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Grain-Size Evolution of Sediments Transported by Runoff Generated by Moving Storms

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ABSTRACT: This study presents the results of laboratory experiments designed to investigate the influence of moving rainfall storms on the dynamics of sediment transport by surface runoff. Experiments were carried out using a soil flume. The movement of rainfall was generated by moving a rain simulator at a constant speed in the upstream and downstream directions along the flume. The main objective of the study was to characterize, in laboratory conditions, the distribution of sediment grain-size transported by rainfall-induced overland flow and its temporal evolution. Grain-size distribution curves were constructed using conventional hand sieving and laser diffraction for overland flow and sediment deliveries collected at the flume outlet. The results of laboratory experiments show that storm movement, affecting the spatial and temporal distribution of rainfall, has a marked influence on the grain-size characteristics of sediments transported by overland flow.

INTRODUCTION

The influence of the spatial and temporal distribution of rainfall on surface runoff and associated solid transport on different types of ground cover has long been investigated. However, for a long time innumerable difficulties have been encountered in characterizing and controlling with precision the parameters that influence runoff. Thus experiments started using rain simulators. Laboratory experiments allowed a better control of parameters and led to improved results. However, many studies did not take into account the effect of the movement of rainfall caused by the action of wind on runoff. Failure to consider the movement of rainfall (i.e., the combined action of wind and rain) can result in under- or over-estimation of peak discharge (e.g., Singh, 1998; de Lima and Singh, 2002). The importance of the combined action of wind and rain, especially the changes in rainfall characteristics (e.g., spatial and temporal distribution, trajectory of drops) and runoff (e.g., height of runoff and speed) has been recognized

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by a number of investigators (e.g., Maksimov, 1964; Yen and Chow, 1968; Wilson *et al.*, 1979; Singh, 1998; de Lima and Singh, 1999; de Lima *et al.*, 2003). Some investigators (e.g., de Lima and Singh, 2002) have considered the movement of rainfall over drainage areas.

This study attempts to characterize the grain-size distribution of sediments carried by runoff, allowing for the evaluation of the influence of rainfall storm movement (upstream, downstream) and of the soil flume gradient on the grain-size distribution. This evolution, evaluated by grain-size distribution curves, was then related to the respective runoff hydrographs, thus identifying the part of the hydrograph with greater erosive impact on soil; this part could be the rising or recession limb or the peak discharge of the runoff hydrograph.

METHODOLOGY

Laboratory Set-up

The rain simulator (Figure 1) comprises a constant level reservoir, a pump, a system of hoses, a stand, 2 electric engines, 1 automatic panel to control the speed at which the apparatus moves, and a sprinkler (nozzles) fixed on a connecting rod in a stand 2.20 m above the surface of the flume. The laboratory experiments had a constant pressure of 2 bars, corresponding to a discharge of 12 l/min. Given the flume area this discharge is the equivalent to a rainfall intensity of 138 mm/h.

Rainfall moving upstream and downstream at a constant speed was simulated over a laboratory soil flume. The rainfall movement was achieved by moving the wheeled stand holding the nozzle over the flume.

The experimental apparatus was moved on wheels on a steel rail, powered by 2 electric motors. The speed of the rain simulator was kept at a constant value of 1.97 m/min, which corresponds to a total of 3.28 liters of water falling on the flume surface. The static rainfall had the nozzle mounted on the vertical line that contains the geometric centre of the flume. The duration of the static rainfall was determined so as to guarantee a rainfall volume equal to the moving rain events.

The soil flume was made of zinc-coated iron and was 3.00 m long, 0.30 m wide and 0.10 deep. The structure allowed the channel slope to be altered by means of adjustable screws. The surface flow was collected at the lower end of the flume. In this study both the type of rainstorm and the soil flume gradient were varied, the latter by using the following gradients: 2%, 7% and 14%.

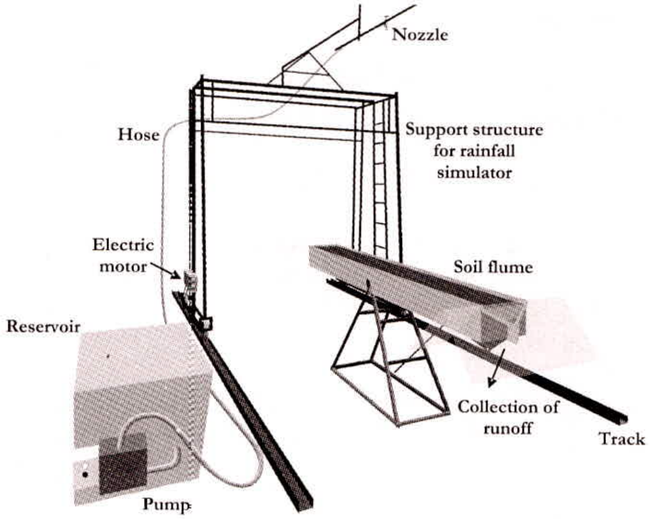

Fig. 1: Laboratory set-up

The sedimentary material used in the laboratory experiments as "soil" was taken from the right bank of the Mondego River, Coimbra, Portugal. The clastic material was readily available and shows, in situ, important signs of water erosion. The material was taken from a Triassic outcrop, consisting mainly of quartz and feldspar, but also including some quartzite, mica and clay minerals. The soil consists of 6% clay, 10% silt, and 84% sand to gravel.

Characterization of Sediment Grain-size

To ensure identical initial conditions, the soil-material in the flume was replaced with original soil before each rain type and was subjected to a standard treatment. The soil was first sieved to remove coarser particles and organic material, and then placed in the soil flume in a series of layers to achieve a 10 cm thick layer. Before each repetition the surface layer's water content was controlled by imposing a 30 minute interval between simulated rainstorm events. The volumetric soil water content was approximately 20% (determined by Time-Domain-Reflectometer measurements) just before the start of each storm event.

Overland flow and sediment loss caused by each rainfall event were measured by collecting samples every 15 seconds in metal containers placed at the downstream end of the soil flume. Rainfall was simulated under free draining conditions. The amount of sediment transported by overland flow was estimated by low temperature oven drying of runoff samples. After drying the runoff samples, the transported sediments underwent grain-size characterization in order to evaluate how their texture evolved over time. There were two distinct phases in this step: one using the laser diffraction particle size analyzer—LS 230 Beckman Coulter (for particles finer than 0,25 mm), and the other using conventional sieving (for particles coarser than 0,25 mm).

Characterization of Flow Transport Capacity

Stream Power is the energy available to transport sediment. Stream Power per unit length of channel (Wm^{-1}) (e.g., Worthy, 2005; Fitzgerald and Bowden, 2006) is,

$$\Omega = \gamma Q s \quad \ldots (1)$$

where γ is the specific weight of water (9810 Nm^{-3}), Q is the water discharge (m^3s^{-1}), and s is the energy slope ($m\ m^{-1}$), which may be approximated by the slope of the channel bed.

For the specific laboratory conditions described in this article, stream power is,

$$\Omega_T = \gamma \frac{\sum_{i=1}^{n} \overline{Q}_i}{n} sL \quad \ldots (2)$$

where Ω_T is the total stream power (W), $\overline{Q}_i$ is the water discharge (m^3s^{-1}) for n sampling time intervals, and L is the slope length (m), which is the length of the flume.

RESULTS AND DISCUSSION

Hydrographs and Transport of Sediments

Figure 2 presents runoff hydrographs (mean values of 4 rain events) and their respective sediment fluxes for different gradients of the soil flume (2%, 7% and 14%) as a function of storm type (storms moving downstream and upstream and static storms). It is observed that the distribution of both discharge and soil material transported by runoff depend on the storm type.

The time when runoff started was affected by both the type of storm and the slope of soil flume. The time was greater for a flume slope with a smaller gradient. The runoff caused by the downstream-moving rainfall started later, because this event began at the upstream end of the flume. However, due to greater infiltration, it produced a smaller runoff volume than did other rainfall storm types. For this type of event, peak discharge was reached quicker and had a higher value.

The upstream-moving storm was the least erosive storm type, with solid transport being less efficient than for other storms types. The downstream-moving storm was the most erosive for soil in terms of both the amount of material carried by runoff and the maximum grain size of sediments. The effect of the static storm was midway between the other two types.

Figure 2 shows that the soil flume slope had little effect on the hydrograph shape and the peak discharge, but it had a strong influence on the transport of sediments. This is because a steeper gradient increases the transport capacity of runoff, regardless of the storm type.

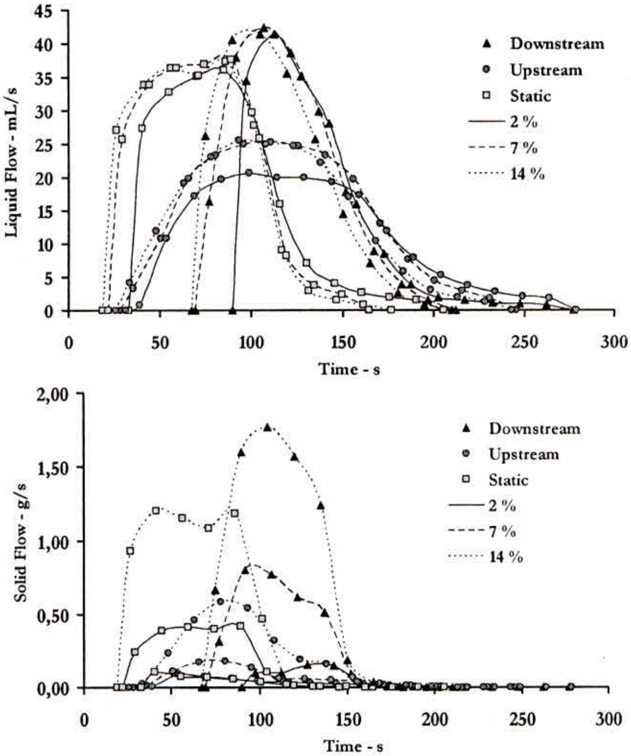

Fig. 2: Comparison of runoff hydrographs and respective sediment fluxes for different slopes and storm types

Figure 3 shows the amount of the total soil transported by runoff for different storm types and surface flume gradients studied. It can be concluded that: (*i*) a steeper slope increases the transported solids; and (*ii*) of the various storm types, the downstream-moving storm is the one with the greatest capacity to transport sediments.

Grain-size Evolution of Sediments Transported by Runoff

The grain-size evolution of the sediments transported by runoff was investigated. Runoff carried away fine material first, and when peak discharge was reached a coarser material was found. In the recession limb of the hydrograph after rainfall ceased, the sediments basically consisted of fine particles. This behavior was observed for all storm types and flume gradients. However, it was found that the grain-size of the transported sediments was more akin to the original soil when the flume gradient was steeper.

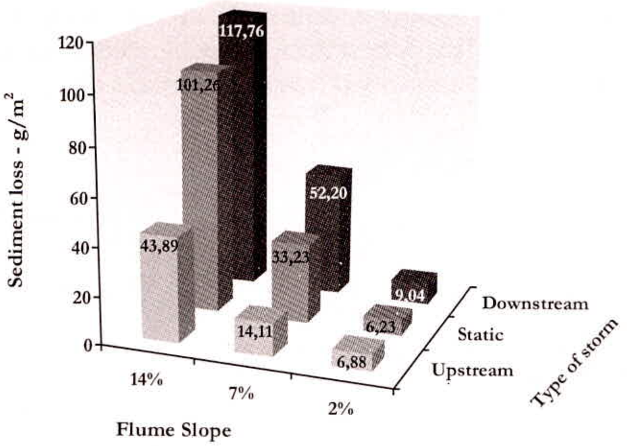

Fig. 3: Total soil loss caused by different rain events as a function of slope and storm types

Figure 4 shows the grain-size evolution (% sand and gravel, % silt and % clay) for different storm types and flume slopes.

Storm movement also affected the characteristics of sediments transported by overland flow. Figure 5 presents grain-size distribution curves of sediments transported by moving storm events (downstream and upstream) for a 14% flume slope, collected at regular time intervals (every 15 seconds) until runoff ceased. The curves show the sediment evolution over time. This behavior can also be observed in the path observed in the Feret Triangle (Figure 5, right), corresponding to the sediment size transported by runoff.

Figure 5 shows that rainfall storms that moved downstream and upstream had grain-size distribution curves that were closer to the curve of the original soil. A similar behavior was obtained for other slopes.

The results show that the steeper the flume gradient, the greater the amount of coarse material, in both the initial samples and the samples corresponding to peak discharge. Steeper gradient therefore implies an energy increment and thus greater water erosion, now characterized not only in terms of sediment weight but also in terms of grain size distribution. The downstream-moving rainfall storms had a greater erosive power than other rainfall. storms for all gradients tested. Furthermore, it can be observed that the solids transported during the upstream-moving storm, regardless of flume gradient, are composed of finer material (silt and clay). However, this percentage of fine material decreases as the flume gradient increases.

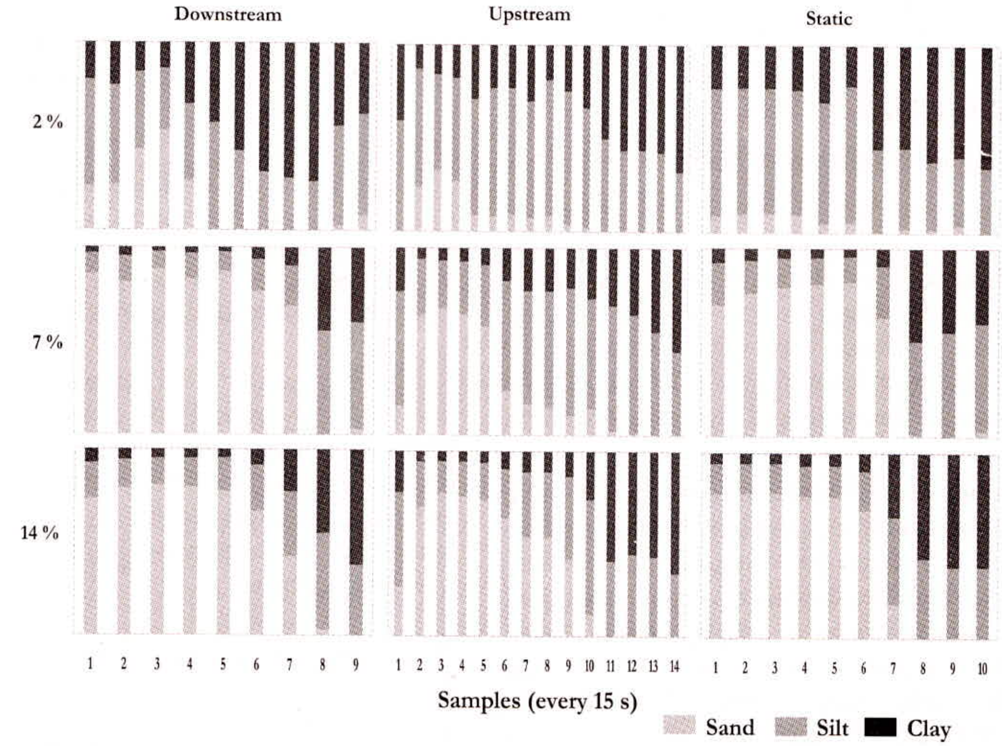

Fig. 4: Grain-size evolution of runoff samples (collected every 15 seconds), as a function of slope, for three studied storm types

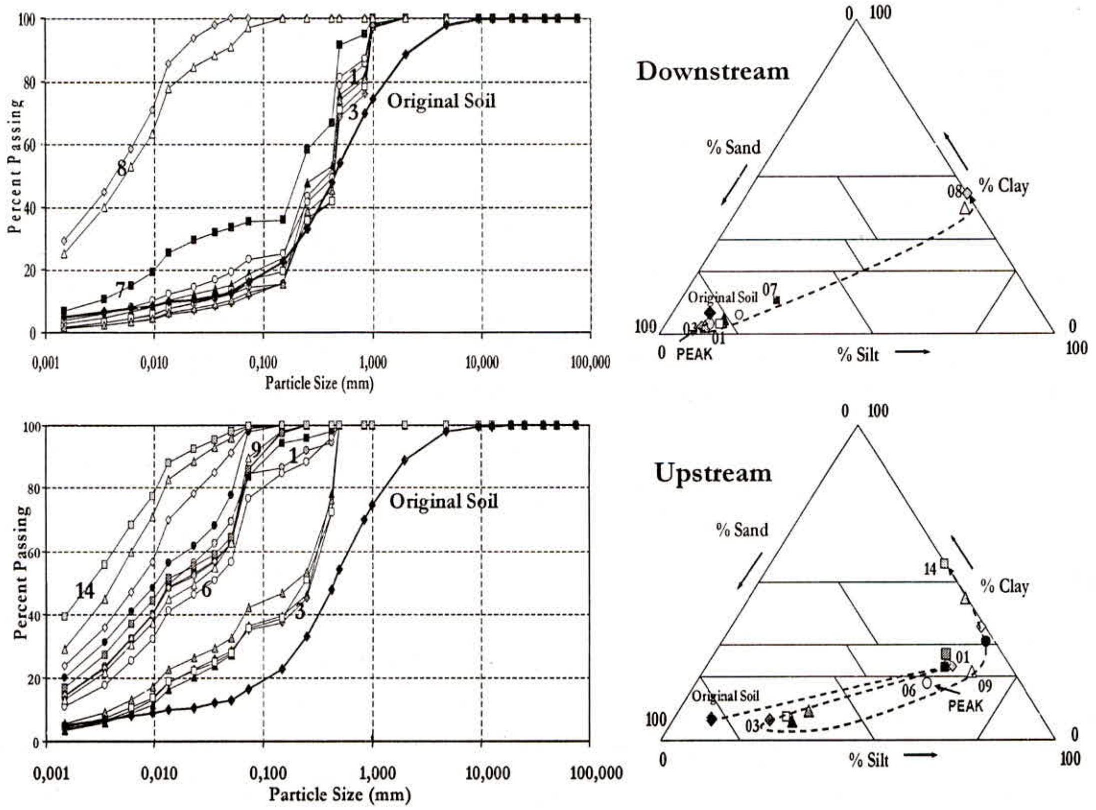

Fig. 5: Grain-size evolution of sediments transported by runoff for 14% soil flume slope and for 2 storm types: Left: Grain-size curves; and Right: Sequence of corresponding positions in the Feret Triangle

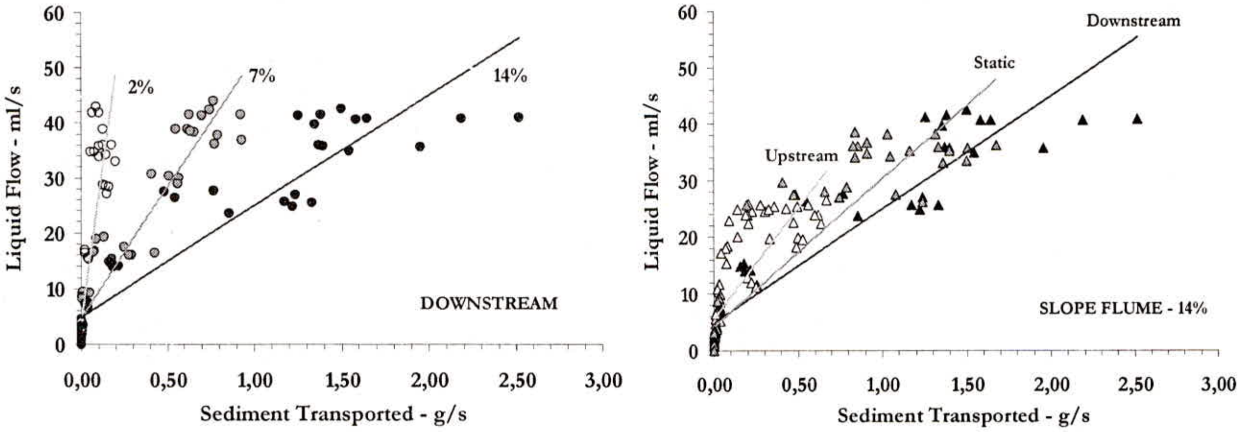

Fig. 6: Relation between liquid flow and sediment transported: Top) Influence of flume slope (downstream storm); Bottom) Influence of storm type for a 14% slope

Stream Power and Sediment Transport

Quantification of the relation between liquid discharge and sediment transport is important to understand the differences between the static storm and moving storms. Slope also plays an important role as can be observed in Figure 6 (top). The data collected are for three different storm types.

Figure 6 (bottom) clearly shows how different storms are capable of transporting sediments by overland flow. Similar results were obtained for other slopes. Independently of the slope of the soil flume, the downstream moving storm is the storm type that possesses the highest capacity for transporting sediments.

Figure 7 shows total stream power as a function of storm type and flume slope. The stream power is an expression of the rate of energy expenditure or flow strength (Figure 3). Total stream power increases with soil flume slope and is higher for downstream-moving storms for a given slope.

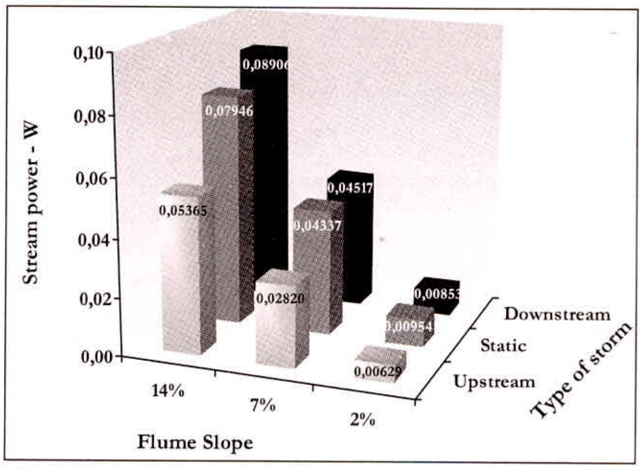

Fig. 7: Total stream power as a function of storm type and flume slope

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The downstream-moving rainfall storms, driven by wind, have more energy associated with runoff (higher stream power) than do other storm types. Therefore, they are better able to drag coarse particles along, and have the most erosive impact on soil.
2. Stream Power increases with flume gradient; hence a greater percentage of coarse material is carried away.
3. The paths (sequence of positions, illustrating evolution in time) in the Feret Triangle associated with upstream-moving storms are different from the paths associated with downstream-moving storm, with finer grain-sizes at the beginning of runoff, evolving to a coarser size as the peak discharge is approached, and to fine particles in the recession limb of the hydrograph. The downstream-moving storm with greater initial flow does not evolve in the same way. At first it exhibits a granulometry almost as coarse as the original soil, which later progressively decreases to finer grained sizes.

REFERENCES

de Lima, J.L.M.P. and Singh, V.P. (1999). "The influence of storm movement on overland flow—Laboratory experiments under simulated rainfall". *Hydrologic Modeling*. Water Resources Publications, edited by V.P. Singh, II Won Seo e J.H. Sonu, 101–111.

de Lima, J.L.M.P. and Singh, V.P. (2002). "The influence of the pattern of moving rainstorms on overland flow". *Advances on Water Resources*, 25(7), 817–828.

de Lima, J.L.M.P., Singh, V.P. and de Lima, M.I.P. (2003). "The influence of storm movement on water erosion: Storm direction and velocity effects". *CATENA*, 52, 39–56.

Fitzgerald, E. and Bowden, B. (2006). "Quantifying increases in stream power and energy". *Stormwater*, 7(2), March/April,http://www.stormcon.com/sw_0603_quantifying.html.

Maksimov, V.A. (1964). "Computing runoff produced by a heavy rainstorm with a moving center", *Sov. Hydrol.*, 5, 510–513.

Singh, V.P. (1998). "Effect of the direction of storm movement on planar flow". *Hydrological Processes*, 12, 147–170.

Wilson, C.B., Valdes, J.B. and Rodrigues-Iturbe, I. (1979). "On the influence of the spatial distribution of rainfall on storm runoff". *Water Resources Research*, 15(2), 321–328.

Worthy, M. (2005). "High-resolution total stream power estimates for the Cotter River, Namadgi National Park, Australian Capital Territory". *Roach I.C. ed. 2005. Regolith 2005–Ten Years of CRC LEME. CRC LEME*, 338–343.

Yen, B.C. and Chow, V.T. (1968). "A study of surface runoff due to moving rainstorms". *Hydraulic Engineering Series* No. 17, Department of Civil Engineering, University of Illinois, Urbana, (USA).