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.

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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
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 modelling: 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 griddells 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 behaviour. 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 CCH2D, CH3D (Wu, 2001), Hec-Ras (Brunner, 1995), TuFlow (Syne, 2001), 3D (Dahm et al., 2014) and Delft 2D (Deltas 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 flood flash 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 modeling. 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 ($m$).
This equation is valid for all the implemented flow approximations and forms the basis for the numerical methods. In the rest of this section, equations that describe conservation of momentum for the flow approximations are stated.

2.1. Dynamic flow

The momentum balance equations for water flow approximations are typically derived from the Navier-Stokes equations for incompressible flow. When this set of equations is depth averaged and internal friction forces are neglected, the Saint Venant equations result (Barré de Saint-Venant, 1871) (Eqs. (2) and (3)).

\[
\frac{\partial u_x}{\partial t} + \frac{\partial (hu_x^2 + \frac{1}{2}gh^2)}{\partial x} + \frac{\partial (hu_xu_y)}{\partial y} = gh(S_x - S_{f,x})
\]

(2)

\[
\frac{\partial u_y}{\partial t} + \frac{\partial (hu_x^2 + \frac{1}{2}gh^2)}{\partial x} + \frac{\partial (hu_xu_y)}{\partial y} = gh(S_y - S_{f,y})
\]

(3)

Here \( g \) is the gravitational acceleration (m/s²), \( S \) is the bed slope term (–), and \( S_{f} \) is the bed friction term (–).

The friction slope terms, which are the friction forces divided by the water height and the gravitational acceleration, can be calculated using the Darcy-Weisbach friction law (Te Chow, 1964) (Eqs. (4) and (5)).

\[
S_{f,x} = n^2 \frac{u_x |u_x|}{h}
\]

(4)

\[
S_{f,y} = n^2 \frac{u_y |u_y|}{h}
\]

(5)

where \( n \) is Manning’s n friction coefficient (m/s).)

2.2. Diffusive flow

In the diffusive flow approximation, inertial terms are assumed very small when compared to other acceleration terms. When the inertial terms are neglected, velocity is determined predominantly by hydraulic gradient, friction forces and the gravitational force. This assumption leads to a simplified set of equations (Eqs. (6) and (7)).

\[
\frac{\partial h}{\partial x} = (S_{f,x} - S_x)
\]

(6)

\[
\frac{\partial h}{\partial y} = (S_{f,y} - S_y)
\]

(7)

2.3. Kinematic flow

In the kinematic flow approximation, both inertial acceleration and acceleration due to a hydraulic gradient are assumed very small when compared to the other acceleration terms. In this assumption, velocity is, at any moment, determined by the friction and gravitational force (Eqs. (8) and (9)).

\[
0 = (S_{f,x} - S_x)
\]

(8)

\[
0 = (S_{f,y} - S_y)
\]

(9)

In this set of equations, the velocity depends directly on a balance between gravitational and friction forces and flow always moves in the direction of steepest descent. Solving the kinematic flow equations with Manning’s friction law leads to Manning’s law for overland flow velocity (Te Chow, 1964) (Eq. (10)).

\[
u = R^2 \frac{\sqrt{q}}{n}
\]

(10)

where \( u \) is the flow velocity (m/s), \( R \) is the hydraulic radius (m) and \( n \) is the Mannings coefficient of the surface (m/s).)

2.4. Hydrology and data layers in openLISEM

The flow methods described in this paper have been used to further the development of OpenLISEM, which is open source and freely available. The integration of flooding into the model allows the detailed investigation into the processes that lead to the flood event. The OpenLISEM model implements multiple types of infiltration models such as Smith & Parlange (1978) and the SWATRE full vertical soil water balance model (Bastiaanssen et al., 1996). The simulations in this paper use the Green & Ampt infiltration model, which assumes a wetting front moving down into the soil due to infiltrating rainfall (Green & Ampt, 1911). The resulting potential infiltration is subtracted from the available surface water (Eq. (11)).

\[
f_{pot} = -K_s \left( \psi \frac{\theta_i - \theta_b}{F} + 1 \right)
\]

(11)

where \( f_{pot} \) is the potential infiltration rate (m/s), \( F \) is the cumulative infiltrated water (m), \( \theta_i \) is the porosity (m³/m³), \( \theta_b \) is the initial soil moisture content (m³/m³), \( \psi \) is the matric pressure at the wetting front (h = \( \psi + Z \)) (m) and \( K_s \) is the saturated conductivity (m/s).)

Input data consists of soil, land surface and terrain properties, and can be defined on a sub-cell basis by using fraction maps as input (Fig. 1). The infiltration of water and routing of overland flow are fully coupled and thus computed for each numerical timestep. Further details on the underlying physical principles of OpenLISEM can be found in Baartman et al. (2012a) and Jetten (2002) and De Roo et al. (1996).

2.5. Numerical implementations

The numerical implementations of flow equations can, if not appropriate, influence behavior and validity. A numerical method should be appropriate to the assumptions of the equations and provide a stable, accurate and realistic simulation. Therefore, separate numerical methods were implemented for the flow approximations. The numerical methods that were implemented during the development stages of OpenLISEM are presented in this section.

2.6. Saint-Venant flow – cell-boundary fluxes

The implemented solution for Saint-Venant flow is based on the FullSWOF2D library (Delerste et al., 2014). This library uses a Monotonic Upstream Cell-Centered (MUSCL) scheme to provide a second order spatial accurate solution. This method uses a linear approximates of the flow parameters on the cell boundaries in order to calculate the flow at these boundaries (Fig. 2). The estimation of cell interface fluxes furthermore corrects for elevation differences based on a hydrostatic reconstruction (Audusse et al., 2004). This results in a solution that is both Total Variation Diminishing and preserves a steady state at rest. Using the Harten-Lax-van Leer Riemann-solver, shock-wave behavior is captured (Harten et al., 1983). Finally, new water heights are calculated using the hydrostatic reconstruction. In order to gain second order accuracy in time, Heun’s predictor-corrector method is used, which is a 2 step-Runga-Kutta solver.
2.7. Diffusive flow – bilinear interpolation

If inertial acceleration terms are ignored, behavior will become unnatural surrounding local depressions in elevation. While Tayfur and Kavas (1994) use a cell-boundary based method to solve diffusive and kinematic flow, Liu et al. (2004) note that irregularities in the Digital Elevation Model (DEM) cause difficulties for such a method. Thus, we implement a distinct advection scheme in order to solve diffusive flow. For any cell, the location of the water volume is updated by the velocity (Fig. 3). The water volume is then distributed to the cells that surround the new location (Courant et al., 1952).

2.8. Kinematic flow – flow network

A numerical solution for kinematic flow must be coherent with the assumptions that lead to the kinematic flow approximations. Pressure forces are ignored and flow directions are completely determined by terrain slope. Because of this, converging slopes will cause unnatural, oscillating, behavior. To avoid this unnatural behavior, kinematic flow is implemented using a pre-defined flow direction network (Fig. 4).

This network must ignore any local depressions to ensure validity of kinematic flow. Furthermore, the flow direction network allows for a one-dimensional implementation of kinematic flow along the network, strongly increasing computational speed. Creation of this network is done using the Open-Source freeware Raster GIS PCRASTER (Karssenberg et al., 2010).

2.9. Connecting one and two-dimensional flow

Channel flow can be simulated in one dimension using the same equations as for overland flow. Within the model, the channel is assumed to be rectangular, with limited flow depth. To calculate the inflow from the land surface into the channel, it is assumed that the direction of overland flow, in cells containing channels, is perpendicular to the channel direction. The channel is furthermore assumed to be located in the middle of the cell. This way, using the channel width and flow velocity, the fraction of runoff water that flows into the channel can be calculated (Eq. (12)).

\[ f_{\text{wh}} = \frac{dtu}{0.5(C_{xy} - B_c)} \]

where \( B_c \) is the channel width at the surface (m).

Similar methods have been shown to provide accurate estimations of channel inflow (Bradbrook et al., 2004; Yin et al., 2013). Channel overflow immediately adds to flooding. If the channel

![Fig. 1. The input data for OpenLisem (left), and a simplified flowchart (right).](image1)

![Fig. 2. The MUSCL scheme performs piece-wise linear interpolation.](image2)

![Fig. 3. Cell coordinates, discharge and an advected cell. \( \Delta x \) and \( \Delta y \) are the cell length in the two spatial dimensions.](image3)

![Fig. 4. An example of a local drainage direction file (Karssenberg et al., 2010).](image4)
has extra capacity, available flooding water is likewise immediately transported into the channel (Fig. 5).

### 2.10. Connecting overland flow and flooding

Besides channel water, overland flow enters and thus adds to the flood volume. When overland flow and channel flooding are not approximating using the same method, their interactions cannot be solved based on normal Saint-Venant flow. In reality, overland flow water must be added to the flood depth and an exchange of momentum takes place. For the kinematic and diffusive wave, momentum conservation neglects important terms that are present in the flood water. Therefore, the process of overland flow mixing with flood water is approximated using an empirical relationship (Eq. (13)).

\[
f_{rf} = \min \left(1, 0.1 - e^{-\frac{h_f}{h_r}}\right)\tag{13}
\]

where \(f_{rf}\) is the fraction of runoff water transferred to the flood water, \(c_r\) is a coefficient (–), \(h_f\) the flood depth (m) and \(h_r\) is the overland flow depth (m). Here, the \(h_f\) and \(h_r\) are at each moment taken from the local flow properties. The coefficient \(c_r\) is purely based on modelling experience generally taken to be 2.0, since flood artifacts disappear at this value.

Using this approximation, Overland flow water is gradually transferred to the flood water while it does not unnaturally affect flood momentum.

### 3. Materials and methods

Three study sites are used to investigate the validity of the implemented flow approximations. An overview of the topography, saturated conductivity and manning’s N for these catchments are shown in Figs. 6–8.

The first of these is the Danangou catchment, a rural area in the Loess plateau in China, where soil erosion is a major problem due to agriculture on steep slopes and the erodibility of loess soil (Hessel and van Asch, 2003). This area was previously used by Hessel et al. (2003a, see also Hessel et al., 2003b; Hessel & van Asch, 2003; Hessel & Jetten, 2007) to calibrate and validate a previous version of the LISEM model. This 257 ha region is characterized by steep slopes (>20°) large eroded gullies. Land use consists predominantly of woods, wild grasslands and parts of cropland in the upper regions. For this catchment three precipitation events from 20-07-1999, 23-08-1998 and 01–08-1998 will be used. The events were recorded by three rainfall gauges in the area, and rainfall maps based on the nearest station are therefore used as input. The rainfall events are typically characterized by short bursts of intense precipitation, with durations around 30 min, intensities up to 100 mm/h and high spatial variability. During such events, hydraulic conductivity is a limiting factor in the amount of infiltration. Together with measured rainfall intensity, discharge after these events is available for every two minutes. More details on the events and area are available in Hessel et al. (2003a). The spatial resolution of this dataset is 10 m. The channel network in the area consists of small not-channelized streams and gullies that converge near the main outlet. For validation and calibration, discharge data is available at a 2 min interval. Discharge values have been estimated using water height timeseries at a weir and a stage-discharge curve.

A second catchment in Prado, South-Eastern Spain, will be used. This 50 km² semi-arid region experiences between 250 mm and 530 mm of rainfall each year. The area has previously been used with LISEM by Baartman et al. (2013; Baartman et al., 2012a; Baartman et al., 2012b). Land cover consists mainly of natural shrubs, forests and dryland farming such as cereals. Soil information was obtained by Baartman et al. (2013) using in-situ measurements of all parameters required for OpenLISEM. The soil types are primarily Calcic Cambisols and Calcaric Fluvisols. Rainfall data is available for three rainfall events on 29-09-1997 (top), 09-12-2003 (middle) and 17-10-2003(bottom) (Baartman et al., 2012a). The events have a total rainfall of 19.7, 26.9 and 49 mm respectively, and a duration of around 2 h. The channel network in the area consists of small not-channelized streams and gullies that converge near the main outlet. Discharge data has been gathered at the outlet of the described catchment at a 5 min interval. Discharge values have been estimated using water height timeseries at a weir and a stage-discharge curve. The spatial resolution of this dataset is 20 m.

The third catchment is a 164.5 km² region along the northern Italian Alps that has been investigated by Chen et al. (2014). Land use in the region consists mainly of multiple types of forest and heathland in the upslope areas, and small build-up regions in the lower. Rainfall data is available for an intense precipitation event on the 29th of August 2003, which took place after several weeks of droughts and had a return period between 200 and 500 years.

**Fig. 5.** Coupling of overland flow, channel flow and flooding. The channel acts as a main link between the flow domains.
(Norbiato et al., 2007). Peak rainfall intensity reached 81 mm/h during an hour at Pontebba, located at the outlet of the selected catchment. Here, total precipitation for the event of 389 mm. For a detailed description of the precipitation event on the 29th of
August 2003 and the methodology in estimating the rainfall intensities, see Borga et al. (2007). Multiple upslope branches of tributaries of the Fella River experienced flash flooding at small drainage areas (Borga et al., 2007; Nikolopoulos et al., 2013). Besides flooding, the area experienced severe geomorphic impacts during the event, which might have influenced the flow dynamics (Marchi et al., 2009). The river network in the area consists of many non-channelized steep side branches, leading to the fella river. The main river branch has a wide base (>25 m) and features culverts near the local highway. The outlet discharge data for this event is based on a stage-discharge relationship, and is available for every half hour. The location of this outlet is the Fella river at Pontebba (Borga et al., 2007). During a post-event survey, peak discharge estimates were determined for one additional location in the catchment: Uqua at Ugozivza (Borga et al., 2007). The dataset for this catchment was made as part of the IncREO project (Increasing Resilience through Earth Observation-IncREO). An elevation model and land use map were made available from the project. The alpine area features steep slopes and the majority of the area is covered by coniferous forest. Soil information was collected from the ISRIC database, Wageningen (Hengl et al., 2017) and literature data from Saxton and Rawls (2006). The majority of the area has loam-like soil characteristics. The vegetation index was derived from spot-4 satellite images. The available spatial resolutions are 20, 40 and 80 m.

3.1. Simulated scenarios

To investigate the performance of the described flow approximations, several are used to simulate identical scenarios on the Danangou and Prado catchments. The used flow approximations are: kinematic, diffusive and dynamic flow for overland flow and respectively kinematic, kinematic and dynamic flow for channel flow. Based on the best calibrated simulation, performance of the flow approximation will be analyzed. Furthermore, spatial patterns in flow height are used to see how the flow approximations and processes such as infiltration influence each other.

To investigate the performance of the flow approximations in flash flood modelling, the Fella basin is simulated using all combinations of flow approximations. This includes kinematic, diffusive and dynamic overland flow. These types of overland are combined with respectively kinematic, kinematic and dynamic flow for the channels. Finally, these flow approximations are combined with dynamic channel flooding, leading to a total of 5 combinations of flow approximations. To investigate the influence of spatial resolution on the performance of these flash flood simulations, spatial flood depth is analyzed for the distinct flow approximations and spatial resolutions.

3.2. OpenLISEM input data

The input data of OpenLisem can be separated into three categories. Firstly, a catchment description has to be provided in the form of spatial rasters. The provided catchment data was already available in the correct raster format. Preparation of the dataset was performed using the PCRaster open-source GIS package (Karssenberg et al., 2010). For both the Danangou and Prado catchment, maps of soil and land cover parameters were available. In the case of the Fella river basin, the original dataset has a spatial resolution 20 ms. Using PCRaster, this dataset was resampled to 40 and 80 m resolution. On the resampled elevation models, a simple pit filling algorithm was used to restore flow pathways. Secondly, boundary conditions have to be provided to complete the description of the event. Time series of catchment-averaged rainfall intensity were available as text tables for the Prado and Fella Catchments. These were used as input in OpenLISEM. From these tables, spatially homogeneous rainfall over the catchment area was assumed. A list of four rainfall stations combined with station locations were available for the Danangou catchment. Based on these rainfall stations, spatial maps of rainfall intensity were made that assigned every cell the rainfall intensity of the closest rainfall station. These were then used as input for OpenLISEM to provide spatial rainfall during the simulation. Outflow boundary conditions were set to allow outflow at any point. No inflow besides rainfall was specified for the simulations. Finally, the OpenLISEM simulation parameters are required. A table of these parameters for the described datasets is shown in Table 1.

3.3. Calibration

For all the described study sites, the simulations are calibrated to discharge data. Discharge data was available with a 10 min resolution for the Prado catchment, a 30 min resolution for the Fella catchment and a 15 min resolution for the Danangou catchment. While several measurements were removed for several reasons, the available data provided enough certainty in the calibration process. To calibrate the simulations, the saturated conductivity, Manning’s coefficient and initial soil moisture content is varied. These parameters have been found to have the highest influence on simulation behavior (Hessel and Jetten, 2007). The values for these parameters are kept between 50 and 200% of their original values in order to maintain a physically meaningful simulation.

The Nash-Sutcliffe model efficiency coefficient is used as the measure of performance (Eq. (14)), where 1 indicates perfect correlation and increasing negative value a decreasing correlation.

$$E = 1 - \frac{\sum (Q_t^o - Q_t^m)^2}{\sum (Q_t^o - \bar{Q}_t)^2}$$  \hspace{1cm} (14)

where $E$ is the Nash-Sutcliffe model efficiency coefficient, $Q_t^o$ is the observed discharge at time $t$ ($m^3 s^{-1}$), $Q_t^m$ is the modelled discharge at time $t$ ($m^3 s^{-1}$) and $\bar{Q}_t$ is the average observed discharge ($m^3 s^{-1}$).

4. Results and discussion

4.1. Danangou and Prado catchments

Both measured and simulated discharge for the Danangou and Prado catchment are shown in Figs. 9 and 10. Calibrated simulations for the kinematic, diffusive and Saint-Venant flow approximations are provided. Calibration parameters had to be altered from the original values used by Hessel and Jetten (2007) due to the usage of different model efficiency functions. The values of the Nash-Sutcliffe correlation coefficients and average calibration parameters for each are provided in Tables 2 and 3.

### Table 1

Input simulation parameters for the OpenLISEM simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Danangou</th>
<th>Prado</th>
<th>Fella</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timestep (s)</td>
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<td>10</td>
<td>60</td>
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<tr>
<td>Min Timestep</td>
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<td>Simulation duration (m)</td>
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<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Runoff to flood Coefficient (-)</td>
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<td>2.0</td>
<td>2.0</td>
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<tr>
<td>Canopy Openness factor (-)</td>
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<td>0.450</td>
<td>0.450</td>
</tr>
<tr>
<td>Spatial resolution (m)</td>
<td>20 m 2000 x</td>
<td>20 m 583 x</td>
<td>20 m 881 x</td>
</tr>
</tbody>
</table>
4.2. Connectivity of overland flow

The simulation results for the Danangou catchment show significant differences in performance for the various flow approximations. The time of peak discharge is simulated with substantially higher accuracy by diffusive and Saint-Venant flow. Both the timing and general shape of the simulated hydrographs lead to substantially higher correlation coefficients for the diffusive and Saint-Venant flow when compared to kinematic flow.

Hessel and van Asch (2003) concluded that, for this catchment, the timing of the discharge peak was especially difficult to predict. The authors mentioned that inaccuracy of the digital elevation could have led to steeper slopes. This would have increased average overland flow velocity. However, comparison with dynamic and diffusive wave simulations showed that flow velocities have been increased by the inherent properties of the kinematic flow approximation.

Where diffusive and Saint-Venant flow spread due to pressure forces, kinematic flow concentrates to the width of a single cell. When the spatial resolution is high, this leads to unrealistically high water heights. Because of this increase in flow height, flow velocity increases. This effect is furthermore strengthened by the fact that the routing network ignores local depressions. In Fig. 12, maximum flow depth for the July rainfall event are shown. While kinematic flow forces a direct path through any rough terrain, diffusive and dynamic flow are partly blocked and re-routed. Both of these effects increase the average flow velocity of kinematic flow and cause the approximation to over-estimate connectivity in the catchment. The results of this over-estimation can be seen in the form of the early peak discharge time for the kinematic flow simulations. Therefore, the kinematic flow approximation, instead of the digital elevation model, was the dominant reason for the inaccuracy. The influence of flow approximations on average flow velocities is furthermore visible in the final calibration parameters, where Manning’s ‘N’, the frictional coefficient, is significantly lower for kinematic flow. This indicates that during calibration, the flow had to be artificially slowed down to gain accuracy.

The simulation results for the Prado catchment show significant differences in performance for the distinct flow approximations. All three flow approximations provided satisfactory results in calibration for the three rainfall events. Dynamic overland flow performed best in recreating the shape of measured hydrographs. Both diffusive and dynamic flow showed an increase in accuracy when compared to the kinematic flow approximation.

Fig. 13 shows the simulated spatial patterns of overland flow for the July rainfall event in the Prado catchment. A predominant difference in these patterns is the concentration of flow. Compared to the dynamic flow, which performed best in calibration, kinematic and diffusive flow respectively over-estimate and under-estimate flow concentration. This is evident from the mathematical and numerical descriptions of their behavior. Kinematic flow forces flow through the width of a single cell, artificially concentrating flow. Diffusive flow adds pressure terms, which act as a diffusive force, and neglects other forces, causing an overestimation of flow diffusion. A second difference between the flow approximations is caused by differences in infiltration. On locations where flow concentrates, infiltration is limited by the infiltration capacity and the active surface for infiltration. Flow concentration strongly influences the available surface area for infiltration. In the north of the Prado catchment, runoff is generated that flows South through an area of high infiltration. Kinematic flow concentrates and limits the active surface area of infiltration, thus flowing through areas with high infiltration capacity quicker. The diffusive and dynamic

![Fig. 9. Calibration results from different flow approximations for the Danangou Catchment. Rainfall events from 01-08-1998 (top), 20-07-1999 (middle) and 23-08-1998 (bottom).](image-url)
flow are predominantly infiltrated due to their more diffusive flow. Within the final calibration parameters, the same effect is visible. Due to the larger amount of infiltration with diffusive flow, the calibration lead to lower values for the saturated conductivity, which increases final discharge.

Based on the results of both the Danangou and Prado catchment, kinematic flow is highly accurate and efficient in the correct setting. When flow heights relative to spatial resolution is low, velocity and flow diffusion are correctly estimated. Mathematical analysis for the use of flow approximations such as those by Vieira (1983) can be used to support the use of flow approximation. A crucial difference in behavior is however caused by spatial modelling. In the case of spatial flow modelling, concentration of flow can quickly change flow properties. Due to several effects, hydrological connectivity can be substantially over-estimated by kinematic flow. Furthermore, because the routing scheme for kinematic flow is bound by cell size, errors increase with increasing spatial resolution. Therefore, in the case of spatial modelling, the ratio of catchment size versus cell size plays an important role in the applicability of the kinematic flow approximation.

### Table 2
Nash-Sutcliffe coefficients and calibration parameters for the simulated rainfall events for the catchment in the Chinese Loess Plateau. Calibration parameters are relative to base dataset value.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Flow</td>
<td>–0.71</td>
<td>0.61</td>
<td>0.12</td>
</tr>
<tr>
<td>Diffusive Flow</td>
<td>–0.22</td>
<td>0.78</td>
<td>0.89</td>
</tr>
<tr>
<td>Saint-Venant Flow</td>
<td>0.58</td>
<td>0.81</td>
<td>0.88</td>
</tr>
<tr>
<td>Average Calibration Parameters</td>
<td>Kinematic</td>
<td>Diffusive</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Mannings N</td>
<td>1.86</td>
<td>1.09</td>
<td>0.87</td>
</tr>
<tr>
<td>Saturated Conductivity</td>
<td>1.67</td>
<td>0.68</td>
<td>0.74</td>
</tr>
<tr>
<td>Initial Moisture</td>
<td>1.49</td>
<td>0.93</td>
<td>0.86</td>
</tr>
</tbody>
</table>

### Table 3
Nash-Sutcliffe coefficients and calibration parameters for the simulated rainfall events for the Prado catchment. Calibration parameters are relative to base dataset value.

<table>
<thead>
<tr>
<th>Nash-Sutcliffe Coefficients</th>
<th>29-09-1997</th>
<th>09-12-2003</th>
<th>17-10-2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Flow</td>
<td>0.242</td>
<td>0.613</td>
<td>0.793</td>
</tr>
<tr>
<td>Diffusive Flow</td>
<td>0.302</td>
<td>0.770</td>
<td>0.845</td>
</tr>
<tr>
<td>Dynamic Flow</td>
<td>0.519</td>
<td>0.891</td>
<td>0.875</td>
</tr>
<tr>
<td>Average Calibration Parameters</td>
<td>Kinematic</td>
<td>Diffusive</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Mannings N</td>
<td>1.44</td>
<td>0.78</td>
<td>0.72</td>
</tr>
<tr>
<td>Saturated Conductivity</td>
<td>1.25</td>
<td>0.87</td>
<td>0.93</td>
</tr>
<tr>
<td>Initial Moisture</td>
<td>1.28</td>
<td>0.91</td>
<td>0.94</td>
</tr>
</tbody>
</table>

4.3. Validation with flooding

Simulated and measured discharge for the 2003 Fella-Basin flood event are shown in Fig. 11. Simulations using kinematic, diffusive and Saint-Venant approximations both with and without Saint-Venant based channel flooding have been calibrated and are provided. The Nash-Sutcliffe correlation coefficient for the
Fig. 11. Maximum simulated overland flow depth in the Danangou catchment for the 20-07-1999 rainfall event.

Fig. 12. Overland flow depth for the northern part of the Prado catchment at identical times in the simulation for the 17-10-2003 rainfall event.

Fig. 13. Simulated and measured discharge for the 2003 flood event in the Fella basin at the Pontebba outlet using different flow approximations.
discharge simulations of the Fella-Basin flood event are provided in Table 4.

4.4. Flood behavior

In the case of the 2003 flood event in the Fella river basin, the gradual decline in measured discharge after the event confirms the reports of flooding. The decrease in flow height and slope outside of the channel causes a gradual return of flood water into the channel. Flood depth maps for the coupled Kinematic, diffusive and Saint-Venant simulations with channel flooding are provided in Fig. 14. For three representative locations, flood depth time series for the same simulations are shown in Fig. 15.

The difficulty in recreating the hydrograph differed for the distinct flow approximations. Without channel flooding, kinematic and diffusive flow were not able to provide an accurate recreation of the measured hydrograph. The kinematic flow approximation completely neglects the flooding behavior. The diffusive flow approximation strongly underestimates flow velocities at the incline of the hydrograph. This leads to a late increase in discharge. The cause of the underestimated velocities can be found in the over-estimation of the spread of the water flow. This is due to the presence of pressure term but lack of inertia related acceleration. The inertia-related acceleration terms would increase flow concentration in sharp incised channels.

When the kinematic flow approximation is combined with Saint-Venant based channel flooding, accuracy increases substantially. However, channel flooding only slightly increases accuracy in the tail of the hydrograph. The combination of diffusive flow with Saint-Venant channel flooding and a full Saint-Venant approximation show accurate recreation of the 2003 Fella-basin flood-hydrograph. The main reason for this is shown in Fig. 7. The flooding during the simulation with kinematic flow is mainly present near the main channel. When this flood water re-enters the channel, it can quickly leave the area. For the diffusive and Saint-Venant flow, flooding takes place substantially more in the upstream areas. Because of this, water takes a longer time to reach the outlet once it re-enters the channel. Thus, while addition of channel-based flooding improved calibration accuracy for kinematic flow, this method has limited predictive power when compared to diffusive and dynamic overland flow. For these flow approximations, flooding behavior can take place at any location, allowing a greater degree of accuracy in the simulations.

While dynamic and diffusive flow outperform kinematic flow when using a spatial resolution of 20 m, difficulties arise in the case of 40 and 80 m. For both 40 and 80 m resolution, the coarser resolution creates local depressions in the digital elevation model. The routing network that is used for kinematic flow neglects these local depressions, while diffusive and Saint Venant flow first fill these, leading to spurious flooded cells. Correction to the elevation model could be made to increase connectivity for diffusive and dynamic flow. However, such corrections are a difficult process and can substantially alter slopes on a complex topography.

Another disadvantage of diffusive and dynamic flow on coarse resolutions, is that flow spread is generally over-estimated when pressure terms are included. When spatial resolution is coarse, flow spread should not be wider than a single cell. However, due to pressure terms, diffusive and dynamic flow generally use two or more cells.

However, despite the inaccurate flooding of local depressions, both flooding extent and flooding depth are substantially more consistent with the results of the 20-m simulation in the case of diffusive or dynamic flow. For kinematic flow, it is visible that a decrease in spatial resolution causes the flooding to take place increasingly upstream. This can be explained by the strong over-estimation of connectivity in the Fella-basin. Because of terrain with high spatial variability, flow velocities are lower when details are included. On coarser resolution, kinematic flow ignores an increasing amount of details in the topography, increasing the over-estimation of connectivity and flow velocity. This would cause the runoff to arrive at the channel earlier, causing flooding in increasingly upstream areas.

Summarizing: in the performed simulations, due to the strong over-estimation of connectivity on both higher and lower spatial resolutions, the usage of a kinematic flow approximation could not accurately recreate flow behavior. Thus, both the calibration performance, and the consistency of flood extent and volume for varying spatial resolution are substantially higher in the case of diffusive and dynamic flow.

The influence of spatial resolution on flood connectivity has been described earlier by Haile & Rientjes (2005). In their case, re-sampling of flood-plain elevation influenced the hydraulic connectivity, and thus the simulated flood extent. They conclude that, especially in terrain with high spatial variability, important details in elevation are lost in coarser resolutions. When simulating flooding within a catchment model, that includes rough upstream topography, the effect of spatial resolution on flow connectivity should therefore be of even higher importance. The manner in which flow approximations are influenced by the topography has been recognized previously (Kazeyilmaz-Alhan and Medina, 2007). In their simulations, steeper slopes (>0.11 degrees) show higher accuracy in using kinematic and diffusive wave approximations in a one-dimensional setting. In our two-dimensional simulations, similar effect are visible. Steep slopes tend to provide larger gravitational acceleration. Therefore, inertial and primarily pressure forces, which are ignored by the kinematic flow approximation, lose relative magnitude when compared to the gravitational forces. The slope values for the described catchments are shown in Fig. 16. Particularly the Danandau catchment, which features steep slopes, and. While the catchment edges in the Fella basin feature very steep slopes (>40 degrees), the central river area is very flat, leading to inaccurate behavior of kinematic flow. Finally, the Prado catchment features mostly gentle slopes (<5 degrees). As expected, performance differences between flow approximations are less noticeable when compared to the other catchments.

A final consideration in the performance of the flow approximations in flash flood modelling is mass conservation. Typically, numerical flow computations loss or gain water outside of the normal water balance when computational errors are made. An overview of the water balance errors in the Fella flash flood simulations are shown in Table 5. Within the implementation of the kinematic and diffusive flow, numerical errors are strictly limited to machine precision rounding errors, since the flow advection is implemented in a strictly mass-conserving manner. For dynamic flow, this is not the case, and mass balance errors increase during the simulations. The total amount of water lost in the full dynamic flow simulation is 8.7e−2. Due to the insignificant amounts of water lost during the simulation, there is no relationship with the quality of the simulation.

<table>
<thead>
<tr>
<th>Simulation Method</th>
<th>Nash-Sutcliffe Correlation Coefficient</th>
<th>Simulation Time (Minutes)</th>
<th>Mass Balance Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic</td>
<td>0.42</td>
<td>108</td>
<td>7.4e−12</td>
</tr>
<tr>
<td>Kinematic &amp; SV</td>
<td>0.76</td>
<td>432</td>
<td>1.3e−3</td>
</tr>
<tr>
<td>Diffusive</td>
<td>0.65</td>
<td>389</td>
<td>7.6e−12</td>
</tr>
<tr>
<td>Diffusive &amp; SV</td>
<td>0.93</td>
<td>532</td>
<td>2.5e−11</td>
</tr>
<tr>
<td>Saint Venant</td>
<td>0.91</td>
<td>621</td>
<td>8.7e−2</td>
</tr>
</tbody>
</table>
4.5. Sensitivity analysis

Results from a sensitivity analysis are shown in Fig. 17. Calibrated parameters for the Fella flash flood simulations are shown in Table 6.

The result of the sensitivity analysis show several variables to which the flow methods is highly sensitive. Both saturated conductivity and Manning’s coefficient have a strong influence on the output of the model. The influence of model resolution on the simulation is relatively low when compared to the saturated conductivity and the Manning’s coefficient. Especially average flood depth and flood velocity are substantially affected by the input parameters.

The distinct flow approximations have substantial differences in sensitivity. The kinematic flow approach has the highest sensitivity to resolution changes. This is caused by the usage of the local drainage network. This causes flow to move through the width of a single cell. When cell sizes are changes, this significantly influences flow height and thus velocity. For the other methods, the sensitivity of flood properties is comparable to similar detailed flood models (Haile & Rientjes, 2005; Horritt and Bates, 2001).

Generally, the kinematic flow approximation shows the lowest sensitivity to the Manning’s coefficient and the saturated conductivity. In these cases however, it is important to note that a lower sensitivity does not necessarily mean higher accuracy. In the case of kinematic flow, infiltration for example, is not limited by the hydraulic conductivity, but rather by the flow width. This decreases sensitivity to a change in hydraulic conductivity. The diffusive flow approximation shows an especially high sensitivity for maximum flood depth and maximum flood velocity. Finally, the Saint-Venant flow shows an average sensitivity for all investigated variables.

5. Conclusions

Based on the simulation results, diffusive and dynamic flow overland flow provide a substantial increase in calibration performance when compared to kinematic flow. In both the Danangou and Prado catchment, kinematic, diffusive and dynamic flow performed respectively least to most accurate in calibration to measured hydrographs. For these catchments, with a spatial resolution of 10 and 20 m, kinematic flow performed substantially less. In both catchments, the kinematic flow approximation overestimated connectivity within the catchment. Both due to flow concentration, the use of a routing network and decreased infiltration.
Fig. 15. Flood depth trends for the calibrated settings with Dynamic Wave flooding in three locations in the Fella area.

Fig. 16. Slope values for all described catchments: Danangau (left), Fella (middle), Prado (right).

<table>
<thead>
<tr>
<th>Outlet Point</th>
<th>Estimated Peak Discharge ($m^3 s^{-1}$)</th>
<th>Kinematic</th>
<th>Kinematic &amp; SV</th>
<th>Diffusive</th>
<th>Diffusive &amp; SV</th>
<th>Saint Venant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uqua at Ugovizza</td>
<td>200</td>
<td>325</td>
<td>292</td>
<td>245</td>
<td>231</td>
<td>182</td>
</tr>
<tr>
<td>Fella at Pontebba</td>
<td>680</td>
<td>692</td>
<td>673</td>
<td>677</td>
<td>678</td>
<td>697</td>
</tr>
</tbody>
</table>
tion, hydrological connectivity is in some cases highly over-estimated when kinematic flow is used. Therefore, the assumptions that lead to kinematic flow have a high influence on hydrological connectivity.

For simulations of flood events, kinematic flow similarly provides the least accuracy. The implementation of Saint-Venant based channel flooding strongly increased calibration performance. The transition to Diffusive and Saint-Venant equations for overland flow further increased accuracy and realism. The best results were obtained with a combination of diffusive overland flow and dynamic flow for channel flooding. Both this combination and full dynamic flow were able to recreate the hydrograph of the 2003 Fella-Basin flood event. The primary cause of this was that for diffusive and dynamic flow, flood behavior is not limited by the presence of a channel. For kinematic flow, flooding is initiated along the channels, limiting the predictive nature of the model. Spatial resolution of the dataset has a significant impact on the performance of the flow approximations. In the case of coarser resolutions (40 m or higher), local depressions were ignored by kinematic flow. This improved the relative accuracy of this method. In the case of higher spatial resolutions, pressure forces within water flow become important. As a result of the substantial over-estimations of connectivity and flow velocity on both lower and higher spatial resolutions, the usage of kinematic flow can have a significant impact on the model. Usage of this flow approximation should then be based on a thorough investigation. The extent in which a kinematic, diffusive or dynamic wave can be used in flow simulations at different spatial resolutions depends on the type of area and particularly the slopes and spatial variability of the topography. In the case of flood simulations, the implementation of channel-based flooding with dynamic flow is required for catchment-based simulations of flooding. Ignoring pressure terms by assuming infinite channels results in unrealistic flow heights and velocities. For the same reason, kinematic flow was, for the Fella river simulations, not an appropriate method for simulating overland flow. The usage of a flow network artificially increases flow concentration and ignores pressure terms, which are crucial in describing the behavior of flood water. Similarly, in applications related to spatial hazard susceptibility, usage of routing networks and kinematic flow should generally only be considered as a viable alternative when the investigations shows the topography, slopes and spatial resolution do not lead to inaccurate behavior of the flow approximation.

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