Geomorphology 127 (2011) 53–63

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Impact of slope gradient on soil surface features and infiltration on steep slopes in northern Laos

O. Ribolzi [a,*], J. Patin [b], L.M. Bresson [c], K.O. Latsachack [d], E. Mouche [b], O. Sengtaheuanghoung [e], N. Silvera [f], J.P. Thiébaux [d], C. Valentin [g]

[a] Laboratoire des Mécanismes et Transferts en Géologie (LMTG), UMR 5563, IRD (Institut de Recherche pour le Développement), Université de Toulouse, UPS (OMP), CNRS, 14 Av Edouard Belin, F-31400 Toulouse, France

[b] Laboratoire des Sciences du Climat et de l'Environnement (LSCE), UMR 1572, CEA-CNRS-UVSQ, Gif sur Yvette, France

[c] Département Agronomie-Environnement UMR INRA-INAPG Environnement et Grandes Cultures - Institut National Agronomique Paris-Grignon - 78850 Thiverval-Grignon, France

[d] IRD, International Water Management Institute (IWMI), National Agriculture and Forest Institute (NAFRI), BP 06 Vientiane, Lao Democratic People's Republic

[e] NAFRI, Agriculture Land Research Center (ALRC), P.O. Box 811, Vientiane, Lao Democratic People's Republic

[f] IRD, Land Development Department (LDD), Office of Science & Land Development 2003/61 Pahon Yothin road, Chatuchak 10900 Bangkok, Thailand

[g] IRD, Université Pierre & Marie Curie (UPMC-Paris 6), UMR 7618 Bioemco, 32, av. H. Varagnat, 93143 Bondy cedex, France

ARTICLE INFO

Article history:
Received 20 May 2010
Received in revised form 24 November 2010
Accepted 3 December 2010
Available online 13 December 2010

Keywords:
Infiltration
Runoff generation
Steep slopes
Hillslope processes
Rainfall simulation

ABSTRACT

It was recently demonstrated that, infiltration into mountain-tilled soils with highly stable microaggregates, increases with increasing slope gradient. In this work we investigate the processes that underpin this phenomenon by means of field experiments and modelling. The study area is located in northern Laos. Rainfall simulations were conducted in two 1-m^2 plots using a portable field simulator. The drop size distribution and kinetic energy were similar to that occurring on the occasion of tropical downpours. Soils exhibited a clay loam texture and very similar organic matter contents across experimental plots, but differed greatly in slope gradient (30% and 75%). Runoff water samples were collected at intervals ranging from 1 to 3 min, depending on the runoff intensity. Plots microtopography was measured before and after rainfall simulations using an automatic surface roughness meter on a 1-cm grid. High-resolution bulk density images were obtained from soil slices using a standard X-ray generator. Final infiltration rates of 6 and 21 mm h^{-1}; soil detachment of 667 and 310 g m^{-2}; surface lowering due to soil loss of 0.82 and 0.38 mm; surface lowering due to compaction of 1.21 and 0.90 mm; percentage area with sieving crust of 36% and 90%; percentage area with erosion crust of 63% and 0%; were obtained for the 30% and 75% slopes, respectively. Three main conclusions can be drawn from this work: (1) high intensity rainfall can rapidly transform soil surface features of steep bare soil; (2) on steeper slopes, the micro-relief tends to form micro-terraces much more pervious and less erodible than the ripple-like roughness that formed on gentler slopes; and (3) there was a more pronounced lowering of the soil surface due to compaction and denser microlayers on gentler slopes. The latter conclusion confirms the hypothesis that higher effective rainfall intensity is responsible for the formation of less permeable erosion crusts under 30% slope gradients while more permeable structural crusts develop under 75% slope gradients. The runoff results were modelled with the Green and Ampt model which accounts for time evolution of soil hydraulic conductivity. This modelling shows that soil is undoubtedly non homogeneous, evolves with time and that infiltration kinetics is slower and soil permeability greater for the 75% slope.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The hydrological behaviour of the tropical mountains environments of Southeast Asia, has been dramatically transformed by recent human activities (e.g. Turkelboom et al., 2008; Lacombe et al., 2010). An increasing population pressure together with "market forces" have induced rapid changes in the farming systems (e.g. Thongmanivong and Fujita, 2006) that prevail in the uplands; thus, in response to the increasing demand for food, fibres and commodities traditional subsistence-based shifting cultivation has substantially declined to the advantage of monoculture plantations and semi-permanent cash crops. Severe land degradations have been associated with these rapid land use/cover changes, including changes in stream response (Gafur et al., 2003), increase in soil erosion (Valentin et al., 2008; Ziegler et al., 2009) and a decline in stream water quality (Vigiak et al., 2008).

Understanding the impact of land use changes on water resources is recognized as one of the most challenging issues of hydrology (e.g. Stonestrom et al., 2009). On steep terrain – i.e. where slope gradient

* Corresponding author. Tel.: +33 5 61 33 26 41; fax: +33 5 61 33 25 61.
E-mail address: ribolzi@ird.fr (O. Ribolzi).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.12.004

>20% according to Lal (1990) – this challenge finds itself reinforced due to a critical lack of basic knowledge about the partitioning of rainfall into overland flow and infiltration (e.g. Harden and Delmas Scruggs, 2003). Infiltration is controlled by several bio-physical factors among which ground cover, soil hydraulic properties, rainfall intensity, soil surface features (roughness and crusting) and slope gradient, are most influential. Although it received little attention from concerned scientists, particularly on steep slopes (e.g. Janeau et al., 2003), slope gradient is suspected to play a central role in the control of infiltration (e.g. Essig et al., 2009). Chen and Young (2006) proposed new developments of the Green and Ampt equation (Green and Ampt, 1911) to account for slope effects in infiltration descriptions and predictions. The slope angle α influences two factors that determine a soil's infiltration rate: (1) it controls the maximum surface storage capacity and ponding pressure head, which, as they both decrease with increasing slope gradient, indicates that infiltration should theoretically decrease with increasing slope (e.g. Fox et al., 1997) and (2) it reduces the raindrop density per unit of surface area and hence the effective rainfall intensity, i.e., vertical rain intensity multiplied by $\cos\alpha$ (e.g. Rudolph et al., 1997). Consequently the kinetic energy of rain drops and associated risks of soil crusting also decrease on steeper slopes, which might lead to increased infiltration.

Experimental studies have yielded contradictory results about the effect of slope on infiltration. Some authors did not find any relationship between slope gradient and infiltration rate (e.g. Singer and Blackard, 1982; Mah et al., 1992; Cerdà and García-Fayos, 1997). Others have reported a decrease in infiltration with increasing slope (e.g. Chaplot and Le Bissonnais, 2000; Essig et al., 2009). Fox et al. (1997) observed decreasing infiltration rates with increasing steepness up to a critical threshold of ~18%; beyond this threshold infiltration rate remained unchanged. Cheng et al. (2008) determined a similar threshold of ~36%. More counterintuitive are the studies that showed increased infiltration rate with increasing slope gradient (e.g. Poesen, 1986; Abrahams et al., 1988; Assouline and Ben-Hur, 2006). Poesen (1986) inferred that increased infiltration on steeper slopes resulted from reduced soil crusting, due to the inverse relationship that links slope gradient and raindrops kinetic energy per unit surface area. Similarly, Ribolzi et al. (2006) observed that the steep windward slopes of sandy micro-dunes which are exposed to raindrop impacts and sandstorms, exhibit no or very few thin surface crusts, and are therefore most infiltrable. In Southeast Asia, based on rainfall simulations on shallowly tilled loamy soils, Janeau et al. (2003) clearly found a positive relationship between infiltration and slope gradient. Following Poesen (1986), they interpreted this significant effect as a result of increased crusting on gentler slopes; on this loamy soil, they identified packing crusts made of highly stable tightly micro-aggregates, and observed more compacted surface features on gentler slopes. Contrary to Assouline and Ben-Hur (2006) who worked on a sandy soil, Janeau et al. (2003) observed a reduction in soil detachment as slope gradient increased.

The formation of structural crusts at the surface of bare soils exposed to the direct impact of raindrops is dominated by a wide variety of factors including soil properties, rainfall characteristics, and flow conditions (e.g. Assouline, 2004). A number of experimental studies have investigated the relative effect of the factors that determine crust formation (i.e. soil texture, wet antecedent conditions, rainfall intensities and kinetic energy, and biotic factors), either during its dynamic stage (e.g. Valentin, 1991; Fang et al., 2007), or once the crust is fully developed (e.g. Valentin and Bresson, 1997; Wakindiki and Ben-Hur, 2002; Valentin et al., 2004). Bresson et al. (2004) generated high resolution bulk density profiles using X-radiography imaging which allowed them to confirm that slaking, infilling and coalescing structural crusts are characterised by a non-uniform vertical structure. However, up to now, researchers seldom investigated the effect of slope gradient on the lateral uniformity of soil surface crusting and hence on infiltration rate.

The purpose of this study is twofold: (1) to gain more insight into the interactions among slope gradient, rainfall, surface features (microrelief and crusting), infiltration and soil detachment; and (2) to develop a model of infiltration on steep slopes.

2. Materials and methods

2.1. Study site

The study site is located in a headwater catchment, 10 km south of Luang Prabang city in Northern Lao P.D.R. (Fig. 1a). The mean annual temperature is 25.3 °C. Two distinct seasons characterize the study site: a wet season from mid-May to mid-October and a dry season from November to March. The mean annual rainfall recorded at Luang Prabang from 1960 to 2006 is 1263 mm, about 77% of which falls during the monsoon season, with high inter-year variability (*SD* [standard deviation] = 345 mm, *VC* [variation coefficient] = 27%) with a minimum of 444 mm and a maximum of 2100 mm. Altitudes within the catchment range from 435 to 716 m. The mean slope gradient is 52% with a maximum of 135% and a minimum of 1% (*SD* = 21%, *VC* = 41%). This catchment is representative of the slash and burn system of Southeast Asia (Fig. 1b) with no chemical inputs and submitted to a reduction of the fallow period from 10–15 years to 5–2 years. The geological substrate is mainly constituted by argilites, siltstones and fine-grained sandstone from Permian to Upper Carbonifer (Department of Geology and Mines, 1990/1991). The soils are classified in three major orders (US Taxonomy soil classification system): Entisols, Utisols and Alfisols which occur over about 20%, 30% and 50% of the catchment area, respectively. The experimental plots described in the following section were located on Alfisols.

2.2. Experimental plots preparation and description

Two experimental plots, Plot75 and Plot30 roughly 10 m^2 each, were set up along a hillslope representative of the catchment (Fig. 1a). Prior to the experiment, they were hoed to a depth of ~0.07 m and rolled to produce a seedbed with aggregates less than 4 mm (Fig. 2a) according to the protocol of Fox et al. (1997). Care was taken to avoid generating any microrelief at the surface of the soil and to reproduce similar surface conditions in the two plots. A 1 × 1 m rigid metal frame was then installed at the centre of each plot. The lateral sides of these frames were inserted to a depth of 0.1 m (Fig. 2b). Subsurface fluxes within the seedbed, from the upper to the downsides of the frame were free.

The two plots were selected so as to belong to the same soil type (Alfisol) but differ greatly in slope gradient. Plot75 was placed on the upper part of the hillslope and had a mean slope gradient of 75%, while Plot30 was installed on the lower part and had a mean slope gradient of 30%. The initial overall slope gradient of the plots was accurately measured using a spirit-level. Table 1 shows some physico-chemical characteristics of the top-soil layer (i.e. material used to prepare the seedbed) for the two plots. The texture, determined by the classical pipette method, was clay loam in both situations. The organic matter content, estimated by the Walkley-Black method, was fairly large (4.1–4.4%) and similar in the two plots. Bulk density (g cm^{-3}) prior to seedbed preparation was assessed using a standard 100-cm^3 cylinder (height 6 cm, diameter 4.6 cm). The resultant values were also similar in the two plots. The mean antecedent bulk density for the seedbeds, assessed by filling a standard 100-cm^3 cylinder with the seedbeds material, was 0.82 g cm^{-3} (*SD* = 0.07 g cm^{-3}, $n = 8$).

2.3. Procedure for simulating rainfall

The experiment was conducted during the dry season (early February). Two successive simulated rains (Table 2) were performed on each plot using a portable field simulator (Casenave and Valentin,

Download English Version:

https://daneshyari.com/en/article/4685709

Download Persian Version:

https://daneshyari.com/article/4685709

Daneshyari.com