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A dual finite volume method scheme for catastrophic flash floods in channel networks

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ABSTRACT

This paper develops a new numerical scheme for flash floods based on the one-dimensional shallow water equations in channel networks, referred to as the dual finite volume method (DFVM) scheme. The scheme uses an upwind spatial discretization based on staggered meshes so that the flows in multiply connected channel networks are consistently handled without complicated treatment at junctions. The scheme is firstly examined with a series of test cases including idealized and experimental dam break problems to demonstrate its accuracy and versatility. The scheme is then applied to numerical simulation of a flash flood resulting from an earthquake-induced complete dam failure in Japan. Channels from a reservoir to the downstream rivers are modelled as a multiply connected channel network with non-prismatic cross-sections, steep slopes, and bends. The computational results agree well with the field observations and eyewitness reports. Numerical simulation of alternative scenarios as possible cases is also performed to analyze potential risks of the downstream area.

1. Introduction

Dams play a central role in basic human activities, such as agriculture and fishery. However, there are always potential failure risks associated with dams. The consequences of a dam failure can be catastrophic, potentially involving the loss of human life. A huge number of dam failures and resulting flash flood events have occurred throughout history. Singh [1] summarized more than 60 major historical dam failures throughout the world, including the Malpasset Dam failure in France [2] and the St. Francis Dam failure in the United States of America [3], both of which resulted in numerous deaths. Numerical simulation is an essential tool for effective flood risk analysis. Three-dimensional description of flash floods requires the use of a hydrodynamic model such as the Navier–Stokes equations [4,5]. Although hydrodynamic models exhibit high reproducibility for experimental water flows, such models are computationally very demanding and are still difficult to apply to numerical analysis of flows on natural topography. The most reasonable and efficient alternatives to the hydrodynamic models are the cross-sectionally averaged one-dimensional and the depth-averaged two-dimensional shallow water equations (SWEs) with the hydrostatic pressure assumption. Aleixo et al. [6] experimentally verified the relevance of the hydrostatic assumption for dam break problems. The SWEs are highly nonlinear and their closed-form solutions are only applicable to a limited number of cases, such as flows in prismatic and frictionless channels [7,8]. Therefore, numerical methods have generally been used to solve the SWEs in engineering applications.

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Shallow water modeling of flash flooding involves a number of difficulties, such as unsteady transcritical flows, irregular bed topography, and wet and dry interfaces. Development of accurate and robust numerical methods capable of solving the SWEs under such severe conditions is a challenging task. Most existing numerical schemes for the SWEs are classified as finite volume method (FVM) schemes with approximate Riemann solvers [9,10], which use analytical solutions to local Riemann problems in evaluating numerical fluxes on cell interfaces. Toro and Garcia-Navarro [11] extensively reviewed Godunov-type schemes as Riemann solvers and summarized future trends and recommendations for these schemes. Since the conventional Godunov-type scheme is, in general, too diffusive for capturing sudden flow transitions, high-resolution algorithms such as total-variation-diminishing (TVD) reconstruction based on slope limiters [12,13] and adaptive remeshing [14,15] must be incorporated. Other high-resolution schemes such as the discontinuous Galerkin finite element method (FEM) scheme [16], the essentially non-oscillatory (ENO) scheme [17], the weighted ENO (WENO) scheme [18], and multi-moment FVM schemes [19] have also been applied to the SWEs. On the other hand, researchers have developed sufficiently accurate numerical schemes without using approximate Riemann solvers or high-resolution algorithms. Sabbagh-Yazdi and Zounemat-Kermani [20] applied a Galerkin FVM scheme to the 2-D SWEs, adding a fourth-order artificial dissipation term as a stabilization technique. Ying et al. [21] developed an FVM scheme for dam break problems in non-prismatic and non-rectangular channels with a weighted average-based water surface treatment. Unami et al. [22] developed a cell-centered FVM scheme with a Froude number-based upwind method to predict dam break events in Ghanaian inland valleys, which actually occurred at a later date [23]. A one-dimensional counterpart of the scheme has also been developed [24].

For rapidly varied flows in steep and narrow channels in the presence of flow bifurcations and conversions in particular, such as river networks and mountainous valleys, the 1-D SWEs are more effective and computationally efficient than the 2-D SWEs [25,26]. In such cases, the domain of the flow is approximated as a locally one-dimensional open-channel network extending over the horizontally two-dimensional plane. Due to the singularity of the 1-D SWEs at junctions in the domains, appropriate internal boundary conditions are required in order to determine local flow behaviors around the junctions, causing difficulties in implementing high-resolution algorithms. Sanders et al. [27] simulated contaminant transport in tidal river networks by nesting a 2D model at junctions, so that the converging and diverging behaviors of the flows are accurately resolved. Capart et al. [28] developed a characteristic-based FVM scheme for the 1-D SWEs in natural channels and applied the scheme to flow routing of a typhoon-induced flood event in an existing river network. Kesserwani et al. [29] investigated several nonlinear internal boundary condition models for subcritical flows at junctions and compared them with a series of experimental data. Kesserwani et al. [30] carried out numerical analysis of free surface water flows at a T-shaped junction in the context of the 1-D SWEs with source terms for discharge and momentum losses by flow divisions. Trancoso et al. [31] developed a staggered FVM scheme for open-channel network flows and coupled this scheme with distributed hydrological models. Van Tsang et al. [32] applied a lattice Boltzmann method to shallow water flows in a complicated irrigation canal network equipped with hydraulic structures. Zhu et al. [33] established an efficient numerical method to deal with backwater effects at junctions based on the method of characteristics. Until now, only a limited number of studies have investigated flows in multiply connected (looped) channel networks with steep, non-rectangular, and non-prismatic channels. Since natural channels are typically irregular and have the above characteristics [34], an appropriate numerical scheme that can consistently deal with junctions and handles rapidly varying flows under severe computational conditions is strongly desired for reliable flash flood simulations.

Recently, Unami and Alam [35] proposed a versatile numerical scheme for rapidly varying flows in multiply connected channel networks, here referred to as the Finite Element/Volume Method (FEVM) scheme. The FEVM scheme applies the standard Galerkin FEM with linear basis and an upwind cell-centered FVM to the continuity equation and to the momentum equation, respectively, so that the flows at junctions are handled consistently. The FEVM scheme is explicit in time; however, it requires iterative matrix inversions at each time step. Ishida et al. [36] have developed a similar numerical scheme that has the same drawback. This study develops a more computationally efficient numerical scheme, referred to as the Dual-FVM (DFVM) scheme, which works effectively in preserving monotonic water surface profiles in some transient flows. The continuity equation is defined as a local integral in which junctions are dealt with as the implicit internal boundary conditions. Spatial discretization in the DFVM scheme is based on the concept of Voronoi diagram [37], which has been used to design staggered schemes for different transport equations, such as the 1-D SWEs in single channels [38], the 2-D SWEs [39], the governing equations of three-dimensional hydrostatic free surface water flows [40], and the advection–dispersion equations [41]. Application of the Voronoi diagram to the 1-D SWEs in channel networks has not been presented in the literature. In the DFVM scheme, water surface elevation and discharge are taken as the unknowns arranged in a staggered manner. A non-upwind, vertex-centered FVM and a cell-centered FVM employed in the FEVM scheme with a semi-implicit treatment of the friction slope term are applied to the continuity equation and to the momentum equation, respectively. The DFVM scheme is verified with a number of numerical tests in order to determine its accuracy. Finally, the DFVM scheme is applied to numerical simulation of catastrophic flash flooding that results from a recent earthquake-induced dam failure in Japan.

The remainder of the present paper is organized as follows. In Section 2, a brief introduction of locally one-dimensional open-channel networks and 1-D SWEs is provided. In Section 3, numerical formulation for the DFVM scheme is presented. In Section 4, the DFVM scheme is verified through a number of test problems. In Section 5, the scheme is applied to the numerical simulation of a recent flash flood caused by an earthquake-induced complete dam failure in Japan. Section 6 concludes this study.