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Impact of soil surface and subsurface properties on soil saturated hydraulic conductivity in the semi-arid Walnut Gulch Experimental Watershed, Arizona, USA

R. Becker[a,*], M. Gebremichael[a], M. Märker[b]

[a] UCLA Civil & Environmental Engineering, 420 Westwood Plaza, 6722 Boelter Hall, Box 951593, Los Angeles, CA 90095-1593, USA
[b] Pavia University, Department of Earth and Environmental Sciences, Via Ferrata 2, 27100 Pavia, Italy

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ABSTRACT

The estimation of saturated hydraulic conductivity (Ks) is of high relevance to correctly reproduce water fluxes, such as infiltration rates or surface runoff in hydrological simulations. Yet, estimation of Ks is challenging especially in semi-arid regions with particular soil surface characteristics like crusting and sealing. This study presents results of a field campaign in the semi-arid Walnut Gulch Experimental Watershed, Arizona (US), where surface and subsurface Ks measurements were undertaken across the watershed. Data of saturated hydraulic conductivity on crust covered and crust-free surfaces was collected and compared to results of commonly used methods to retrieve spatially distributed Ks data. Results reveal that methods typically used for estimating Ks, such as exponential decay functions or pedo-transfer functions (PTFs), can be inadequate in such regions. The analysis shows that in our study area the presence of surface crust is the dominating factor for determining the spatial distribution of Ks. Furthermore, the results reveal that remote sensing data can provide useful information for estimating surface Ks values as it could be successfully applied for the spatial detection of surface crust characteristics.

1. Introduction

Saturated hydraulic conductivity (Ks) is a key parameter for controlling soil moisture storage and water movement in the soil layer (Wang et al., 2013). Saturated hydraulic conductivity is therefore one of the principal parameters used in hydrological and land-surface modeling for land surface hydrology, and land surface-atmosphere dynamics. However, due to the high spatial and temporal variability of Ks as well as the effort needed for a sound ground based data collection, it is often difficult to obtain accurate Ks information at the resolution required by most hydrological or land surface models.

Often, Ks at the topsoil (hereafter referred to as “surface Ks”) is indirectly estimated from spatially available soil data like soil texture information through pedo-transfer functions (PTFs) (Saxton and Rawls, 2006; Sobieraj et al., 2001). Yet it has been shown by several researchers (Gutmann and Small, 2007; Soet and Stricker, 2003) that this approach produces large errors in the resulting Ks estimates particularly when these empirical relationships are applied to areas they were not developed for. The Ks in the subsurface layer approximately 15 ≈ 20 cm (hereafter referred to as “subsurface Ks”) is typically estimated either from PTFs (Cosby et al., 1984; Saxton and Rawls, 2006) or from surface Ks through an exponential decay function where, the decay parameter varies with soil texture (Wang et al., 2006).

Semi-arid regions have unique land surface characteristics where the soil surface layer is dominated by soil crusts, which could significantly reduce infiltration capacities and increase surface runoff (Assouline et al., 2015; McIntyre, 1957, 1975; Mualem and Assouline, 1996; Ries and Hirt, 2008; Valentin and Bresson, 1992). Many studies have indicated the importance of incorporating soil crust information into hydrological and land surface models (Casenave and Valentin, 1992; Mualem and Assouline, 1996). Simple empirical and complex numerical equations have also been developed to estimate the infiltration through soil crusts (Edwards and Larson, 1969; Hillel and Gardener, 1969). Nevertheless, such equations are rarely used in models primarily because of the several parameters that need to be estimated from field data. As a result, currently hydrological and land surface studies in semi-arid regions still use the typical approach, where surface Ks is estimated from soil texture through PTFs and subsurface Ks is estimated from surface Ks through exponential decay function whose parameter depends again on soil texture.

The purpose of this study was to investigate how to achieve accurate spatially distributed information about Ks to improve hydrological

* Corresponding author.
E-mail address: rbecker@ucla.edu (R. Becker).

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models in semi-arid regions. Within this scope we examined the validity of the commonly-used approach of estimating surface and subsurface Ks through PTFs in a semi-arid environment with crusted soil surface characteristics using in-situ field measurements of Ks as validation data. Furthermore, we used remote sensing images to delineate a crust map of the study area, which we validated using ground sampled data on presence or absence of crust layers. Subsequently, we investigated if a relationship between the in-situ Ks measurements and the remote sensing derived crust map can be established and how this method could be used to derive detailed spatial Ks information. Our study region was the Walnut Gulch Experimental Watershed (WGEW), a semi-arid region that was the site of NASA's SMAP (Soil Moisture Active Passive) Validation Experiment in 2015 (Colliander et al., 2017). The watershed is dominated by extensive crust formation at the soil surface which has a significant impact on the estimation of soil moisture fluxes in the upper soil layer, which led us to the research goals mentioned above.

2. Materials and methods

2.1. Study area

The Walnut Gulch Experimental Watershed (WGEW), located in southeast Arizona, USA, with a catchment area of 149 km^2, is one of the best instrumented research watersheds of the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) (Moran et al., 2008) (Fig. 1). Its climate is semi-arid, with long term average rainfall of 350 mm $year^{-1}$ and potential evapotranspiration of 260 cm $year^{-1}$ which is approximately 7.5 times the annual precipitation (Renard et al., 2008). It lies in the transition zone between the Chihuahuan and the Sonoran Deserts. Two-thirds of the annual rainfall falls in July and August, during the North American Monsoon season. Land use is dominated by shrub and grass covered rangeland. Soils in the WGEW have developed on top of a complex underlying geology of consolidated rocks and fan and alluvial deposits. Aridisols, are the most abundant soil types and they cover 75% of the catchment area. Entisols developed on steep slopes and cover 17%. Vertisols cover 5% of the study area and are mainly found in river beds. A minor part of the catchment is covererd by Mollisols and Alfisols which account for 3% of the catchment soils. Soil properties vary between sand and loam textures, with deeply, well drained as well as thin, young and poorly drained soil layers (Osterkamp, 2008). The meteorological as well as soil hydrological characteristics have been well documented in Goodrich et al. (2008) and Keefer et al. (2008). During our sampling activities, a clear development of soil crusts, particularly in the low-lying, flash flood prone areas, could be observed in vast parts of the watershed.

2.2. Field campaign

NASA's SMAP-Validation-Experiment-2015 (SMAPVEX15) took place in the WGEW in September 2015 (Colliander et al., 2017). The aim was to validate soil moisture data products obtained from the SMAP satellite. During the field campaign, we undertook field measurements of surface and subsurface Ks at 17 sampling sites across the watershed (Fig. 1). To test for variability of Ks at the same location, we conducted multiple measurements at selected sites and took their mean for further analysis. Standard deviations of Ks at sites with multiple samples were found to be 0.03 cm h^{-1} for surface Ks and 0.5 cm h^{-1} for subsurface Ks. The sampling sites were chosen adjacent to the USDA-ARS meteorological measuring sites in the WGEW to take advantage of the long-term database of climate and soil data at these sites. We adapted the USDA-ARS nomenclature for the station enumeration. “RG” stands for “Rain Gauge” and the number indicates the selected USDA-ARS rain gauge station of the dense WGEW gauging network.

To obtain surface Ks measurements, we performed tension

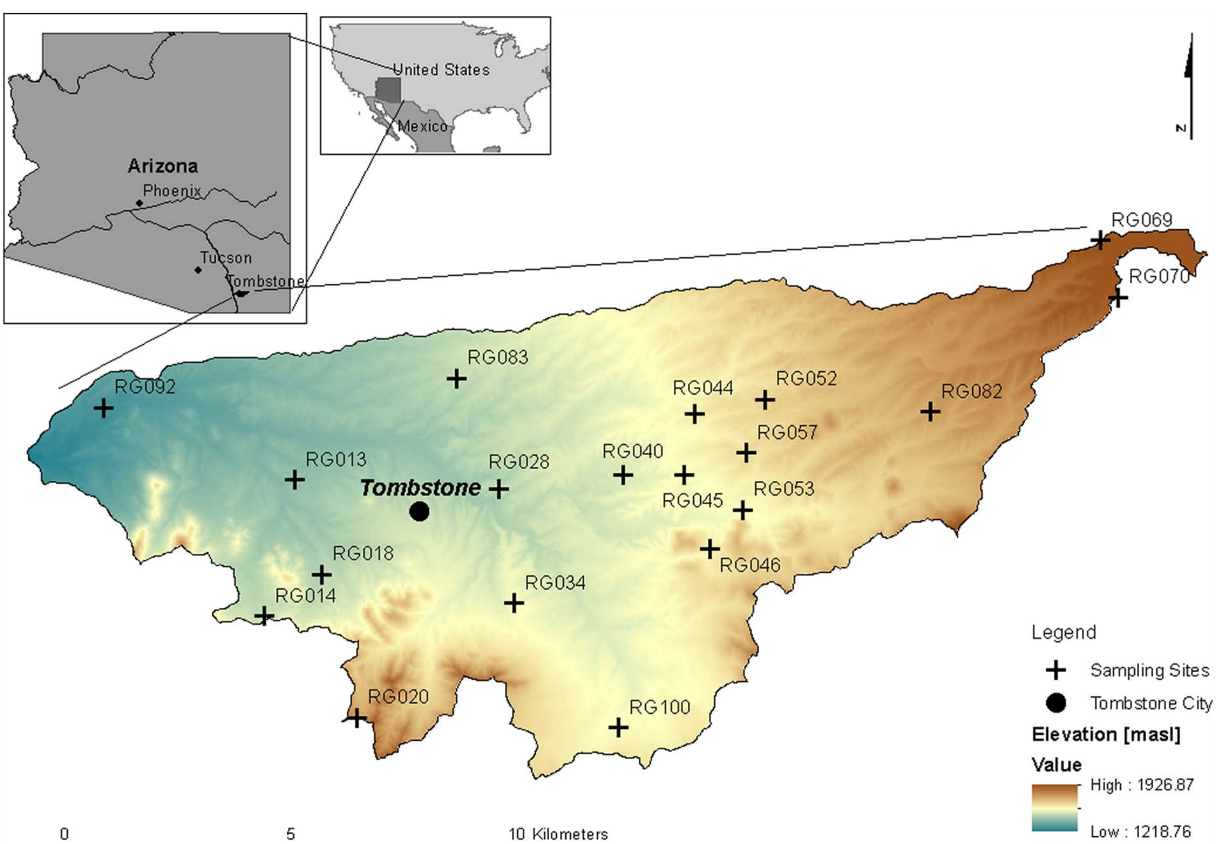

Fig. 1. The Walnut Gulch Experimental Watershed (WGEW), Arizona, US.