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Control charts for monitoring drip irrigation with different hydraulic heads

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ABSTRACT

This study monitored a drip irrigation system with different hydraulic heads, using control charts. The study included 25 tests, and was conducted at the Experimental Nucleus of Agricultural Engineering of the State University of Western Paraná, located in the municipality of Cascavel, Paraná. The drip irrigation system was operated by gravity, and had four hydraulic heads (10, 11, 12 and 15 kPa). The uniformity of the system was determined based on uniformity distribution. Uniformity monitoring was performed using Shewhart and exponentially weighted moving-average (EWMA) control charts. An increase in the hydraulic head increased uniformity. The use of 12 and 15 kPa hydraulic heads yielded good performance, whereas 10 and 11 kPa yielded regular performance. The use of control charts proved to be efficient; the Shewhart control chart was more robust, whereas the EWMA control chart, which indicated trends and deviations not shown by Shewhart control charts, was more sensitive.

Keywords: EWMA control chart, micro irrigation, Shewhart control chart, uniformity.

Gráficos de controle no monitoramento da irrigação por gotejamento com diferentes cargas hidráulicas

RESUMO

Nesse estudo, um sistema de irrigação por gotejamento com diferentes cargas hidráulicas foi monitorado por gráficos de controle. Este experimento foi conduzido no Núcleo Experimental de Engenharia Agrícola da Universidade Estadual do Oeste do Paraná, localizado no município de Cascavel, Paraná. Neste estudo, o sistema de irrigação por gotejamento foi conduzido por gravidade, com 4 cargas hidráulicas (10, 11, 12 e 15 kPa); 25 ensaios foram realizados para cada carga hidráulica. Além disso, sua uniformidade foi determinada pelo coeficiente de uniformidade de distribuição. O monitoramento da sua uniformidade foi realizado pelos gráficos de controle de Shewhart e da Média Móvel Exponencialmente Ponderada (MMEP). O aumento da carga hidráulica aumentou a uniformidade de distribuição. O uso das cargas hidráulicas de 12 e 15 kPa obtiveram uma boa uniformidade, enquanto que as

cargas hidráulicas de 10 e 11 kPa produziram uma uniformidade regular. A utilização dos gráficos de controle mostrou ser eficiente, o gráfico de controle de Shewhart demonstrou ser mais robusto, enquanto que o gráfico de controle MMEP, indicou tendências e desvios não apresentados pelo gráfico de controle de Shewhart, sendo mais sensível.

Palavras-chave: gráfico de controle MMEP, gráfico de controle Shewhart uniformidade, microirrigação.

1. INTRODUCTION

Drip irrigation requires high investment in construction and equipment for water collection, conduction, control and distribution, in addition to energy and labor costs (Da Silva *et al.*, 2003). Hence, the use of drip irrigation is limited for small rural producers who do not have the required financial resources.

One technique that reduces the initial cost and the variable cost of drip irrigation is gravity irrigation. In this technique, reservoirs are raised to a minimum height of 1m for the supply of water in small areas, thus eliminating the use of hydraulic pumps (Souza *et al.*, 2009). The possibility of performing drip irrigation without electricity and the low cost of the dripper make this tool more attractive, as it can contribute to the development of small rural producers.

One of the main parameters used in the evaluation of drip irrigation systems is the uniformity of water application over the irrigated area (De Souza *et al.*, 2006). Uniformity characterizes an irrigation system based on the difference in water volume applied by emitters and directly affects irrigation management, efficiency, cost, as well as crop quality and productivity (Azevedo and Saad, 2012). Further, irrigation control prevents physiological and phytosanitary problems, thus reducing unnecessary losses of water, energy and nutrients (Trevisan *et al.*, 2016).

Control charts are most frequently used to monitor the performance of processes over time (Vieira, 2014). A control chart is a graphic representation of sample measurements of a given process and indicates the need to investigate and adjust a process according to the size of deviations presented.

Shewhart's and exponentially weighted moving-average (EWMA) control charts are among the best-known and the most frequently used ones (Frigo *et al.*, 2016). The success of Shewhart's control chart is owing to its simplicity, in which the ease of the decision rule is based only on examining the last observed point. However, this is also a major disadvantage, as any information provided by the previous sequence of points is disregarded, which renders the Shewhart control chart relatively insensitive to minor changes in the process (Walter *et al.*, 2013).

Minor variations in a process cannot be perceived by the Shewhart control chart; in this case, it is advisable to use the EWMA control chart. This control chart is more sensitive in detecting minor deviations from the average of a process. Therefore, such a method offers high speed and credibility in identifying minor mismatches in the process.

Vilas Boas (2016) reported that the use of control charts in irrigation provides several benefits: compliance with irrigation quality standards, monitoring of systematic errors in the irrigation process, provision of information regarding the status of the irrigation process, calculation of measurement uncertainty in irrigation, provision of objective evidence for demonstrating quality of measurements, and provision of a source of historical data on the measurement process in irrigation. Andrade *et al.* (2017a) concluded that micro irrigation uniformity can be analyzed through control charts.

Irrigation systems are commonly monitored using control charts; however, they are rarely monitored using hydraulic heads. Therefore, this study was conducted to evaluate the

uniformity of a drip irrigation system with different hydraulic heads through Shewhart and EWMA control charts.

2. MATERIAL AND METHODS

The study was performed at the Experimental Nucleus of Agricultural Engineering of the State University of Western Paraná, located in the municipality of Cascavel, Paraná, Brazil, with geographical coordinates of 24º58' S and 53º27' W.

The system consisted of flat drip tubes (SIPLAST^{TM}, Model P1) with a diameter of 16 mm, an inlet filter with an area of 7.5 mm^2, and a total of eight holes. There was a 0.20 m space between the drippers, and potential flow equation = 0.19.pressure^{0,52}. Considering a main line and four lateral lines, the system included 75 drippers per line, thus totaling 300 drippers. To reduce clogging, a 120-mesh screen filter was installed close to the reservoir.

For data collection, the methodology proposed by Keller and Karmeli (1975) was used, which involved determining the flow in four emitters per lateral line; the first dripper, drippers located at 1/3 and 2/3 of the lateral line length and the last dripper in four lateral lines. The system was pressurized by gravity. Figure 1 shows the experimental set-up and the data collection technique.

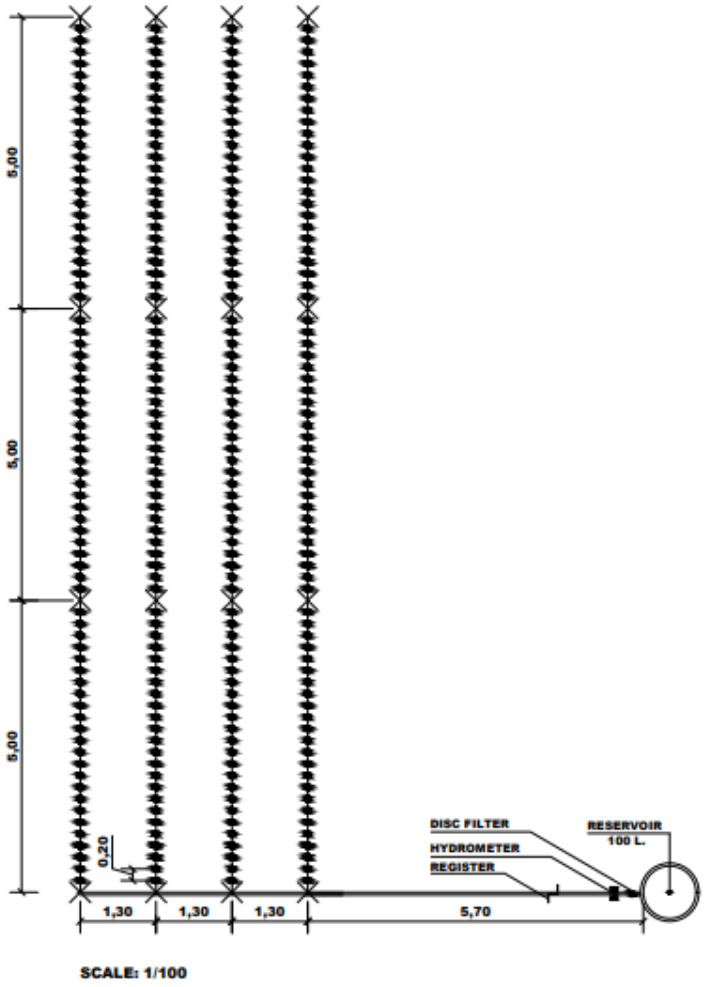

Figure 1. Experimental set-up and data collection technique.

After assembling the system, four different hydraulic heads were evaluated: 10, 11, 12 and 15 kPa. A total of 25 tests were performed for each hydraulic head, and the number of samples recommended by Montgomery (2016) for quality control tests was used. Furthermore, a

descriptive statistic was performed to measure the central tendency.

To assess the uniformity of the irrigation system, the distribution uniformity (UD) proposed by Merrian and Keller (1978) was used, as expressed in Equation 1.

$$UD = \left(\frac{Q_{25}}{\bar{\bar{Q}}}\right) \quad (1)$$

Where:

UD: uniformity distribution, (%);

Q_{25}: average of the ¼ smaller flow rates of the drippers, (L h^{-1});

$\bar{\bar{Q}}$: arithmetic mean of flows (L h^{-1}).

The following classifications were used to classify the UD data, which are listed in Table 1.

Table 1. UD classification.

UD	Classification
>90%	Excellent
80-90%	Good
70-80%	Regular
60-70%	Bad
<60%	Unacceptable

Source: Bernardo *et al.* (2008).

To monitor UD, a Shewhart control chart was prepared to investigate the parameters during the tests. It is necessary to prepare the control charts to determine the upper control limit (UCL) and lower control limit (LCL) using Equations 2 and 3, respectively.

$$UCL = \bar{\bar{X}} + 3\,\frac{\overline{\overline{AM}}}{d_2} \quad (2)$$

$$LCL = \bar{\bar{X}} + 3\,\frac{\overline{\overline{AM}}}{d_2} \quad (3)$$

Where:

UCL: upper control limit;

LCL: lower control limit;

$\bar{\bar{X}}$: data average;

$\overline{\overline{AM}}$: average of data amplitudes;

d_2: constant equal to 1.128 for n = 2, considering individual measures (Montgomery, 2016).

In addition to the Shewhart control chart, the EWMA control chart was used, which detected minor variations in behavior and provided a new estimate of the new process average, which might change the desired quality characteristics. This control chart accumulates successive information, weighs the samples, and provides more weight to the most recent information.

The EWMA control chart consisted of plotting Z*i* versus sample number i (or time), which

can be calculated using Equation 4, according to Roberts (1959).

$$Zi = u0 = \bar{\bar{X}} \quad (4)$$

Where:

$0 < \lambda \leq 1$;

$Zi = u0 = \bar{\bar{X}}$ (target value or mean value in x_i control).

The variance of the variable Z is expressed as Equation 5.

$$\sigma_{zi}^2 = \sigma^2 \left(\frac{\lambda}{2-\lambda}\right) \left[1 - (1 - \lambda)^{2i}\right] \quad (5)$$

Where:

σ: standard deviation of the data in relation to the mean;

λ: weight assigned to each sample;

i: order of sample used.

Roberts (1959) reported that the UCL and the LCL of the EWMA control chart can be calculated by Equations 6 and 7, respectively.

$$UCL = \bar{\bar{X}} + L\sigma\sqrt{\frac{\lambda}{(2-\lambda)} [1 - (1 - \lambda)]^{zi}} \quad (6)$$

$$LCL = \bar{\bar{X}} - L\sigma\sqrt{\frac{\lambda}{(2-\lambda)} [1 - (1 - \lambda)]^{zi}} \quad (7)$$

Where:

$\bar{\bar{X}}$: average of the data;

λ: weight assigned to each sample, which varies from 0 to 1;

L: number of standard deviations to control the mean to be detected;

i: order of sample used.

In this study, 0.25 is the weight constant of the sample, and for the width of the λ limits the factor is L = 2.

3. RESULTS AND DISCUSSION

An exploratory analysis was performed to provide a general characterization of the irrigation process. Table 2 summarizes the descriptive statistics for UD using different hydraulic heads.

The greatest uniformity was achieved using 15 kPa hydraulic head (89.91%), and the 12 kPa hydraulic head performed relatively well (87.12%). However, the 11 kPa hydraulic head indicated a regular uniformity (79.11%), whereas the 10 kPa hydraulic head demonstrated the lowest uniformity (77.00%). Gris *et al.* (2012) used hydraulic heads measuring 1.5 and 2.0 m in a drip irrigation system with cassava wastewater and obtained UD values exceeding 90%. Souza *et al.* (2009) evaluated drip irrigation systems by gravity using microtubes and obtained an average UD value of 87%.

It is observed that the hydraulic head is proportional to uniformity; the higher the hydraulic head, the greater the uniformity. A situation finding has been discovered by Klein *et al.* (2013), who used 15, 18 and 20 kPa hydraulic heads in irrigation and fertigation systems, and consistently obtained greater uniformity at 20 kPa. According to Hermes *et al.* (2018), the hydraulic head affects the flow rate during irrigation. The distribution uniformity generally increases with the hydraulic heads (Ella *et al.*, 2009).

Table 2. Exploratory analysis of UD of drip irrigation system tests with different hydraulic heads.

Hydraulic heads	10 kPa	11 kPa	12 kPa	15 kPa
Minimum	59.69	66.95	78.51	83.66
Q_1	68.87	70.95	85.37	87.24
Average	77.00	79.11	87.12	89.81
Q_3	83.72	84.47	90.12	92.28
Maximum	89.73	89.07	91.46	95.47
Standard deviation	8.23	7.26	3.23	3.01
Variance	67.73	52.74	10.47	9.11
CV (%)	10.69	9.18	3.72	3.36
Asymmetry	-0.57	-0.46	-0.73	-0.12
Kurtosis	-0.83	-1.38	0.58	-0.76

Notes: Q_1: First quartile, Q_3: Third quartile, CV: Coefficient of variation.

Shewhart control charts for different hydraulic heads are shown in Figure 2. It was observed that the hydraulic head classified as regular in terms of uniformity (10 and 11 kPa), presented points outside the control limits, indicating points outside of the statistical control process, whereas the 12 and 15 kPa hydraulic heads, whose uniformity was classified as good, were under statistical control, with no trend or no point was outside the control limits. In the study by Andrade *et al.* (2017b), although most processes were simple, they were classified as controlled by the Shewhart control chart and considered significant for the evaluation of irrigation.

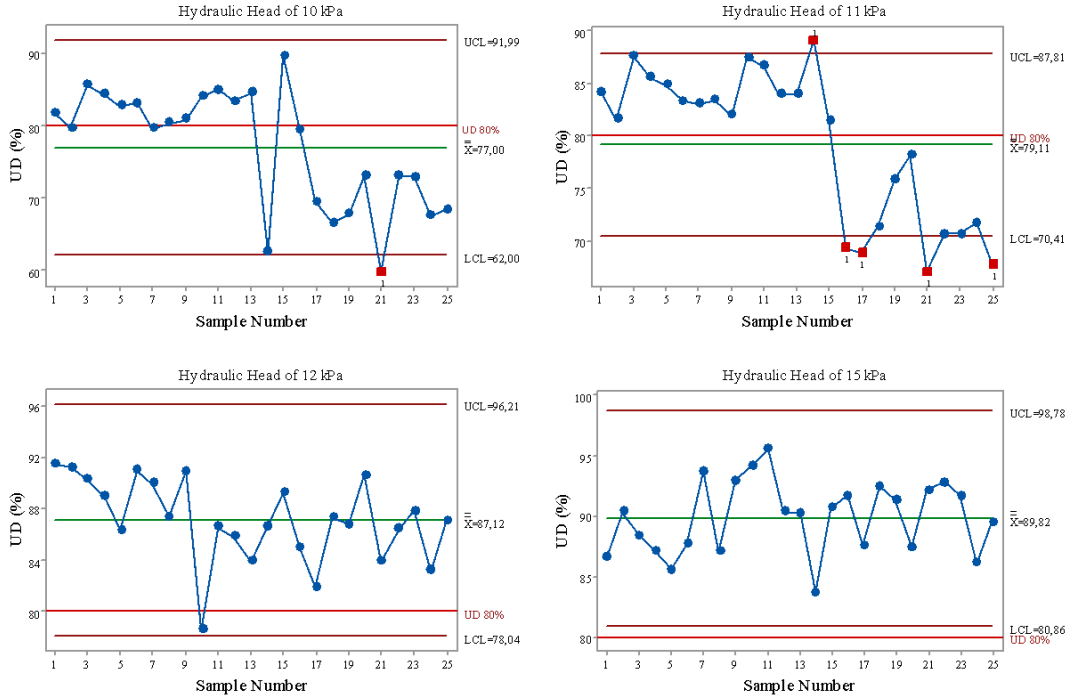

Figure 2. Shewhart's control charts for drip irrigation with different hydraulic heads.

The 10 kPa hydraulic head presented an isolated point outside the control lines, which can be caused by factors such as low pressure (Saraiva *et al.*, 2014), clogging of drippers, energy fluctuations, pressure variations, and climatic factors (Justi and Saizaki, 2016). During the first tests to 10 and 11 kPa, the process was under control (1st to 13th tests). Over time, there was a decrease in the quality of process that is attributed to non-controllable factors such as the clogging of emitters, temperature and pressure (Chinchilla *et al.*, 2018).

By analyzing the EWMA control chart for the UD variable (Figure 3), it is evident that the drip irrigation process is out of statistical control, because in addition to presenting points outside the UCL and LCL (10 and 11 kPa), descending sequences also decreased from the 13th test (10 and 11 kPa) until the end, characterizing a decrease in the uniformity of the system. Sequences of six points in the descending order characterize an out of statistical control process (Montgomery, 2016). The EWMA control chart is the most suitable for micro irrigation assessment, as it detects minor variations in the process (Siqueira *et al.*, 2018).

The 12 and 15 kPa did not present points outside the control limits. With the increase in the hydraulic head, system pressure, and water speed, the clogging of drippers decreased, and the system uniformity increased (Silva *et al.*, 2017). Consequently, eight consecutive sequences were obtained on the same side of the central line, characterizing the process as out of statistical control (Montgomery, 2016).

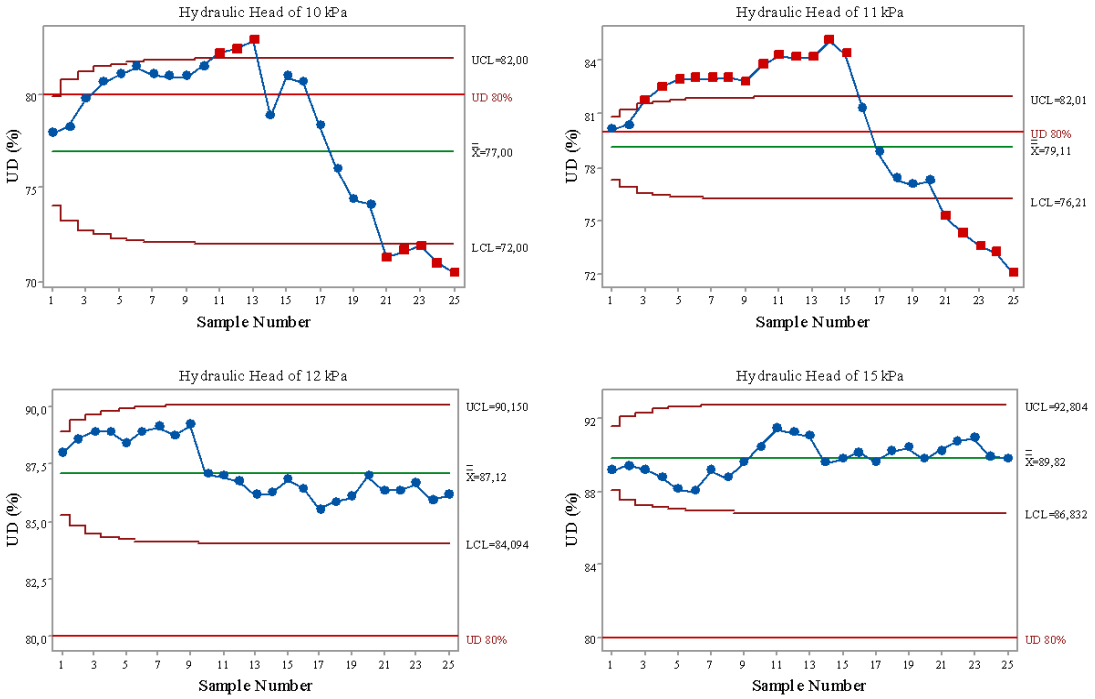

Figure 3. EWMA control charts for drip irrigation with different hydraulic heads.

4. CONCLUSIONS

The increase in hydraulic head increased the uniformity of the drip irrigation system. The use of 12 and 15 kPa hydraulic heads demonstrated good performance, with uniformities exceeding 80%, whereas the 10 and 11 kPa hydraulic heads demonstrated regular performance.

The use of control charts was effective in monitoring the system uniformity of drip irrigation based on different hydraulic heads. The Shewhart control chart was more robust, whereas the EWMA control chart, which indicated trends and deviations not shown by the Shewhart control chart, was more sensitive.

In sum, it is recommended that the drip irrigation system by gravity be used, with hydraulic heads greater than 12 kPa.

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