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On storm-runoff transformations in an urban and a forested subtropical basin: laboratorial and field monitoring design to a watershed modeling

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Abstract

In most subtropical regions, population growth seals the lands and, as a consequence, increases peakflows. This work aims to study overland flow generation in paired subtropical basins (one urbanized, other forested), in the metropolitan region of Campinas. Both, Cachoeira stream basin (urbanized) and the Jardim creek basin (forested) are to be monitored with lysimeters, to assess overland flow, water retention and groundwater recharge, stage-meters, to catch peakflows, and weather stations, to follow atmospheric physical conditions. A standpipe lysimeter is also to be constructed in laboratory to reproduce the field lysimeter water fluxes, in terms of top excess water with a faced spillway at the of the soil column, water retention with tensiometers along the column height, and percolation water with gravels and a drainage collector. It is expected throughout this work to contribute to 1) application of soil sciences in hydrological analysis and 2) testing soil profiles in laboratory.

Keywords

Surface hydrology, soil water; overland flow generation; lysimeters; subtropical climate

INTRODUCTION

Subtropical regions are all yearlong visited by different air mass systems, showing a complex climate with large range of temperatures and complex rainstorms too; land soils and soil coverage respond with overland runoff. As population grows and economics prospers, nested urban settlements and rural activities develop lands, seals the soils and impacts stream peakflows. Hazardous events become more frequent because of smallest peakflow recurrence and closer flood presence. Among other things, reasons to rainfall related disasters include drainage system overflows in flashfloods and floodrisk assessment. Floodrisk assessment has amounts of both, natural uncertainty factors and systemic uncertainty factors, which are epistemic ones. Merz and Thieken (2005) studied discrepancies in observed and simulated preakflow histograms to make distinction between what discrepancies were from natural causes and what were from epistemic causes. Merz and Thieken (2005) reduced significant epistemic uncertainties in accordance to some theoretical hydrological hypothesis like stationary time series. Early, Binley et al. (1991) pointed out large amounts of control parameter in spatially distributed hydrologic models and loose of context in data collection as sources of large uncertainties. Soil water processes and boundary conditions are what determine stormwater production over the lands, the rapid part of the storm-runoff. Otherwise, soil water infiltration theories are not very useful in surface hydrologic analysis. According to Vereecken et al. (2008), soil water estimates and monitoring methods are not enhancing confidence of runoff analysis in more advantageous levels than runoff-only calibrated models. Surface hydrology with its fluxes of overland water, evapotranspiration and groundwater recharge depends on the soil water dynamics. Quantifying these fluxes requires both spatial and temporal land characterization with soil water data surveys and surface hydrologic models able to relate the surface water fluxes. Extensive remote sensing studies with microwaves survey and local point soil water studies have been made as attempts of some group of scientists to describe relations of soil water and surface water, but the small number of attempts have not allowed to find significant advantages in soil water measures near surface to predict peakflows and floods with surface hydrologic models and results have been contested by other groups (Vereecken et al., 2008). Studies use soil water estimates with microwave measures on 320 river basins to explain that miss advantage of including soil data in hydrologic models is that predicting peakflow with precipitation and discharge data and land parameters calibration is always sufficiently satisfactory (Vereecken et al., 2008). Vereecken et al. (2008) review points those discharge prediction errors with soil water data are associated with water budget errors, which range from 20 to 50% or higher.

On the other hand, practices in stormwater engineering most include soil infiltration techniques. Such soil infiltration techniques aims to manage water quality volumes (WQV) with retaining water in soils, eliminate contaminants from water and safely transfer stormwater to aquifers. Knowledge to successfully design and maintain these technologies come from well understanding how forests slowdown and clean stormwater. Bonell (1993) says taking soil mechanisms into account is a challenge for the task of describing flow discharge in natural channels. Bazemore et al. (1994) say that soil water is a key-unknown in determining environmental issues to river basin scales. Bazemore et al. (1994) made evaluations of soil water dynamic with natural tracers in zero-tension lysimeters and hydrometric methods in a forested small river basin in Virginia, USA. Bazemore et al. (1994) observed in a severe storm event that previous soil water gave 36% of total discharge and dominated flow peak with two-third part. A small rainfall, a small part of soil water leaves the lands. This study (Bazemore et al., 1994) was one of the main pioneers in making natural tracers a trustable method in hydrological analysis.

Latron and Gallart (2008) analyzed overland flow in one small Mediterranean river basin by continuous piezometric head data in saturated zones, soil matrix potential registers in unsaturated zones with field tensiometers and flow discharge in response to rainfalls for six years. Diary registers show a large range of soil matrix potential (from –4.0 to 0.05 atm) and strongly non-linearity of flow discharge to rainfalls, circumstantiated by previous measures, as well as in the piezometric soil heads with respect to rainfalls. Soil matrix potential measures alongside discharge and piezometric head data showed frequent evidences of perched saturation layers in the unsaturated profile, which was demonstrated positive soil matrix potential and runoff increase. Soil water retention was also observed in the measures, with highly negative soil water potential measures and discharge peak delays. Several methods exist to estimate soil water content. Most of them are based in the soil water retention characteristic curve. However, soil water retention characteristic curve, which plots soil water contents against soil matrix potential, is expected to show hysteresis, where different correspondences are found as a result of particular physical conditions. Hence, such a tensiometric survey (Latron and Gallard, 2008) would better be valid as a characterization of peakflow formation with some kind of paired result, like lysimetric data, in order to try to isolate hysteresis as a source of uncertainty. Nichol et al. (2008) have built a laboratory soil column experiment to study water distributions alongside steady state infiltration rates. The soil column works as a standpipe lysimeter with 56cm diameter and 3.6 m height. A time schedule was elaborated to run simulations that represent field physical conditions of a determined study area, with soil material that has same typical granulometric curve. Water application rates were simulated with a peristaltic pump to drip constant volumes of water on the top lysimeter along sufficient time (days or weeks) to reach steady state and both, tensiometric and volumetric measures were made. As advantages with respect to expensive laboratorial techniques, this indoor standpipe lysimeter was made of a low cost tank and makes possible to replace it for field lysimeter studies. Because of steady state assumptions of Nichol et al. (2008) lysimeter do not allowed simulations of both stormwater rainfall intensities and overland flow generation.

The aim of this work is to represent natural combined soil infiltration and overland generation processes looking forward an attempt to elaborate soil water based surface hydrologic models and a laboratory technique for soil infiltration tests. We plan to carry out water fluxes measures in field and laboratorial experiments to model field behavior. With this, we expect to find physical reasons for eventual field measures and laboratory results discrepancies, as well as, uncover direct and indirect soil parameter relationships.

METHODS & MATERIALS

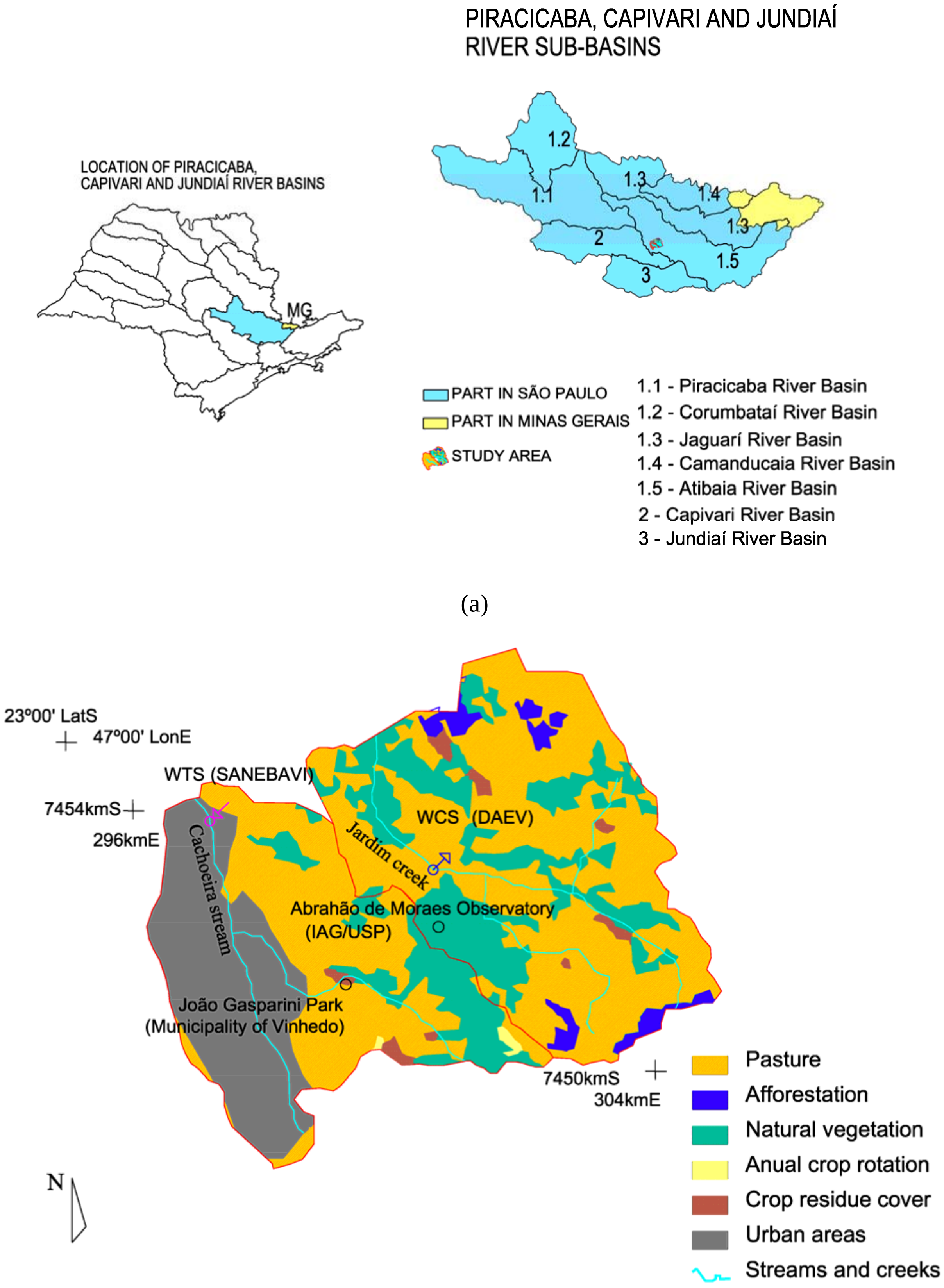
Study area

Study area is planned to two river basins located in the Campinas metropolitan region, in Vinhedo and Valinhos municipalities. Cachoeira stream and Jardim creek catchment areas have, respectively 18.1 km² in Vinhedo municipality and 22.5 km² in Valinhos municipality. Cachoeira stream's catchment area is major occupied by urban areas and pastures. According to the government, in 2007 Vinhedo's population has 57 thousands inhabitants, 50 thousands in urban areas; this number grows 6.6% a year. The economy is founded on fruit crops and food industry. Jardim creek's catchment area is occupied by pasture, with 60%, and native vegetation plus afforestations, with 40% fold in area (Figure 1).

Atmospheric measures and soil measures are planned in the urban area, at the João Gasparini Park, which is a Vinhedo's Municipality lot and at the Abrahão de Moraes Observatory lot, which is due to the Institute of Astronomy and Geophysics of the State University of São Paulo (IAG, USP) (Figure 1). Flow measurement in Cachoeira creek is planned to be performed at a Wastewater Treatment Station (WTS) lot of Vinhedo's Basic Sanitation Company (Portuguese acronym, SANEBAVI). In Jardim creek, flow measures are to be performed at the Moninho Velho Dam, the Water Capture Station (WCS) of Water and Sewer Department of Valinhos (Portuguese acronym, DAEV) (Figure 1).

Water budget of river basins

A hydrologic monitoring plan is prepared to the Cachoeira and Jardim streams with atmospheric data, soil water data and river water flow measurement. Precipitation and evaporation variables, as the main source of water storage and water loss in watersheds, respectively, are to be measured with the aid of a weather station. Soil measures include the soil water content, terrain excess water, with overland flow generation, and deep soil water percolation. Weight lysimeters are proper to soil water content studies because they are equipped to accurately register mass variations. The soil water content, in mass, is extracted from variations in the lysimeter mass. Eventually, wind speed, raindrops speed and changes in atmospheric pressure may cause interferences in the lysimeter weight. Fortunately, such combination of factors is a well-known issue in Engineering, so their separation is possible with those atmospheric variables registers in the weather station.



(a)

(b)

Figure 1: Cachoeiera and Bom Jardim creek basins location in the Sao Paulo State, Brazil

Terrain excess water is to be isolated from a lysimeter. Then, ruffs are present around the lysimeter borehole to isolate the lysimeter from runoff incomings. Boarders in the lysimeter tank are present to overflow excess water up from top lysimeter (Figure 2). Excess water escaped from lysimeter is collected in a gutter (overland gutter in Figure 2) that canalizes water to recipients of 60 liters of capacity. Water percolation is to be drained by gravels in the lysimeter bottom and dropped out, passing by 4 water short tubes (flanges), in the percolation gutter. Percolation water volumes are collected in a beaker recipient (Figure 2).

Considering evapotranspiration to be null alongside rainfall events, one may find the soil water storagement in the lysimeter as (1):

$$\Delta U \times Vol = P \times A - Q - R \qquad (1)$$

where ΔU is the mean soil water content [-], Vol is the lysimeter volume [m³], which the product ΔU times Vol gives the soil water storagement in the lysimeter [m³]; A is to the lysimeter top horizontal area [m²], P is the atmospheric precipitation lamina [m], Q is the volume of excess water [m³] and R is the water percolation volume [m³].

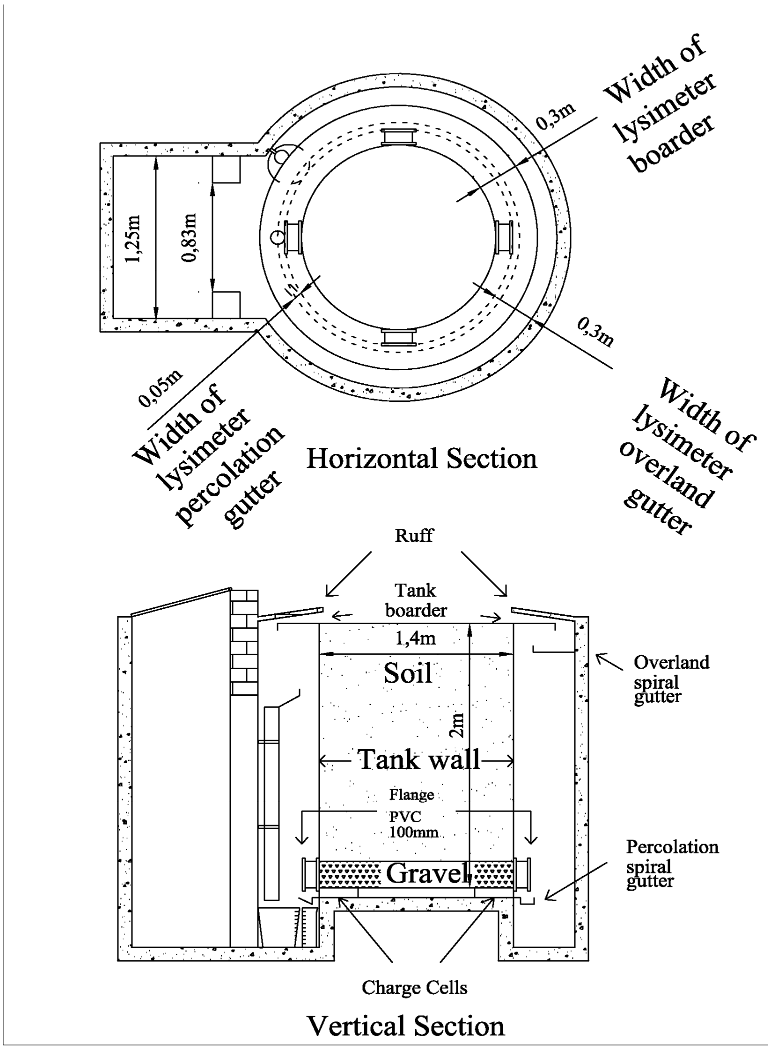


Figure 2: Field lysimeter schematic horizontal and vertical sections

The soil water retention characteristic curve is also to be explored in the lysimeter with tensiometers. Tensiometric registers aligned in several depths gives the soil moisture profile, after the transformation of the tensiometric values in soil water content by the retention curve. Integrating moisture profile gives the water volume, which is to match the soil water storagement in the lysimeter, measured indirectly by weight. Comparing both water content results, from tensiometric measures and from weight measures, allow one to discuss eventual discrepancies, which is expected to happen mainly because of hysteretic effects present in the soil water retention characteristic curve.

In a rainfall event, the soil infiltration capacity decays as the soil water content grows. After storm, the soil infiltration capacity is recovered by the soil water loss. Considering evapotranspiration to take place between rainfall events, soil water loss in the lysimeter is going to be expressed by (2).

$$\Delta U \times Vol = AET \times A + R \qquad (2)$$

where the product ΔU times Vol herein gives the soil water loss in the lysimeter [m³]; A is the top lysimeter horizontal area [m²], AET is the actual evapotranspiration rate [m] and R is the percolated water volume [m³]. Measurement of soil water loss alongside dry periods (periods without rainfalls) will permit real evapotranspiration rate assessments.

Flood waves are to be measured as the total runoff of storm water from the basin. So current meter techniques have to be used efficiently to find and to measure peakflows. Acoustic-Doppler methods permit rapid profile surveys along river sections in that the surveying period does not experiences any significant hydraulic transient. Lu et al. (2006) studied errors in current flow estimate with different acoustic frequency emissions in 5 flow gauge stations in Wu and Chochui rivers in the middle of Taiwan. It was demonstrated that mini acoustic-Doppler profilers (ADP) installed in tethered boats give efficient results even in steeped flow conditions and shallow flows. Limitations in portable ADP meter applications were reported when high sediment concentrations are present. Normally, tethered ADP systems are released on the water surface either from bridges or from stream temporary bank operated cableways. Cachoeira stream and Bom Jardim creek gauge stations do not have neither a bridge nor a cableway available. Because of the small stream width of both streams, a mobile mini telescopic crane may lead the ADP with a tethered boat across the stream width, operated from the stream bank (Figure 3). The mini telescopic crane has the advantage over fixed structures of being cheaper, since it is only one transportable structure to two gauge stations. It has a telescopic boom that consists of tubes fitted to slide inside the other to increase the total length of the boom.

Then, the storm water volume is the integral of the flood wave hydrograph in the variable of time. Since the integral of a continuous hydrograph with a discontinuous sampling of the flow measurements can not be exact, it must be validated by theoretical and additional field observation surveys. With the aid of the meteorological station measures and the lysimeter measures, the water balance of the gauge stages is expressed by (3):

$$Q = P \times A - E \times A - \Delta S \qquad (3)$$

where P is the average rainfall rate over the basin, E is the average basin evapotranspiration rate, A is the basin area, Q is the surface water volume drained to the gauge station and ΔS is the basin storage variation, consisted of increase of unsaturated soil water content and release of soil water content to the saturated groundwater level (recharge rate). Equation (3) states that all components, including surface water (Q) are disconnected from each other, as the excess of water in basin terrain. Stream flows put surface water runoff and subsurface water runoff together in the hydrograph. According to Latron e Gallart (2008) runoff generation is resulting from three processes: infiltration excess during dry conditions, saturation excess in scattered perched water tables, during wetting-up conditions, and linked perched water tables to the rise of shallow water table during wet conditions. Runoff generation processes may be observed in soil by lysimeters and tensiometers and may serve to simply identify error sources in the water balance of equation (3) or to furnish elements to support hydrograph separation methods.

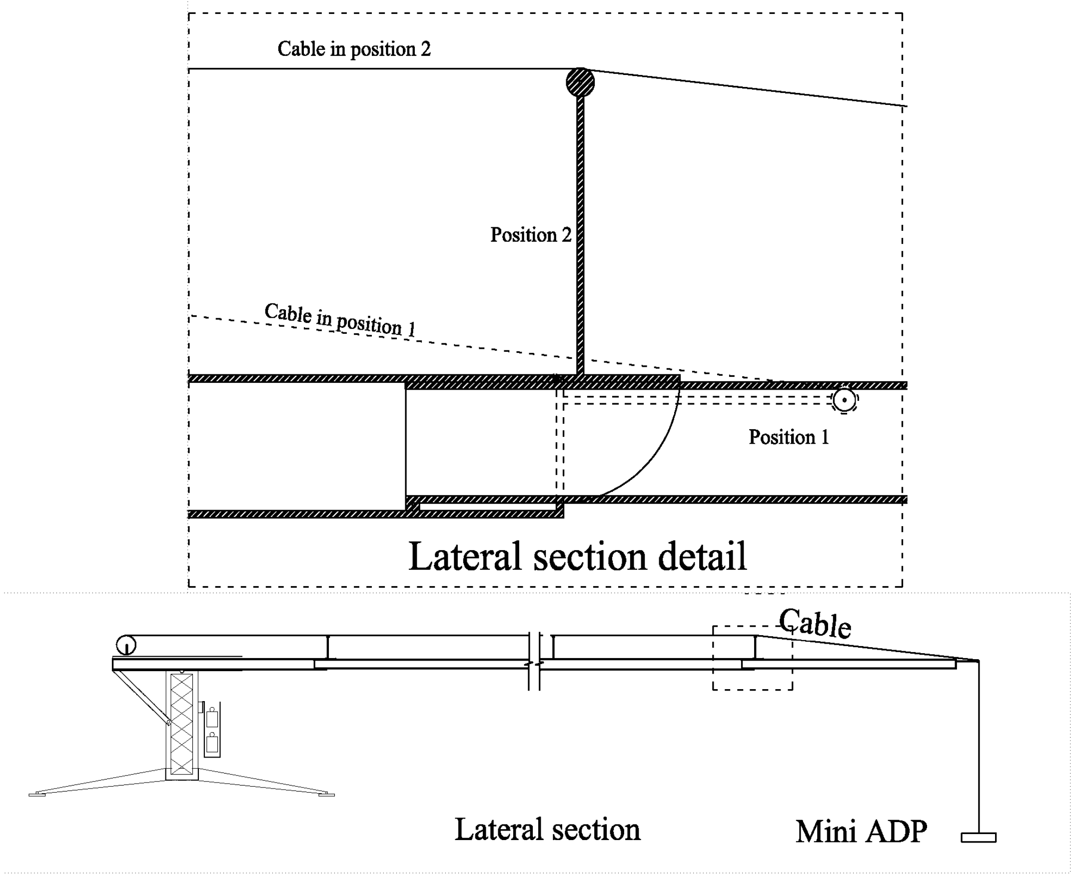


Figure 3: Lateral section and a section detail of the mini telescopic crane for mini ADP tethering

Simulations in a standpipe lysimeter

A standpipe lysimeter will be constructed in laboratory to reproduce the field lysimeter behaviour. The runoff generation in the Cachoeira stream and Jardim creek will be considered for to represent in the laboratory lysimeter too. The relationship of standpipe lysimeter and the field is established as much as the field hydrological factors of runoff generation and soil water infiltration are conveniently simplified and well represented in the experiment. The experiment is to reproduce the precipitation, the soil profile and the terrain hydraulic parameters as the most influencing factors of runoff generation and soil water infiltration. This study is made by providing the standpipe lysimeter with soil in similar conditions to the field soil and equipping the top lysimeter with a rainfall simulator, similar to the standpipe lysimeter of Nichol et al. (2008). Differently from the Nichol's lysimeter, which is for runoff-free experiments, this study provides a top lysimeter outlet for excess water (Figure 4).

The outlet is made as a triangular spillway depressed in the top tank wall not deeper than the topsoil position in the tank. The spillway cross-sectional area and its roughness give the water head on the topsoil as the boundary conditions for the soil water infiltration and the hydraulic characteristics of the runoff analog to the terrain slope and roughness in field. This permits that infiltration rate measures, and then the unsaturated soil water movement, shows its correlation, and later its equation, with the terrain hydraulic properties and the soil hydraulic properties combined.

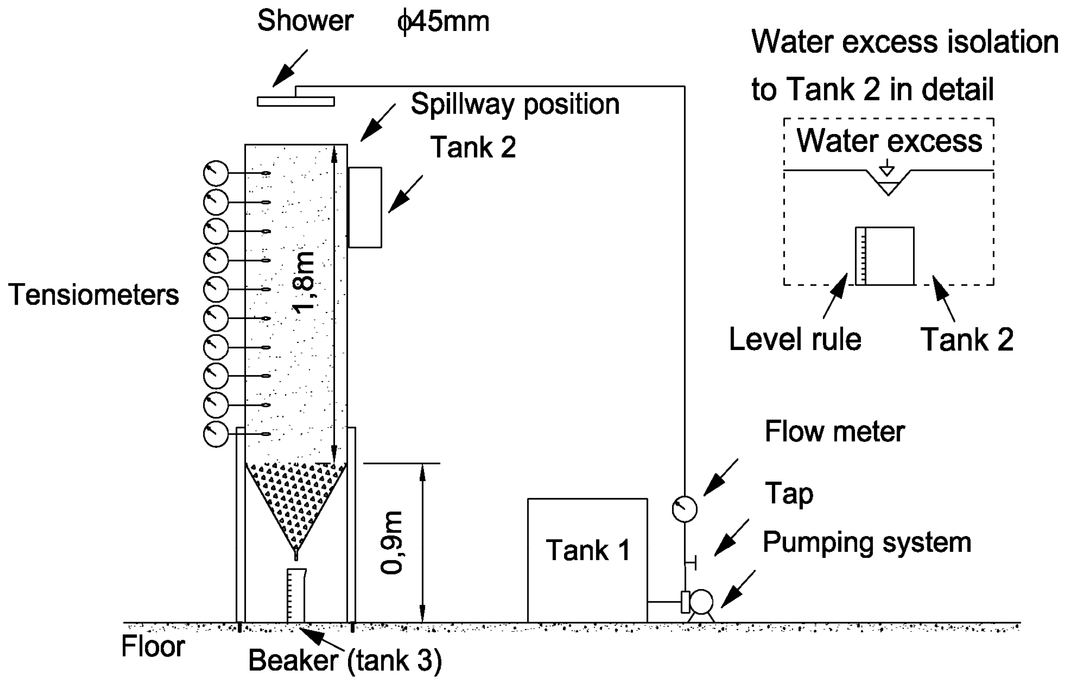


Figure 4: Configuration of the laboratory experiment using standpipe lysimeter with measure instruments (tensiometers and a beaker), the rainfall simulator system (pumping system, flow controls and a shower) and the excess water isolation system in detail (spillway and tank 2).

The standpipe lysimeter consists of a 1.8m-height 0.6m-diameter suspended fiberglass tank drained in the bottom by a conic funnel filled with gravel soil, with the top of the tank open to the air and with a triangular depression. The soil tank is monitored with an array of tensiometers and the bottom and the top separate excess water into two recipients, which are monitored with volume meters. The rainfall simulation is carried out by a controlled pumping rate that supplies with water a 45mm-diameter shower (Figure 4).

The top lysimeter triangular outlet permits the cross-sectional area to be modified just by sliding a mask in front of it. This is especially useful to perform the adjustment of the runoff flow lamina in the experiment to the field conditions. The soil water profile in the standpipe lysimeter may also be fit leaded either by naturally drying process or by adding soil moisture. After the runoff fitting and the initial soil water profile fitting for a given simulated rainfall, it is expected as, a consequence, that the soil water infiltration in the standpipe lysimeter reproduces the field infiltration rates.

EXPECTED RESULTS

General results

It is expected as a result of this study:

- an evaluation of the water retention in two subtropical urban and forested stream basins;
- an evaluation of the soil infiltration capacity restoration in the Cachoeira stream basin and Jardim creek basin;
- an evaluation of the peakflows in the Cachoeira stream and in the Jardim creek;
- an evaluation of the storm water volume reduction in the Cachoeira stream basin.

First results

The first steps toward the general results are:

- the runoff generation isolation and measurement in a subtropical field lysimeter alongside rainfall events;
- peakflow measures in two subtropical urban and forested basins;
- a soil water infiltration simulation with synthetic rainfall rates in a standpipe lysimeter.

CONCLUSION AND PERSPECTIVES

It demonstrates technical viability to the elaboration of a field and laboratorial study to separate, measure and integrally analyze both the overland flows and the soil water accretion as one of the most interfering factors in the subtropical flooding formation process. Soil column experiments have already been elaborated however not studying the overland flow generation. Field and laboratorial lysimeters are planned to separate the runoff generation. Measures of topsoil water excess, soil water profile and recharge rate are to be used to monitor overland flow generation and soil water infiltration combined. Meteorological measures are needed to perform the evapotranspiration estimate for basins with the aid of lysimeter weight measures. The estimation of the soil infiltration capacity restoration is expressed by it. The amount of overland water in the two basins will be given by the flow measurement and soil water measurement. The standpipe lysimeter may fit field data by simulating rainfall rates in the top lysimeter and reconfiguring the soil column moisture profile and the topsoil outflow cross-section. Future studies will evaluate technical viability to monitor soil temperatures and atmospheric physical variables as interfering factors in floods and to simulate evaporation rates, eventually evapotranspiration rates, in standpipe lysimeters.

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