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Multiple porosity shallow water models for macroscopic modelling of urban floods

Vincent Guinot *

Université Montpellier 2, HydroSciences Montpellier, CC MSE, Place Eugéne Bataillon, 34095 Montpellier Cedex 5, France

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ABSTRACT

A multiple porosity model is proposed for the macroscopic modelling of urban floods. The macroscopic flow field is described using different regions with distinct porosities, water depths and velocity fields. These regions can exchange mass and momentum based on water level difference. Street networks or alignments of buildings along preferential directions are accounted for by introducing anisotropic velocity distributions in some of the regions. Dead zones, storage yards in buildings and other stagnant areas are accounted for in the model. The mass and momentum exchange between the flow regions induce additional head loss terms. The proposed model can be formulated in differential form, thus making equation discretization method- and mesh-independent. Computational examples show that, although the representative elementary volume does not exist at the scale of an urban area, the proposed model can give reliable results compared to classical refined two-dimensional shallow water models, with a computational effort reduced by a factor 20–200 depending on the test case.

1. Introduction

A salient feature of free surface flow in urban areas is the strong variability of the urban geometry, that induces complex flow patterns. Although two-dimensional (2D) free surface flow models appear as promising tools for the modelling of urban floods [34], their use is hampered by a number of issues: the required level of detail for geometry description imposes typical mesh element sizes between 0.1 m and 1 m near singularities, while backwater effects most often preclude the isolated study of small areas without knowledge of the flow conditions in surrounding areas (except in areas with steep slopes and very shallow flows). Consequently, meshing entire urban areas within a two-dimensional flow model remains a time-consuming task, associated with huge computational operating costs. The development of parallelized versions of 2D models is increasingly seen as a solution to this problem [37,45].

An alternative consists in developing simplified models. Two approaches may be considered: (i) simplifying the mathematical description of the flow phenomena, or (ii) simplifying the description of the geometry.

- An example of the first approach can be found in [32]. A one-dimensional (1D) model is used for the street and urban drainage systems that exchange water with stagnant bodies [32]. In [33], a 1D model is coupled with a 2D storage cell model. In the 2D cells, a porosity is introduced to account for subgrid-scale topography variations, as proposed in [16]. The exchanges between the cells are modelled using a two-dimensional diffusive wave approximation. A similar approach is presented in [46,20] as an evolution of the original LISFLOOD-FP model [6]. A recent variation incorporates the influence of inertial terms in the 2D storage model, thus increasing computational rapidity of explicit discretizations of the governing equations [7]. Simplifying the mathematical description of the flow processes, however, does not always allow the computational burden to be eliminated, thus motivating the development of parallelized code versions [45].
- In the second option, the full two-dimensional description of the flow using the dynamic equations is retained, but the geometry is described using statistical descriptors of subgrid-scale features. This allows much coarser computational grids to be used. A typical example is the porosity-based model proposed in [18] and later developed by other authors [5,24,26,29,38,37,39]. In such models, the macroscopic properties of the urban geometry are accounted for by a porosity, that reflects the reduction in storage area and flow conveyance due to the presence of buildings and other urban singularities. In [30], the porosity approach is used in a different way: buildings are represented as porous media that can store water in the framework of a subsurface flow model. Although not satisfactory from the point of view of mass balance and wave propagation properties if the buildings do not store water, the model is shown to provide better results than classical models with increased roughness.

Recent experiments [10] tend to indicate that fully dynamic two-dimensional models for urban flood modelling give better

* Tel.: +33 (0)4 67 14 90 56; fax: +33 (0)4 67 14 47 74.
E-mail addresses: guinot@msem.univ-montp2.fr, vincentguinot@hotmail.com

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results than simplified descriptions such as diffusive wave-based descriptions. Therefore, this approach is retained in the present paper and the development effort focuses on increasing the accuracy of the macroscopic description of the urban geometry and flow features.

Two essential points about macroscopic models for urban floods are raised in [38]: (i) the relevance of the Representative Elementary Volume (REV) and (ii) the description of anisotropic features induced by preferential flowpaths in macroscopic models. The latter issue had been addressed previously in [29], with the conclusion that two different types of porosity should be defined: a "storage porosity" and a "connection porosity". However, at that time, no satisfactory definition or correspondence could be derived for these two types of porosity and they were assumed identical.

One of the conclusions of [38] is that macroscopic descriptors such as the porosity of the urban fabric are directionally dependent at the scale of the mesh elements, thus implying that the REV cannot be defined at this scale. The numerical experiments reported in [38] support this statement. They provide convincing evidence that an anisotropic porosity allows the macroscopic features of urban floods to be represented more accurately than by a classical isotropic porosity model such as derived in [18,26,29,39]. In [38], an improved macroscopic description is provided for singular head losses induced by urban singularities. This approach yields results comparable to those initially provided in [24,39]. Sanders et al. [38] also question the relevance of a differential writing of the governing equations when the discontinuous character of the urban geometry rules out differentiability.

Another point raised in e.g. [20] is the non-stationary character of some hydraulic parameters (such as the Manning coefficient) in the model with respect to changing grid resolution. In [20], the existence of critical mesh size with respect to the typical size of buildings and typical building spacing is shown. Upscaling two-dimensional free surface flow models for urban floods thus remains a challenging issue.

The purpose of the present work is to provide practical solutions to these issues. An improved 2D macroscopic model with porosity is proposed. The following conclusions are derived from the present work.

1. The accuracy of the macroscopic description of the flow model is increased dramatically by introducing a multimodal description of the velocity field. A multiple porosity model is proposed. The concept bears similarities with that of multiporosity/multipermeability used in fractured reservoir hydrodynamics [3,4,13,44]. The proposed model is mesh-independent and allows flow configurations to be modelled when a classical single porosity model fails to represent the macroscopic features of the flow.
2. Numerical experiments indicate that the multimodal description of the velocity field suffices to describe the head losses induced by buildings and building blocks obstructing the flow when sharp transients are dealt with. Using a special head loss coefficient proves to be useless in a number of cases. Head losses are obtained via the transfer of mass and momentum between regions flowing at different speeds. The formulation involves a discharge coefficient that must be fine-tuned, but numerical values can be provided a priori for this coefficient.
3. The multimodal velocity field also allows wave propagation speeds to be better described in the macroscopic model than in the original single porosity model. This was expected, because accounting for mass storage in dead zones near the main channel has been reported to be an influential factor to the propagation properties of flood waves [27].
4. It is indeed impossible to define the REV at the scale of the grid elements, even in a macroscopic model with porosity. This is because the size of the REV is generally one order of magnitude larger than the size of building blocks. It may even exceed the size of the urban area.
5. Although this should be expected to make the continuum-based description and the differential form of the equations invalid, this does not preclude macroscopic descriptions from being used successfully, even at spatial scales that are only a few times the size of the urban singularities, as shown by the application examples presented in Section 5.

This paper is structured as follows.

In Section 2, a dual porosity model with isotropic flow properties is presented. In Section 3, the approach is extended to a multiple porosity model with preferential directions to account for the influence of avenues and main streets. Section 4 is devoted to a discussion on the relevance of the REV, the implications of the multimodal velocity field description on head loss coefficients and the relevance of the differential formulation of the equations. The applicability of the proposed multiple porosity model is demonstrated in Section 5 using several computational examples and a comparison with experimental data. Section 6 is devoted to conclusions. Appendix A details the derivation of the governing equations for the isotropic model. Appendix B is devoted to the analysis of the wave propagation properties of an asymptotic version of the isotropic dual porosity model. The numerical implementation of the model is detailed in Appendix C.

2. Dual porosity model for isotropic flow

2.1. Conceptual model

The purpose of this model is to account for the presence of dead zones, or zones with very small flow velocities. Examples of such zones are inner building yards connected to the street network, water stored in building basements or apartments as a consequence of the flood, but also swirling zones in the wake of buildings when the velocity of the surrounding flow is large.

From a macroscopic point of view, the urban geometry is assumed to be represented by a porous medium. Consider a domain Ω in plan view. Three regions are distinguished (Fig. 1).

– Buildings. This region, denoted by Ω_b, is assumed impermeable to the flow. By definition, there is no water in this region. The fraction of space occupied by the buildings in plan view is $1-\phi$, where ϕ is the porosity, that is, the fraction of space available to water in plan view.
– Mobile water. This region is denoted by Ω_m hereafter. In this region, the water with depth h_m flows at a speed $\mathbf{u}_m$, thus yielding a unit discharge $\mathbf{q}_m = h_m\mathbf{u}_m$. The fraction of space occupied by the mobile water in plan view is denoted by ϕ_m, the mobile porosity.
– Stagnant water. This region is denoted by Ω_s hereafter. In this region, the water with depth h_s flows at a zero speed, $\mathbf{u}_s = 0$, thus yielding a zero unit discharge, $\mathbf{q}_s = h_s\mathbf{u}_s = 0$. The fraction of space occupied by the stagnant water in plan view is denoted by ϕ_s, the so-called stagnant porosity.

Note that with these definitions, $\phi = \phi_m + \phi_s$. Also note that, in the current version of the model, the porosities ϕ_m and ϕ_s are assumed constant in time. Although this may be wrong in a number of situations (especially if sharp transients occur near the transition between the mobile and stagnant regions), this simplification