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The validity of flow approximations when simulating catchment-integrated flash floods

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ABSTRACT

Within hydrological models, flow approximations are commonly used to reduce computation time. The validity of these approximations is strongly determined by flow height, flow velocity and the spatial resolution of the model. In this presentation, the validity and performance of the kinematic, diffusive and dynamic flow approximations are investigated for use in a catchment-based flood model. Particularly, the validity during flood events and for varying spatial resolutions is investigated. The OpenLISEM hydrological model is extended to implement both these flow approximations and channel flooding based on dynamic flow. The flow approximations are used to recreate measured discharge in three catchments, among which is the hydrograph of the 2003 flood event in the Fella river basin. Furthermore, spatial resolutions are varied for the flood simulation in order to investigate the influence of spatial resolution on these flow approximations. Results show that the kinematic, diffusive and dynamic flow approximation provide least to highest accuracy, respectively, in recreating measured discharge. Kinematic flow, which is commonly used in hydrological modelling, substantially over-estimates hydrological connectivity in the simulations with a spatial resolution of below 30 m. Since spatial resolutions of models have strongly increased over the past decades, usage of routed kinematic flow should be reconsidered. The combination of diffusive or dynamic overland flow and dynamic channel flooding provides high accuracy in recreating the 2003 Fella river flood event. Finally, in the case of flood events, spatial modelling of kinematic flow substantially over-estimates hydrological connectivity and flow concentration since pressure forces are removed, leading to significant errors.

1. Introduction

Both due to climate change and population growth, global risk for fluvial floods has been found to increase (Kron et al., 1999; IPCC, 2012; Hirabayashi et al., 2013). Different processes can lead to flooding in an area, and based on the perception of the dominant process, different types of floods are recognized in Disaster Risk Management. Flash floods are characterized by both the spatial and temporal scales in which they take place. They often take place in or close to upstream runoff generating areas and are characterized by rapid release of water from a catchment. This type of flood event often takes place within a few hours of the rainfall event and often lasting less than a day. The dynamics of a flash flood are closely related to the dynamics of the rainfall event. The dynamics of floods that are generated by an overflowing river channel vary according to the spatial and temporal scales of the catchment. When the dynamics of the flood depend less on the rainfall characteristics and more on the characteristics of the contributing river system (the incoming wave) we tend to term these slower and long lasting floods as 'fluvial floods'. Other mechanisms of flooding are a rise of groundwater above the surface, and poor drainage in flat areas with excessive rainfall. While physically similar, it makes sense to recognize and define different flood types from a disaster risk reduction perspective, as people have developed a sense of the associated problems, the timing needed for early warning, and a certain impact with these different flood types. In this analysis, we focus on flash flood events, which cause substantial damage in various regions around the world (Re, 2005; Schiermeier, 2006). Thus, research into understanding of the hydrological processes that precede (flash) flood events and analyzing best ways of simulating flow dynamics is of key importance.

Spatial numerical modelling is commonly used to investigate both flash floods and the preceding hydrological processes. Within numerical models, flow approximations are widely used to provide appropriate and efficient simulation of water flow (Te Chow, 1964; Tsai, 2003). Water flow on the surface can be simulated by solving a mass and momentum balance, using gravity, pressure differences

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and momentum. Under different environmental conditions, pressure differences and/or inertial momentum are not included in numerical solutions for flow. In practice, two types of model systems are used for flood modeling: a) decoupled systems, in which the source areas are separated from the flooded areas; and b) integrated catchment models. The decoupled model systems have essentially two models, one that generates an incoming discharge wave and one that simulates the flood process from this incoming discharge. The advantage is that both model systems can be separate, with different principles, scales and resolutions. Upstream models divide space in regular gridcells or polygons representing landscape elements, and even entire subcatchments that generate runoff which is collected in a stream network to create a discharge wave. Downstream flood models can adopt a gridcell size optimal for flood modelling. The disadvantage is the assumption that there are a few clearly defined inflow points (which is not always the case). Examples of this type of models are Hec-HMS (Scharffenberg & Fleming, 2006), Hec-Ras (Brunner, 1995), TuFlow (BMT WBM, 2010) and Mike-She (Prucha et al., 2016). The second type of models are integrated catchment models, that simulate the complete hydrology and flow, generating runoff, leading to discharge and then to flooding. The advantages are that there are no entry points but instead open boundaries where runoff can lead directly to flooding, the disadvantages are that there is generally one spatial resolution for the entire domain, and computationally these models can be less efficient.

While integrated catchment models require more computation, depending on the event they can be required for accurate simulations. In many situations, flash floods cannot be simulated with a decoupled model system. Often a flash flood is not strictly related to an overflowing channel, as they occur in accentuated terrain. Sloping areas are prone to overland flow that adds directly to the flood water, especially in hilly urban areas where impermeable surfaces dominate. Flash floods are often a combination of an overflowing channel, overland flow and even direct rainfall. Also, rapid changes in water height and fluxes may occur over short distances which need robust numerical solutions to cope with. Examples of integrated catchment models are FLO-2D (O'brien, 2007) and TREX (Velleux, England & Julien, 2008). Both these models however use simplified equations to describe flow behavior. Recent approaches to integrated flood simulations in a catchment model use hybrid modelling. Bellos and Tsakiris (2016) combined the FLO-R2D model (Tsakiris & Bellos, 2014) and unit hydrograph theory. Nguyen et al. (2015) developed the HiResFlood-UCI model, which uses the output from a lumped rainfall-runoff model for their flood simulation. However, both methods use clumped runoff, and have limited interactions between flood water and other hydrological processes such as rainfall and infiltration. While both these approaches thus provide improvement over traditional methods, a fully integrated approach to simulate floods in a catchment model could improve understanding of the processes that lead to floods.

In the majority of models that include hydrology and flow routing, three ways of routing are used to simulate surface and channel flow. The kinematic flow approximation, which simplifies water flow by neglecting pressure and inertial momentum, gained popularity in the early years of numerical modelling for its computationally efficient and robust estimations of flow patterns. Kinematic wave solutions use a predefined converging flow network that connects the spatial elements (e.g. through the steepest slope) and the channel system. This means that there is always connectivity between the spatial elements, the flow does not have to fill up small storages before it can continue. The only way to influence the timing of the flow is by the surface friction parameters. Models such as SWAT (Arnold et al., 1998), and Trex (Velleux, England & Julien, 2008) use clumped and spatially routed kinematic flow respectively. The diffusive flow approximation implements pressure in the momentum equations. Using this method, models such as LISFLOOD (Van Der Knijff et al., 2010) approximate flood behavior. For detailed spatial modelling of flood behavior, the Saint-Venant equations (dynamic wave) for shallow flow are commonly used. This approximation, which requires more computation, is used by models such as CCHE2D, CH3D (Wu, 2001), Hec-Ras (Brunner, 1995), TuFlow (Syme, 2001), 3DI (Dahm et al., 2014) and Delft 2D (Deltares Hydraulics, 1999). Both the diffusive wave and dynamic wave use the DEM directly and water pressure differences between spatial elements and momentum allow the flow to converge and diverge. Connectivity is not pre-defined, local storages can exist and need to fill before the flow continues.

While the implementation of flow approximations improves efficiency, both the spatial and temporal scale of the simulation determine the validity of the approximation. The validity then limits the possible application of models to the temporal and spatial scales of flash floods (Tsai, 2003). In practice this is largely ignored: the availability of high-resolution data has increased strongly in the past decades (with for instance LIDAR derived digital terrain models). The general tendency in thinking is that a higher resolution offers greater accuracy, but it ignores the validity of flow approximations. Furthermore, during flash flood events, high water heights, flow velocities, and small spatial resolutions influence the validity of kinematic and diffusive flow further. Therefore, a detailed investigation into the influence of flow approximations on flash flood modelling is required.

The objective of this paper is to investigate the influence of spatial resolution on the validity of the kinematic, diffusive and dynamic flow approximations for use in integrated flood modelling. This investigation is separated into two parts. First, the behavior of these flow approximations for spatial runoff modelling is investigated for several spatial resolutions. Secondly, the flow approximations are coupled with channel flooding, and the influence of flow approximations on the flood simulation is investigated. Study catchments from China (Hessel and van Asch, 2003) and Spain (Baartman et al., 2013) are used with a spatial resolution of 10 and 20 m to investigate runoff behavior. For flooding, calibration is performed on 20, 40 and 80 m spatial resolution from the Italian alps (Borga et al., 2007). Calibration is performed on discharge data for those catchments. The open source Limburg Soil Erosion Model (OpenLISEM) (Jetten, 2002; Starkloff and Stolte, 2014; Hu et al., 2015) is to perform the simulations. Kinematic, diffusive and dynamic flow are implemented for overland and channel flow dynamics. In order to simulate flooding in a catchment environment, dynamic wave channel flooding is included in all three combinations. For each combination, flow types are fully linked with both each other and other hydrological processes (explained below).

2. Theory

For the simulation of overland and channel flow, three commonly used approximations for water flow have been implemented: Kinematic flow, diffusive flow and Saint-Venant flow. For the simulation of channel flooding, Saint-Venant flow is used. In this section, the derivation and required assumptions for these flow approximations are described.

In order to describe continuity of any substance with advection, the mass balance equation is the basis (Eq. (1)).

$$\frac{\partial h}{\partial t} + \frac{\partial (hu_x)}{\partial x} + \frac{\partial (hu_y)}{\partial y} = R - I \tag{1}$$

where h is the flow height (m), u is the flow velocity ($m\,s^{-1}$), R is the rainfall (m) and I is the infiltration (m).