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Research paper

A robust coupled model for solute transport driven by severe flow conditions

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Abstract

This paper introduces a computationally efficient model that solves a 4 × 4 matrix form of the hyperbolic conservation laws consisting of the 2D shallow water and advection-diffusion equations. The model allows automatic shock-capturing due to the implementation of a finite volume Godunov-type scheme featured with an HLLC approximate Riemann solver. The numerical scheme is also able to provide well-balanced solutions and maintain non-negative water depth and solute concentration for applications involving wetting and drying over complex domain topographies. Implemented on a simplified adaptive grid system, the model can save 3–17 times of computational cost without compromising solution accuracy for those simulations with predominant localised complex hydrodynamic or flow features, as demonstrated by the numerical experiments. Therefore, the current model provides a potential tool for efficient simulation of large-scale solute transport as well as flow hydrodynamics during a highly transient flood event caused by dam failure or flash flooding.
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1. Introduction

Recently in 2012, a number of severe flash flood events have been reported in different places around the globe. For example, in January 2012, with nearly 200 mm of rain recorded in 24 h, severe flash flooding occurred in different parts of Brisbane in Australia, not long after the massive 2011 flood had claimed 38 lives. In July 2012, a devastating flash flood killed 144 people in the Krasnodar Region in Russia, and Beijing in China, Uttarakhard in India and Manila in the Philippines have also since been struck. Most commonly associated with torrential rainfall, these flash floods are characterised by a sudden rise in the water level in rivers and floodplains and very high flow velocity. Due to their violent and unpredictable nature, flash floods pose a great threat to human lives and property. In a city, this type of flood events may strike and damage water treatment plants or other facilities that have potential to release pollutants. More commonly, water quality problem may be linked to surcharge of sewer systems under the extreme flood conditions that exceed the design capacity. This will affect public health and worsen the already devastated impacts of the flood that have posed on people. In order to facilitate the flood risk management associated with polluted flood water, it is important to have a robust model that can predict the fate of the point-source pollutant/solute that is transported by flood waves. In this context, a model should 1) allow shock-capturing as to accurately describe the violent flow hydrodynamics induced by flash floods including rapid wetting and drying processes, 2)

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be able to represent the complex topographic features in a real-world floodplain, especially in a developed urban area, and 3) be very efficient to facilitate risk analysis.

In the last two decades, due the availability of a rich source of high-resolution catchment and floodplain data and the development of computing hardware and modern computational methods, two-dimensional hydraulic flood modelling tools have been widely reported and applied in different types of flood management work. By using different form of the momentum equations, these hydraulic models may be generally classified as dynamic-wave, diffusion-wave and kinematic-wave models. Among them, the diffusion-wave models have gained particular popularity due to the use of substantially simplified governing equations and hence the possibility of increased computational efficiency (e.g. Bates and De Roo, 2000; Bates et al., 2010; Aricò et al., 2011; Wang et al., 2011). Aricò et al. (2011) and several references therein provided a more detailed discussion.

However, in relation to the aforementioned problem of pollutant spreading caused by dam breaks or flash floods, the flow and solute dynamics may be highly complex and involve discontinuous flood waves and contact interfaces over irregular domain topographies. Seeking reliable numerical solution to this type of problems is beyond the capability of the diffusion-wave or other simplified models. This requires a robust modelling tool with shock-capturing capability and it is more appropriate to solve simultaneously the shallow water and pollutant transport equations in an integrated form (Toro, 2001; Liang et al., 2003). The resulting integrated governing equations represent a system of hyperbolic conservation laws that possess the same mathematical property as the original shallow water equations. Therefore the shock-capturing Godunov-type numerical schemes that have been widely applied to solve the shallow water equations can be directly adopted to resolve the integrated conservation laws (Toro, 2001). A number of models of this kind have been reported in literature in recent years and most of them focus on seeking stable and well-balanced numerical solutions in the context a shock-capturing Godunov-type scheme for applications related to wetting and drying over rough terrains (Murillo et al., 2005, 2006; Benkhaldoun et al., 2007; Petti and Bosa, 2007; Murillo et al., 2008, 2009; Liang, 2010b; Murillo and García-Navarro, 2011; Cea and Vázquez-Cendón, 2012). Among these, the well-balanced finite volume Godunov-type scheme presented recently by Liang (2010b) was incorporated with a non-negative reconstruction technique and so is more suitable for practical simulations that involve wetting and drying over complex domain topographies. However, the model was originally developed on uniform Cartesian grids and may be computationally highly demanding in case of large-scale high-resolution simulations.

Allowing the density of the underlying computational mesh to be adjusted according to the flow solution during a simulation, adaptive mesh refinement (AMR) provides an effective way to improve numerical efficiency without compromising too much the solution accuracy. A number of different adaptive grid systems have been reported in literature to achieve AMR simulations. For example, an effective block-structured AMR was introduced by Berger and Oliger (1984) and Berger and Colella (1989), which was later implemented in Berger et al. (2011) for solving the shallow water equations and subsequently used by George (2011) for dam-break simulations. Due to their flexibility in performing grid adaptation, quadtree grids have been widely used to solve the shallow water equations for different applications, e.g. (Roger et al., 2001; Liang et al., 2003; Liang and Borthwick, 2009; Popinet, 2011). In order to further simplify the quadtree data structure for storing grid information, Liang (2012) recently proposed a simplified adaptive grid systems for solving partial differential equations. Starting from a non-uniform but locally structured grid, the simplified adaptive grid system allows dynamic grid adaptation by simply altering the subdivision level of a coarse background cell according to certain criteria. No data structure is required for neighbour finding. The new grid systems have been implemented in different numerical schemes (Wang and Liang, 2011; Kesserwani and Liang, 2012; Zhang et al., 2013) to solve the shallow water equations for flood simulations.

In this work, the model reported by Liang (2010b) will be incorporated with the simplified adaptive grid system to improve its performance for practical applications. Compared with its uniform grid counterpart, the new adaptive grid based model is able to produce results with similar solution accuracy but at a much lower computational cost. Therefore it has a better potential in large-scale simulations of real-world problems.

2. Grid generation

To enable solution adaption, a simulation generally starts from a non-uniform grid. This work proposes a simple grid adaptation strategy realized on a non-uniform Cartesian grid system recently reported by Liang (2011), which can be generated according to the following four steps:

1) Fit the computational domain into a rectangle (or square);
2) Discretize the rectangular domain by a coarse uniform grid, which is referred to as background grid hereafter;
3) Check each cell on the background grid and subdivide it by simply allocating specific subdivision levels according to certain criteria;
4) Regularize the grid to ensure that there is no computational cell having a neighbour more than two times bigger or smaller and this is called the 2:1 condition.

Fig. 1 shows a typical configuration of a final regularized grid, where the background cells $(I-1, J)$, (I, J) and $(I+1, J)$ respectively have a subdivision level of 0, 1 and 2. On such a grid, the structured property of a uniform grid is locally maintained and the neighbour information is entirely determined by simple algebraic relationships. Therefore, there is no necessity of explicit data structure to store the neighbour information and so it may be referred to as a structured but non-uniform grid (refer to (Liang, 2011) for details on neighbour

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