

How Surface Conditions Affect Sediment and Chemical Transport

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Abstract: Soil erosion process research produces knowledge and science used in the development of current process-based erosion prediction models. This paper highlights recent progresses at the USDA-ARS National Soil Erosion Research Laboratory (NSERL) on effects of soil surface conditions, i.e., roughness and moisture gradient, on sediment and chemical transport. We showed that surface depression caused a delay in runoff initiation. But once runoff was initiated, surfaces with depressions did not show any sediment reduction as compared those without depressions. On the surface hydrologic effects, saturation and seepage conditions greatly enhanced sediment and chemical transport. These findings showed the importance of understanding surface condition effects for better management strategies to minimize the sediment and chemical transport at the landscape. Also included in this paper are brief descriptions on experimental techniques using (1) a line-scan laser system to measure surface microtopography; and (2) a multiple-box system to quantify processes at a hillslope segment.

1 Introduction

Soil erosion process research not only furthers the understanding of the science and knowledge, the results can also be used in the development of process-based erosion prediction models. The US Department of Agriculture (USDA) –Agricultural Research Service (ARS) National Soil Erosion Research Laboratory (NSERL) at West Lafayette, IN has been the US national focal center in soil erosion process research and erosion prediction model development.

A historic flash in erosion process research at W. Lafayette is presented here. In 1954, the US Department Agriculture established the National Runoff and Sediment Data Center at West Lafayette, Indiana, where the natural runoff plot data collected from various states, predominately from the US Midwest, since the mid 30s were compiled and summarized. In the 1950's, parallel to the development of Universal Soil Loss Equation (USLE) by Walter Wischmeier, L.D. Meyer evaluated rainfall simulation technologies, identified the Spraying Systems VeeJet nozzle for artificial rainfall generation and initiated erosion process research at West Lafayette. Rainfall simulation allows collection of erosion data in a controlled fashion in a relatively short time as compared to erosion data derived under natural rainfall conditions. Rainfall simulation studies conducted in the 60s were mainly focused on providing data sets to support the USLE development. Noted works in this period were those from Meyer, Wischmeier, Manning, Moldenhauer and Romkens on cropping and tillage effects, soil erodibility and the crop residue or mulch factor on soil erosion. Beginning in the early 70s, rainfall simulation studies gradually shifted toward more process-oriented basic studies, largely due to the work by Meyer and Wischmeier (1969) in that separate detachment and transport processes were proposed. In the early 70s, conceptual developments in erosion processes by L.D. Meyer and G.R. Foster became the foundation of current US process-based erosion model, i.e., Water Erosion Prediction Project (WEPP). As the result of Foster and Meyer's proposition to separate erosion processes to those occurring in rill and interrill areas, erosion process studies were also diverting into quantifying rainfall-dominated interrill and flow dominated rill erosion processes. Since then, the rill-interrill process separation has dominated the erosion process research up till today. Significant works in the 70s and 80s included studies of flow hydraulics and

sediment transport capacity by Neibling, Foster and Lu; raindrop impact and detachment, surface soil strength measurement, and interrill erosion by Bradford and his graduate students; and surface sealing and micromorphology research by Norton.

A lot of efforts in soil erosion research have been devoted to quantifying soil erodibility as functions of soil properties. This line of work dated back to the 30s when Middleton and his coworkers first identified physical and chemical properties that affect a soil's response against erosive forces (Middleton, 1930; Middleton *et al.*, 1932, 1934). Key soil properties identified from early research works were soil texture, aggregate stability, and dispersion index. Many soil properties indeed contribute to soil erodibility, some directly and some indirectly. Since soil composition do not change appreciably in a short time, such as within a year, relationships for soil erodibility and soil property tend to be held better for predicting long-term soil loss but less accurate for seasonal and short-term variations. The transient soil surface condition has been known to affect runoff and soil erosion.

This paper highlights recent progresses, including the development of the line-laser scanner for measuring surface microtopography and the multiple-box system for simulating hillslope hydrologic conditions, in studying surface boundary effects, particularly roughness and moisture gradient, on runoff, sediment and chemical transport.

2 Line-scan laser system for surface microtopography

The measurement of soil surface micro-topography is usually performed using stereo-photography, contact probe or laser scanners. Recent focus has been in the development of digital stereo photography (photogrammetry) and laser scanning since these techniques deliver high-resolution surface elevation data. While digital photogrammetry is capable of producing high quality surface data, the cost of camera and software and time required to process the images limited the wide spread use of this technology. Currently, laser scanning is probably the most feasible technique for measuring surface microtopography.

Point-scan laser system used the triangulation principle to measure surface elevation. A laser beam was projected vertically onto the surface and a line-camera detected at the light point reflected from the surface. Because of the constant camera-laser geometry, the surface height was estimated using a simple triangulation procedure. Missing value or the shadow effect was encountered in triangulation-based laser scanners because some part of the surface blocked the view of the laser point to the camera. Since the point scan system measures surface elevation at one spot, to obtain surface topography, the laser and camera assembly needs to be mounted in a 2-dimensional traversing frame to scan an area. Limitations of the point-scan laser system include: traversing frame (i.e., size, weight, and portability) and long scanning time for large surface scans.

A recent improvement to the point-scan laser system is the use of line-laser to acquire a surface profile instantaneously (Darboux and Huang, 2002). Using the same triangulation principal, the line-scan laser system uses a laser line generator and a CCD-array camera. This projected laser line is in the field of view of the CCD-array camera. The profile can be characterized on the CCD-array by a series of cells receiving a high flux of laser light. A computer software converts the CCD coordinates (row and column) to spatial coordinates (x and z) and produces instantaneously the height variations along a profile. To map the surface heights, the laser-camera unit is moved automatically along a linear transect (or rail). Current system contains a 4 m long rail that can scan a 0.5 m wide (width of the laser line) 4 m long surface in 7 minutes with elevation data in a spatial grid of 0.5 mm along the profile and 1.5 mm grid between successive profiles. This system has been used routinely in both lab and field studies.

3 Multiple-box system to study processes in a hillslope segment

Most erosion studies were conducted in fix-sized plots or soil boxes without any upslope contribution of runoff and sediment into the study area. Any segment along a hillslope, unless situated at the upper most portion, would receive runoff and sediment from its upslope contributing area (Fig.1). A multiple-box system, consisting of a cascade of soil boxes up and down slope to each other, is developed to simulate the hillslope runoff-runoff process. The development of the multiple-box system also opens a new avenue to test the process-based erosion model concept. The traditional fixed-sized plot only

produces total sediment delivery or an integrated result at the discharge point. The total sediment delivery can then be related to rainfall, runoff, slope gradient, and surface conditions, such as tillage practices, crops and crop residues, etc., in an empirical approach like the USLE. Sediments from a multiple-box system or plots of different lengths allow a first approximation of the differential quantity in a process-based model formulation, which estimates erosion and deposition along the runoff route.

Currently, the multiple-box system at the NSERL consists of a cascade of three boxes, a 1.2 m wide, 1.8 m long up-slope sediment feeder box, 1.2 m wide, 5 m long mid-section test box and 0.6 m wide, 4.5 m long down-slope rill box. All three boxes have independent rainfall simulators and slope adjustments. In addition, the two lower boxes, i.e., 5 m and 4.5 m ones, have water circulation systems to control the near-surface hydraulic gradient to different levels of seepage and drainage gradients. The combination of different up-slope and down-slope conditions can be used to evaluate sediment detachment, transport and deposition processes and to identify specific conditions that a specific sediment process or regime becomes dominating.

4 Near-surface hydraulic gradient effects on sediment delivery

It is hypothesized that different hillslope positions will affect the hydrological conditions that will, in turn, affect the erosion processes (Fig. 1). For example, drainage conditions are dominant near the summit through the upper backslope. The small amount of surface flow contributed from the area upslope leads to interrill-dominated processes in the upper locations of the hillslope. At locations further downslope, the increased water from contributing area upslope enhances the concentration of surface flow, hence rill erosion processes. Near the toe of the slope, seepage may occur during periods of excessive soil moisture. In fact, seepage induced rills and gullies have been found in fields with an impeding layer during periods of excessive soil moisture. In some of the fields where rills and gullies were found, soil conservation practices, e.g., no-till and crop residue management, have been implemented for several years. This observation led to a laboratory effort to quantify the near-surface hydraulic effects, specifically seepage and drainage conditions, on soil erosion.

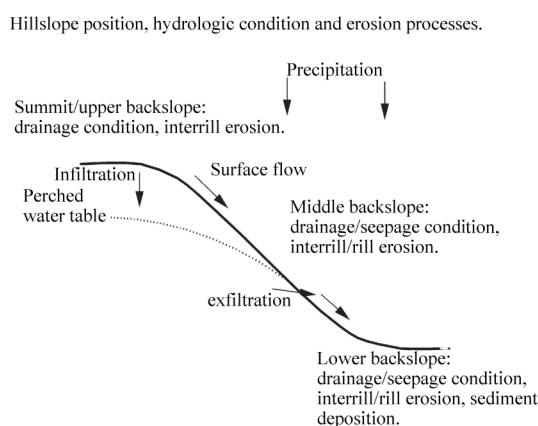


Fig. 1 Conceptual hillslope model showing interactions between hillslope position, hydrologic condition and erosion processes.

Experimental results from the multiple box system confirmed the hypothesis (see Gabbard *et al.*, 1998; Huang *et al.*, 1999 for data). At 5% slope and under drainage conditions, knickpoints were formed randomly throughout the bed. In several cases, these knickpoints developed into scallop-shaped depressions and crescents. As the slope was increased to 10%, the crescent-shaped pits eroded headward until they coalesced with the next crescent shaped pit upslope. Over time this process may lead to the development of shallow rills as the flow becomes concentrated in these areas where the crescent-shaped pits coalesce into one another.

Under seepage conditions, severe rilling occurred during the run. At 5% slopes, the bed surface after the run had wide, shallow, meandering rills that resembled miniature rivers. Under 10% slopes, rills were

incised much deeper and meandered less. In some instances, extensive collapsing of the sidewalls and rapid headcut advancement, similar to gully erosion, occurred during the run.

5 Run-on sediment effects on down-slope erosion processes

As stated earlier, any hillslope segment, except those situated at the upper most location near the divide, would be receiving runoff from its upslope contributing areas. It has been hypothesized that the detachment potential of the runoff water would decrease as the sediment content is increased until a sediment transport capacity, T_c , is reached and the excessive amount of sediment beyond T_c would then be deposited. Translating this concept onto a hillslope setting implies that water and sediment from upslope areas would affect erosion processes on a down-slope segment. The multiple-box system allows a testing of this hypothesis or the run-on water effect and the sediment transport capacity concept.

Results from a study on the run-on sediment effects (Zheng *et al.*, 2000) are briefly presented here. This study used two upper boxes with the 1.8-m feeder box as the sediment source and the 5-m box as the test section. The sediment content from the up-slope feeder box was varied by covering portions of the surface with a landscape fabric, thus creating a different amount of sediment in a similar runoff water input. Condition on the 5-m test section was varied for different rainfall intensity, slope steepness and the near-surface hydraulic gradient. Results from the 5% slope runs, plotted as the net erosion or deposition rate as a function of upslope sediment input, were presented in Fig. 2. A 1:1 line is also plotted in the graph. Data following the 1:1 trend line signifies a constant sediment delivery from the test box regardless the level of the run-on sediment input. Or, in other words, a dynamic equilibrium condition has been reached and the sediment delivery is at the hypothetical transport capacity value. Results shown in Fig. 2 under the drainage conditions follows the ideal scenario: a decrease in run-on sediment content caused a corresponding increase in downslope sediment detachment resulting in a relatively constant sediment delivery from the test box. Under seepage conditions, sediment deliveries were much greater and did not seem to follow the ideal 1:1 curve than those observed under drainage conditions. In general, sediment detachment from the run-on water increased as either slope or rainfall intensity was increased or when the surface condition was changed from a drainage to a seepage hydrologic regime. These results demonstrated that the sediment delivery reached a dynamic equilibrium, specific to the surface condition of the hillslope segment, and the multiple-box system can be used to study erosion processes similar to those occurring on a hillslope.

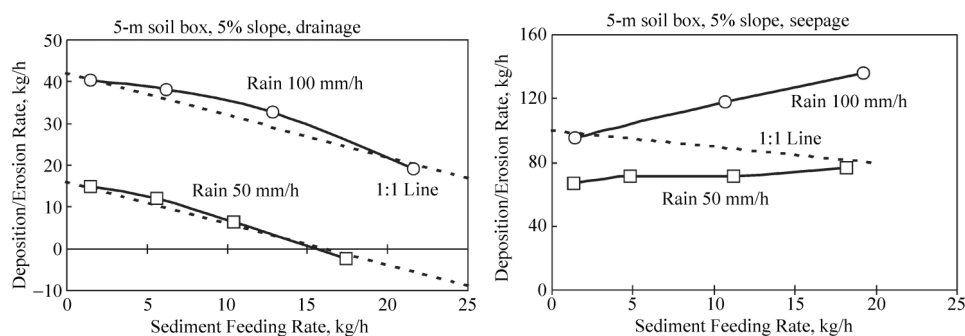


Fig. 2 Erosion and deposition rate in the 5-m test box as a function of upslope runoff sediment input under drainage and seepage conditions. The 1:1 line signifies the hypothetical situation when sediment delivery is at its transport capacity.

6 Near-surface hydraulic gradient effects on chemical transport

Excessive agricultural chemicals, such as fertilizers and pesticides, transported in runoff and eroded sediments to the receiving water bodies have caused environmental problems. Almost all the studies on chemical transport in runoff water were mainly conducted under drainage condition with a downward or infiltrating moisture gradient at the soil surface without considering the potential for seepage to occur.

Since we have shown a significant increase in sediment delivery under artesian seepage, and the seepage flow only occurs when the soil moisture is saturated, the potential for an increased chemical dissolution, combined with increased sediment delivery, may accelerate chemical transport in surface runoff.

A rainfall simulation study on the hydrologic effects was conducted on small soil pans, 45-cm long, 32-cm wide and 35-cm deep (Zheng *et al.*, 2001). A nominal rate of fertilizer, P: 40, N: 100 kg/ha, was mixed in the top 2 cm of the soil box and runoff water quality was studied under three near-surface hydrologic conditions: free drainage (Fd), saturation (Sa), and artesian seepage (Sp). The seepage treatment also included seep flow only and seep flow under rainfall (Sp+R).

Results are summarized in Table 1. $\text{NO}_3\text{-N}$ and P concentrations in runoff under the drainage condition were very low. When the near-surface moisture condition shifted from the drainage condition to saturation and seepage, $\text{NO}_3\text{-N}$ and P concentrations increased greatly. Under the applied fertilizer input, $\text{NO}_3\text{-N}$ concentrations from saturation (Sa), seep flow alone (Sp), and seepage with rain (Sp+R) averaged 45, 5800 and 730 times greater than those under free drainage condition. Similarly, average P concentrations in runoff were 5, 8 and 7 times greater in Sa, Sp, and Sp+R, as compared to the Fd condition. Total nutrient loss from the 90 minute run followed a similar trend. These data shows that seepage condition has a significant contribution to the water quality problem. Therefore, it is important to focus on understanding and controlling seepage occurrence on the hillslope.

Table 1 Average nitrate and dissolved P concentrations and total losses in runoff during a 90 min. storm at 50 mm/h intensity

Hydrologic Treatment	Concentration		Total Loss	
	Nitrate	Dissolved P	Nitrate_kg/ha/h	Dissolved P_g/ha/h
Free drainage (Fd)	0.09	0.11	0.04	48.7
Saturation (Sa)	4.05	0.56	2.3	511
Seep alone (Sp)	523	0.94	37.4	63.5
Seep with rain (Sp+R)	65.6	0.79	43.3	519

7 Soil roughness effects on runoff and erosion

Soil surface roughness is a key factor in affecting runoff generation and erosion. Nevertheless, how roughness affects runoff and erosion is not clear, because contradictory results are found in the literature. With the recent development of second-generation line-scan laser scanning technology, it is possible to acquire high-resolution soil microtopographic data rapidly, thus, enabling a further exploration of soil roughness effects on runoff and erosion.

A laboratory experiment was designed to assess the consequences of surface depression on overland flow under two contrasting hydrologic conditions: drainage and seepage. In a 5-m-long soil box, paired surfaces, one with and one without depressions were compared under a sequence of three simulated rainfall events.

Table 2 Time to runoff during a sequence of three rainfall events under drainage condition from 4 replicate runs

Rainfall Event	Time to Runoff	
	Without depressions	With Depressions
First Rain	6' 05", 5' 15", 2' 40", 3' 30"	19' 40", 14' 00", 12' 45", 11' 30"
Second Rain	2' 00", 1' 40", 1' 10", 1' 30"	3' 00", 2' 20", 4' 00", 3' 00"
Third Rain	1' 45", 1' 00"	1' 30", 2' 10"

Under drainage conditions, the depressions always delayed runoff initiation during the first event (Table 2). Due to the decrease in surface storage capacity from either erosion or sediment filling, the

delay effect was less pronounced for the second rain event and disappeared for the third rain event. Depressions did not have any effect under seepage conditions because depressions were already filled at the beginning of the rain. If the surface can store rainwater, runoff initiation is delayed. This condition is not met if depressions are initially filled (seepage) or if depressions were eroded by previous rain (drainage – third event).

The sediment flux, plotted as the ratio of surfaces with to without depressions from the paired plots, showed a different trend (Fig.3). Under drainage, surfaces with initial depressions gave higher particle fluxes than initially-flat surfaces. This effect is present for all rain events, indicating it is not related to the presence of depressions. The slightly elevated sediment flux could be caused by differences in the geometry of the flow network: flow appeared more concentrated on the surfaces with initial depressions. This could have increased flow velocity and therefore, the detachment of particles. Under seepage conditions, no significant differences were observed during the first two rain events, while rills were developing in the soil box. During the third event; erosion was higher for the surface with initial depressions. Like for drainage conditions, the flow network seems more relevant to explain difference in erosion than the presence of depressions. In conclusion, soil roughness could either increase or decrease erosion depending on surface moisture gradient and the duration of the rainstorm. A mechanistic approach with detailed surface microtopographic measurements using laser scanning will eventually unravel the myth of the surface roughness effects.

Surface roughness, by affecting flow properties, modifies water and sediment mass-balance along hillslope segments. A mechanistic approach with detailed surface microtopographic measurements using laser scanning will eventually unravel the myth of the surface roughness effects.

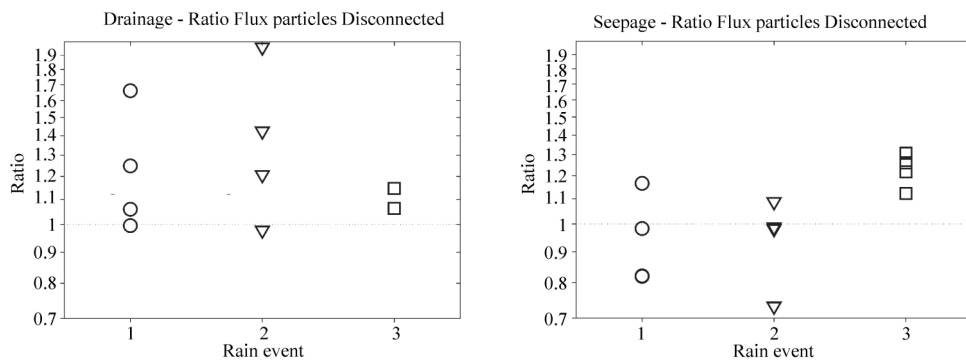


Fig. 3 Comparison of erosion rates between initial surfaces with and without depressions under drainage and seepage conditions. A ratio higher than one means surfaces with depressions had higher erosion rate than those without depressions

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