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Significance of preferential flow at the rock soil interface in a semi-arid karst environment

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ABSTRACT

In many semi-arid environments, the surface materials are frequently characterized by thin soils and large proportions of bare rock, both of which are expected to considerably influence infiltration and groundwater recharge processes. In this study, small plot scale irrigation experiments in combination with dye tracer application, as well as real-time and subsequent soil moisture measurements and soil particle size analysis, were conducted to investigate the significance of preferential flow at the rock soil interface. Large scale assessments of soil depth and surface type distribution were used to upscale the findings of the irrigation experiments to the scale of a complete hillslope and, further, to estimate percolation properties of a hypothetical rainfall event.

The two experimental plots were each located in the West Bank Mountains close to Ramallah. Each irrigation experiment was designed with 50 mm of precipitation, applied on an area of 1 m^2 during the course of ca. 2.5 h. Each irrigation plot had a surface share of approximately 50% rock outcrop and 50% soil surface. Percolation properties were investigated by subsequent soil moisture measurements at high spatial resolution on vertical soil profiles on the irrigated plot. Dye tracer application on the rock outcrop during the sprinkling allowed for tracking of resulting outcrop runoff in the subsurface.

The soil depth survey included 2100 measurement points on 7 transects, which allowed the estimation of local soil depth distribution. Results of the irrigation experiments showed that precipitation-induced runoff from rock outcrops continued below ground as preferential flow along the rock–soil interface, while water from the soil surface percolated mainly vertically and much more homogeneously. This was evident from the high density soil moisture measurements, as well as from the dye tracer patterns. Outcrop runoff percolated faster and to greater depths than water infiltrating directly from the soil surface, thus possessing a greater potential for groundwater recharge.

1. Introduction

The concept of non-uniform or preferential flow in the vadose zone was introduced in the 19th century by Schumacher (1864) and Lawes et al. (1882) and has been studied intensively ever since. Preferential flow is known to be induced by soil macropores, either through abiotic swell and shrink behavior or biotic processes, such as earthworm burrows and root channels (Beven and Germann, 1982, 2013). At larger scales, preferential flow is mostly due to spatial differences in soil conductivity, such as layering or change in stone content. This can be studied using infiltration experiments (Hendrickx and Flury, 2001).

Since the high hydraulic conductivity of karstified limestone allows for a relatively fast infiltration into the uppermost layer on the fractured bedrock, preferential flow can only be expected to occur on a relatively small scale. This was demonstrated by Wilcox et al. (2008), who studied the hydrologic response of a semi-arid karst in Texas. They found lateral preferential flow to be dominant inside fractured bedrock, while runoff on the soil–rock interface was of minor importance at the hillslope scale. There are many studies which demonstrated that infiltration rates on Mediterranean soils usually exceed occurring precipitation and that most surface runoff follows soil saturation (Cerdà, 1996, 1997, 1998).

Studies in semi-arid areas about the effect of discrete stones on infiltration were summarized by Wilcox et al. (1988). The studies included by Wilcox et al. (1988) show a positive correlation between stone cover and infiltration rates due to the fact that the stones provide protection from splash erosion and surface sealing. Poesen et al. (1990) demonstrated that the direction of the correlation depends on whether the rocks lay on top of the soil or are embedded within. In the latter case, a negative correlation between stone cover and infiltration rate was reported because of a reduction of the surface area where infiltration may take place (Cerdà, 2001).

Particular features of karst generally promote preferential flow into the bedrock, since its surface is mostly uneven and highly fractured. In

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solid carbonate rocks, cracks and fissures are enlarged by chemical dissolution (Ford and Williams, 2007). The dissolution widely depends on flow rates and on the degree of undersaturation of dissolved carbonate in the water. Once a preferential flow path is established, a positive feedback due to higher water flow and higher undersaturation of dissolved carbonate in this flow occurs, leading to intensified dissolution and widening of flow paths (Williams, 1983; Liedl et al., 2003). It is still unclear, if similar processes take place at the interface of the soil and the epikarst.

Spatial infiltration patterns in Mediterranean karst were found to be highly dependent on surface components, such as hydrophobic crusts and stone cover, as well as on the presence of vegetation, which allows for preferential flow along root channels (Abrahams and Parsons, 1991; Cerdà, 1997; Bergkamp, 1998; Ruiz Sinoga and Martinez Murillo, 2009; Cantón et al., 2011). Cammeraat et al. (2010) showed that wetting front propagation is faster under plants compared to bare soil and hypothesize that plants redistribute rainfall through their stem–root flow system. Furthermore, the distribution of vegetation may also depend on external factors such as grazing (Kröpfl et al., 2011).

Differences in hydraulic conductivity of surface components can lead to surface water redistribution through discontinuous runoff if the infiltration capacity of crusted or stone-rich surface sections is locally exceeded (Bergkamp, 1998; Calvo-Cases et al., 2003). Redistribution of surface water is most intensive in areas where rock outcrops display large proportions of nearly sealed surface areas. This was demonstrated by Lange et al. (2003) and Yair (1983), who conducted large scale irrigation experiments in the Judean Mountains and on a hillslope in the Negev Desert. In both experiments, discontinuous runoff from rock outcrops occurred almost immediately after the start of the sprinkling, but later dissipated into the surrounding soil. Continuous runoff did not occur until complete saturation of the soil pockets around the outcrops was reached. This raises the general question how outcrop runoff is distributed in the surrounding soil. Depending on the saturated conductivity of the soil, outcrop runoff might either directly infiltrate along preferential flow paths until reaching the bedrock, or it may successively exceed the infiltration capacity of the topsoil around outcrops, causing it to infiltrate over a larger area. The ecological effect of water redistribution from rock outcrops on the nearby vegetation was shown during afforestation (Jiménez et al., 2013) and land rehabilitation of limestone mines (Raizada and Juyal, 2012). Overland flow contribution from outcrops may be regarded as an important component to combat desertification, which is a common problem in dryland karst (Bai et al., 2013).

In sum, preferential flow must be considered an important hydrological process on semi-arid slopes, while the connection between soil water dynamics and deep percolation remains largely unknown. Measuring dripping rates in karstic caves in response to rainfall events has proven to be a valuable method to investigate this issue. Arbel et al. (2010) conducted a tracer study in a karst cave in the Carmel Mountains (Israel) in the rainy seasons of 2005 to 2007. Post-storm preferential flow dominated deep percolation with effective vertical travel times of 35 cm h^{-1} to 41 cm h^{-1}. However, post-storm dripping was only observed after the cumulative precipitation of the respective rainy season exceeded 120 mm. Lange et al. (2010) conducted a sprinkling experiment above the same cave, measuring dripping response in the cave. Bromide and electric conductivity were used as tracers and yielded additional information on flow patterns. Bromide tracing revealed vertical flow velocities of up to 4.3 m h^{-1}. A mixing analysis suggested that old water in the vadose zone was mobilized via piston flow. The study confirmed that under dry conditions significant quantities of water – in this case more than 70 mm over the course of 7 h – have to be applied before deep percolation is initiated.

It is the aim of this study to investigate the role of preferential flow at the rock–soil interface, its potential to contribute to deep percolation and groundwater recharge. Infiltration characteristics along the soil–rock interface and in the soil matrix are determined via irrigation experiments with dye tracer application, as well as subsequent high-density spatial soil moisture measurements along vertical profiles in the irrigated plot. This data is used to assess and compare infiltration patterns along the soil–rock interface and in the soil matrix. In a second step, it is used together with an extensive set of soil depth measurements to upscale the effect of the rock–soil interface for a whole slope. While it is beyond the scope of this study to predict actual recharge rates at the study site, the percolation below the soil layer and into the epikarst at least offers an indication as to potential recharge mechanisms, thresholds and the temporal distribution of infiltration. This type of information is essential to understand rapid recharge mechanisms as described in Rushton and Ward (1979), Geyer et al. (2008) and Schmidt et al. (2014).

2. Study site

The two experimental slopes are located close to Ramallah on the eastern flank of the West Bank Mountains (Fig. 1).

The NNW exposed Ein Samia hillslope is located southeast of the Ein Samia well house and stretches from 409 m to 474 m AMSL. In its lower part, the slope is rather uniform and flattens towards the hilltop. Steeper sections with widely exposed rock are found in the eastern part of the slope. Many surface features reflect the long history of various types of land use, such as grazing and historic terraces, as well as antique ruins and burial grounds. Bare rock and annual plants cover most of the area; select areas are occupied by a shrub layer, which consists mainly of *Poterium spinosum*. Average rainfall yielded 315 mm a^{-1} in the rainy seasons from winter 2009 to spring 2012. Rendzina and Terra Rossa soils are dominant in the region, including the experimental slopes (Dan and Raz, 1970). Due to multiple fault lines in the direct vicinity, the geology of the Ein Samia hillslope is quite complex. Six different strata of limestone and dolomite from the upper Cretaceous are found in addition to Quaternary sediments on the valley floor (Begin, 1974).

The ESE-exposed Kafr Malek hillslope is located north-west of the eponymous village. Experiments were conducted at levels ranging between 737 and 814 m AMSL. The slope angle ranges from extremely steep at the peak of the hilltop to moderate at the hillside toe. The surface cover is composed of rock outcrops and soil pockets covered by shrubs, which consist almost exclusively of *P. spinosum*. Current and historic olive cultivation led to considerable soil displacement over the entirety of the lower and middle slope. Rainfall from winter 2009 to spring 2012 yields on average 466 mm a^{-1}. The study area consists solely of a hard dolomite limestone (Shachnai, 2000).

3. Methods

3.1. Soil texture analysis

We collected two samples at each of the ten plots of the sprinkling experiments and three additional locations at a depth of 10 cm. The first sample was collected directly at the rock–soil interface and the second one in a horizontal distance of 50 cm from the interface. We compared the two groups of samples regarding particle size distribution and organic carbon content.

The particle size analysis was performed using the Köhn-pipetting-method (ISO DIN 11277, 2002), where the rate of descent of the soil particles is used as a proxy for particle size. The fraction of particles with a diameter of >0.063 mm was determined by wet sieving. The soil organic carbon content was measured with a combined effort of the Woesthoff apparatus and a Carlo Erba NA 1500 Series 2 CNS-analysis device. The first was used to determine the amount of inorganic carbon, while the latter measures the amount of total carbon. The difference of the two values accounts for the soil organic carbon. Since the root mean square deviation of the sample groups were not equal, the two-sided