Geophysical Research Abstracts
Vol. 14, EGU2012-10257, 2012
EGU General Assembly 2012

A sandpile model of grain blocking and consequences for sediment dynamics in step-pool streams

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Coarse grains (cobbles to boulders) are set in motion in steep mountain streams by floods with sufficient energy to erode the particles locally and transport them downstream. During transport, grains are often blocked and form width-spannings structures called steps, separated by pools. The step-pool system is a transient, self-organizing and self-sustaining structure. The temporary storage of sediment in steps and the release of that sediment in avalanche-like pulses when steps collapse, leads to a complex nonlinear threshold-driven dynamics in sediment transport which has been observed in laboratory experiments (e.g., Zimmermann et al., 2010) and in the field (e.g., Turowski et al., 2011). The basic question in this paper is if the emergent statistical properties of sediment transport in step-pool systems may be linked to the transient state of the bed, i.e. sediment storage and morphology, and to the dynamics in sediment input.

The hypothesis is that this state, in which sediment transporting events due to the collapse and rebuilding of steps of all sizes occur, is analogous to a critical state in self-organized open dissipative dynamical systems (Bak et al., 1988). To exlore the process of self-organization, a cellular automaton sandpile model is used to simulate the processes of grain blocking and hydraulically-driven step collapse in a 1-d channel. Particles are injected at the top of the channel and are allowed to travel downstream based on various local threshold rules, with the travel distance drawn from a chosen probability distribution. In sandpile modelling this is a simple 1-d limited non-local model, however it has been shown to have nontrivial dynamical behaviour (Kadanoff et al., 1989), and it captures the essence of stochastic sediment transport in step-pool systems. The numerical simulations are used to illustrate the differences between input and output sediment transport rates, mainly focussing on the magnification of intermittency and variability in the system response by the processes of grain blocking and step collapse. The temporal correlation in input and output rates and the number of grains stored in the system at any given time are quantified by spectral analysis and statistics of long-range dependence.

Although the model is only conceptually conceived to represent the real processes of step formation and collapse, connections will be made between the modelling results and some field and laboratory data on step-pool systems. The main focus in the discussion will be to demonstrate how even in such a simple model the processes of grain blocking and step collapse may impact the sediment transport rates to the point that certain changes in input are not visible anymore, along the lines of "shredding the signals" proposed by Jerolmack and Paola (2010). The consequences are that the notions of stability and equilibrium, the attribution of cause and effect, and the timescales of process and form in step-pool systems, and perhaps in many other fluvial systems, may have very limited applicability.