E_A = 100 - (20.3 + 0.214U^2 - 2.29 \times 10^{-3} RH^2)$
Beskow et al. (2008)	$E_A = 100 - [-0.0304WP + 13.2976(e_s - e_a)^{0.5} + 5.485U]$

E_A is the application efficiency (%); $(e_s - e_a)$ is the vapor pressure deficit (kPa); WP is the sprinkler working pressure (kPa); U is the mean wind speed ($m s^{-1}$); T is the air temperature ($^{\circ}C$); and RH is the relative air humidity (%).

The vapor pressure deficit (Δe) and vapor saturation pressure (e_s) were obtained by eqs (3) and (4):

$$\Delta e = e_s(T) - [RH \times e_s(T)] \quad (3)$$

$$e_s = 0.61078 \exp\left(\frac{17.266 \times T}{T + 23.3}\right) \quad (4)$$

Where:

Δe is the vapor pressure deficit (kPa);

e_s is the vapor saturation pressure (kPa);

T is the temperature ($^{\circ}C$), and

RH is the relative humidity (%).

The following statistical indicators were used to verify the performance of the models using the observed values: root mean square error (RMSE), mean bias error (MBE), in addition to the parameters recommended by Legates & McCabe (1999), Willmott agreement index (d) and mean absolute error (MAE). The magnitude of the coefficient of determination (R^2) and Pearson correlation coefficient (r) was used to correlate the measured with

the estimated data.

RESULTS AND DISCUSSION

The Christiansen uniformity coefficient (CUC) values were increasingly ordered and associated with the sprinkler working pressure, ranging from 66.51 to 92.04% and 44.1 to 196 kPa, respectively (Figure 3).

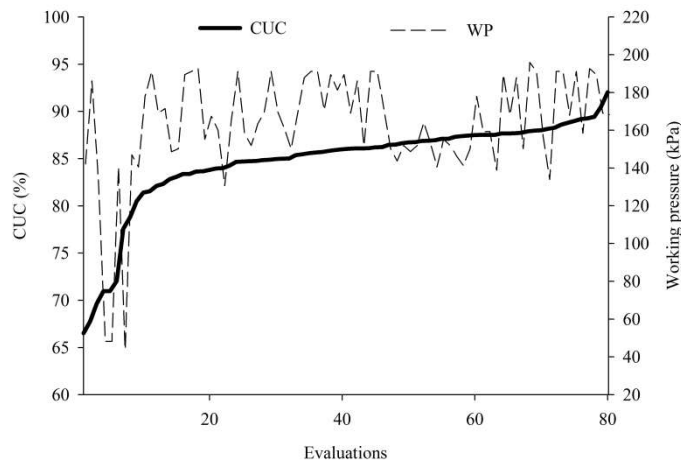


FIGURE 3. Christiansen uniformity coefficient (CUC) and working pressure near sprinklers (WP) in kPa for 80 evaluations of a conventional sprinkler irrigation system. Viçosa, MG, Brazil, DEA–UFV, 2017.

The 72 evaluations of the irrigation system through CUC showed results higher than 80%, and one of the main factors influencing the distribution uniformity was sprinkler working pressure (Figure 3). In contrast, due to the characteristics of the study area and range of weather variation during the study, weather elements affected the distribution uniformity with less intensity (Figure 4).

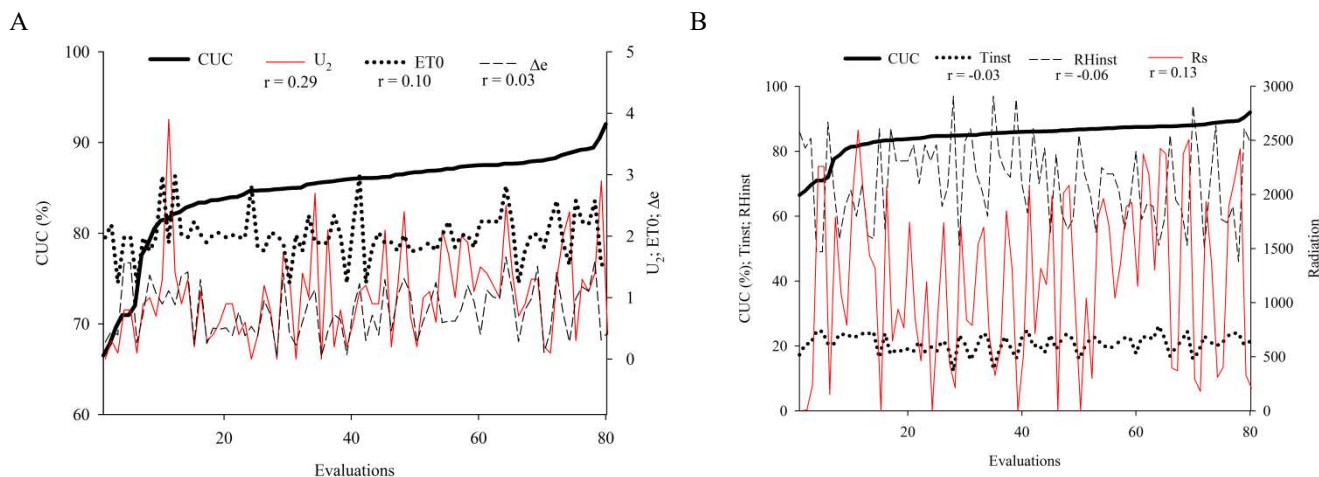


FIGURE 4. Christiansen uniformity coefficient (CUC) values versus (A) wind speed (U_2) in $m s^{-1}$, reference evapotranspiration (ET_0) in $mm d^{-1}$, vapor pressure deficit (Δe) in kPa, (B) instantaneous temperature (T_{inst}) in $^{\circ}C$, instantaneous relative humidity (RH_{inst}) in%, and solar radiation (R_s) in $KJ m^{-2}$ for 80 evaluations of a conventional sprinkler irrigation system. Viçosa, MG, Brazil, DEA–UFV, 2017.

The variable CUC had a low Pearson coefficient (r), i.e., a weak correlation with all the weather elements. The water distribution of an irrigation system mainly depends on the spacing, type, size, internal design, and working pressure of emitters (Zhu et al., 2015).

The variation in the uniformity of water distribution evaluated at different times, working pressures, and weather conditions have been reported in other studies. Li et al. (2015) evaluated a sprinkler irrigation system in which the working pressure ranged from 200 to 350 kPa

and found CUC values from 73.27 to 81.11%. Robles et al. (2017), on the other hand, studied the effect of wind speed on distribution uniformity and found CUC values of 89 and 67% for low and high wind speed conditions, respectively. Justi et al. (2010) evaluated 25 irrigation events and found mean and maximum CUC values of 79.72 and 89.45%, respectively.

Sheikhesmaeili et al. (2016) suggested being acceptable CUC values of at least 80% in sprinkler irrigation systems. Most evaluations presented CUC values

above 80% (Figures 3 and 4), but values below 80% can be found due to working pressure and wind speed variations, as observed in this and other studies. This behavior discourages the use of only one evaluation to represent the uniformity of water distribution in conventional sprinkler irrigation systems.

A reference value needs to be adopted when an irrigation system has several CUC values. This value can be used to determine their irrigation efficiency and,

therefore, provide adequate irrigation management, turning the net water depth into gross. The CUC_{mean} of 84.66% shown in Figure 5 represents the mean of all evaluations. CUC_{median} had a value of 86.04%, which is higher than the CUC_{mean} . In contrast, the $CUC_{cumulative}$, which represents CUC considering the sum of water depths distributed in the area over time, presented a value of 90.64%, which is higher than the others are.

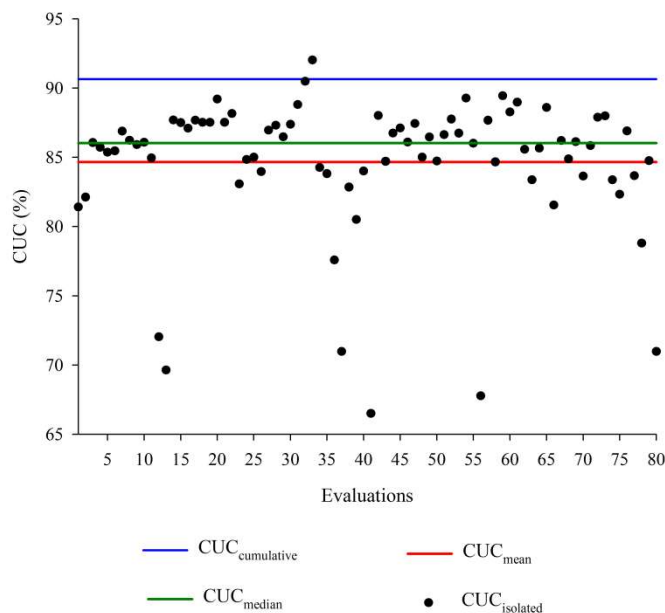


FIGURE 5. Christiansen uniformity coefficient values obtained in isolation ($CUC_{isolated}$) with their respective mean (CUC_{mean}), median (CUC_{median}), and cumulative values ($CUC_{cumulative}$) values for 80 evaluations of a conventional sprinkler irrigation system. Viçosa, MG, Brazil, DEA - UFV, 2017.

Water distribution in the irrigation area varies over time, significantly changing its uniformity when considering multiple irrigations. Usually, a point of the area to be irrigated may receive water depths equal to, lower than or higher than that of the mean at different irrigation events because of the random pattern of the collected precipitation, which is influenced by some weather parameters and/or working pressure. Therefore, the same point that received a low irrigation depth and was in deficit compared to other areas can receive a water depth higher than the mean in the next irrigation event, partially

or totally supplying the deficit that occurred in the first irrigation. Thus, when CUC_{mean} or CUC_{median} are adopted, it is disregarded that a region that receives different water depths may have in time a higher and more representative CUC of the area, especially in areas of the semi-arid, which receive high and more frequent water depths.

Figure 6 shows three distinct distribution uniformities for an irrigation system. Evaluations 1 and 2 presented CUC values of 84.96 and 86.06%, respectively. The $CUC_{cumulative}$ of all 80 evaluations was 90.64%.

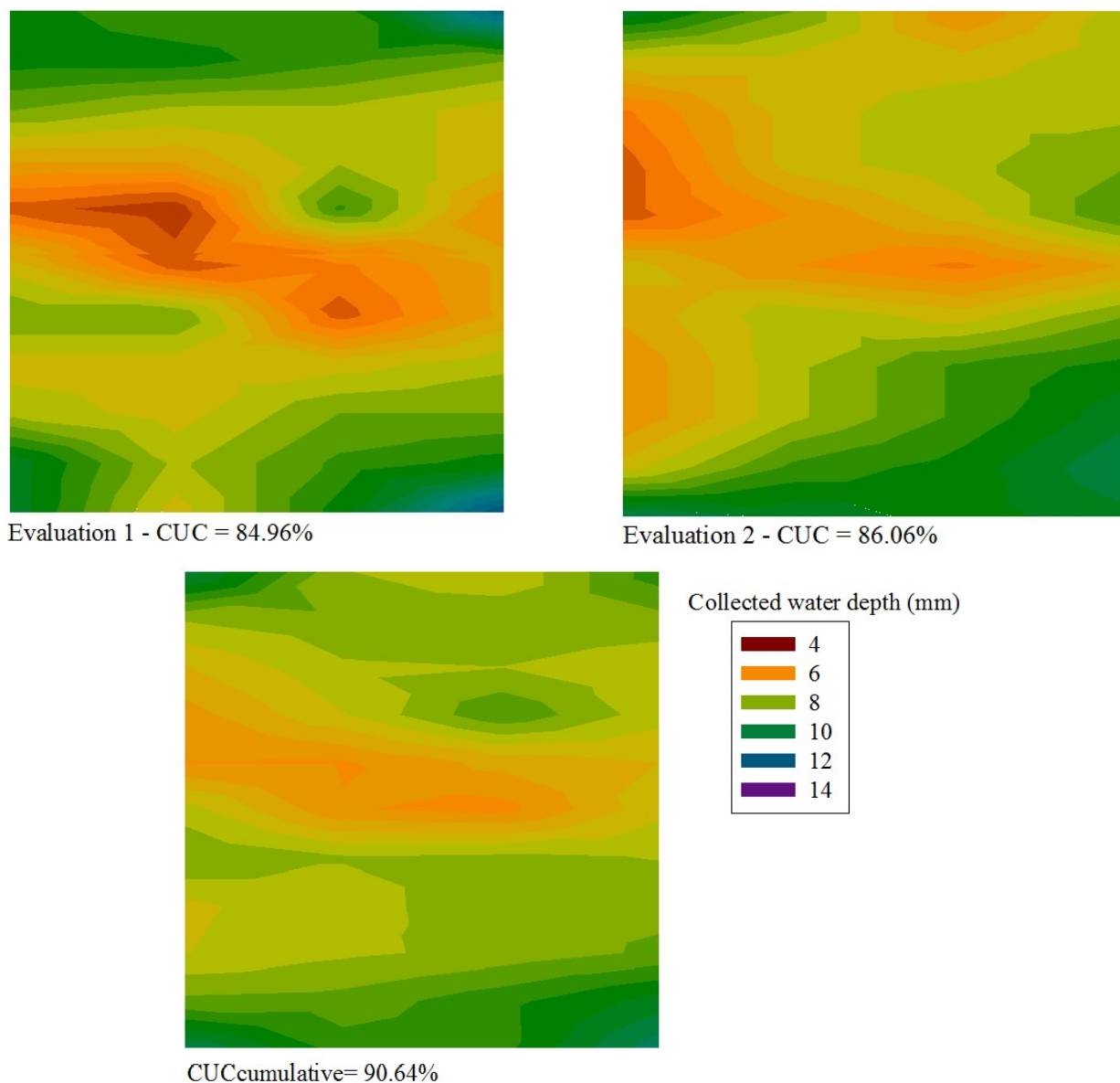


FIGURE 6. Distribution uniformity of an irrigation system at three different times. Evaluation 1 had a CUC value of 84.96%; Evaluation 2 presented a CUC of 86.06%; and $CUC_{cumulative}$ presented a value of 90.64% for 80 evaluations. Viçosa, MG, Brazil, DEA–UFV, 2017.

Among the various causes that affect the distribution uniformity of a sprinkler irrigation system, special attention should be given to working pressure and wind speed and direction (Li et al., 2015). Variation of these factors is undesirable, as they tend to reduce the distribution uniformity coefficient. Weather factors are dynamic, even choosing less windy times is not a guarantee of even distribution. Assuming that wind speed and direction vary, it is possible to understand that a conventional sprinkler irrigation system operating at different times and low irrigation frequency can redistribute water in the area to be irrigated, thus promoting a better irrigation uniformity over time, as shown by the $CUC_{cumulative}$ (Figure 6).

Water redistribution by irrigation systems occurs in different applications or within the same application

depending on the duration of the irrigation. It would be a new way of understanding the dynamics of irrigation and CUC use, often underestimated. In this sense, it has already been proposed to monitor the uniformity of water distribution in the soil profile, as it can redistribute water and, thus, present a CUC closer to reality (Rocha et al., 1999).

The $CUC_{cumulative}$ values for every ten evaluations ranged from 88.50 to 89.39%. On the other hand, the CUC_{mean} comprised values from 83.25 to 86.07%, and CUC_{median} values ranged from 83.91 to 87.51%. Based on the mean of the eight groups of evaluations (replications), the $CUC_{cumulative}$ was higher than CUC_{median} and CUC_{mean} (Table 2). CUC_{mean} was the variable that most underestimated distribution uniformity.

TABLE 2. Determination of $CUC_{cumulative}$, CUC_{mean} , and CUC_{median} every ten evaluations. Viçosa, MG, Brazil, DEA–UFV, 2017.

Evaluation	$CUC_{cumulative}$	CUC_{mean}	CUC_{median}
1–10	88.78	85.13	85.82
11–20	88.94	84.09	87.51
21–30	88.92	86.07	86.72
31–40	89.39	83.53	83.91
41–50	88.72	84.29	86.29
51–60	88.82	85.42	87.20
61–70	88.95	85.46	85.62
71–80	88.50	83.25	84.21
Mean	88.88a	84.66c	85.91b

Means followed by the same lowercase letter for different CUC determinations do not differ from each other by the Tukey test at 0.05 significance level.

Under practical conditions, conducting eighty evaluations to propose a more representative CUC of the area becomes unfeasible. Therefore, it was suggested in Table 2 to perform at least ten evaluations using the $CUC_{cumulative}$, as CUC_{mean} and CUC_{median} underestimate

distribution uniformity, besides presenting higher variations between evaluations.

Application efficiency (E_A) was determined, ordered in increasing order, and correlated by Pearson’s coefficient (r) with weather elements (Figure 7).

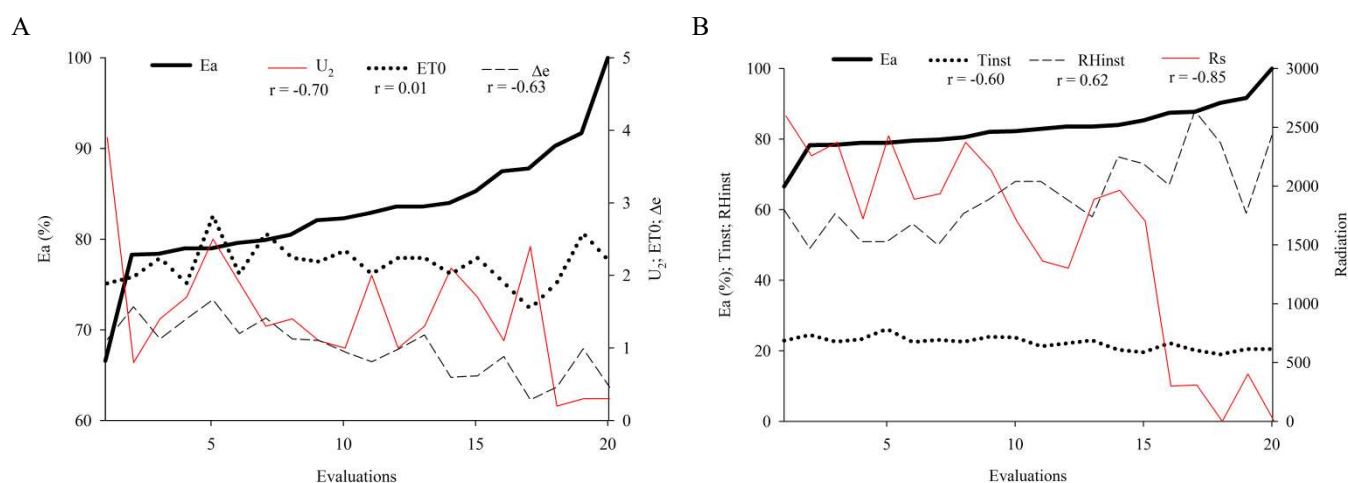


FIGURE 7. Values of application efficiency (E_A) versus (A) wind speed (U_2) in $m\ s^{-1}$, reference evapotranspiration (ET_0) in $mm\ d^{-1}$, vapor pressure deficit (Δe) in kPa, (B) instantaneous temperature (T_{inst}) in $^{\circ}C$, instantaneous relative humidity (RH_{inst}) in%, and solar radiation (R_s) in $KJ\ m^{-2}$ for 20 evaluations of a conventional sprinkler irrigation system. Viçosa, MG, Brazil, DEA–UFV, 2017.

The higher the wind speed, the lower the application efficiency, thus promoting higher wind drift ($r = -0.70$). The vapor pressure deficit, solar radiation, and relative humidity directly correlated with E_A , with values of -0.63 , -0.85 , and 0.62 , respectively. Thus, these weather elements increased evaporation and wind drift (Figure 7). Evaporation and wind drift were also reported by Cavero et al. (2016) for the day and night periods. The

positive correlation between weather data with E_A is paramount to search for models that best fit a particular location (Saraiva et al., 2013).

Table 3 shows the statistical indices for application efficiency (E_A) estimations, as proposed by Keller & Bliesner, Playán, Tarjuelo, and Beskow in relation to the values measured in the field.

TABLE 3. Root mean square error (RMSE), mean absolute error (MAE), Willmott agreement index (d), mean bias error (MBE), and Pearson’s correlation coefficient (r) of the observed data with those estimated by application efficiency models. Viçosa, MG, Brazil, DEA–UFV, 2017.

Model	RMSE	MAE	d	MBE	r
Keller	15.98	14.85	0.35	14.64	0.72
Playán	7.21	6.49	0.62	5.56	0.74
Tarjuelo	8.93	8.00	0.52	7.28	0.83
Beskow	2.98	2.54	0.94	0.77	0.90

The results show that the Beskow method was the most efficient in the estimation of E_A , which is evidenced by lower values of RMSE, MAE, and MBE, besides higher d and r . On the other hand, the other evaluated methods presented low performance, with high RMSE and MAE values. Beskow et al. (2008), analyzing the Playán and Tarjuelo models to estimate E_A , worked with a single sprinkler operating and several sprinklers operating simultaneously, and found unsatisfactory adjustments.

In addition to statistical indices, the analysis in Figure 8 shows the distribution of the measured and estimated E_A values by each method. Except for the Beskow method, all others had unsatisfactory performance in relation to the measured values, showing a tendency to overestimate them, which is also indicated by the high MBE values. The Beskow method presented good precision ($R^2 = 0.803$) and accuracy ($a = 18.939$ and $b = 0.781$), but there was a small dispersion of data due to systematic and random errors.

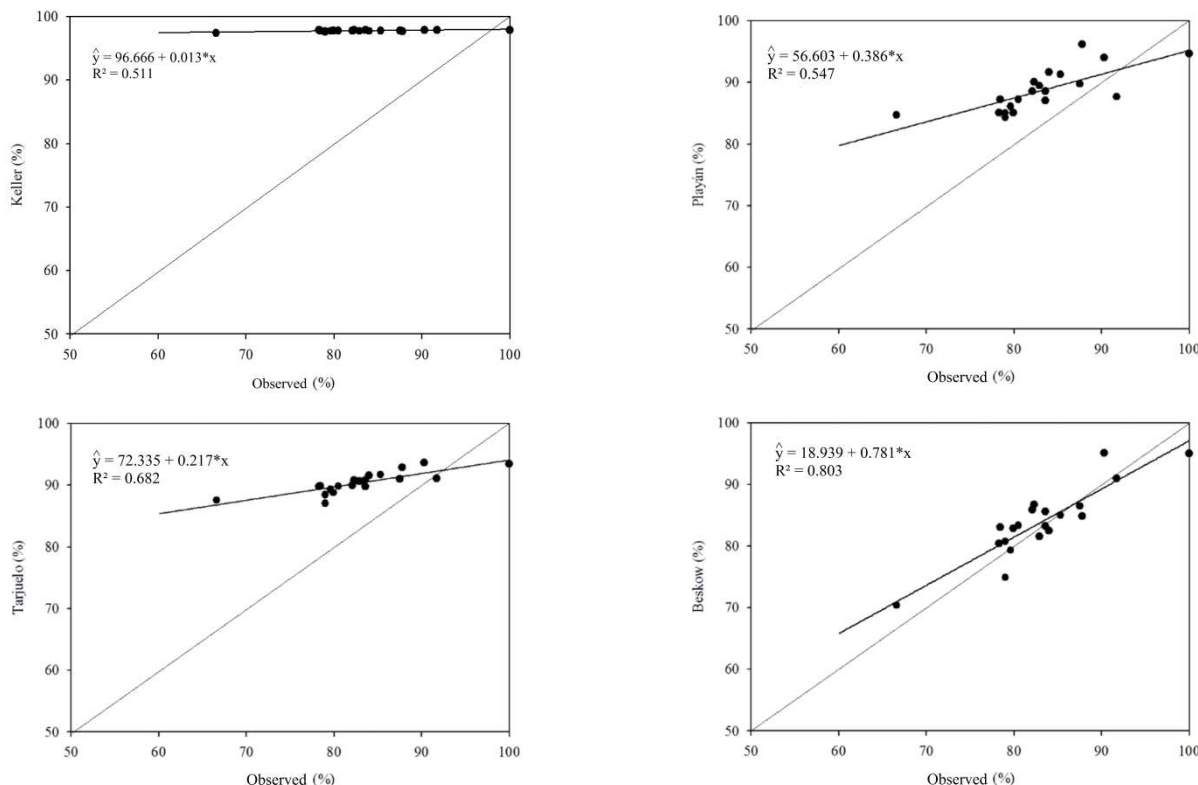


FIGURE 8. Linear regressions between the observed application efficiency values with those estimated by the Keller & Bliesner, Playán, Tarjuelo, and Beskow equations. Viçosa, MG, Brazil, DEA–UFV, 2017.

The Beskow method showed better agreement, possibly due to the regional approximation and similarity of weather conditions of the present study. This method was developed under the conditions of Lavras, MG, Brazil (Beskow et al., 2008), and the other models in the United States (Keller & Bliesner, 1990) and Spain (Playán et al., 2005; Tarjuelo et al., 2000). Saraiva et al. (2013) found similar results.

Figure 8 also shows that it is important to draw attention to the fact that the values estimated by the Keller

& Bliesner method presented a very small variation. This method presented low sensitivity to weather variations, which possibly corroborated for this model to present the worst performance.

The Keller & Bliesner (1990) model underestimated evaporation and wind drift and/or overestimated application efficiency (Figures 8 and 9). Faci et al. (2001) observed similar results in working with spray-type sprinklers.

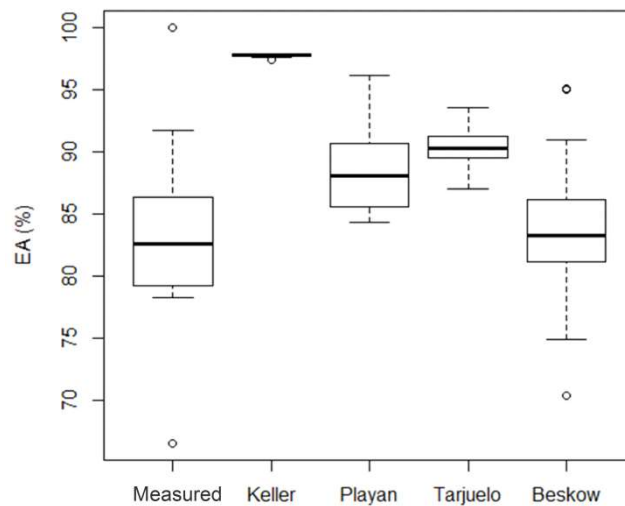


FIGURE 9. Application efficiency (E_A) measured and predicted by the Keller & Bliesner, Playán, Tarjuelo, and Beskow equations. Viçosa, MG, Brazil, DEA–UFV, 2017.

As shown in Table 3 and Figures 8 and 9, the used models tended to overestimate the observed field data, and one of the factors that may be related to this application efficiency overestimation is the nozzle size used for model generation. The sprinkler nozzle used in the present study had 4 mm. According to Beskow et al. (2008), smaller nozzles promote higher spraying of droplets and, thus, have a larger area per unit of mass, which may result in higher evaporation loss and susceptibility to drift by the wind.

Even finding a model that fits well with field conditions, it requires caution when using a model to estimate E_A of a conventional sprinkler irrigation system. It is always important to analyze model limitations, such as nozzle diameter, working pressure, and jet slope used to generate the predictive model (Beskow et al., 2008). Sprinkler height may also favor E_A , as the longer the riser pipe, the longer the droplet will be exposed to the environment (Faci et al., 2001; Playán et al., 2005).

CONCLUSIONS

The distribution uniformity given by the Christiansen uniformity coefficient had high variation during the experimental period (66.51 to 92.04%). The highest and lowest CUC for the experimental area was the $CUC_{cumulative}$ and CUC_{mean} , respectively. The Beskow model was the best alternative for predicting application efficiencies. The Keller & Bliesner model is not recommended for the study conditions to predict application efficiency, as it presented low sensitivity to input parameters.

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