https://doi.org/10.1590/S1413-415220200365

Technical Article

Development of a large-scale rainfall simulator for urban hydrology research

Desenvolvimento de um simulador de chuva de grande escala para pesquisa em hidrologia urbana

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RESUMO

Este trabalho apresentou o desenvolvimento e teste de um simulador de chuva em larga escala (*large-scale rainfall simulator* — LSRS) para utilização em pesquisa sobre o processo de chuva-vazão e processos associados em áreas urbanas. O simulador é composto por um sistema pressurizado de abastecimento de água que abastece um conjunto de 16 bicos aspersores. Chuvas artificiais com diferentes intensidades de precipitação podem ser produzida sobre uma bacia de drenagem com área de 100.0 m^2 em forma de V. O simulador é protegido por uma estrutura em acrílico que elimina a influência do vento e da chuva natural. A vazão é medida e coletada no exutório da bacia de drenagem, de onde é bombeada para um reservatório de armazenamento que permite a reutilização da água. Hidrogramas de vazão e polutogramas são apresentados como exemplos de possíveis resultados de ensaios a serem realizados com este equipamento. O LSRS demonstrou ser possível reproduzir o processo de chuva-vazão e processos associados sob eventos de chuva simulada com intensidade e distribuição espacial semelhantes a outros experimentos descritos na literatura.

Palavras-chave: chuva-vazão; drenagem urbana; modelagem hidrológica.

ABSTRACT

This work presented the development and testing of a large-scale rainfall simulator (LSRS) to be used as a research tool on rainfall-runoff and associated transport processes in urban areas. The rainfall simulator consists of a pressurized water supply system which supplies a set of 16 full-cone nozzles. Artificial rainfall with different rainfall intensities can be produced over an area of 100 m^2 in a V shape. The assembly is housed in a tailor-made acrylic structure to eliminate the influence of wind and natural rainfall. Runoff is measured and collected at the outlet of the drainage basin, from where it is pumped to a storage tank that enables the reuse of water. Runoff hydrographs and pollutographs are presented as examples of possible outcomes from this facility. The LSRS is showed to be able to reproduce the rainfall-runoff and pollutant transport processes under simulated rainfall events with intensity and spatial uniformity similar to other experiments described in the literature.

Keywords: rainfall-runoff; urban drainage; hydrological modelling.

INTRODUCTION

Urbanization in cities, among other consequences, leads to changes in land use with an increase of the impervious area, particularly noticeable in small basins. Soil sealing diminishes the infiltration and detention capacity of natural soil, thus increasing runoff. This contributes to alterations of the hydrological cycle, with consequences such as urban flooding and water quality. The fast rise of urban population from 10% in 1900 to more than half of the world's total population in the beginning of this century — a trend that will continue (GRIMM *et al*., 2008) —, indicates that changes in the hydrological cycle in urban areas will only become exacerbated over time. Thus, there is a strong need for further knowledge on the processes by which urbanization modifies the natural water cycle and, particularly, on how the urban structure influences the rainfall-runoff process.

Rainfall simulators are indispensable research tools for visualization and analysis of the rainfall-runoff dynamics and associated processes. Rainfall simulation is a technique widely used in soil science (KATUWAL *et al*., 2013), agronomy (MARDAMOOTOO *et al*., 2015), hydrology (SILVEIRA *et al*., 2016), and in other fields such as meteorological metrology (LIU *et al*., 2015) and building science (BLOCKEN; CARMELIET, 2004). Advantages of rainfall simulation are thoroughly described in the literature. Main advantages can be summarized as: ability to run experiments without having to wait for natural rainfall, ability to have controlled and replicable rainfall events, and low-cost

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Conflicts of interest: the authors declare there are no conflicts of interest.
Funding: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES), under the program Ciência sem Fronteiras (CSF), project n.88881.030412/2013-01; and Fundação para a Ciência e Tecnologia – Portugal (FCT), through the strategic project UIDB/04292/2020.
Received: 10/20/2020 – **Accepted:** 03/17/2021 – **Reg. ABES:** 20200365

and simplicity of use. However, large-scale simulators are expensive and may need continuous maintenance by skilled technicians.

In urban environments, where the increased imperviousness of the terrain, the existence of buildings, and the high intensity of human activities lead to major changes in the natural water cycle (HENGEN *et al.*, 2016), rainfall simulation becomes a rather important tool to deal with the idiosyncrasies of the urban environment. Rainfall simulation has been used in recent years to obtain answers to specific urban environmental issues. Herngren *et al.* (2005) developed a rainfall simulator to undertake urban stormwater pollution research. Egodawatta and Goonetilleke (2008) used simulated rainfall over small road surface plots to study pollutant wash-off on residential road surfaces. Júnior and Siqueira (2011) developed a rainfall simulator to research the behavior of permeable pavements, studies on urban water quality, and evaluation of build-up and wash-off. Isidoro, Lima and Leandro (2012; 2013), and Isidoro and Lima (2014) used a laboratory rainfall simulator to study the influence of high-rise building density, rooftop connectivity, and building height on the rainfall-runoff process in impervious areas.

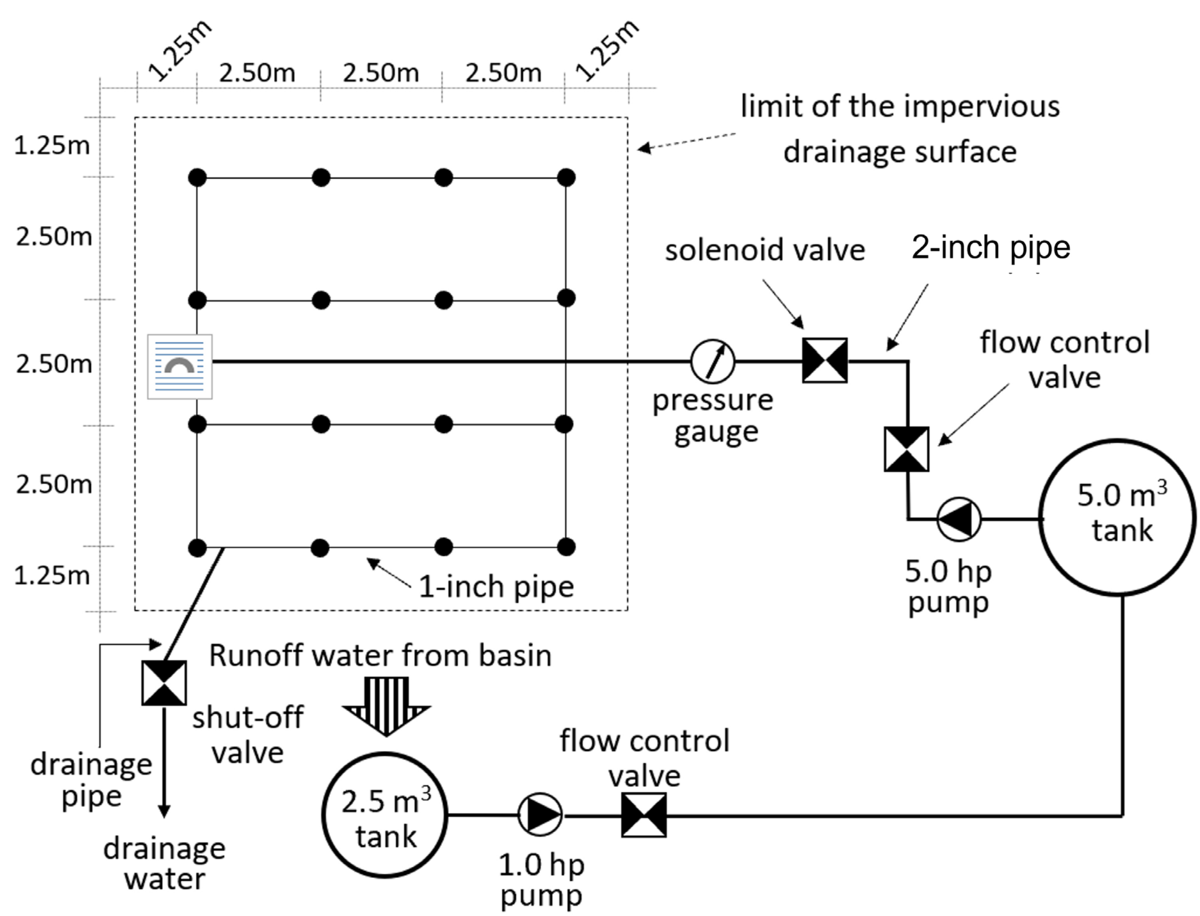
The main objective of this study was to present the development and testing of a large-scale rainfall simulator (LSRS) for urban hydrology studies. The LSRS is one of the largest rainfall simulators in the world, the largest of which is the National Research Institute for Earth Science and Disaster Prevention (NIED) rainfall simulator located in Tsukuba, Japan (NIED, 2016). This facility can be particularly useful for studies on, *e.g.*, urban flood management, best management practices, and water sensitive urban design.

METHODS AND MATERIALS

The LSRS consists of: a closed-circuit pressurized water supply system, including reservoirs, pumps, and nozzles to produce artificial rainfall; a 10 × 10 m impervious drainage basin to collect rainfall, and a measurement and data collection system for runoff and associated transport. Each of these components are further detailed below. An acrylic structure was built to house the pressurized water system and the impervious drainage basin. The acrylic structure eliminates the influence of wind on rainfall, thus allowing for undisturbed vertical rainfall.

Artificial rainfall production

The artificial rainfall production (Figure 1) system consists of a 5 m^3 constant water level reservoir, from which water is pumped by a 5 hp pump (BC-21R 2; Schneider) to a set of 16 downward-oriented full-cone nozzles (FullJet® HH-W ¼; Spraying Systems Co.) through a network of 1- and 2-inch diameter rigid PVC pipes. A small drain controlled by a manually operated valve is placed



Source: elaborated by the authors.

Figure 1 – Schematic of the large-scale rainfall simulator (LSRS) hydraulic system.

in the lower side of the pipe network to improve the temporal uniformity of each simulated rainfall event. Runoff is collected in a 2.5 m^3 holding tank at the outlet of the impervious drainage basin (see section "Impervious drainage basin") from where it is pumped by a 1.0 hp pump (ICS-110A; Eletroplas) to the 5.0 m^3 constant water level reservoir, thus closing the cycle to allow for the reuse of water. A light-steel frame structure bears the pressurized PVC pipe network where the nozzles are placed. A flow control valve, a solenoid valve, and a pressure gauge (DG-10; WIKA) are at the intake source of this network. The flow control valve allows to adjust the system's operating pressure (and rainfall intensity). The remote-controlled solenoid valve quickly opens and closes the circuit. A switch panel allows to control the pumps and the solenoid valve.

Regarding the spatial distribution of rain on the surface, the LSRS presented Christiansen Uniformity Coefficients (CHRISTIANSEN, 1941) in the range of 51.0 to 71.4%, for experiments carried out with average rainfall intensities from 36.3 to 55.0 mm/h.

Impervious drainage basin

A 10.0×10.0m impervious drainage basin with a v-shaped profile was built to represent a hypothetical urban area (Figure 2). Urban areas are comprised not only of impervious surfaces such as asphalt, concrete pathways, and rooftops. However, these are of major importance, particularly in downtown areas. The longitudinal and transversal slopes of the drainage basin are, respectively, 5 and 2.5%, conveying runoff water to a rectangular-shaped metal gutter draining the basin at its axis. The basin is made of concrete with its surface protected by an epoxy coating to assure the sealing of concrete, durability, and a smoother surface.

Operation of the large-scale rainfall simulator (LSRS) and overland flow hydrograph reconstitution

Rainfall intensity is initially set by means of operating the flow control valve. A switch panel allows to control the two electric pumps and the solenoid valve. After the pumps are running, the solenoid valve is opened to initiate a simulated rainfall event. The rapid shut-off valve is closed immediately after the equalization of the pressure in the system, allowing for a stable rainfall intensity throughout each simulated rainfall event. To obtain the overland flow hydrographs at the outlet of the scale model, a pressure transducer (Levelogger Edge; Solinst) was placed inside a dedicated 1-inch (2.54 cm) piezometer connected to the 2.5 m^3 in a holding tank. The transducer allowed continuous monitoring of the water level measurements and data logging.

With this experimental setup, it was possible to reconstitute the complete flood hydrographs at the outlet of the scale model.

RESULTS

Outcomes of the LSRS are exemplified by hydrographs and pollutographs acquired from two different experiments, after a simulated event with a rainfall intensity of 55 mm·h^{-1} (maximum of the LSRS for the present setup) and duration of 180 s over scaled physical models. These examples are representative of the versatility and capabilities of the LSRS.

Rainfall-runoff simulation

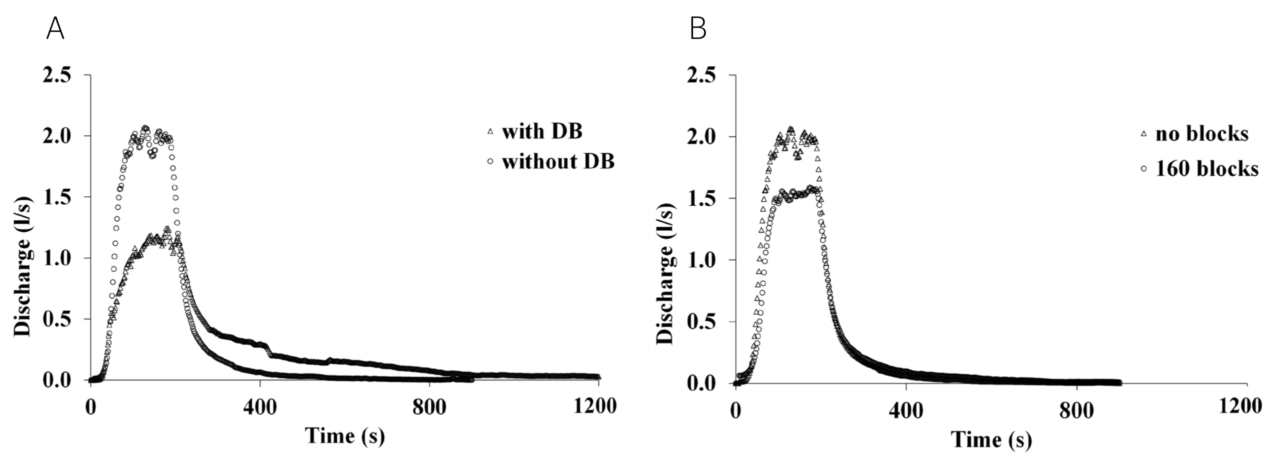
Figure 3A shows the influence of a detention basin (DB) on the rainfall-runoff process. The DB scaled model has a cubic shape with 0.50 m sides, built in polymethylmethacrylate. Runoff water was pumped from the metallic gutter of the drainage basin into the DB, and then slowly released through an orifice with 10 mm of diameter. Figure 3B shows the influence of buildings in an urban area. 160 blocks of expanded polystyrene (each with 0.40 × 0.40 × 0.60 m) were used to simulate a dense urban area. Blocks were displaced uniformly, covering 25.6% of the drainage basin area.

Pollutant transport simulation

To exemplify the LSRS capabilities to simulate transport processes associated to runoff, sodium chloride (NaCl) was applied to drainage basin surface to simulate a diffuse pollutant. NaCl has been used for similar purposes (DENG *et al*., 2005) because (indirect) measurement of NaCl concentration in water is inexpensive and straightforward. NaCl was uniformly spread over a single line, at the center of the impervious basin surface and normal to the main slope. Subsequently, a simulated rainfall event with an intensity of 55 mm·h^{-1} and a duration of 180 s took place. NaCl was measured using a conductivity probe (CON-BTA; Vernier). Based on the same experiments exemplified in Rainfall-runoff simulation section, Figure 4A and Figure 4B show, respectively, the influence of the DB and the buildings in the pollutant mass discharge.

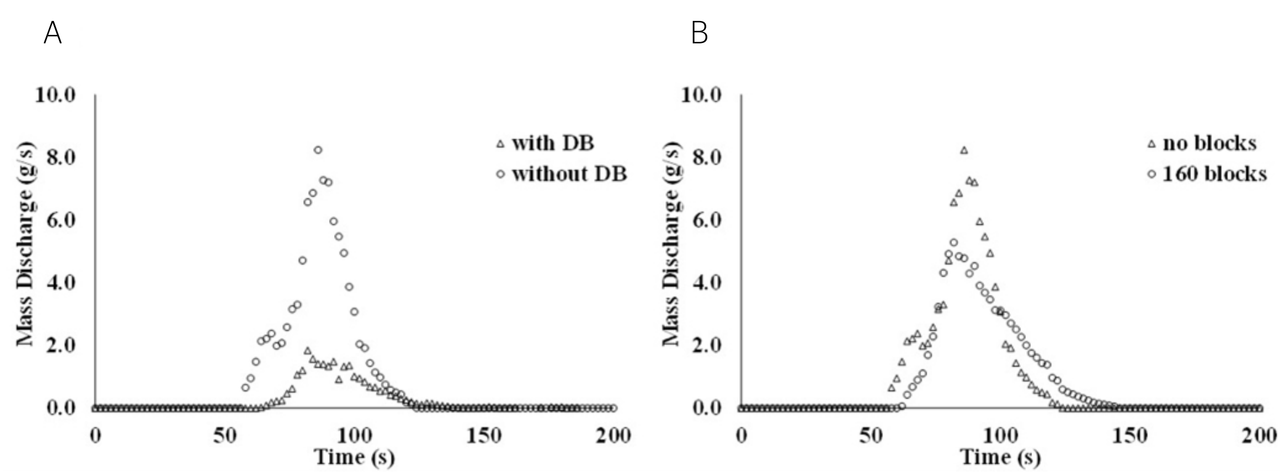
Source: elaborated by the authors.

Figure 2 – Large-scale rainfall simulator (LSRS): (A) External view of the acrylic housing; (B) internal view, where it is possible to distinguish the concrete V-shaped surface and the light-steel structure to which the pipe network and nozzles are fixed.



Source: elaborated by the authors.

Figure 3 – Example of hydrographs at the outlet of the experimental basin: (A) with and without detention basin (DB); (B) with and without blocks simulating buildings.



Source: elaborated by the authors.

Figure 4 – Example of pollutographs at the outlet of the experimental basin: (A) with and without detention basin (DB); (B) with and without blocks simulating buildings.

CONCLUSIONS

The faster hydrological response of urbanized basins compared to natural areas is one of the major issues of urbanization. Aiming to improve our understanding of hydrological processes in urban areas, a LSRS was designed, developed, and tested. The LSRS proved to be an efficient facility for simulating rainfall-runoff and associated transport processes. Overall conclusions are as follows:

- The LSRS allows to simulate rainfall over a 10 x 10 m basin, with different rainfall intensities, within a controlled environment, namely without the disturbance of wind;
- Continuous data collection at the outlet of the drainage basin is possible with high temporal resolution;
- Complete flood hydrographs can be reconstituted, with high reproducibility;
- Transport processes associated with overland flow can be simulated with the LSRS, such as, *e.g.*, pollution and particle transport;
- The LSRS can be a useful tool for urban hydrology engineering and environmental research.

AUTHORS' CONTRIBUTION

Silveira, A.: conceptualization, funding acquisition, investigation, methodology, project administration, supervision, writing – original draft, writing – review & editing. Isidoro, J. M. G. P.: conceptualization, investigation, methodology, supervision, writing – original draft, writing – review & editing. Lima, B. O.: investigation, methodology, writing – original draft.

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