Development of CCHE1D Model for Overland Flow Simulations on 2D Complex Domains

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Abstract

This paper presents enhancements of the one-dimensional (1D) CCHE1D channel network model, developed by National Center for Computational Hydroscience and Engineering (NCCHE), for overland flow simulations on two-dimensional (2D) complex domains. This study is based on the hypothesis that 1D models could be surrogates of 2D models for overland flow simulations on 2D complex domains by mimicking 2D models in computational mesh generation; and, with one dimension reduced, the surrogate model simulation would have acceptable accuracy with much higher computing efficiency. The whole study is divided into two parts: (1) the generation algorithm of 1D channel networks for 2D complex domains; and (2) the numerical simulations for verifying and validating the above hypothesis. The generation algorithm for 1D channel network follows two principles: (1) geometrically cover the whole domain without overlapping and interception; and (2) hydrologically follow the steepest slopes. Several benchmark cases based on laboratory and field-scale studies with complex topography were selected to demonstrate the generation algorithm and compare the CCHE1D model simulation with the CCHE2D-Hybrid model simulation. These numerical simulations demonstrated that the CCHE1D model is capable of efficiently simulating overland flow on 2D complex domains with comparable accuracy. This 1D surrogate modeling study of 2D overland flow can be considered a pilot study for rainfall-induced flooding and soil erosion problems, where 2D hydrodynamic models may have computing efficiency concerns and 1D models could be alternative modeling choices for fast solutions with comparable accuracy. The developed CCHE1D model can further be applied to evaluate soil erosion control practices for agricultural land management.

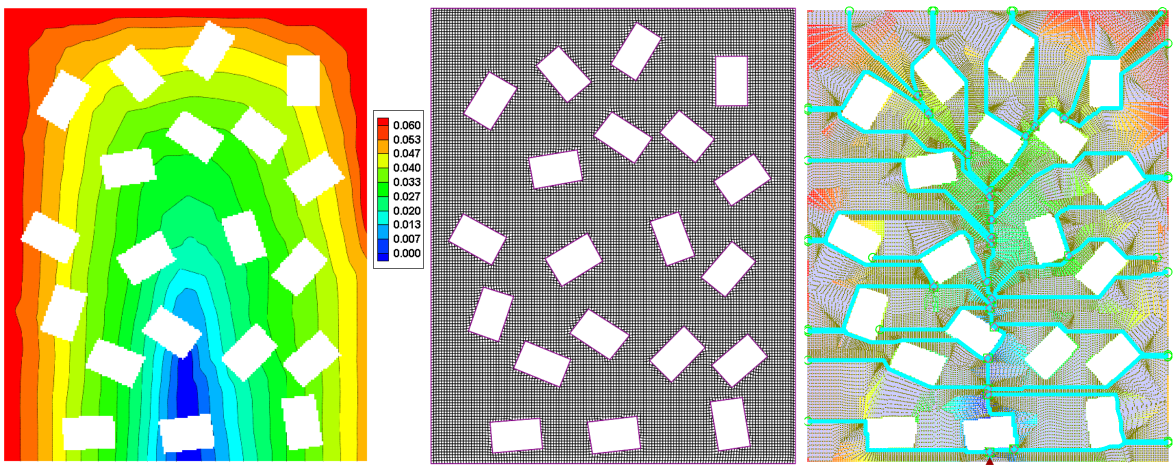
Methods

A 1D channel network model, CCHE1D model (Wu et al., 2004; Zhang, 2015), is selected in this study for overland flow simulations. The 1D results are compared to simulations using a 2D hybrid FVM (Finite Volume Method) model developed by Zhang et al. (2015). Based on the delineation tool developed by Zhang and Jia (2020), the proposed generation algorithm for 1D channel networks follows two principles: the geometric principle that the cross sections geometrically cover the whole domain without overlapping and interception, and the hydrologic principle that the channels hydrologically follow the steepest slopes.

Example and Application

An example based on the experimental study of rainfall-runoff conducted by Cea *et al.* (2010) is presented. The experiment was performed on a 2 × 2.5 m² rectangular domain with the designed bed slope of 0.05. There were twenty 20 × 30 × 34 cm³ buildings in eight different layouts in the domain. In this study, layout A20, as shown in Figure 1, was selected to compare the 1D model and the 2D model. Results from a rainfall event Q25T20 with an intensity of 25 l/min for 20 s are presented here.

Figure 1b shows one 2D hybrid mesh generated for these two domains using CCHE-MESH (Zhang, 2017), where the buildings were considered as interior boundaries. In the 1D channel network, there are 48 channels with 2989 computational nodes and 22 junctions. Figure 2 compares the simulated runoff at the outlet with that measured. Runoff simulated by both models compared well with measurements.



(a) Topography (b) 2D hybrid mesh (c) 1D channel network

Figure 1. Layout and topography of the study domain with irregular layout of buildings (experimental study of Cea *et al.*, 2010)

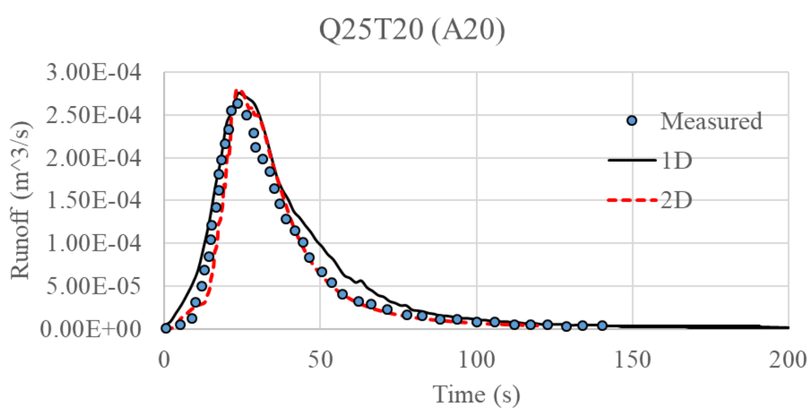
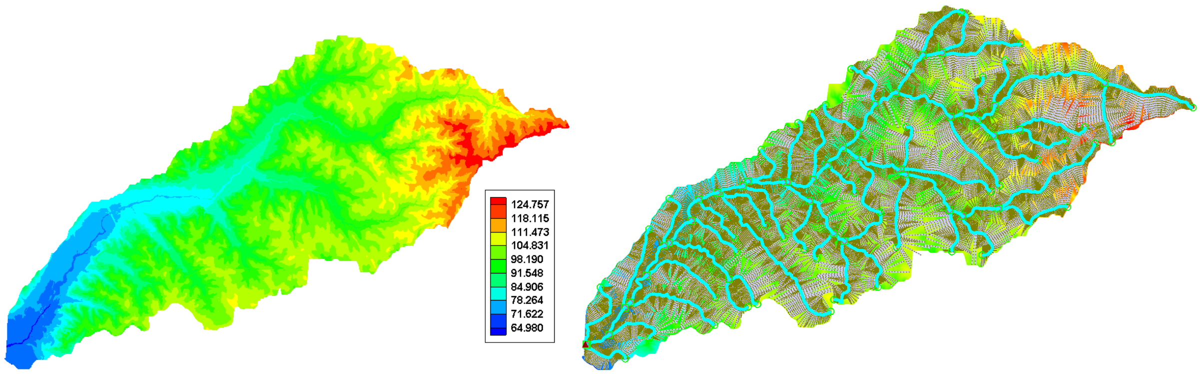


Figure 2. Runoff at the outlet of a rectangular domain with buildings (experimental study of Cea *et al.*, 2010)

The proposed 1D model was applied to the 21.3 km^2 Goodwin Creek Experimental Watershed (GCEW) in North-Central Mississippi, where USDA-ARS has long-term measured data. A 1 m resolution DEM of 2009 was used to represent the watershed's topography (Figure 3a). A 1D channel network of 86 channels, 42 junctions, and 3909 computational nodes was generated (Figure 3b). An unsteady rainfall event from 2/27/2009 to 2/28/2009 was selected (see Figure 4) for the runoff simulation. Infiltration was calculated by the Philip's method (Philip, 1957).



(a) A 1m DEM (10601 × 7400) (b) 1D channel network

Figure 3. Topography and 1D channel network of GCEW

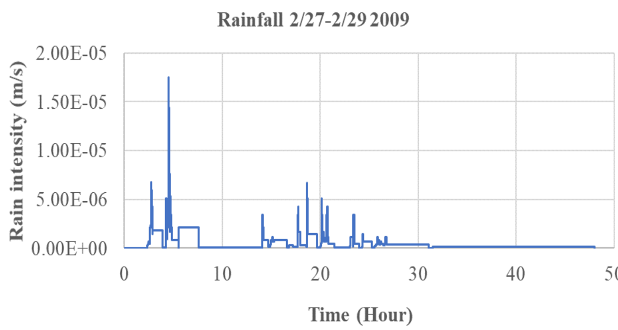


Figure 4. The rainfall event of 2/27-28 2009

The rainfall event lasted 48 hours and the total 2D model simulation time was 69.44 hours (= 250,000 s), which is computationally not affordable for 2D models, considering the 1 m high-resolution DEM. Figure 5 compares the simulated and measured runoff, where the general trend of runoff was well captured by the proposed 1D model, especially the first peak and the falling limb. However, the proposed 1D model under-estimated the second peak (the simulated 5.3 m^3/s is about 16.8% lower than the measured 6.38 m^3/s), and in the rising limb a phase discrepancy (about 16.5%) can be observed as well. The overall performance of the proposed 1D model demonstrates the capabilities of the model to simulate complex runoff conditions.

Conclusions

A study is presented based on a hypothesis that 1D models could be surrogates to 2D models for overland flow simulations on 2D complex domains; and with one dimension reduced, the 1D modeling would have much higher computing efficiency with comparable accuracy to the 2D model. Through comparisons in example and application, this study has numerically validated the proposed hypothesis as well as the effectiveness of the generation algorithm of 1D channel networks.

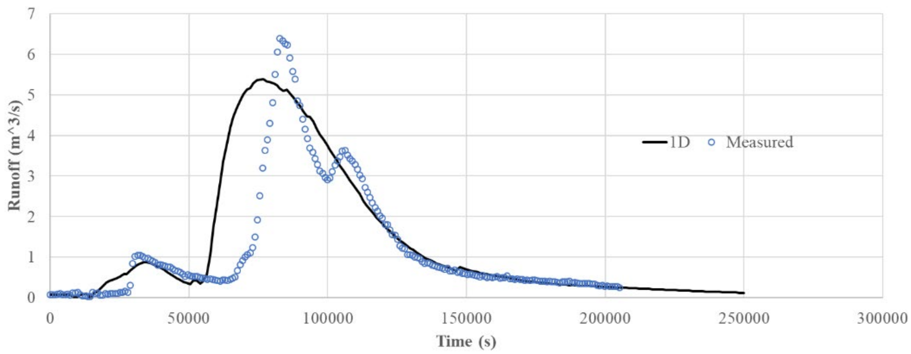


Figure 5. Comparison of simulated and measured runoff at the outlet of GCEW

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