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Multifractal characterisation of a simulated surface flow: A case study with Multi-Hydro in Jouy-en-Josas, France

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ABSTRACT

In this paper we suggest to innovatively use scaling laws and more specifically Universal Multifractals (UM) to analyse simulated surface runoff and compare the retrieved scaling features with the rainfall ones. The methodology is tested on a 3 km^2 semi-urbanised with a steep slope study area located in the Paris area along the Bièvre River. First Multi-Hydro, a fully distributed model is validated on this catchment for four rainfall events measured with the help of a C-band radar. The uncertainty associated with small scale unmeasured rainfall, i.e. occurring below the 1 km × 1 km × 5 min observation scale, is quantified with the help of stochastic downscaled rainfall fields. It is rather significant for simulated flow and more limited on overland water depth for these rainfall events. Overland depth is found to exhibit a scaling behaviour over small scales (10 m–80 m) which can be related to fractal features of the sewer network. No direct and obvious dependency between the overland depth multifractal features (quality of the scaling and UM parameters) and the rainfall ones was found.

1. Introduction

The combined effects of a growing urbanisation - approximately 80% of Europe's population will live in cities by 2020 (EEA, 2014) - and potential increase of extreme events as a consequence of climate change (IPCC, 2013) expose more and more people to surface pluvial flooding. Pitt (2008) carried out a review on flood events in the United Kingdom and showed that two thirds of the flood related damages were caused by surface water flooding. Urban flooding has become a growing concern in Europe, hence a significant number of European research projects address this issue, along with national counterparts. The purpose of these projects is to increase the resilience of urban areas through improvement of both real time management of extreme events and long term planning. We can cite FP7 SMARTesT (http://floodresilience.eu/), CORFU (http://www.corfu-fp7.eu/), Climate KIC Blue Green Dream (www.bgd.org.uk) or the INTERREG IV RainGain project (http://www.raingain.eu) among others.

There is a need to improve the understanding of urban surface flow. Indeed, there is a growing interest for 2D models in urban environment for both operational and research applications (Bolle et al., 2006; Carr and Smith, 2006; Chen et al., 2007; Deltares, 2013; DHI, 2011; Giangola-Murzyn et al., 2014; Innovyze, 2012, 2013; Phillips et al., 2005; XP Solutions, 2012). Such models aim at actually modelling processes in a physically based manner, while the most commonly used semi-distributed models take them into account through tailored lumped models. In case of overflow they simply consider a volume output from the sewer system and deduce a local water depth, but the dynamical behaviour of the water added on the ground is not addressed. Basically, urban surface flow is not commonly perceived as a geophysical process and is therefore not addressed with geophysical tools capable of grasping its intrinsic complexity visible across all scales. Indeed, it results from the non-linear interactions between the highly spatially and temporally variable rainfall field, the topography and the strongly inhomogeneous land use cover.

In this paper we suggest to use multifractal tools, which are commonly used in geophysics to characterize and simulate fields extremely variable over a wide range of scales; such as wind

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turbulence, rainfall, river flow or topography (see Schertzer and Lovejoy, 2011 for review). Such tools have seldom been used in an urban context. Gires et al. (2013, 2014b) used them to downscale rainfall to quantify the uncertainty associated with small scale rainfall variability, or to characterize the variability across scales of simulated flow in conduits (sewer). To the knowledge of the authors it has never been used to study either surface runoff flow (urban drainage) or surface flow in general including stream rivers. Investigating the potential multifractal features of surface flow and notably whether it inherits rainfall features is the main purpose of this paper and constitute its main novelty. In addition, this case study will also be used to quantify the uncertainty associated with small scale rainfall variability, not only on the simulated flow which has already been done on other catchments, but also on the surface flow.

Given the lack of measurements of distributed data of surface runoff, outputs of a numerical model are analysed. The model used is Multi-Hydro (El Tabach et al., 2009 for an initial version and Giangola-Murzyn, 2014 for a recent one) developed at the Ecole des Ponts ParisTech. It is implemented on a 3.017 km^2 *peri*-urban catchment in Jouy-en-Josas (South-East of Paris), which exhibits steep slopes and both forest and urbanised areas. Achieving such an analysis is relevant only if a distributed rainfall field is used as model input. Météo-France radar mosaics with a resolution of 1 km in space and 5 min time (Tabary, 2007; Tabary et al., 2007) for four events that occurred between 2009 and 2011 are used. When needed, the rainfall field is downscaled both in space and time from the raw radar data, in order to simulate the improvement that could be made with higher radar resolution.

The model and the study area data for its implementation are presented in details in Section 2. The multifractal framework and analysis methods are presented in Section 3. Results are discussed in Sections 4 and 5. More precisely, the validation of the model and quantification of the uncertainty associated with small scale unmeasured rainfall variability on both simulated sewer flow and maximum water depth is carried out in Section 4. Multifractal characterization of overland water depth is addressed in Section 5. Main conclusions are highlighted in Section 6.

2. Model and catchment

2.1. The Multi-Hydro model

Multi-Hydro is a multi-module model whose goal is to model and predict the impacts of rainfall events in urban and *peri*-urban areas. In this paper, there is an emphasis on heavy rainfall events. Following the approach of various recent developments of hydrological models (Djordjevic et al., 1999; Fletcher et al., 2013; Hsu et al., 2000; Jankowfsky, 2011; Rodriguez et al., 2008); it makes different modules interact, each of them echoing a portion of the water cycle in urban areas (surface runoff, infiltration, ground water flow, sewer flow).

Each of the modules integrated in Multi-Hydro relies on open-source software packages that have already been widely used and validated by the scientific community. The surface module is based on TREX (Two dimensional Runoff, Erosion and eXport model, Velleux et al., 2011) which solves fluid mechanics equations for surface flow (diffusive wave approximation of 2D Saint-Venant, see p. 6–7 of the TREX user manual) and infiltration (simplification of Green and Ampt equation). The sewer or drainage module, which is based on SWMM developed by the US Environmental Agency (Storm Water Management Model, Rossman, 2010), is a 1D-model dealing with sewer flows through numerical solutions of Saint-Venant 1D equations in pipes. The interactions between the surface and sewer flow is handled through the gully pixels. These interactions (input or output of water) between the surface and sewer flow are carried out every 3 min. When there is no overflow, gully pixels are considered to have an infinite infiltration rate, and the water passing through them is directly inputted into the corresponding node of the sewer model. This way of modelling implies that a large transport capacity is assumed for gully, especially with 10 m pixel size as in this paper (see below). Future developments of Multi-Hydro will enable to improve the model with regards to this coarse assumption. They could notably rely on the experimental and computational studies of gully inflow capacity, including 3D CFD studies, which analyse phases in the flow, inlet capacity, reverse flow when the piezometric level in the sewer is beyond the ground level (Despotovic et al., 2005; Djordjević et al., 2005). In case of sewer overflow through a node, the corresponding gully pixel is converted into a road pixel and the water exiting the node is inputted on this pixel (considered as a source in TREX). There is also a module handling ground water flow which was not included in this study to limit computation time.

In order to run Multi-Hydro, data needs to be shaped in a standard format. Commonly available Geographical Information System (GIS) data, such as land use and topography provided in France by IGN (the French agency producing geographical information) are inputted to MH-AssimTool (Richard et al., 2014). This software formats the inputs with the desired resolution and makes Multi-Hydro a transportable model, rather easy to implement on a new catchment. Once a resolution is chosen, one has to affect an elevation and a land use class to each pixel. The elevation is obtained by an interpolation of the raw available data. With regards to the land use, a priority order has been determined to assign a unique land use class for a given pixel according to the hydrological importance of the given class instead of the surface represented by this class: if a gully is located on a pixel, the entire pixel will be considered as a gully. This process is repeated in the following order for this case study: roads, houses, forest, grass, and water surface. See Ichiba et al. (2018) for a comparison with other possible strategies.

In this paper, the model was implemented with pixels of size 10 m x 10 m. Given the obtained results discussed below it was not found necessary to run it at higher resolution which makes computation time too long. For an in-depth analysis of the relation between the selected pixel size and simulated flow, which is not the purpose of this paper, refer to Ichiba (2016). Multi-hydro was not calibrated, i.e. standard values for the parameters describing a land use class are used (hydraulic conductivity, capillary suction, moisture deficit, Manning's coefficient, depth of interception). Raw or downscaled radar data are used as input of the model.

2.2. Presentation of the study area

The catchment studied in this article is located in Jouy-en-Josas (Yvelines County, South-west of Paris). It occupies a 3.017 km^2 area, mainly on the left bank of the Bièvre River. A small portion of the right bank near the river bed is also included. The remaining portion of the right bank is drained to a small river that flows into the Bièvre River downstream the outlet of the studied catchment. The Bièvre River is a tributary of the Seine River which it meets in Paris. It flows through increasingly urbanised areas along its 33 km path. This has led to strongly modify its natural bed, both in underground pipes which are integrated in the storm water sewer system, or in a highly artificial open air bed. An effort is currently undertaken to restore its "natural" aspect.

A striking feature of this catchment is that, unlike the previous ones studied with Multi-Hydro (Giangola-Murzyn et al., 2014; Gires et al., 2014a), it exhibits steep slopes. There is a difference of approximately 100 m between the plateau in the north of the