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Sediment budgets and self-organization in a cellular landscape model

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Abstract Self-organization is the development of ordered patterns in the functional and morphological characteristics of a system. Drainage basins exhibit self-organization resulting from the interaction of the slopes and channels, which are linked by exchanges of water and sediment. This paper discusses a cellular model of the sediment dynamics of a fluvial landscape. Sediment transport is triggered by the occurrence of rainstorms of varying magnitude. Starting with a randomly generated topography, over time a drainage network evolves. For storms of a specific magnitude, total sediment yield varies over more than three orders of magnitude, even though there are no external factors in the model that can be invoked to explain these variations. Instead, total sediment yield reflects the recent sediment dynamics of the basins. The frequency distribution of total sediment yield normalized using storm magnitude plots as a single curve, enabling prediction of total sediment yields for unrecorded high magnitude rainstorms.

Key words self-organization; sediment yield; cellular model; sediment budget

INTRODUCTION

A sediment budget is a quantitative statement of the transfer and storage of sediment as it is transported from its sources within the drainage basin to its eventual exit from the drainage basin (Reid & Dunne, 1996). In its full form, a sediment budget accounts for processes and rates of erosion and sediment transport on hills and in channels, for temporary storage of sediment in bars, alluvial fans, and other sites, and for weathering and breakdown of sediments while in transport or storage. A sediment budget allows sediment yields to be estimated before the results of long-duration sampling programmes are known. Field-based studies of sediment budgets and sediment yields are frequently hampered by the limited availability of data. Collection of such data is expensive and labour intensive. Even when a detailed process study is feasible, data can only be collected at a small number of points during the period of measurement, which immediately raises the question whether the data set is representative for larger or smaller basins over longer periods of time. The alternative is to use an historical approach, using proxy data derived from reservoir sedimentation, channel cross-sections, topographical surveys and similar methods, which allows the period of measurement to be extended into the past (e.g. Trimble, 1981, 1999). Typical limitations inherent in the historical approach, however, are a limited temporal resolution, resulting from scarcity of datable materials; limited spatial resolution because of the scarcity of suitable sites; and incomplete information because of gaps in the depositional record, possibly resulting from erosional events. Thus, sediment budgets are frequently characterized by limited spatial and temporal coverage and resolution.

Computer models may be used to supplement the information derived from field-based process and historical studies. A model can be used to calculate sediment yields over periods of any given length, at spatial and temporal resolutions that are only limited by the model's capability. This enables the investigation of issues that cannot be investigated effectively in a field-based study. An example of such an issue is the relationship between the small-scale local rules of sediment transport and the large-scale rules describing sediment dynamics at the drainage basin scale. The large-scale rules emerge from the repeated application of the small-scale rules, but it is not clear how the two sets of rules are related. Another example of a problem for which computer models are eminently suited is the investigation of the effect of climate change on sediment yield and landform evolution at the landscape scale. The objective of this study is to investigate the rules of sediment dynamics at the large or drainage-basin scale that emerge from the repeated application of small-scale sediment transport rules in a cellular landscape model, and to evaluate how a change in the model's rainfall characteristics affect sediment yields and landscape evolution.

MODEL DESCRIPTION

The model used for this study is Cascade 5, which is described in detail by De Boer (2001). Some of the key features of the model, however, will be outlined here. Cascade 5 is a highly simplified representation of a fluvial landscape. It does, however, capture the most essential features and processes. The model belongs to the class of cellular automata, in which adjacent cells in a two-dimensional grid interact according to a set of rules. The value in each grid cell represents the local elevation. Results presented here were derived using a 210 × 210 grid, for a total of 44 100 cells. Each model run starts with an initial topography that is modified as time in the model progresses. The results of the model runs discussed here were obtained with an initial topography with a random elevation for each cell ranging from 0 to 1. To create relief in the model, all cells on the edge of the grid had their elevation lowered by 100, and base level was set at the elevation of the lowest cell on the grid's edge. Earlier investigations showed that, given enough time, the initial topography is modified to such an extent that the starting point for long model runs is immaterial in the end.

Transport laws

Following Kirkby (1976), Armstrong (1976, 1987) and others, sediment fluxes are computed with the equation $F = a\,S^b + c\,\sin(\text{arc}\tan(S))$. In this equation, F is the total sediment flux from the originating cell to its lowest neighbour, a is a coefficient, S is the elevation difference between the originating cell and its lowest neighbour, b is an exponent, and c is a coefficient. In the transport equation, $a\,S^b$ is the wash component, the sediment flux caused by flowing water; and $c\,\sin(\text{arc}\tan(S))$ is the creep component, the sediment flux caused by small mass movements. All results described herein were obtained using $a = 0.015$, $b = 1.5$ and $c = 0.1$. The values of a, b and c were selected such that the maximum sediment flux from an originating cell to its lowest neighbour is less than half the elevation difference between the two cells. Thus, the lowest neighbour cannot become higher than the originating cell in one time step. At the edge of the grid, sediment is exported and the sediment yield is calculated using S as the elevation difference between the cell on the edge and the base level. During the model runs discussed here, the base level was lowered each time sediment was exported from the cells on the edge of the grid, effectively resulting in instantaneous isostatic rebound.

Rainstorm frequency distributions

The model operates by repeatedly applying rainstorms to the cells. The location of rainstorms is selected randomly. Rainstorms in the model are square, and can range in area from 1×1 to 210×210 cells. During some of the model runs for this paper, the probability of occurrence of a rainstorm is inversely proportional to its areal extent so that, for example, the probability of occurrence of a rainstorm covering 3×3 cells is 3^{-2} or 1/9 of the probability of occurrence of a rainstorm covering 1 cell. This results in a rainstorm frequency distribution given by $f \propto A^{-1}$, where f is the frequency of occurrence and A is the storm area. For comparison, during other model runs the rainstorm frequency distribution is $f \propto A^{-0.75}$, which means that, for example, the probability of occurrence of a rainstorm covering 3×3 cells is $3^{-1.5}$ or 0.19 of the probability of occurrence of a rainstorm covering 1 cell, resulting in an increase in the frequency of occurrence of large rainstorms. All cells in the area of the rainstorm receive one unit of precipitation, and the sediment flux down the steepest slope from cell to cell is calculated. Once all the sediment mobilized by a rainstorm has been deposited within the grid or exported from the grid, a new rainstorm is applied, and the whole process starts again.

Starting with the initial topography, the model is allowed to run until all traces of the original topography are removed and there are no more dramatic changes in the topography. During the model runs, a detailed record is kept of precipitation (storm area and location) and sediment export from the grid (sediment yield, coordinates of cells from which export occurs, and base level). In addition, elevations at all grid cells are recorded periodically for analyses of topography, drainage network configuration, and mass balances.

Spatial and temporal scales of Cascade 5

Cascade 5 was developed as a heuristic model, i.e. it was written for exploring and understanding the sediment dynamics of fluvial landscapes rather than to model the evolution of a specific landscape in order to predict or postdict its sediment transport record. Thus, the model is aimed at prediction, i.e. estimating the magnitude of the sediment yield associated with a hypothetical rainfall or exceedance probability, rather than forecasting, i.e. estimating the sediment yield at a specified time (Dingman, 2002). As a result, the spatial and temporal scales of the model need not be strictly defined, other than that in general terms the model concerns large temporal and spatial scales. An important spatial scale consideration is that each cell represents an area with a size of the order of 10^1–10^2 km^2. Thus, the processes in each cell are a combination of channel and slope processes, and no distinction is made between channel and slope cells. In terms of temporal scale, the model is aimed at evaluating landscape evolution and sediment dynamics over periods of 10^3–10^5 years.

RESULTS AND DISCUSSION

A landscape in Cascade 5 is a dissipative system in which individual cells interact with their neighbours. Groups of cells form drainage basins, which interact with adjacent drainage basins and in turn form part of larger drainage basins, which also interact with adjacent drainage basins and are part of still larger drainage basins and so on. In this way, the repeated application of the small-scale, or local, rules describing the interaction between adjacent cells results in a hierarchical structure displaying large-scale, or global, properties. The rules describing these global properties, however, cannot be predicted from the local rules. Some global properties describe the morphology such as, for example, the frequency distribution of slope angles or the Horton ratios that characterize drainage network configuration. Other global properties describe how the landscape functions as a unit, and enable a process-based description at the global scale.

Rules describing sediment transport at the landscape-scale can be formulated in various ways. An important functional characteristic of a fluvial landscape is the frequency distribution of sediment yield for various sizes of storms (Fig. 1). The frequency distributions of sediment yield for each storm size show a central peak, with decreasing frequencies of occurrence for smaller and larger sediment yields. The

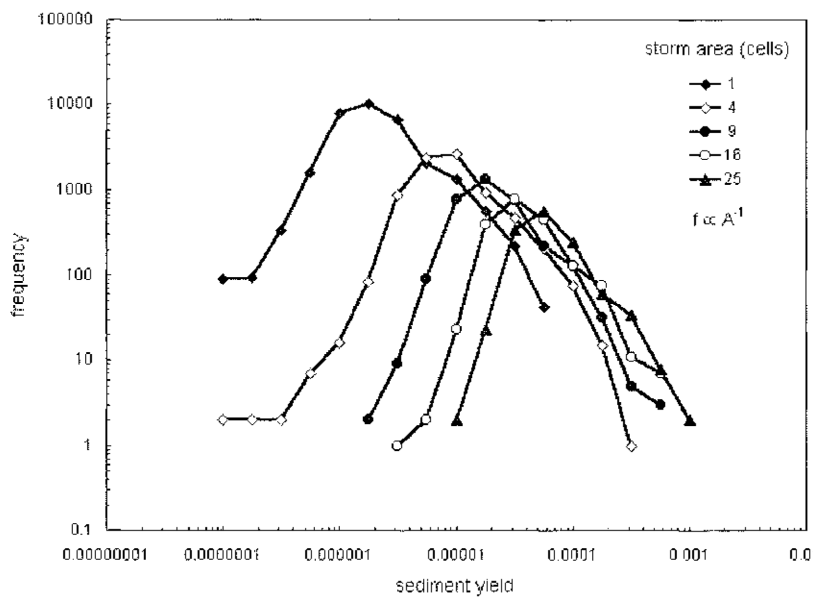

Fig. 1 Frequency distributions of sediment yield for rainstorm frequency distribution of $f \propto A^{-1}$.

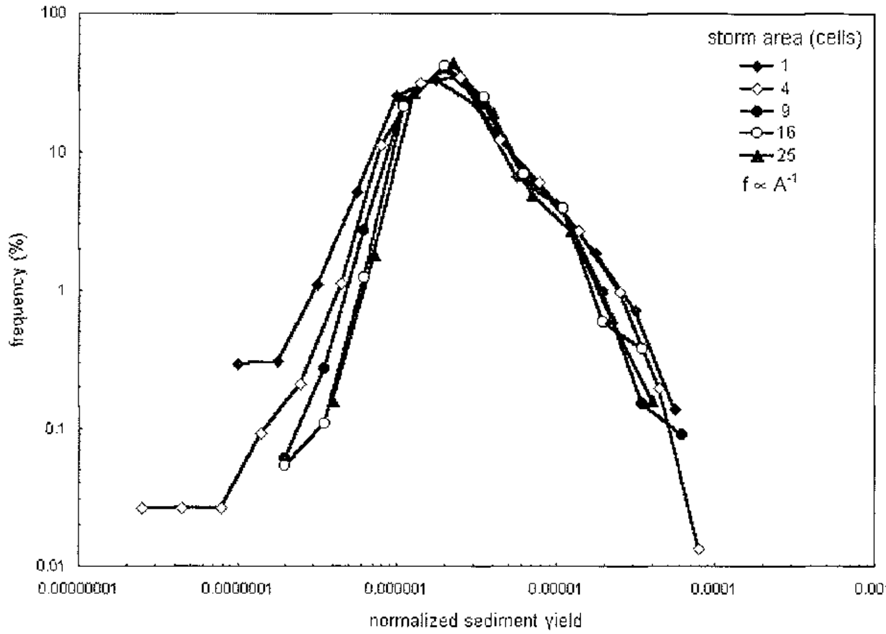

Fig. 2 Normalized frequency distributions of sediment yield for rainstorm frequency distribution of $f \propto A^{-1}$.

sediment yield with the highest frequency varies directly with storm size, so that larger storms have greater sediment yields. Sediment yields for a storm with a specific area range over more than three orders of magnitude, depending on the recent erosional history and the storm location. Normalized frequency distributions of sediment yield can be obtained by scaling the frequency distributions with storm size and frequency (Fig. 2). Normalized frequency distributions of sediment yield of the various storm sizes generally have the same shape. The normalized frequency distributions are a property of the entire landscape and cannot be predicted in advance, even though they result from the repeated application of the small-scale sediment rules in combination with the rainstorm frequency distribution. Thus, the frequency distributions of sediment yield are an emergent property of the landscape.

Of course, normalized frequency distributions of sediment yield are partly determined by the rainstorm frequency distribution. To investigate the effect of rainstorm frequency distribution on sediment yields, Cascade 5 was also run with a rainstorm frequency distribution of $f \propto A^{-0.75}$. The normalized frequency distributions of sediment yield for these model runs (Fig. 3) have the same general shape as those shown in Fig. 2. A close comparison, however, shows some differences in detail. The normalized frequency distributions for storms with an area of 1 cell, for example, show that the greater frequency of large rainstorms associated with a rainstorm frequency distribution with $f \propto A^{-0.75}$ results in a slightly lower peak frequency, and higher frequencies for smaller and larger normalized sediment yields (Fig. 4). The same result was found for all other rainstorms sizes. The increase in frequency of the larger normalized sediment yields can possibly be explained by the greater frequency of large rainstorms. The increased frequency of small normalized sediment yields is harder to

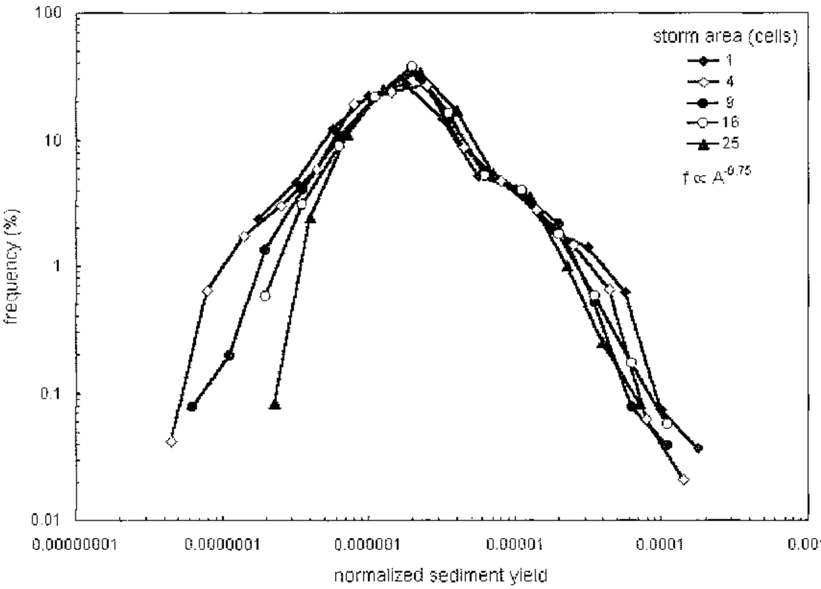

Fig. 3 Normalized frequency distributions of sediment yield for rainstorm frequency distribution of $f \propto A^{-0.75}$.

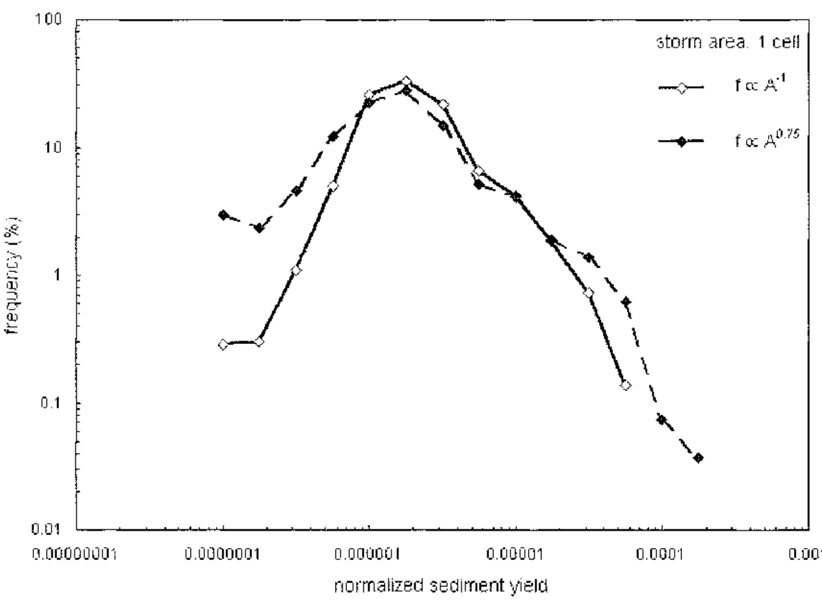

Fig. 4 Normalized frequency distributions of sediment yield for rainstorm with an area of 1 cell for rainstorm frequency distributions of $f \propto A^{-1}$ and $f \propto A^{-0.75}$.

explain, but could be the result of a decrease in sediment storage within the landscape as the larger rainstorms export large amounts of sediment.

Since Cascade 5 keeps a record of surface elevations and sediment fluxes it is possible to evaluate the effect of changing rainstorm frequency distributions on the morphology of the landscape. Figure 5 shows the topography of drainage basin 99, which is one of the largest drainage basins on the grid. Using the digital elevation model shown on Fig. 5 as a starting point, Cascade 5 was run twice, once with a rainstorm frequency distribution of $f \propto A^{-0.75}$ and once with $f \propto A^{-1}$. In both runs, approximately 270 000 cells received rainfall, so that the amount of rainfall was similar in both runs. Figure 6 show a comparison of the resulting topographies as the difference between the surface elevations obtained with $f \propto A^{-1}$ and those obtained using $f \propto A^{-0.75}$. As Fig. 6 shows, all values are positive, meaning that the surface obtained using $f \propto A^{-0.75}$ was lower overall than the surface obtained using $f \propto A^{-1}$. This indicates that the increased frequency of larger rainstorms associated with $f \propto A^{-0.75}$ results in greater surface lowering than was the case with $f \propto A^{-1}$, even though the total rainfall was similar in both

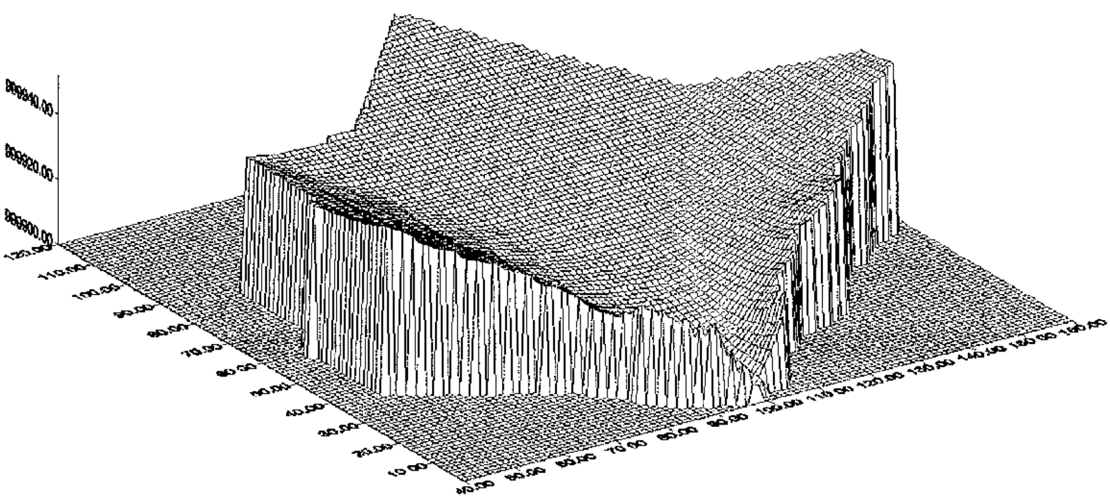

Fig. 5 Digital elevation model of drainage basin 99.

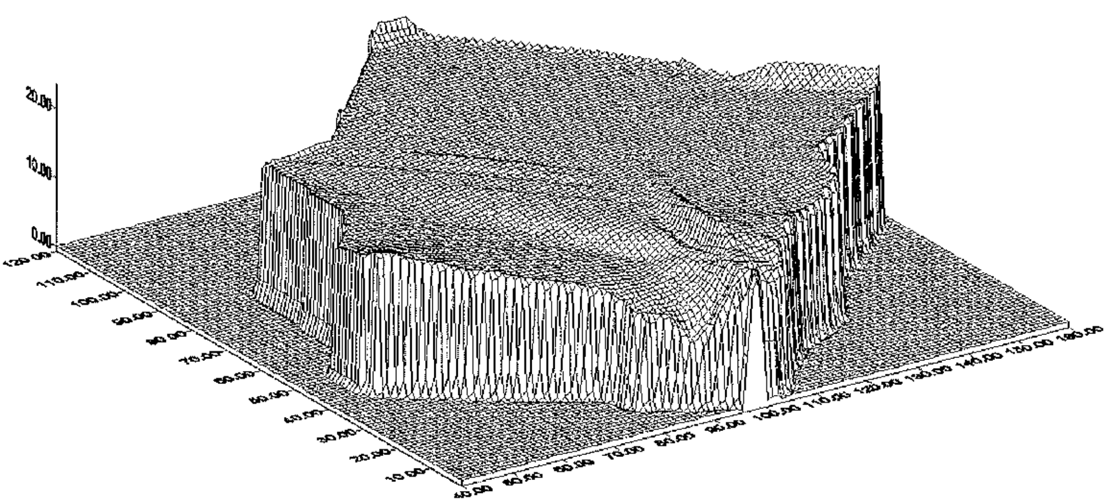

Fig. 6 Difference in surface lowering between rainstorm frequency distributions of $f \propto A^{-1}$ and $f \propto A^{-0.75}$ in drainage basin 99.

cases. Figure 6 also allows evaluating where in the drainage basin the two rainstorm frequency distributions result in the greatest differences in surface lowering. The highest values in Fig. 6, indicating the greatest differences between the two scenarios, are found along the drainage divides away from the mouth of the drainage basin. In addition, high values are found along the main valley near the mouth. High values in Fig. 6 indicate that these portions of the basin are sensitive to changes in rainstorm frequency distribution, which has implications for the design of monitoring programmes aimed at evaluating the impact of climate change on erosion and landscape evolution.

CONCLUSIONS

A landscape in Cascade 5 displays self-organization. Starting with local rules of sediment transport, through time drainage basins develop. The resulting landscape that results from the repeated application of the small-scale local rules is characterized by large-scale global rules that cannot be deduced from the small-scale rules, but instead emerge from their repeated application. An example of a large-scale rule is the normalized frequency distribution of sediment yield. This frequency distribution scales with storm size, which allows the forecasting of the potential impact of extreme events. The normalized frequency distribution of sediment yield changes with the rainstorm frequency distribution, with a decrease in the frequency of the most common sediment yield, and an increase in the frequency of other sediment yields. Additional model runs are required, however, to characterize in greater detail the relationship between the frequency distribution of rainstorms and normalized sediment yield.

One of the potential applications of a heuristic model such as Cascade 5 lies in the insight it provides into the relationship between rainstorm magnitude and sediment yield. In Cascade 5, rainstorms of a specific magnitude result in sediment yields that vary over more than three orders of magnitude, depending on storm location and the recent erosional history of the basin, and the modelled drainage basins display complex response (Schumm, 1977). The practical significance of this finding is that variations in sediment yield cannot automatically be interpreted as reflecting changes in rainfall characteristics. Instead, an attempt should be made to construct and analyse the sediment yield frequency distribution and its relationship to climate characteristics.

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