Influence of wind-driven rain on urban runoff: Laboratory simulations

J. M. G. P. Isidoro and J. L. M. P. de Lima

Auswirkungen von windbeeinflussten Niederschlag auf den Abfluss im städtischen Bereich: Laboruntersuchungen

1 Introduction

Although rainfall has been assumed spatially uniform in conventional hydrological modelling for rainfall-runoff simulations, storm movement and wind-driven rain has a substantial influence on flow hydrographs. In fact, it is well known that the rain cell movement and the presence of wind affect the temporal and spatial distribution of natural rainfall, thus modifying the input of the rainfall-runoff process (e.g. Yen & Chow, 1968; Isidoro & De Lima, 2014). Incorporation of storm movement and wind-driven rain effects on the rainfall-runoff process thus helps to achieve better simulations of real systems.

Storm movement regards the displacement of a rain cell (or a group of rain cells) over a given area. In windless conditions near the ground level rainfall will only have vertical speed, despite it comes from a static or a moving storm. If wind exists near the ground level, the rain will gain horizontal speed and will be carried by the wind thus having a non-vertical trajectory. This latter description corresponds to wind-driven rain, which, as explained, only depends on the existence of wind near the ground level, regardless if the rainfall is originated by a static or by a moving storm.

Rainfall simulation in the laboratory is a commonly used tool to study the influence of wind-driven rain on the rainfall-runoff process. Laboratory simulation allows the analysis of a given hydrological process taking place in a

Zusammenfassung

Der Abfluss ist eine der wichtigsten Komponenten des Wasserkreislaufes im Speziellen bei hydrologischen Untersuchungen in städtischen Einzugsgebieten. Das tiefere Verständnis des Niederschlags-Abflussprozesses ist daher für eine optimale Planung von Stadtentwässerungssystemen wesentlich. In dieser Arbeit werden mehrere, physikalische Modellanordnungen und die Auswirkungen von windbeeinflussten, künstlichen Regenereignissen auf die Abflussbildung beschrieben. Der bewegliche Regensimulator ist mit Winddüsen ausgestattet. Die Bewegungsrichtung und der Wind haben großen Einfluss auf die Abflussbildung und die Form der resultierenden Abflussganglinie.

Schlagwörter: Bewegliche Regenfront, Windbeeinflusster Regen, Niederschlags-Abflussprozess, Stadthydrologie, Regenexperiment.

Summary

Runoff is one of the most important components of the hydrological cycle. It is of the highest importance for hydrological studies, namely for urban drainage basins. A deeper knowledge of the rainfall-runoff process is thus essential for better design of e.g. urban drainage systems. In this work several laboratory physical models are briefly reviewed to evaluate, under artificial rainfall, the influence of wind-driven rainfall and storm movement on urban runoff. The rainfall simulator consisted of a movable structure with nozzles which could generate wind fields. Wind-driven rain and storm movement has shown to have an important influence on the rainfall-runoff process, leading to significant changes in the shape of the runoff hydrographs.

Key words: Moving storms; Wind-driven rain, Rainfall-runoff process, Urban hydrology, Experimental methods.

well-characterized setting (e.g. ISIDORO, 2012). The characteristics of rainfall (e.g. spatial distribution of rainfall intensity and kinetic energy) and the environmental conditions (e.g. air temperature) can be individually controlled and repeated indoors. Thus, an in-depth analysis of their influence on the simulated hydrological process can be attained with laboratory rainfall simulation.

Laboratory experimentation on the influence of storm movement on runoff hydrographs started at the University of Illinois during the late 60's (SINGH, 1997). Among other runoff affecting- factors, storm movement showed to produce systematic changes in the flood hydrographs. Peak discharges and the hydrograph's recession limbs showed to be largely affected by the storm movement.

DE LIMA and SINGH (2000, 2003) started to use a sprinkling-type rainfall simulator with the ability to move over rails in order to simulate the storm movement. The simulations showed that, when compared with downstream moving storms, storms moving upstream produced hydrographs with earlier rise, lower peak discharge and longer base time, thus in agreement with the previous referred experimentations held at the University of Illinois. Both for storms moving in the downstream and upstream directions, the highest ratio of peak discharge to total discharged volume was obtained for a storm velocity equal to the average overland flow velocity.

On natural and agricultural areas studies to analyse erosion processes are well documented. Urban environments have singular characteristics regarding the rainfall-runoff process. The increased imperviousness of the terrain and the existence of buildings promote considerably changes in the natural water cycle (USEPA, 2003; GRIMM et al., 2008). In urban areas, an important parcel of terrain is sealed by impervious or low-permeability surfaces (e.g. asphalt, concrete, buildings and rooftops).

In the last decade, storm movement and wind-driven rain have re-gained particular interest, with studies at different scales, from small catchments to field plots and laboratory soil flumes (e.g. NUNES et al., 2006; DE LIMA et al., 2008, 2009; FERREIRA et al., 2011). ISIDORO et al. (2012, 2013) and ISIDORO and DE 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 under wind-driven rainfall. From these studies it was concluded that disregarding these characteristics could lead to under- or over-estimation of important hydrologic parameters (e.g. peak discharge, runoff base time).

This work aims to briefly review several laboratory experiments with different experimental setups, such as scale models and flumes under simulated pressurized rainfall. These experiments were set to study the influence of wind-driven rainfall and storm movement on urban runoff.

2 Experimental setups

The experimental facilities consisted mainly on an electrically-driven rainfall simulator with the ability to move along rails, forward and backward, over a flume, soil flume or small catchment area.

The rainfall simulator used in the laboratory experiments comprises a constant water level reservoir, a pump, a set of flexible rubberized hoses, a steel support structure, 2 electric engines, downward-oriented full-cone nozzles (from Spraying Systems Co.) and a set of eleven fans. Moving storms are restricted to forward and backward movements over the rails and are automatically controlled by a control switch panel. The nozzle is fixed to the moving structure by a steel rod which maintains its relative position during the movement of the assembly. The vertical distance from the nozzles exit to the surface of the flume surface is approximately 2.0 m, depending of the flume used in each specific experiment. The set of fans can create a wind field to produce inclined rainfall. For a more detailed description of this simulator see e.g. ISIDORO et al. (2012).

Several types of flumes, soil flumes or catchment areas have been used in the last decade. Different geometries of flumes can be placed under the rainfall simulator, in different positions, to ascertain e.g. the influence of storm movement direction on hillslope hydrology. Diverse, pervious or impervious, surface characteristics can also be simulated, or elements added (e.g. blocks simulating buildings). Figure 1 shows sketches of some experimental setups used.

The dimensions of the rectangular flumes vary from 0.10 m×2.00 m to 1.25 m×6.00 m. Circular flume has a diameter of 2.00 m. Convergent and divergent flumes are sectors of a circle with 2.00 m of radius. The flumes can be set with different slopes, some separately in the longitudinal and transversal directions. The 6.00 m soil flume allows simulating different hillslope cross-sections, such as concave, linear or convex, by adjusting the slope of each of its 3-segments. Most of these flumes are soil flumes and can be filled up with, at least, a layer of 0.10 m. The v-shaped square flume that has 4.00 m^2 is composed of a steel sheet.

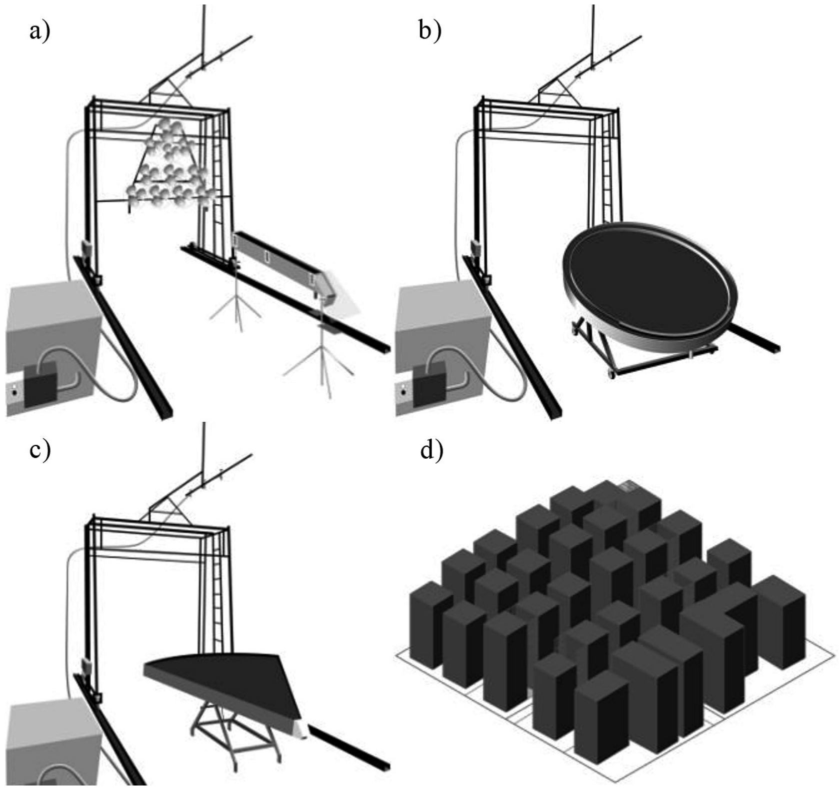

Figure 1: Sketches of different set-ups used: a) long rectangular soil flume under wind-driven rain; b) circular soil flume under moving storms; c) converging and diverging flumes under moving storms; and d) square flume with rectangular blocks simulating buildings

Abbildung 1: Darstellung verschiedener Modellanordnungen: a) langgestreckter, rechteckiger Untergrund bei windbeeinflusstem Regen; b) runder Untergrund bei beweglicher Niederschlagsfront; c) konvergierender und divergierender Untergrund bei beweglicher Niederschlags-front; d) quadratischer Untergrund mit rechteckigen Gebäudeblöcken

3 Results

Laboratory experiments conducted by the authors (Figure 2), using pervious and impervious surfaces (e.g. flumes and soil flumes), has consistently shown that storm movement and wind-driven rainfall has a marked influence on the rainfall-runoff process.

Figure 3 presents the resulting hydrographs obtained when comparing downstream and upstream moving storms for windless and wind-driven rain scenarios. The set of experiments that gave this particular result were conducted on the 4.00 m^2 v-shaped rectangular impervious catchment, set with longitudinal and transversal slopes of, respectively, 10.0 % and 2.5 %. A single rain cell with an average intensity of 120 mm/h moved with an average constant velocity of around 0.04 m/s for both windless and wind-driven rain scenarios along longitudinal axis of the catchment. In wind-driven rain simulations the wind always blows in the same direction of the storm movement.

Results showed that downstream storm cell movement lead to higher peak discharge and steepness of the rising limb of the hydrograph, and lower base time, when compared to upstream movement. Wind-driven showed to reduce these mentioned differences under these specific nozzles and wind generation devices (11 fans). These outcomes drawn from the resulting hydrographs are common in wind-driven rainfall-runoff simulation. Similar results can be found in DE LIMA and SINGH (2000, 2003), DE LIMA et al. (2008, 2009), ISIDORO et al. (2012, 2013), ISIDORO and DE LIMA (2014). Laboratory rainfall simulation showed to be a very useful tool for the study of the rainfall-runoff process, being also flexible enough to simulate this processes on specific built environments.

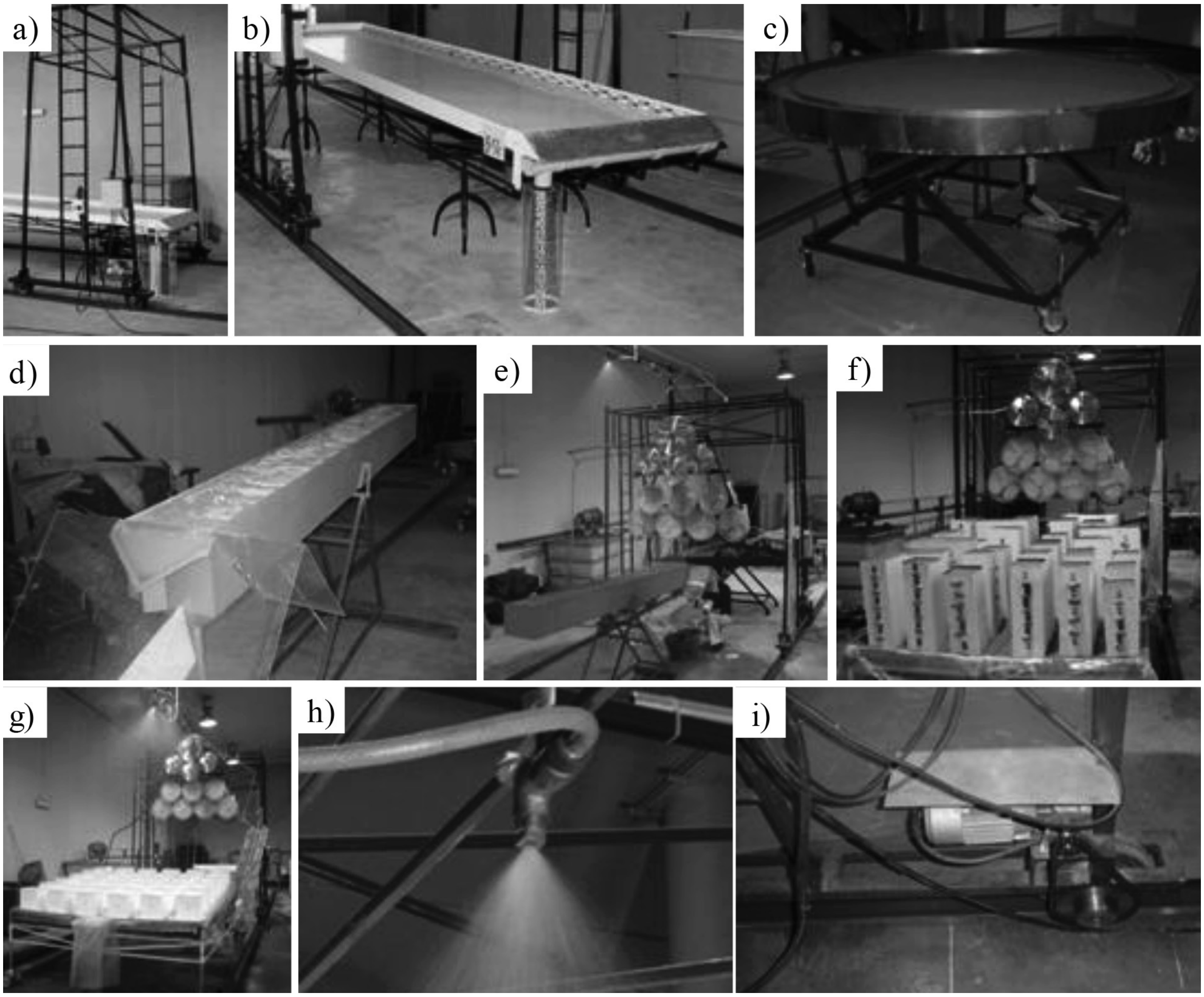

Figure 2: Photographs of laboratory experiments: a) and b) 5.00 m long impervious flume under simulated moving storms; c) 2.00 m diameter circular soil flume; d) 3.00 m long rectangular soil flume with Portuguese cobblestones; e) 3.00 m long rectangular soil flume different soil use under simulated wind-driven rainfall; f) and g) 4.00 m^2 square impervious flume with blocks simulating buildings under simulated wind-driven rainfall; h) detail of pressurized full-cone nozzle during operation; i) detail of electric engine and rail, part of the rainfall simulator apparatus

Abbildung 2: Fotos der Laborexperimente: a) und b) 5 m langer undurchlässiger Untergrund bei beweglicher Regenfront; c) runder Untergrund (2 m Durchmesser); d) 3 m langer rechteckiger Untergrund mit Bepflasterung; e) 3 m langer rechteckiger Untergrund mit windbeeinflussten Regen; f) und g) 4 m^2 quadratischer, undurchlässiger Untergrund mit rechteckigen Gebäudeblöcken mit windbeeinflussten Regen; h) Detail einer Druckdüse im Betrieb; i) Motorantrieb und Transportschiene des Regensimulators

4 Conclusions

The hydrological response is conditioned by storm movement and wind-driven rainfall, resulting in changes in the shape of the flood hydrographs. Downstream moving storms have shown to present higher peak flows and smaller base times than upstream moving storms. Wind-driven rain have shown to reduce these differences.

Laboratory work is sufficiently flexible to accommodate the natural variability of urban and semi-urban areas, being useful for quantifying the response of specific built environment features which is indispensable to the design of urban drainage systems.

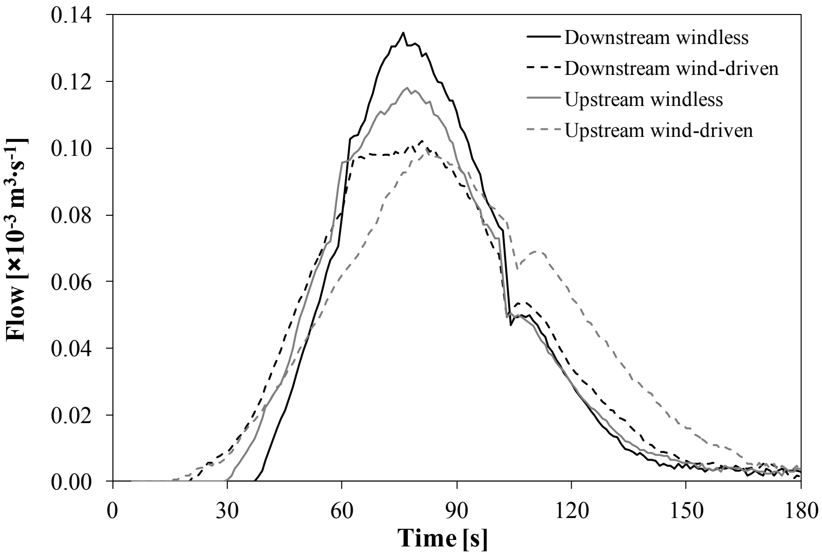

Figure 3: Runoff hydrographs measured at the outlet of the 4.00 m^2 square impervious flume. It is visible how the hydrograph shape is influenced both by the storm movement (in the downstream and upstream direction) and the existence or absence of wind

Abbildung 3: Beobachtete Abflussganglinie am Auslass des 4 m^2 großen quadratischen, undurchlässigen Untergrund. Die Beeinflussung durch die Frontbewegung und den Wind wird anhand der unterschiedlichen Ausbildung der Ganglinien ersichtlich

Future works should encompass also outdoor laboratory experiments with greater dimensions and other layouts to accommodate the study of transport processes in more complex systems.

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