Journal of Hydrology (2006) **330**, 709–720

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Numerical modeling of surface runoff and erosion due to moving rainstorms at the drainage basin scale

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Received 27 August 2004; received in revised form 26 April 2006; accepted 27 April 2006

KEYWORDS
Soil erosion;
Storm movement;
Drainage basin;
Numerical modeling

Summary A physically-based distributed erosion model (MEFIDIS) was applied to evaluate the consequences of storm movement on runoff and erosion from the Alenquer basin in Portugal. Controlled soil flume laboratory experiments were also used to test the model. Nine synthetic circular storms were used, combining three storm diameters (0.5, 1 and 2 times the Alenquer basin's axial length) with three speeds of storm movement (0.5, 1 and 2 m/s); storm intensities were synthesized in order to maintain a constant rainfall depth of 50 mm. The model was applied to storms moving downstream as well as upstream along the basin's axis. In all tests, downstream-moving storms caused significantly higher peak runoff (56.5%) and net erosion (9.1%) than did upstream-moving storms. The consequences for peak runoff were amplified as the storm intensity increased. The hydrograph shapes were also different: for downstream-moving storms, runoff started later and the rising limb was steeper, whereas for upstream moving storms, runoff started early and the rising limb was less steep. Both laboratory and model simulations on the Alenquer basin showed that the direction of storm movement, especially in case of extreme rainfall events, significantly affected runoff and soil loss.

Introduction

Quantifying water erosion is a complex task, due to the great variability (spatial and temporal) of rainfall, relief,

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.04.037

vegetation, seasonal land practices, soil properties, and drainage network. However, the understanding of the water erosion process and the determination of the soil material transported is needed in a multitude of engineering studies (e.g., agricultural soil management and sediment transport to rivers and water reservoirs).

Water erosion is the result of the combined effect of the processes of soil detachment and transport by the raindrop impact and surface flow (e.g., Guy et al., 1987; Römkens et al., 1997). The modeling of runoff and soil loss has been well documented in the literature (e.g., Dunne, 1978; Bryan and Poesen, 1989; Singh, 1997; Huang et al., 2002; Erpul et al., 2002) but still continues to be the object of intensive research worldwide.

Heavy rainstorms are a determinant factor for soil erosion, namely in the Mediterranean climatic regions. Natural rainfall is highly variable in both time and space (e.g., Eagleson, 1978; Sharon, 1980; Foufoula-Georgiou and Georgakakos, 1991; Ladoy et al., 1991, 1993; de Lima, 1998). The majority of studies on these regions do not take into account the effect on the hydrologic response caused by the movement of storms across drainage areas. However, the problem of how storm movement affects flows (shape of the hydrograph and peak discharge) has been recognized for some time (e.g., Maksimov, 1964; Yen and Chow, 1968; Wilson et al., 1979; Jensen, 1984; Singh, 1998; Singh, 2002a,b), normally based on laboratory or numerical simulations. Ignoring the storm movement can result in (considerable) over- or under-estimation of the runoff peak (e.g., Maksimov, 1964; Yen and Chow, 1968; Wilson et al., 1979; Jensen, 1984; Singh, 1998; de Lima and Singh, 2002; Singh, 2002b). When compared with storms moving downstream, storms moving upstream are characterized by hydrographs with: (1) earlier rise; (2) lower peak discharge; (3) less steep rising limb; and (4) longer base time. These results for one-dimensional flows have been obtained theoretically on planar surfaces (e.g., Singh, 1998, 2002a,b; de Lima and Singh, 2002) and experimentally, in the laboratory, for overland flow on impermeable surfaces (e.g., de Lima and Singh, 2003) and soil flumes (de Lima et al., 2003).

Because of the relation between runoff and water erosion, the movement of storms (direction, velocity, etc.) is also expected to affect the associated soil loss (e.g., de Lima et al., 2003). Furthermore, the raindrop splash transport process is affected by wind-driven rains (e.g., de Lima et al., 1992, 2002; van Dijk et al., 1996; Erpul et al., 2002). However, most of the studies reported in the literature have quantified soil loss in time only in controlled laboratory conditions. Thus, there is also a lack of studies on estimation of erosion under moving storms on natural basins.

This work investigated the variability of runoff and erosion processes caused by the movement of rainstorms over a drainage basin. A numerical model was used to simulate the response of a basin to rainstorms moving up or down the basin area at a range of speeds, simulating a single dry—wet—dry cycle. Controlled laboratory experiments using a soil flume and a movable sprinkling-type rainfall simulator were used to test the model's capability to adequately simulate slope responses to changes in the storm movement direction. However, the main objective of this study was to quantify the influence of the storm movement on water erosion at the basin scale. The model was applied to the Alenquer drainage basin, with an area of 120 km^2, in Portugal.

Materials

Laboratory experimental set-up: flume and soil

Laboratory experiments were conducted on a soil flume using a movable sprinkling-type rainfall simulator (Fig. 1).

The soil flume had the following dimensions: 3.0 m length × 0.3 m width × 0.3 m height. The flume bed had a slope of 10%. The soil material, described in de Lima et al. (2003), had a uniform thickness of 0.1 m and consisted of 11% clay, 10% silt and 79% sand. Standard laboratory permeability tests gave a saturated hydraulic conductivity of $K_s = 5.7 \times 10^{-5}$ m/s. The saturated soil water content was 39%.

Laboratory experimental set-up: rainfall simulator

The basic components of the rainfall simulator were three equally spaced downward-oriented full-cone nozzles (Fig. 1), a support structure in which nozzles were installed, and connections with water supply and pump. The spacing between the nozzles was 0.95 m. The nozzles had a height of 2.2 m, measured above the geometric centre of the soil surface. The working pressure in the nozzles was kept constant at 50 kPa. The simulated rainfall consisted of small raindrops approximately with 1.5 mm median diameter (de Lima, 1997). The storm movement was obtained by moving the nozzles on wheels back and forth.

Alenquer drainage basin

The Alenquer drainage basin (Fig. 2) was selected as a test area for this study; it is a medium-sized (120 km^2) drainage

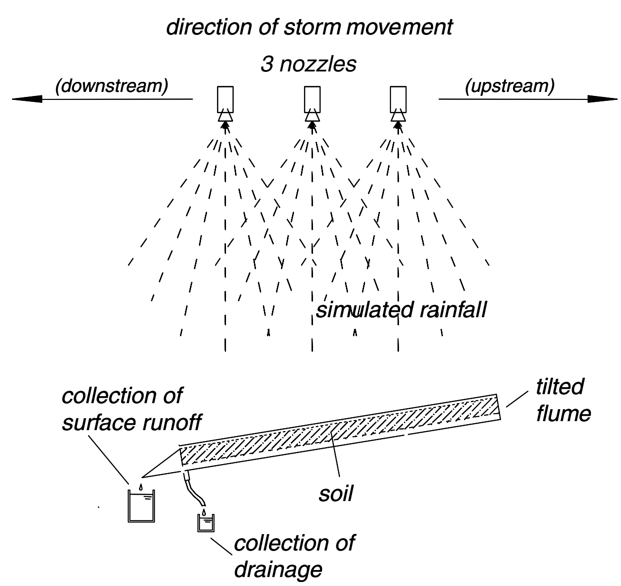

Figure 1 Schematic representation (side view) of soil flume and the nozzles. The storm movement was obtained by moving the support structure of the rainfall simulator at a constant speed. Surface runoff was collected at the end of the flume.

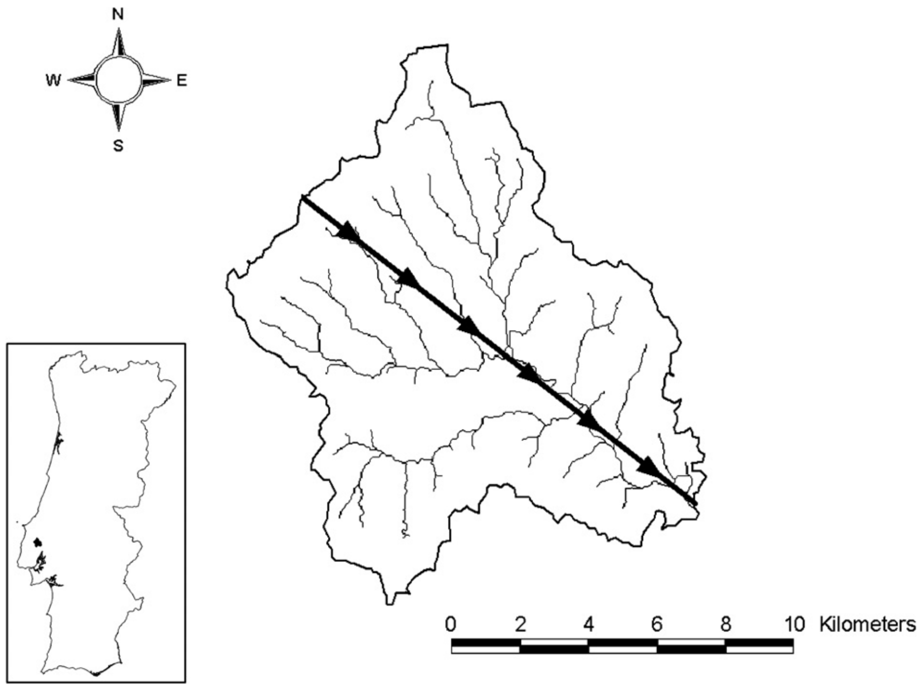

Figure 2 The Alenquer drainage basin and its location in Portugal, with the drainage direction axis superimposed.

basin located near Lisbon, Portugal. The Alenquer River and its tributaries flow from the Montejunto range (360 m) to the wide Tagus valley (30 m); the slope in the basin averages out to be 13%. Soils are generally shallow, mostly Cambisols (50% occupation) and Luvisols (34%). The land use in the drainage area is also diverse, with forest and scrubland in the upper reaches (19% occupation) and agriculture in the rest of the area (42%, mostly cereal cultivation and vineyards), interspersed by abandoned fields (20%, usually bare soil) and urban areas (16%). The rainfall season runs from October to February, when several heavy precipitation events occur. Most of these events are of frontal type, moving eastwards across the watershed.

Numerical model MEFIDIS

MEFIDIS, short for Physically-based Distributed Erosion Model (Nunes and Seixas, 2003; Nunes et al., 2005a,b), is a high-resolution soil erosion model for extreme rainfall events. The model is spatially distributed, dividing the area of simulation into a grid of square cells (30×30 m^2 for the Alenquer basin, which is simulated by a grid with approximately 130,000 cells), each considered homogenous. The channel network is simulated separately from this grid; the location of channels used for this simulation is shown in Fig. 2. Given rainfall data, runoff generation and soil detachment are simulated within each cell; rainfall excess is then routed to the neighboring cells following the steepest slope, transporting sediment in suspension. The process is dynamically iterated using small time steps (3 s for the Alenquer drainage basin) and as simulation progresses, runoff and the detached soil generated in all points within the drainage basin are routed to the outlet. The processes simulated by MEFIDIS are shown schematically in Fig. 3.

Runoff generation and routing are calculated using St. Venant's continuity equation for one-dimensional water flow (Chow et al., 1988)

$$\delta Q/\delta x + \delta A/\delta t = r_i - r_f \tag{1}$$

where Q is the surface flow rate (m^3 s^{-1}), x is the flow length (m), A is the surface flow cross-sectional area (m^2), t is the time (s), r_i is the rainfall rate per unit length of flow (m^3 m^{-1} s^{-1}) and r_f is the infiltration rate per unit length of flow (m^3 m^{-1} s^{-1}).

The model solves this equation using a finite difference approximation by an FTBS (forward-time backwards-space) explicit scheme (Huggins and Burney, 1982). The infiltration rate as a function of time is calculated using the Green-Ampt method (Chow et al., 1988). After the surface retention storage is computed following Linsley et al. (1975), inflow and outflow rates are calculated by a kinematic wave approach, using Manning–Strickler's equation (Chow et al., 1988). MEFIDIS separates channel flow from overland flow in user-defined regions.

Soil erosion is simulated in two parts: soil detachment and sediment transport. Soil detachment occurs as a result of rain splash and overland flow (following Toy et al., 2002). MEFIDIS uses the continuity equation for sediment transport (Foster, 1982)

$$\delta(Q \cdot C_s)/\delta x + \delta(A \cdot C_s)/\delta t = r_s + r_r \tag{2}$$

where C_s is the sediment concentration in the flow (kg m^{-3}), r_s is the sediment delivery from splash erosion per unit length of flow (kg m^{-1} s^{-1}) and r_r is the flow detachment/sedimentation rate per unit length of flow (kg m^{-1} s^{-1}).

This equation is also solved using a finite difference approximation with an FTBS explicit scheme (Foster, 1982). Interrill erosion is considered to occur only due to

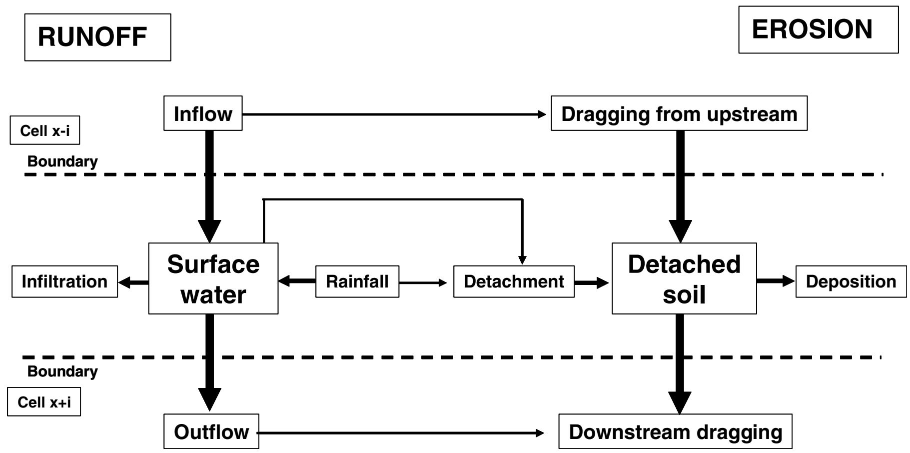

Figure 3 Processes simulated inside each cell and at the cell boundaries by the MEFIDIS model.

rain splash detachment and is calculated following Sharma et al. (1993). Flow detachment and deposition are dependent on the sediment transport capacity of overland flow. When suspended sediment is below the transport capacity, soil detachment occurs; otherwise, suspended sediment deposits over the cell (Govers, 1990). Any sediment remaining in suspension is then routed along with surface runoff.

This description presents a general overview of the MEFIDIS model; a full description can be found in Nunes et al. (2005a,b).

MEFIDIS was applied to the Alenquer drainage basin. Model parameters were derived from altimetry, land use and soil maps for the region, all with a resolution of $30 \times 30\,m^2$. Altimetry was derived from 1/25,000 topographical maps published by the Army Geographical Institute (Portugal). Land use data was acquired by performing a supervised classification (Chuvieco, 1986) on multi-spectral images derived from a winter survey flight using an airborne Daedalus TMS radiometer. 1/50,000 soil maps showing 12 soil classes were provided by the Portuguese Ministry of Agriculture.

Altimetry data was used to map slope and flow directions inside the basin. Land use and soil spatial data were used to map the parameters listed in Table 1. These parameters were calibrated with a series of field rainfall experiments made by using the equipment described by Cerdà (1998). Six sites with different soil types and land uses were selected; for each site, at least two rainfall experiments were performed. Each experiment had rainfall falling during 60 min with $50\,mm\,h^{-1}$ intensity; measurements included antecedent soil moisture, runoff and soil loss. A single-cell version of the MEFIDIS model was run for each experiment and calibrated by adjusting model results to measured values.

Three storms, with characteristics (rainfall depth, duration and maximum 30-min intensity) as shown in Table 2, were selected for model validation. These storms are considered as representative of the range of storm intensities usually observed in this basin, as reported by de Macedo (1996) for the 1981–1994 period. For each storm, antecedent soil moisture maps were estimated from the river base flow and a topographic wetness index using the TOPMODEL approach (Beven, 2000). The results of validation in terms of runoff, peak runoff and net erosion (sediment leaving the basin through the outlet) are shown in Table 2. Results indicate that the model performs satisfactorily within the range of conditions investigated.

Table 1 MEFIDIS land use and soil type parameters and estimation methods and sources

Map	Parameter	Parameterization method/sources
Land use	Manning's roughness coefficient	USDA (1986)
	Vegetation canopy cover	In situ estimates[a]
	Stone/pavement cover	In situ estimates[a]
	Depression storage capacity	Linsley et al. (1975)
	Interception storage capacity	Calculated from leaf area index values (Scurlock et al., 2001) following Hoyningen-Huene (1983)
Soil type	Effective porosity	Cardoso (1965)
	Saturated hydraulic conductivity	Cardoso (1965)
	Suction below the wetting front	Calculated from soil texture (Cardoso, 1965) following Brakensiek (1977)
	Median particle diameter	Calculated from soil texture (Cardoso, 1965) following Bittelli et al. (1999)
	Critical detachment shear stress	In situ measurements (torvane)[a]
	Depth	Cardoso (1965)
	Clay mass fraction	Cardoso (1965)

Parameters were estimated for 8 land use classes and 12 soil types.
[a] In situ observations performed during calibration.

Table 2 Characteristics of natural, uniformly distributed, rainstorms used in model validation for the Alenquer drainage basin (Portugal), and model validation results

		Mar-02	Nov-97	Feb-88
Storm characteristics				
Rainfall (mm)		30.1	47	36
Duration (h)		43.5	15.8	15.5
Maximum 30-min rainfall intensity (mm/h)		5.2	18	8
Validation results				
Runoff (mm)	Simulated	1.16	3.0	9.1
	Measured	1.17	2.7	11.5
Peak runoff rate (mm/h)	Simulated	0.06	0.69	1.87
	Measured	0.04	0.66	1.98
Net erosion (ton/ha)	Simulated	0.004	0.058	0.45
	Estimated	0.005	0.050	0.44
Comparison between simulated and measured hydrographs	r^2	0.86	0.90	0.83
	Average unsigned error (mm/h)	0.003	0.03	0.17
	Nash-Sutcliffe efficiency index[a]	0.86	0.88	0.80

Rainfall was measured by the Portuguese Water Institute at the center of the basin. Runoff and peak runoff were measured at the outlet. Net erosion was estimated using a sediment/discharge curve calculated from existing runoff and suspended sediment measurements at the outlet ($r^2 = 0.76$, $p < 0.01$).

[a] Beven (2000).

Methodology

Storms, runoff and soil loss on the laboratory flume

Rainstorms moving upstream and downstream with a constant speed were simulated over a laboratory soil flume. The storm movement was obtained by moving, on wheels, the support structure of the nozzles over the flume. This was accomplished with the help of electric motors. The wheels followed tracks, as illustrated in de Lima et al. (2003).

The distribution of rainfall intensity supplied by the rainfall simulator (static) on a horizontal surface is presented in Fig. 4. As in natural spatial rainfall fields, a high intensity rainfall area was embedded within areas of lower intensity, as described by Sivapalan and Wood (1986) and Willems (2001), among others. The average storm intensity was 3.24 mm/min and the total length of the storm (length of water application) was 5.3 m. It should be noted that in these experiments the length of the moving storm is larger than the length of the flume (3 m long). The rainfall intensity was assumed constant across the width of the flume (0.3 m width).

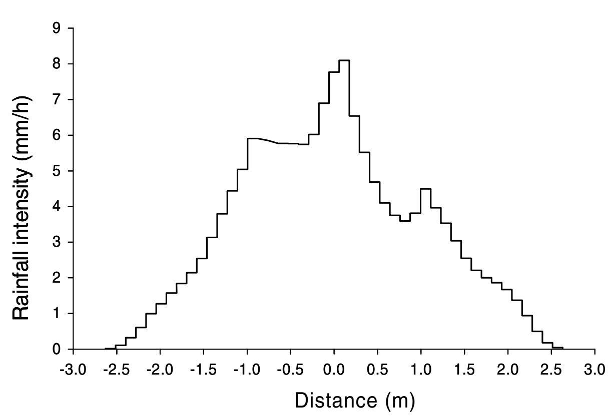

Figure 4 Rainfall intensity (mm/min) under the three nozzles (see sketch presented in Fig. 1). The horizontal axis represents the horizontal distance from the vertical containing the central nozzle.

Before starting the experimental runs, the soil was wetted up to field capacity to approximately attain the same initial moisture condition in the superficial layer of the soil for every rainstorm event. The volumetric soil water content was approximately 20% (determined by Time-Domain-Reflectometer measurements) just before the start of the storm events.

Overland flow and sediment loss caused by each rainfall event were measured by collecting samples every 10 s in metal containers placed at the bottom end of the soil flume. The measurement starting-time for each storm event corresponded to the initiation of overland flow at the outlet of the flume. The simulated rainstorms were conducted under free-draining conditions. The amount of sediment transported by overland flow was estimated by low-temperature oven-drying of the runoff samples. The data obtained under controlled laboratory conditions were used to test the numerical model MEFIDIS.

Storms, runoff and soil loss on the Alenquer drainage basin

Simulation in the Alenquer drainage basin involved nine storms combining different areal extents (diameters) and movement speeds (Table 3). The selection of the storm diameters (circular shaped storms) took into consideration

Table 3 Characteristics of the nine test storms simulated for the Alenquer drainage basin (Portugal) study

	Description (size/speed)	Diameter (km)	Speed (m/s)	Intensity (mm/h)
LF	Large/fast	30.4[a]	2	12.1
LM	Large/medium		1	6.1
LS	Large/slow		0.5	3.0
MF	Medium/fast	15.2	2	26.1
MM	Medium/medium		1	13.0
MS	Medium/slow		0.5	6.5
SF	Small/fast	7.6[b]	2	74.1
SM	Small/medium		1	37.1
SS	Small/slow		0.5	18.5

[a] Doubles the basin axial length.
[b] Halves the basin axial length.

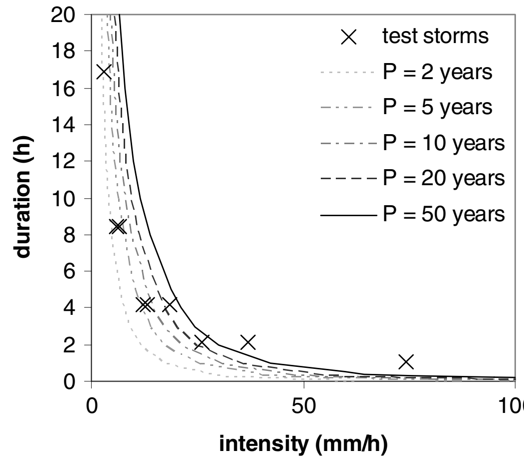

Figure 6 Frequency of test storms; IDF curves for S. Julião do Tojal, near Alenquer drainage basin (Portugal), determined by Brandão et al. (2001) (P = return period).

the axial length of the Alenquer drainage basin (15.2 km; see Figs. 2 and 5; and Table 3). Within the areal extent and for the duration of each storm, rainfall intensity was maintained constant at the rates shown in Table 3. Three storm speeds were selected (0.5, 1 and 2 m/s). In order to make the storms comparable, the total rainfall depth over the basin was maintained constant at 50 mm by varying the storm intensity according to storm area and speed (de Lima and Singh, 2002). MEFIDIS was run for each storm type, with the storm's centre moving both downstream and upstream along the basin's axis (Fig. 5).

For each case, the storm intensity was determined from the basin area under rainfall (calculated using a GIS) and from the storm duration (dependent on the storm movement speed and storm diameter). The test storms can be considered as representative of a number of possible atmospheric and hydrologic conditions over the Alenquer drainage basin, associated with various return periods. Fig. 6 presents the Intensity–Duration–Frequency curves available for the Alenquer drainage basin; most storms used (also represented in Fig. 6) fall between the 2-year and the 50-year return period range.

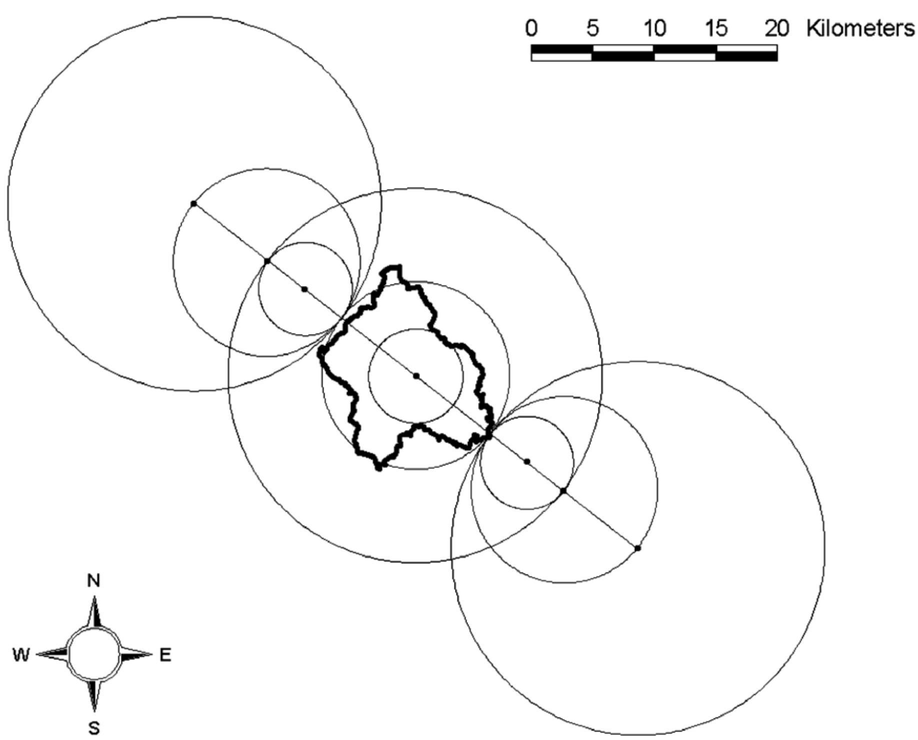

Figure 5 Spatial extent of test storms (0.5, 1 and 2 times the basin axial length). Circumferences in the upper left and lower right show the beginning and the end of storm movement over the basin axis which is represented by the diagonal line.

Results and discussion

Soil erosion and runoff at the flume scale

Experimental runs were carried out for rainstorms moving over the soil flume at different speeds. For each storm speed tested there were storms moving upstream and storms moving downstream. These pairs of simulated rain events had equal precipitation depth, duration and drop size distribution. The Hortonian overland flow occurred on the flume when the rain intensity exceeded the infiltration rate. The transport of fine erodible soil material was mainly due to overland flow.

Analysis of the overland flow hydrographs and of the evolution of sediment transport during the runoff events showed distinct hydrologic responses for storms moving in different directions. Fig. 7 presents runoff hydrographs and Fig. 8 the respective evolution of soil loss obtained for a storm speed of 0.12 m/s, both for downstream and upstream moving rainstorms. These results show significant differences in runoff and soil loss between identical simulated rainstorms moving downstream and upstream. Downstream moving storms yielded higher soil loss than did upstream moving storms. A similar behaviour was observed for other speeds.

Comparison of MEFIDIS results with laboratory data

MEFIDIS was used to simulate the processes of runoff and sediment loss involved in the laboratory experiments described above. The objective was to determine the model's ability in simulating the effect of storm movement over conditions analogous to a single hill slope. The experimental set-up, simulated by the model as a one-dimensional slope, was divided into ten $0.3 \times 0.3\ m^2$ cells; the moving storm intensity pattern shown in Fig. 4 was also taken into account. Figs. 7 and 8 show the model performance for both runoff and accumulated soil loss for a storm moving at 0.12 m/s. Although the results for sediment discharge rates were not very good, the results do show that MEFIDIS was able to adequately simulate the differences between storms moving upslope and downslope over the soil flume. While the experimental set-up is considerably less complex than an actual drainage basin, this comparison demonstrated the model's ability to simulate the consequences of storm movement over smaller-scale components such as single hillslopes.

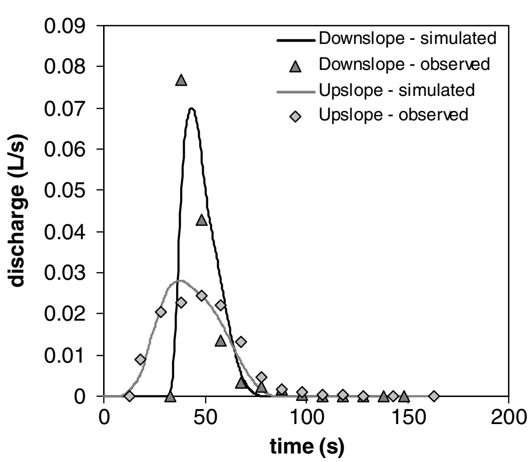

Figure 7 Numerical simulation (continuous line) and observed (laboratory data measured in soil flume) runoff hydrographs for downstream and upstream moving storms, for the 10% surface slope, for 0.12 m/s storm speed, and for the rainfall intensity shown in Fig. 4.

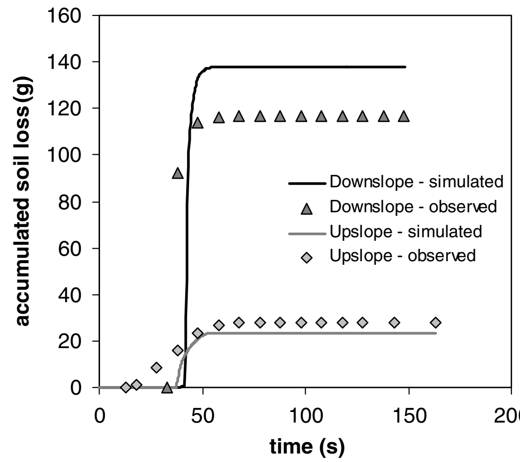

Figure 8 Numerical simulation (continuous line) and observed (laboratory data measured in soil flume) accumulated sediment loss results for downstream and upstream moving simulated storms, for the 10% surface slope, for 0.12 m/s storm speeds, and for the rainfall intensity shown in Fig. 2.

Modeling soil erosion and runoff by MEFIDIS at the basin scale

MEFIDIS was used to simulate the test storms, described in Table 3, moving over the Alenquer drainage basin. The storms were simulated in pairs: one storm moving downstream and another upstream, along the basin's axis. In total, 18 model runs were undertaken. Table 4 summarizes the results; ''gross erosion'' should be understood as the amount of soil detached by rain splash and overland flow, without deposition (Foster, 1982), while ''net erosion'' should be understood as the basin's sediment export, equaling the gross erosion minus deposition.

Overall, the downstream storm movement generated greater peak runoff rates and more net erosion than did the upstream storm movement (Fig. 9). When comparing the consequences of upstream- and downstream-moving storms by peak runoff rates increased on average by 56.5% (16.8–78.3%) and the net erosion rates increased on average by 9.1% (0–21.7%, with significant increases in smaller and faster storms only).

The results were less significant for total runoff, which increased on average by 2.4% (0.8–5.1%). Gross erosion was in most cases not significantly affected by storm movement, and in some cases increased slightly with upstream-moving storms (0.5%). occurred These results contrast with those found in laboratory experiments (Figs. 7 and 8). One possible explanation stems from the fact that runoff generation and gross erosion, as defined above, are processes that occur on hill slopes. In a spatially complex basin, such

Table 4 Summary of all simulation results for all tests conducted in the Alenquer drainage basin (Portugal); runoff and net erosion are for the basin's outlet

Test	Direction	Runoff (mm)	Peak runoff (mm/h)	Net erosion (ton/ha)	Gross erosion (ton/ha)
LF	Downstream	5.1	1.92	0.21	0.49
	Upstream	4.9	1.20	0.19	0.50
LM	Downstream	2.1	0.35	0.017	0.056
	Upstream	2.0	0.25	0.016	0.057
LS	Downstream	1.54	0.11	0.004	0.009
	Upstream	1.49	0.09	0.003	0.009
MF	Downstream	8.5	4.9	0.8	1.4
	Upstream	8.4	2.8	0.7	1.4
MM	Downstream	5.9	2.0	0.29	0.59
	Upstream	5.7	1.1	0.25	0.60
MS	Downstream	2.4	0.39	0.027	0.079
	Upstream	2.3	0.26	0.027	0.079
SF	Downstream	20.9	14.4	2.0	2.4
	Upstream	20.7	8.1	1.9	2.4
SM	Downstream	17.3	6.4	1.2	1.5
	Upstream	17.1	4.0	1.1	1.5
SS	Downstream	12.0	2.4	0.5	0.6
	Upstream	11.8	1.6	0.4	0.6

For nomenclature see also Table 3.

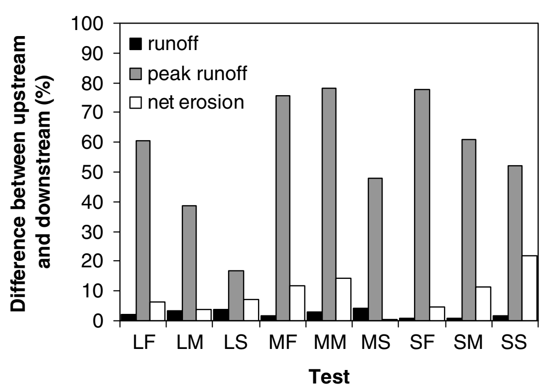

Figure 9 Relative difference between the results for upstream and downstream storm movements shown in Table 4; positive values indicate that the results increase with downstream movement.

as Alenquer, hillslope direction is not uniform; hillslopes face all possible directions, and the water lines (where most of the concentrated flow erosion occurs) change directions several times, therefore reducing or even cancelling the effects of storm movement. Furthermore, several other factors affect the spatial variability of total runoff and gross erosion inside a basin, such as the spatial distribution of vegetation and soil properties (Foster, 1982), and their importance could be much more significant than the relationship between hill slope orientation and the storm movement direction.

One possible explanation for the difference between the impact of storm movement on slope processes (runoff generation and gross erosion) and basin-scale processes (peak runoff rate and net erosion) is the scale difference itself. At the basin scale, the positioning of different tributary basins along the main channel appears to be more important than slope orientation. This statement can be exemplified with an analysis of Fig. 10, which shows an example of the simulated hydrographs for the medium/medium test (as defined in Table 3) calculated for several cross-sections of the drainage network. Some conclusions can be taken from the figure:

- There is a clear delay of the starting time of the hydrograph, especially in the upstream water courses of the basin as expected; downstream moving storms are associated with faster hydrological responses than are upstream moving storms.
- Peak flows in the main river and in the tributaries are higher for downstream moving storms than are for upstream moving storms. This can be partly explained by the layout of the drainage network: the water courses are all positioned approximately in the direction of the movement of the storms.
- In the main river and in the tributaries, the rising limb of the hydrograph is steeper for downstream moving storms.
- At the outlet of the main stream, upstream moving storm hydrographs have an earlier rise than do corresponding downstream moving storm hydrographs as expected. The different behavior observed for some upstream sub-basins is due to the relative position of these basins

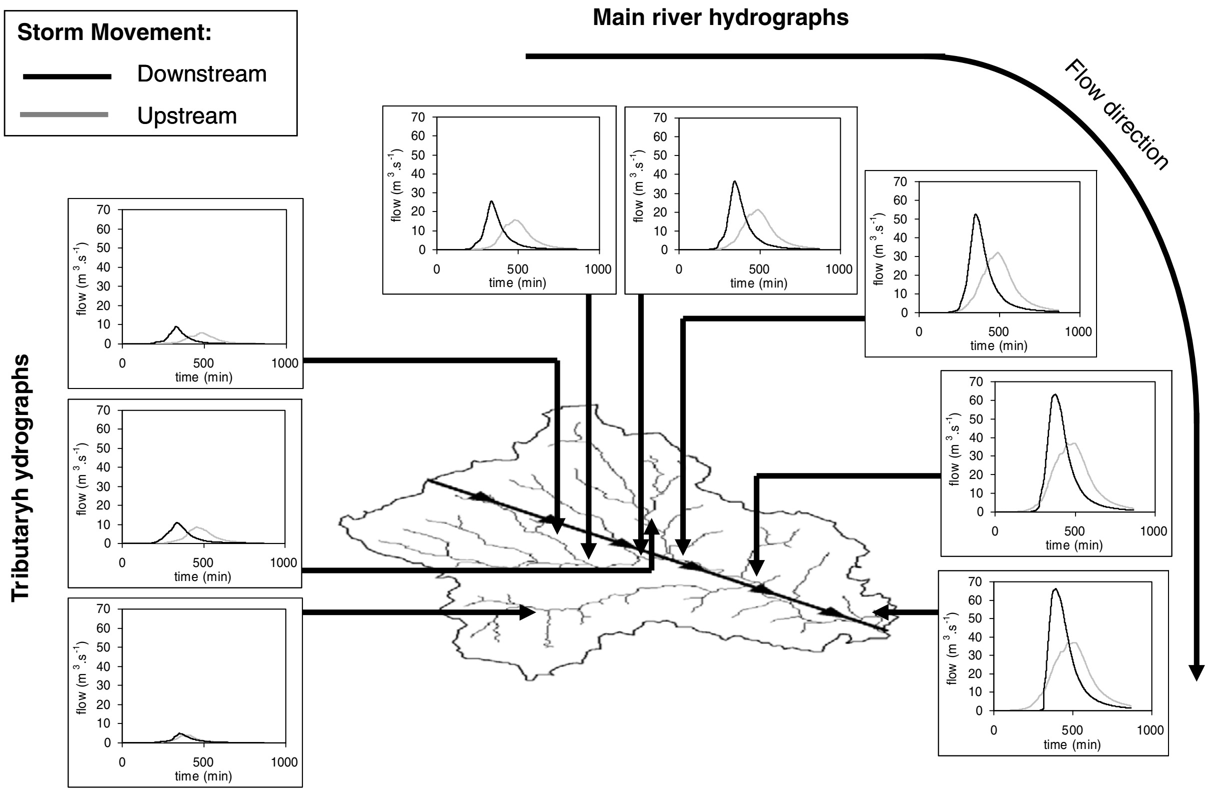

Figure 10 Simulated hydrographs for several sections in the Alenquer river (right) and its tributaries (left) for test medium/medium, for both downstream and upstream storm movements. See also Table 3.

with respect to the outlet (it should be noted that for upstream moving storms, time starts when the storm enters the Alenquer basin near the outlet).

- The difference between peak flows for upstream and downstream moving storms increases along the river's length. This indicates that when storms move downstream, a ''cascade effect'' of tributaries discharging runoff in the main river could be responsible for these differences in peak flows.

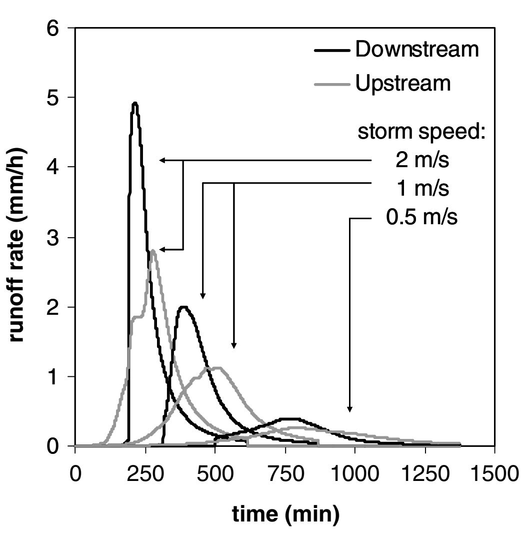

Figure 11 Simulated hydrographs at the Alenquer basin's outlet for tests medium/fast (left), medium/medium (center) and medium/slow (right), for both downstream and upstream movements. See also Table 3.

The ''cascade'' effect of runoff discharging from tributaries was observed in all other tests and therefore appears to be the most likely reason for the differences in peak runoff rates shown in Table 4 and Fig. 9. Also, in all tests the outlet hydrographs showed larger flow peaks with a steeper rising limb for downstream moving storms, although the storm size and speed influenced the magnitude of the differences; Fig. 11 exemplifies these differences for the medium-sized

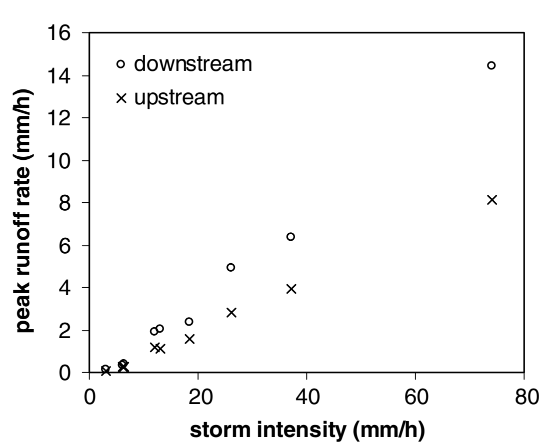

Figure 12 Simulated peak runoff rate at the Alenquer basin's outlet as a function of storm intensity, for all 18 tests.

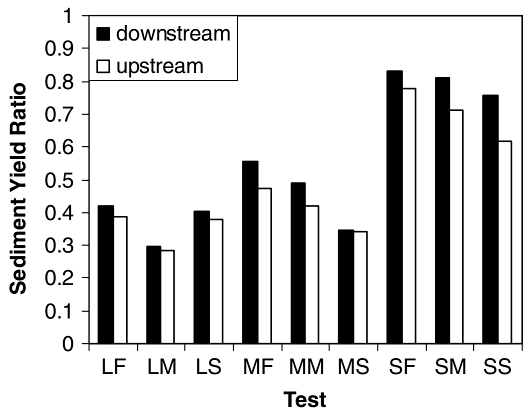

Figure 13 Sediment yield ratio (net erosion/gross erosion) for downstream and upstream storm movements. See also Table 3.

storms (tests MF, MM and MS). The hydrologic behavior is similar to the ones observed in the laboratory tests (Fig. 7), although less pronounced, and follows the theoretical expectations (e.g., Singh, 1998; de Lima and Singh, 2002).

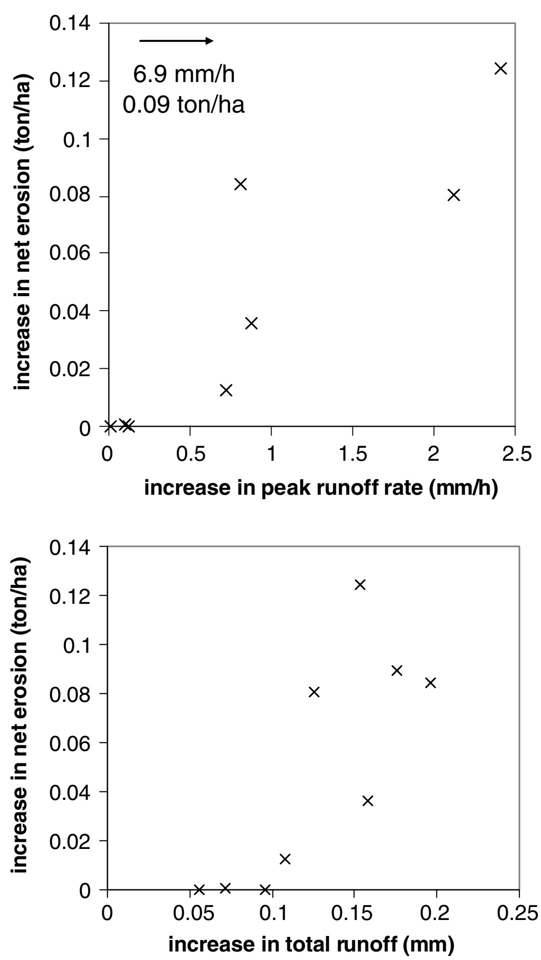

Figure 14 Net erosion increase with downstream storm movement, in the Alenquer basin, for all 18 tests, correlated with the increase in peak runoff rates (above) and total runoff (below); the arrow in the upper figure indicates the position of one outlying value.

Fig. 9 shows some consequences of storm size and movement speed on the peak runoff rate difference, which increases both with increasing storm speed and decreasing storm size. Since the smaller and faster storms used in the tests had larger intensities (Table 3), this result points to a correlation between storm intensity and the difference in peak runoff rates; this correlation can also be seen in Fig. 12.

The impact of storm movement direction on net erosion appears to be a direct consequence of the impact in peak flow rates, through an increase of the sediment yield ratio (defined as net erosion/gross erosion); Fig. 13 shows that the sediment yield increases with downstream movement for every test. One possible explanation is the fact that the larger peak runoff rates in downstream-moving storms increase the sediment transport capacity of the main river and its tributaries (Govers, 1990), thereby reducing sedimentation in the channel bed. In other words, more of the sediment eroded in the upland is exported from the basin. Another possible explanation is the increase in total runoff for downstream-moving storms; albeit it is small (as referred to above), the flow generated upslope travels towards the basin outlet, reducing the likelihood of soil eroded in upslope areas depositing in the lower bottom of the slopes (Favis-Mortlock et al., 2001). Fig. 14 shows that both these processes appear to contribute to the increase in the net erosion.

Conclusions

The results of the present study show that the storm movement significantly affects runoff and water erosion processes at both small (laboratory plot) scale and basin scale, although through different processes. Both the laboratory experiments and the numerical modeling with MEFIDIS at the small-scale basin of Alenquer show that the soil loss is clearly linked with the characteristics of runoff hydrographs resulting from rainstorms moving in the upstream and downstream directions.

The following main conclusions can be drawn:

1. Rainfall intensity patterns induced by moving storms, whatever the direction they may have, influence the characteristics of runoff and soil erosion. Downstream storm movement is potentially more hazardous in terms of peak flow discharges or sediment yield.
2. Storm movement is more likely to affect peak flow than the total surface runoff production. The effect of storm movement on peak flow increases with storm intensity. This may have serious repercussions on the impact of extreme flood events.
3. During downstream moving storms, river flow rates rise at a faster pace and peak flow occurs earlier than during storms moving in other directions.
4. For the same speed and approximately the same runoff volume, downstream moving storms yield larger quantities of net erosion than do upstream moving storms. This is not due to an increase in upland erosion; rather, it is due to a decrease of sedimentation rates within the main channels.
5. Further investigation of these processes will require detailed monitoring of the movement of storms (e.g., wind direction, rain patterns) which, combined with data

on flow rates and sediment transport on water courses, could allow a better view of the complex interactions involved between movement direction and the spatial variability within the drainage basin.

Acknowledgments

The first author, a doctoral research fellow, acknowledges the support given by the Foundation for Science and Technology of the Portuguese Ministry of Science and Higher Education, Lisbon, Portugal and the European Union under Operational Program ''Science, Technology and Innovation'' (POCTI), Ph.D. grant ref. SFRH/BD/5059/2001, inserted in the IIIrd Community Support Framework (2000—2006).

The laboratory experiments described were conducted in the Department of Civil Engineering of the Faculty of Science and Technology of the University of Coimbra (Portugal), in 2002, which were funded by the Foundation for Science and Technology (Research Project FCT — POCTI/MGS/35661/2000) of the Portuguese Ministry of Science and Higher Education, Lisbon, Portugal, within the Programme POCTI.

MEFIDIS was developed in the Environmental Systems Analysis Group (GASA) of the Faculty of Sciences and Technology, New University of Lisbon (FCT/UNL). The Environmental and Water Resources Systems research group of Cornell University has cooperated in this research. Development of MEFIDIS was partially funded by the Ministry of Science and Technology (MCT) and the General-Directorate for the Environment (DGA).

This study was also partly funded by the Foundation for Science and Technology through the research Projects: POCTI/AGG/38957/2001 and POCTI/MGS/39039/2001 of the Foundation for Science and Technology of the Portuguese Ministry of Science and Higher Education, Lisbon, Portugal.

Finally, the authors thank two anonymous reviewers for their important contributions to the improvement of this article.

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