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Modeling rain-driven overland flow: Empirical versus analytical friction terms in the shallow water approximation

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SUMMARY

Modeling and simulating overland flow fed by rainfall is a common issue in watershed surface hydrology. Modelers have to choose among various friction models when defining their simulation framework. The purpose of this work is to compare the simulation quality for the Manning, Darcy–Weisbach, and Poiseuille friction models on the simple case of a constant rain on a thin experimental flume. Results show that the usual friction law of Manning is not suitable for this type of flow. The Poiseuille friction model gave the best results both on the flux at the outlet and the velocity and depth profile along the flume. The Darcy–Weisbach model shows good results for laminar flow. Additional testing should be carried out for turbulent cases.

1. Introduction

The rain falling on agricultural fields produces overland flows, which lead to soil erosion (Moss et al., 1979; Morgan et al., 1999), pollutant transport (Cai et al., 2007; Benkhaldoun et al., 2007) and flood events downstream (Cea et al., 2010; An et al., 2015). To prevent and understand these often undesirable effects, rain-induced flows have to be modeled accurately, thanks in particular to numerical simulations. As long as the flows have a horizontal length scale larger than the vertical one, the vertical velocity profile can be integrated, leading to a 2D system of equations, called the shallow-water equations (de Saint-Venant, 1871). Such shallow-water equations are commonly used for modeling overland flow (*e.g.* Smith et al., 2007), tsunamis (*e.g.* Popinet, 2011), dam breaks and flood events (*e.g.* An et al., 2015) or river flooding (*e.g.* Bates et al., 2010), which are generally flows at high Reynolds numbers. Because numerical simulations of such systems play a significant role in government decision-making to prevent or control inundation risks, it is crucial to properly model the underlying physical mechanisms as well as develop accurate and validated numerical schemes.

One of the key points in the shallow-water framework is the effective friction term which depends on the assumption made for the vertical velocity profile. This friction term depends on several parameters, but principally on the dynamical characteristics of the flow (*i.e.* laminar or turbulent). In general, because the flows are at high Reynolds numbers and also because of complex topography and scale effects (see for instance Smith, 2014), empirical laws are used, in particular the Darcy–Weisbach and the Manning models (see for instance Chow, 1959; Smith et al., 2007; Viollet et al., 1998; Chanson, 2004; An et al., 2015). However, it is important to notice that for rain-induced flow, the thin liquid films involved have small Reynolds numbers. Hence, the use of turbulent modeling is questionable, compared to the classical laminar friction term deduced from a Poiseuille velocity profile. Moreover, quantitative experiments are still rare (Esteves et al., 2000), underlying the need for systematic quantitative comparisons between numerical models and experimental measures.

In this paper, we focus on an "ideal rain" over a rough impermeable substrate. Experimental laboratory results are compared with

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numerical results of the shallow-water equations using both empirical (Darcy–Weisbach and Manning models) and a laminar (Poiseuille model) friction terms. We will show that in this case, the laminar version of the shallow-water equations is the suitable model for overland flows that can be generalized using a Darcy–Weisbach approach. The configuration studied is presented in the next section as well as the experimental setup. The numerical methods are described in Section 3, as well as validating cases. The numerical results are compared with the experimental measurements in Section 4, and a general discussion is then given.

2. Materials and methods

2.1. The "ideal rain" case

The numerical simulations of the shallow-water equations are compared with experimental measurements on an ideal configuration of overland flow produced by rain. Real cases in nature are complicated to model for various reasons: firstly the topography is often complex and not always well-known; then rainfall is usually not measured everywhere; finally many different physical mechanisms are imbricated in nature (rain, erosion, infiltration, *etc.*). Dedicated experiments where these different effects can be isolated then need to be designed. We focus here on an ideal case of rain falling on a flat impermeable surface as shown in Fig. 1. The same experimental setup was used before to evaluate the validity of numerical schemes in Delestre et al. (2009). The flat topography is tilted by an angle a and a constant rain intensity equal to I (mm h^{-1}) is imposed. The flume has a length $L = 4.04$ m (direction x) and width $l = 11.5$ cm (direction y), and is initially dry. The rain leads to an overland flow which is characterized by $h_{2D}(x,y,t)$ the water depth and $u_{3D}(x,y,z,t)$ the velocity profile, and finally $S_0 = \tan(a)$ is the absolute value of the flume slope. We also define the transverse averaged water depth profile:

$$h(x,t) = \frac{1}{l}\int_{-l/2}^{l/2} h_{2D}(x,y,t)dy,$$

and the transverse and depth averaged velocity profile:

$$u(x,t) = \frac{1}{lh(x,t)}\int_{-l/2}^{l/2}\int_{0}^{h(x,t)} u_{3D}(x,y,z,t)dy\,dz.$$

The rain intensity $R(x,t)$ is taken homogenous in space and constant during a duration t_{stop} yielding:

$$R(x,t) = \begin{cases} I & \text{if } t \in [0,t_{stop}] \\ 0 & \text{if } t > t_{stop} \end{cases} \quad \text{for } x \in [0,L]. \qquad (1)$$

Three dynamical regimes can thus be identified on the measured outflow discharge:

- between $t = 0$ s and a time t_s, the water depth in the flume is increasing as well as the outflow discharge: it is the transient, or rising stage,

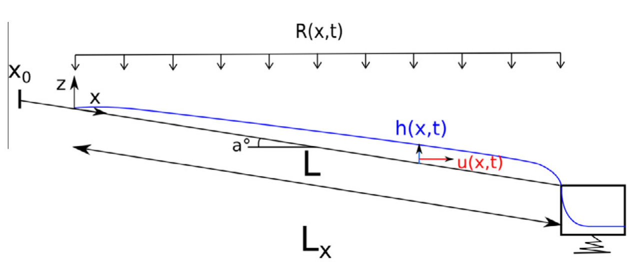

Fig. 1. The "ideal rain" case: an homogeneous rain is falling on a tilted flume, producing overland flow.

- between t_s and t_{stop} the flow is in its steady stage, and
- for $t > t_{stop}$ the rain event is finished and the outflow discharge decreases: it is the recessing stage.

This ideal configuration will be studied both experimentally and numerically in order to investigate and validate an effective rainflow overland model.

2.2. Experimental setup

2.2.1. Overall design

These experiments were carried out at the Rainfall Simulation Hall of the French Institute for Agricultural Research (INRA, Orléans, France). The test bench is a 4.04 m long and 11.5 cm wide flat flume having a rectangular section (Fig. 2). A sheet of glued printing paper is added on the flume for its hydrophilic property, avoiding the formation of threaded flow. The varying parameters of this experiment are the channel slope S_0 and the rainfall intensity. The slope of the panel can be adjusted and is measured using a spirit level (accuracy: 0.5 mm m^{-1}) and a stainless steel rule. The rainfall is produced by a nozzle-type rainfall simulator based on the design of Foster et al. (1979) and located above the channel. Water pressure is set to 90 kPa. Five oscillating nozzles are uniformly distributed over the flume (1.1 m between them). Using a combination of nozzles with slightly varying openings (Veejet 6540, 6550 and 6560; Spraying System Corp.), a coefficient of variation limited to 8.5% for the spatial variability of the rain intensity is obtained. Before each experiment, the channel is pre-wetted. A frequency of 55 sweeps per minute is used for the prescribed 50 mm h^{-1} rainfall intensity (half for the 25 mm h^{-1}).

The experimental cases differences are based on the prescribed rainfall intensity (25 or 50 mm h^{-1}) and slope (2% or 5%). The three cases considered thereafter are:

- 25 mm h^{-1} and 2%,
- 25 mm h^{-1} and 5%,
- 50 mm h^{-1} and 2%.

2.2.2. Measurements

The data of these measurements can be found in Supplementary material section.

2.2.2.1. Outflow hydrograph. The outflow discharge is recorded during the whole run, including both the rising limb of the hydrograph (at the beginning of the rainfall) and its recessing limb (after the

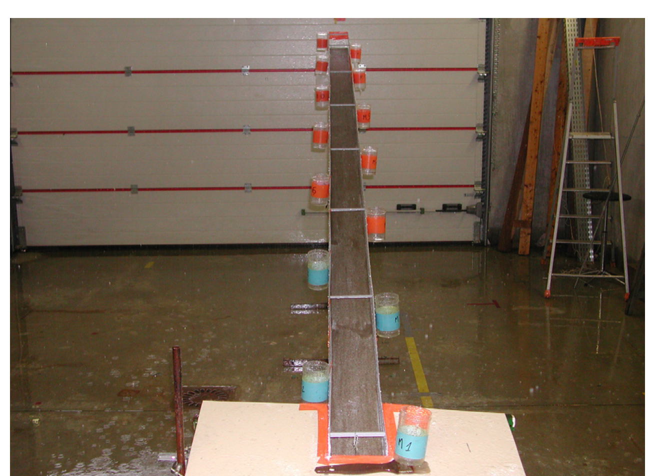

Fig. 2. Front picture of the flume in the Rainfall Simulation Hall.