Reduced raindrop-impact driven soil erosion by infiltration

Jeffrey D. Walker a, M.Todd Walter a,*, Jean-Yves Parlange a, Calvin W. Rose b, H.J. Tromp-van Meerveld c, Bin Gao a, Aliza M. Cohen a

a Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, United States
b Faculty of Environmental Science, Griffith University, Nathan, Qld 4111, Australia
c Simon Fraser University, Department of Geography, Burnaby, BC, Canada V5A-1S6

Received 1 November 2006; received in revised form 15 May 2007; accepted 4 June 2007

KEYWORDS
Sediment transport; Infiltration; Shield formation; Soil erosion; Rainfall impact; Deposition

Summary We used a simple laboratory experiment to investigate whether infiltration influences raindrop-impact induced soil erosion. There was substantially less erosion under infiltration conditions than with no infiltration. This was because a "shield" layer of deposited particles developed more rapidly under infiltration compared to "no-infiltration" conditions. Interestingly, the "shield" depth that fully protected the underlying soil from raindrop-impacts was shallower under infiltrating conditions. We found that the Rose soil erosion model captured the erosion dynamics well ($R^2 \approx 0.9$). Predicting the "full-shield" depth remains unresolved. These results add evidence to previous studies indicating that saturated, slowly draining areas in the landscape are particularly susceptible to soil erosion from raindrop impact.

© 2007 Elsevier B.V. All rights reserved.

Introduction

After more than a half-century of intense study, water-induced soil erosion mechanisms continue to stir controversy. It is widely recognized that upland erosion is largely initiated by the impact of raindrops on the soil surface (e.g., Kinnell, 1982; Morgan, 1995), a process that has been recently investigated using some simple, small-scale experiments that allow researchers to isolate the role of raindrop impact from overland flow (e.g., Heilig et al., 2001; Gao et al., 2003; Gao et al., 2005). These studies have also corroborated various aspects of the Rose model, a mechanistic model of soil erosion on a hillslope (e.g., Rose and Dalal, 1988; Hairsine and Rose, 1991; Rose et al., 1994; Hairsine et al., 1999), adding to findings from other researchers that used more complicated, and realistic, experiments (e.g., Proffitt et al., 1991; Sander et al., 1996; Rose et al., 1998; Parlange et al., 1999). The objectives of this short study were to see if infiltration influences soil erosion due to raindrop-
impact and to test the Rose model’s ability to correctly capture these influences. It is traditionally recognized that reduced infiltration may lead to increased surface runoff, which can be extremely erosive (e.g., Meeuwis, 1970; Bradford et al., 1987; Shakesby et al., 2000; Nord and Esteves, 2005). Interaction between infiltration and raindrop-impact driven erosion in the absence of runoff shear forces has not been directly studied. There is good evidence that reduced infiltration will increase raindrop-impact erosion, but it is often difficult to see the effects of raindrop impact in the absence of other processes (e.g., Torri et al., 1999) or specific soil properties like hydrophobicity (e.g., Terry and Shakesby, 1993) and surface sealing (e.g., Bradford et al., 1987). Therefore, in this study we have chosen to use a simple soil structure in order to isolate the interactions between infiltration and raindrop-impact erosion.

Brief review of the Rose model (Hairsine and Rose, 1991) for raindrop-impact erosion

We characterize soil as being composed of $l$ particle classes of equal mass and differentiated by settling velocity. The mass balance for particle class $i$ is:

$$\frac{\partial (Dc_i)}{\partial t} + \frac{\partial (qDc_i)}{\partial x} = e_i - r_i - d_i,$$  

where $D$ is the depth of surface flow (l), $c_i$ is the suspended sediment concentration of class size $i$ in the overland flow (ML$^{-3}$), $q$ is the volumetric water flux per unit width of slope (LT$^{-1}$), and $e_i$, $r_i$, and $d_i$ are the rates of ejection of original soil, re-erosion of deposited material, and deposition, respectively.

One unique aspect of the Rose model is the development of a "shield" layer composed of deposited particles. As the shield layer develops, the underlying soil is increasingly protected from erosion by raindrops. The ejection or erosion rate, $e$, is therefore described as:

$$e = ap \left(1 - H\right),$$

where $p$ is the rain rate (LT$^{-1}$), $a$ is the soil detachability (ML$^{-3}$), and $H$ is the shielding parameter; i.e., $H = 0$ indicates no soil erosion and $H = 1$ indicates complete shielding and no additional erosion of the underlying material, and can be estimated as:

$$H = \frac{M_d}{M_d^*}.$$  

where $M_d$ is the accumulated mass of deposited material and $M_d^*$ is the mass of material needed to completely shield the soil.

We typically assume, in the absence of infiltration, that suspended particles will settle out of the surface runoff according to Stokes’s law, so that the $d_i$ is dependent on the particle class’s size and weight. In the presence of infiltration, the downward flux of the infiltrating water will also contribute to the settling rate and we assume the deposition rate of particles that would normally remain suspended will be equal to the rate of infiltrating water.

Methods

Our experimental apparatus was essentially the same as Gao et al. (2003); Gao et al. (2004); Gao et al. (2005). Briefly, pre-saturated soil was placed in a small plexiglass cylinder (diameter = 7.5 cm). Four small holes in the cylinder’s walls maintained a constant ponding depth and a hole in the bottom of the cylinder allowed water to drain from the soil. To facilitate drainage, the soil rested on a porous plate (0.5 cm thick, pour sizes of 45–90 μm) below which the column was filled with glass beads (diameter of 4 mm) and a second porous plate to keep the beads from falling out of the chamber (Fig. 1); free drainage from our column was 0.0041 cm min$^{-1}$. The bead-layer and porous plate were saturated prior to adding the soil. The soil was a homogeneous mixture of 90% black sand (180–212 μm) and 10% white clay (hydrous Kaolin supplied by Englehard Corp., NJ), by mass (i.e., $I = 10$), pre-saturated at a ratio of 3 g soil to 1 g water. As noted earlier, this simple soil largely removes many complicating processes that would be present in a natural soil and, because the sand and clay are contrasting colors, we can easily see the "shield" layer (e.g., see photographs in Heilig et al., 2001). The soil column was placed ~3 m below a computer-controlled rain maker at the soil and water laboratory in Cornell University’s Biological and Environmental Engineering Department. The rain intensity was constant for all experiments (0.115 cm min$^{-1}$); measured once for each experiment. An initial 0.6 cm ponding depth was attained by placing a piece of wetted filter paper directly on the soil surface while water was slowly added. The filter paper minimized disturbance to the soil surface and was carefully removed once the ponding depth was achieved. Samples of the ponded water were taken every 15 s over the first 10 min of each experiment; samples were taken using a pipette, which was inserted into one of the overflow holes and the sample size was $\approx 1\%$ of the total volume of ponded water. Each experiment was videotaped and run until the ponded water became completely clear indicating complete formation of the shield. The video was used to confirm that we had steady conditions throughout each experiment, e.g., check to see if the depth of ponded water changed substantially. We ran experiments under no-infiltration and free-drainage conditions and each was duplicated. We measured clay concentrations with a spectrophotometer (wavelength = 590 nm). At the end of each experiment we carefully removed, dried, and weighed the erosion shield to measure its final mass, $M_d$. As a check, we also back-calculated $M_d$ as nine times the total mass of

![Figure 1 Schematic of the experimental soil chamber.](image-url)
Reduced raindrop-impact driven soil erosion by infiltration

clay that was eroded. We observed no sediment on the splash guard at the end of the experiments; thus, all sediment either left the chamber with the overland flow or remained in the soil column.

Following Heilig et al. (2001); Gao et al. (2003); Gao et al. (2005), we assumed that the sand particles settle instantaneously and the clay, in the absence of infiltration, has a settling velocity of zero; henceforth we are modeling for the clay unless otherwise noted. Overland flow export of clay is \( q = c \) and the overland flow, \( q \), from the system is constant:

\[
q = p - f
\]

where \( f \) is the constant infiltration rate and \( p \) is the rain rate. The deposition rate of the clay is assumed to be proportional to the infiltration rate

\[
d = f \cdot c
\]

Knowing the sand:clay ratio in our original soil (9:1), the rate of sand accumulation in the shield can be calculated by substituting Eq. (3) into Eq. (2) and multiplying Eq. (2) by 9, i.e., \( dM_d/dt = 9e \):

\[
\frac{dM_d}{dt} = ap\left(1 - \frac{M_d}{M_3}\right)
\]

Our experiment is designed to have a small infiltration rate relative to rain intensity, thus, the rate of clay deposition into the shield is negligible compared to the potential for rain to re-entrain the deposited clay. Thus, we assume that the shield is essentially completely composed of sand and can we can rewrite Eq. (3) by solving Eq. (6) for \( M_d \):

\[
M_4 = \left(1 - \frac{c}{c_0}\right)M_3
\]

Because \( D \) is constant in our experiments, Eq. (1) can be simplified by substituting Eqs. (2), (4), and (5) for \( e \), \( q \), and \( d \), respectively, and Eq. (7) for \( H \):

\[
\frac{dc}{dt} = \frac{1}{D} \exp\left(-\frac{ap}{D}t\right) - (q + f)c
\]

Note that \( " q + f " \) in Eq. (6) can be replaced by \( " p " \) (Eq. (4)), which is the same form of the model used by Heilig et al. (2001); Gao et al. (2005), who have previously shown that the solution is:

\[
c(t) = \frac{a}{10 - \frac{a}{d_0}} \exp\left(-\frac{a}{D}t\right) \times \left[\exp\left(\frac{D}{t} - \frac{a}{10M_3}\right) - 1\right]
\]

Results and discussion

The general behavior of suspended clay concentrations over time are similar to previous results (Heilig et al., 2001; Gao et al., 2005), with a rapid increase in concentration which slows and then dilutes as the shield develops and clay flows from the chamber (Fig. 2). However, with infiltration, this progression is substantially faster (Fig. 2). It is remarkable how large an effect infiltration had on erosion rates given that the infiltration rate (free drainage) was so small. We ran one experiment at a ~20% higher infiltration rate (Table 1) by putting a small amount of suction on the bottom of the column with a peristaltic pump and observed an associated decrease in soil erosion (Fig. 2).

Interestingly, and perhaps counter-intuitively, the shield depth at the end of the infiltration experiments (0.4 ± 0.1 cm) was much shallower than with no infiltration (~0.8 ± 0.1 cm) and \( M_d \) was considerably smaller for infiltration (Table 1). The shield was even smaller for our higher infiltration experiment, although we cannot draw any strong conclusions based on a single experimental run. One possible explanation for this is that the density of the shallow, infiltration-induced shield (i.e., \( M_d/shield \) depth) was ~30% higher than for the free-draining, infiltration case than in the no infiltration case and, thus, may have been more resistant to raindrop impact. Another speculative explanation might be that some drop energy was absorbed as water moved into the soil under infiltration, thus, less energy was transferred to soil ejection.

We applied the Rose model (Eq. (7)) to our experiments and were able to achieve good corroboration with our experimental data (Fig. 2; Table 1). Although we found that the best-fit soil detachability, \( q \), varied from 1150 mg cm\(^{-2}\) with infiltration to 800 mg cm\(^{-2}\) for no infiltration, our results were not very sensitive within this range and we found that the model using \( a = 800 \) mg cm\(^{-2}\) agreed with the data nearly as well as the best-fit \( a \) values (Fig. 2 uses \( a = 800 \) mg cm\(^{-2}\) for all experiments).

Of course this simple study was designed to isolate the role of infiltration on raindrop-impact driven erosion. Natural soils contain components like organic matter, calcium carbonates, and various oxides that will undoubtedly play important and possibly complex roles in raindrop-impact erosion. However, our results suggest that inasmuch as these characteristics influence infiltration, they will play an associated role in erosion as shown here. Indeed, there are many other factors that will contribute to raindrop-impact erosion and, although many require attention (e.g., surface sealing), some have already been investigated, e.g., the effect of ponded water in absorbing raindrop-impacts (e.g., Gao et al., 2003) and how rain intensity influenced...
enches raindrop-impact erosion (e.g., Heilig et al., 2001). By understanding the roles of individual processes in isolation, we can start to develop better hypotheses about how these processes may interact.

Conclusions

Using a simple soil erosion experiment, we found that infiltration profoundly reduces soil erosion from raindrop-impact. It had been widely recognized that low infiltration rates can lead to high erosion rates due to increased surface runoff, but these results indicate that soil infiltration may increase even in areas where there is not substantial overland flow. The Rose model captures the behavior, although further work is needed to develop predictive models of shielding behavior. Although the simple soil composition used here helped isolate the specific role that infiltration plays, additional experimentation is needed to see how significant the role of infiltration is in the context of natural soils' more complex composition. Based on our findings, we speculate that soil (or landscape) characteristics that promote infiltration will probably reduce susceptibility to raindrop-impact erosion.

Acknowledgements

The authors note that Aliza Cohen's "leaky" experimental apparatus lead us to the hypothesis for this study. The authors also acknowledge Laura Agnew and Rickia Malcolm who investigated some "dead ends" along the way. This work was partially supported by Grants from the National Science Foundation (NSF REU/EEC 0139529), the Cornell University Agricultural Experiment Station (Hatch, Federal Formula Funds), and the Cornell undergraduate Learning Initiatives for Engineers (LIFE) program.

References


Reduced raindrop-impact driven soil erosion by infiltration

Walker, J.D. et al., Reduced raindrop-impact driven soil erosion ..., J. Hydrol. (2007), doi:10.1016/j.jhydrol.2007.06.003