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The influence of storm movement on water erosion: storm direction and velocity effects

João L.M.P. de Lima[a,*], Vijay P. Singh[b], M. Isabel P. de Lima[c]

[a] *Institute of Marine Research (IMAR), Coimbra Interdisciplinary Centre, Department of Civil Engineering, Faculty of Science and Technology, Campus 2, University of Coimbra, 3030-290 Coimbra, Portugal*
[b] *Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA*
[c] *Institute of Marine Research (IMAR), Coimbra Interdisciplinary Centre, Department of Forestry, Agrarian Technical School of Coimbra, Polytechnic Institute of Coimbra, Bencanta, 3040-316 Coimbra, Portugal*

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Abstract

Although the problem of storm movement affecting flows (shape of the hydrograph and peak discharges) has been recognised for a long time, most overland flow and water erosion studies do not take into account the effect on the runoff response caused by the movement of the storm across the catchment. Ignoring of the storm movement can result in considerable over- and underestimation of runoff volumes and peaks, and associated soil loss by sheet erosion.

This work shows the results of laboratory experiments that were undertaken to study the effect of moving storms on the water erosion process. The experiments were carried out using a soil flume adjustable to different slopes and a movable sprinkling-type rainfall simulator. Both the effects of storm velocity and direction, and surface slope were studied. To simulate moving rainstorms, the rainfall simulator was moved upstream and downstream over the soil surface. The results show that the storm direction and velocity strongly affect the water erosion process. The soil loss caused by the downstream moving rainstorms is higher than that caused by the identical upstream moving rainfall storms.

Keywords: Soil erosion; Storm movement; Rainfall simulation; Overland flow

1. Introduction

Soil erosion is a natural phenomenon influencing soil genesis and landscape dynamics. An understanding of the water erosion dynamics and the determination of soil material

* Corresponding author. Fax: +351-239-797-179.
E-mail address: plima@dec.uc.pt (J.L.M.P. de Lima).

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transported by overland flow are needed in engineering studies and such activities as agricultural soil management, evaluation of soil nutrient losses and sediment transported to rivers and water reservoirs.

Soil erosion represents the combined effect of the processes of soil detachment and transport by raindrop impact and surface flow (e.g., Römkens et al., 1997). Soil erosion is highly affected by rainfall, which drives both the overland flow and soil erosion processes. Any factor influencing surface flow characteristics also influences soil erosion. Topographic and hydrological factors that affect runoff generation and soil loss were well documented in the literature in the decades past but still continue to be the object of research (e.g., Dunne, 1978; Meyer, 1981; de Lima, 1988; Bryan and Poesen, 1989; Auzet et al., 1995; Basic et al., 2001; Larue, 2001; Huang et al., 2002).

Although infiltration, runoff and soil erosion have been extensively studied in the field and laboratory, most studies using simulated rainfall have applied rainfall at a constant rate. This contrasts with natural rainfall, which is highly variable in both time and space (e.g., Huff, 1967; Eagleson, 1978; Sharon, 1980; de Lima, 1998; Willems, 2001).

The spatial and temporal distributions of rainfall are amongst the main factors affecting watershed and hillslope runoff. Nevertheless, most methods used in hydrologic studies assume that the storm arrives instantaneously over the drainage area and then remains stationary. Therefore, these hydrologic studies do not take into account the effect on the runoff response caused by the movement of storms across the drainage area. Ignoring of the storm movement can result in considerable over- and underestimation of runoff peaks (e.g., Maksimov, 1964; Yen and Chow, 1968; Wilson et al., 1979; Jensen, 1984; Singh, 1998; de Lima and Singh, 1999; Singh, 2002). Because of the interrelation between rainfall and runoff, the movement of storms is expected to affect runoff and the associated soil loss (de Lima et al., 2002a,b); for moving storms, the distribution of rainfall intensity in space and time is continuously changing.

Laboratory- and field-based rainfall simulation studies have been widely used to investigate soil erosion (e.g., Bryan and De Ploey, 1983; Bowyer-Bower and Burt, 1989; Morgan, 1995). The effect of wind on rainfall simulations has also been studied (e.g., Seginer et al., 1991; de Lima et al., 2002a,b). Experiments in the laboratory enable an exploration of a large range of hydrologic conditions occurring at the plot and hillslope scale and, in particular, events with a strong spatial and temporal variability as moving storms.

The main objective of this laboratory study is to quantify the influence of the storm direction and velocity on soil loss from sloping areas. Experiments were carried out using a soil flume adjustable to different slopes and a rainfall simulator. The simulated rainfall moved upstream and downstream, with different velocities, over the soil surface. Several bed slopes were used for carrying out the experiments.

2. Experimental setup

The experiments described in this work were carried out using a soil flume and a rainfall simulator. Fig. 1 shows a schematic representation of the experimental setup.

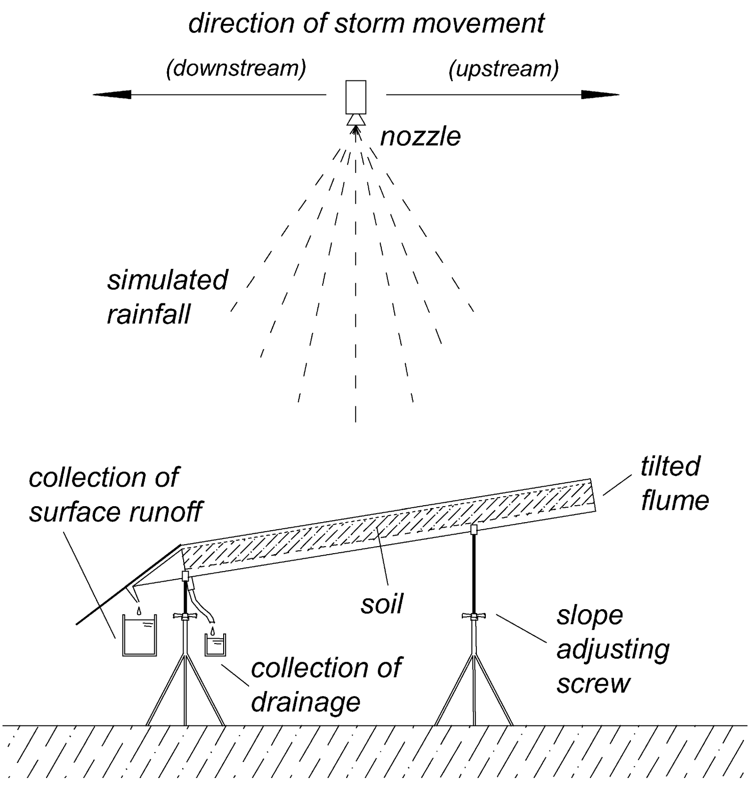

Fig. 1. Schematic representation (side view) of the soil flume and hydrological variables involved in the laboratory experiments.

2.1. Characteristics of the soil flume

The soil flume was constructed with metal sheets and had the following dimensions: 2.0 m length × 0.1 m width × 0.12 m height. No buffer zone was used around the plot in order to compensate for water and sediments ejected outside the flume as used by some authors (see, e.g., Poesen et al., 1990; Borselli et al., 2001). Surface runoff and drainage water were collected at the end of the flume. The structure had two slope adjusting screws allowing the control of the flume slope (Fig. 1). Slope is one of the critical factors controlling soil erosion by overland flow (e.g., Bryan and Poesen, 1989).

2.2. Characteristics of the soil

The soil used in the laboratory experiments was collected at the right margin of the Mondego River in the city of Coimbra, Portugal. The selection was made because this terrigenous sedimentary material was readily available in large quantities and it exhibited extensive soil erosion morphologies (e.g., gullies) under natural rainfall. This soil originated from disaggregated material from an outcrop of Triassic age, and is composed of sedimentary rocks dipping 10° west. With respect to mineralogy, it is mainly composed of quartz, feldspars, quartzite, muscovite and clay minerals. The soil material consisted of 11% clay, 10% silt and 79% sand.

After being collected from the original place, the soil was submitted to a standard procedure involving pre-sieving through a 4.75 mm aperture square-hole sieve to remove coarse rock and organic debris.

The soil material was uniformly spread in the flume. To obtain a flat surface, a sharp, straight-edged blade that could ride on the top edge of the sidewalls of the flume was used to remove excess soil. The blade was adjusted such that the soil level in the flume equalled the retaining bar at the bottom end of the flume. Afterwards, the soil was gently tapped with a wooden block, aiming to attain a uniform bulk density of approximately 1100 kg/m^3. The resulting soil surface was smooth, without rough elements such as microtopographic protuberances, stones or plant stems. The soil presented a uniform thickness of 0.1 m. Before starting the experimental runs, the soil was wetted-up to field capacity. These procedures were repeated for all cases.

Standard laboratory permeability tests gave a saturated hydraulic conductivity of $K_s = 5.7 \times 10^{-5}$ m/s, with a standard deviation of 1.8×10^{-5} m/s, for 10 replicates. The samples were obtained following exactly the same procedure as used in filling the flume, and had the same bulk density. The saturated soil water content was 39%.

2.3. Characteristics of the rainfall simulator

The basic components of the sprinkling-type rainfall simulator used in this study were nozzles, a support structure in which the nozzle was installed, and the connections with the water supply and the pump. The laboratory experiments were conducted using a single downward-oriented full-cone nozzle spray (3/4 HH—four FullJet Nozzle Brass-Spraying Systems). The nozzle height was 1.5 m, measured above the geometric centre of the soil surface.

A flexible rubberised hose distributed water from the pump to the nozzle. A pressure gauge monitored the pressure at the nozzle. The working pressure on the nozzle was maintained constant at 50 kPa. The maintenance of a stable pressure avoided variations in rain intensity during the simulated rainfall events (Fig. 2).

The storm movement was obtained by moving on wheels, back and forth, the support structure of the nozzle, as shown in Figs. 1 and 2. This was achieved using two electric motors. During a given event, the nozzle was moved at a constant velocity. Because of the non-windy laboratory conditions, there was no interaction of the simulated raindrops and sediments with wind (e.g., wind drag effects). The simulated laboratory storms aimed at representing the behaviour of short-duration natural storms induced by steady one-directional winds.

2.4. Characteristics of the water

The characteristics of the tap water used in the rain simulations are listed in Table 1. Water quality is known to affect the infiltration and erosion rates of different soils because it affects soil dispersion. A recent paper by Borselli et al. (2001) discusses the

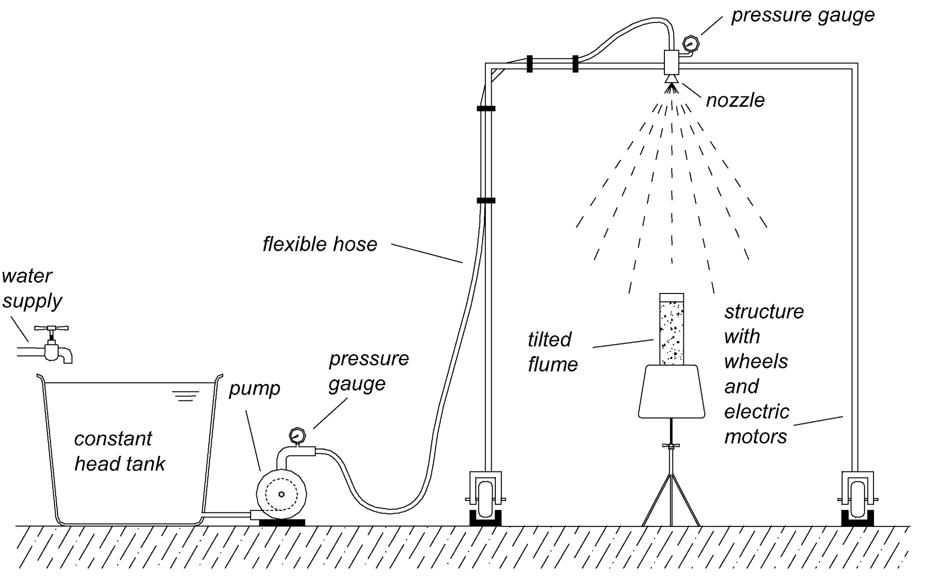

Fig. 2. Schematic representation (front view) of the rainfall simulator including the connections with the water supply and the movable support structure.

problems in using solute-rich tap water in rain simulation experiments, and demonstrates that demineralised water should be used whenever comparisons are made between different soils. Because the present experiments were restricted to one soil type, the quality of the water used in the rain simulations is not expected to affect the comparison of the hydrologic responses with respect to differences in storm direction and velocity. Being storm motion as the main objective of the present study, water quality does not affect the message of this paper.

Table 1
Characteristics of the simulated rain (tap water) used in the experiments (SMASC, 2001, 2002)

	Temperature (°C)		Conductivity (S/cm)		pH	Cl (mg/l)	SO_4 (mg/l)	NH_4 (mg/l)
First experiments[a]	18		107		7.0	12.5	10.9	0.032
Second experiments[b]	17		124		7.0	14.4	12.9	< 0.05
	NO_3 (mg/l)	NO_2 (mg/l)	HCO_3 (mg/l)	Na (mg/l)	Ca (mg/l)	K (mg/l)	Fe (μg/l)	Zn (μg/l)
First experiments[a]	3.8	0.003	27.6	10.3	7.9	1.3	70	140
Second experiments[b]	4.2	0.005	31.2	[c]	9.1	[c]	70	[c]

[a] First set of experiments—soil loss measurements for different slopes, conducted in the period October–December, 2001.

[b] Second set of experiments—soil loss measurements for different velocities, conducted in the period January–February, 2002.

[c] Information not available.

3. Methodology

Two sets of experiments were undertaken. The first set consisted of simulated rainstorms moving upstream (13 replicates) and downstream (13 replicates) over the soil surface, which were applied to bed slopes of 5%, 10%, 15%, 20% and 25%. The storm movement velocity and storm duration remained constant for all the 130 experimental runs. The velocity was 0.33 m/s.

The second set of experiments was conducted for a flume slope of 10%, moving the simulated rainstorms at different velocities (62 events using 23 different storm velocities). In same cases, duplicate and triplicate measurements were made for the same velocity.

The soil used in the various storm events had always the same characteristics. In the first set of experiments, the soil material placed in the flume was changed whenever the slope was changed. In the second set of experiments, the soil was also replaced whenever experiments were conducted with a different storm velocity. The initial soil water conditions were approximately identical for all runs.

3.1. Rainfall measurements

The laboratory experiments were limited to one simulated rainfall pattern, since the nozzle was used at a fixed pressure. During storm simulations, the total amount of rain only depended on storm velocity because the rainfall intensity pattern did not vary.

The rainfall intensity and distribution are dependent on the nozzle size and type, water pressure at the nozzle, and the height above the plot surface. The rainfall distribution was measured on a horizontal plane with equally sized gauges for a time period of 30 s, maintaining the nozzle static. The gauges consisted of 0.1 mm diameter cylindrical containers. The measurements were repeated five times and mean values were calculated for these replicates.

The width of the soil surface is small (0.1 m), thus, the pattern of the simulated rainstorm can be simplified and assumed one-directional, as shown in Fig. 3. The average rainfall intensity was 8.3 mm/min and the water application length was 2.3 m. As in natural spatial rainfall fields, a high-intensity rainfall area was embedded within areas of lower intensity, as described by Bras and Rodrigues-Iturbe (1976), Sivapalan and Wood (1986) and Willems (2001), among others.

The estimated average drop-size (equivalent drop diameter) was approximately 1.5 mm (de Lima, 1997). The measurements were done using the stain method (e.g., Hall, 1970). The sample consisted of 113 raindrops, obtained for the simulated rainfall with controlled discharge and pressure, at flume level. One is aware that larger sample sizes are required in order to estimate the drop-size distribution with accuracy (Salles et al., 1999).

In this study, storms with equal precipitation height, equal duration and equal drop-size distribution are called identical storms.

Fig. 4 shows a schematic representation of the motion of a rectangular-block storm over an impervious plane surface.

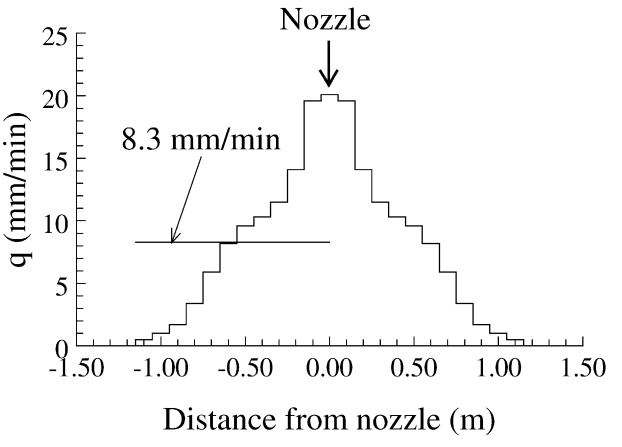

Fig. 3. Distribution of rainfall intensities supplied by the nozzle (static) on a horizontal surface, for an operating pressure of 0.5 bar, at a height of 1.5 m.

For that situation, from the instant the rainfall enters (at $x=0$) until it leaves (at $x=L$, where L is the length of the plane) the surface, the total rainfall dropped on the surface by the storm moving over the plane is:

$$h = q\frac{L_S}{V_S} \tag{1}$$

where h is the total rainfall (m), q is the rainfall intensity or lateral inflow (m/s), L_S is the length of the storm (m) and V_S is the velocity of the storm (m/s).

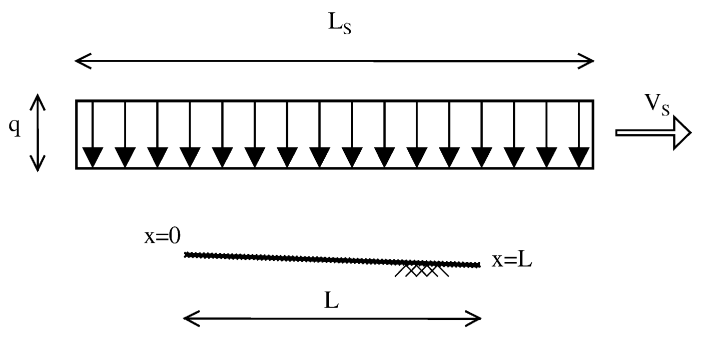

Fig. 4. Schematic representation of a rectangular rainstorm of intensity, q, and length, L_s, moving across a plane of length, L (one-dimensional), at a constant velocity, V_s.

If one considers a complex rainfall pattern consisting of n rainfall blocks, which is the case of these experiments (see Fig. 3), then the total rainfall is:

$$h = \sum_{i=1}^{n}\left(q_i \frac{L_{S_i}}{V_S}\right) = \frac{\sum_{i=1}^{n} q_i \sum_{i=1}^{n} L_{S_i}}{n V_S} \tag{2}$$

where q_i is the rainfall intensity (m/s) of block i, L_{S_i} is the length of the storm block i (m), and V_S is the velocity of the storm (m/s). Consequently, for:

$$\overline{q} = \frac{\sum_{i=1}^{n} q_i}{n} \tag{3}$$

and

$$L_S = \sum_{i=1}^{n} L_{S_i} \tag{4}$$

then the total rainfall is:

$$h = \overline{q}\frac{L_S}{V_S} \tag{5}$$

where $\overline{q}$ is the average rainfall intensity, and L_S and V_S are the length (m) and velocity (m/s), respectively, of the storm consisting of n rainfall blocks.

3.2. Runoff and soil loss measurements

The fixed simulated rainfall pattern, shown in Fig. 3, moved in an alternating sequence, upstream and downstream, over the soil surface. The consecutive rainfall events were generated at regular time intervals, such that all the overland flow from the previous event had ceased, maintaining approximately the same moisture conditions in the superficial layer of the bed soil. The overland flow caused by each rainfall event was collected in a metal container placed in the bottom end of the soil flume for determination of the runoff volume and soil loss. The sediment weight was estimated by low-temperature oven drying of the samples.

4. Results

4.1. Soil loss measurements for different slopes

For each slope (5%, 10%, 15%, 20% and 25%) tested, 13 runs were conducted, with each run representing a pair of rainfall events: one corresponding to a storm moving

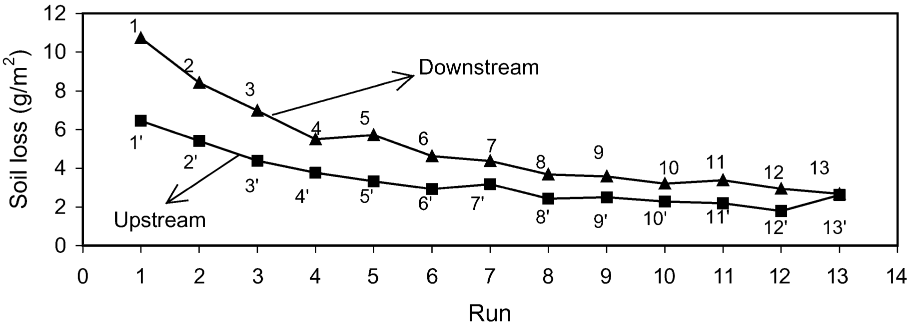

Fig. 5. Soil loss for an alternating sequence of downstream and upstream moving rainstorms, for the 10% surface slope.

upstream the soil surface and the other one to a storm moving downstream. These two simulated rain events had equal precipitation depth, duration, and drop-size distribution. Thus, a total of 130 runs were carried out.

Eqs. (2)–(5) were used to check the water balance of each storm event. Runoff was measured and infiltration was determined by weighting the soil flume before and after each event.

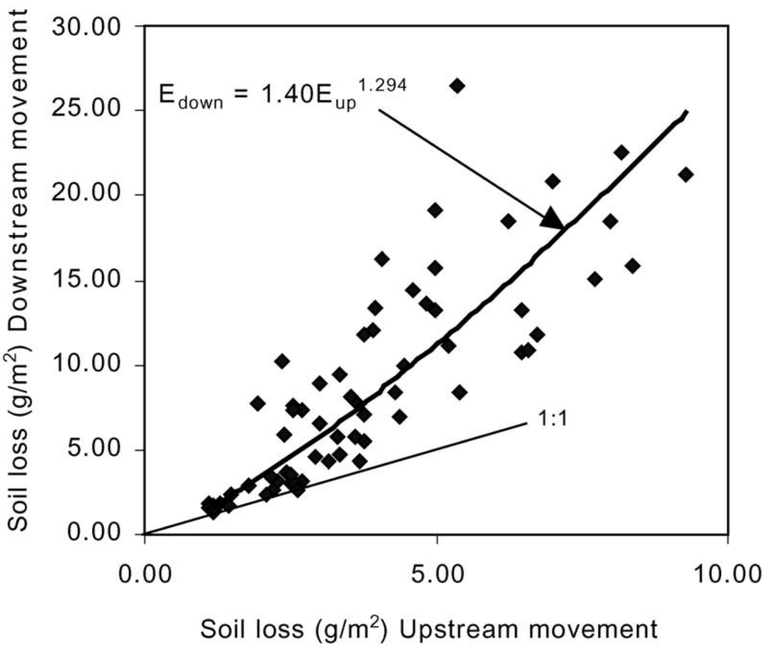

Fig. 6. Soil loss for downstream moving storms (E_{down}; 65 events) against soil loss for upstream moving storms (E_{up}; 65 events), for slopes of 5%, 10%, 15%, 10% and 25%.

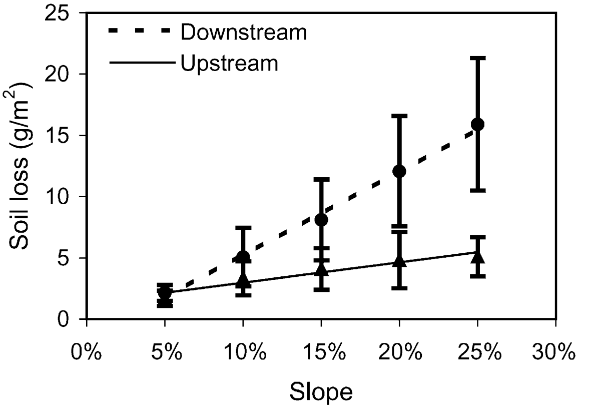

Fig. 7. The mean soil loss and standard deviation as a function of soil surface slopes, for storms moving in the upstream and downstream directions (see Table 2).

The Hortonian overland flow occurred clearly on the flume when the rain intensity exceeded the infiltration rate. Because the erosive rainfall was moving, the Hortonian overland flow occurred usually only on parts of the soil surface, depending on the storm velocity. The topsoil saturation overland flow did not take place due to the short period of time during which the moving rainfall was effectively falling on the soil surface. In these experiments, seepage (interflow) also did not take place.

In these experiments, the transport of fine erodible soil material was mainly due to overland flow. The sediment transported by rain splash had a relatively minor contribution. The greatest effect was caused by rain falling on a thin overland flow layer, when present, leading to both strong sediment detachment and transport.

The results of these experiments showed significant differences in the soil loss between identical simulated rainfall moving downstream and upstream. Plots of soil loss obtained for an alternating sequence of downstream and upstream moving storms are shown in Figs. 5–8. Fig. 5 illustrates the soil loss for a 10% soil bed slope. A similar behaviour was observed for other slopes (5%, 15%, 20% and 25%). The results show that the downstream moving storms yielded higher soil loss than the upstream moving storms. As the number

Table 2
Summary of soil loss data for different soil surface slopes (first set of experiments). Storm velocity was 0.33 m/s. STDV = standard deviation

Slope (%)	Runs	Soil loss (g/m^2)			
		Downstream		Upstream	
		Mean	STDV	Mean	STDV
5	13[a]	2.15	0.64	1.70	0.62
10	13[a]	5.06	2.40	3.33	1.37
15	13[a]	8.10	3.30	4.10	1.70
20	13[a]	12.07	4.50	4.82	2.32
25	13[a]	15.90	5.40	5.10	1.60

[a] Thirteen events for downstream moving storms and thirteen events for upstream moving storms.

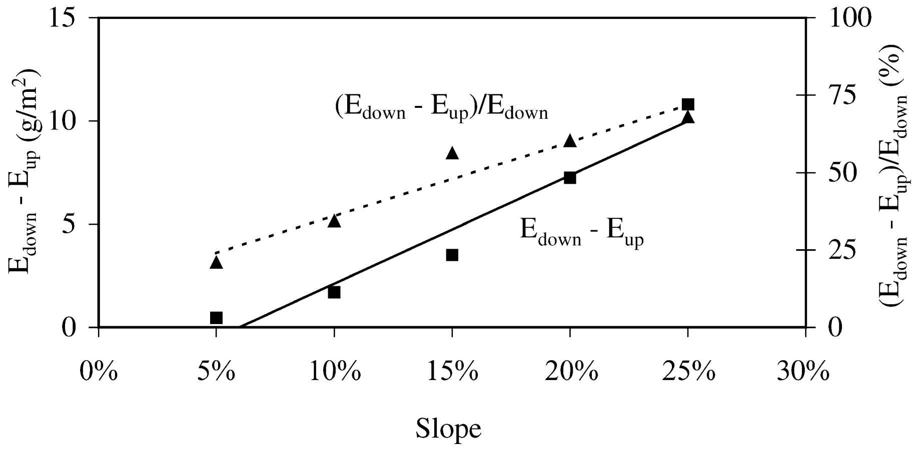

Fig. 8. Absolute (left axis) and relative (right axis) differences between soil losses, for storms moving in the downstream and upstream directions as a function of soil surface slope, where E_{down} is the soil loss for the downstream moving storm (g/m^2) and E_{up} is the soil loss for the upstream moving storm (g/m^2). Storm velocity was 0.33 m/s.

of simulated rainstorm events increased, the difference of soil loss between downstream and upstream moving storms decreased due to the changes of the characteristics of the surface layer of the soil, namely, the reduction of fine sediment materials transported by overland flow in previous runs.

Fig. 6 shows the soil loss caused by the downstream moving storms against the soil loss due to identical upstream moving storms. The data show some variability, which increases with slope. This variability can be explained not only by the simulated rain variability, but also by the experimental procedure related to the preparation of the soil material and to the

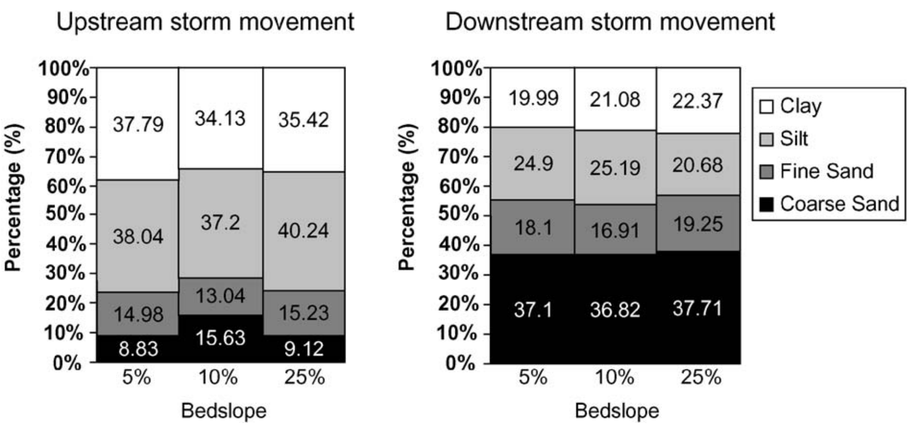

Fig. 9. Percentage of clay, silt, fine sand and coarse sand in the soil material eroded by upstream and downstream moving storms (for the 5%, 10% and 25% surface slopes). See also Fig. 10.

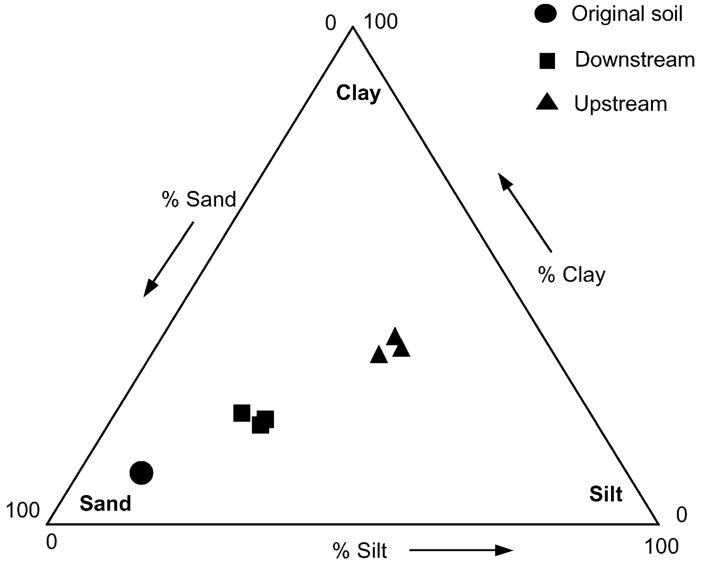

Fig. 10. Representation in a triangular diagram of the percentage of clay, silt and sand in the original soil (used to fill the flume) and in the soil material eroded by upstream and downstream moving storms (for the 5%, 10% and 25% surface slopes). See also Fig. 9.

filling of the flume with soil. The curve fitted to the data in Fig. 6 was used only to highlight the differences in soil loss for storms moving upstream and downstream.

Fig. 7 shows the mean soil loss and standard deviation as a function of soil surface slope, for storms moving in the downstream and upstream directions. A summary of the results obtained for all the slopes tested is shown in Table 2. For this specific soil and

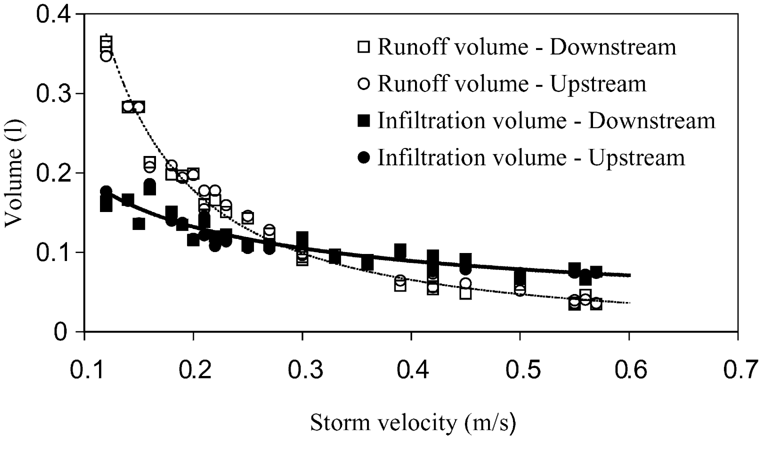

Fig. 11. Total volumes of runoff and infiltration for storms moving upstream and downstream as a function of storm velocity. The slope of the flume was 10%. The data are for 62 storms (see Table 3).

simulated rainfall, the difference between the soil loss for downstream and upstream moving storms is small for slopes up to approximately 5%. For higher slopes, the soil erosion increases strongly (see Fig. 7).

The absolute and relative differences between soil losses for storms moving in the downstream and upstream directions increased with slope, as shown in Fig. 8.

Besides differences in quantities, there are also qualitative differences in the sediment loss associated with storms moving in opposite directions. Since the hydraulic characteristics of overland flow are altered, its transport capacity is also changed as it is illustrated by the comparison of the characteristics of sediment loss produced by storms moving in the downstream and upstream directions, shown in Fig. 9. This figure shows that, for the 5%, 10% and 25% slopes, the grain-size distribution of the sediment loss is different from

Table 3
Summary of soil loss data for different storm velocities (second set of experiments). Bed slope was 10%

Run	V_s (m/s)	Rainfall (l)	Downstream		Upstream	
			Surface runoff (l)	Soil loss (g/m^2)	Surface runoff (l)	Soil loss (g/m^2)
1	0.12	0.524	0.365	256.0	0.347	35.0
2	0.12	0.524	0.360	216.0	0.347	23.5
3	0.14	0.449	0.283	236.5	0.284	53.0
4	0.15	0.419	0.283	136.0	0.283	13.5
5	0.16	0.393	0.213	128.5	0.207	19.0
6	0.18	0.349	0.198	65.0	0.209	8.0
7	0.19	0.331	0.196	89.0	0.194	12.5
8	0.2	0.314	0.199	83.5	0.197	9.5
9	0.21	0.299	0.160	16.0	0.178	8.0
10	0.21	0.299	0.161	28.5	0.154	3.0
11	0.22	0.286	0.166	31.0	0.178	6.5
12	0.23	0.273	0.151	14.5	0.159	4.0
13	0.25	0.251	0.143	19.0	0.146	6.0
14	0.27	0.233	0.124	6.5	0.128	4.0
15	0.3	0.210	0.099	3.5	0.098	1.5
16	0.3	0.210	0.091	1.5	0.097	1.0
17	0.3	0.210	0.094	3.5	0.097	3.0
18	0.33	0.190	0.097	3.0	0.096	2.0
19	0.36	0.175	0.085	2.5	0.090	2.0
20	0.39	0.161	0.058	1.0	0.065	1.5
21	0.39	0.161	0.067	1.0	0.309	1.0
22	0.42	0.150	0.054	1.0	0.073	1.0
23	0.42	0.150	0.057	1.0	0.056	1.5
24	0.42	0.150	0.067	1.0	0.056	1.0
25	0.45	0.140	0.048	1.0	0.061	1.0
26	0.5	0.126	0.059	1.0	0.052	1.0
27	0.55	0.114	0.034	1.5	0.036	1.0
28	0.55	0.114	0.036	0.5	0.040	0.0
29	0.56	0.112	0.047	0.0	0.040	0.0
30	0.57	0.110	0.035	1.0	0.036	0.5
31	0.6	0.105	0.032	0.5	0.040	0.5

that of the original soil. It also shows that downstream moving storms produce much coarser sediment loss than do identical upstream moving storms. This is clearly illustrated in Fig. 10 by the position of the data in the standard soil texture triangular diagram; the data plotted are for the original soil and the material eroded by downstream and upstream moving storms, for the 5%, 10% and 25% slopes.

4.2. Soil loss measurements for different storm velocities

This set of experiments aimed at evaluating the effect of storm velocity and direction on the soil loss. The slope of the flume was kept constant at 10%. A total of 62 events were simulated using 22 storm velocities, ranging from 0.12 to 0.60 m/s. For each storm velocity, there was always a couple of events: one moving upstream and another moving downstream.

Fig. 11 and Table 3 show how storm velocity affected surface runoff and infiltration volumes. The infiltration volume did not vary much with storm velocity, although the duration of the rainfall event decreased as the storm velocity increased. On the other hand, the runoff volume increased exponentially for slower moving storms. For faster moving storms, the total amount of infiltrated water was higher than the runoff volume. Fig. 11 also shows that the storm direction (upstream or downstream) did not affect significantly runoff volumes because the storms were identical.

The soil loss for upstream and downstream moving storms was significantly affected by storm velocity, as observed in Fig. 12. Slower moving storms, both with downstream and upstream directions, produced large amounts of soil loss, which is related to the runoff volume. Downstream moving storms yielded larger amounts of eroded soil when compared to upstream moving storms. This is valid for every storm velocity but more pronounced for slower moving storms.

Fig. 13 plots the soil loss for downstream moving storms against the soil loss for upstream moving storms, for velocities ranging from 0.12 to 0.60 m/s; the data are from

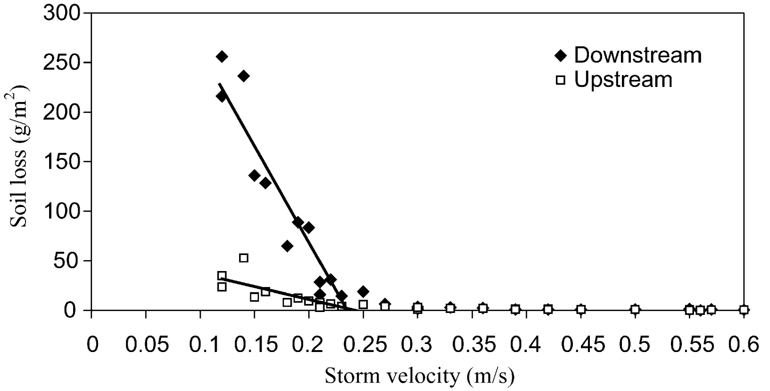

Fig. 12. Soil loss as a function of storm velocity, for storms moving in the downstream and upstream directions. The slope of the flume was 10%. The data are for 62 storms (see Table 3).

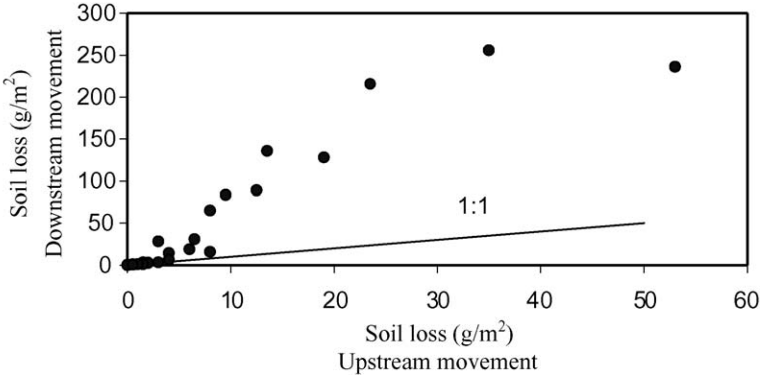

Fig. 13. Soil loss for downstream moving storms (31 events) against soil loss for upstream moving storms (31 events), for velocities ranging from 0.12 to 0.60 m/s. The slope of the flume was 10% (see Table 3).

62 events. Although the runoff volume was not significantly affected by the storm direction (see Fig. 11), soil erosion was much higher for downstream moving storms; this is illustrated in Fig. 13. These results are consistent with the soil loss produced by storms moving downstream and upstream the soil surface with a velocity of 0.33 m/s, for bed slopes of 5%, 10%, 15%, 20% and 25%, as described in the last section (see Fig. 6).

In addition, the absolute and relative differences between soil losses caused by storms moving in opposite directions (downstream and upstream) decreased with storm velocity (see Fig. 14).

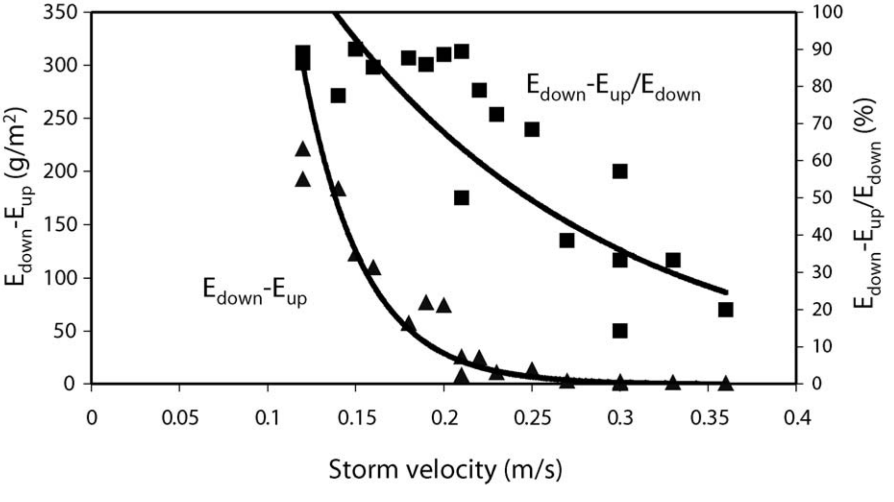

Fig. 14. Absolute (left axis) and relative (right axis) differences between soil losses, for storms moving in the downstream and upstream directions as a function of storm velocity, where E_{down} is the soil loss for the downstream moving storms and E_{up} is the soil loss for the upstream moving storms. Soil surface slope was 10%.

5. Conclusions and discussion

The laboratory experiments described in this work show that the spatial and temporal distributions of rainfall have a marked influence on water erosion. In the experiments, besides storm direction and bed slope, all other parameters were kept constant (e.g., rainfall intensity, soil). The results show that downstream moving storms yielded higher soil loss than did identical upstream moving storms. These soil loss results are clearly linked with the characteristics of the overland flow hydrographs resulting from rainstorms moving in the upstream and downstream directions. Among others, Singh (1998, 2002) and de Lima and Singh (1999) identified distinct hydrologic responses for storms moving upstream and downstream. When compared to storms moving downstream, storms moving upstream are characterised by hydrographs with: (1) earlier rise, (2) lower peak discharge, (3) less steep rising limb and (4) longer base time. These results were obtained theoretically (Singh, 1998, 2002) and experimentally (de Lima and Singh, 1999) for overland flow on an impermeable plane.

The results of this study show that an increase in bed slope causes: (1) an increase in soil loss for both upstream and downstream moving storms, and (2) an increase in the relative differences between soil losses for identical storms moving in the downstream and upstream directions.

The results also reveal that storm velocity affects runoff volumes and, consequently, the associated soil loss. An increase of storm velocity causes: (1) a reduction of soil loss for storms moving in the upstream and downstream directions, and (2) a reduction of the absolute and relative differences between soil loss yields from identical storms moving in opposite directions.

This study aims at contributing to increased understanding of water erosion factors and processes. Future laboratory experiments will consider a wider range of conditions, including the storm intensity, rainfall patterns, and storm lengths. A larger and deeper flume should be used with a buffer zone around the plot to compensate for water and sediments ejected outside the flume. Recent publications have demonstrated that runoff and erosion are dependent on the size of the plots (e.g., Stomph et al., 2001). The evolution of sediment transported during the runoff event should also be characterised.

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