**Natural Hazards
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# Patterns of grain-size temporal variation of sediment transported by overland flow associated with moving storms: interpreting soil flume experiments

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**Abstract.** This study describes and interprets the evolution of grain-size distribution of sediment yields generated in an experimental soil flume subjected to downstream and upstream moving rain storms. Results of laboratory experiments show that downstream moving storms cause more soil loss than do upstream moving storms. The pattern of sediment grain-size evolution in time during a runoff event exhibits a clear dependence on the direction of storm movement. A strong relationship between overland flow discharge and mean sediment size is found. Nevertheless, the mean grain-size of sediments transported during the rising limb of the hydrograph is coarser than during the recession limb of the hydrograph. This is more marked for downstream moving storms.

## 1 Introduction

Soil erosion, particularly the erosion associated with rainfall events, is a natural process that affects the genesis and dynamics of landscapes (e.g. Harvey, 2001; Hooke, 2003; O'Farrell et al., 2007). It is a major concern in agricultural management, engineering studies, and land planning.

Although soil erosion and surface water flow have been extensively studied, many studies have tended to focus mainly on rainfall intensity, leaving out other characteristics of natural storms which are highly variable both in time and space (e.g. Sharon, 1980; Willems, 2001). The high number of variables involved and the difficulties in understanding, characterizing, and simulating the entire set of parameters and interacting processes hamper the accurate prediction of runoff, sediment erosion, and sediment transport processes (e.g. Morgan, 1995; Seeger, 2007). In order to investigate the mechanisms associated with rainfall-related soil erosion, experimental studies in the field and in the laboratory have been conducted with the help of rainfall simulators (see e.g. Cerdá et al., 1997). With rainfall simulators it is possible to control most of the relevant parameters by forcing some of the variables involved.

The grain-size of sediments generated from soil erosion can be determined by many factors, such as: grain-size distribution of the original soil, the settling velocities of different size classes, the processes of aggregate breakdown due to splash erosion, and the occurrence of selective transport processes for different size classes (Rose et al., 2006; Asadi et al., 2007; Kinnell, 2009a). A few erosion-transport-deposition models have been formulated to simulate the particle size distribution of sediment transport (e.g. Hairsine and Rose, 1992a, b). However, some results remain difficult to explain due to the high number of factors that control the

grain-size distribution of the produced sediment (Beuselinck et al., 2002; Rose et al., 2006).

The characteristics of rainfall, particularly the spatial-temporal variability of rainfall intensity, play a major role in sediment yield (e.g. Römkens et al., 2001; Parsons and Stone, 2006). Some investigations took into account the effect of the movement of rainfall storms (i.e. the combined action of wind and rain) across drainage areas, which can strongly affect runoff generation and soil erosion rates, resulting in under- or over-estimation of discharge and soil erosion (e.g. Singh, 1998; de Lima and Singh, 2003; de Lima et al., 2008). Wind-driven rain is described as raindrops falling through a wind field at an angle from vertical under the effect of both gravitational and drag-forces. In this situation, raindrops gain some degree of horizontal velocity and hit the soil surface with an angle.

The importance of the combined action of wind and rain, especially the changes in rainfall characteristics (e.g. spatial and temporal evolution and trajectory of drops) and the runoff dynamics (e.g. volume, speed, and surface spreading), has long been recognized by a number of researchers (e.g. Maksimov, 1964; Yen and Chow, 1968; Wilson et al., 1979; Singh, 1998; de Lima and Singh, 1999; de Lima et al., 2003; Erpul et al., 2003). Experimental simulations have demonstrated that the peak discharge values and sediment yields are higher for downstream moving storms than for upstream moving storms (e.g. de Lima and Singh, 2003; de Lima et al., 2003). Similar results have been obtained from modelling runoff and erosion generated by moving storms at the drainage basin scale (e.g. Nunes et al., 2006; Chang, 2007). However, the evolution of grain-size distribution of sediments generated from soil erosion and their relation to the variables that may determine the dynamics of overland flow and erosion potential have not been fully investigated.

This study is based on laboratory experiments and the main objective is to increase the understanding of the differences in grain-size distribution of sediments generated on slopes, when rainstorms are moving along distinct directions, inducing different spatial and temporal rainfall characteristics over a drainage area.

## 2   Laboratory set-up and procedure

This section describes the laboratory set-up used in this study and the methodology applied to characterize soil grain-size distributions. The laboratory experiments use a soil flume and simulated rainfall events. In this study tests were carried out for two types of rainstorm directions, downstream and upstream, along the length of the flume.

### 2.1   Rainfall and storm movement

The experimental work simulates a rain cell moving across a drainage area. This was accomplished through the displacement of a rainfall simulator, at a constant speed, over a soil flume. The rainfall pattern was geometrically invariant along the flume.

The rainfall simulator (Fig. 1 – left) comprised a constant level reservoir, a pump, a system of hoses, a stand, two electric motors, an automatic control panel to set the speed at which the apparatus moves, and a sprinkler. The laboratory experiments were conducted using one single downward-oriented full-cone nozzle spray (3/4 HH – 4 FullJet Nozzle Brass-Spraying Systems Co.). Full cone sprays (solid circular pattern of drops) are commonly used in rainfall simulations, both in the field and in the laboratory. A full-cone nozzle spray provides a high velocity water jet which is dispersed into the air in a set of drops and droplets.

The sprinkler was fixed on a connecting rod in a stand placed 2.20 m above the flume surface and produced a full cone spray (solid circular pattern of drops). The estimated average raindrop-size (equivalent drop diameter) was 1.5 mm; the measurements were taken by a distrometer (laser precipitation monitor – Thies Clima) at different positions across the wetted area. The hydraulic system of the laboratory set-up was operated at a constant pressure of 2 bar, corresponding to a water discharge of $12.0 \, \mathrm{l\,min^{-1}}$. From this discharge, a total of 3.28 l of water fell on the flume surface during each experimental run. As the flume surface area was $0.90 \, \mathrm{m^2}$, this discharge was equivalent to an average rainfall intensity of $138 \, \mathrm{mm\,h^{-1}}$, with the maximum intensity (approximately $270 \, \mathrm{mm\,h^{-1}}$) falling directly below the nozzle. The rain intensity distribution over the flume was measured by 21 small rain gauges (7 rows of 3 gauges) during 5 min of exposure (Fig. 1 – right). Although the rainfall intensities used in this study were very high, similar intensities are nevertheless observed in nature for short periods, in heavy bursts. The Intensity-Duration-Frequency curves proposed by Matos and Silva (1986), for a large portion of mainland Portugal, associate a return period of 5 yr to a rain spell of the same duration and mean intensity, similar to the simulated in the laboratory. For the same return period, a 1 min burst has an estimated mean intensity of approximately $260 \, \mathrm{mm\,h^{-1}}$. The IDF curves in Matos and Silva (1986) are often used for the design of hydraulic structures in Portugal; for other studies on high intensity rain events in Portugal and IDF curves see e.g. Brandão and Rodrigues (2001).

The spatial distribution of the rainfall simulated in the laboratory resembles natural conditions in that it is not uniform. The spatial rainfall pattern generated by the nozzle represents a rain cell that moves across a drainage basin. This spatial variation induces a temporal rainfall distribution at each point of the soil flume. In space and time, this situation is closer to reality than uniform rainfall patterns. But there are technical limitations to simulating in the laboratory the extreme variability observed in natural rain. Once raindrops are catapulted from the nozzle, they begin to move under the action of gravity and frictional forces. At the tail end of the nozzle spraying cone ,the angle of impact of the raindrops is
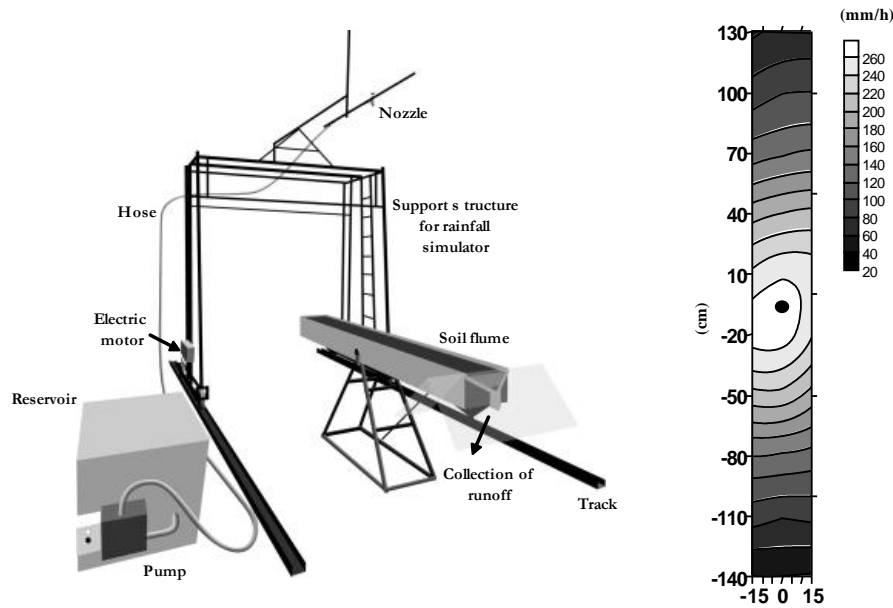
**Fig. 1.** Laboratory set-up (left) and spatial distribution of rainfall intensity (right), under the nozzle located at (0,0).

slightly higher than in the area just beneath the nozzle where raindrops fall vertically.

In the laboratory, the nozzle spray was operated in still-air for both static and moving storms. Kinetic energy and rainfall intensity under a nozzle in still-air (laboratory conditions) are highly concentrated as observed in the peaks shown in Fig. 1 (right), which is a characteristic of sprays formed by a solid circular pattern of drops.

The higher the surface gradient, the bigger the difference between raindrop impact angle for the leading edge and tail end. However, because the rain simulations were conducted in windless conditions, the raindrop impact angles remained approximately the same for each slope.

The upstream and downstream displacement of rainfall over the soil flume was obtained by moving the wheeled stand holding the nozzle on a steel rail. This movement was powered by 2 electric motors and kept constant at $1.97\,\text{m}\,\text{min}^{-1}$. Each experimental run started when the rainfall spraying cone entered the soil flume. From that moment, the rainfall cone took approximately 91 s to reach the opposite end of the flume channel and 183 s to definitively leave the flume channel.

### 2.2 Soil and flume

The laboratory soil flume (Fig. 1 – left) was made of zinc-coated iron and was 3.0 m long, 0.30 m wide, and 0.10 m deep (soil layer dimensions). The slope of the flume was adjustable by a screw system. Tests were carried out for three soil flume gradients: 2 %, 7 %, and 14 %.

The flume structure was filled with natural soil, which consisted of 7 % clay ($<4\,\mu\text{m}$), 9 % silt (4-63 $\mu\text{m}$), 73 % sand (63–2000 $\mu\text{m}$), and 11 % gravel ($>2000\,\mu\text{m}$), similar to the soil used in de Lima et al. (2003, 2008). The grain-size distribution of the original soil was characterized by a $D_{50}$ of 0.49 mm and a $D_{90}$ of 2.1 mm. The soil was previously sieved using a 15 mm mesh; all vegetative material and atypical coarser particles (e.g. stones, roots) were removed. Afterwards the soil was re-mixed mechanically with a hand shovel. The objective was to obtain homogeneity of the soil material placed in the flume, aiming at using soil material with the same characteristics in the different repetitions. This homogeneity was controlled by grain-size analyses of random samples to guarantee homogeneity of the soil material placed in the flume for different experimental repetitions. Before the experimental runs, the soil in the flume was saturated in order to conduct the experiments with soil moisture close to field capacity. To avoid disturbances on the soil surface associated to this process, water was directly applied by hand on the surface, with a hose, using low discharge rates.

### 2.3 Overland flow measurements

Overland flow was collected manually at the flume outlet every 15 seconds to obtain individual samples for grain-size analysis in a very short period of time. Each experimental run started (i.e. $t = 0$) when the leading edge of the rainfall cone crossed the outlet (for upstream moving storms) or the upper end of the flume channel (for downstream moving storms). In these experiments the overland flow sheet was very shallow (between 1 and 2 mm at peak discharge at the downstream

end of the flume). The water depth on the soil surface was measured directly with a point gauge manually adjusted to touch the water surface (readings are taken using a *vernier* scale); it was also estimated through the measurements of mean flow speeds by dye tracing (see e.g. Dunkerley, 2001). The water depth was fairly uniform across the flume; no significant rills were observed at the soil surface after the end of an experimental run. Experiments for each combination of slope and storm movement direction were repeated four times. To ensure similar conditions for each case, the soil was replaced between different rain-type experiments.

## 2.4 Sediment discharge measurements and grain-size analysis

During experimental runs, runoff collected every 15 s yielded a total number of 291 samples: 176 samples for upstream moving storms and 115 samples for downstream moving storms. In these experiments the average sediment concentration in runoff water was about 60 g l$^{-1}$. The sediment content in each sample was subject to grain-size analysis. The repetition of the experimental run types resulted in 4 samples for the same experiment time; each run type represented a particular combination of storm direction and flume gradient. Whenever the samples were too small to allow for grain-size analysis, the corresponding samples were added prior to grain-size analysis. The objective of the grain-size analysis was to trace the evolution of the characteristics of the washed-out sediments during the runoff and soil loss event.

The sediments transported by overland flow and collected at the flume outlet had different proportions of coarse (sand and gravel) and fine (silt and clay) particles. Hence, the bulk grain-size distribution of these sediments could not be easily determined with a single technique; therefore, a two-fold approach was adopted. The grain-size of coarser particles was determined by conventional sieving, while the grain-size of finer particles was determined by laser diffraction using a Coulter LS 320 instrument that can measure particles with size between 0.04 µm and 2000 µm. Although different particle properties were measured with sieving and laser diffraction (weight and volume, respectively), the two sets of data were compared and combined because we assumed that the sediments have a homogeneous density. As there was no evidence of heavy mineral enrichment in any size-fraction, we considered that any small difference in density was not sufficient to derail a combination of the two techniques.

Several researchers have shown that sieving and laser diffraction give different size results and that laser diffraction tends to indicate higher proportions of coarser particles (e.g. Jonasz, 1991; Konert and Vandenberghe, 1997; Eshel et al., 2004; Blott and Pye, 2006). When laser and sieving procedures are used to characterize the bulk grain-size distribution, the selection of a threshold diameter to separate two sub-samples to be measured by different methods must guarantee that a minimal bias is introduced. Because

laser diffraction cannot be used to measure representative sample suspensions containing medium sand or coarser particles, this study adopted a threshold diameter of 0.25 mm. Thus, the particles with a grain-size larger than 0.25 mm were determined by conventional sieving and the size smaller than 0.25 mm by laser diffraction. Hence, the option for 0.25 mm was a compromise solution that allowed obtaining high number of grain-size data based on a single technique (laser diffraction). If we would have adopted a finer diameter, it would have been necessary to integrate sieving in more samples; the option for a coarser diameter was rejected because laser diffraction tends to overestimate the proportion of coarse (>0.5 mm) particles (Blott and Pye, 2006).

In studies on the grain-size distribution of sediments generated by natural processes, it is usual to define the limits of grain-size classes using a logarithmic scale with equal intervals (Wentworth, 1922). Based on this approach, a comparative analysis of frequency curves was conducted and the constituent sub-populations were characterized. Furthermore, this approach allowed the definition of statistical parameters that describe a single distribution, which is highly convenient when a large number of samples are to be compared. The bulk grain-size results, obtained by both sieving and laser diffraction, were integrated on a conceptual scale (e.g. Wentworth, 1922; Krumbein, 1934; Krumbein and Pettijohn, 1938) based on a logarithmic transformation (base two logarithm) of the particle diameter (in mm). Thus, the percentages of particles present in the grain-size classes limited by 0.001, 0.002, 0.004, 0.008, 0.016, 0.032, 0.063, 0.125, 0.25, 0.5, 1, 2, and 4 mm were determined. The average grain-size was obtained with the "Moments" method (Krumbein and Pettijohn, 1938; Friedman, 1979).

## 3  Results and discussion

### 3.1  Hydrographs and sediment graphs

Figure 2 presents mean runoff hydrographs and associated sediment-loss graphs of the events corresponding to combinations of 3 surface slopes and 2 storm directions: upstream and downstream; the data are the mean of 4 repetitions of each experiment-type. The grain-size temporal variation of the sediments transported by overland flow were analysed. The shape of the hydrographs are clearly controlled by the type of the input (space and time variation of rainfall induced by storm movement) (Fig. 2 – top). The differences are explained by the coincidence of the direction of the overland flow movement and the downstream-moving storm direction, which leads to an intensification of discharge, contrasting with the opposite direction for an upstream moving storm (see also: de Lima and Singh, 2003; de Lima et al., 2008).

The soil flume gradient has a strong influence on the soil loss produced; on steeper slopes the total amount of sediment
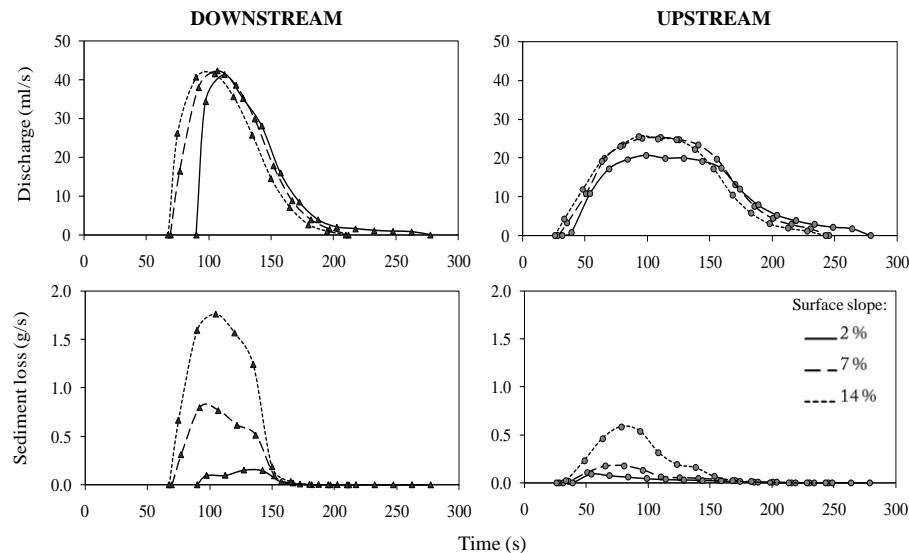
**Fig. 2.** Runoff hydrographs (top) and respective sediment graphs (bottom) for different surface gradients (2 %, 7 % and 14 %), for downstream and upstream moving rainstorms. Each graph represents mean values from 4 experimental runs.

**Table 1.** Total measured runoff volumes (l), Runoff Coefficients, and total measured soil losses (g m$^{-2}$) as a function of surface slope and direction of rainstorm movement, for all the experimental runs.

| | | Runoff (l) and Runoff Coefficient (%) | | Soil loss (g m$^{-2}$) | |
|---|---|---|---|---|---|
| | | Downstream moving storms | Upstream moving storms | Downstream moving storms | Upstream moving storms |
| Surface slope (%) | 2 | 2.61 (79 %) | 2.72 (82 %) | 9.04 | 6.88 |
| | 7 | 2.96 (90 %) | 3.08 (93 %) | 52.20 | 14.11 |
| | 14 | 2.92 (88 %) | 2.93 (89 %) | 117.76 | 43.89 |

Note: since the speed of the rain simulator was kept at a constant speed of 1.97 m min$^{-1}$, a total amount of rainfall of 3.3 l of water fell on the flume surface in each experimental run.

loss is higher (Fig. 2 – bottom; Table 1). This can be justified based on the energy available, which increases with flume gradient; hence, a greater percentage of material was carried away. It should be noted that the total amount of rainfall and runoff remained approximately constant since they resulted from similar storm events that moved with the same velocity and, furthermore, the soil was at field capacity for all events (checked by soil moisture TDR probes).

Sediment yield is also highly dependent on the direction of the rainstorm movement. Downstream-moving rainfall storms were responsible for higher runoff peaks and the corresponding sediment graphs were more peaked than those obtained for upstream-moving storms (Fig. 2). Sediment-loss graphs followed the pattern of the corresponding hydrographs. The rainfall spatial distribution below the nozzle (Fig. 1 – right) also affected the sediment delivery during each event.

### 3.2 Grain-size distribution of sediments transported by overland flow

The sediment load generated by downstream moving storms presented a different behaviour in terms of grain-size distribution curves for higher slopes (7 % and 14 %) and for a gentle slope (2 %) (Fig. 3). For downstream storms the sediment transported by runoff was dominated by 0.125 to 2.0 mm particles, which are also dominant in the tested soil. The recession limb of the hydrograph was dominated by particles mainly finer than 63 µm (silt and clay). The sediment generated by a downstream moving storm on the 2 % gradient tended to be dominated by silt and clay-size particles, with a significant proportion of sand only during the rising limb of the hydrograph (Fig. 3c).

The sediment grain-size distributions, generated by upstream-moving storms, showed a similar behaviour: the
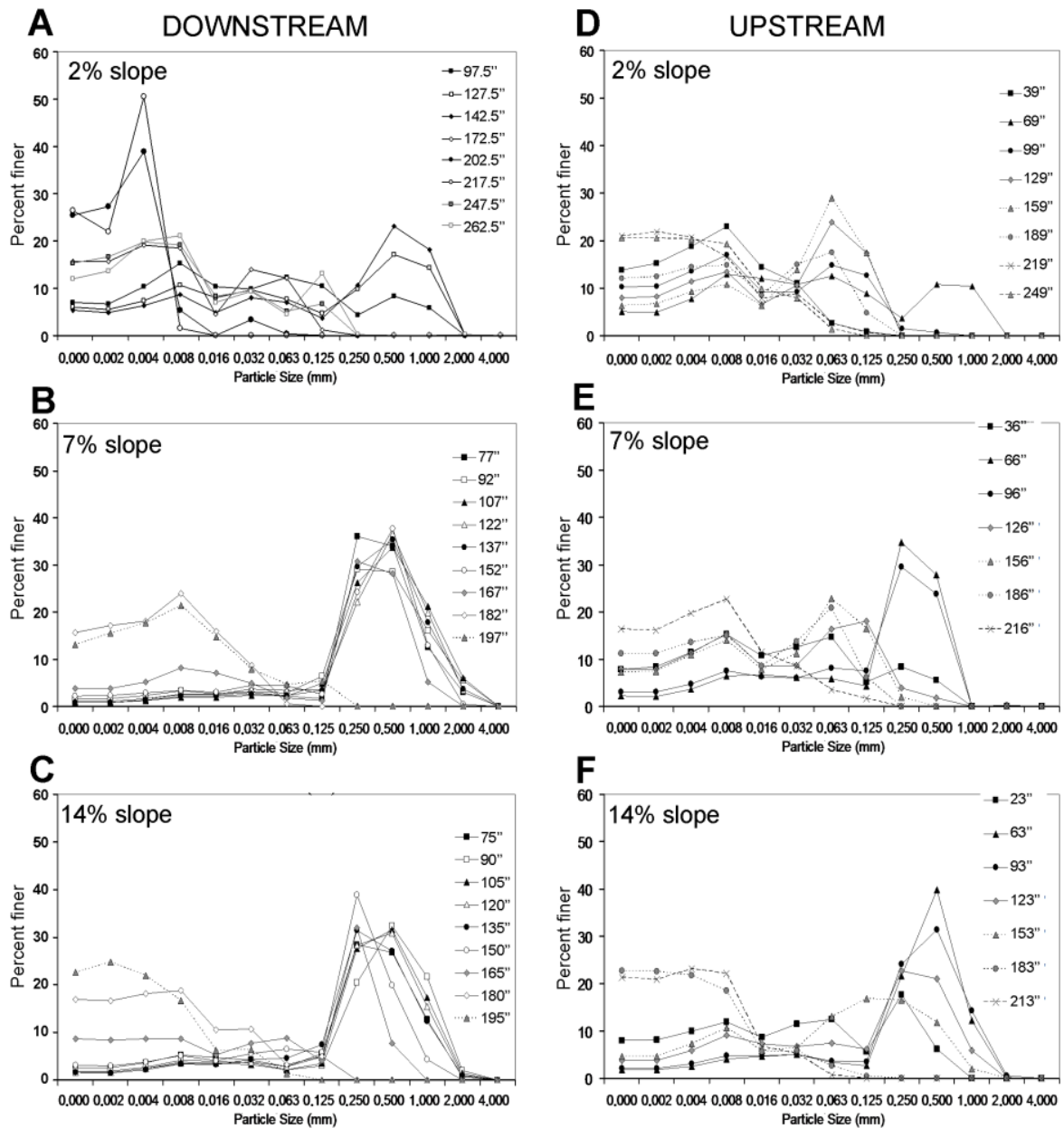
**Fig. 3.** Evolution in time (seconds) of grain-size distribution curves of sediments transported by overland flow obtained for storms moving downstream (left) and upstream (right) over surface gradients of 2 %, 7 %, and 14 %. Each curve represents mean values from 4 experimental runs.

higher surface gradients led to a significant percentage of particles between 0.125 and 2.000 mm, which was typically above 50 % of the total amount of sediments.

The variation of the mean grain-size of the sediments transported by the overland flow generated during the experimental runs is shown in Fig. 4. The data plotted in this figure were obtained from the four repetitions of each event and for the corresponding average; in each plot the arrow indicates, for the average behaviour, the grain-size evolution throughout the events. When the mean grain-size is plotted against

discharge for the 2 % flume gradient and downstream moving storms, it can be seen that the maximum in mean grain-size is reached later than the peak discharge (Fig. 4a). For upstream moving storms and also for the higher flume gradients, the opposite occurs. Moreover, the sediments transported during upstream-moving storms are much more dominated by clay and silt particles than those yielded by downstream moving storms. This can be justified based on the smaller energy available for upstream moving storms than for the downstream moving storms.
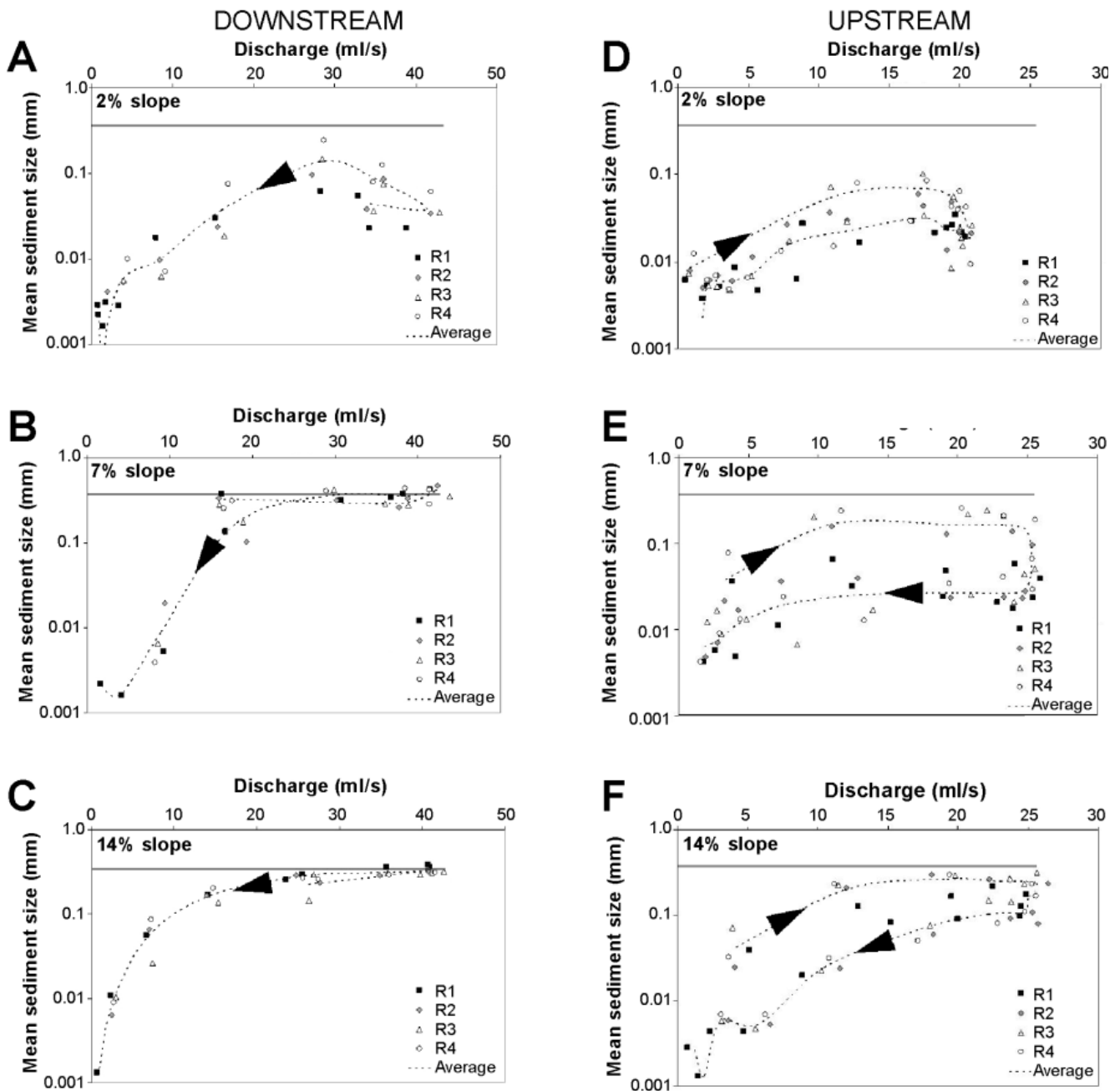
**Fig. 4.** Relationship between mean sediment grain-size and runoff discharge for 2 %, 7 %, and 14 % surface gradients for downstream moving storms (left) and upstream moving fronts (right). The data are from four independent repetitions (R1, R2, R3, and R4). The horizontal grey line represents mean grain-size of the original soil. Arrow indicates grain-size evolution throughout the experiment. Note the different discharge scale for upstream and downstream moving storms.

For downstream moving storms and for 7 % and 14 % flume gradients, during higher discharges the mean grain-size of the transported sediments almost equalled that of the original soil (horizontal line in graphs – Fig. 4b and c), which defined an upper limit for the generated sediment size. Mean grain-size dropped strongly for the last part of the recession limb of the hydrograph. However, for downstream moving

events and the surface gradient of 2 %, the maximum mean grain-size of the transported sediments occurred later than the peak runoff discharge. For this surface gradient, the mean grain-size of the transported sediments was smaller than that of the original soil.

For upstream moving storms it was observed that the mean grain-size of the transported sediments was much higher
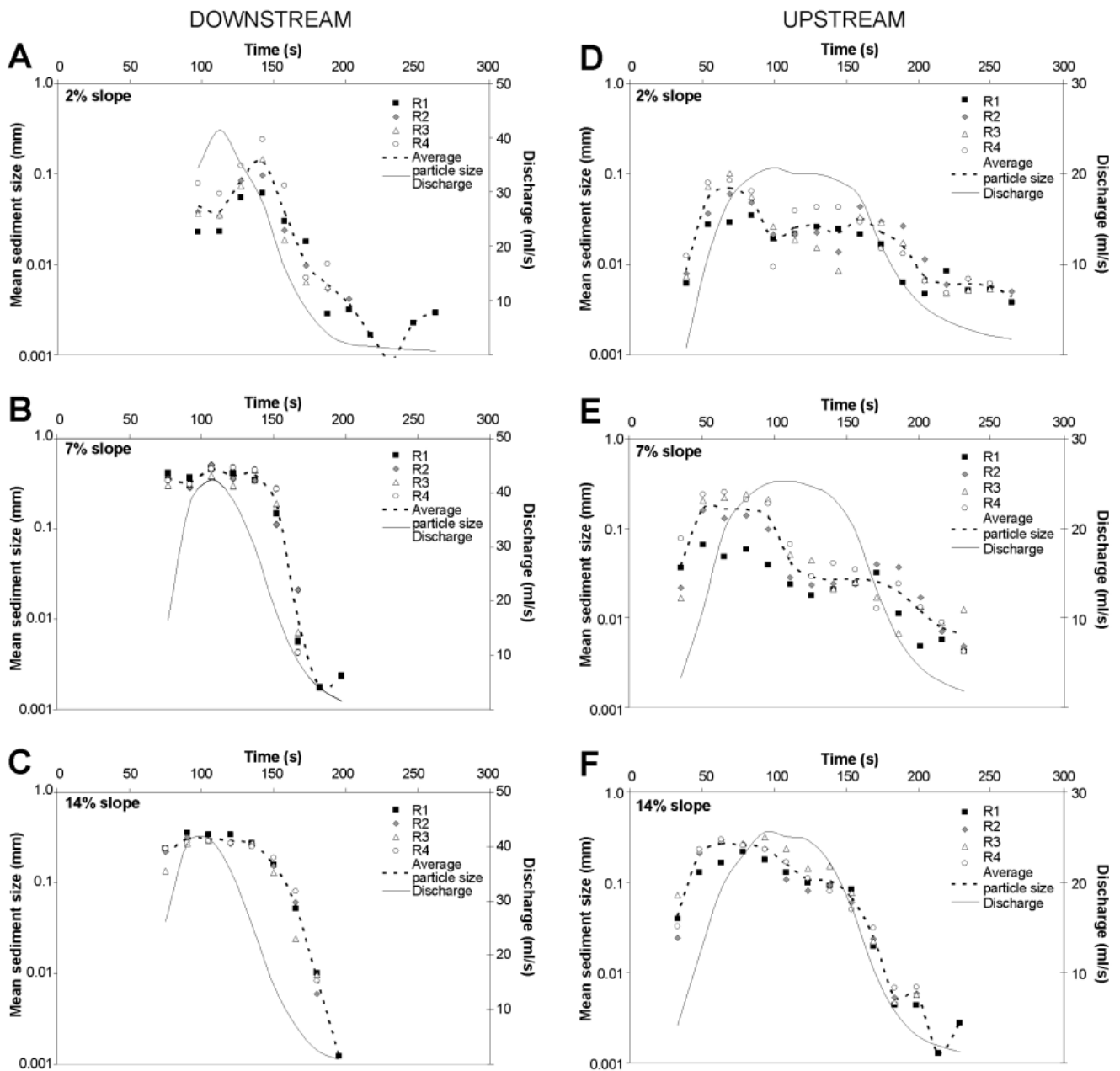
**Fig. 5.** Evolution over time of mean grain-size of transported sediments and runoff discharge, during each laboratory run, for storms moving downstream (left) and upstream (right) for surface gradients of 2 %, 7 %, and 14 %. Grain-size data are for four independent repetitions (R1, R2, R3, and R4); broken line represents the regression line through these four repetitions.

during the recession limb of the hydrograph. This led to a loop in the curve that was not so clearly observed in downstream moving storms (Fig. 4).

As occurs for downstream moving storms tests, the mean grain-size of the transported sediments yielded from upstream moving storms was further away from the mean grain-size of the original soil as surface slope increased (i.e. smaller grain-size). The maximum grain-size was attained for higher discharge.

The same data presented in Figs. 6 and 4 – top, particularly the mean grain-size of sediment-loss and discharge, is in Fig. 5 – plotted against time for downstream and upstream moving storms. The plot is used to confirm the occurrence of time lags between the occurrence of peak discharge and maximum mean grain-size of the transported sediments.

For all gradients tested, with increasing discharge it can be seen that, for certain discharges, the associated mean sediment size was coarser during the initial phase of the test than
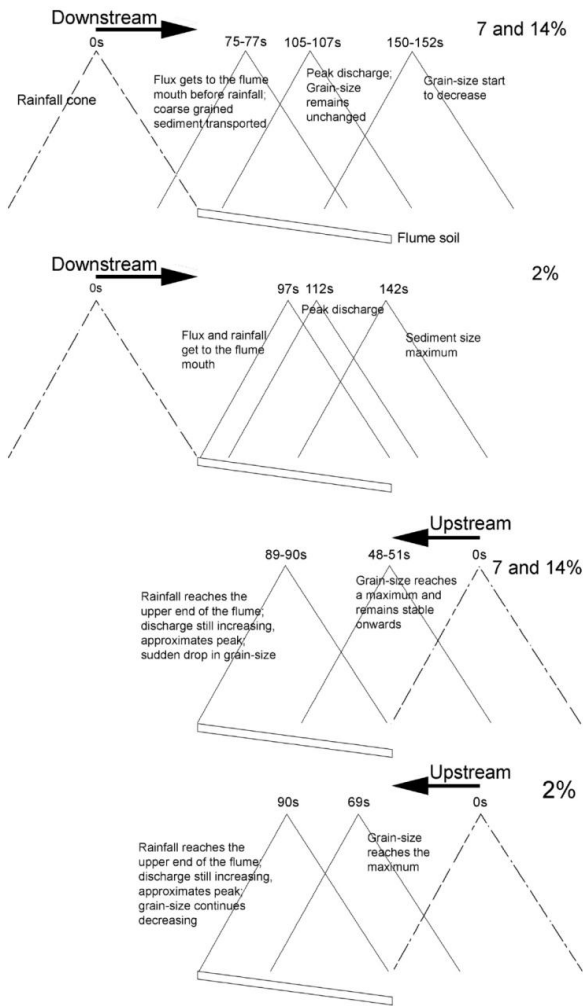
**Fig. 6.** Schematic representation of the location of the nozzle, in time, with respect to the soil flume, during the experimental procedure for the two directions of moving storm (downstream and upstream). Milestones of changing-trends in sediment yield grain-size are identified.

along the following phases (Fig. 5d, e and f). It was possible to recognize rising and receding limbs in the discharge rates versus grain-size curve, in which the rising branch was always related to coarser grain-sizes than the receding branch. This difference attenuated in the 2 % slope experiments.

Taking into account the velocity of the moving rainstorm ($1.97\,\mathrm{m\,min^{-1}}$) and the length of the soil channel (3 m), the time of sudden drop in the mean grain-size of sediments generated by downstream storms (approximately 150 s) was the same as the time required for the passage of the vertical that contained the nozzle to reach the flume channel outlet. The decay of the sediment mean grain-size was more abrupt for the downstream moving storms (whatever the slope), which also typically showed higher peak discharges and steep rising and receding limbs.
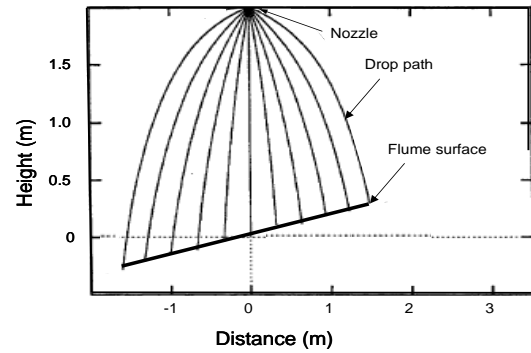


**Fig. 7.** Two-dimensional drop paths of a 1-mm drop ejected in different directions with a velocity of $5\,\mathrm{m\,s^{-1}}$, in still-air. The slope of the receiving plane is 10 % (adapted from de Lima et al., 2002).

The out-of-phase evolution of grain-size and discharge observed for downstream experiments with 2 % gradient (Fig. 5a; see time lag between maximum discharge and maximum mean grain-size) may be related to detachment and deposition processes along the flume channel throughout the experiment. Deposition in the downstream and upstream moving storm movement occurs when the raindrop related turbulence ceases after rain stops (i.e. direct rainfall impact of drops on overland sheet stops and consequently stopping splash), corresponding to the recession limb of the hydrograph. On the one hand, it is usually recognized that relatively large amounts of soil particles cannot be transported by raindrop splashes under windless rain (e.g. Erpul et al., 2004a). However, in some circumstances, depending on factors which include soil characteristics, slope, and energy dissipated when raindrops impact the soil surface, large amounts of sediment can be transported by raindrop-impacted overland flow in windless conditions (e.g. Kinnell, 1981; 2009a, b). On the other hand, the splash-saltation process can cause net transportation in the prevailing wind direction since variations in splash-saltation trajectory due to the wind are expected in wind-driven rain (e.g. Erpul et al., 2004a). The fall vector of raindrops not only affects the soil detachment but also the shallow flow hydraulics (e.g. Erpul et al., 2004b). However, in fact, the experiments described in this work do not entirely represent the conjugated action of wind and rain (typically called wind-driven rain). The laboratory experiments were performed without wind, and therefore there was no added horizontal wind component.

Figure 6 expresses an attempt to identify specific instants during the rainfall-runoff event, where variations of grain-size could be identified. The objective of this figure was to assist in the interpretation of Figs. 3 to 5. The position of the nozzle over the soil flume, defining the distribution of rainfall on the soil surface, had an influence on the grain-size distribution of the transported sediments. When the nozzle-vertical left the flume, changes in sediment properties occurred because of a reduction of the direct impact

of raindrops on the overland flow sheet (disturbed flow). It was under the nozzle-vertical that the highest intensities were measured.

The issue of the angle of inclination of the trajectory of drops generated by nozzles is difficult to solve. All experiments using nozzles conducted in recent decades have had the same problem (for both static and moving storms).

The scheme in Fig. 6 is not an exact illustration of the drop trajectory and impact angle of the drops on the hedge of the wetted area. In fact, the falling drops hit the soil surface at inclination angles that are much smaller than represented in this figure, as shown in Fig. 7. It is observed that the angles of inclination of the trajectories of drops at impact, measured from the vertical, increase as the distance to the nozzle increases, (Fig. 7). Thus, larger angles of inclination of the trajectories of drops are observed in areas where the rainfall is less intense. Areas with higher rainfall intensity have approximately vertical fall drop trajectories.

## 4 Conclusion and discussion

This paper identifies significant differences in soil losses associated with storms moving in different directions (downstream and upstream) and interprets the results through a detailed analysis of nearly 300 grain-size curves. The study aims at getting a better insight into the processes induced by these types of storms.

The results of laboratory experiments show that downstream moving storms produce more soil loss than upstream moving storms. The pattern of sediment grain-size evolution shows a clear dependence on the direction of storm movement. For downstream-moving storms, a strong relationship between overland flow discharge and mean sediment size is found. For a particular discharge, the mean grain-size of sediments transported during the rising limb of the hydrograph is always coarser than during the recession limb.

The evolution patterns of mean grain-size distribution of transported sediments by overland flow are only partially consistent with the evolution of overland discharge. Generally, under higher discharge the transported sediment tends to be coarser. For lower slopes, the available energy is likely to be insufficient to carry the coarser particles, regardless of rainfall intensity, and the coarser particles tend to remain on the soil surface. Downstream moving storms have greater peak discharges and can more easily mobilize particle sizes present on the soil surface. Regardless of the slope and type of moving rainstorm, the maximum mean grain-size of transported solids is bounded by the mean grain-size of the original soil, which constitutes an upper limit for the size of the transported material.

This study is mainly focused on the consequences of the spatial and temporal distribution of rainfall events, as a result of the rainfall simulator displacement, which is one of the main factors affecting runoff and sediment transport. This type of study should also be conducted in small drainage basins to validate the findings on larger scales. At this time it is not possible to discuss scale issues related to these processes: namely, the complexity of the surface geometry and length of the slopes on a natural basin in contrast with the regular surface of the 3 m long laboratory flume. Considerable differences are expected on the transport and deposition processes of the eroded material. However, the advantage of conducting laboratory experiments offers the possibility to reduce and constrain the number of variables playing a role in the precipitation-overland flow transformation and in the erosion process. Thus, the main objective of this study was attained, which was to understand qualitatively the effect of the direction of moving storms on the relevant processes. We consider that the laboratory conditions made it possible to significantly reduce (most likely not to eliminate) the effect of other main variables which allow the movement of the storm to play a dominant role.

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