HYDROLOGICAL PROCESSES
Hydrol. Process. **20**, 67–84 (2006)
Published online 26 August 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5899

Modelling of sediment dynamics in a laboratory-scale experimental catchment

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Abstract:

The variability of hillslope form and function is examined experimentally using a simple model catchment in which most landscape development parameters are either known or controlled. It is demonstrated that there is considerable variability in sediment output from similar catchments, subjected to the same hydrological processes, and for which the initial hillslope profiles are the same. The results demonstrate that, in the case of catchments with a linear initial hillslope profile, the sediment output is initially high but reduces through time, whereas for a concave initial profile the sediment output was smaller and relatively constant. Concave hillslope profiles also displayed reduced sediment output when compared with linear slopes with the same overall slope. Using this experimental model catchment data, the SIBERIA landscape evolution model was tested for its ability to predict temporal sediment transport. When calibrated for the rainfall and erodible material, SIBERIA is able to simulate mean temporal sediment output for the experimental catchment over a range of hillslope profiles and rainfall intensities. SIBERIA is also able to match the hillslope profile of the experimental catchments. The results of the study provide confidence in the ability of SIBERIA to predict temporal sediment output. The experimental and modelling data also demonstrate that, even with all geomorphic and hydrological variables being known and/or controlled, there is still a need for long-term stream gauging to obtain reliable assessments of field catchment hydrology and sediment transport. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS landscape simulator; erosion; surface hydrology; geomorphology; sediment transport; SIBERIA landscape evolution model

INTRODUCTION

One of the major issues facing hydrology and geomorphology is the predictability, and the limits to such predictability, of field catchment form and function (Entekhabi, 2001). Runoff and sediment production from a hillslope are spatially and temporally variable and very difficult to quantify, as there is little reliable long-term data available with which to evaluate variability (Huang *et al.*, 2001). Without a thorough understanding of the variability in natural systems, there is little chance of managing the environment when subject to human disturbance, let alone of developing reliable predictive models (Wendt *et al.*, 1986).

Variability can be examined in a number of ways: first, by making use of available field catchment data (Walling, 1974); second, by using experimental-scale model landscapes (Parker, 1977; Schumm *et al.*, 1987); and third, by using numerical models of landscape processes (Willgoose *et al.*, 2003). The advantage of using field data is that scale issues are minimized and the variability in field-scale processes is considered directly. Nevertheless, in a natural system each season is different, vegetation differs both temporally and spatially within a catchment, and reliable measurements are often difficult to obtain and interpret (Negev, 1969; Walling, 1974; Wood, 1977; Wendt *et al.*, 1986; Reid and Frostic, 1994; Selby, 1994; Knighton, 1998; Huang *et al.*, 2001; Walling *et al.*, 2001). Paired catchments can offer some insight but tey can also pose many difficulties,

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Received 30 October 2003
Accepted 14 January 2005

as few, if any, field catchment pairs are of the same size or have the same geology or vegetation. Also, it is difficult to assess rainfall variability across catchments, and its relationship to sediment transport (Reid and Frostick, 1998), as there are rarely enough rain gauges across a catchment to assess rainfall variability accurately.

To address the difficulties of field studies, laboratory-scale experimental model catchments and numerical models of landscape processes offer many possibilities. Experimental-scale model landscapes and numerical models overcome many of the difficulties of field catchments (Schumm *et al.*, 1987; Willgoose *et al.*, 2003). For example, initial conditions for landscape development are known and can be reproduced. Also, rainfall, erodible material and geological history are known and the landscape can be studied throughout its evolution, which can span a few hours to a few days. Further, transient landscapes, or those that have not reached an equilibrium form, can also be examined (Parker, 1977; Hancock *et al.*, 2002).

In recent years, several physically based numerical landform evolution models have been developed (Willgoose *et al.*, 1991a–d; Howard, 1994; Tucker and Slingerland, 1994; Braun and Sambridge, 1997; Tucker *et al.*, 2001, Coulthard *et al.*, 2000; Coulthard, 2001). The SIBERIA (Willgoose *et al.*, 1991a–d) model is one of these models and is the focus of this study. Previous studies have examined SIBERIA's ability to model natural landscapes over geological time scales (Ibbitt *et al.*, 1999; Hancock *et al.*, 2002), post-mining landscapes over shorter time scales (approximately 50 years; Hancock *et al.*, 2000) and also transient and declining equilibrium experimental model landscapes (Hancock and Willgoose, 2001c, 2002).

For the purpose of examining hydrological and sedimentological variability and our ability to model this variability using SIBERIA, a rainfall-erosion landscape simulator was developed in which experimental model landscapes were allowed to evolve under controlled conditions of rainfall and material erodibility. To test SIBERIA, the evolution of one-dimensional experimental catchments was compared with the evolution of SIBERIA-simulated catchments using the same initial conditions and rainfall. A one-dimensional catchment has flow in only one direction, with an absence of stream branches, and is the simplest situation in which landform development might occur.

The aim of this paper is to examine hydrological and sedimentological catchment outputs for sets of identical tests where rainfall and erodible material type are kept constant both through time and between experiments (Wendt *et al.*, 1986). Sediment transport variability from the experimental catchments is examined, as well as SIBERIA's ability to model this variability. SIBERIA is also tested for its ability to simulate two types of one-dimensional catchment, i.e. linear slopes and concave slopes. Total sediment output (bed load and wash load), catchment volume and final landscape form are used to measure landscape change and variability through time.

The experimental apparatus and techniques in this study have been used extensively to examine catchment behaviour at the model scale (Willgoose and Hancock, 1998; Hancock and Willgoose, 2001a–c, 2002, 2003). It has already been demonstrated that the experimental apparatus can provide model catchments with many features similar to field-scale catchments (Hancock and Willgoose, 2001a–c, 2002, 2003). Consequently, it is considered that these experiments using this laboratory apparatus can provide an understanding of hydrological and sediment transport variability, as well as being a valid test of SIBERIA.

EXPERIMENTAL APPARATUS AND METHODS

For this study, a previously developed experimental model landscape has been employed (Hancock and Willgoose, 2001c) in which (1) the erodible material has little or no cohesion between particles (so as to allow the landscape to erode rapidly), and (2) rainsplash (triggering diffusive transport processes) is minimized by the use of a rainfall simulator with raindrop sizes significantly smaller than those observed in the field (Figures 1 and 2; Hancock and Willgoose, 2001a,b, 2003).

In this study, three slopes were used: a linear slope of 10%; a linear slope of 5%; and a concave profile (see 'Design of concave slopes' section) of overall average slope of 10%. The different catchment profiles

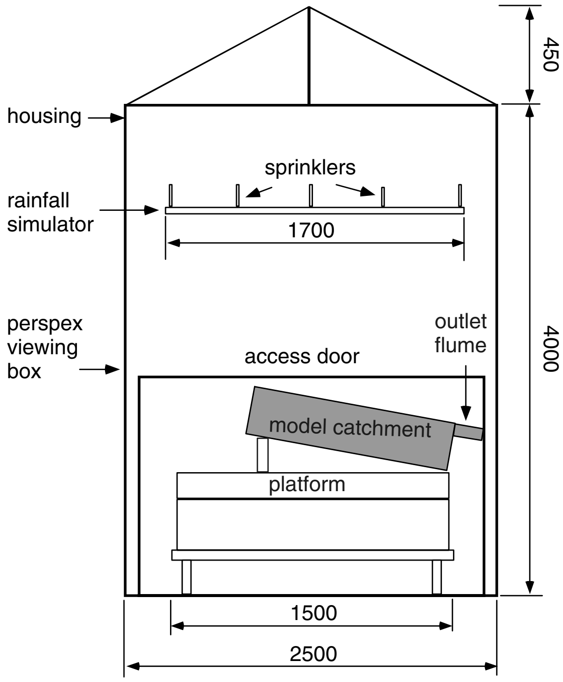

Figure 1. Landscape simulator in which the experiments were conducted. All dimensions are in millimetres

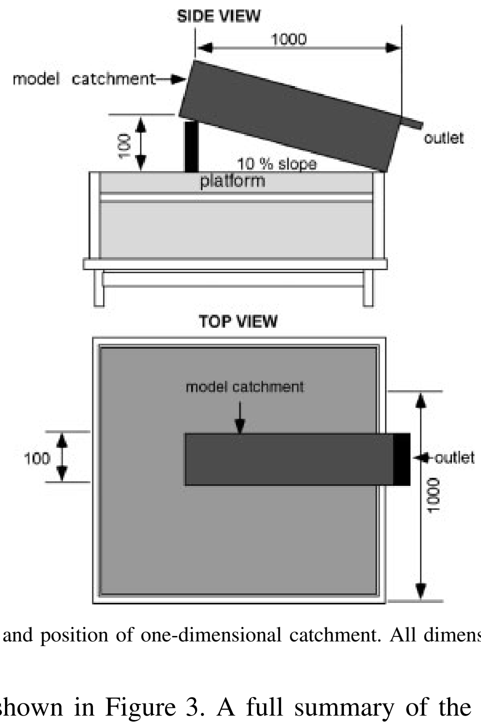

Figure 2. Dimensions and position of one-dimensional catchment. All dimensions are in millimetres

in the downslope direction are shown in Figure 3. A full summary of the tests undertaken for this study is presented in Table I. These slopes are similar to those examined in other field and laboratory studies (e.g. Parker, 1977; Wendt *et al.*, 1986; Brunton and Bryan, 2000; Hancock and Willgoose, 2001c).

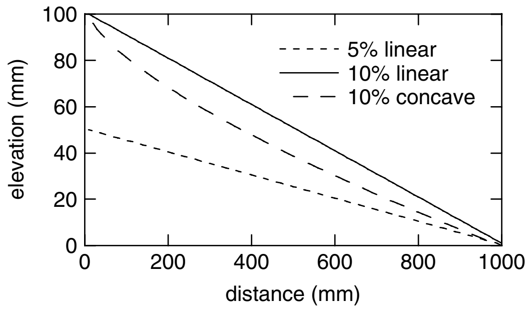

Figure 3. Initial hillslope profiles used for the experiments and SIBERIA simulations

Table I. Number and type of experiments conducted using the one-dimensional catchment

	High rainfall	Low rainfall
5% linear slope	5	5
10% linear slope	5	5
10% concave slope	5	5

Landscape formation simulator

The landscape formation simulator (Figures 1 and 2) consisted of a rainfall simulator suspended above a box containing a small one-dimensional experimental catchment. The whole apparatus was housed in a Perspex enclosure with a roof, which allowed viewing while protecting the rainfall simulator from external air movements. The one-dimensional catchment was 1000 mm long by 100 mm wide, containing soil 300 mm deep (Figure 2). The length to width ratio (10 : 1) of the catchment is typical of that observed for straight reaches of natural channel (Richards, 1982). The catchment soil was contained in a box constructed of 20 mm marine ply with 16-gauge stainless-steel sheet lining the inside of the box. Holes were cut in the base of the box, which was then lined with filter fabric to allow free drainage without soil loss. The outlet of the catchment was the same as the full catchment width.

To scale diffusive and fluvial processes, the rainfall simulator was designed to reduce the effect of rainsplash-induced diffusion, relative to the effect of fluvial processes, by reducing the drop size. The rainfall simulator used microsprinklers, which produced drops with little or no rainsplash. Drop size was determined using a Malvern laser particle-sizer. It was found that 90% of the drops were less than 330 μm in diameter, and 50% of the drops were less than 195 μm in diameter. Rainsplash has been demonstrated to occur when droplets are approximately twice the former drop diameter (Stow and Hadfield, 1981). The kinetic energy of the simulated rainfall was many times less than natural rain. This effectively eliminated diffusive erosion processes, producing a landscape dominated by fluvial erosion (i.e. channelized flow), thus simplifying the model comparison.

The experimental landscape was constructed of fly ash, which is the common name given to the burnt remains of coal from coal-fired electricity-generating stations. Fly ash, which has little or no cohesion between particles, is readily eroded at low shear stresses and has an infiltration capacity considerably less than the chosen rainfall rate so that runoff could occur. Testing indicated that a blend of medium (two-thirds by weight) and fine grade (one-third by weight) had low infiltration capacity and low cohesion. The medium-grade fly ash has a particle size distribution where 90% of the material was less than 310 μm in diameter and 50% of the material was less than 113 μm, whereas the fine-grade material has a distribution where 90% of the material was less than 62 μm and 50% of the material was less than 16 μm. The blended fly ash had an asymptotic steady-state infiltration rate of 20 mm h^{-1}. Blended fly ash was used for all reported experiments in this paper.

The slopes considered in this study (linear slopes of 5 and 10%) and the concave profile of overall slope 10% (see Table I and Figure 3) are well within the operating limits of the experimental apparatus, ensuring that the majority of erosion would occur by surface wash processes.

Rainfall was measured either pre- or post-experiment to check there was no drift in spatial or temporal rainfall distribution by 10 rain gauges (90 mm diameter, 120 mm tall) placed over the catchment surface, covering the majority of the catchment area (Tables II and III). Two target rainfall intensities were selected for this project: a 'high' rainfall of average intensity 126 mm h^{-1} and a 'low' average rainfall of 54 mm h^{-1}. These intensities were chosen as they have been used in past studies (Hancock and Willgoose, 2001c, 2003)

Table II. High-intensity rainfall data

Average rainfall (for 10 rain gauges) (mm h^{-1})	SD
142	20
199	16
210	18
191	20
155	18
126	15
111	9
101	10
108	7
114	9
142	20
Mean: 146	

Note: each row presents rainfall statistics measured before or after one of the experiments.

Table III. Low-intensity rainfall data

Average rainfall (for 10 rain gauges) (mm h^{-1})	SD
50	9
67	10
71	7
66	7
59	7
53	6
48	4
45	3
43	3
37	3
50	9
Mean: 54	

Note: each row presents rainfall statistics measured before or after one of the experiments.

and whilst they are significantly different from each other, they are well within the working limits of the system and they allowed landscape development to occur in the absence of rainsplash. Rainfall was reduced from high to low by placing covers over some of the microsprinklers, preventing their contribution to the rainfall that fell onto the landscape surface. However, as discharge from the covered sprinklers was not prevented, the water pressure in the simulator was not altered, and consequently, the particle size distribution of the raindrops did not change.

Experiment setup and catchment measurement

To prepare each of the experimental catchments for testing, a free-draining filter zone was constructed by placing the geotextile material over the holes in the base of the box and then adding a 100 mm layer of beach sand. A 200 mm layer of the erodible material, new fly ash, was then placed over the sand by pouring it quickly from just above the surface, to slightly overfill the box. A straight edge was then placed over the rigid catchment walls and moved over the fly ash surface, striking off any excess fly ash so as to achieve the required initial level. This resulted in a surface with only minor imperfections. The required surface slope was achieved by gently raising one end of the box to a predetermined position. Rainfall was then turned on and maintained until the surface appeared saturated. Rainfall was then paused and the surface checked with a straightedge. If needed, further fly ash was added and the surface wetted again, producing a satisfactory surface.

To begin each test, rainfall was commenced and allowed to continue until the surface of the catchment displayed runoff. Rainfall was then stopped and the catchment allowed to free drain for 5 min before commencing the experiment. By following this procedure, a consistent initial condition (e.g. initial soil water content) was ensured for all experiments. Continuous rainfall was then commenced and continued for 135 min, as this time period ensured that a significant amount of erosion had occurred.

Variation in sediment yield during catchment evolution was measured by collecting sediment samples from the outlet flume at regular intervals during each experiment (Walling, 1974; Walling *et al*., 2001). Samples were collected at approximately 5 min intervals for the first hour and at approximately 10 min intervals in the second hour (at times of 5, 11, 17, 23, 29, 35, 41, 47, 53, 59, 70, 81, 82, 103, 124 and 135 min) after the commencement of rainfall.

Sediment samples were collected by placing a bottle under the outlet flume to collect all of the runoff that occurs in a 1 min period. The mass of sediment and water derived during each sampled minute was determined from measurements of the mass of clean, dry bottles prior to sample collection, the mass of bottle, water and sediment immediately after sample collection, and the mass of the bottle and dry sediment after the water was driven off by placing the collected sample in an oven for several days at 90 °C.

As the samples were collected manually, it is estimated that an error of up to ± 2 s could occur during insertion and extraction of the collection bottles, giving a maximum possible error in collection time of ± 4 s. The use of an automated sampler was beyond the scope of this project. Sediment yields are expressed in units of grams per minute.

Spot height measurements of the eroded landform at 135 min were measured relative to a fixed reference plane, on a regular grid of 50 mm (downslope) by 20 mm (cross-slope) using vernier callipers (20 grid points longitudinally and five across the catchment). This allowed the change in elevation at 100 grid points to be determined to an accuracy of better than 1 mm. From these data, catchment volumes and down-slope profiles were determined.

Design of concave slopes

Catchments with uniform underlying geology, and with fluvial erosion dominant, generally have a convex upper hillslope profile and a concave profile moving down the slope (Kirkby, 1971). The concavity in the lower section of the slope profile can be described by the area–slope relationship, which relates the area draining through a point to the slope at that point and thus effectively quantifies the local topographic gradient as a function of drainage area. It is given by a relationship of the form

$$A^{\alpha}S = \text{constant} \tag{1}$$

where A is the contributing area to the point of interest, S is the slope at the point of interest and α is the concavity of the hillslope for natural catchments, with values ranging between 0·2 and 0·7 (Hack, 1957; Flint, 1974; Gupta and Waymire, 1989; Tarboton *et al.*, 1989; Willgoose, 1994).

In this study, the area–slope relationship was determined from previous experimental model catchments using fly ash as the erodible material and the rainfall simulator described above (Hancock and Willgoose, 2001c). Using this data ($\alpha = 0{\cdot}30$), and a given the slope length of 1000 mm, a constant value can be calculated and the concave hillslope profile constructed (Figure 3). In this study we only examine a concave hillslope with average slope of 10%. The experimental catchment concave slopes were constructed in the same way as for the linear slopes, except that the box had concave sides.

SIBERIA CALIBRATION AND SIMULATIONS

SIBERIA links widely accepted hydrology and erosion models to predict the action of runoff and erosion (Willgoose *et al.*, 1991a–d). For long-term elevation changes it is convenient to model the average effect of the above processes with time. Accordingly, individual events are not normally modelled; rather, the average effect of many aggregated events over time is modelled. Consequently, SIBERIA describes how the catchment is expected to look, on average, at any given time. Currently, SIBERIA does not model soil development or weathering processes, but this ability is being implemented. The sophistication of SIBERIA lies in its use of digital terrain maps for the determination of drainage areas and geomorphology, and also in its ability to adjust the landform with time efficiently in response to the erosion that occurs on it.

The erosion equation of SIBERIA consists of two terms

$$q_{\text{s}} = q_{\text{sf}} + q_{\text{sd}} \tag{2}$$

where q_{s} (m^3 s^{-1} m^{-1}) is the volumetric sediment transport rate per unit width, q_{sf} (m^3 s^{-1} m^{-1}) is the fluvial sediment transport term and q_{sd} (m^3 s^{-1} m^{-1}) is the diffusive transport term. The fluvial sediment transport term q_{sf} is based on the Einstein–Brown model (Henderson, 1966), so that

$$q_{\text{sf}} = \beta_1 Q^{m_1} S^{n_1} \tag{3}$$

where Q (m^3 s^{-1} m^{-1}) is the discharge per unit width, S (m m^{-1}) is the slope in the steepest downslope direction and β_1, m_1 and n_1 are parameters of the model. The rate constant β_1 controls the rate of fluvial erosion and requires calibration to match the observed erosion rate. The diffusive term q_{sd} (e.g. rainsplash, soil creep) is composed of

$$q_{\text{sd}} = DS \tag{4}$$

where D (m^3 s^{-1} m^{-1} width) is Fickian diffusivity where transport is proportional to slope.

The low kinetic energy of the rainfall simulator used ensured that this diffusive transport can be ignored. For the experiment, the simplicity of the rainfall simulator means one can relate the discharge Q (m^3) to the area, so that

$$\mathrm{Q} = \beta_3 \mathrm{A} \tag{5}$$

where A (m^2 m^{-1} width) is specific area and β_3 is the runoff rate constant. β_3 can be varied spatially for non-uniform runoff over a catchment.

As this was a model landscape with unusual soil (i.e. fly ash), m_1 and n_1 were calibrated as it could not be assumed that any *a priori* values were appropriate. Calibration of m_1 and n_1 was carried out separately to the main experiment using the hypsometric curve (Willgoose and Hancock, 1998; Hancock and Willgoose, 2001c). To calibrate m_1 and n_1, the one-dimensional experimental catchment was used. Calibration was performed by comparing hypsometric curves of the one-dimensional experimental catchment with SIBERIA simulations of the experimental catchment for various values of m1 and n1 (Hancock and Willgoose, 2001c).

Values of $m_1 = 1{\cdot}62$ and $n_1 = 2{\cdot}1$ were found to produce a curve that closely fitted the experimental data. These values were considered to be within the range of realistic values as found by previous authors (Kirkby, 1971; Willgoose, 1994). The rate constant β_1 was calibrated by matching catchment total mass and sediment output to SIBERIA simulations using the calibrated m_1 and n_1 values over a range of β_1 values. A value of $\beta_1 = 0{\cdot}003$ was used for all simulations discussed in this paper.

SIBERIA simulations were run using the constructed initial conditions (5 and 10% linear slope and a concave profile with average slope of 10%; Figure 3) of the experiments on a 10 mm by 10 mm grid (i.e. 10 nodes by 100 nodes). The outlet of the catchment was the catchment width. To simulate the initial roughness of the fly ash surface resulting from construction, a uniformly distributed random elevation perturbation of between ± 1 mm was added to each elevation to match the measured roughness (Hancock and Willgoose, 2001c). Rainfall conditions used in the modelling were that of the spatially variable rainfall as measured from the rain gauges (Tables II and III). Further simulations were run using the mean rainfall with plus/minus two standard deviations to investigate the impact of rainfall variability on sediment transport.

RESULTS AND DISCUSSION

Using the one-dimensional catchment, the experiments listed in Table I were carried out. Five runs were conducted using the same rainfall for each slope (Table I). The experimental data are displayed as average sediment output through time with plus/minus two standard deviations added to capture the variability in the data. SIBERIA simulations were run for the same hillslope initial conditions and used the calibrated parameters. Rainfall was varied in the simulations by using mean rainfall plus/minus two standard deviations (Tables II and III).

Experiment and SIBERIA-simulated sediment transport

The results of the experimental study demonstrate that several replications are needed to estimate confidently the sediment loss for each slope and rainfall intensity examined (Wendt *et al.*, 1986); but the sediment output data overall comply with a power function with negative exponent (Parker, 1977; Knighton, 1998), similar to other field and laboratory studies (Parker, 1977; Lane and Sheridan, 2002), and provide confidence in our methodology and results (Figures 4–9). Analysis of coefficients of variation for sediment output found that the scatter at each sampling time is largely constant for three or more experiments (Wendt *et al.*, 1986).

The results demonstrate that a reduction in the rainfall by half causes a corresponding reduction in the sediment output by approximately half (Figures 4–9), and reduction of the initial slope from 10% to 5% can reduce sediment output by an order of magnitude (Figures 4–9). These data suggest that there is a threshold in slope where a significantly increased shear stress is exerted on the catchment surface somewhere between slopes of 5 and 10% (Selby, 1994). The use of initially concave slopes approximately halved sediment loss when compared to the initially linear slopes with the same overall initial slope (Table IV).

The SIBERIA-simulated sediment output displays a similar decline through time and is able to match the experiments for the majority of the data (except for the low rainfall 5% slope and high rainfall 10% slope; Figures 4 and 7), but it displays little of the variability observed in the experiments. The use of mean rainfall plus/minus two standard deviations in the simulations, while accounting for some range in the experimental data, does not produce the sediment variability observed in the experiments.

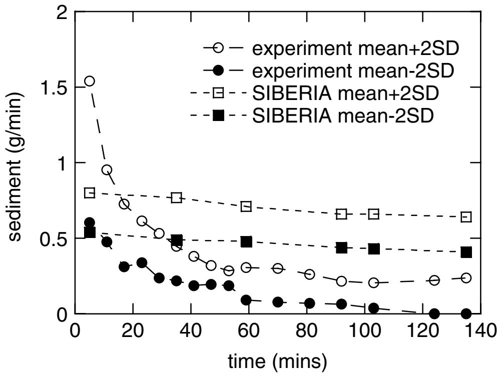

Figure 4. Sediment output data through time for low rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial linear slopes of 5%. Lines have been drawn through the data points for clarity

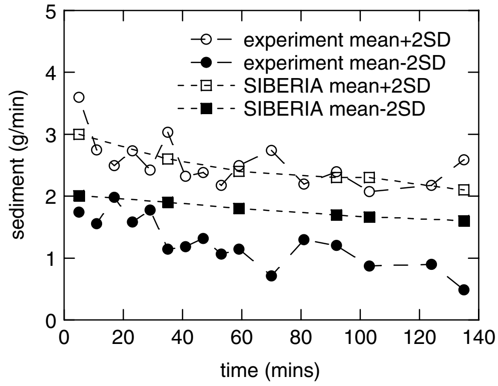

Figure 5. Sediment output data through time for high rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial linear slopes of 5%. Lines have been drawn through the data points for clarity

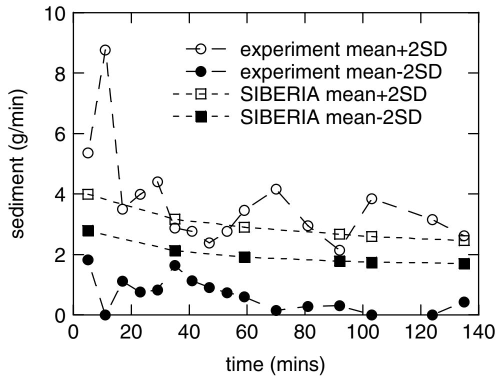

Figure 6. Sediment output data through time for low rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial linear slopes of 10%. Lines have been drawn through the data points for clarity

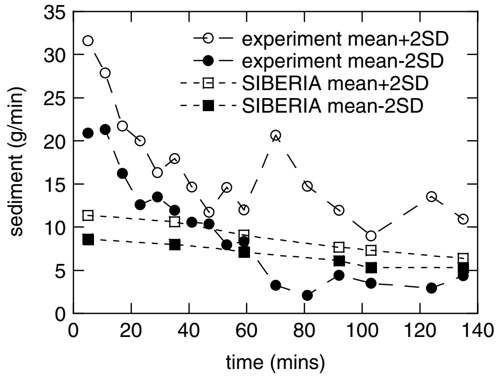

Figure 7. Sediment output data through time for high rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial linear slopes of 10%. Lines have been drawn through the data points for clarity

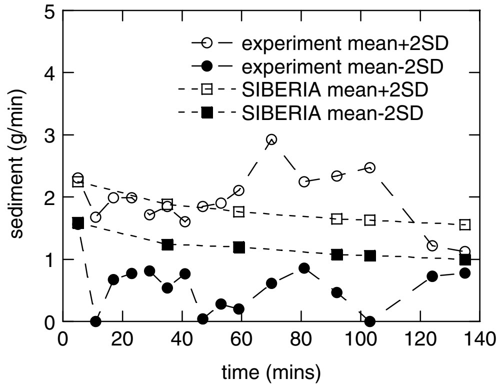

Figure 8. Sediment output data through time for low rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial concave slopes of 10%. Lines have been drawn through the data points for clarity

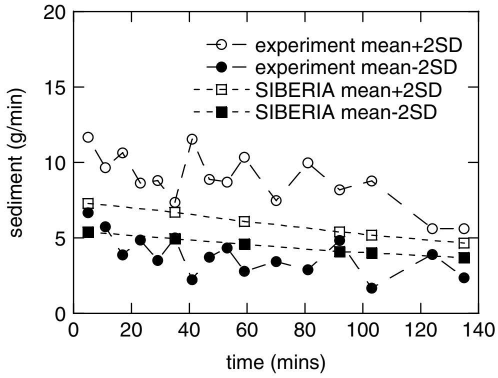

Figure 9. Sediment output data through time for high rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using the range of measured rainfall (mean plus/minus two standard deviations) for catchments with initial concave slopes of 10%. Lines have been drawn through the data points for clarity

Table IV. Volume of sediment (cm^3) eroded from the experimental and SIBERIA-simulated catchments after 135 min of rainfall

Experiment	5% linear low rain	5% linear high rain	10% linear low rain	10% linear high rain	10% concave low rain	10% concave high rain
A	117	384	361	1781	190	956
B	94	390	293	1749	178	1038
C	94	385	349	1793	290	1158
D	149	384	362	1690	240	1063
E	162	413	397	—	286	1176
Average	123	391	352	1753	237	1078
SD	31	12	38	46	52	90
SIBERIA	20–54	290–371	323–455	1001–1270	214–295	657–848

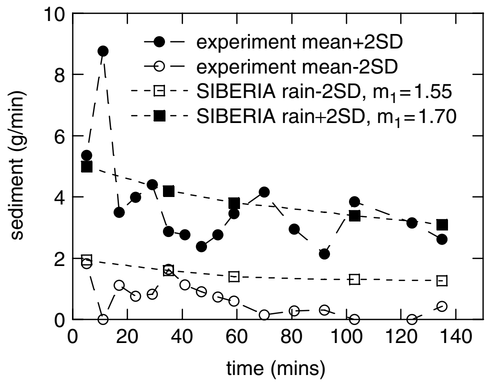

Figure 10. Sediment output data through time for low rainfall experiments (mean plus/minus two standard deviations) and SIBERIA simulations using $m_1 = 1{\cdot}55$ (and mean minus two standard deviations rainfall) and $m_1 = 1{\cdot}70$ (and mean plus two standard deviations rainfall) for catchments with initial linear slopes of 10%. Lines have been drawn through the data points for clarity

An increased range in simulated sediment output can be achieved by adjusting the erosion parameters slightly up or down within the scatter observed for the area–slope relationship for previous experimental catchments (i.e. $m_1 = 1{\cdot}55$ to $1{\cdot}70$) (Hancock and Willgoose, 2001c); this, combined with rainfall variability (mean rainfall plus/minus two standard deviations), will account for much of the observed variability (Figure 10). Consequently, this suggests that much of the variability in sediment output observed in the experimental system is due to short-term fluctuations in both the erosion and sediment transport processes occurring in the experimental catchments, which the temporally static parameters used in SIBERIA are unable to capture. Nevertheless, long-term mean behaviour is modelled. Greater variability can be obtained if random error of $\pm 6{\cdot}6\%$ is added to the sediment output data from SIBERIA (to represent the maximum potential error in collecting the experimental sediment output by hand of ± 4 s).

To examine the impact of different initial surface roughness on the SIBERIA-simulated sediment transport, a series of catchments with different initial roughness were created (i.e. different uniformly distributed random elevation perturbations between $+1$ mm and -1 mm). It was found that, for the 10% slopes, different random initial roughness produced slightly different sediment output in the early stages of the simulations, but in all cases the sediment output at the end of the simulations was the same. For the 5% slopes it was found that initial surface roughness had a large impact on sediment output in the early stages of landscape development and that this scatter approximately matched the variability observed in the experiments. Nevertheless, in all cases this variability quickly reduced, and after 35 min the simulations all had sediment output matching that of mean sediment transport rates. This finding suggests that initial surface roughness on a catchment surface can produce variability in catchment sediment output in the short term, but this roughness is quickly reduced and the catchment sediment output displays mean properties. The results also suggest that, for catchments subject to low erosion thresholds, such as the 5% catchments examined here, this variability is considerably greater than the catchments subject to high erosion pressures. Despite differences over the short term, all simulations displayed very similar long-term behaviour, which raises issues in regard to the timing of collection of sediment measurements from field catchments and the use of these data in calibration of sediment transport models.

Nevertheless, SIBERIA is unable to model sediment output for all experiments examined here at all times (i.e. 5% linear slope low rainfall and 10% linear slope high rainfall catchments; Figures 4 and 9). For the 5% linear-slope low-rainfall simulations, SIBERIA is able to match sediment output for the initial part of the experiment, but it is consistently higher for the remainder of the experiment. Conversely, for the 10% linear-slope high-rainfall experiments, SIBERIA is unable to match sediment output in the early stages of the experiment, but it provides a good match at later times. These findings are believed to be the result of thresholds within the experiment that SIBERIA is unable to capture. First, for the 5% linear-slope low-rainfall experiments it is believed that, although the fly ash is largely cohesionless, the low slope and low rainfall are below the threshold for which predicted sediment transport will occur and for which the model is currently calibrated (Hancock and Willgoose, 2001c, 2002). Second, for the 10% linear-slope high-rainfall experiments, gullying was observed to be a common occurrence. The gullies originated near the catchment outlet and progressed headward, incising to a depth of a few millimetres and releasing large amounts of sediments in pulses. SIBERIA was not calibrated for this high rainfall and high sediment transport rate. In both cases the SIBERIA erosion model parameters can be adjusted to capture the sediment dynamics observed, but a single set of parameters will not capture the behaviour of all the experiments examined here.

Experiment and SIBERIA-simulated long profiles

To ensure that SIBERIA was not just capturing the sediment transport characteristics of the catchments, the hillslope morphologies of both the experimental catchments and SIBERIA simulations were examined (Figures 11–16). Comparison of the experimental long profiles demonstrated that the high-rainfall catchments had declined from their original hillslope profiles to have long profiles that were considerably lower than those formed in the low-rainfall experiments. The data sets display a concave final slope profile, typical of that observed for a fluvially dominated soil-mantled landscape, steepest in the upper reaches of the catchment but with steepness reducing as elevation decreases (Kirkby, 1971). For the catchments with initial slopes of 5%, subjected to low-intensity rainfall, there was no measurable change in the surface profile of the catchment during the 135 min of the experiment.

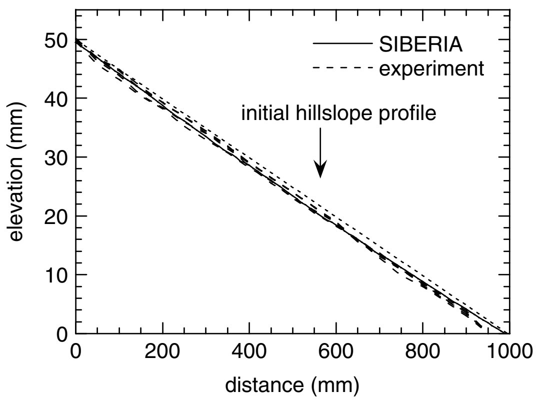

Figure 11. Long profiles for low rainfall experiments and SIBERIA simulation for catchments with initial linear slopes of 5%

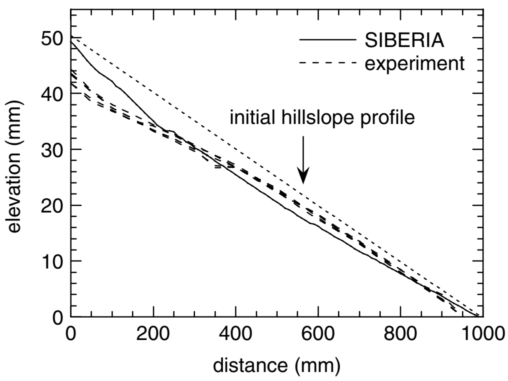

Figure 12. Long profiles for high rainfall experiments and SIBERIA simulation for catchments with initial linear slopes of 5%

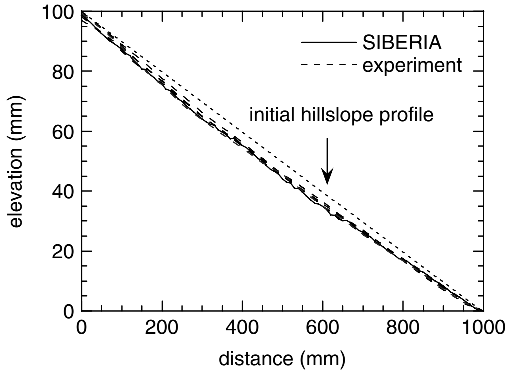

Figure 13. Long profiles for low rainfall experiments and SIBERIA simulation for catchments with initial linear slopes of 10%

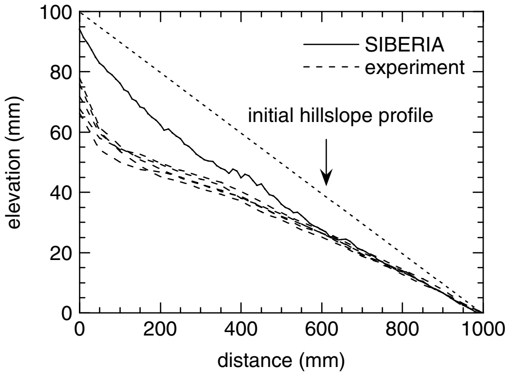

Figure 14. Long profiles for high rainfall experiments and SIBERIA simulation for catchments with initial linear slopes of 10%

Similar to the laboratory sediment transport results, good matches are observed when comparing the SIBERIA-simulation long profiles for the 5% and 10% low-rainfall linear and 10% low-rainfall concave slopes. Poor matches were found for the 5% and 10% high-rainfall linear and 10% concave slopes. The volume of sediment eroded from the experiments was also broadly matched by SIBERIA for the 5% and 10% linear high- and low-rainfall slopes and with the 10% concave low-rainfall slope (Table IV). As the sediment

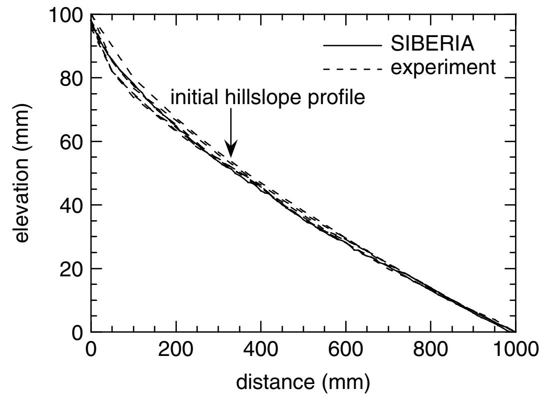

Figure 15. Long profiles for low rainfall experiments and SIBERIA simulation for catchments with initial concave profile with average slopes of 10%

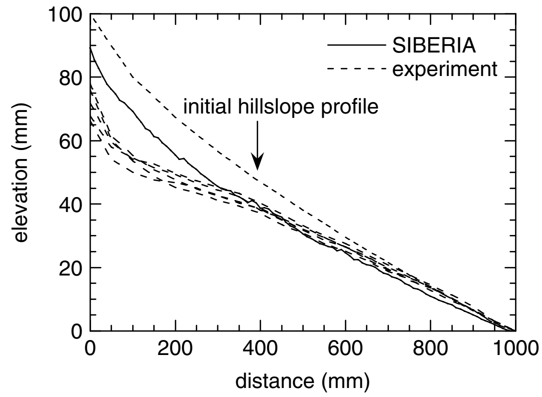

Figure 16. Long profiles for high rainfall experiments and SIBERIA simulation for catchments with initial concave profile with average slopes of 10%

transport rates are low for the 5% low-rainfall experiments, there is no measurable difference in long profiles and the SIBERIA simulations; but for the 10% linear-slope high-rainfall experiments, poor matches were obtained for these experiments when comparing long profiles. In this case, the SIBERIA-simulated long profiles demonstrate a less eroded profile than the experimental data and reflect the reduced sediment output of SIBERIA in comparison with the experiments.

Nevertheless, long profiles are not perfectly simulated by SIBERIA in all cases, despite the good match with sediment volume and output. In the cases of the high rainfall 5% linear initial slope and the 10% concave initial slope the SIBERIA-simulated long profile is higher in the upper reaches of the catchment and lower in the bottom half of the catchment when compared with the experimental data, despite sediment output and eroded sediment volumes being similar. This is believed to be the result of the inability of SIBERIA to match the transient nature of the hillslope profile over the short time scales examined for the erosion parameters used here (Hancock and Willgoose, 2001c, 2002). Further, the SIBERIA erosion parameters were calibrated for lower intensity rainfall (Hancock and Willgoose, 2001c), and the SIBERIA simulated long profile reflects this calibration value.

The long profiles demonstrate that the initial linear hillslope catchments develop a concave profile through time that SIBERIA is able to match. The initial linear 10% slope catchments have a very similar long profile to those of the initial concave catchments with 10% overall slopes after 135 min of high-intensity rainfall

(Figures 14 and 16). This suggests that linear hillslope catchments will evolve to a characteristic concave profile with steep upper reaches and increasingly moderate slopes toward the catchment outflow (Willgoose and Hancock, 1998; Hancock *et al*., 2002).

Study limitations

In considering the results of this study, the limitations of experimental model catchments in studying field processes must be recognized. Despite taking reasonable account of the effects of scale, the erodible material (with a fine grading) and rainfall with little rainsplash are different to that of field catchments. There is also the problem of a rigid boundary that does not move (unlike a field catchment). However, unlike field catchments, experimental model landscapes offer the opportunity to examine the development of landscapes under a controlled environment and provide the ability to control and manipulate most of the important variables in simple land-surface forming processes (Schumm *et al*., 1987). Indeed, the validity of the present study is supported by previous studies showing that the experimental landscapes created using the apparatus and methods described here have scale properties that are similar to field catchments (Hancock and Willgoose, 2003).

In this series of experiments, considerable effort has gone into reducing the variability in initial conditions and temporal forcing as much as possible, so that the inherent variability in catchment form and function during landscape development can be assessed. Nevertheless, some of the variability in the experimental results can potentially be attributed to experimental variation due to a number of factors.

Some of the variation in sediment output is likely to be due to micro-topographic differences in the initial catchment surfaces (Favis-Mortlock, 1998; Favis-Mortlock *et al*., 2000). While great care was taken to produce consistent initial surface slopes, surface imperfections caused by the passage of the profiling tool (such as small scratches less than 1 mm deep) were evident and could not be eliminated. Such imperfections, although barely perceptible, constituted subtle differences between catchments. These differences were most evident in the 10% linear catchment slopes subjected to high rainfall, which developed gullies at positions across the lower third of the catchment, seemingly as a result of concentrations of flow caused by the surface imperfections. It was found that any small incision at the start of the experiment, regardless of how small, will affect flow direction and cause a consequent concentration of flow.

To reduce the potential for errors in the measured sediment output, individual sediment samples were collected for a duration of 1 min, at strictly observed times throughout the experiment. This meant that sediment sampling took place for 16 min out of a total of 136 min of experimental run time. It is believed that this 1 min sample collection time is sufficiently frequent to provide a reliable measure of sediment output, yet sufficiently precise to be representative of the sediment output at a particular instant in time. Nevertheless, there is some potential for exaggeration in the measured sediment output. This is especially the case for the 10% sloping catchments (linear and concave) with high rainfall, in which the initiation and intermittent development of a gully resulted in intermittent, rapid, visually observable increases in the rate of sediment leaving the catchment. Consequently, if a sample was collected at a time when a gully was rapidly advancing, then a higher sediment output would be measured than that of the mean sediment output.

There is also probable variability in rainfall, both through time and between experimental runs. Variation in rainfall at different times throughout the experimental programme is recorded in the data of Tables II and III, and was discussed in the 'Landscape formation simulator' section. However, as rainfall cannot be measured during an experiment, it is impossible to know whether (and if so, how) rainfall varied during any of the experiments described in this study. Analysis of the volume of water collected from the catchment outlet during sediment collection, although displaying consistency through time, does not give a reliable measure of rainfall consistency because of the estimated potential error in sampling time of up to ± 4 s, due to limitations in the collection of samples by hand.

Whilst the factors identified here are acknowledged as likely contributors to the observed variability in the results, it is considered that their contribution constitutes only a small proportion of the total variability in the experimental results. Thus, it is concluded that the trends in the experimental results are dominated by the characteristics of the catchment forming processes, and not by unintended aspects of the experimental setup.

Modelling results and application to field assessment

The catchments and rainfall intensities used in this study allowed an examination of landscape development and reproducibility under controlled laboratory conditions. Although the results demonstrated are not for field-scale catchments, they provide an important step in testing landscape evolution models in a controlled environment. It is believed that this is the first study that examines the ability of a landscape evolution model to predict sediment transport in the initial stages of catchment development using a set of geomorphic measures that are considered to be statistically useful rather than subjective or visual comparisons (Hancock, 2003; Willgoose *et al.*, 2003).

The experiments and SIBERIA simulations examined here demonstrate that, when compared with experimental data, within the range for which SIBERIA was calibrated, a good match was observed. This demonstrates that SIBERIA can largely match the temporal variation in sediment output over the experiments examined. Difficulties arise when studying data that are outside the calibration range. This finding is not surprising, as other erosion models, such as the RUSLE and WEPP, can only be reliably used within their calibration range, and extrapolation outside of known input/calibration data is not advisable. Nevertheless, SIBERIA erosion parameters can be adjusted to capture the extremes of the data. The advantage of SIBERIA over other models is that it dynamically predicts landscape change and adjusts the hillslope profile, something that the RUSLE and WEPP cannot do. It is fully recognized that the model has only been examined in an experimental setting over a limited range of slopes and rainfall intensities, but this provides a necessary first step in testing SIBERIA for its ability to predict temporal sediment transport.

These findings have implications for the measurement and analysis of sediment discharge rates from field catchments and calibration of numerical erosion models. The observations of the physical mechanisms of erosion in the experimental catchments, and the resultant variability in the sediment output, demonstrate that timing of sample collection can, by chance, have an impact on the measured value (e.g. if the field sample was collected when sediment output was elevated because a gully was rapidly advancing or, conversely, when there was no incision and the measured sediment output was below the average) (Parker, 1977; Wendt *et al.*, 1986; Walling *et al.*, 2001; Lane and Sheridan, 2002). Also, choice of initial surface roughness in the initial conditions of the catchment used for the computer simulations can have an impact on modelled sediment output at low rainfall intensities and low slopes. The variability observed in these experiments also has implications for the use of mathematical models for the simulation of runoff and sediment loss, as this inherent variability is often not accounted for in their development and calibration (Wendt *et al.*, 1986; Evans, 2000; Entekhabi, 2001; Hancock, 2003; Willgoose *et al.*, 2003). The results demonstrate that long-term field data are needed for a reliable calibration of an erosion and sediment transport model.

CONCLUSIONS

The variability in catchment form and function was examined experimentally using a small model catchment. The results demonstrate that the consequent sediment output and final landscape form are broadly similar when catchments with the same initial hillslope form are subjected to temporally constant rainfall. In this study, we demonstrate that a doubling of rainfall approximately doubles sediment output, whereas a doubling of slope increases sediment output by an order of magnitude. Sediment outputs from concave hillslope profiles are around half those of linear hillslopes with the same overall slope. Investigation of temporal sediment output trends for the linear slopes demonstrates that sediment output declines exponentially through time, whereas sediment output for concave slope catchments is considerably less and relatively constant. Measurements of hillslope long-profiles are used to demonstrate that linear hillslopes evolved, through erosion, into a concave form after some time.

Using this sediment transport and hillslope profile data, the SIBERIA landscape evolution model was tested for its ability to predict temporal sediment transport in a laboratory-scale landscape simulator. The results demonstrate that, when calibrated for the erodible material and rainfall, SIBERIA is able to model temporal sediment output in the experimental simulations. SIBERIA is also able to capture the hillslope profile at the completion of the experiments.

An examination of sediment output for the experimental catchments shows that sediment output and final landscape form are broadly similar when catchments constructed of the same erodible material, and with the same initial hillslope profile, are subject to temporally constant rainfall. Multiple experiments are needed to capture the variability in sediment transport. The results demonstrate that there is considerable temporal variability in sediment output from the laboratory-scale experimental catchments and that SIBERIA is unable to capture this temporal variability without incorporating model parameter variability. Nevertheless, mean sediment transport behaviour is well modelled in the majority of catchments examined, and this provides confidence in the model. The methods presented here provide a framework for evaluating landscape evolution models in the early stages of landscape development and provide a statistically defensible testing process for both sediment transport and landscape evolution models.

ACKNOWLEDGEMENTS

This project was supported by a Research Management Committee Project Grant from The University of Newcastle. The technical support of the Department of Civil, Surveying and Environmental Engineering laboratory staff, together with Chris Dever and especially Peter Loughran (School of Environmental and Life Sciences), and review comments by David O'Brien are gratefully acknowledged. The advice and support of Garry Willgoose is also very much appreciated. Comments of the two anonymous referees are also acknowledged.

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