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Catena 46 (2001) 177–188

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Hillslope topographic and hydrologic effects on overland flow and erosion ☆

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Abstract

Variability in surface condition occurs at different spatial and temporal scales. Locally, surface conditions interact with soil components and determine the dynamic of surface sealing, biomass, and roughness. At the hillslope scale, conditions at the surface vary with the topographic position that can cause different hydrologic regimes and erosion. This paper presents our efforts in quantifying how hillslope position and moisture condition affected runoff generation and sediment production. In the field, we monitored runoff and sediment productions from a hillslope under natural conditions. Sediment production under seepage condition was quantified in a laboratory dual-box system under simulated rainfall. Field results showed that variability in runoff and sediment production could be attributed to topographically induced and localized surface variations in addition to seasonal changes in rainfall pattern and crop canopy. Based on rainfall pattern and changes in surface conditions, three different stages of runoff and sediment productions were identified in an annual cycle. Laboratory experiments in soil moisture gradient (i.e., seepage vs. drainage) effects on erosion showed that drainage conditions limited sediment detachment while seepage conditions enhanced rilling. These results showed a close linkage between surface moisture condition and erosion process, and consequently, the dominant sediment regime. These different methodologies improved the understanding of runoff and erosion processes occurring at the hillslope and the role of topographic position and hydrology on these processes. Published by Elsevier Science B.V.

Keywords: Soil erosion; Topographic position; Runoff; Sediment; Spatial and temporal variability

☆ This paper is dedicated to our colleague, Ms. Sylvie Cros-Cayot, who contributed significantly to the field study at Rennes; unfortunately, she could not see the fruition of her work.

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0341-8162/01/$ - see front matter. Published by Elsevier Science B.V.
PII: S0341-8162(01)00165-5

1. Introduction

Runoff and sediment productions from a hillslope segment are highly variable, both spatially and temporally. This variability is resulted from differences in surface conditions ranging from catchment to local scales as well as from the changing seasonal rainfall and crop growth patterns. Auzet et al. (1995) showed a close correlation between runoff contributing area and conditions of the surface in the catchment and demonstrated the time dependent interactions among climatic (i.e., rainfall and dry period), crop growth and timing of agricultural operations that either compacted or loosened the surface soil. Specific surface factors found to affect runoff and erosion were stages of crust development, distribution of wheel tracks, and roughness in the direction of tillage operations (Auzet et al., 1995).

Topographic and hydrologic factors that affect runoff generation have been extensively documented in the literature, e.g., Dunne, 1978. A conceptual model which incorporates interactions among hillslope position, hydrologic condition and erosion process is illustrated in Fig. 1. The underlying assumption that we seek to demonstrate is the close linkage between topographically induced surface hydrologic condition and dominant runoff and erosion processes. In addition topographic factors, erosion may be highly variable due to climatic and pedologic conditions. For example, profile drainage may dominate near the summit through the upper backslope. At these locations, the small amount of surface flow from upslope contributing areas leads to interrill-dominated processes. At locations further downslope, the increased runoff from upslope contributing areas enhances flow concentration, hence rill erosion processes. Near the toe of the

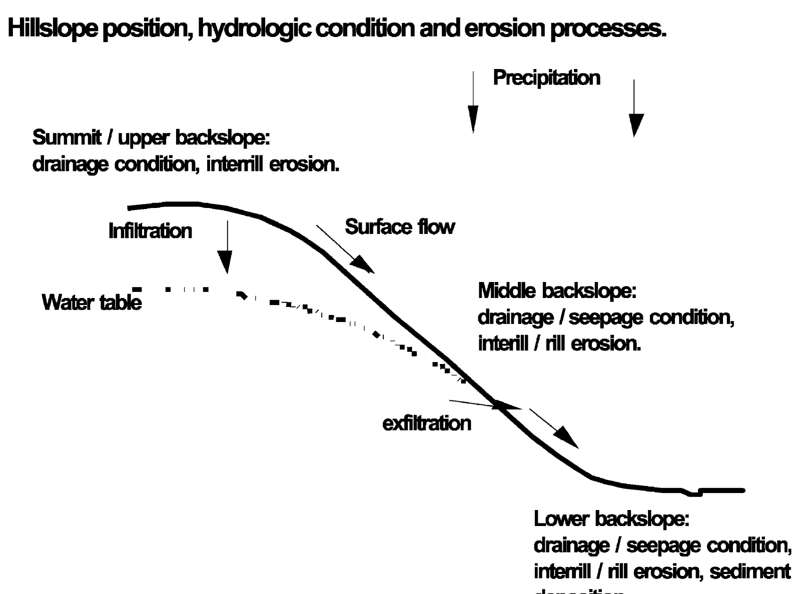

Fig. 1. Conceptual hillslope model showing interactions between hillslope position, hydrologic condition and erosion processes.

slope, seepage may occur during the wet season. In fact, seepage-induced rills and gullies were observed in fields with an impeding layer during periods of excessive soil moisture and the seepage effects had been quantified in laboratory studies (Huang and Laflen, 1996; Gabbard et al., 1998)

Measurements of runoff and erosion are frequently measured from field plots which do not consider the inherent topographic and surface hydrologic effects in runoff initiation and sediment production. Therefore, these plot data cannot be extrapolated to quantify hillslope scale processes that could be significantly affected by the topographic and hydrologic variations. In order to develop a process-based erosion prediction model, we need to understand relationships between surface condition and processes of runoff and sediment production at different spatial and temporal scales. For example, changes in slope steepness and soil properties can affect runoff and sediment production and their subsequent redistribution on the hillslope, resulting in runoff production from a small area but not from a large scale hillslope (Cros-Cayot, 1996; Gascuel-Odoux et al., 1996).

The assessment of variations of sheet flow and erosion is limited in the literature due to difficulties of acquiring quality data in both spatial and temporal scales. On the other hand, significant efforts have been invested into the development and validation of process-based erosion prediction models that can predict runoff and erosion in various spatial and temporal scales (Nearing et al., 1989). One major difficulty to test these erosion process models is the lack of proper experimental data representative for the same scales as that of the prediction model. Erosion data are mostly collected as total sediment delivery at the outlet, representing integral quantities that have been integrated over space and time. Since it is very difficult to make measurements in a small unit area on the soil surface during the rainfall event in a true differential sense, two possible alternatives are to actually measure sediment deliveries at different spatial and temporal scales in the field and to conduct laboratory rainfall simulation studies on a dual-box system.

This paper addresses spatial and temporal variability in runoff and erosion processes caused by topographic and hydrological variations. Research efforts included monitoring natural runoff and sediment production in the field at different hillslope positions and recreating specific surface hydrologic conditions in a controlled laboratory setting. Sediment delivery, Qs, collected form a laboratory dual-box system or from field plots covering different slope lengths can be used to study how Qs varied along the runoff route. This data set can then be used to approximate the spatial distribution of erosion and deposition at the hillslope. These approaches provide a basic framework toward the understanding of hillslope scale erosion processes that would eventually be used to build a physically based erosion prediction model.

2. Materials and methods

2.1. Field study under natural hillslope conditions

The field study site was located near Rennes in western France. The soil is loamy (distric and aquic eutrochrepts) and well drained. The study is situated in a gentle slope.

After a short flat summit sloping at 2%, there is a midslope section approximately 200 m long sloping at 4.5% and gradually changing to 1.5% in the last 50 m, resulting in a slightly convex–concave downslope element. The soils are fairly homogeneous. Some weak hydromorphic features occur in the plough layer in the lowest part of the field, presumably caused by ephemeral saturation. Slight variations in soil constituents are also observed. Silt content decreases from 72% on the hillslope to 69% on the footslope. Clay content and organic matter are slightly greater on the toeslope, increasing from 15% and 1.65% on the hillslope to 17% and 2.25% on the toeslope, respectively. The soil is structurally weak. The study field had been in maize for silage with rows directly downslope. Maize was planted at the beginning of May and harvested in November. There was no autumn tillage operation. The field remained bare through winter months until next April when the soil was tilled for planting.

The experimental design consists of a network of fifteen plots with collectors that allow easy runoff and sediment transport measurements. The field was ridged at approximately 0.75 m spacing and the crop rows were oriented up and down the slope. We installed the runoff collectors in the crop rows to intercept overland flow from one row. Each collector was connected to a 60-l container. These runoff collectors were installed at five topographic positions, i.e., summit, shoulder, midslope, footslope and toeslope with three replicates at each hillslope location (Fig. 2). The upslope contributing area was delimited by the upslope limit of the field and the two parallel ridges. Slope lengths at these five topographic positions, measured from the upslope boundary, were approximately 52, 107, 166, 218 and 270 m. Detailed descriptions of the field site, collector placement and runoff collection procedure were given by Cros-Cayot (1996) and Gascuel-Odoux et al. (1996).

These runoff plots were monitored for 1 year, from April to April. Total runoff and sediment were measured after each rainfall event when the rainfall amount was greater than 4 mm. We have neglected those data when the rainfall was less than 4 mm because of its low or nil runoff values. Certain large events caused the collector to overflow, hence, the runoff and sediment production from these events were underestimated. Therefore, we performed a semi-quantitative analysis on the field data based on three class intervals: <1 l, 1 to 60 l and >60 l (when the collector overflowed). The relative frequencies of the three-class intervals were compared for the five slope positions.

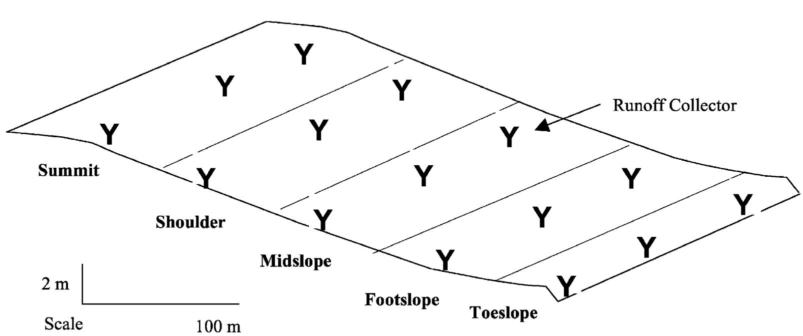

Fig. 2. Distribution of runoff collectors for studying the spatial and temporal variation of overland flow and erosion under natural hillslope conditions.

2.2. Laboratory study under controlled soil moisture regimes

The laboratory study was conducted on a dual-box system consisting of a 5-m-long test box and a 1.8-m-long feeder box (Fig. 3). Both boxes are 1.2-m wide and 0.3-m deep. The feeder box is positioned upslope from the test box. These two boxes can be connected such that sediment from the feeder box can be fed to the upper-end of the test box. When disconnected, runoff samples can be collected separately from each box. The connection and disconnection can be done quickly, i.e., in 10–15 s, without stopping the rain.

Both boxes have watering/drainage ports at the bottom for setting seepage or drainage conditions. The drainage condition is set when the ports are open to allow water to free drain from the boxes. The seepage condition is created when all the ports are connected by tubes to a water circulating system which maintains a constant hydrostatic pressure above the soil surface and forces the water to flow upward and exit at the surface. A detailed description of the water circulation system is given by Gabbard et al. (1998). In this study, the seepage condition was applied with a 20-cm hydrostatic pressure above the soil surface.

The experiment was conducted on a Cincinnati silt loam soil. During this experiment, the feeder box was free drained and set to 10% slope. The test box was set to 5% slope and under either 20-cm seepage pressure or free drainage condition. The rainfall intensity on the test box varied form 25 to 150 mm h^{-1} while the intensity at the feeder box remained constant at 150 mm h^{-1}.

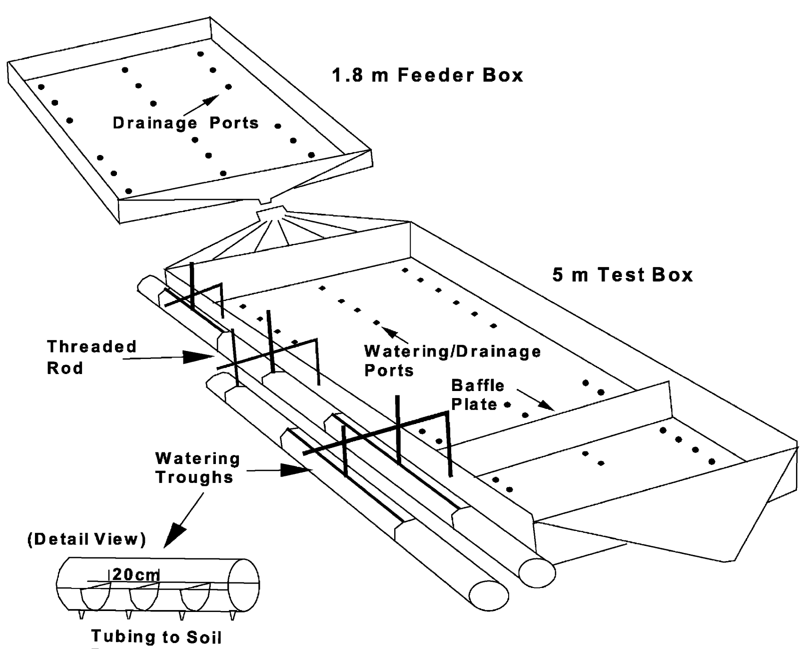

Fig. 3. Schematic diagram of the dual-box system.

During the run, runoff samples were collected from both boxes disconnected first. Then, the connection was made and runoff samples were collected from the test box with feeder input. After sampling with the two boxes connected, the connecting piece was removed and two additional samples were collected from each box separately. These two final samples were used to account for the temporal change of the sediment delivery as the surface was being eroded. The sequence of connection and disconnection allows us to identify sediment mass balance scenarios. Let Q_F represent the sediment from the feeder box, Q_{Td} the sediment from the test box without feeder input and Q_{Tc} the sediment from the test box with feeder input. Depending on the magnitude of Q_{Tc}, relative to Q_{Td} and Q_F, there are five possible process scenarios on the test box (Huang et al., 1999):

Scenario 1	$Q_{Tc} < Q_F$	net deposition or deposition > erosion
Scenario 2	$Q_{Tc} = Q_F$	equilibrium or deposition = erosion
Scenario 3	$Q_F < Q_{Tc} < Q_F + Q_{Td}$	net erosion or erosion > deposition
Scenario 4	$Q_{Tc} = Q_F + Q_{Td}$	net erosion, no runon sediment effect
Scenario 5	$Q_{Tc} > Q_F + Q_{Td}$	additional erosion from runon water

These different sediment process scenarios are based on the dynamic balance of three simultaneous processes: detachment, deposition and transport. Changes from Scenario 1 to 5 indicate the shift in the dynamic balance from a deposition-dominated (Scenario 1) to detachment-dominated (Scenario 3) and finally a transport-dominated (Scenario 5) process regime. The transport-dominated sediment regime occurs, as to be illustrated later, when the soil has little resistance against erosive forces and can be detached easily. Consequently, the sediment delivery is controlled by the transport capacity of the flow. These different mass balance scenarios help us to understand processes occurring in a hillslope segment receiving run-on water and sediment from upslope areas.

3. Results and discussion

3.1. Runoff and sediment regimes under natural conditions

During the sampling year, a total of 42 rainfall events were monitored, ranging from 4 to 35 mm in precipitation and from 1 to 14.5 mm h^{-1} in mean hourly intensity. The field did not show any sign of surface rilling.

Total runoff and sediment productions, averaged over three replicates, at the five hillslope locations for two periods, May to September (late spring–summer) and October to April (fall–winter–early spring), were illustrated in Fig. 4. Both runoff and sediment productions during the winter months showed a slight increasing trend toward the

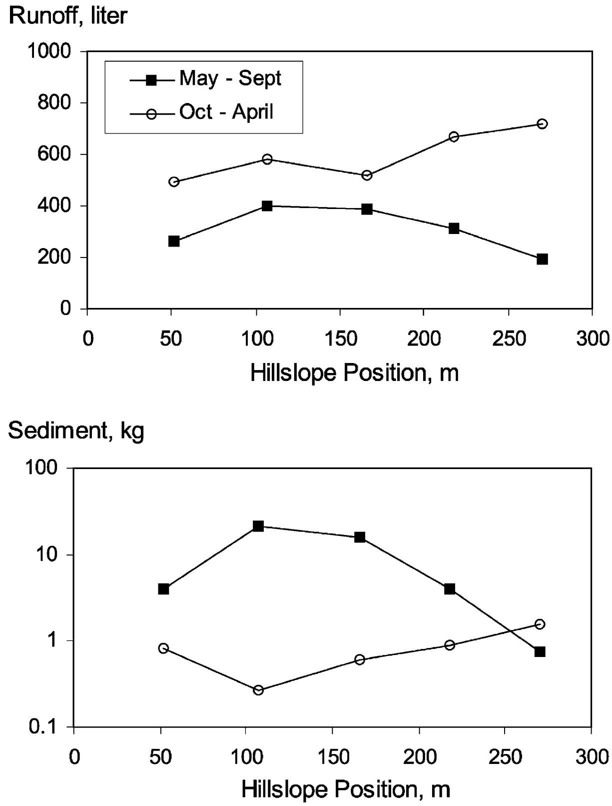

Fig. 4. Average runoff and sediment productions at different hillslope positions, measured from the upper boundary, for two periods: May to September and October to April.

bottom of the hillslope. In summer months, runoff and sediment productions were greater at the shoulder and mid-slope section where the slope was relatively steep and convex in shape. Deposition near the foot- and toeslope sections caused a very low net sediment delivery.

Runoff data were further analyzed for individual storms according to three proposed runoff class intervals: < 1, from 1 to 60, and > 60 l, corresponding to no runoff, small and local runoff, and high hillslope runoff, respectively. Four sediment concentration levels were used in this analysis: < 1, from 1 to 10, from 10 to 50, and > 50 g l^{-1}. The 42 rainstorms were decomposed into three stages of 7, 9 and 26 events, respectively, according to soil surface and climatic conditions. The first two stages corresponded to more frequent heavy spring and summer storm events on dry soil conditions but differed from each another by soil conditions. During the first stage, the surface crust was developing and a sedimentary crust was well developed during the second stage. The third stage corresponded to the fall–winter rainy period and wet soil conditions. The relative contribution of each class interval was computed for each slope position and for a group of rains that implicitly took into account the natural variability of the rains for a given period and soil conditions. Relative contributions of different runoff and erosion intensities were summarized in Fig. 5.

During the first stage that corresponded to soil crust development from spring planting to early summer, sheet flow was low and restricted to the upslope region. The degree of crust development depended on soil constituents that vary slightly with landscape position. Large aggregates were clearly visible at the lower portion of the hillslope, i.e., from footslope to toeslope, where runoff was low. At upslope locations with higher runoff, structural and depositional crusts developed in depressions and along flow pathways. During this period, the soil erodibility was high, but a high soil roughness and infiltrability limited runoff and sediment production. During the second stage which last up to crop harvesting, the soil was dry and well crusted at the surface. Heavy rainfall events induced sheet flow and sediment transport from the upslope to the footslope. A similar spatial distribution as the first stage, high at portions of high slope gradients and decreasing downslope, was observed but at a much higher intensity.

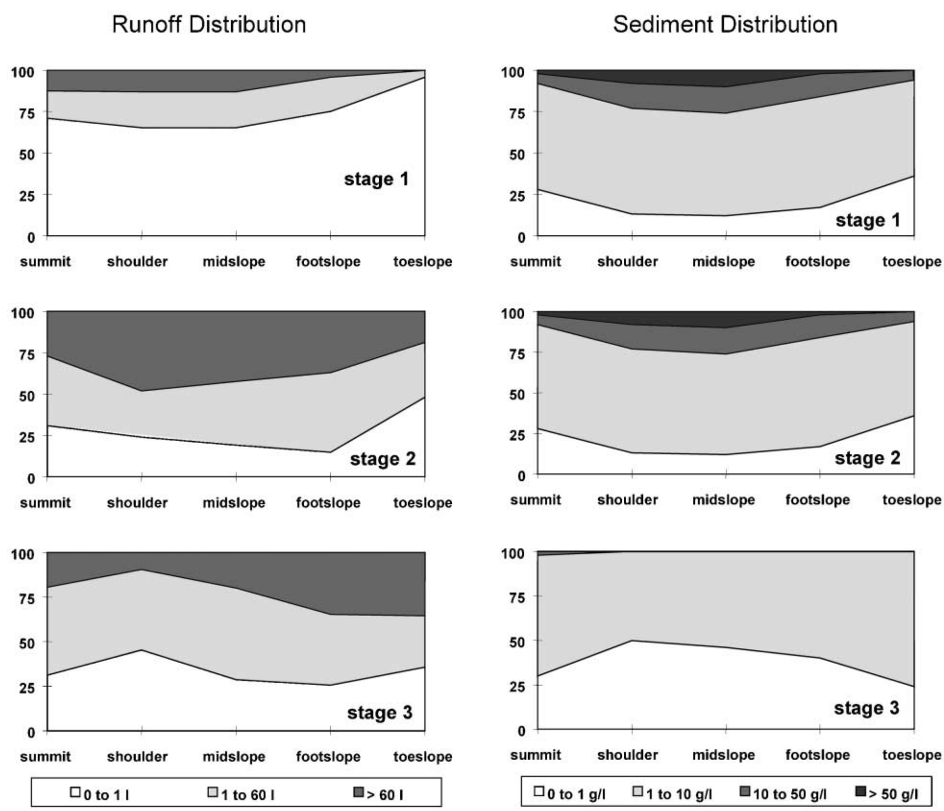

Fig. 5. Relative contribution of different class interval of runoff and erosion intensity, for each slope position and for three stages.

Sediments were mostly deposited beyond the footslope except during higher intensity rainfall events. The third stage, from fall to early spring, corresponded to a period of numerous low intensity rainfall events. During this stage, sheet flow was frequent but mainly came from the lower slopes. The sediment load was low, measuring only a few grams per liter. This spatial distribution was due to lower infiltrability and higher moisture contents at the bottom portion of the hillslope that facilitated the buildup of water table, quick saturation condition and overland flow. Despite a high sheet flow at the lower slope portions, the sediment transport remained low due both to low slope gradients and short slope segments, and cohesion of soil due to sealing and natural compaction in the ploughed layer related to wet conditions (Heddadj and Gascuel-Odoux, 1999).

An annual sediment budget for the midslope section showed a sediment redistribution of 1.5 t ha^{-1} with most severe erosion occurring during the second stage. Nevertheless, the net sediment output as measured at the toeslope section was only 0.3 t ha^{-1} with a majority coming off during the third stage for the same year, indicating the need to understand spatial and temporal interactions in the hillslope scale.

Reasons for different stages of runoff and sediment production are postulated here. During the first stage, the soil crusting development and its topographic variation, partly depending both of soil constituents and slope gradient, controlled runoff and erosion processes. During the second stage, the slope gradient was the major controlling factor, while soil crusting and moisture conditions are fairly homogeneous along the hillslope. During the third stage, the hydrologic condition controlled runoff and erosion processes. Wet soil and low infiltrability at the toeslope section triggered runoff production at this hillslope domain (Heddadj and Gascuel-Odoux, 1999). These results demonstrate the space and time distributions of sheet flow and sediment transport being closely affected by rainfall characteristics, vegetation cover, and soil moisture and surface conditions. This shows the difficulty of extending data from small runoff plots to field situations without first knowing characteristics and conditions of the hillslope. Our spatially distributed sampling approach has brought elements that would not have been depicted from a point measurement system.

3.2. Soil moisture effects on dominant erosion processes and sediment regimes

Laboratory rainfall simulation data showed significant differences in sediment delivery and dominant erosion processes under different near-surface hydraulic gradients, i.e., seepage vs. drainage conditions. Severe rilling occurred under seepage condition while the surface under drainage showed minor scours without any evidence of rilling. Differences in the surface features between seepage and drainage conditions are also confirmed by the sediment delivery data that showed 2 to 5 times higher sediment delivery under seepage conditions (Table 1). In Table 1, sediment scenarios were assigned using an arbitrarily selected threshold value of 2 kg h^{-1}, which means that any two values have to differ by more than this threshold to be ranked different.

Under drainage condition, the erosion process in the test box changed from net deposition (Scenario 1) to net erosion (Scenarios 4 and 5) as the rainfall intensity was increased from 25 to 150 mm h^{-1}. Under seepage, runoff from the feeder box caused

Table 1
Sediment deliveries and process scenarios from the multiple box system. The 1.8-m feeder box was set to 10% slope and rained at 150 mm h^{-1}. The 5-m test box was at 5% slope and set to either drainage or seepage conditions

Feeder box	Test box				Process scenario
Q_F (kg h^{-1})	Rain (mm h^{-1})	Q_{Td} (kg h^{-1})	$Q_{Td}+Q_F$ (kg h^{-1})	Q_{Tc} (kg h^{-1})	
	Test box: drainage				
19	25	3	22	15	1
23	50	7	30	21	2
17	75	20	37	41	5
16	150	52	68	68	4
	Test box: seepage				
16	25	15	31	41	5
17	50	33	50	66	5
15	75	51	66	90	5
14	150	108	122	135	5

Q_F: Feeder sediment input; Q_{Td}: sediment from the test box without feeder input; Q_{Tc}: sediment from the test box with feeder input.

additional sediment transport in the test box (i.e., Scenario 5), indicating a transport-dominated sediment regime. Increases in slope steepness, rainfall intensity and soil erodibility shifted the dominant erosion process from deposition to transport.

The Scenario 1 net deposition in the test box is caused by both excessive sediment input from the feeder box and insufficient sediment carrying capacity of the flow in the test box at low slope and rainfall intensity. In field conditions, Scenario 1 simulates erosion processes at a concave shoulder portion of a hillslope or runoff from a highly erosive and erodible region to a lower one. An increase in raindrop impact and flow transport from increased rainfall intensity shifted the sediment deposition regime to an equilibrium condition at which the runon water and sediment from the feeder box caused neither additional detachment nor deposition in the test box.

Under seepage conditions, the soil strength is low and sediment is easily detached and transported. The flow from up-slope runon water caused additional sediment delivery from the test box. The change in slope gradient to 10% increased the sediment transport capacity of the flow, despite increased soil strength under drainage conditions. The increased sediment transport capacity also brought forth additional sediments from the test box. The process of additional flow detachment for the Scenario 5 situation is, therefore, triggered by increasing either soil erodibility or flow transport capacity. Scenario 5 can be considered as a transport-dominated regime in the sense that sediment delivery is dictated by the flow transport capacity because of low soil strength and high flow shear. In field conditions, Scenario 5 regime represents processes that occur at the backslope or footslope locations under excessive soil moisture.

The effect of near-surface hydraulic gradient on soil erosion is further illustrated by a data set for which sudden reversal from seepage to drainage condition occurred during the rainstorm (Fig. 6). The study soil was a Glynwood clay loam, with a 20-cm seepage

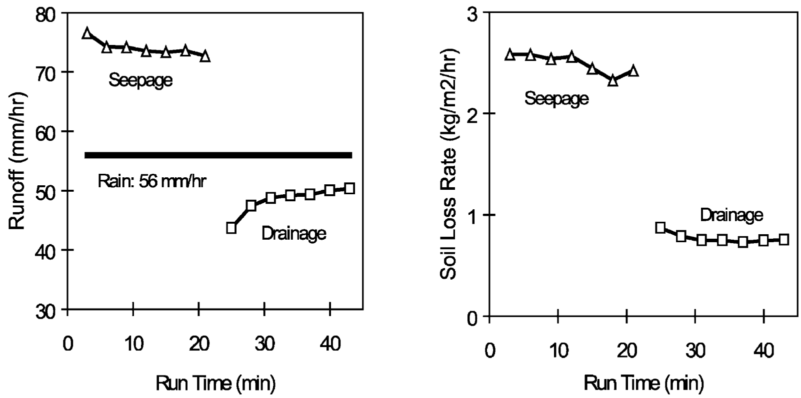

Fig. 6. Changes in runoff and sediment deliveries as the test box was changed from seepage to drainage conditions during the rainstorm.

pressure under 56 mm h^{-1} rainstorm. The reversal from seepage to drainage condition caused a reduction of runoff from 75 to 48 mm h^{-1} and sediment delivery from 2.5 to 0.7 kg m^{-2} h^{-1}.

This illustrates the role of surface hydrologic conditions, especially seepage and drainage gradients, in erosion and sediment regime.

4. Conclusion

This paper showed examples of relating surface boundary conditions to runoff and sediment productions. In natural field situations, annual rainfall pattern, tillage operations, and crop growth affected the surface boundary condition, in addition to the hillslope positional effects. From the natural runoff data, we identified three different stages of runoff and sediment productions as the soil moisture regime varies in an annual cycle from a row-cropped field near Rennes, France. Despite a high sediment production from the steeper part of the midslope section during the second stage under severe summer storms, total sediment production from the entire hillslope was minimal due to higher infiltration near the lower portion of the hillslope. This type of data will help us formulate erosion process research programs to further understand surface hydrological effects on the process of erosion and to develop appropriate erosion control practices.

Results from our laboratory studies demonstrated the capability of a dual-box system to quantify erosion process scenarios from deposition-dominated to transport-dominated regimes. In addition, experimental results showed the dependency of dominant erosion process on slope gradient, rainfall intensity and soil erodibility. An increase in soil erodibility from the seepage condition triggered transport-dominated regime, while a decrease in soil erodibility from profile drainage limited sediment detachment and enhanced sediment deposition. Besides testing for different sediment scenarios, the dual-box system is also capable of simulating processes occurring at a hillslope segment. Changes in slope gradient, rainfall distribution and soil erodibility, and their effects on erosion processes can be quantified by setting different conditions for different boxes. These recent developments in laboratory soil box procedures will yield valuable information for the understanding of erosion processes occurring at a scale similar to those occurring on hillslopes.

Quantifying spatial and temporal variability in runoff and erosion is paramount in building process-based hillslope models. This paper demonstrates a multi-scale approach encompassing both field and laboratory projects that contributed to the further understanding of erosion science. Since field results are affected by variable climatic and surface conditions, their interpretation requires knowledge gained from basic studies conducted under controlled situations. Experiments in the laboratory may explore large ranges of hydrologic conditions occurring spatially and temporally at the hillslope. Continued efforts need to be focused on developing new knowledge in hillslope runoff and erosion processes.

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