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Research papers

Comparison of new generation low-complexity flood inundation mapping tools with a hydrodynamic model

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ABSTRACT

The objective of this study is to compare two new generation low-complexity tools, AutoRoute and Height Above the Nearest Drainage (HAND), with a two-dimensional hydrodynamic model (Hydrologic Engineering Center-River Analysis System, HEC-RAS 2D). The assessment was conducted on two hydrologically different and geographically distant test-cases in the United States, including the 16,900 km^2 Cedar River (CR) watershed in Iowa and a 62 km^2 domain along the Black Warrior River (BWR) in Alabama. For BWR, twelve different configurations were set up for each of the models, including four different terrain setups (e.g. with and without channel bathymetry and a levee), and three flooding conditions representing moderate to extreme hazards at 10-, 100-, and 500-year return periods. For the CR watershed, models were compared with a simplistic terrain setup (without bathymetry and any form of hydraulic controls) and one flooding condition (100-year return period). Input streamflow forcing data representing these hypothetical events were constructed by applying a new fusion approach on National Water Model outputs. Simulated inundation extent and depth from AutoRoute, HAND, and HEC-RAS 2D were compared with one another and with the corresponding FEMA reference estimates. Irrespective of the configurations, the low-complexity models were able to produce inundation extents similar to HEC-RAS 2D, with AutoRoute showing slightly higher accuracy than the HAND model. Among four terrain setups, the one including both levee and channel bathymetry showed lowest fitness score on the spatial agreement of inundation extent, due to the weak physical representation of low-complexity models compared to a hydrodynamic model. For inundation depth, the low-complexity models showed an overestimating tendency, especially in the deeper segments of the channel. Based on such reasonably good prediction skills, low-complexity flood models can be considered as a suitable alternative for fast predictions in large-scale hyper-resolution operational frameworks, without completely overriding hydrodynamic models' efficacy.

1. Introduction

With an increasing stress of climate and land use changes in recent times, flood events are becoming more frequent and perhaps more disastrous (Hirabayashi et al., 2013). In the past 30 years, estimated costs of average annual flood damage is approximately $8 billion within the United States (US) (National Weather Service – Hydrologic Information Center, 2016). Accordingly, there is a growing interest in regional to continental scale high/hyper resolution flood forecasting and risk assessment across various parts of the globe (e.g. Alfieri et al., 2013; Bierkens et al., 2015; Paiva et al., 2011; Pappenberger et al., 2012; Winsemius et al., 2013; Wood et al., 2011). Maidment (2015) proposed a modeling architecture to forecast streamflow in 2.7 million river

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reaches across the continental US, which became operational in 2016 under the National Water Model (NWM) framework (http://water.noaa.gov/about/nwm). Despite these advancements, translating streamflow forecasts into time-varying flood inundation maps with reasonable accuracy and speed remains an outstanding concern.

Hydrologic models contain a rainfall-runoff estimator and a channel routing scheme, therefore, another model component is required to simulate the over-bank conditions (i.e. flood inundation). Many model applications for inundation mapping exist in literature (Table 1). Out of these alternatives, Hydrologic Engineering Center-River Analysis System (HEC-RAS), with 1D flow simulation functionality, has been the principal model used in US Federal Emergency Management Agency (FEMA)'s National Flood Insurance Program (FEMA, 2015) and National Oceanic and Atmospheric Administration (NOAA)'s Advanced Hydrologic Prediction Service (NOAA, 2011). The ability of performing coupled 1D/2D analysis has been recently added to HEC-RAS (hereafter, HEC-RAS 2D; Table 1) which is still being tested under different geophysical settings. With a few exceptions of the LISFLOOD-FP model (e.g. Alfieri et al., 2014; Rajib et al., 2016; Schumann et al., 2013), most of the model applications listed in Table 1 are limited to small spatial scales over either a single river reach or a low-density river network.

Executing most of the hydraulic/hydrodynamic models requires modelers' intervention to provide substantial spatial details (e.g. channel and flood-plain cross-sections, optimum parameter values), which are often not readily available. Accordingly, the majority of these modeling packages come with a "black-box" configuration that can be executed only for research purposes in a stand-alone desktop environment (Kauffeldt et al., 2016; Néelz, 2009). These models also require considerable setup and computation time, especially with high resolution river networks. Accordingly, using a model that is as realistic as possible is not the panacea (Hunter et al., 2007); the choice should be balanced against several other considerations when it comes to the question of integration into a continental scale operational system such as the NWM.

Table 1
Existing models being applied by researchers and flood modeling communities along with those applied in current study.

	Model	Reference(s)	Developer (s)
1	FESWMS-2DH (Finite Element Surface Water Modeling System for 2D flow in the Horizontal plane)	Froehlich (1989) and Musser and Dyar (2007)	US Geological Survey
2	FaSTMECH (Flow and Sediment Transport with Morphological Evolution of Channels)	Kim et al. (2011) and Nelson et al. (2003)	
3	MIKE 11 1D, MIKE 21 2D and MIKE FLOOD 1D/2D coupled hydrodynamic suit of models	Ballesteros et al. (2011), Patro et al. (2009), Wright et al. (2008)	The Danish Hydraulic Institute
4	SOBEK 1D/2D	Vanderkimpen et al. (2009)	Deltares-Delft Hydraulics
5	BreZo/HiResFlood	Begnudelli and Sanders (2007), Nguyen et al. (2015a), Nguyen et al. (2015b), Sanders (2007)	University of California, Irvine, US
6	FLDWAV (Flood Wave Dynamic Model)	Fread (1998)	US National Weather Service
7	HEC-RAS (Hydrologic Engineering Center-River Analysis System) 1D	USACE (2014)	US Army Corps of Engineers
8	HEC-RAS (Hydrologic Engineering Center-River Analysis System) 2D*	Brunner (2014)	
9	LISFLOOD-FP	Alfieri et al. (2014), Bates and De Roo (2000), Bates et al. (2010), Rajib et al. (2016), Schumann et al. (2013)	University of Bristol, UK
10	AutoRoute*	Follum (2012) and Follum et al. (2017)	US Army Corps of Engineers
11	HAND (Height Above the Nearest Drainage) for continental US*	Maidment et al. (2016) and Zheng et al. (2016)	Liu et al. (2016)

* Models being applied and tested in current study.

Choice of a hydraulic/hydrodynamic model as component of a large scale framework is determined less by the superior model physics and more by its suitability to be executed in cyber infrastructures, computational overhead, interoperability with the driver hydrologic model, output retrieval, and visualization capabilities (Rajib et al., 2016). Being driven by such constraints, Follum (2012) introduced AutoRoute (Table 1) as a rapid tool to create flood inundation mapping over large scales. Using the simulated streamflow outputs from Tavakoly et al. (2017) as an input forcing to the AutoRoute, Follum et al. (2017) generated high resolution (~10 m) flood maps for the Midwest US (230,000 km^2) and the Mississippi Delta (109,500 km^2). Despite such intensive application, computational overhead for executing AutoRoute was remarkably small. Liu et al. (2016) adopted the concept of Height Above the Nearest Drainage (HAND; Nobre et al., 2011; Rennó et al., 2008) and transformed 10 m National Elevation Dataset (NED) for the continental US into a HAND raster. This HAND raster shows the relative height of a given location above the nearest reach in the nationally mapped river network (National Hydrography Dataset Plus). Maidment et al. (2016) featured several case studies based upon the loose coupling of NWM streamflow outputs with this HAND raster to generate near real-time flood inundation maps. Considering these recent advancements, it is timely to examine whether fast-computing, "low-complexity" inundation mapping tools with simplified input requirements and process-representations can be preferred from an operational standpoint, particularly in time-limited emergency response scenarios, over computationally exhaustive, input intensive, physics based and presumably accurate hydraulic/hydrodynamic models.

Ability to capture natural floodplain processes and the influence of man-made control structures is different in each model. No model has the perfect realization of flooding; hence, simplification of the model physics may further undermine its already-limited ability. In this regard, a multi-model comparison can help measure relative accuracy of each model. Previous studies are heavily skewed towards the comparison of 1D versus 2D hydraulic/hydrodynamic models (Cook and Merwade, 2009; Alho and Aaltonen, 2008; Benjankar et al., 2014; Horritt and Bates, 2002; Leandro et al., 2009; Tayefi et al., 2007; Vojinovic and Tutulic, 2009). Several studies have compared different 2D models (Horritt and Bates, 2001; Vanderkimpen et al., 2009) or the same model under different configurations of topographic resolution and/or surface roughness (Bates et al., 2003; Cook and Merwade, 2009; Horritt and Bates, 2001; Mason et al., 2003; Pappenberger et al., 2005). Effects of other geophysical and man-made attributes including channel bathymetry, levees, and bridges on model-simulated flood inundation has remained relatively unexplored (e.g. Cook and Merwade, 2009; Pappenberger et al., 2006).

The new-generation low-complexity inundation mapping tools, such as AutoRoute and HAND, have not been compared with each other, or with advanced hydrodynamic models (e.g. HEC-RAS 2D). Although AutoRoute was compared with reference inundation extents (Follum et al., 2017), HAND's efficacy is yet to be tested. This study, developed upon the preliminary work of Afshari et al.