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Application of a new cellular model for bedload transporting extreme events at steep slopes

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ABSTRACT

A cellular model for bedload transport at steep channel gradients and alluvial fans has been developed to simulate lateral distribution of erosion and deposition on alluvial fans of mountain streams. The cellular model, named FluviSed, applies a quasi-steady-state routing of a flood hydrograph over a rectangular grid. Bedload transport is calculated and the morphological changes are updated after each time step. FluviSed is designed to complement existing one-dimensional bedload transport simulation tools by using their outcome as an input for the simulation of inundated areas. The model has been evaluated against Tom^{Sed}, a one-dimensional bedload transport model. Further, a back-calculation of a laboratory bedload experiment and a real flood event from 2005 at Schnannerbach in Austria are provided to test the model's suitability for reproducing morphological changes caused by flood events at high channel gradients.

1. Introduction

Floods with fluvial bedload transport are a natural hazard and source of risk in the alpine environment. Badoux et al. (2014) analysed 40 years of damage data for natural hazards in Switzerland and showed that about 35% is based on bedload transport processes. A systematic event documentation of torrential processes in Austria showed that fluvial bedload transport is responsible for most damages during the summer months. Hübl et al. (2011) showed that about two-thirds of the torrential events documented by the Austrian Service for Torrent and Avalanche Control in the year 2010 can be related to fluvial bedload transport.

In recent years, several models, to simulate bedload transport, have been adapted or developed for mountain streams. They differ from traditional sediment transport models, intended for lowland rivers, mainly by neglecting suspended material and by considering steep channel slopes (>5%), as well as the effects of shear stress and macroroughness—later playing an important role in the bedload transport system of mountain streams (Chiari & Rickenmann, 2011; Nitsche et al., 2011; Nitsche et al., 2012; Rickenmann & Recking, 2011). A sound overview of applied bedload transport models for mountain streams—supporting hazard and risk assessment activities in Austria, Bavaria and Switzerland—can be found in Rimböck et al. (2013).

One-dimensional simulation models for bedload transport, like 3ST1D (Papanicolaou et al., 2004), TOPKAPI (Todini & Ciarapica, 2002; Konz et al., 2011), Tom^{Sed} (formerly known as SETRAC) (Chiari et al., 2010; Chiari & Rickenmann, 2011), or sedFlow (Heimann et al., 2015) show appropriate results of estimated volumes transported to the fan apex but can only account for bedload transport in predefined crossections. However, bedload transport events typically cause damages by overflowing the main channel, which makes it necessary to consider also the lateral distribution of erosion and deposition within a potential inundation area. For this reason two-dimensional simulation models become more relevant when delineating endangered zones prone to bedload transport processes. Beside the simulation of overflowing, two-dimensional simulation models are also an appropriate tool to account for the complexity of flow conditions within mountain streams, like changes in crossections, influence of superelevation effects or changes of hydraulic conditions (Rickenmann, 2014). Examples for two-dimensional models applicable for steep slopes are Flo2D (O'Brien et al., 1993), Flumen (Beffa, 2005) or BASEMENT (Vetsch et al., 2015). Nevertheless, especially for the simulation of bedload transport on torrential fans, hardly any experience exists (Rickenmann, 2014).

Flow is the main driver for the geomorphological processes in alluvial environments (Van De Wiel et al., 2007; Fryirs & Brierley, 2013). Flow routing in bedload simulation models can either be realised by the application of traditional computational fluid dynamic (CFD) approaches, based on Navier–Stokes equations, or by the cellular automation concept. Simulation models based on CFD approaches can be computationally too demanding to be used for estimating lateral distribution of erosion and deposition. Further, a reliable calibration in the case of severe torrential flood events is not feasible, which implies that better results, in terms of reliability, do not necessarily depend on the application of more sophisticated numerical models. Cellular modelling of geomorphic and torrential processes has therefore become popular

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during the last decades (Coulthard et al., 2002, 2007; Iovine et al., 2005; D'Ambrosio et al., 2006; Scheidl & Rickenmann, 2011). Cellular automaton is a discreet dynamic system that is developed by repeating simple deterministic rules (e.g., Wolfram, 2002; Scholz, 2014). Murray & Paola (1994) developed a cellular model showing the main features of braided systems. Coming from a landscape evolution model, Van De Wiel et al. (2007) implemented sediment transport processes to model meandering rivers. Doeschl-Wilson & Ashmore (2005) tested a cellular model against a physical model of a braided river reach but were only able to reproduce some aspects of braided river morphodynamics. However, these models have not been tested for the calculation of morphological changes caused by bedload transport during flood events in steep torrential catchments, showing fast morphological reactions.

In this paper we present FluviSed, a cellular model intended to simulate lateral distribution of erosion and deposition on alluvial fans of mountain streams. FluviSed is designed to make use of the results of Tom^{Sed} (Chiari et al., 2010) and is able to simulate lateral erosion and deposition behaviour on the fan. However, the proposed model also might complement other existing one-dimensional bedload transport simulation tools by using their outcome as an input for the simulation of inundated areas, starting from the fan apex. We assume that the application of a more simple model, requiring less data for calibration, could be more promising when simulating bedload transport in steep torrential channels. Instead of a CFD algorithm, which affects the entire simulation perimeter at each timestep, we chose a flow-sweeping algorithm that calculates a steady-state, uniform flow approximation to the flow field, similar to CAESAR, the cellular automaton landscape evolution model of Coulthard et al. (2000, 2002).

First, background and concept of the new model are explained; and results of (i) a comparison with the one-dimensional bedload transport model Tom^{Sed}, (ii) a back-calculation of a laboratory bedload experiments and (iii) a back-calculation of a real flood event from 2005 at Schnannerbach in Austria are provided. Finally the advantages and limitations of the proposed model are discussed.

2. The FluviSed model

FluviSed is based on a cellular model approach to simulate temporal and spatial (2D) bedload transport within a channel reach or fan area. The flow algorithm is a modified Manhattan D4 algorithm (Scholz, 2014), defining a positive bed-gradient for upslope flow directions and a negative bed-gradient for downslope flow directions. The model combines a hydrodynamic and a morphodynamic approach at each timestep. Input parameters are

- a digital elevation model (DEM) of the simulation perimeter,
- an erosion layer defining the possible erodible depth,
- a hydrograph,
- a sedigraph, and
- characteristic start values.

Start values are (i) the coordinates of the start point of the simulation, defined in the same projection as the digital elevation model (DEM) as well as the digital model of the erosion layer; (ii) characteristic grain sizes, here d_{90}; d_{50}, and d_{30}, and; (iii) a porosity factor; (iv) the density of water as well as (v) the density of sediment; and finally (vi) an exponent for macroroughness calibration (α).

The model does not provide pre- or post-processing interfaces, to avoid dependencies on commercial programmes. All the input and output data are therefore either in ASCII- or txt-file format. FluviSed is a console application, written in VB.net and was tested on WinXP© and Win7©. The source code as well as executable files are made available as free downloads at www.bedload.at.

2.1. Performance

The spatial and temporal resolution of process-based models cannot be regarded independently (Van De Wiel et al., 2011). The simulation has therefore to be balanced with the available data and computational resources. The temporal resolution of the spatial discretisation is solved in FluviSed by a variable timestep, depending on the flow depth in sinks and on flat terrain. The variable timestep is calculated with

$$\Delta t_{comp} = \frac{h_{max} d_{grid}{}^2}{Q_{max}} \tag{1}$$

based on the gridsize of the DEM (d_{grid}), the maximum water depth (h_{max}), and the maximum discharge in the central cell (Q_{max}). The maximum water depth (h_{max}) can be defined by the user, and we recommend a value of $h_{max} = 0.1$ m for high resolution elevation models generated for instance by airborne LiDAR. With this solution numerical stability is achieved for varying discharge. Low discharge allows for larger computational timesteps.

2.2. Hydrodynamic model

The hydrodynamic approach applies a quasi-steady-state routing of a flood hydrograph over a rectangular grid for the timestep Δt_{comp}. The model partitions the specific fluid discharge of each central cell ($q_{f_{in}}$) and distributes it to orthogonal neighbour cells ($q_{f_{out}}$) with negative flow gradients (S_{E_i}). The specific fluid discharge $q_{f_{in}}$ results either from all inflow discharges of upslope neighbour cells or directly from the input hydrograph if the central cell equals a start cell. The estimation of the flow gradient (S_{E_i}) allows us to overflow neighbour cells with positive bed gradients (Fig. 1) owing to the application of a central water level (H_c) by adding a water depth (h) to the elevation above sea level (asl; z) of the actual central cell:

$$H_c = h + z \tag{2}$$

with

$$h = \frac{q_{f_{in}}}{v_f} \tag{3}$$

and

$$v_f = \frac{1.3 g^{0.2} q_{f_{in}}{}^{0.6} S^{0.2}}{d_{90}{}^{0.4}}. \tag{4}$$

In Eq. (4), g denotes the acceleration caused by gravity, $q_{f_{in}}$ is the specific fluid discharge (flow rate per unit width), S is the average slope (bed gradient) to all outflow neighbour cells, and d_{90} is the grain size of the surface bed material for which 90% of the bed material is finer. Eq. (4) was originally proposed by Takahashi (1987) based on laboratory experiments on debris flows and successfully applied by Rickenmann (1991) to experimental sediment transporting flows.

For negative flow gradients, the actual central cell will act as a source. In this case, the specific fluid discharge ($q_{f_{in}}$) is distributed to all downslope neighbour cells as a function of their individual flow gradient. Hence, the deepest neighbour cell will gain the highest amount of the specific fluid discharge.

If all flow gradients to the neighbour cells are positive, the actual central cell will act as a sink. In this case, the actual central cell will be filled with water (and subsequently with sediment) until negative flow gradients are reached again.