A self-organizing dynamic systems approach to hillslope rill initiation and growth: model development and validation

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Abstract No current erosion model is capable of explicitly forecasting the location and subsequent evolution of hillslope rill systems. As a result, modelled estimates can only represent some spatially generalized result. Observational evidence suggests that it is possible to apply an evolutionary analogy to rill growth and development, with the most "successful" dominating over those which are less well favoured. A model was constructed to evaluate this concept, based upon work on self-organizing dynamic systems. This model (*RillGrow*) applies simple rules to govern the iterative interaction between microtopography, runoff routing and soil loss. Runoff is conceptualized as consisting of discrete "packets": thus a Lagrangian frame of reference is adopted, in contrast to the more usual Eulerian perspective. This paper describes the conceptual basis of the *RillGrow* model together with the results of two sets of experiments. The first indicated that *RillGrow* is able to generate convincing rill-like networks which reproduce—on the scale of centimetres to metres—many quantitative observed features of erosional systems (such as a decrease of mean rill spacing and a nonlinear increase of total erosion with steepening slope). The second is a validation study using a field rainfall simulator. Photogrammetric techniques were used to generate digital elevation surfaces of the plot's microtopography, before and after simulated rainfall is applied. The model-generated erosional network compares well with the pattern of erosion produced during the experiments.

INTRODUCTION

Soil erosion models of the present generation—such as WEPP, CSEP, EUROSEM, EPIC and GLEAMS—are reasonably successful at estimating rates of water erosion on field-sized hillslope areas over time scales of days to several years (Boardman & Favis-Mortlock, 1998). However, they are not capable of explicitly specifying the initial location and subsequent spatial development of hillslope rill systems in real landscapes: at best, rates may be determined for points down a "representative" hillslope profile or flow strip. Without such a capability, models of soil erosion by water can only produce spatially generalized estimates of erosion and of its impacts, both under agriculture and under natural vegetation. To improve the spatial performance of models, there is therefore a clear need for a modelling approach which is capable of an explicit spatial representation of the initiation and development of erosional systems. Such a model must adopt a distributed approach at a scale relevant to rills, and begin simulations prior to the initiation of rills.

MODEL DESCRIPTION

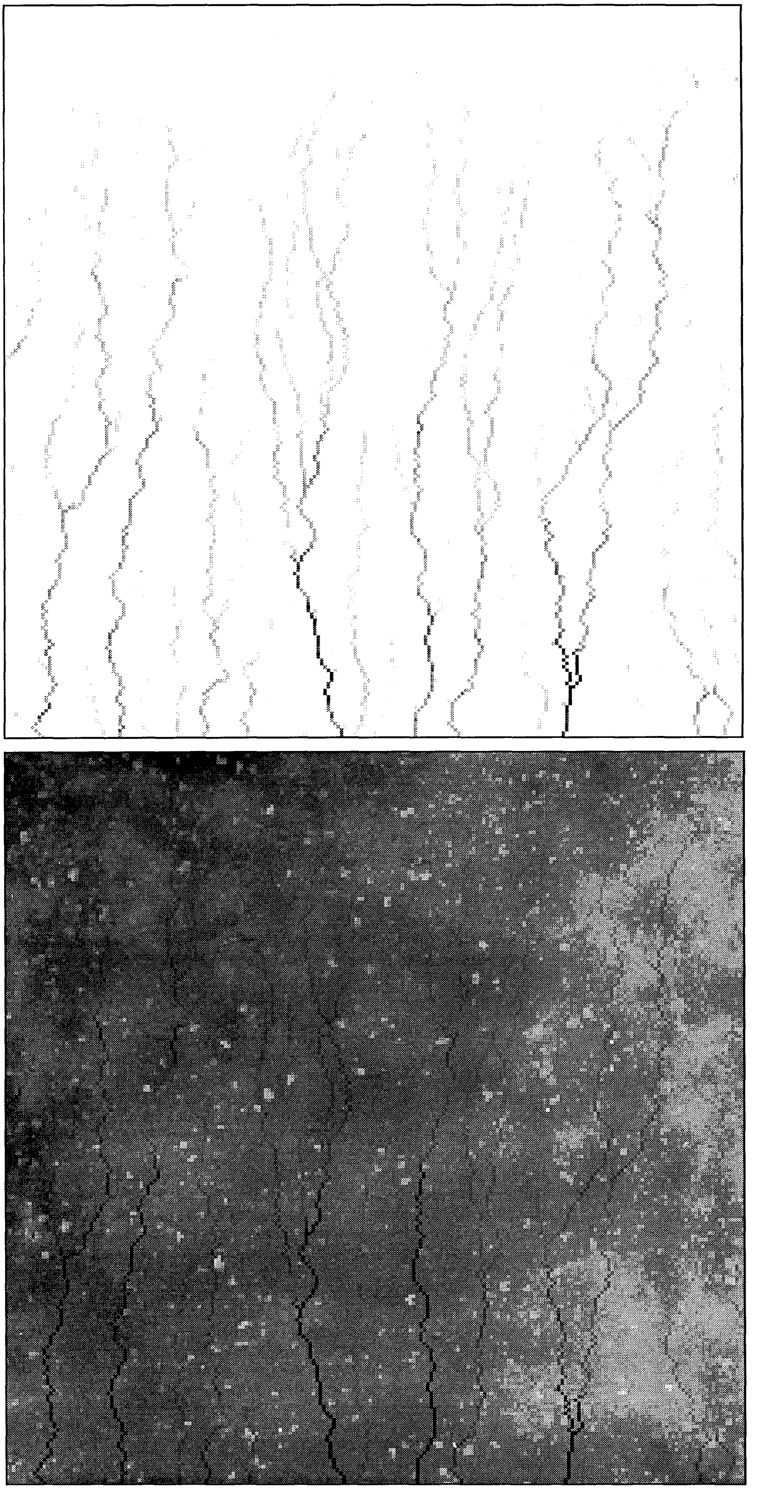
Favis-Mortlock (1996, in press) speculated "Is the initiation and development of hillslope rill systems driven by relatively simple rules acting on a much smaller scale?". This hypothesis was tested by constructing a simple model (*RillGrow*). This uses an approach drawn from theoretical work on self-organizing dynamic systems (e.g. Coveney & Highfield, 1995) to represent rill initiation and growth on the bare soil of a small hillslope area.

In this single-event model, microrills (e.g. Merritt, 1984) are assumed to be formed both by the runoff resulting from individual raindrops (infiltration is ignored) and from the overflow of ponded surface water; the location of all microrills is also assumed to be determined solely by microtopography. However, microtopography is itself modified by erosion. This influences the subsequent movement of runoff, creating a feedback loop. Microrills thus "compete", with the most "successful" of these deepening to become discontinuous rills. These in their turn also compete, with a subset dominating to form continuous rills. In this scheme, no explicit separation is made between rill and interrill processes, which are deemed instead to be end-members of a continuum.

The further assumption is made that runoff may be conceptually discretized into many small "packets" which move on a grid of microtopographic elevations: the model thus adopts a Lagrangian frame of reference in contrast to the more conventional Eulerian (Eringen, 1967). This approach has been successful in describing three-dimensional fluid flow (the so-called "lattice gas" approach) (Wolfram, 1984, 1986; Garcia-Sanchez *et al.*, 1996). Packet routing in *RillGrow* is controlled only by microtopography. The majority of packets are small, and with an initial random position (i.e. produced by a single "raindrop"). These flow down the line of steepest microtopographic gradient until they either leave the grid, or form or enter a pool in a microtopographic hollow. In the course of each simulation a smaller number of larger packets are also formed, which result from the overflow and breaching of pools.

Table 1 The rules used by the RillGrow model (from Favis-Mortlock, 1996, in press).

Rule	Description
1	Raindrops fall randomly on the cells making up the hillslope grid; the whole of each raindrop becomes a runoff "packet". One raindrop falls per iteration of the model
2	Runoff always tries to move to a lower adjacent cell down the steepest slope until it leaves the grid. If no adjoining cells are lower, the runoff stays where it is, forming (or adding to, if the cell is already wet) a pool
3	When runoff leaves a cell, it erodes it, thus lowering the elevation of that cell
4	If pools fill sufficiently, they breach. The water which overflows from the pool is routed to the next cell outside the breach and handled using rule 2, and so on



(a)

(b)

Fig. 1 Plan view of the network formed at the end of the simulations which used the laser-scanned surface on a 20% slope. (a) Shows the depth eroded. Darker tones are deeper. (b) Shows the relationship with the microtopography. Again, darker tones are deeper. Note how the network avoids high spots such as the lighter coloured aggregates. From Favis-Mortlock (in press).

As each packet moves across the grid, it erodes the surface, using an S-curve (logistic) streampower-based expression developed by Nearing *et al.* (1997). Erosion thus lowers surface elevation, and so modifies the local microtopography; this in turn affects the routing of subsequent packets (Table 1). This forms a feedback loop as discussed above. By means of this feedback loop, the model "learns", i.e. is able to modify its subsequent behaviour based on past events. As a result the system "evolves" i.e. displays self-organizing, emergent behaviour.

RESULTS

In a first set of experiments (Favis-Mortlock, 1996, in press), a digital elevation model (DEM) of microtopographic heights was produced by laser scanning the surface of a Glynwood clay loam soil which had previously received 50 mm from a rainfall simulator. This DEM was then input to *RillGrow*. Results obtained using this dataset indicated that although the movement of runoff in the model is governed only by relatively simple rules (Table 1) acting upon microtopographic relief at a millimetre scale, the model is capable of reproducing apparently realistic erosional networks on a scale of centimetres to metres (Fig. 1). Emergent macroscale responses of the model include a narrowing of rill spacing with increased slope angle (Fig. 2), an increased contribution of rill erosion with downslope distance (Fig. 3),

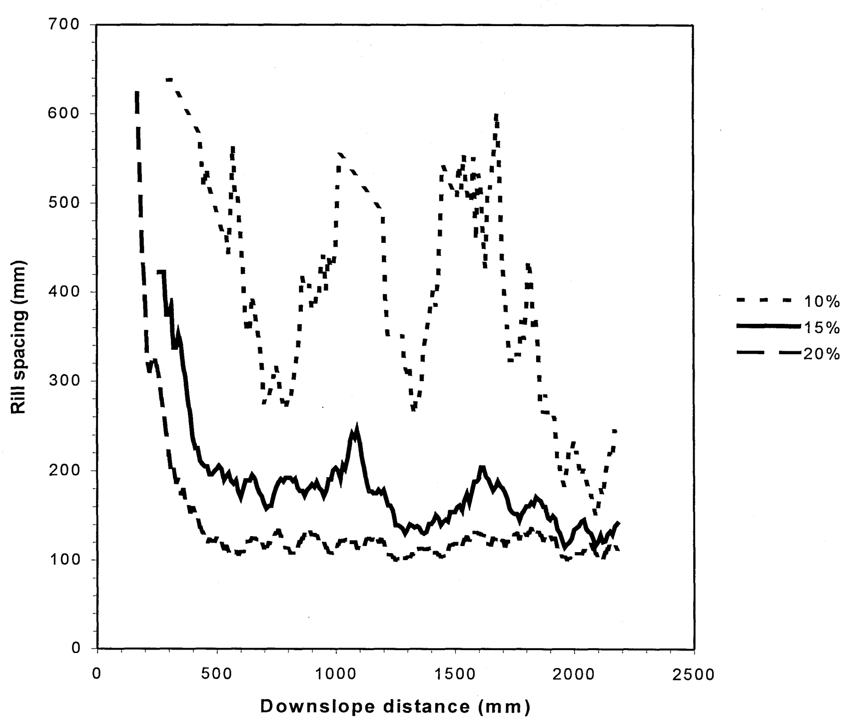


Fig. 2 Simulated rill spacing for slope angles of 10, 15 and 20% (from Favis-Mortlock, 1996, in press). A value of 0.5 mm depth eroded was taken to be the threshold separating rill and interrill areas

and a nonlinear increase of total erosion with slope steepness (Fig. 4). Additionally, simulated networks exhibit such features as an increase in rill depth below confluences. The microtopographic grid shows a decrease in the correlation of cell–cell elevations, primarily at short correlation lengths.

Experiments were also carried out using a variety of stochastically generated microtopographic surfaces (Fig. 4). While networks did form on these surfaces, they appeared less realistic than those formed on the scanned microtopography. Subsequent work with the laser-scanned dataset has concentrated upon an investigation of the sensitivity of the model, and its ability to produce "higher-level" emergent features such as rill capture (Favis-Mortlock, in preparation).

The aim of a second experiment was to validate the spatial patterns of erosion produced by the model. Digital photogrammetry was used to create DEMs of the surface of a 1 m × 0.5 m pre-wetted raked bare soil plot before, during and after the production of a microrill/rill network by means of a portable rainfall simulator (Guerra *et al.*, in preparation). The experiment—lasting 1 h—was carried out at Manor Farm, Littleworth, Oxfordshire. Runoff (2.8 litres) and soil loss (16.54 g) were collected at the end of the experiment.

The DEM of the uneroded surface was input to *RillGrow* (Favis-Mortlock *et al.*, in preparation). Real and model-generated patterns of erosive flow are compared in Figs 5(a) and (b). The model succeeds in predicting the location of most erosional

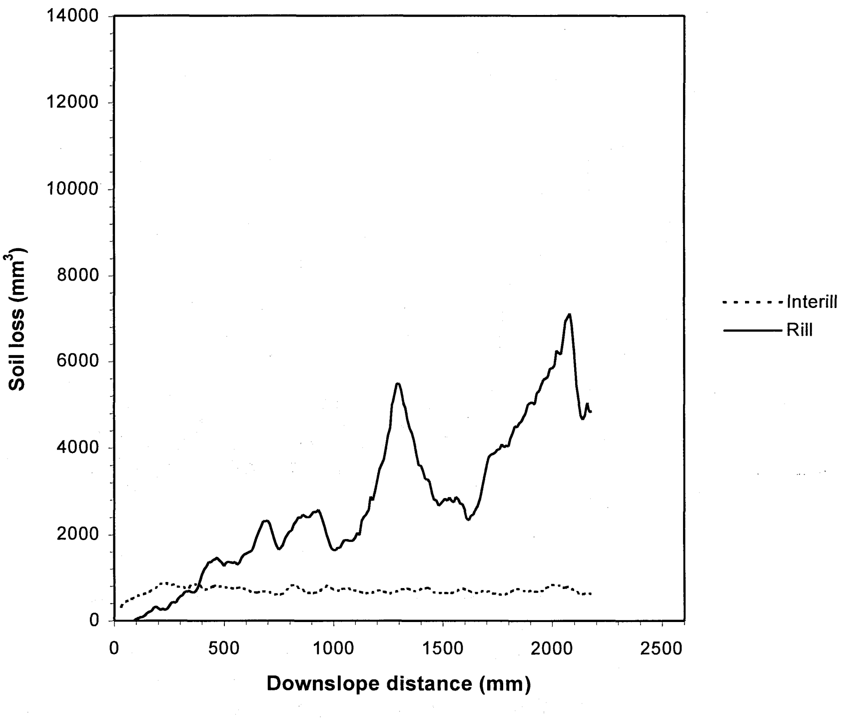


Fig. 3 Simulated rill and interrill contributions on a 15% slope. From Favis-Mortlock (1996, in press).

areas. Differences between observed and modelled patterns of erosion appear to be related (in part, at least) to intermittent deposition during the formation of the network which deactivated initially active microrills. The present version of *RillGrow* does not explicitly consider deposition.

DISCUSSION

Despite its simplicity, this modelling approach appears very promising. It suggests that relatively similar rules, when applied to runoff routing at the scale of microtopography, can explain and indeed predict the spatial patterning of erosional features on a hillslope scale. A basically similar approach at a larger scale has been applied by Murray & Paola (1994) to model the evolution of braided streams; their approach, however, does not consider ponding. More recently the same authors (Murray & Paola, 1997) have extended their work to also consider the formation of hillslope erosional networks, suggesting an intriguing connection between the two sets of phenomena.

As currently implemented, the *RillGrow* model has three main limitations. Firstly, many process descriptions (e.g. infiltration and deposition) are omitted

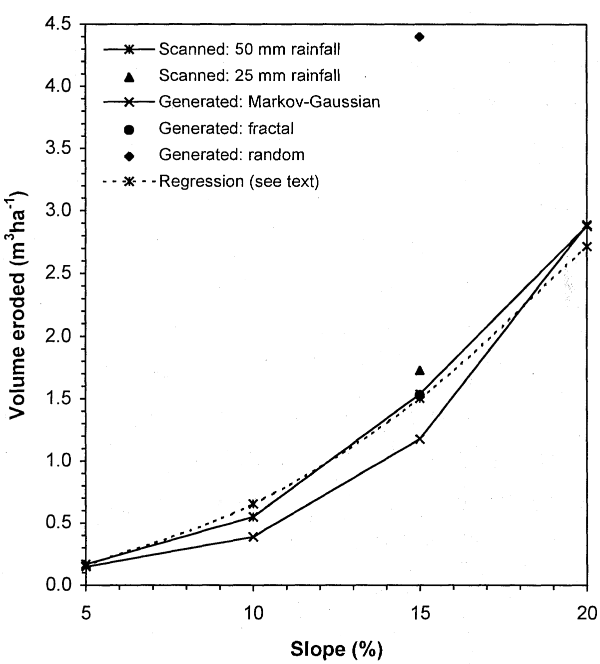


Fig. 4 Total simulated erosion and slope angle for the laser-scanned soil surface, plus several stochastically-generated microtopographic distributions. A curve (R^2 = 0.991) has been regressed to the data for the scanned surface (after 50 mm simulated rainfall) of the form *soil loss* = *a slope*^{b} where *a* and *b* are constants. The value of the exponent *b* for this curve is 2.05. Morgan (1996) considers a very similar value to be reasonable for rill flow. From Favis-Mortlock (in press).

Fig. 5(a) Patterns of erosive flow produced by a field rainfall simulator on a 1 m × 0.5 m plot with a 7% slope, after 9 min. Due to the low slope angle, deposition occurred readily in areas of erosive flow. Lighter shades represent areas of deposition (note that the absolute depth of deposition differs between the two diagrams, however). Flow is down the page in both cases. Dark lines are an overlay of the pattern of microrills/rills produced by the RillGrow model on a DEM of the uneroded plot; the model does not consider deposition. From Favis-Mortlock *et al.* (in preparation).

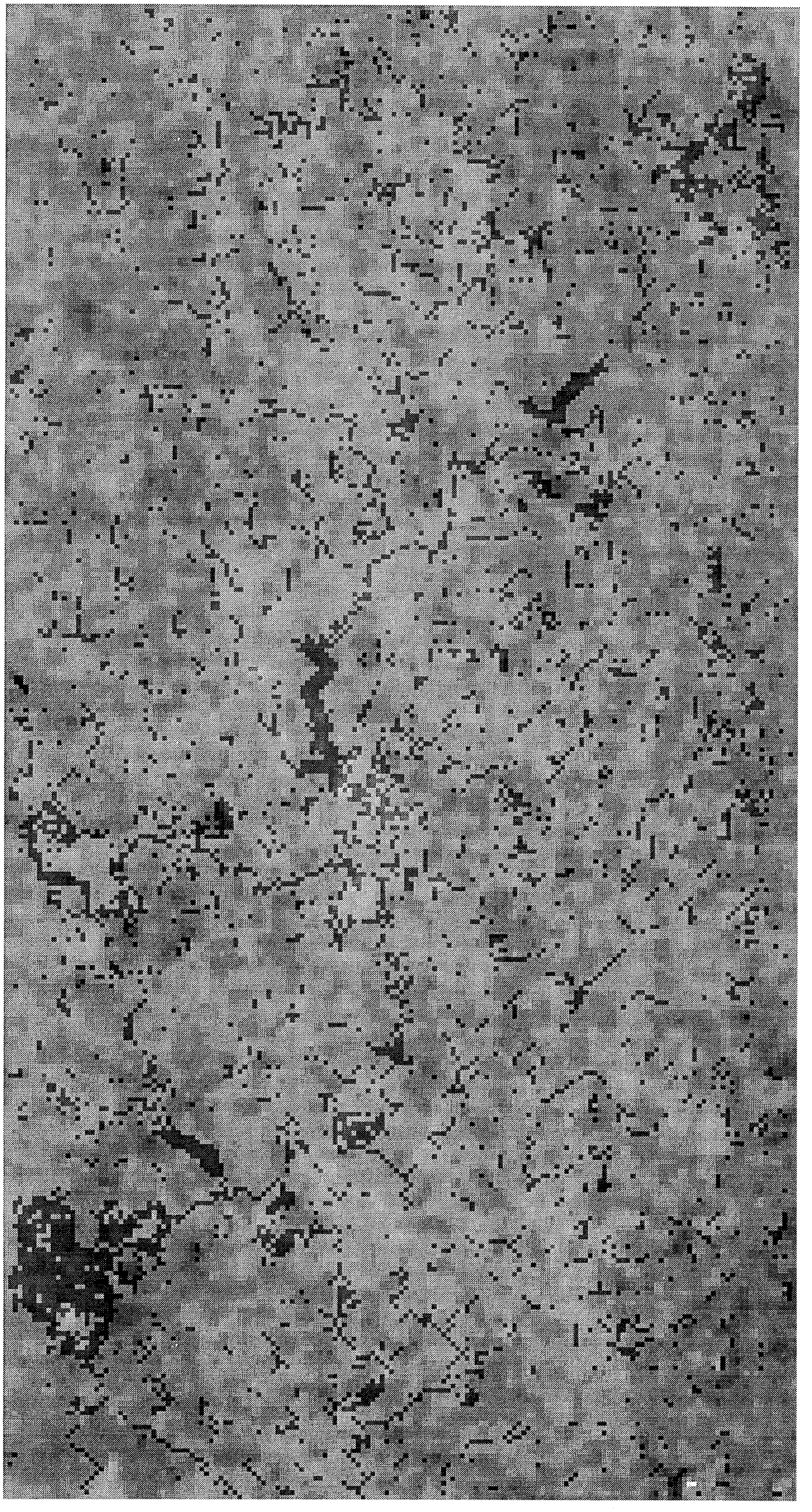


Fig. 5(b) Patterns of erosive flow produced by a field rainfall simulator on a 1 m × 0.5 m plot with a 7% slope, after 1 h. Due to the low slope angle, deposition occurred readily in areas of erosive flow. Lighter shades represent areas of deposition (note that the absolute depth of deposition differs between the two diagrams, however). Flow is down the page in both cases. Dark lines are an overlay of the pattern of microrills/rills produced by the RillGrow model on a DEM of the uneroded plot; the model does not consider deposition. From Favis-Mortlock *et al.* (in preparation).

completely. These could be added fairly readily, however. Secondly, the approach is very demanding of computational resources; for present-day hardware, this constrains the size of area to which it may be applied. Thirdly—and most importantly—the model demands a great deal of data regarding microtopography. While this might appear to place a severe limit on its practical application, the use of stochastically generated microtopographic surfaces might offer a way forward. However, none of the generated surfaces used here appeared to satisfactorily replicate the properties of the scanned surfaces. Further research appears necessary (cf. Bertuzzi *et al.*, 1995).

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