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Clay dispersion: An important factor in channel runoff generation in a semi-arid, loess-covered area with very low rain intensities

Aaron Yair [a,*], Naftaly Goldshleger [b,c], Milica Kasanin-Grubin [d]

[a] Department of Geography, Hebrew University of Jerusalem, 91905 Jerusalem, Israel
[b] Soil Erosion Research Station, Ministry of Agriculture, Bet Dagan, Israel
[c] Ariel University, Department of Civil Engineering, Ariel, Israel
[d] Institute of Chemistry, Technology and Metallurgy, Belgrade, Serbia

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ABSTRACT

Overland flow is usually regarded as an important contributor to storm channel flow. This observation is certainly applicable to dryland areas, where base flow is often irrelevant, particularly in small watersheds. This study examines channel runoff generation in the extensive loess-covered areas that characterize the mildly arid area of western Israel, where the average annual rainfall is 280 mm. Hydrological data point to a peculiar hydrological behavior of the ephemeral streams that experience a high frequency of sporadic channel flow events. Even in extreme rain events, peak discharges are exceptionally low, indicative of a limited contributing area. Hydrographs are characterized by very steep rising and falling limbs, usually representative of saturated areas, located in the vicinity of the runoff recording station. Based on this observation, we advanced the hypothesis that storm runoff originated in the limited area of the active channel, with negligible runoff from the adjoining hillslopes. We argue that a quasi-permanent surface seal, at the top of the alluvial deposit, drastically limits the hydraulic conductivity of the alluvial fill, allowing runoff generation at very low rain intensities. The occurrence of the surface seal is ascribed to the combination of two main factors. A high clay content (~40%), where the dominant clays are smectite and illite, characterized by a laminar structure and a high-water absorption capacity. The swelling of the clay particles considerably reduce the porosity of the alluvial material, allowing runoff generation at very low rain intensities while limiting the depth of water penetration in the channel itself. Data presented fit the concept of "Partial Area Contribution" identified in humid areas. However, the application of this concept to dryland areas is based on completely different reasons.

1. Introduction

The term rain-splash is often used to describe the effects of raindrop impacts on a bare soil. The beating action of the raindrops leads to the breakdown of soil aggregates, to soil detachment, surface sealing, runoff generation and soil erosion. A vast literature exists on various aspects of rain-splash effects (Ellison, 1947; Young and Wiersma, 1973; Lattanzi et al., 1974; David and Beer, 1975; Meyer et al., 1975; Schultz et al., 1985; Poesen, 1986; Mualem et al., 1990; Hoffman and Ries, 1991; Parsons et al., 1994; Romkens et al., 1995; Sharma et al., 1995; Terry, 1998). There is a general agreement that rain-splash detachment depends greatly on raindrop size and kinetic energy. The development of a soil crust under the impact of raindrop increases the soil strength, reduces the hydraulic conductivity and increases runoff generation (Moore, 1981; Mualem et al., 1990; Mualem et al., 1993; Assouline and Mualem, 1997; Richard, 2001; Malam-Issa et al., 2004; Assouline and Mualem, 2006; Knapen et al., 2007). Three topsoil crusts have been identified: (1) structural crusts, (2) depositional crusts and (3) crusts caused by "slaking". Structural crusts result from the destruction of soil aggregates by raindrop impact (Chen et al., 1980; Agassi et al., 1981; Valentin and Bresson, 1992). Boiffin (1986), Ben-Hur (2008), and Goldshleger et al. (2002, 2009) state that intermittent rainfall has a greater sealing impact than continuous rain. Depositional crusts are formed by the deposition of fine-grained particles at the end of a flow (Chen et al., 1980; Southward et al., 1988; Tarchitsky et al., 1984). The term "slaking" is often used for crusts that develop due to the swelling of clay particles. During soil wetting (in the absence of raindrop impact), clay swelling and soil dispersion are the important mechanisms responsible for the reduction of connected pores in the soil (Chen et al., 1980; Shainberg and Letey, 1984; Tarchitsky et al., 1984; Southward et al., 1988; Casenave and Valentin, 1992). Due to water absorption, the clay particles expand, turn into a slush and fill the small interstices, leading to the development of a very efficient seal and fast

* Corresponding author.
E-mail address: aaron.yair@mail.huji.ac.il (A. Yair).

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runoff generation (Casenave and Valentin, 1992). Furthermore, slaking leads to aggregate disruption and the formation of structural crusts in which the original macro-porosity is destroyed.

Regardless of the type of surface crust, a basic requirement for the development of a surface seal is a high percentage of clay minerals. According to Abo-Shahar et al. (1987), Ben-Hur and Lado (2008), and Shainberg et al. (1997), a clay content below ~20% will not allow the formation of an efficient seal. Above ~40% there is a rapid increase in the chances for clay dispersion, and surface sealing. The mineralogical composition of the clay fraction also plays an important role in surface sealing (Stern et al., 1991). Clay particles, due to their large surface area, are the dominant factor in soil water retention, especially the highly dispersive smectite clay. Smectite and illite, characterized by their high expandable capacity, play an important role in surface sealing, especially in semi-arid areas where these clays are very widespread (Oster et al., 1980; Katzman et al., 1983; Magaritz et al., 1988; Singer, 1988; Singer, 2002; Lado and Ben-Hur, 2004; Sandler, 2013). The high-water absorption capacity of these expandable clays reduces the effective porosity of the soil (Kutilek, 1996; Moutier et al., 1998; Shabtai et al., 2014).

Notwithstanding the conditions listed above, one would not expect rain-splash to play an important role in runoff generation in areas characterized by low rain intensities. In addition, the importance of rain-splash would be expected to be negligible in a vegetated area where the vegetation cover limits the direct raindrop impact on the underlying soil.

All works cited above refer to the process of overland flow generation over hillslopes. They cannot explain a high frequency of storm channel flow in areas where hillslope overland flow is negligible due to the combination of low rain intensities and high final infiltration rates of the local soil. Such a situation has been recently described in a semi-arid, loess-covered area, where average annual rainfall is 280 mm. (Yair et al., 2016). Hydrological data available for the Haggedi watershed (11 km^2) point to a peculiar hydrological behavior of the ephemeral streams in this loess-covered area. The frequency of sporadic flow events is extremely high (4–8 flows per year). However, even during extreme rain events, peak discharges are exceedingly low (0.23–0.4 $m^3\ s^{-1}$; Fig. 1), representing no more than ~0003% of the rain received by the whole watershed at peak flow. The limited runoff in the Haggedi watershed sharply contrasts with hydrological data reported for the hyper-arid Dead Sea area and the southern part of the rift depression. Recorded peak flows in these areas (for drainage basins draining ~10 km^2) vary in the range of 80–120 $m^3\ s^{-1}$ (Greenbaum et al., 2010; Tarolli et al., 2012).

The hypothesis advanced here for the very high frequency of storm flows and very low peak discharges under low rain intensities was that storm channel flow originated in the channel itself, with negligible contribution from the adjoining hillslopes. This hypothesis is based on several indirect considerations. (1) Hydrographs are characterized by very steep rising and falling limbs characteristic of saturated areas that respond quickly to rainfall. (2) Channel runoff occurred even at rain intensities as low as ~4 mm/h (Fig. 1). Such rain intensities are below the final infiltration rates reported for the loess soils in the study area of 10–15 mm/h (Rawitz and Hillel, 1971; Morin et al., 1979; Kadmon et al., 1989). (3) A detailed study of the chemical variation of soil properties along a hillslope 400 mm long in the Haggedi watershed, shows no significant differences in the downslope direction. Similar results were also obtained for the particle size distribution and the soil moisture content (Yair et al., 2016). The lack of pedological trends in the downslope direction is regarded as an indication of the limited hydrological connectivity along the slope, and therefore negligible runoff contribution to channel flow.

The major aim of the present study is to provide direct evidences in support of the hypothesis that runoff generation is limited to the channel area where a quasi-permanent seal at the top of the alluvial deposit drastically limits the hydraulic conductivity of the alluvial fill, allowing runoff generation at very low rain intensities. The occurrence of the surface seal is ascribed to the combination of two processes: (1) deposition of compacted fine-grained particles characterized by a very low efficient porosity, and (2) slaking, or clay dispersion, in the upper part of the alluvial fill.

2. Location and methodology

The study area is located in the northern Negev Desert, where the average annual rainfall is 280 mm (Fig. 2). It is characterized by an extensive aeolian loess deposit cultivated with annuals (Fig. 3). The loess mantle was deposited during a wet climatic phase in the Upper Pleistocene (Bartov et al., 2007; Crouvi et al., 2009; Lisker et al., 2010; Torfstein et al., 2013). The loessial soil is classified as a brown-grumusolic soil with a clay-loam texture (Wieder et al., 2008). The area is characterized by extensive flat areas devoid of a well-organized drainage network (Fig. 4) except for a few wide channels characterized by steep vertical banks. The vertical banks display a dense network of pipes at a shallow depth of 30–50 cm (Fig. 5). Channel width in these streams is 5–10 m.

The methods focus on identifying the factors that may affect the hydraulic conductivity of the upper part of the alluvial fill. We first described the stratigraphy of the upper part of the alluvial deposit. We used images of the upper part of the alluvial material produced with an Environmental Scanning Microscope (ESM) to provide relevant data regarding the structure and porosity of the top of the alluvial fill, and their possible effects on infiltration. Photos of the upper part of the alluvial material, obtained with an Environmental Scanning Microscope (ESM), may provide relevant data regarding its structure and porosity, and their possible effects on infiltration. Because surface sealing requires a high percentage of clay (Lado et al., 2004; Oades and Waters, 1991), we determined the particle size distribution of the alluvial deposit down to 80 cm. We determined the abundance of expandable clays by analyzing the clay mineralogy using x-ray diffraction (XRD) from a sample taken from the top of the alluvial deposit. The XRD analysis of the clay fraction was conducted by the Geological Survey of Israel. Due to the high frequency of flow events that sometimes last for several hours (Fig. 1B), one would expect deeper infiltration

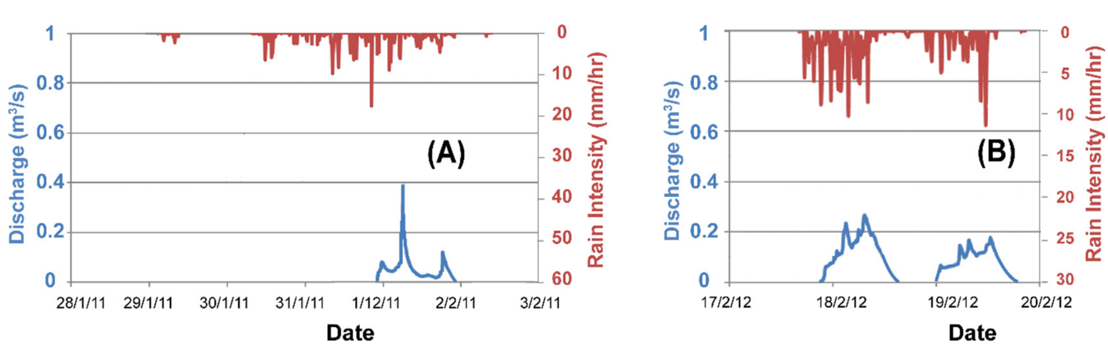

Fig. 1. Representative hydrographs recorded in the Haggedi basin. (A) High intensity rainfall, steep rising and falling limbs of the hydrograph, and low peak discharges. (B) Low rain intensities, continuous rainfall and runoff at very low peak discharges.