# Hydraulic system to ensure constant rainfall intensity (over time) when using nozzle rainfall simulators

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## ABSTRACT

Rainfall simulation is widely used in the laboratory and in field work to produce artificial rainfall for small-scale surface hydrology and soil erosion studies. Simulated rainfall produced by simulators must be predictable, accurate and consistent to be useful to model the related physical processes. Pressure fluctuations in the water supply system frequently cause variation in rainfall intensity during simulated events. This study describes a hydraulic system that is attached to the outlet (nozzle) of a rainfall simulator to ensure constant pressure and discharge, which consequently facilitates constant rainfall intensity at ground level, throughout the rainfall event, especially in the controlled environment of the laboratory. Fifty rainfall events were simulated (five different pressure levels at the water intake). More than 750 pressure measurements were collected for each rainfall event at the water intake and at the nozzle, adding a total of more than 75,000 pressure measurements. Standard deviation of pressure measured at the water intake was always higher than at the nozzle (ranging from 1.978 to 4.199 times higher). The results show that with this hydraulic system rainfall simulators can operate with constant (rainfall) intensity throughout the entire simulation or sequence of events, even if the water supply pressure fluctuates.

**Key words** | artificial rainfall, nozzles, pressure fluctuations, rainfall intensity, surface hydrology

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## INTRODUCTION

Rainfall simulators are used to generate artificial rainfall under controlled conditions, and are particularly useful in surface hydrology and soil erosion studies, both in the laboratory (e.g., de Lima *et al.* 2003, 2005; Deng *et al.* 2008; Montenegro *et al.* 2013; Arguelles *et al.* 2013; Isidoro & de Lima 2014) and in the field (e.g., Jin *et al.* 2008; Iserloh *et al.* 2013a, b; Ries *et al.* 2014). A rainfall simulator is required to produce an accurate reproduction of the physical features of natural rainfall; however, some tolerance has to be allowed in the interests of simplicity and cost (e.g., Hudson 1993). Thus, although permitting a controllable, reliable and predictable simulation of rainfall events, rainfall simulators cannot replicate precisely the unpredictable variability of natural rainfall. Meyer (1988), often cited, states that: 'The goal of rainfall simulator research should be the collection of accurate, useful data, not a perfect rainfall simulator.' Even though rainfall simulators cannot perfectly replicate natural rainfall, they are still the best means to study overland flow generation (Reaney 2003), as a helpful tool to study the rainfall–runoff process on a small scale.

Artificial rainfall can be generated through two types of simulator: pressurized spraying nozzles and non-pressurized drop-formers. The former use gravity (less common) or pumping (more common) to attain the required head at the nozzle while, in the latter, raindrops are formed either from a set of short pipes or needles connected to a tank or directly from holes in the base of the tank. In this study, we are only looking at pressurized spraying nozzles. In these systems, a constant discharge and pressure at the nozzle of the rainfall simulator generates the rainfall cells which, as in nature, do not have a uniform spatial distribution and normally show higher rainfall intensity areas encircled by lower intensity ones (e.g., Willems 2001).

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The main advantage of rainfall simulation is that the spatial and temporal distribution of certain rainfall patterns can be accurately reproduced as desired. However, pressure fluctuations in the rainfall simulator supply system can lead to significant changes in the physical characteristics of rainfall (e.g., rainfall intensity, drop size, drop velocity) (e.g., Hudson 1993; Humphry *et al.* 2002; Dunkerley 2008; Carvalho *et al.* 2014), which compromises this advantage. Improvement of rainfall simulators will result in models that are more consistent and useful, or a better visualization and understanding of the physical processes.

This study aims to present a cost-effective hydraulic system that is attached just in front of the (pressurized) spraying nozzle of a rainfall simulator to eliminate pressure fluctuations, even if the water supply pressure changes over time. With this system it is possible to get a stabilized pressure at the nozzle over time, which guarantees a more stable rainfall intensity over time (independently of the simulated rainfall intensity). This is a common concern with laboratory and field rainfall simulators, namely, when flexible hoses are used. Thus, the use of this system can improve the quality of data obtained by experimental rainfall simulation. This hydraulic system, developed at the Laboratory of Hydraulics, Water Resources and Environment of the Department of Civil Engineering of the University of Coimbra, has been used successfully in many laboratory studies in the last five years, namely, de Lima *et al.* (2009, 2011, 2013), Isidoro *et al.* (2012, 2013), Isidoro & de Lima (2013, 2014) and Montenegro *et al.* (2013).

The system's ability to control the rainfall intensity is demonstrated by carrying out a set of laboratory simulations monitored by pressure transducers. The results show that, with this hydraulic system, rainfall simulators can operate at constant pressure, and therefore provide constant (rainfall) intensity for the entire simulation. This is particularly relevant at the early and final stages of the simulated rainfall events where the use of flexible hoses, respectively, cause an initial pressure burst and the adjustment to the static pressure. The initial pressure burst leads to higher rainfall intensity after the start of a wet-cycle. The adjustment to the static pressure leads to dripping of water from the nozzle after the start of a dry-cycle.

## MATERIALS AND METHODS

### Hydraulic system

The hydraulic system used to ensure a constant pressure at the nozzle was equipped with pressure transducers (just in front of the constant pressure system and at the water inlet to the nozzle) to test its performance (Figure 1). It is composed of:

- a small-mesh stainless steel filter (F) placed at the intake of the water supply, to retain any small particles carried by the flow;
- a pressure reduction valve (PRV) placed after the filter, to limit the maximum pressure in the system (Caleffi);
- a relief valve (RV) placed in front of the return hose, to limit the minimum pressure in the system (Giacomini);
- an electric retention valve (ERV) for the remote operation of the nozzle (start and stop rainfall) (Asco);
- a T-junction (T1) to split the water flow to the ERV and relief valve (RV);
- a T-junction (T2) to allow the attachment of a pressure gauge (PG);

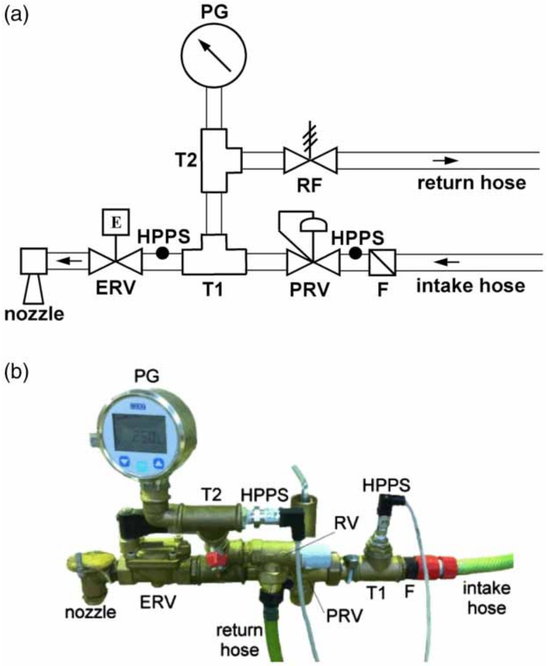

**Figure 1** | Operating scheme (a) and photograph (b) of the constant pressure hydraulic system. This system consists of: intake and return hoses, small-mesh filter (F), PRV, RV, ERV, T1 and T2, PG and outlet (nozzle). It is also possible to visualize the two high-precision pressure sensors used in the laboratory simulations described in this work.

- a PG for tuning the PRV/ERV and the continuous (visual) monitoring of the water pressure in the system (Wika).

The operation of this hydraulic system is simple and straightforward. The water is kept at a constant pressure between the PRV, ERV and RF at a level preset by means of the PRV and RF. During a rainfall event, the PRV prevents any loss of pressure in the system caused by hose elasticity. When the rainfall event stops, the RF, which is regulated to a slightly lower pressure level than the PRV, get rid of the excess pressure which, without this hydraulic system, would cause higher pressure at the nozzle than the pressure of the water supplied through the intake hose, thus leading to rainfall intensity being too great at the beginning of each rainfall event. This hydraulic system makes it possible to have a continuous flow of water in the return hose which is directed to the reservoir and is negligible when compared to the rainfall sprayed by the nozzle. Despite the price of each specific part of the hydraulic system varying considerably depending on the location and availability, an upper boundary limit budget of 350 EUR is estimated for the whole system (except the PG which was used only for the purpose of acquiring data for this study, but is unnecessary for the system operation).

## Laboratory setup

To test the constant pressure hydraulic system, an experimental setup was prepared (Figure 2). It consists of:

- the constant pressure hydraulic system, described above;
- a 1.0 $m^3$ constant head tank fed by the urban water supply system;
- a variable speed submersible pump placed inside the water reservoir;
- a set of flexible hoses to connect the pump to the hydraulic system (intake hose) and the latter to the reservoir (return hose);
- a full-cone nozzle (Spraying Systems Co.) placed at the outlet of the constant pressure system;
- two high-precision pressure sensors placed at the water intake and in front of the ERV;
- a data-logger to register the pressure values during the simulations.

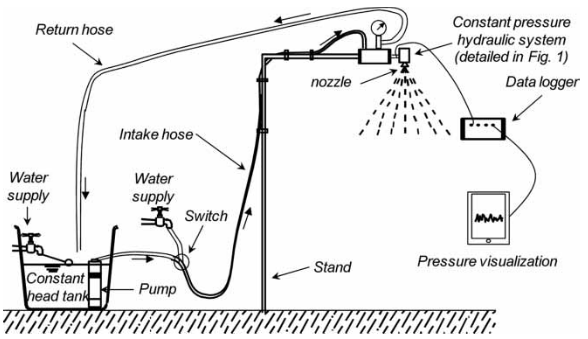

**Figure 2** | Schematic representation of the experimental setup used during the laboratory testing of the constant pressure hydraulic system.

## Procedure

A series of laboratory simulations was conducted to monitor the pressure fluctuations at the water intake (in front of the constant pressure system) and at the water inlet to the nozzle. Five sets of 12 wet-dry-wet cycles (each cycle: ~15 s of simulated rain followed by ~15 s of no rain) were simulated to determine the statistical representativeness of pressure variations. The nozzle was supplied using a variable speed pump (simulations 1–4) and a direct intake from the mains water supply system (simulation 5).

In these simulations, high-precision pressure transducers were used to measure, at a rate of 0.02 s, the pressure at the water intake and immediately in front of the ERV (that opens and closes the water inlet to the nozzle). In all the simulations discharge was measured by collecting and weighing the rainfall water for 240 s. This process was repeated three times. This information is summarized in Table 1.

**Table 1** | Water supply, average discharge and water pressure in front of the ERV (with this valve closed and opened)

| Simulation # | Water supply | Average discharge (L/s) | Average pressure with ERV closed (no-rainfall) (bar) | Average pressure with ERV opened (rainfall) (bar) |
|---|---|---|---|---|
| 1 | From reservoir, using the submersible pump | 0.094 | 1 | 0.9 |
| 2 | | 0.135 | 2 | 1.7 |
| 3 | | 0.164 | 3 | 2.5 |
| 4 | | 0.192 | 4 | 3.6 |
| 5 | Directly from mains water supply system | 0.076 | 1 | 0.6 |

## RESULTS AND DISCUSSION

Figure 3 presents the five experimental tests for different static pressure values at the intake and at the nozzle (see Table 1), thus allowing comparison to be made of using the proposed hydraulic system as opposed to not using it. The water was supplied by the pump (simulations 1–4) and by the laboratory network (simulation 5). The simulations show that this system enables pressure to stabilize faster after opening and closing the valve, and that during each rainfall event (12 events for each simulation) the pressure is more stable between the PRV, ERV and RF than at the water intake. Pressure oscillations are larger near the minimum pressure due to flow turbulence.

Regardless of the static pressure value at the intake, it is clear that this system can significantly reduce the pressure fluctuations and thus allow a constant pressure (and rainfall intensity) at the nozzle.

Table 2 presents the pressure reading statistics and the standard deviation at the water intake (STD1) and in front of the ERV (STD2), where more than 750 pressure measurements were collected for each rainfall event. STD1 and STD2 averages for all five simulations are also presented. The STD1 values are much higher than STD2 ones, with STD1/STD2 ratio ranging from 1.978 (simulation 2; event 6) to 4.199 (simulation 1; event 6), which shows that the pressurized hydraulic system produces a stable pressure at the nozzle (see Table 2, column STD1/STD2). Thus, the system provides constant rainfall intensity throughout each and every simulated rainfall event.

## CONCLUSIONS

A hydraulic system consisting of a set of valves (PRV, RF and ERVs), a PG and some simple pipe T-junctions was designed with the aim of controlling pressurized rainfall simulators. It should be positioned just upstream of the nozzle of the rainfall simulator. Laboratory experiments conducted over more than 5 years have shown that the

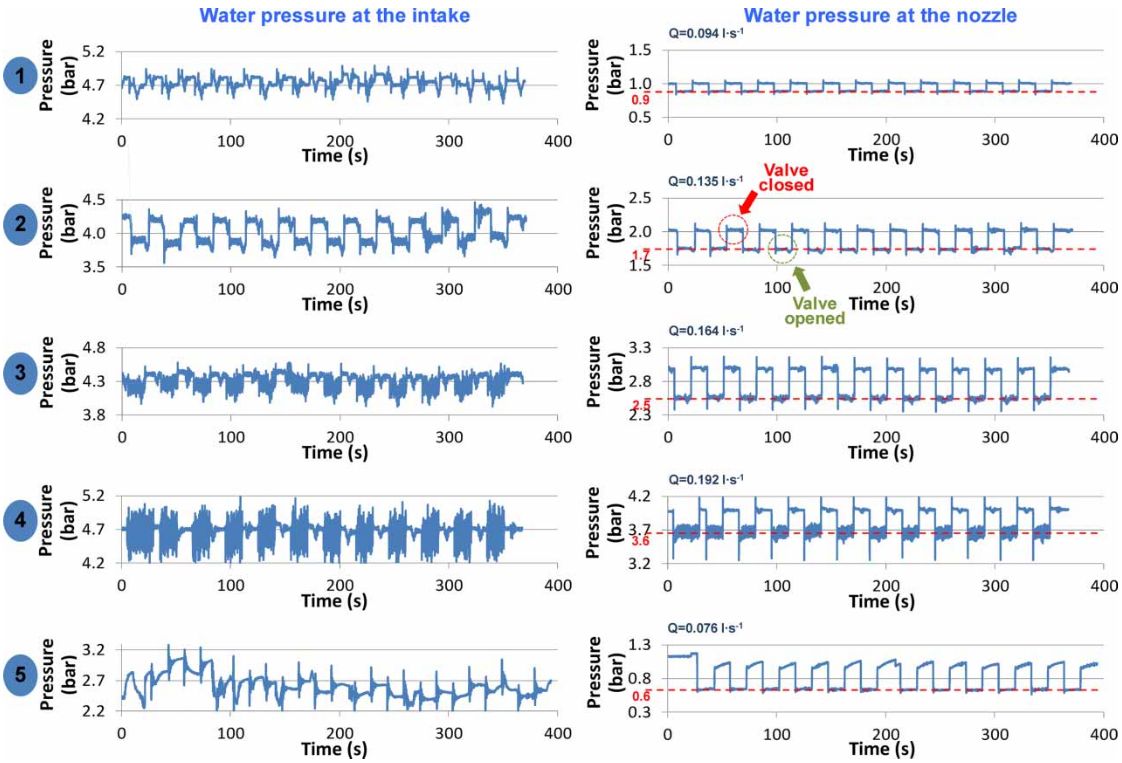

**Figure 3** | Comparison of using the proposed hydraulic system against not using it, for different pressures. (Left) Pressure fluctuations at the water intake (in front of the constant pressure system, i.e., as if the hydraulic system was not used). (Right) Pressure fluctuations at the nozzle. Dashed lines (graphs on the right) show pressure at the nozzle during operation. 'Valve closed' and 'Valve opened' dashed circles exemplify, respectively, the pressure response in the system to closing and opening the ERV.

**Table 2** | Pressure statistics for different simulations at the water intake (STD1) and in front of ERV (STD2). *n* is the number of pressure measurements for each rainfall event

| Simulation # | Event # | n | STD1 | STD2 | STD1/ STD2 | Mean STD1/ STD2 |
|---|---|---|---|---|---|---|
| 1 | 1 | 778 | 0.063 | 0.019 | 3.395 | 3.55 |
| | 2 | 769 | 0.063 | 0.019 | 3.346 | |
| | 3 | 774 | 0.067 | 0.019 | 3.593 | |
| | 4 | 761 | 0.057 | 0.018 | 3.161 | |
| | 5 | 778 | 0.075 | 0.018 | 4.067 | |
| | 6 | 757 | 0.078 | 0.019 | 4.199 | |
| | 7 | 777 | 0.053 | 0.018 | 2.884 | |
| | 8 | 771 | 0.062 | 0.019 | 3.357 | |
| | 9 | 760 | 0.069 | 0.019 | 3.650 | |
| | 10 | 773 | 0.067 | 0.018 | 3.801 | |
| 2 | 1 | 763 | 0.046 | 0.017 | 2.659 | 2.44 |
| | 2 | 756 | 0.053 | 0.022 | 2.375 | |
| | 3 | 762 | 0.058 | 0.023 | 2.585 | |
| | 4 | 763 | 0.051 | 0.021 | 2.474 | |
| | 5 | 766 | 0.054 | 0.022 | 2.479 | |
| | 6 | 758 | 0.043 | 0.022 | 1.978 | |
| | 7 | 758 | 0.046 | 0.021 | 2.238 | |
| | 8 | 756 | 0.058 | 0.024 | 2.400 | |
| | 9 | 771 | 0.070 | 0.028 | 2.511 | |
| | 10 | 751 | 0.056 | 0.020 | 2.738 | |
| 3 | 1 | 763 | 0.059 | 0.029 | 2.038 | 2.25 |
| | 2 | 756 | 0.053 | 0.026 | 2.022 | |
| | 3 | 761 | 0.071 | 0.029 | 2.436 | |
| | 4 | 760 | 0.073 | 0.030 | 2.428 | |
| | 5 | 756 | 0.063 | 0.028 | 2.243 | |
| | 6 | 767 | 0.072 | 0.031 | 2.321 | |
| | 7 | 759 | 0.072 | 0.032 | 2.262 | |
| | 8 | 765 | 0.069 | 0.031 | 2.271 | |
| | 9 | 763 | 0.072 | 0.032 | 2.253 | |
| | 10 | 762 | 0.079 | 0.036 | 2.220 | |
| 4 | 1 | 760 | 0.129 | 0.050 | 2.561 | 2.44 |
| | 2 | 767 | 0.130 | 0.053 | 2.431 | |
| | 3 | 767 | 0.130 | 0.056 | 2.310 | |
| | 4 | 763 | 0.134 | 0.054 | 2.499 | |
| | 5 | 765 | 0.129 | 0.052 | 2.465 | |
| | 6 | 758 | 0.135 | 0.054 | 2.507 | |
| | 7 | 767 | 0.129 | 0.054 | 2.386 | |
| | 8 | 769 | 0.127 | 0.055 | 2.326 | |
| | 9 | 769 | 0.128 | 0.054 | 2.362 | |
| | 10 | 770 | 0.136 | 0.054 | 2.522 | |
| 5 | 1 | 754 | 0.080 | 0.024 | 3.278 | 2.93 |
| | 2 | 757 | 0.090 | 0.022 | 3.996 | |
| | 3 | 758 | 0.069 | 0.022 | 3.075 | |
| | 4 | 756 | 0.062 | 0.028 | 2.212 | |
| | 5 | 766 | 0.067 | 0.022 | 3.015 | |
| | 6 | 753 | 0.067 | 0.025 | 2.719 | |
| | 7 | 752 | 0.061 | 0.025 | 2.447 | |
| | 8 | 759 | 0.065 | 0.023 | 2.795 | |
| | 9 | 755 | 0.069 | 0.023 | 3.070 | |
| | 10 | 755 | 0.065 | 0.024 | 2.681 | |

system is robust and functions as expected. Also, it can be easily adapted to any pressurized system.

The results show that rainfall simulators equipped with this system are capable of operating at a constant pressure and discharge which, from current knowledge, consequently facilitates constant rainfall intensities. This hydraulic system can thus be a low-cost solution for improving rainfall simulations.

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