Self-organized criticality in river basins: Challenging sedimentary records of environmental change

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ABSTRACT

For many years researchers have linked increases in sediment and bedload from drainage basins to external factors such as increased rainfall. However, natural systems have always shown a high degree of scatter or nonlinearity in this response, which has made prediction of sediment yields difficult. We identify and describe a mechanism for self-organized criticality in the bedload sediment output from a simple drainage basin evolution model. This implies that identical floods will give considerably different sediment yields, which effectively renders the system unpredictable. Therefore, existing empirical methods for estimating sediment yields may need to be radically reevaluated. Furthermore, sedimentary records used to infer past climate or environmental conditions could simply reflect the internal system dynamics instead of external drivers.

INTRODUCTION

Catchment bedload sediment yields vary nonlinearly through time, from both a short-term and a long-term perspective (Coulthard et al., 2005; Phillips, 2003). This is usually attributed to changes in external drivers such as precipitation events, climate change, alterations in land use, and tectonics. However, nonlinear sediment dynamics can also occur in response to internal catchment reorganization, even under constant external forcing, as has been observed in natural channels (Cudden and Hoey, 2003), laboratory experiments (Ashmore, 1988; Gomez and Phillips, 1999; Sapozhnikov and Foufoula-Georgiou, 1997), and in numerical simulations (Coulthard and Van De Wiel, 2007). These internally induced, or autogenic, nonlinear fluctuations in bedload yield might be indicative of self-organized criticality (SOC) in the catchment (Coulthard and Van De Wiel, 2007). If true, bedload yields from SOC systems would effectively be unpredictable, which has massive implications for engineering predictions and the use of sedimentary records for paleoenvironmental reconstruction.

SOC is one form of nonlinear behavior in dynamic systems, indicating a scale invariance in the temporal dynamics of the system. Following the initial studies on sand piles (Bak et al., 1987, 1988), SOC has been proposed as an explanation for the dynamics in several environmental systems, such as the occurrence of forest fires (Malamud et al., 1998), earthquakes (Turcotte and Malamud, 2004), river meandering (Stølum, 1996), and riverbank failures (Fonstad and Marcus, 2003). Although there is no strict set of sufficient conditions to diagnose SOC in a system, there are several necessary conditions: (1) nonlinear temporal dynamics in the occurrence of disturbance events within the system; (2) an inverse power-law relation between of the magnitude and frequency of the events; (3) the existence of a critical state of the system to which the system readjusts after a disturbance; and (4) the existence of a cascading process mechanism by which the same process can initiate both low-magnitude and high-magnitude events.

In the following sections we apply a numerical landscape evolution model to show that each of these necessary conditions is fulfilled with regard to catchment sediment dynamics. In particular we find evidence for a cascading erosional process that may be at the root of this nonlinear behavior. The implications of SOC-driven bedload yield are then discussed.

MODEL AND SIMULATION SETUP

The simulations are performed with the CAESAR computational landscape evolution model (Coulthard et al., 2002; Van De Wiel et al., 2007). The key features of this grid-based model are subevent time steps, multiple flow routing, multiple grain-size erosion and deposition, and slope processes (diffusive creep and landslides). CAESAR uses a flow-sweeping algorithm, which calculates a steady-state uniform flow approximation to the flow field (Coulthard et al., 2002; Van De Wiel et al., 2007). Bedload transport is calculated using Einstein's (1950) equation for bedload transport, which allows for fractional transport of different sediment sizes. The CAESAR model has previously been applied to real-world scenarios, which have been successfully compared to independent field data. These include simulating 9000 yr of catchment evolution (Coulthard and Macklin, 2001), predicting patterns of contaminated sediment dispersal (Coulthard and Macklin, 2003), and patterns of sedimentation in Alpine environments (Welsh et al., 2009). In this study, however, the model setup is deliberately simplified to achieve the minimal conditions under which SOC-driven sediment output can occur. The simulations are run over a simple rectangular catchment with a thalweg (Fig. 1A). Sediment distribution is heterogeneous, consisting of sediments of nine different size classes (varying from 0.5 mm to 128 mm), but is spatially uniform at the start of the simulation. The catchment is submitted to a regular daily rainfall regime, with 1 h of rainfall (at 30 mm/h) followed by 23 h of no rainfall (Fig. 1B). This was repeated 25,000 times.

RESULTS

Hydrologically and geomorphologically, the simulations result in expected behavior: daily peak flow occurs toward the end of the hour of rainfall (Fig. 1B), a channel is gradually cut out in the center of the thalweg (Fig. 1C), and the channel develops an armored bed (Fig. 1D). The simulated bedload yield, however, is strongly nonlinear (Fig. 2A) and can be analyzed with respect to the four necessary conditions for SOC.

Nonlinear Temporal Dynamics

Daily simulated sediment output from the catchment is varying over more than an order of magnitude (Fig. 2A), even though the daily precipitation is the same every day. On a subdaily scale, the flow hydrographs are very regular, in response to the regular precipitation, but sediment discharges are highly erratic from day to day, and within each day (Fig. 2B). Thus, there is little correlation between flow discharge and sediment discharge (Fig. 2C), even though a deterministic transport equation is used in the model. This implies that a supply limiting condition must be active in the catchment and controlling the bedload yield. Thus, the nonlinearly fluctuating bedload yield, arising from regular rainfall and flow discharge, is the result of internal catchment reorganization, which affects the duration of sediment transport. This is discussed in the following.

Inverse Power-Law Relation

Although bedload yields vary over a wide range of magnitudes, days with high total daily bedload yield occur less frequently than days with moderate or low bedload yield. In particular, the variations in total daily bedload yield exhibit an inverse power-law magnitude-frequency relation (Fig. 2D). This property is often a first diagnostic of

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Geology, January 2010; v. 38; no. 1; p. 87–90; doi: 10.1130/G30490.1; 3 figures.

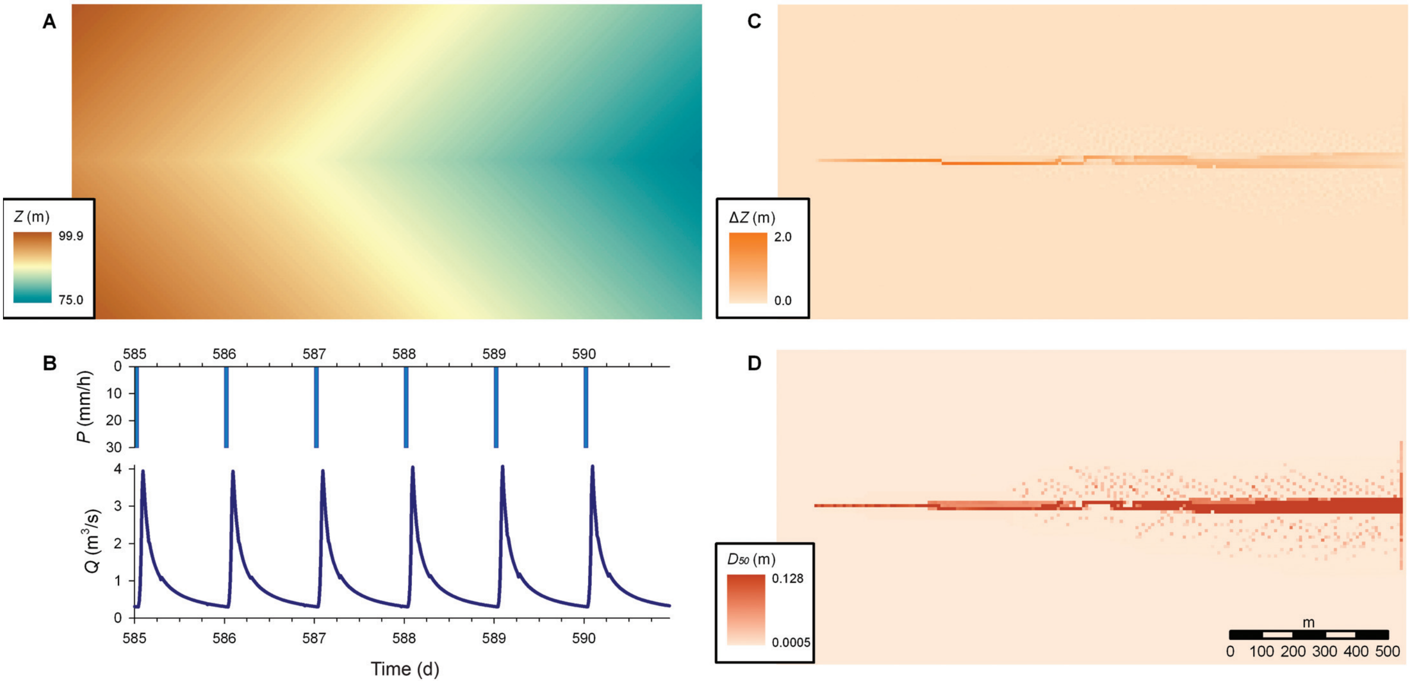

Figure 1. Model setup. A: Initial elevations (*Z*). Simulations were conducted on rectangular virtual catchment (2 km × 1 km), consisting of two valley slopes and a thalweg. Grid resolution is 10 m. B: Temporal distribution of rainfall (top, *P*) and simulated discharge at the catchment outlet (bottom, *Q*) for simulations. Regular rainfall patterns of 1 h of rainfall followed by 23 h of nonrainfall (shown here for six days only) are repeated throughout simulation. The resulting hydrograph exhibits similar temporal regularity, with peak flow occurring around 2 a.m. every day. C: Simulated change in elevation (Δ*Z*) at day 590. Erosion is concentrated in thalweg, with highest simulated net erosion in the upper thalweg. Effectively, the thalweg is developing a concave longitudinal profile. D: Median grain size (D_{50}) at surface at day 590. Dark colors in thalweg represent coarsening of median grain size and indicate thalweg channel bed armoring.

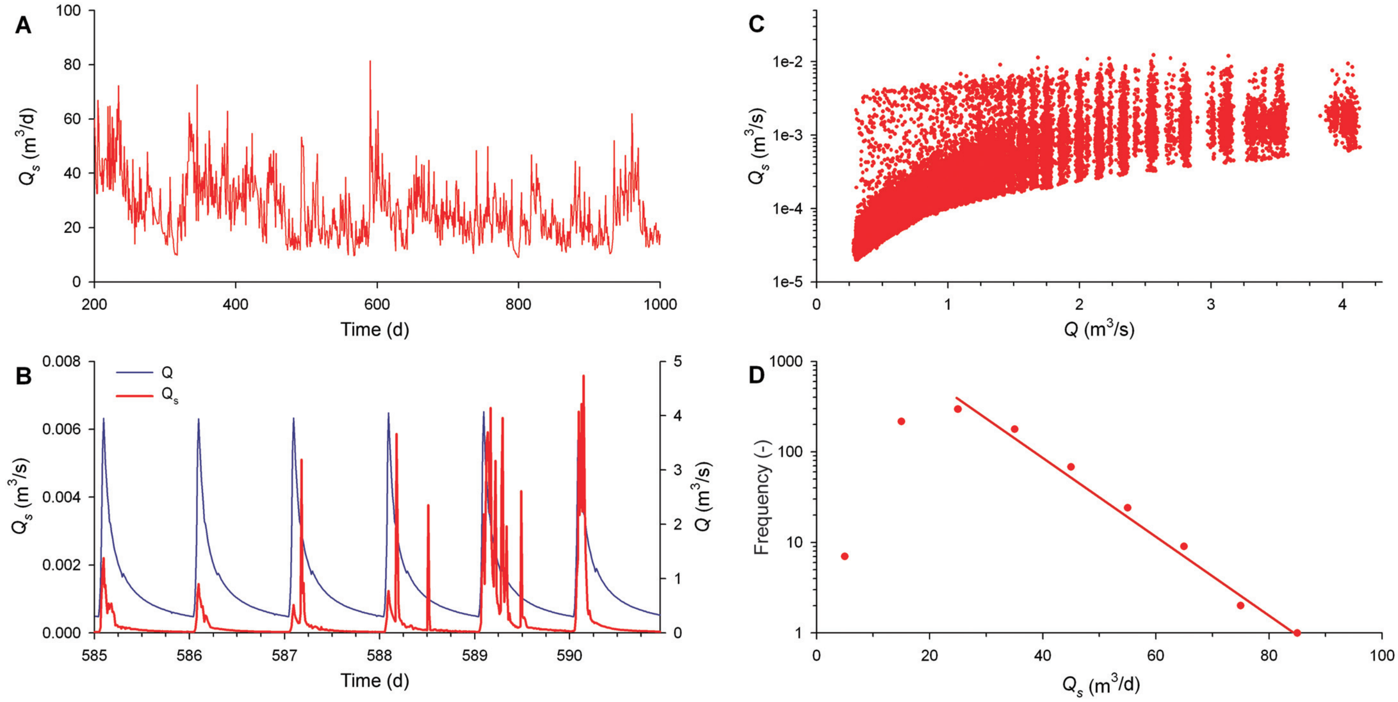

Figure 2. Simulated bedload yield (Q_s) at catchment outlet. A: Daily bedload yield varies significantly throughout simulation. Average daily bedload yield is 26.95 m³/day. B: Intraday bedload yield (red) and water discharge (blue), in 15 min intervals. The regular daily pattern of variations in water discharge is not repeated in sediment discharges, which exhibit irregular variations in amplitude and periodicity. C: Relation between water discharge and sediment discharge. Although there is general positive trend, this is largely obscured by variability. For any given water discharge, sediment discharges can vary by as much as two orders of magnitude. D: Magnitude frequency relation of daily bedload yields (binned in 10 m³/day intervals), showing log-linear decline in frequency (with exception of lower ranges, which are underrepresented as a consequence of bed's armoring).

the occurrence of SOC in a system. However, it should never be the only diagnostic, since it can also occur under a range of non-SOC conditions. It should also be noted that the inverse power law does not extend to the very low sediment yields, due to bed armoring restricting the supply of smaller sediment at low flows, thereby reducing the frequency of smaller magnitude sediment yields.

Critical State

The system settles on a dynamic equilibrium, at which the topography at any point in the catchment is adjusted to convey the incoming sediment load under the prevailing discharge, without net deposition or net erosion. If more sediment is delivered to a certain point than is removed, the difference is deposited, causing a local increase in the downstream slope and a local decrease in the upstream slope. Hence, the upstream sediment transport capacity is decreased, reducing the sediment influx, while the sediment outflux is increased through an increased transport capacity. In short, the topography is adjusted to address the excess sediment inflow at the point. A similar self-adjustment occurs, through local erosion, when local sediment outflow exceeds sediment inflow. The critical state of the system is exactly this dynamic equilibrium state, which essentially is an extension of the graded river concept (Mackin, 1948). Whereas the original graded river concept was applied to the river longitudinal profile, the critical state as defined here extends the basic principle to the entire catchment.

Cascading Process Mechanism

In our simulations, the irregularities in sediment delivery arise through breakup of a sediment armor layer. The armor layer results from preferential entrainment of finer sediments, leaving the coarser material on the bed (Fig. 1D). It is important to note that separate simulation scenarios with homogeneous sediment did not exhibit nonlinear bedload yields (see Coulthard and Van De Wiel, 2007). The armor layer, although more resistant to erosion than the finer material, is nonetheless gradually being eroded and may eventually be breached. When a local breach occurs, the finer sediment underneath is suddenly exposed and entrained by the flow, resulting in a sediment pulse moving down the system, and a drastic lowering of the local cell elevation. This local erosion results in an increased slope to the upstream cell and may trigger the breaching of the armor layer in that upstream cell soon after (Fig. 3A). The potential of this secondary effect occurring depends on the thickness of the upstream armor layer, but if it does occur it will cause another sediment pulse to follow the initial one. Thus, the prolonged duration of sediment transport is directly related to the extent of the cascading breakup of the armor layer (Fig. 3). When several successive armor breaches occur in one day, the total daily bedload yield can exceed the long term average by more than an order of magnitude.

DISCUSSION

Our results show that the necessary conditions for self-organized critical bedload yield dynamics can occur in very simple landscapes. We have for the first time identified a cascading mechanism that leads to SOC in catchment sediment dynamics. This, together with the existence of a critical quasi-equilibrium state, the nonlinear temporal dynamics of the sediment dynamics, and their inverse magnitude-frequency distribution demonstrate that catchments can behave like self-organized critical systems in terms of their bedload yield. It is important to note that this occurs without an explicit representation of turbulence, the presence of which can be used to explain other forms of nonlinear behavior in rivers (Da Silva, 2006). Furthermore, this simulation is deliberately parsimonious. In more complex landscapes the simulated mechanisms will lead to nonlinear deposition and subsequent remobilization, thus amplifying the effect. In addition, natural river systems are far more heterogeneous than our simple

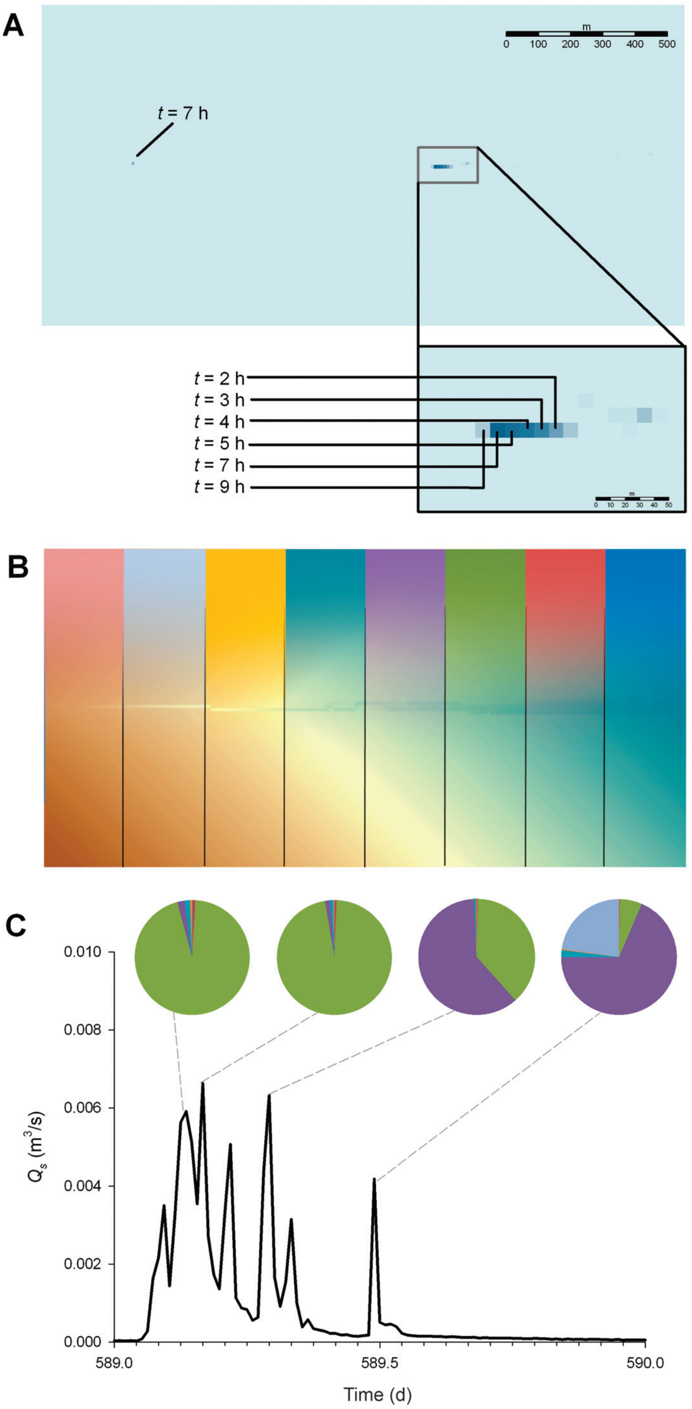

Figure 3. Spatial origins of maximum simulated bedload yield (Q_s) (day 590). A: Spatial and temporal occurrence of erosion during day 590 (*t* denotes hour of day). Breaking up of armor layer starts at one seeding point (between 1 a.m. and 2 a.m., at peak water discharge), and then gradually cascades upstream (until 7 a.m., during declining limb of hydrograph). A second seeding point is observed at upper end of catchment (at 7 a.m.), but this does not trigger further cascade. B: Sediment origins can be traced through numerical tags (effectively color-coding sediments). We used eight tags, each representing a catchment zone. C: Bedload yield at outlet during day 590. Pie charts indicate proportional contribution of each tracer zone to bedload yield. Early sediment output is dominated by sediments that were eroded from zone 3 (green), where armor breakup initiated. As the breakup cascades upstream, sediment output is gradually more dominated by zone 4 (purple). Sediments entrained from the second seeding point in zone 7 (light blue) reach the outlet at about 12 noon.

model and exhibit considerable additional potential for nonlinearity, for example through bank failures, in-channel and alluvial channel storage, landslides, or exposure of buried sediments. Many of these processes are nonlinear and may augment the cascading mechanism found here.

The identification of SOC in bedload yield has major implications for our understanding of fluvial systems. Principally SOC means that we are unable to predict the behavior of the system. Identical system inputs (here precipitation events) can lead to drastically different outputs from each event. Aside from rendering predictions of bedload yield uncertain, which has implications for engineering applications, this means that we may not be able to link cause to effect. Although there is undoubtedly a relation between bedload yield and external drivers such as precipitation or flow discharge, the autogenic processes within the catchment add a nonlinear variability over a wide range of magnitudes, which could be of similar or greater magnitude than those typically associated with the variability of the external drivers. Thus, in the absence of other data, it is impossible to attribute any individual peak in sediment output to changes in external conditions.

This has major implications for some areas of sedimentological and paleoenvironmental research. Many studies relate the thickness, composition, and/or frequency of sediment layers as being indicative of external drivers, such as climate change or tectonic events (e.g., Macklin and Lewin, 2003; Menounos and Clague, 2008). Our findings mean that some of these records could instead reflect the autogenic signal generated by the internal dynamics of the drainage basin.

The presence of SOC, however, need not make such studies or engineering predictions completely redundant. For example, the power-law distribution of bedload magnitude and frequency has a maximum value and a slope, allowing us to make some predictions. Furthermore, different climates or changes in other driving variables could change the slope of the power law (as per Dearing and Zolitschka, 1999), which could permit us to discern the influence of longer-term external forcings in a statistical or aggregate sense. However, it would still not be possible to attribute an individual event to either SOC or external drivers.

ACKNOWLEDGMENTS

We thank the two referees for their frank and helpful comments. The CAESAR model is free to download from http://www.coulthard.org.uk/downloads/.

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Manuscript received 25 June 2009
Revised manuscript received 6 August 2009
Manuscript accepted 11 August 2009

Printed in USA