Geoderma 243–244 (2015) 58–68

Contents lists available at ScienceDirect

Geoderma

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

Spatial variability of saturated hydraulic conductivity at the hillslope scale: Understanding the role of land management and erosional effect

Athanasios (Thanos) N. Papanicolaou [a,*], Mohamed Elhakeem [b,c], Christopher G. Wilson [b], C. Lee Burras [d], Larry T. West [e], Hangsheng (Henry) Lin [f], Ben Clark [g], Brad E. Oneal [h]

[a] Civil and Environmental Engineering, University of Tennessee, Knoxville, TN 37996, USA
[b] University of Tennessee, Knoxville, TN 37996, USA
[c] Abu Dhabi University, Abu Dhabi, P.O. Box 59911, United Arab Emirates
[d] Iowa State University, Ames, IA 50011, USA
[e] Soil Systems LLC Fayetteville, AR 72764, USA
[f] Pennsylvania State University, University Park, PA 16802, USA
[g] Public Works Department, Iowa City, IA 52240, USA
[h] Pioneer Hi-Bred International, Inc., Johnston IA 50131, USA

ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form 7 December 2014
Accepted 14 December 2014
Available online 30 December 2014

Keywords:
Saturated hydraulic conductivity, K_{sat}
Soil properties
Management practices
Erosion
Spatial variability
Iowa

ABSTRACT

In this study, detailed field experiments were conducted at three hillslopes in southeast Iowa with different agricultural management practices, namely Conservation Reserve Program (CRP), no-till, and conventional till, to identify the effects of land use on saturated hydraulic conductivity, K_{sat}, variability. On average, 40 measurements per field were concomitantly performed using an array of semi-automated double ring infiltrometers (DRIs) to ensure adequate spatial representation of K_{sat} per hillslope. The semi-automated DRIs allowed for continuous operation up to 200 h so that a “true” steady state condition could be reached during the monitoring period. These measurements were complemented with pedon measurements for soil texture, bulk density, and other biogeochemical properties at the same locations. A statistical analysis showed that K_{sat} exhibited a log-normal distribution and the harmonic mean of the K_{sat} values proved to be the most representative mean. Two distinct patterns were observed in the developed K_{sat} spatial distribution maps for the three hillslopes. The map for the CRP hillslope showed a “strip pattern” while the cultivated fields depicted a “mosaic pattern”. The strip pattern at the CRP was attributed to past flow-driven preferential erosion along the main drainage-way, which removed the finer soil fractions and exposed a loam substratum with a relatively higher sand content that yielded higher K_{sat} values in the drainage-way. The mosaic patterns in the no-till and tilled fields were attributed to the mixing of soil from cultivation during the crop rotations. A correlation analysis between K_{sat} and different soil properties confirmed the patterns shown in the K_{sat} maps and further revealed the correspondence of K_{sat} with key soil properties. Soil texture dominated the infiltration process in soils with a higher sand content ($>15\%$), whereas bulk density dominated the infiltration process in soils experiencing the effects of compaction due to agricultural activity.

1. Introduction

The infiltration of water from rainfall, snowmelt, or irrigation into the soil is an integral component of the Earth's hydrologic cycle (Linsley et al., 1982; McCuen, 2003). When the rate of infiltration reaches a steady state condition and the hydraulic gradient is equal to unity, it is defined in the literature as the saturated hydraulic conductivity, K_{sat} (Bear, 1987; Smith, 2002). K_{sat} is believed to link uniquely hydrologic and pedologic attributes and constitutes one of the key governing landscape properties for interpreting soils (Chapius, 2012; Schoeneberger and Wysocki, 2005; Tugel et al., 2005). It directly influences the amount of runoff and eroded surface soils that are delivered to local waterways, thereby affecting both in-field soil and in-stream water quality (Abaci and Papanicolaou, 2009; Elhakeem and Papanicolaou, 2012). K_{sat} is also one of the key input variables for a majority of physically based, watershed models used for assessing the impacts of different land uses and management practices on the dynamic behavior of soil and water (Arnold et al., 1998; Elhakeem et al., 2014). Therefore, accurately estimating K_{sat} and its statistical properties is important for predicting hydrologically driven

---

[*] Corresponding author.
E-mail addresses: tpapanic@utk.edu (A.(T.)N. Papanicolaou), mohamed.elhakeem@adu.ac.ae (M. Elhakeem), cgw24@utk.edu (C.G. Wilson), lburras@iastate.edu (C. Lee Burras), larrywestar@gmail.com (L.T. West), henrylin@psu.edu (H.(H.) Lin), ben-clark@iowa-city.org (B. Clark), brad.oneal@pioneer.com (B.E. Oneal).

http://dx.doi.org/10.1016/j.geoderma.2014.12.010
0016-7061/© 2014 Elsevier B.V. All rights reserved.

processes and making catena assessments across landscapes (Lin, 2003; Tietje and Richter, 1992; West et al., 2008). It is not surprising therefore that K_{sat} is part of the core measurements in several hydropedologic studies and is often available in different multidisciplinary databases, such as the National Cooperative Soil Survey, NCSS; UNsaturated SOil DAtabase, UNSODA; World Inventory of Soil Emissions, WISE; and Database of HYdraulic PRoperties of European Soils, HYPRES (Bouma, 1989; Rawls et al., 2001; Wagenet et al., 1991; Wosten et al., 1999).

In recent years there have been several efforts aimed at developing predictive models to quantify K_{sat} from soil texture and other biogeochemical properties (Chapius, 2012; Jarvis, 2007; McKenna and Rautman, 1996; Rawls and Brakensiek, 1985; Stumpp et al., 2009; van Genuchten, 1980; Wosten et al., 1999). These models are known in the literature as Pedo-Transfer Functions (PTFs). The main assumption underlying most of the common PTFs is that textural properties dominate the hydraulic behavior of soils (Lin et al., 2014; Nemes et al., 2009; Onstad et al., 1984; Pachepsky and Rawls, 2004; Rawls et al., 2001; Risse et al., 1995; Schaap, 1999).

Many of these studies were developed for predicting K_{sat} in agricultural fields; however, they treated K_{sat} as a hydropedologic property assuming that it was independent of land use and management practices. Yet, it has been well documented in the literature that tillage-enhanced erosion, in addition to rainfall/runoff-induced erosion, not only affects the composition of surface soils but also their structure, such as the porous network and degree of compaction, all of which collectively affect the spatial distribution of K_{sat} within a field (Abaci and Papanicolaou, 2009; Kuhn et al., 2012; Mohanty and Mousli, 2000; Strudley et al., 2008; van Oost et al., 2005). This is especially germane to intensively managed agricultural landscapes, where soil structure and texture are altered due to compaction by heavy farm machinery and changes in vegetative cover during crop rotations, in addition to tillage practices (Ben-Hur and Wakindiki, 2004; Deb and Shukla, 2012; Elhakeem and Papanicolaou, 2009; Ndiaye et al., 2007; Stavi and Lal, 2011). Studies have shown that human activities and land management can have an added effect on recasting of the soil properties in space and thereby the spatial distribution of K_{sat} within a watershed (Nearing et al., 1996; Refsgaard and Storm, 1995; Taskinen et al., 2008). Therefore, we hypothesize that in intensively managed agricultural landscapes, soil properties alone cannot adequately describe the spatial variability of K_{sat} and that the impacts of crop cover and associated management practices must also be considered. We expect also that K_{sat} would exhibit high spatial variability at the hillslope scale due to various combinations of intrinsic soil properties, such as texture and bulk density, and extrinsic factors, such as land use and vegetation.

Reported K_{sat} in many soil databases were based on infrequent measurements usually acquired over coarser scales (~100 m), thereby limiting the ability to capture the effects of textural and structural changes of soil on K_{sat} variability (Papanicolaou et al., 2008; Tietje and Richter, 1992; Wang and Tartakovsky, 2011; Webster and Oliver, 2001).An adequate description of K_{sat} is also hindered by the uncertainty involved in the duration required for the hydraulic conductivity measurements to achieve a steady infiltration rate (Nemes et al., 2009). The period required to achieve a steady infiltration rate (T_s) at a measuring location can vary significantly, from several minutes up to 100 h depending on factors, such as soil texture, structure, antecedent soil moisture, tillage, and vegetation (Dorner et al., 2010; van Genuchten, 1980).

The overarching objective of this study is to improve our understanding of the effects that land use and management practices have on K_{sat} variability and offer insight on the statistical characteristics of K_{sat} from the collected data and relative to existing PTFs. A secondary objective of this research is to provide a methodology to obtain an adequate spatial representation of K_{sat} and remove the current limitations for achieving a steady infiltration rate using semi-automated double ring infiltrometers (DRIs).

2. Materials and methods

2.1. Study Site

Infiltration measurements were conducted in a 26-km^2 sub-watershed of Clear Creek, IA (Fig. 1a) that is located in the southeastern part of the state and part of the U.S. National Science Foundation Intensively Managed Landscapes-Critical Zone Observatory (IML-CZO). Clear Creek discharges directly to the Iowa River and, ultimately, the Mississippi River. The sub-watershed experiences excessive erosion rates due in part to high slopes (up to ~10%) and highly erodible, smectite soils in conjunction with the intensive agricultural activities (Abaci and Papanicolaou, 2009; Wilson et al., 2012).

Clear Creek is entirely in the Southern Iowa Drift Plain (Prior, 1991) and lies within the west-central part of the Illinois and Iowa Deep Loess and Drift Major Land Resource Area (MLRA-108C). Peorian loess, up to 15 m thick, is found on hillslope summits in the watershed (Ruhe, 1969) and, in some cases, the loess can extend to the footslope. On certain hillslopes, the loess pinches out at the shoulder or backslope exposing either a Yarmouth–Sangamon Paleosol and/or Pre-Illinoian till (Bettis et al., 2003). At the lower toeslope, a blanket of silty colluvium and alluvium can range from a few centimeters to 2 m thick. These variations in soil material along a hillslope produce a complex mosaic of texture, organic matter content, bulk density, and water holding capacity for the soils in the area (Oneal, 2009).

There are four main soil series mapped across the sub-watershed, which comprise approximately 80% of its total drainage area (Fig. 1b). The upland soils are mostly from the Tama (fine-silty, mixed, superactive, mesic Typic Argiudoll) and Downs (fine-silty, mixed, superactive, mesic Mollic Hapludalf) soil series. Both series are well-drained and formed from the Peorian loess. They are respectively considered the end members of a prairie-forest biosequence. The floodplains in the sub-watershed are comprised of the Ely (fine-silty, mixed, superactive, mesic Aquic Cumulic Hapludoll) and Colo (fine-silty, mixed, superactive mesic Cumulic Endoaquoll) soil series. These series are poorly drained and derived from alluvium.

Currently, three main corn–soybean rotations are used in the sub-watershed and have been practiced since 1991. Each rotation involves a unique set of the following management practices: no-till, reduced spring tillage, and conventional fall tillage. Hay farming, pastures, and fields enrolled in CRP comprise the remaining land uses. The management practices of the three hillslopes examined in this study are listed in Table 1 and were explained in detail by Abaci and Papanicolaou (2009).

2.2. Experimental design and test matrix for K_{sat}

Infiltration measurements and soil core extractions were performed in 2007. No measurements were conducted during freeze–thaw periods to avoid introducing errors in K_{sat} estimates from the breaking of soil aggregates during thawing.

An important element of the field design was the development of an experimental test matrix to describe the variability of K_{sat} within the hillslope and its correspondence to the collected soil core samples (Table 2). This matrix incorporated the following: (1) the dominant land use and associated land management practices per hillslope; (2) the number of infiltration measurements per hillslope; (3) the time to steady infiltration rate, T_s, per measuring location within each hillslope; and (4) important soil properties per measuring location within each hillslope (Fig. 1c–e).

The measurements were conducted using an array of semi-automated double ring infiltrometers, described in Section 2.3, at the three hillslopes, all of which exhibit a concave downslope curvature. This was by design to isolate the effects of curvature on K_{sat} with the concave curvature being the most dominant downslope curvature type in the headwaters of the Clear Creek watershed (Abaci and