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Interrill soil erosion processes on steep slopes

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ABSTRACT

To date interrill erosion processes are not fully understood under different rainfall and soil conditions. The objectives are to 1) identify the interrill erosion regime and limiting process under the study condition, 2) characterize the interactive effects of rainfall intensity and flow depth on sediment transport competency and mode, and 3) develop a lumped interrill erosion model. A loess loam soil with 39% sand and 45% silt was packed to flumes and exposed to simulated rainfall. A complete factorial design with three factors was used, which included rainfall intensity (48, 62, 102, 149, and 170 mm h^{-1}), slope gradient (17.6, 26.8, 36.4, 46.6, and 57.7%), and slope length (0.4, 0.8, 1.2, 1.6, and 2 m). Rain splash, sediment discharge in runoff, and flow velocity were measured. Results showed that rainfall intensity played a dual role not only in detaching soil materials but also in enhancing sediment transport. Sediment transport was the process limiting interrill erosion rate under the study condition. Two major sediment transport modes were identified: rainfall-driven rolling/creeping and flow-driven rolling/sliding. The relative importance of each mode was largely determined by flow depth. The competence of the flow in transporting sediment decreased downslope as flow depth increased due to increased dissipation of raindrop energy. The optimal mean flow depth for the maximal interrill erosion rates was <0.1 mm, which is much shallower than the widely reported 2 mm. Slope length was negatively related to interrill erosion rate. The negative correlation seemed stronger for heavier rains, indicating the cushioning effects of flow depth. Lumped interrill erosion models, developed from short slopes, are likely to overestimate erosion rates. Given transport as the limiting process, the so called erodibility value, estimated with those models, is indeed sediment transportability under the study condition. The effects of slope length on interrill erosion regimes need to be studied further under a wider range of conditions.

1. Introduction

Surface soil erosion during rainfall is a complex phenomenon resulting from soil detachment by raindrop impact and surface flow, and sediment transport by rain splash and surface flow (Ellison, 1945, 1947). The identification of these subprocesses of upland erosion laid a solid foundation for more detailed erosion process modeling proposed by Meyer and Wischmeier (1969). These authors explicitly divided upland soil erosion into four subprocesses of detachment by rainfall, detachment by overland flow, transport by rainfall, and transport by overland flow; and were among the first to mathematically model soil detachment and transport separately. In this conceptual framework, soil erosion rate is set to the lesser of the sediment transport capacity and the amount of detached particles available for transport (Meyer and Wischmeier, 1969). Although the sediment transport concept have been widely used in process-based erosion modeling, some researchers have challenged the use of the concept (Wainwright et al., 2015) partially due to the lack of a consentaneous, universal definition of the concept in complicated systems. In the context of interrill sheet erosion, the sediment transport capacity can be defined as the maximum, equilibrium sediment load that a raindrop-impacted sheet flow can carry in a given width per unit time for a given soil under a given hydraulic and rainfall condition. The sediment transport capacity varies with surface flow hydraulics (depth, velocity, etc.), rainfall characteristics (drop size and velocity), and sediment properties (e.g., size and density); and is greatly influenced by interaction between flow depth and raindrop impact as well.

To distinguish between the dominant processes involved in soil erosion and to facilitate the mathematical modeling of the

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subprocesses, upland erosion has been divided into rill and interrill erosion (Meyer et al., 1975). The dominant processes in interrill erosion are detachment by raindrop impact and transport by raindrop-impacted sheet flow (Young and Wiersma, 1973; Meyer et al., 1975; Kinnell, 2005). Detachment by sheet flow alone is negligible on interrill areas due to short slopes and low flow shear stress. Both net transport by rain splash and transport by sheet flow without drop impact are negligible as well. Sediment transport capacity by sheet flow is greatly enhanced by raindrop impact, and the enhancement depends on rainfall intensity and bed slope (Foster, 1982; Singer and Walker, 1983; Guy et al., 1987). These studies demonstrate that raindrop impact is the uttermost driving force for interrill erosion in that it not only detaches soil materials but also greatly enhances sediment transport of sheet flow. Due to its dual role in interrill erosion, it is rather difficult to clearly distinguish the process (soil detachment vs. sediment transport) that limits interrill erosion.

Lattanzi et al. (1974) and Meyer et al. (1975) argued that detachment rate by raindrop impact controlled interrill erosion rates. Meyer (1981) found that interrill erosion rate or sediment delivery was related to squared rainfall intensity for a given soil on short steep slopes of <1 m, which was later replaced by a product of rainfall intensity and unit discharge based on the work of Kinnell (1993), Zhang et al. (1998), and Aggasi and Bradford (1999). Meyer and Harmon (1989) found that slope length had little effect on interrill sediment delivery on unrilled short sideslopes, indicating that soil detachment limited interrill erosion. Foster (1982) postulated that slope length had little or no effect on interrill erosion per unit area. Such postulation was in line with the assertion that interrill erosion is a detachment-limited process (Lattanzi et al., 1974; Meyer et al., 1975).

Foster and Meyer (1975) proposed a conceptual model of interrill sediment delivery with respect to slope steepness. For small steepnesses, the concept denoted that transport capacity on interrill areas could be less than detachment rate, and therefore limits sediment delivery. In contrast, for steeper slopes detachment rate would be smaller than transport capacity and thus control interrill erosion rate. Bradford and Foster (1996) measured both rain splash and sediment delivery with a 61-cm soil pan, and reported that the splash rate was much greater than the wash rate at the 9% slope, indicating that transport was the limiting process at that short slope. Issa et al. (2006) concluded that transport process limited interrill erosion on a 10 m long, 1% field slope based on the fact that splashed particles were notably coarser than washed particles. However, the authors also concluded that raindrop detachment limited interrill erosion on a 50 cm long, 5% erosion pan in the same study simply because a positive correlation existed between sediment concentration in runoff and relative rate of raindrop splash, despite the fact that washed particles were finer than splashed particles and that splash detachment rate was somewhat higher than the total soil loss rate measured at the bottom of the pan. Martinez-Mena et al. (2002) conducted a field rainfall simulation experiment on two soils on 2 m long, 10–15% slopes under two intensities (31 and 56 mm h^{-1}). They reported that for one soil raindrop detachment limited interrill erosion in the 56 mm h^{-1} rain while transport limited interrill erosion in the 31 mm h^{-1} rain. For the other soil, however, raindrop detachment limited interrill erosion in both intensities. The conclusions were based on the premise that a positive correlation between sediment concentration and runoff rate would indicate a transport-limited case while a negative relation would signify a detachment-limited case. This premise is questionable and needs to be further tested.

Gilley et al. (1985) postulated that water depth on the interrill areas played a significant role in both soil detachment and transport, and developed an interrill erosion model that incorporates water depth in both processes. Soil detachment decreases exponentially as water depth increases due to the dissipation of raindrop impact energy. The model predicts that transport capacity by sheet flow is zero at the divide and increases downslope as slope length increases due to increases in flow rate and flow shear stress. Comparatively, soil detachment by raindrop impact is at its maximum near the divide due to thin water depth and decreases with distance. Taken together, the model suggests that transport capacity is limiting near the divide or on short slopes while detachment becomes limiting downslope. As a result, this model predicts that as slope length increases, sediment delivery initially increases (transport-limited) and then decreases (detachment-limited) with distance. Parsons et al. (1994) argued that transport capacity could also limit interrill soil erosion at longer slope lengths based on the simultaneous measurements of rain splash and sediment delivery on a field runoff plot, which showed little correlation between splash and wash rates (i.e., higher sediment delivery occurred at times of lower splash rate).

Interactive effects of drop size and water depth on soil detachment and sediment transport have been studied and documented (Moss and Green, 1983; Torri et al., 1987; Kinnell, 1991; Kinnell and Wood, 1992). Soil splash rate decreased exponentially with water depth, reducing to near zero at the 2-mm water depth (Moss and Green, 1983; Torri et al., 1987). Sediment delivery rate generally reached its maximum at the depth of 1 drop diameter (mostly about 2 mm) and then declined linearly to the depth of 3 drop diameters (Kinnell, 1991), or somewhat leveled off to the depth of 3 drop diameters and then decreased rapidly to the depth of 5 drop diameters (Moss and Green, 1983). Because of the difficulty in controlling water depths shallower than 2 mm, water depths used in all these experiments were generally greater than 2 mm. Thus, the effects of water depth on sediment delivery were not directly measured for depths of <2 mm in the literature. Rather, the effects were interpolated between 0 and 2 mm by assuming the sediment delivery is zero at the zero depth.

On sheet and interrill erosion areas, soil detachment is primarily caused by raindrop impact, while sediment transport is mainly delivered by raindrop-impacted thin overland flow. Kinnell (2005, 2009) proposed six transport modes: 1) raindrop splash, 2) raindrop-induced rolling, 3) raindrop-induced saltation, 4) flow-driven rolling, 5) flow-driven saltation, and 6) suspension. These transport modes may occur simultaneously in parallel or serial, depending on flow depth variation in space and time. When there is no runoff, transport is through raindrop splash. After runoff occurs, ultra-thin sheet flow is generally incapable of transporting detached particles without the stimulation of raindrop impact due to limited flow shear stress. The transport by raindrop-induced rolling and/or saltation is a major transport mode when flow is very shallow, which is termed raindrop-induced flow transport (RIFT) by Kinnell (2005) or rainfall-driven transport by Asadi et al. (2007). As flow depth and velocity increase, interrill flow has the capacity to move detached materials downslope in rolling and/or saltation without the need of raindrop stimulation (referred to as flow-driven transport). RIFT, though being more efficient than raindrop splash, is a transport-limited system (Kinnell, 2005). Flow-driven transport is more efficient than RIFT and can become a dominant system on high slopes (Kinnell, 2000). Transport by suspension spans both rainfall-driven and flow-driven transport.

Both physically and empirically based interrill erosion models have been developed. Detachment by raindrop impact and transport by thin overland flow are modeled separately in the former (e.g., Gilley et al., 1985; Hairsine and Rose, 1992), and are lumped in the latter (e.g., Kinnell, 1991; Flanagan and Nearing, 1995; Zhang et al., 1998, 2014; Wei et al., 2009). Physically based models generally include more parameters and require extensive data for parameterization and validation. In contrast, empirical models, taking the form of multiplication-of-factors, are simple and easy