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Development and calibration of a rainfall simulator for hydrological studies

Desenvolvimento e calibração de um simulador de chuvas para estudos hidrológicos

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ABSTRACT

Rainfall Simulators (RS) have been used as tools for researches involving the estimation of runoff and infiltration on permeable pavements as well as in evaluating storm build-up and wash-off processes on pavements and roofs. Data obtained with the use of RS allows building a database with parameters which are useful in the implementation of BMPs taking local environment conditions into consideration. The purpose of this study was to develop and calibrate a handy and low-cost RS for hydrological researches. The developed RS can reproduce rainfall with intensities from 40 mm h^{-1} to 182 mm h^{-1}. The RS is able to simulate rainfall events with drops of median diameter (D_{50}) of 2.12 mm and kinetic energy of 22.53 J $mm^{-1}m^{-2}$, which represent 90.12% of the kinetic energy produced by a natural rainfall. Spatial distribution of simulated rainfall, which is expressed by the Christiansen's Uniformity Coefficient, was considered satisfactory with a value of up to 87.80%. The developed RS can be used as an alternative for the acquisition of hydrological data in a reduced period of time, under standardized experimental conditions and independently of natural rainfall events. The RS is also capable to simulate rainfall events with varying intensity.

Keywords: Simulated rainfall; Infiltration; Rural and urban drainage.

RESUMO

Simuladores de Chuva (SC) têm sido utilizados como ferramentas em pesquisas com pavimentos permeáveis, na estimativa de escoamento e infiltração, bem como na avaliação de processos de acumulação e carreamento de poluentes em pavimentos e telhados. Os dados obtidos com o uso dos SC permitem a criação de um banco de dados com valores de parâmetros para implantação de melhores práticas de gerenciamento em recursos hídricos, considerando as condições ambientais de cada região. Sendo assim, o objetivo deste trabalho foi desenvolver e calibrar um SC prático e de baixo custo para pesquisas hidrológicas. O SC desenvolvido é capaz de simular eventos de chuva de intensidades entre 40 mm h^{-1} e 182 mm h^{-1}, com gotas de diâmetro mediano (D_{50}) de 2,12 mm e energia cinética de 22,53 J $mm^{-1}m^{-2}$, que representa 90,12% da energia cinética produzida por chuva natural. A distribuição espacial da chuva simulada, expressa pelo Coeficiente de Uniformidade de Chistiansen, foi considerada satisfatório com valores de até 87,80%. O SC desenvolvido pode ser utilizado como alternativa para a obtenção de dados hidrológicos em espaço de tempo reduzido, com condições experimentais padronizadas e sem dependência de eventos de chuvas naturais. O SC ainda é capaz de simular eventos de chuva com intensidade variável.

Palavras-chave: Chuva simulada; Infiltração; Drenagem urbana e rural.

INTRODUCTION

Rainfall simulators (RS) are equipment used to create rain events with specific pre-established characteristics. Its use allows greater experimental control over variable properties that govern natural rainfall events, such as intensity and duration of the event, drop size, kinetic energy and rainfall spatial distribution.

RSs have many advantages, such as the ability to reproduce rainfall events with similar characteristics, possibility of raindrop diameter variation, kinetic energy, rainfall duration time and intensity.

Renard (1985) presents some limitations of RS use, being: (a) the area plots used in the experiments are usually small, ranging from a fraction of square meter to hundreds of square meters, depending on the simulator, and small areas cannot be representative of the researched area; (b) most RSs do not produce raindrop size distribution that represent drop size of natural events; (c) several RSs do not simulate events with rainfall intensity with the temporal variation of natural rainfall, and (d) some RSs do not produce raindrops that reach the terminal velocity of natural raindrops. Low velocity combined with small drops result in lower kinetic energy than the one produced by natural rains. In RS this energy can be only 40.0 or 50.0% of the natural rainfall. However, there are RSs that works at high pressure, which can reach the kinetic energy of natural rainfall.

RSs are an important tool in agricultural researches (MONTEBELLER et al., 2001; ALVES SOBRINHO et al., 2008; ABUDI et al., 2012), infiltration studies (SHAO; BAUMGARTL, 2014; RAHARDJO et al., 2016), soil loss and erosion (SKZ, 2011; ZHANG et al., 2014; SADEGHI et al., 2015) and geotechnical studies, especially soil slides and slope stability (EGELI; PULAT, 2011; CECCONI et al., 2014; MONTRASIO et al., 2016).

Depending on the type of automation added to RS, these can be low-cost tools that eliminate reliance on natural rainfall in researches (HERNGREN et al., 2005). The use of RS in urban hydrology is relatively recent. Tucci et al. (2000), Silva (2006) and Castro (2011), for example, used RS in experiments with permeable pavements, while Egodawatta (2007), Egodawatta et al. (2007, 2009) and Miguntanna (2009) used an RS, developed by Herngren (2005), in researches on the accumulation and transport of pollutants in pavements and roofs, as well as in rainwater quality researches.

Thus, the objectives of this research were: (a) to design and construct a RS for studies of urban hydrology that seeks to overcome some limitations of other RSs already developed; (b) to evaluate the rainfall produced in terms of drop size, fall time, terminal velocity, kinetic energy and spatial distribution of simulated rainfall, and (c) determine the effect of simulation time and rainfall intensity in the spatial distribution of simulated rainfall.

RAINFALL SIMULATOR PROJECT

The developed rainfall simulator (RS) was designed to meet the following requirements: (a) portability, easy assembly and operation; (b) produce drop size distribution, terminal velocity and kinetic energy similar to natural rainfall; (c) capacity to reproduce rains with a range of a varying intensities and (d) capacity to produce rainfall with uniform distribution over the experimental area.

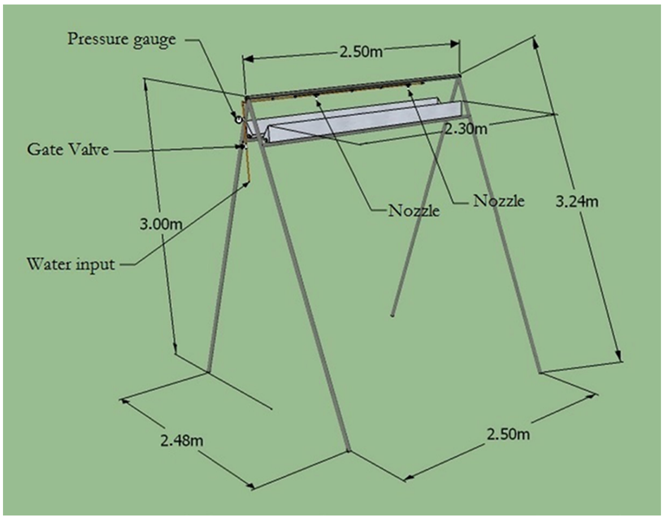


Figure 1. Rainfall simulator schematic design.

The developed RS (Figure 1) consists of an "A" shaped metal structure, iron tube of 38 mm in diameter and total height of 3.0 m. In order to produce rainfall (simulated precipitation), two sprinkler nozzles model Fulljet 1/2 SS HH 40 of Spraying Systems®, spaced 1.06 m apart, were installed in PVC pipe of 12.7 mm at 2.80 m high. This type of sprinkler produces a full cone-shaped sprinkler pattern with uniform distribution of water over the area for a wide range of flow rates and pressure. Water is pumped to the sprinklers by a centrifugal pump with a nominal flow rate of 6.8 $m^3 h^{-1}$, with water supply from a 200 L reservoir. The reservoir, centrifugal pump and PVC pipe are connected by a flexible hose with a diameter of 38 mm. In order to control the inlet flow rate and to check the pressure in the PVC pipe, a ½" gate valve and a 62 mm pressure gauge were connected to this pipe, with a maximum pressure of 70 m.c.a.

To produce varying rainfall intensities, two solenoid valves were installed in the sprinkler nozzles (Figure 2a). The solenoid valves are open when energized by 220 V electrical current. The flow of electric current is controlled by Arduino Duemilenove (Figure 2b), a free-board platform-based controller designed with single-board micro controller (Atmega 328), with support built-in input/output and standard programming language, originating from wiring, that is essentially C/C^{++}. Rain events of variable intensity during the simulation are possible by programming the Arduino to drive the solenoid valves according to the desired precipitation pattern.

The RS has two gutters, 2.30 m long, located below the sprinkler nozzles to capture the excess water, returning it to the reservoir. The equipment produces rain on an area of 3.0 m^2 (1.5 × 2.0 m). The RS was developed and calibrated following the recommendations prescribed by ASTM (2015) and can also be easily disassembled and transported to the field.

RAINFALL SIMULATOR CALIBRATION AND SIMULATED RAIN EVALUATION

All calibration procedures were performed so that simulated rain reproduced more realistically the characteristics of natural rain, respect to drop median diameter (2.0-2.5 mm), spatial distribution of rainfall (CUC above 70.0%) and kinetic energy (25.0 $J m^{-2} mm^{-1}$), in order to meet the recommendations of ASTM (2015).

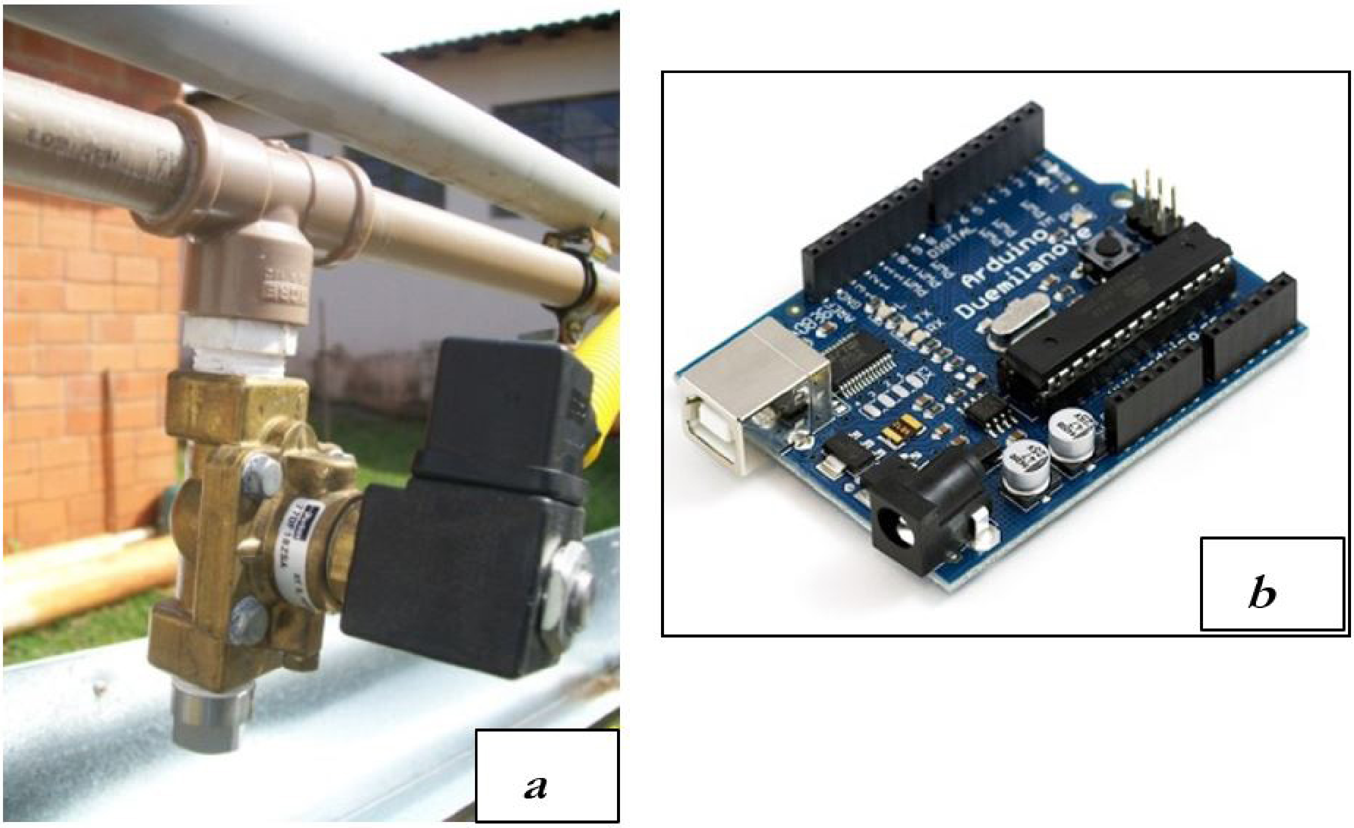


Figure 2. (a) Detail of the sprinkler and solenoid valve; (b) Arduino Duemilenove.

Calibration of real intensity and average intensity of simulated rainfall

For the calibration of simulated real intensity, defined as the intensity that effectively precipitated under the area of 3.0 m^2, the volumetric method of flow measurement was used. As volume control, two zinc-plated sheet collector boxes with dimensions of 1.0 × 1.5 × 0.08 m were used, placed side by side, under RS, 3 m^2 in total. Collector boxes were centralized (with reference to the nozzles) on the soil surface and collected the precipitated volume according to a specific pressure. Precipitated water volume was directed to a PVC pipe of 200 mm diameter, buried vertically in the soil. A water level data logger was used to measure the water level inside this 200 mm tube and then calculate the volume collected. The simulated (precipitated) real intensity (*Ir*) was calculated using Equation 1:

$$I_r = \left(\frac{V}{St}\right)60 \tag{1}$$

where *Ir* is the real intensity of the simulated rainfall (mm h^{-1}), *V* is the collected volume (L), *S* is the collector box area (m^2) and *t* is the total simulation time (minutes).

Average intensity (*Im*) of the simulated rainfall was estimated as the arithmetic mean of the height precipitated in 63 collectors arranged in 7 × 9 mesh spaced 0.25 m in the 3 m^2 area.

The test was performed at pressures of 50, 80, 110, 140 and 170 kPa, with simulation duration of 3 minutes and three repetitions. The relationship between the operating pressure and the simulated rainfall real intensity was determined with the results obtained.

Evaluation of the spatial distribution uniformity of simulated rainfall

Using the same pressures and durations of the previous test, the spatial distribution of the simulated precipitation was evaluated, with an area of 3 m^2 (1.5 × 2.0 m), 63 collectors in a 7 × 9 mesh spaced 0.25 m. The Christiansen Uniformity Coefficient (CUC) was also calculated for 1.5 and 1.0 m^2 areas, eliminating the row of end collectors

CUC was adopted to quantify the rainfall distribution uniformity. According to Herngren (2005), this coefficient is defined by Equation 2:

$$\mathrm{CUC} = 100\left(1 - \frac{\sum_{i=1}^{n} |\mathrm{Xi} - \overline{\mathrm{X}}|}{\mathrm{n}\overline{\mathrm{X}}}\right) \tag{2}$$

where CUC is the Christiansen's Uniformity Coefficient (%), *Xi* is the depth (mm) or the mass of water precipitated in each collector (g), $\overline{X}$ is the mean depth (mm) or the mean water mass (g) precipitated in the collectors and *n* is the number of collecting container.

According to Montebeller et al. (2001) and Silva (2006), several researchers consider CUC values above 80.0% acceptable for distribution uniformity in RS. Miguntanna (2009), however, considers a CUC above 70.0% sufficient for a RS.

Evaluation of the drop diameter distribution and kinetic energy (KE_p) as a function of operating pressure

The raindrop diameter distribution (DSD) was measured using the flour method developed by Hudson (1964) and used in other studies (MONTEBELLER et al., 2001; HERNGREN, 2005; CARVALHO et al., 2012). For this, a 0.05 m^2 tray with uncompacted wheat flour was exposed to the simulated rain at the center of the simulator for 1 second. Then, the flour was dried for 24 hours at ambient temperature, and the formed granules were separated by a series of sieves (4.75 mm, 3.35 mm, 2.36 mm, 1.18 mm and 0.85 mm). These granules were then oven dried for 24 hours at a temperature of 105 °C and then weighed on an analytical balance. Thus the median diameter of the simulated rain drops (D_{50}) of each class was determined from the distribution curve of the accumulated volume of the drops as a function of the average diameter of the drops per sampled class.

This test was performed for operating pressures of 50, 80 and 110 kPa. The objective was to determine which pressure produces drops with D_{50} between 2.0 - 2.5 mm, which is similar to the median diameter of natural rains (MIGUNTANNA, 2009). After determining which pressure produced a desired D_{50}, the terminal velocity of the drops (BRODIE; ROSEWELL, 2007) and the simulated rainfall kinetic energy (PÉREZ-LATORRE et al., 2010) were calculated for the selected pressure.

The calculation of the velocity for each mean drop diameter per sampled class was performed by the fourth-order Runge-Kutta numerical method. In order to calculate the raindrop velocity as a function of soil height, the trapezoidal method for integration was used.

In this work was established as a goal that the kinetic energy produced by the simulated rainfall should be close to 25 J mm^{-1} m^{-2}. This value is representative of kinetic energy of natural rains with intensities above 40 mm h^{-1} (VAN DIJK et al., 2002), Figure 3.

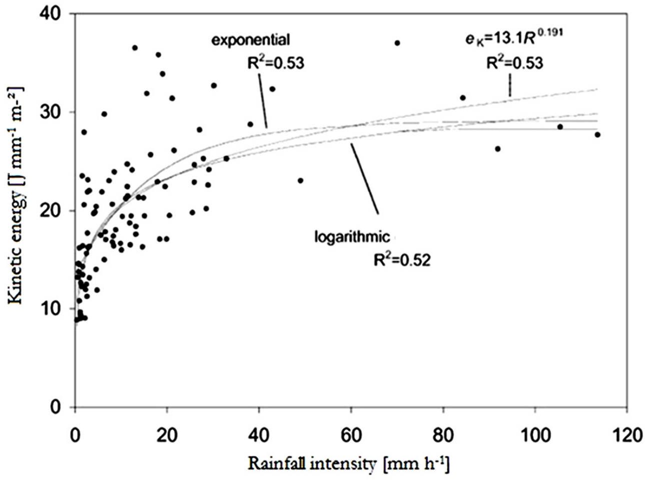


Figure 3. Kinetic energy curves as a function of rainfall intensity. Source: Adapted from Van Dijk et al. (2002).

Calibration of the real intensity produced with the solenoid valve operation

Considering that the maximum intensity produced by RS at the selected pressure (80 kPa) is approximately 180 mm h^{-1}, it was necessary to use some device that would interrupt the flow of water and reduce the volume precipitated when smaller intensities are desired. Several types of devices can perform this task, such as rotating shutters, gears that produce oscillations in the sprinkler axis, among others. The device selected for the RS were two solenoid valves, actuated by programmable controller.

The tests were performed for different opening and closing times of the solenoid valves and the real intensity produced during these operating times was verified. For this, a factorial experiment 2^K was performed, where k is equal to the number of factors, in this case equal to 2, opening time (*ta*) and closing time (*tf*), and two levels, 1 second and 5 seconds, with three repetitions and simulation duration of 5 minutes, for each round.

Multiple linear regression models (MRLM) and polynomial model (MP) were generated from the results of *ta* and *tf* of the solenoid valves, which correlate them with the simulated real intensity for significance range of 5.0%. The fit of the models to the data of the experiment was evaluated and then selected the one that presented better results of the test *F*.

With the objective of evaluating and validating the model developed for the reproduction of project rains, the opening and closing times of the solenoid valves were calculated to reproduce precipitation events with a time of return (*Tr*) between 1 and 10 years and durations of 10, 30 and 60 minutes, for the city of Goiânia, according to the rain equation (IDF) proposed by Costa and Prado (2003).

Evaluation of CUC as a function of simulated real intensity and simulation time

The spatial uniformity of the precipitation was evaluated using the Christiansen Uniformity Coefficient (CUC), for an area of 3.0 m^2. CUC was evaluated in five different simulated real intensities (*Ir*) (19.04, 33.48, 81.08, 151.47 and 164.91 mm h^{-1}), with duration of 3 minutes. In the evaluation of the CUC as a function of the simulation time (*ts*), the intensity of 96.74 mm h^{-1} was fixed for all simulations and duration in 3, 15 and 30 minutes. Each simulation was repeated three times.

The variance analysis (ANOVA) was used for each factor to evaluate the behavior of rainfall uniformity (CUC) as a function of simulated rainfall intensity (*Ir*) and simulation time (*ts*).

RESULTS AND DISCUSSIONS

The developed rainfall simulator (RS) (Figure 4) meets the initial design requirements proposed in the study, being portable, easy to assemble and operate.

Calibration of real and average intensity of simulated rainfall

The relation between the simulated real intensity (*Ir*) as a function of the operating pressure corresponds to a function of the potential type $y = a + bx^c$, (Figure 5).

A positive correlation between the operating pressure and simulated real intensity, as well as a reduction of the relative error between real and average intensities from 140 kPa is shown (Figure 6). With increasing pressure there is better distribution uniformity, causing the average intensity to approximate the real intensity. Also can be seen from Figure 6 real intensity is smaller than average intensity.

In some studies the authors calibrated their RS for the average intensity and did not refer to the precipitated real intensity (HERNGREN, 2005; SILVA, 2006; MIGUNTANNA, 2009). When observing the average intensity greater than the real one, as in this study, the authors could draw erroneous conclusions regarding the object of study, as for example, water infiltrated quantity in a type of pavement, since this one is calculated indirectly, due to precipitation. Theoretically, simulated real and averages intensities would be the same for the CUC of 100%, however, the uniformity coefficients presented in the studies cited above ranged from 70.0 to 80.0%.

Evaluation of the spatial distribution uniformity of simulated rainfall

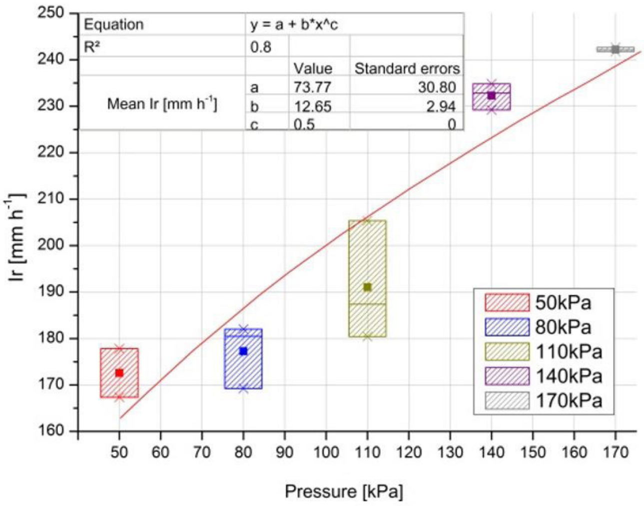
A CUC value above 70.0% is considered sufficient for a RS according to Miguntanna (2009). In this research the tests were conducted without wind protection. The tests were performed in conditions with little or no wind. Those tests where the wind action was perceptible were canceled and performed again.

Figure 7 shows the CUC varied between 52.0% and 87.0%, with lower dispersions obtained for pressures above 80 kPa and 1.0 m^2 area, between 81.0 and 87.0%.

Spohr et al. (2015) obtained CUCs from 80.0 to 82.0% for an area of 1.2 m^2 and 74.4% for an area of 2.24 m^2. For the same RS, CUCs of 85.0 and 70.0% were obtained, respectively, for simulation area of 3 m^2 and pressure of 40 kPa, in the studies of Egodawatta (2007) and Miguntanna (2009). However, the areas used for the disposal the collectors, here called effective areas, were 1.6 m^2 in Egodawatta (2007) and 3 m^2 in Miguntanna (2009). Thus, it is possible to conclude that Egodawatta (2007) overestimated the CUC value by considered the effective area (or sampling area) had the same uniformity of precipitation distribution as the 3 m^2 simulation area. This fact also explains why, under the same simulation conditions, Miguntanna (2009) obtained a lower CUC.

The relationship between the CUC and the effective area used for the disposal of collectors is inversely proportional. Thus, it is necessary to observe if the portion of the area to be used in the rain simulation in hydrological studies is compatible with the area used for the RS calibration. The spatial distribution of precipitation for pressures of 50, 80, 110, 140 and 170 kPa,

Figure 4. Developed rainfall simulator.



Equation	y = a + b*x^c		
R²	0.8		
		Value	Standard errors
Mean Ir [mm h⁻¹]	a	73.77	30.80
	b	12.65	2.94
	c	0.5	0

Figure 5. Relation between simulated rainfall real intensity and operating pressure.

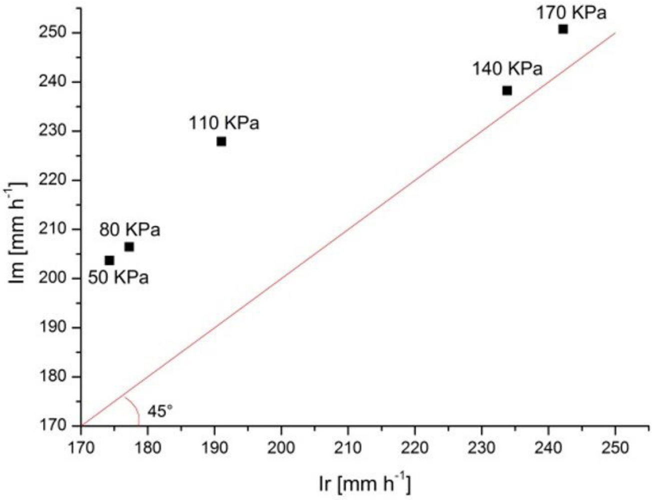


Figure 6. Relationship between the averages of *Ir* and *Im*.

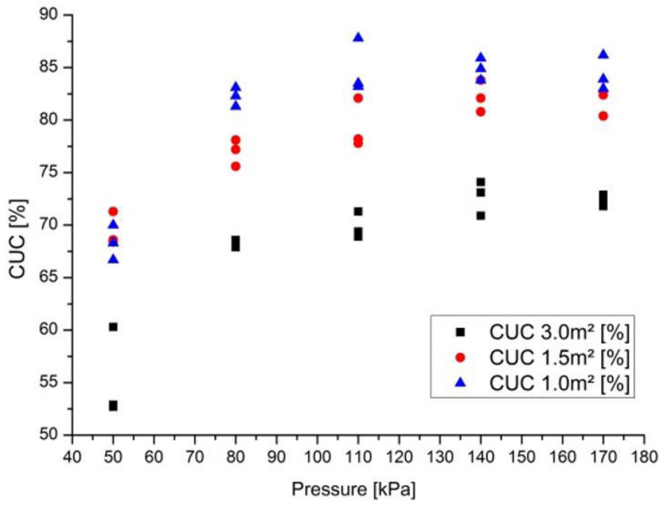


Figure 7. CUC as a function of operating pressure.

presents similar pattern (Figure 8), except for the pressure of 50 kPa, with lower CUC in the tests, of 55.3% for area of 3 m^2.

For the developed RS, there are no visible changes in simulated rainfall distribution patterns for operating pressures above 80 kPa, with CUCs ranging from 68.0 to 72.0%.

Evaluation of the drop diameter distribution and kinetic energy (KE_p) as a function of operating pressure

From the distribution of the number of drops per diameter class for each operating pressure (Figure 9), was verified that the size of produced drops is inversely proportional to the pressure. For the pressure of 110 kPa there is an increase in the number of drops with diameters smaller than 0.85 mm.

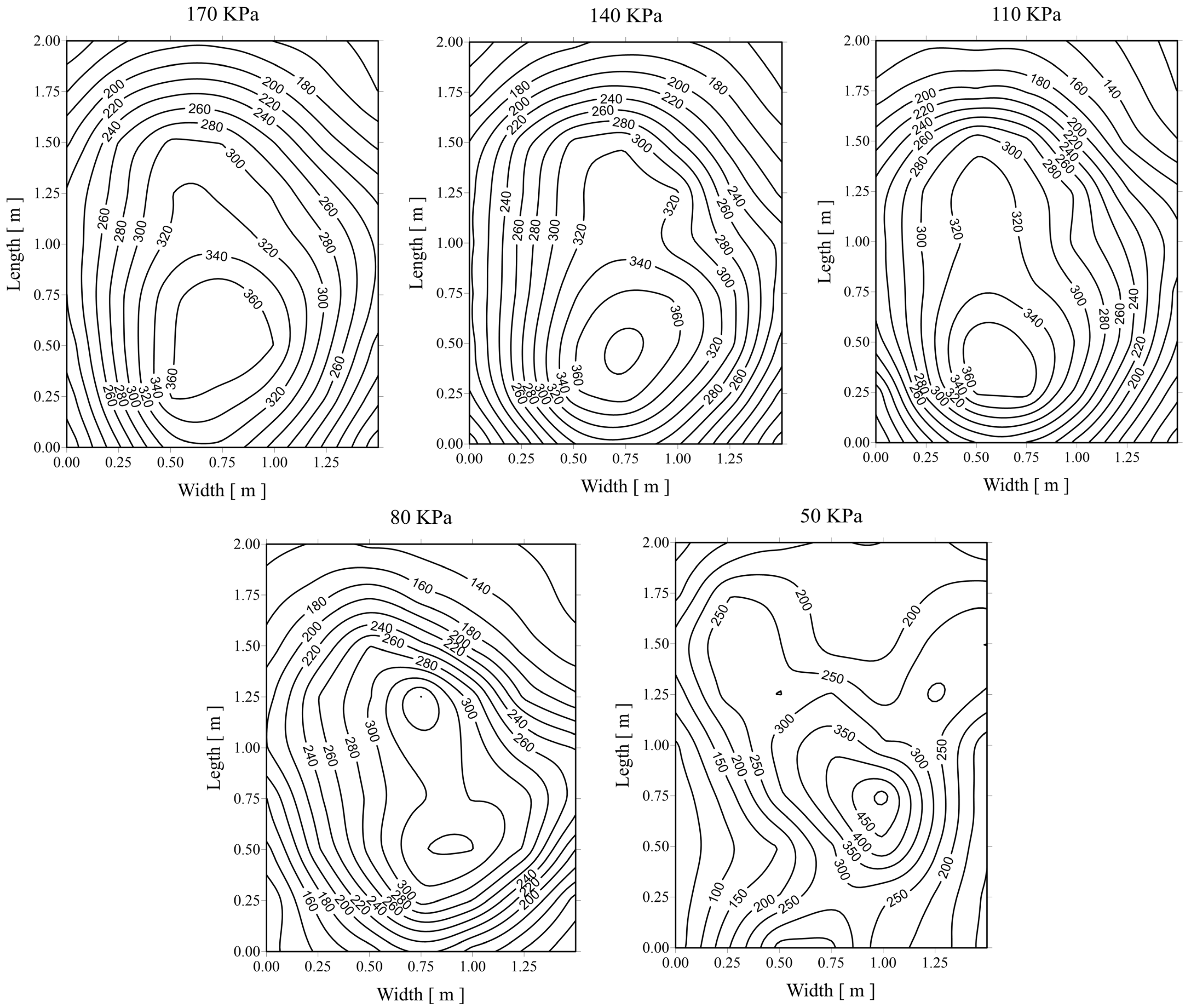


Figure 8. Spatial distribution patterns of simulated rain intensity (mm h^{-1}) for plot of 3 m^2 at pressures of 50, 80, 110, 140 and 170 kPa.

To determine the median volumetric diameter of the drops (D_{50}), defined as the diameter of which 50.0% of sampled drops have diameters above and below this, the graph of the average diameter of the drops per sampled class was plotted as a function of accumulated drop volume (Figure 10).

The operating pressure and the D_{50} of the formed drops are inversely proportional; the D_{50} values for the pressures of 50, 80 and 110 kPa are, respectively, 2.50 mm, 2.12 mm and 1.63 mm (Figure 10).

Evaluating the results of the CUCs and D_{50} of the drops as a function of pressure, the operating pressure to be used in the RS should be 80 kPa. With this pressure was able to produce drops with D_{50} within the ideal range of 2.0 to 2.5 mm (Figure 11), satisfactory CUCs (greater than 70.0%) and lower water consumption compared to higher pressures.

To estimate the drop velocity for each average diameter, the fourth-order Runge-Kutta numerical method was used (Figure 12).

During the tests, the drops of average diameters equal to 0.65, 0.96, 1.37 and 1.99 mm reached the ground at a velocity greater than their respective terminal velocities, that is, they left the sprinkler with an initial velocity greater than the terminal velocity itself (Figure 13). The drops of average diameters of 3.30, 4.18 and 4.75 mm respectively reached 95.79; 94.60 and 86.83% of the terminal velocity corresponding to each drop diameter.

The drop kinetic energy was expressed in terms of specific energy in the volume (*KEp*). The calculated *KEp* value was 22.53 J m^{-2} mm^{-1}, representing 90.12% of the kinetic energy produced by natural rainfall events (25 J m^{-2} mm^{-1}), with an intensity above 40 mm h^{-1} (VAN DIJK et al., 2002). The drops with diameters between 1.7 and 3.35 mm are responsible for the production of 60.0% of the total kinetic energy produced by simulated rainfall (Figure 14).

Calibration of simulated rainfall real intensity with solenoid valve operation

Can be seen from the results of the factorial experiment (2^k) presented in Table 1 that for opening and closing times in the interval of 1 and 5 seconds it is possible to simulate rainfall events within a wide range of intensities.

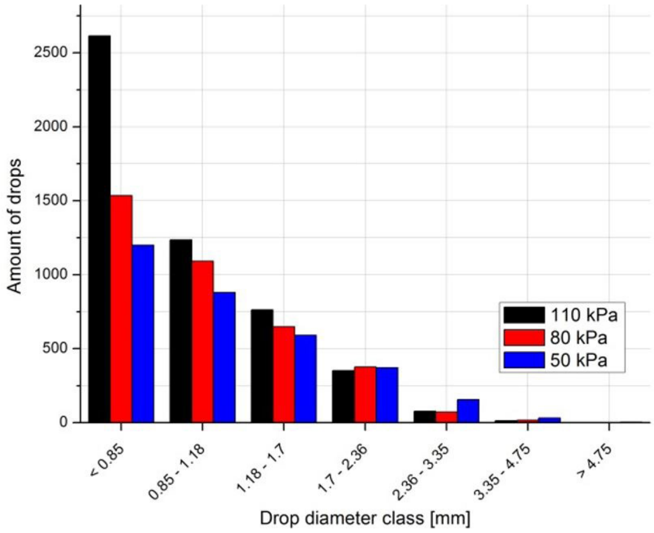


Figure 9. Distribution of the raindrops diameter (DSD).

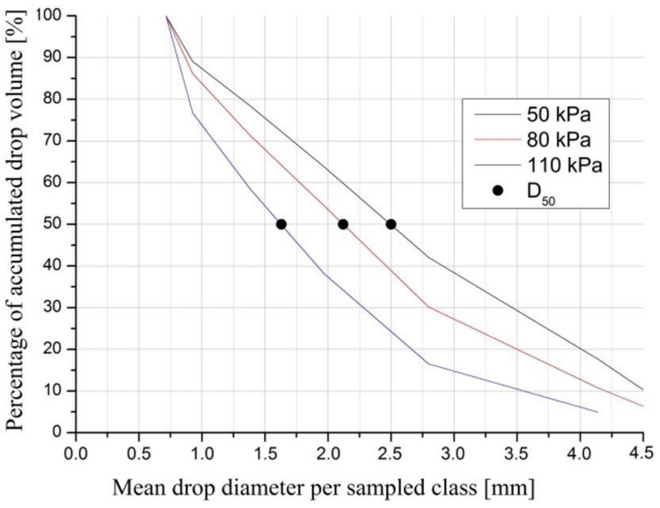


Figure 10. Cumulative rainfall diameter distribution (DSD).

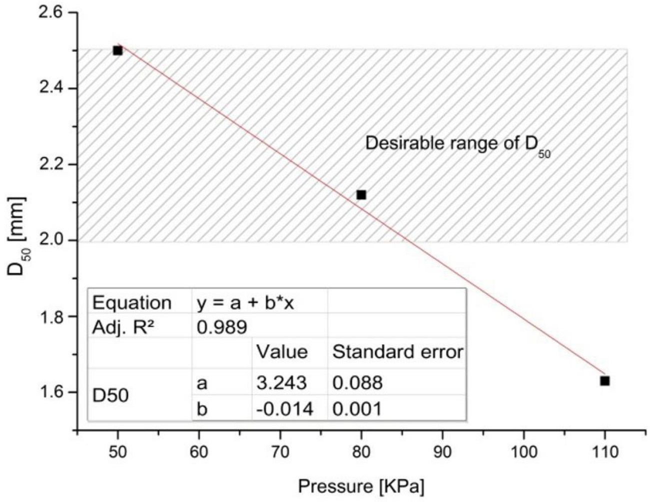


Figure 11. Operating pressure as function of D_{50}.

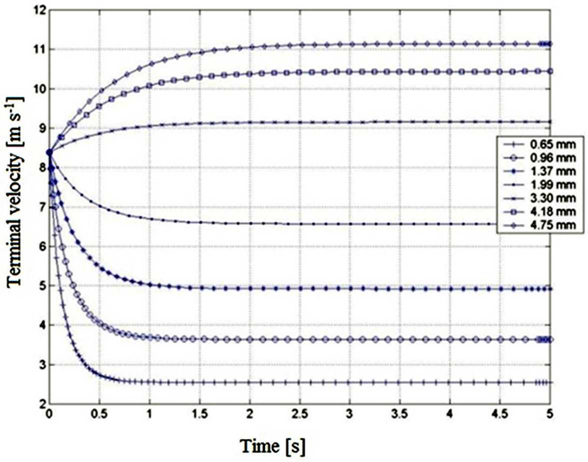


Figure 12. Drop velocity as a function of time (operating pressure 80 kPa).

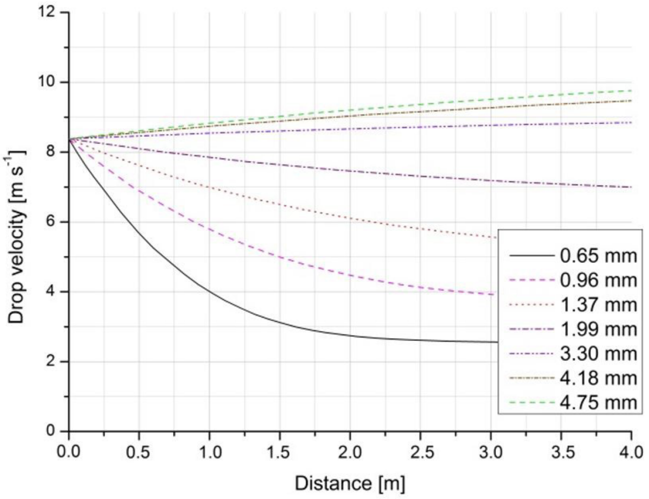


Figure 13. Drop velocity as a function of distance traveled (operating pressure 80 kPa).

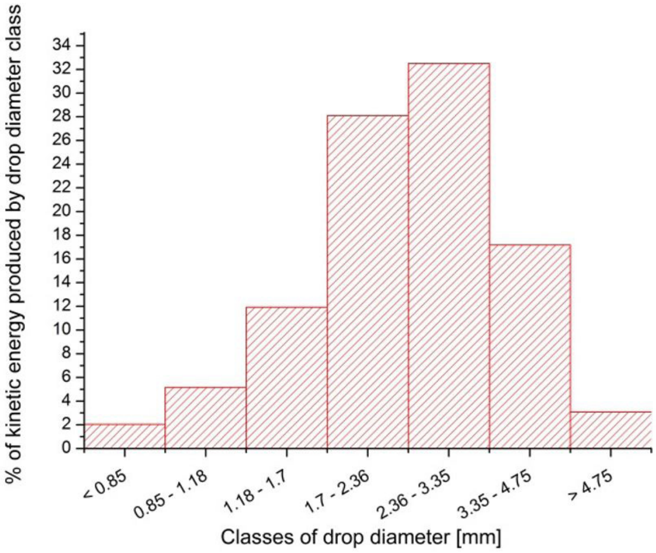


Figure 14. Percentage of kinetic energy produced by each class of drop diameter (operating pressure of 80 kPa).

The multiple linear regression model (MRLM) presented quadratic and relative errors superior to those of the polynomial model (MP) (Table 2).

Since the polynomial model (MP) presented smaller quadratic and relative errors, the results were fitted to this model (Figure 15).

After the calibration of the MP, the averages and variances of the *Ir* and *Ic* shows an approximation as well as a considerable reduction in the quadratic and relative error (Table 2).

The evolution of the result adjustment quality to the MP is evident (Figures 16 and 17).

The developed RS model is able to reproduce project rains of any region, since it respected its domain of application, being it:

- 40 mm h^{-1} $\leq$ *Ic* $\leq$ 182 mm h^{-1};
- 0.5 s $\leq$ *ta* $\leq$ 8.0 s;
- 0.5 s $\leq$ *tf* $\leq$ 8.0 s.

The shortest possible time for *tf* is suggested, thus ensuring a lower degree of intermittence of simulated rainfall, as Armstrong and Quinton (2009) also affirm.

As an example, the opening (*ta*) and closing times (*tf*) of the solenoid valves and respective intensity for the rainfall simulation with 1 $\leq$ *Tr* $\leq$ 10 years and 10 $\leq$ *d* $\leq$ 60 min are presented in Table 3.

CUC evaluation as a function of simulated real intensity and simulation time

In both ANOVA tests, the *p* value was greater than 0.05, which leads to conclude that CUC values are not different when the real rainfall intensity (*Ir*) or the simulation times (ts) are varied. No change in the rainfall distribution uniformity is shown when the *ts* or *Ir* is varied (Table 4).

The CUC ranged from 63.0% to 73.0% and did not correlate with the simulated intensity (Figure 18).

Although the CUC is not different as a function of the simulation time, it is possible to notice from Figure 19 that for the shortest simulation time (3 minutes) the uniformity variation was greater. A possible explanation for this behavior would be that for

Table 1. Results of the factorial experiment to calibrate the real intensity of simulated rainfall.

ta **[s]**	***tf*** **[s]**	***Ir*** **[mm h^{-1}]**	***Ir*** **min [mm h^{-1}]**	***Ir*** **max [mm h^{-1}]**	**Standard deviation**	***Ir*** **mean [mm h^{-1}]**
1	1	100.86	96.11	100.86	2.50	98.94
1	1	99.85				
1	1	96.11				
1	5	31.75	31.75	34.10	1.29	33.22
1	5	33.82				
1	5	34.10				
5	1	165.98	164.29	166.35	1.10	165.54
5	1	166.35				
5	1	16.29				
5	5	99.92	99.92	100.41	0.25	100.19
5	5	100.25				
5	5	100.41				

Where: *ta* and *tf* is the opening and closing time of the solenoid valve, respectively, and *Ir* is the actual simulated rainfall intensity.

Table 2. Test results *F* and quadratic and relative model calibration errors.

MRLM				
Ic [mm h^{-1}] = 98.5 + 16.7ta [s] – 16.4tf [s]				
MP				
Ic [mm h^{-1}] = 106.1046 + 22.5978ta – 32.1052tf – 1.4662ta^2 + 2.3096tf^2 + 0.4107$tatf$				
	MRLM		**MP**	
	Ic	***Ir***	***Ic***	***Ir***
Mean	95.31	104.48	95.31	95.11
Variance	2,767.41	3,860.77	2,767.41	2,772.05
Observations	11	11	11	11
Gl	10	10	10	10
F	0.72		1.00	
P(*F*<=*f*) flow	0.30		0.50	
F critical flow	0.34		0.34	
Quadratic error	**4,696.47**		**288.16**	
Relative error	**330.84**		**0.84**	

Where: *Ic* is the rain intensity calculated by the model; *Ir* is the simulated real rainfall intensity; *ta* and *tf* is the opening and closing time of the solenoid valve, respectively; *gl* is the degree of freedom; *F* corresponds to the test statistic and *P (F <= f)* is the descriptive level of the hypothesis test.

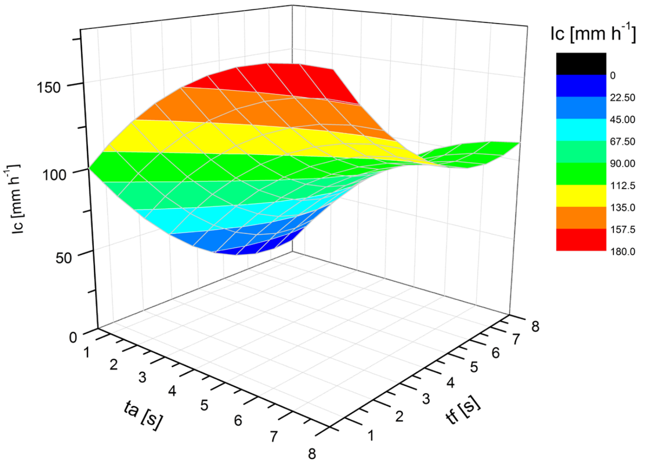


Figure 15. Surface of the polynomial model.

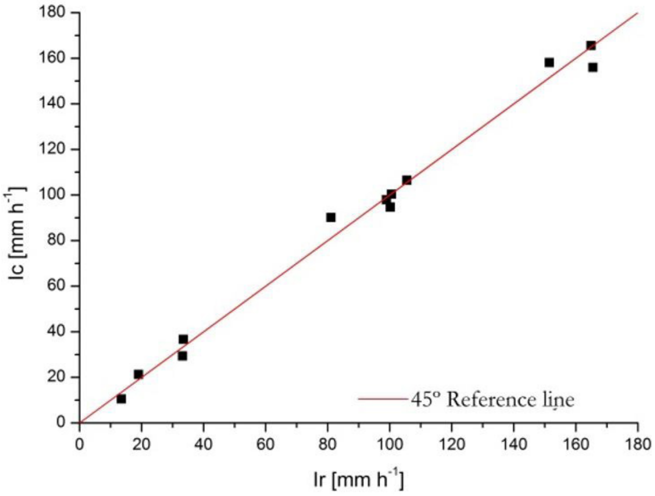


Figure 17. *Ir* versus *Ic* of MP.

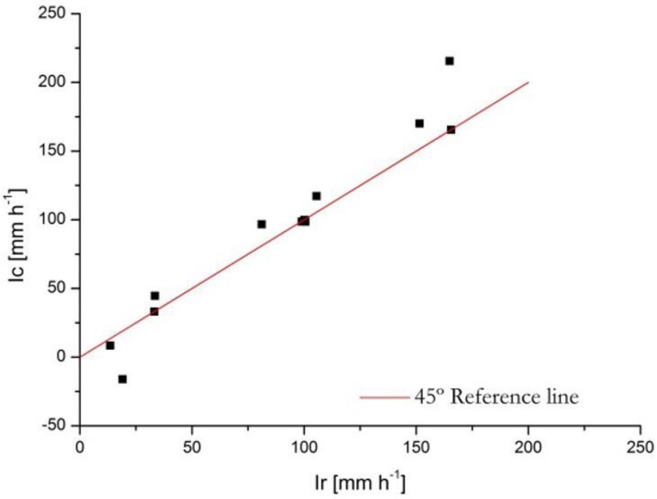


Figure 16. *Ir* versus *Ic* of MRLM.

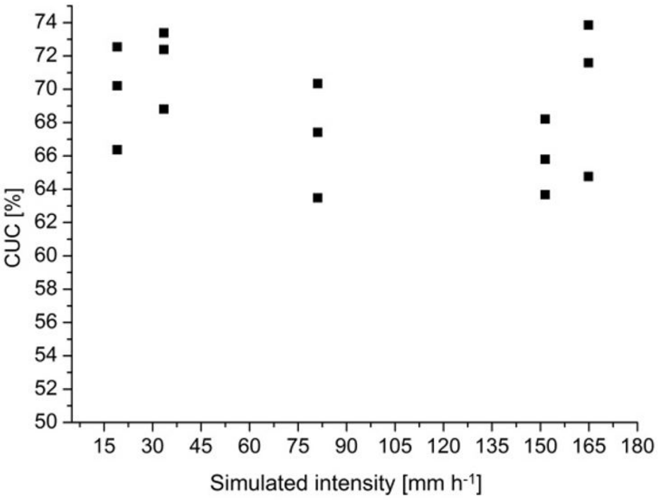


Figure 18. CUC distribution x real simulated rainfall intensity.

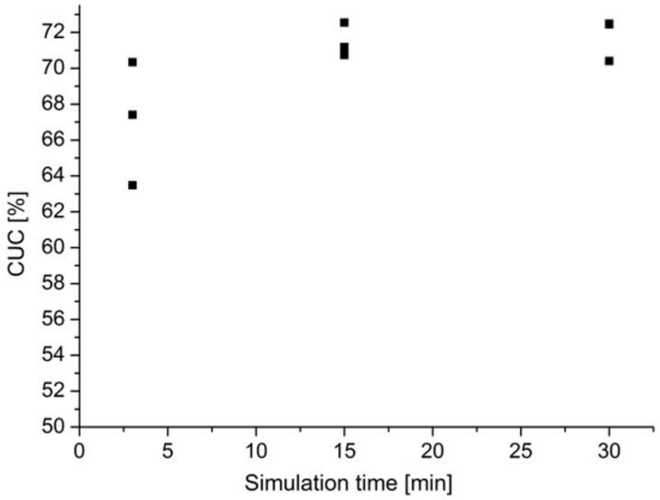


Figure 19. Distribution of CUC × simulation time (ts).

Table 3. Opening and closing times of solenoid valves to simulate rains with $1 \leq Tr \leq 10$ years and $10 \leq d \leq 60$ min.

Tr **[years]**	***d*** **[min]**	***Ic*** **[mm h^{-1}]**	***ta*** **[s]**	***tf*** **[s]**
1	10	107.11	0.76	0.50
5	10	150.6	3.35	0.50
10	10	170.18	5.28	0.50
1	30	68.81	0.50	1.73
5	30	96.74	0.50	0.67
10	30	109.32	0.87	0.50
1	60	44.96	0.50	2.84
5	60	63.21	0.50	1.97
10	60	71.43	0.52	1.64

Where: *Tr* is the return time; *d* is the rain duration; *Ic* is the rain intensity calculated by the model; *ta* and *tf* is the opening and closing time of the solenoid valve, respectively.

Table 4. ANOVA results for CUC as a function of *Ir* and *ts*.

ANOVA CUC x *Ir*					
Source of variation	***gl***	***SQ***	***MQ***	***F***	***P***
Factor	5	63.88	12.78	1.05	0.45
Error	9	109.86	12.21		
Total	14	173.74			
ANOVA CUC x *ts*					
Source of variation	***gl***	***SQ***	***MQ***	***F***	***P***
Factor	2	41.74	20.87	4.42	0.07
Error	6	28.30	4.72		
Total	8	70.05			

Where: *gl* is the degree of freedom; *SQ* is the sum of squares; *MQ* is the middle square; *F* corresponds to the test statistic and p is the probability for *F* tests (p-value).

short simulation times, the wind action may have greater influence on rainfall distribution uniformity. For example, a 30-second gust of wind would have a greater influence on 3-minute simulation than 30-minute simulation. Then, is suggested to be adopted in future researches, simulation times greater than 10 minutes.

CONCLUSIONS

The developed rainfall simulator (RS) meets the proposed project requirements. The RS can be used in hydrological studies as an alternative to obtain data in a reduced time period with standardized experimental conditions and without dependence on natural rainfall events. The use of Arduino also allows simulating rainfall events of variable intensity during the simulation, programming the operation of the solenoid valves according to the desired pattern.

This work allowed verifying methodological aspects not addressed by other researchers. Concluding that, for the RS calibration, the relation between the real intensity (*Ir*) and the average intensity (*Im*) should be considered, as well as the sampling area used to determinate CUC should have the same dimensions as the simulation area. Rainfall simulation duration should be at least 10 minutes, or the simulation area should be protected against wind action, as the drag of the drops can influence the CUC and, therefore, the experimental results.

This research contributes as conceptual and practical basis regarding the development of RS and the use of methods to evaluate the characteristics of the simulated rainfall.

REFERENCES

ABUDI, I.; CARMI, G.; BERLINER, P. Rainfall simulator for field runoff studies. *Journal of Hydrology*, v. 454-455, p. 76-81, 2012. http://dx.doi.org/10.1016/j.jhydrol.2012.05.056.

ALVES SOBRINHO, T.; GÓMEZ-MACPHERSON, H..; GÓMEZ, J. A. A portable integrated rainfall and overland flow simulator. *Soil Use and Management*, v. 24, n. 2, p. 163-170, 2008. http://dx.doi.org/10.1111/j.1475-2743.2008.00150.x.

ARMSTRONG, A.; QUINTON, J. N. Pumped rainfall simulators: the impact of rain pulses on sediment concentration and size. *Earth Surface Processes and Landforms*, v. 34, n. 9, p. 1310-1314, 2009. http://dx.doi.org/10.1002/esp.1810.

ASTM – AMERICAN SOCIETY FOR TESTING AND MATERIALS. *D6459-15: standard test method for determination of rolled erosion control product performance in protecting hill slopes form rainfall-induced erosion*. Philadelphia, 2015.

BRODIE, I.; ROSEWELL, C. Theoretical relationships between rainfall intensity and kinetic energy variants associated with stormwater particle washoff. *Journal of Hydrology*, v. 340, n. 1-2, p. 40-47, 2007. http://dx.doi.org/10.1016/j.jhydrol.2007.03.019.

CARVALHO, M. F.; TARQUI, J. L. Z.; SILVA, V. S.; LOBO, B. R. H. Avaliação do funcionamento de um simulador de chuva pelo método da farinha. *Revista Brasileira de Recursos Hídricos*, v. 17, n. 3, p. 115-124, 2012. http://dx.doi.org/10.21168/rbrh.v17n3.p115-124.

CASTRO, T. Q. *Avaliação do desempenho de pavimento permeáveis*. 2011. 91 f. Dissertação (Mestrado) - Escola de Engenharia Civil, Universidade Federal de Goiás, Goiânia, 2011.

CECCONI, M.; NAPOLI, P.; PANE, V. Effects of soil vegetation on shallow slope instability. *Environmental Geotechnics*, v. 2, n. EG3, p. 130-136, 2014. http://dx.doi.org/10.1680/envgeo.13.00110.

COSTA, A. R.; PRADO, L. A. Espacialização de chuvas intensas para o estado de Goiás e o sul de Tocantins. *Revista de Engenharia Agrícola*, v. 23, n. 2, p. 268-276, 2003.

EGELI, I.; PULAT, H. F. Mechanism and modelling of shallow soil slope stability during high intensity and short duration rainfall. *Scientia Iranica*, v. 18, n. 6, p. 1179-1187, 2011. http://dx.doi.org/10.1016/j.scient.2011.09.010.

EGODAWATTA, P. *Translation of small-plot scale pollutant build-up and wash-off measurements to urban catchment scale*. 2007. 304 f. Tese (Doutorado) - Faculty of Built Environment and Engineering, Queensland University of Technology, Australia, 2007.

EGODAWATTA, P.; THOMAS, E.; GOONETILLEKE, A. Mathematical interpretation of pollutant wash-off from urban road surfaces using simulated rainfall. *Water Research*, v. 41, n. 13, p. 3025-3031, 2007. PMid:17521694. http://dx.doi.org/10.1016/j.watres.2007.03.037.

EGODAWATTA, P.; THOMAS, E.; GOONETILLEKE, A. Understanding the physical processes of pollutant build-up and wash-off on roofs surfaces. *The Science of the Total Environment*, v. 407, n. 6, p. 1834-1841, 2009. PMid:19157516. http://dx.doi.org/10.1016/j.scitotenv.2008.12.027.

HERNGREN, L. *Build-up and wash-off process kinetics of PAHs and heavy metals on paved surfaces using simulated rainfall*. 2005. Tese (Doutorado) - Faculty of Built Environment and Engineering, Queensland University of Technology, Australia, 2005.

HERNGREN, L.; GOONETILLEKE, A.; SUKPUM, R.; SILVA, D. Y. Rainfall simulation as a tool for urban water quality research. *Environmental Engineering Science*, v. 22, n. 3, p. 378-383, 2005. http://dx.doi.org/10.1089/ees.2005.22.378.

HUDSON, N. W. *The flour pellet method for measuring the size of raindrops*. Salisbury: Department of Conservation and Extension, 1964. (Research Bulletin, 4).

MIGUNTANNA, N. S. *Determining a set of surrogate parameters to evaluate urban stormwater quality*. 2009. 311 f. Dissertação (Mestrado) - Faculty of Built Environment and Engineering, Queensland University of Technology, Australia, 2009.

MONTEBELLER, C. A.; CARVALHO, D. F.; ALVES SOBRINHO, T..; NUNES, A. C. S.; RUBIO, E. Avaliação de um simulador de chuvas pendular. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 5, n. 1, p. 1-5, 2001. http://dx.doi.org/10.1590/S1415-43662001000100001.

MONTRASIO, L.; SCHILIRÒ, L.; TERRONE, A. Physical and numerical modelling of shallow landslides. *Landslides*, v. 13, n. 5, p. 873-883, 2016. http://dx.doi.org/10.1007/s10346-015-0642-x.

PÉREZ-LATORRE, F. J.; DE CASTRO, L.; DELGADO, A. A comparison of two variable intensity rainfall simulators for runoff studies. *Soil & Tillage Research*, v. 107, n. 1, p. 11-16, 2010. http://dx.doi.org/10.1016/j.still.2009.12.009.

RAHARDJO, H.; KRISNANTO, S.; LEONG, E. C. Effectiveness of capillary barrier and vegetative slope covers in maintaining soil suction. *Soils and Rocks*, v. 39, n. 1, p. 51-69, 2016.

RENARD, K. G. Rainfall simulators and USDA erosion research: history, perspective and future. In: RAINFALL SIMULATOR WORKSHOP, 1984, Tucson, Arisona. *Proceedings…* Tucson: Society for Range Management, 1985. Available from: <http://www.tucson.ars.ag.gov/unit/publications/PDFfiles/724.pdf>. Access on: 23 jan. 2016.

SADEGHI, S. H. R.; GHOLAMI, L.; SHARIFI, E.; KHALEDI DARVISHAN, A.; HOMAEE, M. Scale effect on runoff and soil loss control using rice straw mulch under laboratory conditions. *Solid Earth*, v. 6, n. 1, p. 1-8, 2015. http://dx.doi.org/10.5194/se-6-1-2015.

SHAO, Q.; BAUMGARTL, T. Estimating input parameters for four infiltration models from basic soil, vegetation, and rainfall properties. *Soil Science Society of America Journal*, v. 78, n. 5, p. 1507-1521, 2014. http://dx.doi.org/10.2136/sssaj2014.04.0122.

SILVA, G. B. L. *Avaliação experimental sobre a eficiência de superfícies permeáveis com vistas ao controle do escoamento superficial em áreas urbanas*. 2006. 180 f. Tese (Doutorado) - Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, 2006.

SKZ – DAS KUNSTSTOFF-ZENTRUM. *Erarbeitung und verifizierung von auswahlkriterien für geosynthetische erosionsschutzsysteme*. Würzburg: Fördergemeinschaft für das Süddeutsche Kunststoff-Zentrum, 2011. 160 p. Schlussbericht des AiF-Projektes Nr. 15717. In German.

SPOHR, R. B.; CORCINI, A. L. M.; PELLEGRIN, J.; BONFANTI, J. B.; SOTO, M. F. D.; CARDOSO, T. Desenvolvimento e validação de um simulador de chuvas portátil. *Revista Brasileira de Recursos Hídricos*, v. 20, n. 2, p. 411-417, 2015. http://dx.doi.org/10.21168/rbrh.v20n2.p411-417.

TUCCI, C.; GOLDENFUM, J.; ARAUJO, P. Avaliação da eficiência dos pavimentos permeáveis na redução de escoamento superficial. *Revista Brasileira de Recursos Hídricos*, v. 5, n. 3, p. 21-29, 2000. http://dx.doi.org/10.21168/rbrh.v5n3.p21-29.

VAN DIJK, A. I. J. M.; BRUIJNZEEL, L. A.; ROSEWELL, C. J. Rainfall intensity-kinetic energy relationships: a critical literature appraisal. *Journal of Hydrology*, v. 261, n. 1-4, p. 1-23, 2002. http://dx.doi.org/10.1016/S0022-1694(02)00020-3.

ZHANG, X.; YU, G. Q.; LI, Z. B.; LI, P. Experimental study on slope runoff, erosion and sediment under different vegetation types. *Water Resources Management*, v. 28, n. 9, p. 2415-2433, 2014. http://dx.doi.org/10.1007/s11269-014-0603-5.

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Silvio Fagundes de Sousa Júnior: First author who contributed with the proposal and simulation design, discussion of results, as well as writing and formatting of the article.

Thiago Augusto Mendes: Corresponding author who contributed with the literature review, obtaining database, discussion of the results, formatting and revision of the article.

Eduardo Queija de Siqueira: Guided all the research and contributed obtaining the database, improving the proposal and reviewing the article.