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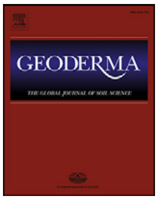

The effect of spatial soil variation on the hydrology of a semi-arid Rocky Mountains catchment

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ABSTRACT

Soil properties can exhibit strong spatial variability, even at the small catchment scale. However, the hydrological implications of actual variability remain widely unknown since the required data are not easily collected. This is especially true for observations of covariation between local soil properties and local hydrological fluxes (e.g. evapotranspiration and drainage) and/or vegetation. We studied the impact of soil variation on the discharge of an incised catchment in the Colorado Rocky Mountains. Soil variation was determined by field and laboratory work on 100 soil profiles in the catchment. Soils were found to have substantially variable properties but had on average sandy texture, weak structure and limited depth to bedrock. Observed soil properties were translated into hydraulic properties using pedotransfer functions and then used in a 1D hydrological model based on Richards' equation to quantify the effect on hydrological fluxes. Hydrological model results indicated that the effect of soil variation on the variation of hydrological model outputs was larger than the effects of variation in topographic influenced parameters. Dependent on the hydrological model output, variation in soil hydraulic parameters is more important than the variation in soil depth and vice versa. Spatial variation of hydrological characteristics is underestimated when spatial variation of the soil information is unknown. As a consequence, knowledge on the spatial variation of input data is important for policy and water-management in order to include spatial variation in the prediction of dry season streamflow in semi-arid catchments.

1. Introduction

Knowledge of the distribution of soils is essential for an understanding of the natural environment. This is because soil properties affect processes such as the hydrological response to rainfall (Lee and Yang, 2010), vegetation growth (Burga et al., 2010) and the risk of erosion and landslides (Thiemeyer et al., 2005). Therefore, knowledge on the effect of soil variability is essential for land use planning and water management (Baartman et al., 2013; Sonneveld et al., 2005). So far however, limited attention has been paid to the role of actual soil variation in determining the hydrological behaviour of catchments. This is possibly the case because soil mapping at a detailed spatial scale is time-consuming.

Recent work in this field, often under the name hydropedology (Bouma et al., 2011; Pachepsky et al., 2006), has highlighted the importance of variation in physical soil properties. Spatial variability in soil properties has often been studied by means of soil moisture variability (Geroy et al., 2011), since soil moisture can easily be measured in the field and is strongly related to soil properties. Vachaud et al. (1985) reported first on the consistent relation between local soil moisture and soil texture. The effect of soil texture on soil moisture and hydrological response is now well-known and has been studied extensively in models and observations (Martinez et al., 2013). Besides soil texture, also soil depth, vegetation properties, and topography affect soil moisture variability. Takagi and Lin (2012) found that local soil depth showed a significant correlation with soil moisture in addition to texture and topography. The effect of topography on soil moisture variability varies with wetness: under wet conditions the soil moisture pattern might reflect topography (Grayson et al., 1997), whereas under dry conditions little correlation with topography exists and local soil and vegetation controls dominate (Grayson et al., 1997; Mahmood and Vivoni, 2011; Penna et al., 2009). Teuling and Troch (2005) showed that although topography, texture and vegetation all influence soil moisture variability, the relative magnitude of these controls can vary strongly. Given the strong effect of spatially variable soil, vegetation and topographic controls on soil moisture, any attempt to simulate variability in hydrological processes at the catchment scale should at least account

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for variability in these properties. Despite the attention for this topic in modelling studies using assumptions of soil variability (e.g. Herbst et al., 2006; Meyerhoff and Maxwell, 2011), only Merz and Mosley (1998) to our knowledge have quantified the effect of soil properties on hydrology. They based this on observations of soil variability — although at an aggregated rather than point scale.

An important reason for this limited use of soil variability in catchment scale studies is the fact that it is difficult and labour intensive to measure soil hydraulic parameters, in particular saturated hydraulic conductivity (McBratney et al., 2002; Pachepsky et al., 2006; Schaap et al., 2001; Vereecken et al., 1988; Wösten et al., 2001). Nevertheless, methods such as pedotransfer functions (PTFs) that relate simple soil properties to complex soil hydraulic parameters are available (Bouma, 1989). Such methods allow a more widespread use of soil variability in hydrological modelling studies than currently the case, as illustrated among others by Temme et al. (2012). This is despite discussions about the validity of large-scale inferences from small-scale observations through PTFs (Jarvis et al., 2009; Twarakavi et al., 2010). In particular when a limited amount of data has been used to derive PTFs, this can result in large uncertainty in simulated water fluxes (Soet and Stricker, 2003; Teuling et al., 2009). Currently, ROSETTA (Schaap et al., 2001), which allows for estimation of the parameters of the van Genuchten model, is among the most widely used PTFs and has been shown to yield satisfactory results (Rubio et al., 2008; Schaap et al., 2001), ROSETTA has been used in this study.

There have been only few observation-based studies that use the opportunities offered by PTFs to quantitatively compare the effect of soil variation to the effects of other types of variation such as snow melt and vegetation on the hydrology of a catchment. The objective of this work is such a comparison, which we perform in a steep, incised catchment in the Colorado Front Range of the Rocky Mountains: Gordon Gulch. Gordon Gulch is easily accessible and one of the catchments studied in the Boulder Creek Critical Zone Observatory (CZO (Anderson et al., 2013; Befus et al., 2011; Langston et al., 2011)), which allowed the use of a rich existing dataset. In particular, we focus on the effect of spatial variability in soil hydraulic parameters on the simulation of leakage below the rooting zone, which is of key importance for water management in semi-arid regions since it controls the discharge in the dry season.

2. Study site

Our study site is the Lower Gordon Gulch catchment, a subdivision of Gordon Gulch. Gordon Gulch (Fig. 1) is located in the upper montane zone of the Colorado Front Range of the Rocky Mountains, a 50 km wide mountain range that rises from the Colorado High Plains to the Continental Divide.

The catchment has been carved by Gordon Gulch, a stream that is intermittently higher in the valley and permanently close to its outlet. The surface area of the Lower Gordon Gulch catchment is around 1.7 km^2, and is characterised by average elevation of about 2600 m and by average slopes of 16.6°. The valley is east–west oriented, resulting in clear north–south aspect differences (Fig. 1).

The valley is largely covered by forest. Forests on north facing slopes are denser and consist mainly of Lodgepole pines (*Pinus contorta*), whilst south facing slopes have fewer trees, mainly Ponderosa pines (*Pinus ponderosa*) and have more understory (Boulder Creek CZO, 2011). Gordon Gulch is located in the montane climate zone, with large seasonal temperature differences (yearly mean temperature is around 5.0 °C). Precipitation is on average about 550 mm a year. The valley is mainly underlain by Precambrium gneisses with some outcrops of Precambrium granite, Precambrium quartz monzonite and dikes of Cretaceous quartz monzonite. Some Quaternary alluvium can be found (Buraas, 2009; USGS, 2005) in small terrace surfaces along Gordon Gulch. Soil textures are categorised as sandy loam, loamy sand and sand (Dethier et al., 2012). Landscape positions highly influence soil properties. The soils are underlain by weathered bedrock, including saprolite and saprock (for definitions see Anderson et al., 2013), which is highly permeable (Buraas and Dethier, 2010).

Previous research in the catchment was mainly performed in the framework of the Boulder Creek Critical Zone Observatory. In particular, a number of transect studies focussing on soil, hydrology and weathering differences were inspired by the clear N–S aspect differences resulting from the E–W extent of the valley (Anderson et al., 2011; Buraas and Dethier, 2010; Dethier et al., 2012; Hinckley et al., 2012; Langston et al., 2011). Overall, the south facing slopes are drier than the north facing slopes. Higher wetness and weathering rates have caused a greater thickness of saprolite and soil on the north facing slopes. This is highly influenced by the snowmelt dynamics. The north facing slopes develop a seasonal snowpack with a persistent melt input, and the south facing slopes develop episodic snowpacks and experience short periods of snowmelt (Hinckley et al., 2012).

3. Methodology

3.1. Soil inventory

Field observations were done on 100 locations in Lower Gordon Gulch. For each location, a site description was made, including observations on slope, aspect, curvature, vegetation (cover), surface stoniness, parent material, runoff features and exposed bedrock. Soil pits were dug to the weathered bedrock (saprolite or saprock), which was usually found at depths less than 40 cm. Consequently, the focus of soil description was on the upper 40 cm of the soil. For each soil pit, Master Soil Horizons were described and structure, stoniness, roots, mottles and concretions were determined using FAO soil description guidelines (FAO, 1990). Soil colour was determined using the Munsell Soil Color Charts (Munsell Color, 2009).

At every location, one sample of every soil horizon was collected together with one bulk density sample of the topsoil (a plastic corer was used to sample a constant volume of the upper 7 cm of the soil). The samples were used to measure bulk density, soil moisture content, soil porosity, texture, pH and organic carbon content in the laboratory. All samples were dried for 3 h at 105 °C, and weighed before and after drying. Based on this, bulk density and volumetric water content (bulk density sample), and soil moisture were calculated. Subsequently, the horizon samples were ground in a mortar and sieved with a 2 mm sieve to remove stones from the sample. They were then split into three subsamples. From the first subsample, texture percentages were measured by sieving and wet deposition. To separate sand from silt and clay, a 0.63 mm sieve was used. To separate clay from silt, 15 to 20 ml of the silt/clay material was mixed with water and soap in a narrow transparent tube, shaken and allowed to deposit over the course of several days. This resulted in a clear boundary between the silt and clay deposits which was measured with a 10^{-4} m ruler. From the second subsample, pH was measured with a calibrated pH meter (YSI 63 pH instrument) in a 1:2 ratio of the subsample and distilled water. From the third subsample, the organic carbon content was measured by heating a subsample of around 5 g in the oven at 550 °C for 2 h. The subsample was weighed with a scale with 10^{-4} g precision before and after drying to calculate the loss of organic carbon.

3.2. Pedotransfer functions (ROSETTA)

The well-known equations of van Genuchten (1980) were used in our model analysis (see next section). These equations describe soil water content (θ [m^3 m^{-3}]) and hydraulic conductivity (K [m s^{-1}]) as a function of the hydraulic pressure head (h [hPa]):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |ah|^n)^{1-\frac{1}{n}}} \tag{1}$$