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

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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

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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

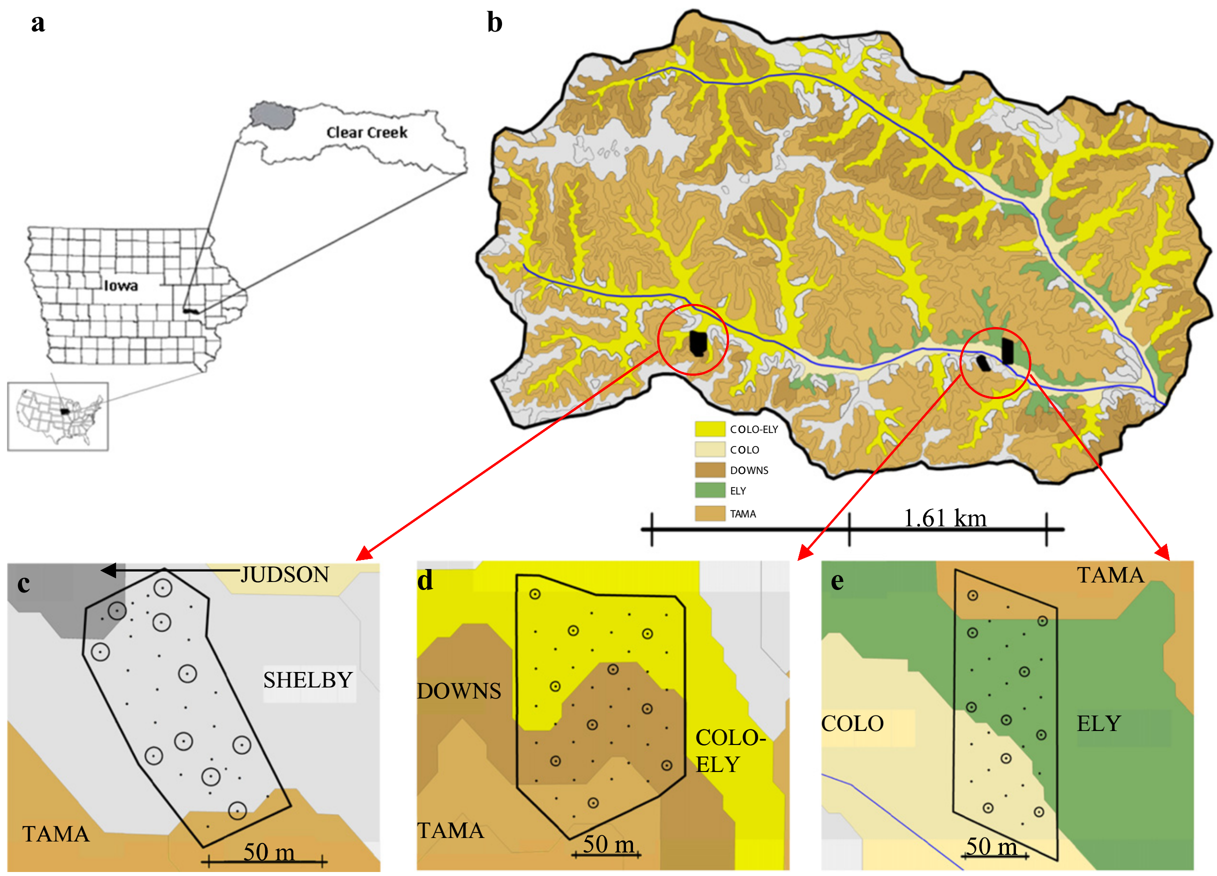

Fig. 1. The study site: (a) The sub-watershed of Clear Creek, IA, shaded in gray, where this study was conducted; (b) a soil map of the sub-watershed from the Iowa County Soil Survey showing the three hillslopes; (c) the CRP hillslope; (d) the no-till hillslope; (e) the tilled hillslope. In panels c–e, the local soil series are identified by name in each hillslope, the black dots show the measurement locations of the double ring infiltrometers, while the black circles show the locations of the collected soil cores. Multiple cores were collected some the circled sites.

Papanicolaou, 2009). Two of the hillslopes were in a 2-yr, corn–soybean rotation. In 2007, they were both cropped with soybeans. One of the two sites experienced a reduced spring tillage following a deeper tillage in the previous fall, herein called the “tilled field” and the other was under no-till, referred to as the “no-till field”. The third hillslope was enrolled in CRP (perennial brome grass) since 2001.

Fig. 1c–e shows the measurement locations in each field obtained via a Trimble GeoExplorer-3 Global Positioning System (GPS) and placed into a Geographical Information System (GIS) database. In Fig. 1c–e, the small dots depict the infiltrometer measurement locations, while the circles around the measurement locations show selective locations along the crest, shoulder and toe of the hillslopes where soil cores were extracted. The spatial density of the array of infiltrometer measurements along each hillslope was developed to provide adequate spatial representation of the soil heterogeneity effects on K_{sat} variability and at the same time eliminate bias from causal connections (i.e., high correlation) between nearby measuring locations. A second order, invariant correlation function (Witten and Sander, 1981) was used to

Table 1
Management practices used at the three hillslopes.

Hillslope	Date	Operation	Description
CRP	N/A	N/A	Un-cut bromegrass
Tilled	04/15/0001	Tillage	Field cultivator, 20 cm[a]
	05/01/0001	Planting	Corn
	10/01/0001	Harvest	50%[b]
	11/15/0001	Tillage	Chisel plow with coulters, 30.5–50.8 cm[a]
	04/15/0002	Tillage	Tandem disk, 17.8 cm[a]
	05/01/0002	Planting	Soybeans
	09/25/0002	Harvest	30%[b]
	11/01/0002	Tillage	Anhydrous applicator w/closing disks
No-till	04/15/0001	Tillage	Field cultivator, 20 cm[a]
	05/01/0001	Planting	Corn
	10/01/0001	Harvest	50%[b]
	05/01/0002	Planting	Soybeans
	09/25/0002	Harvest	30%[b]
	11/01/0002	Tillage	Anhydrous applicator w/closing disks

[a] Depth of tillage.
[b] Harvest index.

Table 2
Experimental test matrix: sampled variables and number of runs.

Test	Variable	Number of measurements per field						Total number of measurements
		CRP		Tilled		No-till		
		S	F	S	F	S	F	
Infiltration	K_{sat}	33	10	30	10	43	10	136
	Time to steady	33	10	30	10	43	10	136
Soil analysis	Bulk density[a]	45	45	–	45	–	45	180
	Clay content[a]	45	45	–	45	–	45	180
	Silt content[a]	45	45	–	45	–	45	180
	Sand content[a]	45	45	–	45	–	45	180
	Carbon content[b]	–	15	–	15	–	15	60
	Nitrogen content[b]	–	15	–	15	–	15	60
	CEC[c]	–	30	–	30	–	30	90
	pH[c]	–	30	–	30	–	30	90

– No measurements are performed; S = summer; F = fall.
[a] Measurements of 3 horizons at 15 locations in each field.
[b] Measurements of 2 horizons at 15 locations in each field.
[c] Measurements of 1 horizon at 15 locations in each field.

examine the interdependency of the measurements (I) and was expressed as follows:

$$I(\Delta x, \Delta y) = \frac{1}{(m-\Delta x)(n-\Delta y)} \sum_{i=1}^{m-\Delta x} \sum_{j=1}^{n-\Delta y} \rho(i,j)\rho(i+\Delta x, j+\Delta y) \quad (1)$$

where m and n are the number of measurements in the x and y directions, respectively; Δx and Δy denote the spacing distance of measurements of neighboring locations in the x and y directions, respectively; $\rho(i,j)$ is a density function associated with the K_{sat} magnitude variation per downslope. Theoretically, $\rho(i,j)$ is equal to 1 when K_{sat} remains constant within an area, and 0 when K_{sat} is variable. A threshold value of $I \leq 0.25$ corresponded to an average spacing of 10 to 15 m between measurement locations. As a result, roughly 30 to 50 measurements were performed per hillslope (Papanicolaou et al., 2008), which satisfied the minimum number of measurements required to provide a statistically adequate representation for data analysis (Shahin et al., 1993).

2.3. K_{sat} measurements

The double ring infiltrometer (Fig. 2a) measures vertical saturated hydraulic conductivity within the top 15 to 30 cm (6 to 12 in) of the soil surface. The infiltrometers were semi-automated by IIHR-Hydroscience and Engineering at the University of Iowa to allow for continuous operation up to 200 h, if needed, so that the steady state condition could be reached during the monitoring period. A total of thirty semi-automated DRIs were operated simultaneously in this study with minimal labor. The semi-automated DRI system (Fig. 2a) included a five-gallon water tank hung from a tripod and connected to a control valve with an adjustable tube to feed the inner ring, a data logger for recording time stamps operated via a 12-volt battery (Fig. 2a), and a five-gallon Mariotte bottle to maintain a constant water head in the outer ring. Fig. 2b shows a close-up of the set-up of the DRIs in the CRP field.

A standard procedure was followed for operating the DRIs (Smith, 2002), which began by hammering the rings into the ground to a depth of 5 to 10 cm with minimum disturbance and filling them with water to an initial ponding depth of 5 to 8 cm. A constant water level was maintained in the outer ring with the Mariotte bottle. The water level in the inner ring was allowed to drop 1.0 cm from the initial ponding depth before refilling of the inner ring. As the water level dropped, a float within the inner ring also dropped along a guide wire until it reached a predetermined depth (here 1.0 cm). At this depth, the float completed a circuit sending an electrical pulse to a controller box, which triggered a valve to open filling the inner ring back to its original depth. The time required for the water level to drop 1.0 cm was recorded continuously by a data logger. The infiltration curve for each measurement was developed from the infiltration rates (f), which were calculated as Green and Ampt, 1911

$$f = \frac{\Delta V}{A\Delta t} \quad (2)$$

where ΔV is the volume of water added to the inner ring during time interval Δt between fillings of the inner ring with 1.0 cm of water and A denotes the cross-sectional area of the inner ring. K_{sat} is the constant value portion of these developed infiltration curves.

Because the infiltrometers were capable of continuous operation up to 200 h, the time to the steady state condition could be reached during the monitoring period. Fig. 3 shows the measured K_{sat} values versus the corresponding values of time to steady infiltration rate, T_s. Past research has not provided sufficient insight into logging T_s as most studies used manually-operated infiltrometers and steady state infiltration was determined subjectively. However, in this study, the semi-automated double ring infiltrometers provided detailed recordings of T_s in the three fields. The time required to reach a steady state infiltration rate for the spatially distributed measurements varied from 10 min to nearly 100 h (Fig. 3) due to different antecedent moisture conditions, soil textures, and land management practices (Dorner et al., 2010).

2.4. Soil characterization

A total of 15 soil cores were collected in each field to a depth of 2.0 m using a truck-mounted Giddings Probe with a 7.5-cm diameter. Each soil core was characterized in-situ and at the Iowa State University Pedometrics Laboratory on a horizon-by-horizon basis using standard morphological nomenclature (Driese et al., 2001; Schoeneberger et al., 2002; Soil Survey Staff, 1998). Soil horizons in this study were determined by pedogenic breaks, with most samples being derived from the A, Bt or Bw, and BC or C. Given horizonation and horizon thicknesses were highly variable, a weighted average was determined to account for horizon depth. Each horizon was analyzed in the laboratory for particle size, and organic matter content (OM), cation exchange capacity (CEC), pH, bulk density and porosity.

Fractions of sand, silt and clay were obtained from standard sieve and hydrometer analyses (Soil Survey Staff, 2004). Organic matter was determined using the dry combustion method described by Soil Survey Staff (1996) with a Leco LC2000 (Model CHN 600, LECO,

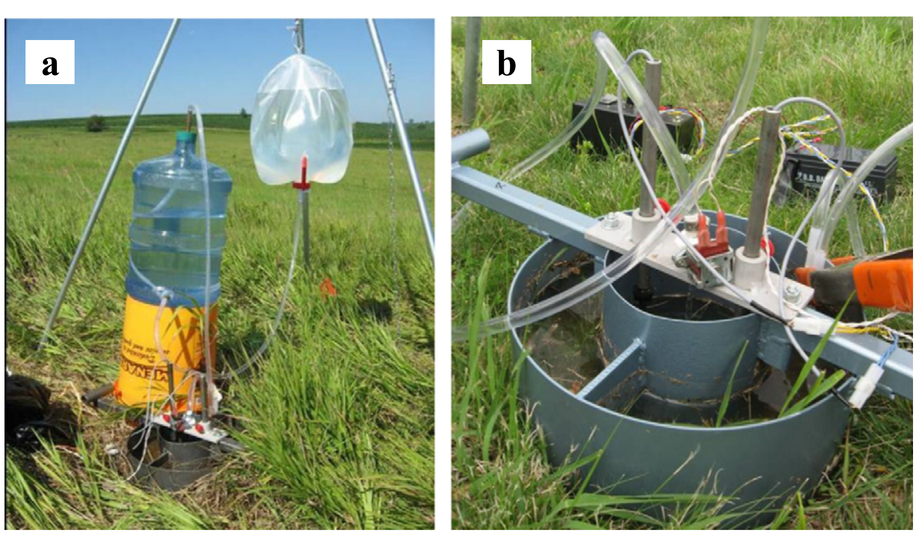

Fig. 2. The semi-automated double ring infiltrometers: (a) A complete view of the DRI system; (b) a close-up view of the infiltrometer.

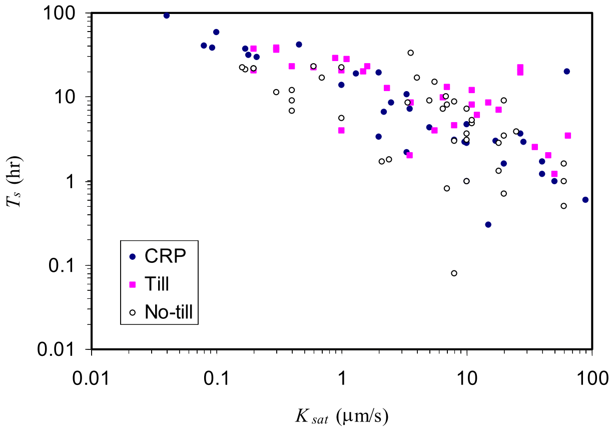

Fig. 3. Time to the steady infiltration rate, T_s, at different locations in the three hillslopes.

St. Joseph, MI). CEC was determined by ammonium displacement of calcium (Jaynes and Bigham, 1986) although the method of displacement was via shaking and centrifugation. Soil pH was determined using both 1:1 water and 1:2 KCl solutions (Soil Survey Staff, 2004). Bulk density values were measured on small (20–60 cm^3) undisturbed sub-samples using the wax clod method and bulk total porosity values were calculated using these bulk density values and assuming a specific gravity of 2.65 for the soil solids.

2.5. Statistical correlation and analysis of variance

This section focuses on the systematic examination of the relationship between K_{sat} and soil properties. The correspondence between K_{sat} and the soil properties was quantified using two statistical methods, namely correlation analysis and analysis of variance (ANOVA). The correlation analysis aimed at identifying the key variables related to K_{sat}, whereas the ANOVA test was performed to quantify the effects of land uses and management practices on K_{sat} for the three hillslopes. The soil properties considered in the correlation analysis were soil texture (described by contents of clay, silt, and sand), bulk density, CEC, pH, and OM.

3. Results and discussion

3.1. K_{sat} statistical properties

The estimated statistical parameters considered were the arithmetic (AM), geometric (GM), and harmonic (HM) mean values, as well as skewness and the arithmetic and geometric standard deviations. Table 3 summarizes the statistical parameters of K_{sat}, while Fig. 4 depicts the probability density functions (pdfs) of the measured K_{sat} values in the three hillslopes. The CRP exhibits higher values for the reported statistical parameters and wider range compared to the other hillslopes, with reasons for this paradoxical behavior being presented in Section 3.2.

The pdfs of the three hillslopes exhibit long right tails for values greater than 1.0 μm s^{-1}. A visual assessment suggests that the skewed

Table 3
Summary of the statistical parameters of K_{sat}.

K_{sat} (μm/s)	CRP	Tilled	No-till
Arithmetic mean	14.10	12.05	10.49
Geometric mean	5.44	3.76	3.59
Harmonic mean	1.21	0.94	0.87
Arithmetic standard deviation	21.06	16.85	15.20
Geometric standard deviation	8.88	5.85	5.76
Skewness	2.10	1.90	1.70

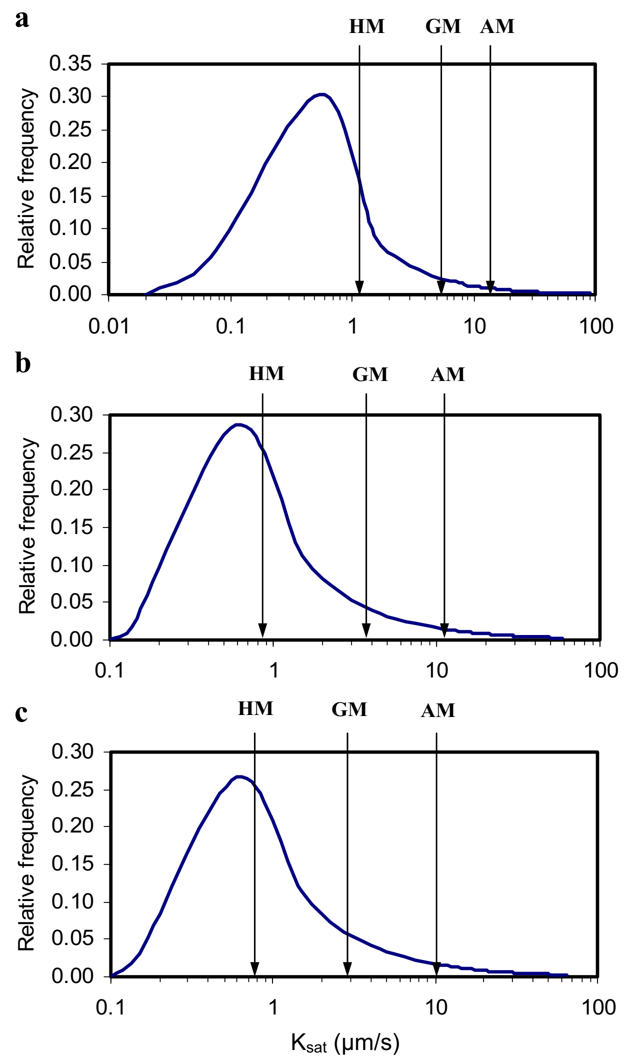

Fig. 4. Density functions of the measured K_{sat} values from the DRIs: (a) CRP hillslope; (b) tilled hillslope; and (c) no-till hillslope. AM = arithmetic mean, GM = geometric mean, HM = harmonic mean.

distributions of K_{sat} resemble the log-normal distribution, which was confirmed below through more rigorous statistical tests. In addition, the range of the distributions (the difference between minimum and maximum values) extends over three orders-of-magnitude (Fig. 4). The lowest value in the CRP, however extends nearly one order of magnitude lower than for the cultivated fields, but the right tail of the distribution exhibits similar trends as the cultivated fields (Fig. 4). The dispersion or spread of the data is also reflected through high values of the arithmetic and geometric standard deviations, as well as skewness. This high variability and wide range of K_{sat} values are also reported by many other investigators (Gwenzi et al., 2011; Legros, 2006; Lin et al., 2007; Ronayne et al., 2012; West et al., 2008) for loess and silt loam soils that experience intense agricultural activities and reworking of the soil from the collective effects of tillage and runoff action.

As can be seen from the pdfs of the measured K_{sat} values of each hillslope (Fig. 4), the harmonic mean, in contrast to the arithmetic and geometric means, is at close proximity to the mode (peak value) of these distributions (Zhu and Sun, 2012), thereby being the most representative mean value for K_{sat}. This is also demonstrated by Gupta et al. (1996) and Shahin et al. (1993), who show that ungrouped, spatially distributed measurements of K_{sat} can be well represented by the harmonic mean, especially when the measurements are obtained at locations exhibiting various combinations of intrinsic soil properties (e.g., texture, bulk density) and extrinsic factors, such as land use, vegetation cover, and precipitation.

The normality of the data is examined using the Kolmogorov-Smirnov test for goodness of fit for the following four probability distributions: normal; log-normal; Gumbel Type I; and Gumbel Type III. The tests show that the log-normal distribution satisfactorily represents the measured values. Graphical representation of the measured data on probability plots shows also that the log-normal distribution is the best fit to the data (Fig. 5), i.e., Log (K_{sat}) ~ N (M, SD^2), where M and SD are the mean and the standard deviation, respectively. This agrees well with other studies, which show that K_{sat} is a reflection of the effective grain size diameter of the surface soil and roughness that also typically follow log-normal distributions (Diiwu et al., 1998; Govindaraju et al., 2012; Gupta et al., 1996; MacDonald et al., 2012; Wang and Tartakovsky, 2011).

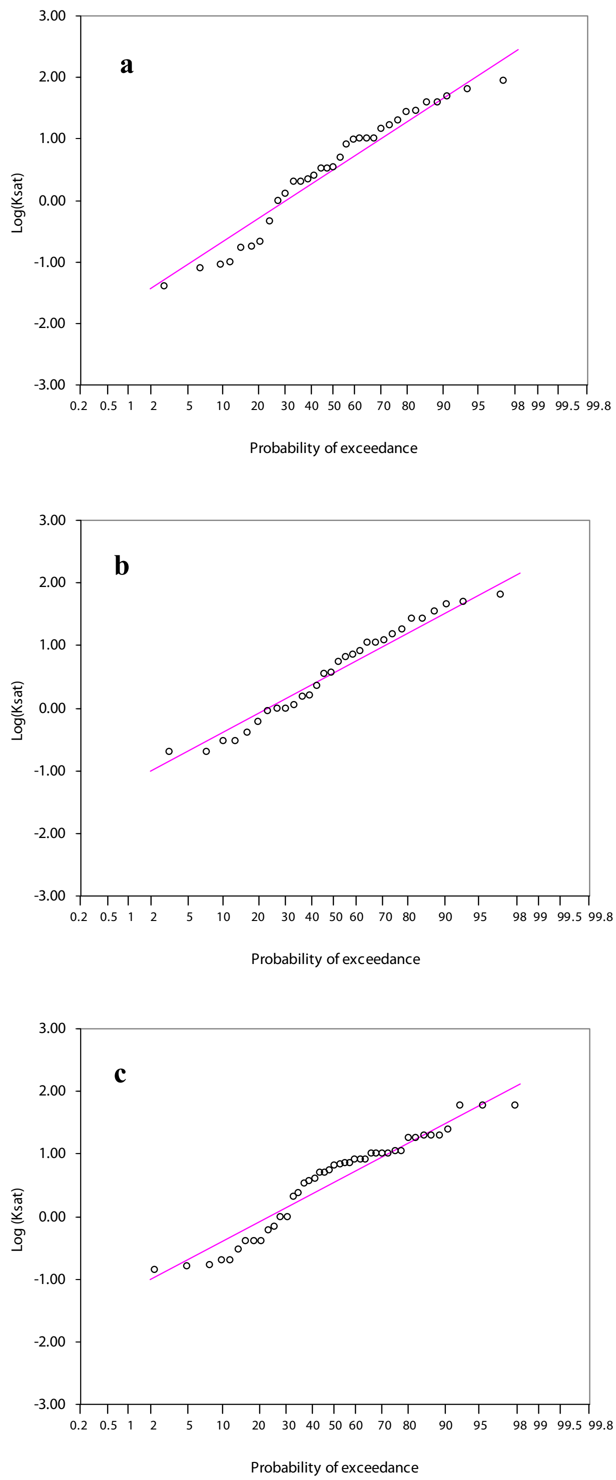

Fig. 5. Fitting the log-normal distribution curve to the measured K_{sat} values from the DRIs: a) CRP hillslope; (b) tilled hillslope; and (c) no-till hillslope.

3.2. K_{sat} variability and explanation of the statistical trends

The differences in the K_{sat} values between the CRP and cultivated hillslopes are confirmed from the detailed core sampling of pedons collected from the adjacent locations where the DRI measurements were conducted in each hillslope. Sampled pedons (Table 4) from the CRP have about 16% sand compared to about 5% in other two fields. In addition, due to the lack of management in the CRP, the bulk density of the cores collected from the CRP averages 1.07 $\pm$ 0.15 g cm^{-3} and is approximately 20% less dense than the bulk densities of the no-till and tilled fields, which average 1.24 $\pm$ 0.15 and 1.31 $\pm$ 0.11 g cm^{-3}, respectively. The higher bulk density in the cultivated fields is attributed to soil compaction resulting from the weight of the farm vehicles atop the soil (Alleto and Coquet, 2009; Lipiec et al., 2009; Orjuela-Matta et al., 2012; Raczkowski et al., 2012; Schwarzel et al., 2011). The higher sand content in the CRP field is attributed to past preferential soil erosion impacts along the drainage-way as explained in details below. These factors collectively explain why the CRP has relatively higher K_{sat} values compared to the other two cultivated fields (see Fig. 6a).

Detailed K_{sat} measurements are used to develop spatial distribution maps showing the variability of K_{sat} within and across the hillslopes (Fig. 6a). The wide range and variability of K_{sat} demonstrated in the statistical analysis are well depicted in the developed K_{sat} spatial distribution maps of the three fields (Fig. 6a). More importantly, visual, cross-site comparisons of the K_{sat} maps (Fig. 6a) reveal that the spatial distribution of K_{sat} in the CRP has a distinctly different pattern from those found in the cultivated hillslopes. The CRP map depicts a "strip pattern" for the spatial distribution of K_{sat} contrary to the maps of the cultivated fields, which depict a "mosaic pattern" for the spatial distribution of K_{sat}. The strip pattern in the CRP is due to the concentrated flow and resulting erosion that occurred along the drainage-way when the CRP was cultivated. This erosion is reflected through the lack of mollic-colored soils (i.e., black to dark brown soils), which comprised the surface soils in this region before settlement, in five of the sampled pedons especially along the main drainage-way (Oneal, 2009). The erosion along the main hillslope drainage-way (see circled region in Fig. 7a) exposed a loam substratum, which is observed nearer to the soil surface than observed along the side slopes. This suggests that runoff was concentrated in the drainage-way causing the significant erosion and entrainment of the smaller fraction of the fines thereby leaving the higher sand content on the hillslope (Alleto and Coquet, 2009; Diiwu et al., 1998; Stavi and Lal, 2011). An outcome of this severe erosion is the texture variation between the drainage-way and the side slopes (Fig. 7b), which produced different K_{sat} values. K_{sat} is higher along the drainage-way of the CRP, where clay-size soil particles are less abundant than along the side slopes from the preferential erosion of the finer soil particles (see Figs. 6a and 7a). The mosaic pattern in the no-till and tilled cultivated fields is attributed to the mixing of soil from tillage during the crop rotations. The CRP is dominated by advective or concentrated flows along the main drainage-way, whereas the cultivated fields experience both the advective and dispersive actions of the flow with the dispersive action being the dominant. This is seen in Dermisis et al. (2010), which looked at representative hillslopes in the same watershed. Similar observations of higher K_{sat} values are found in other studies where the surface soil textures contained lower proportions of clay and advective, concentrated flows along drainage-ways dominated over dispersive, sheet flows (Balland et al., 2008; Gwenzi et al., 2011; Mubaraka et al., 2010; Stavi and Lal, 2011).

Table 4
Summary of the statistical parameters and the results for the tested variables for the surface horizon.

Field	CRP			Tilled			No-till			ANOVA
Variable	AM	SD	ρ	AM	SD	ρ	AM	SD	ρ	p-value
Bulk density (gm/cm^3)	1.067	0.152	−0.271	1.319	0.106	−0.396	1.239	0.147	−0.512	<0.01
% of sand content	16.377	10.990	0.660	5.220	0.981	0.057	4.851	1.638	0.030	<0.01
% of silt content	57.147	9.434	−0.576	69.335	2.217	−0.142	68.372	2.887	−0.187	<0.01
% of clay content	23.619	4.183	−0.507	23.401	1.781	−0.165	24.910	3.322	−0.164	0.46
% of carbon content	2.604	0.763	0.028	1.854	0.266	0.149	1.690	1.362	0.121	0.02
% of nitrogen content	0.253	0.055	0.042	0.190	0.018	0.124	0.178	0.404	0.084	0.03
pH	5.364	0.182	−0.147	6.023	0.379	−0.156	5.693	0.508	−0.169	0.01
CEC (meq/100 g)	30.693	7.465	−0.108	33.969	6.532	−0.095	31.307	8.329	−0.105	0.49

AM = arithmetic mean, SD = standard deviation, ρ = correlation coefficient.

The constructed spatial distribution K_{sat} maps were also compared visually to the soil maps (Fig. 6b) developed from the Iowa Soils Properties and Interpretations Database (ISPAID) in 1967. This comparison can provide an interesting example of the impacts of past land management and soil erosion activities on K_{sat} spatial variability. Unlike the herein developed K_{sat} maps, which showed clearly significant spatial variability in K_{sat}, over three orders-of-magnitude (0.04 to 90 μm s^{-1}), within the hillslopes, the available ISPAID maps developed in 1967 show fairly homogenous soils and thus less variability in K_{sat}.

Data from the three hillslopes collected during the 2007 soil core survey show that the intensive agriculture activities have altered the soil texture of the surface soil by removing finer particles from the A — horizon, which in turn has partially led to a discrepancy between the current core descriptions and the published ISPAID data. Approximately 77% of the characterized pedons do not classify as the originally mapped soil series identified by the ISPAID (Oneal, 2009). In a previous study in the same region (i.e., the Southern Iowa Drift Plain), nearly one-half of the sampled pedons do not classify as the expected soil order, let alone the soil series (Burras et al., 2005).

The discrepancy between the two sets of maps can also be attributed to the fact that the published 1967 ISPAID maps have inherently low spatial resolution, with most of them being surveyed at an order 2

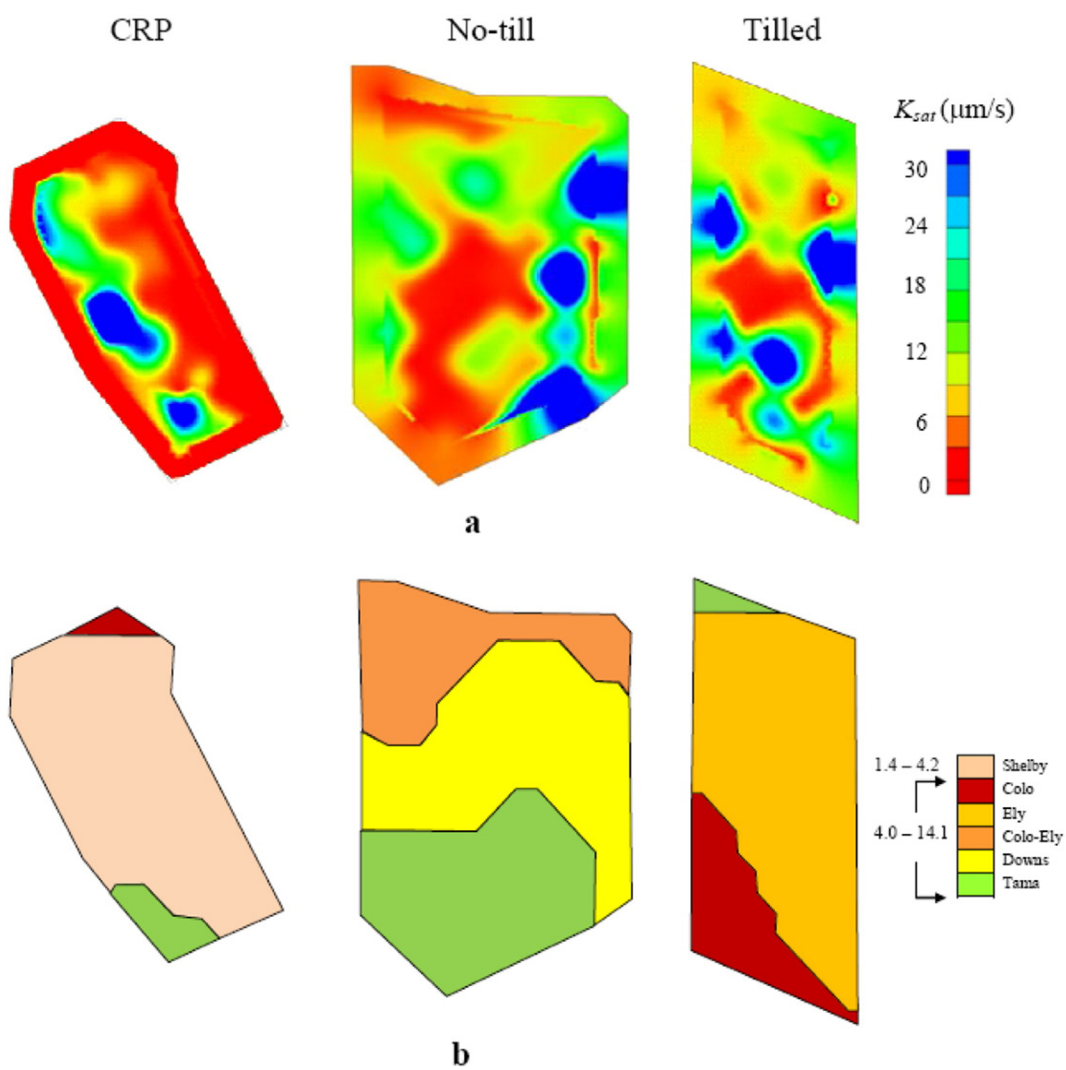

Fig. 6. Spatial variability of K_{sat} in the three hillslopes obtained from: (a) The DRI measurements; (b) the ISPAID maps.

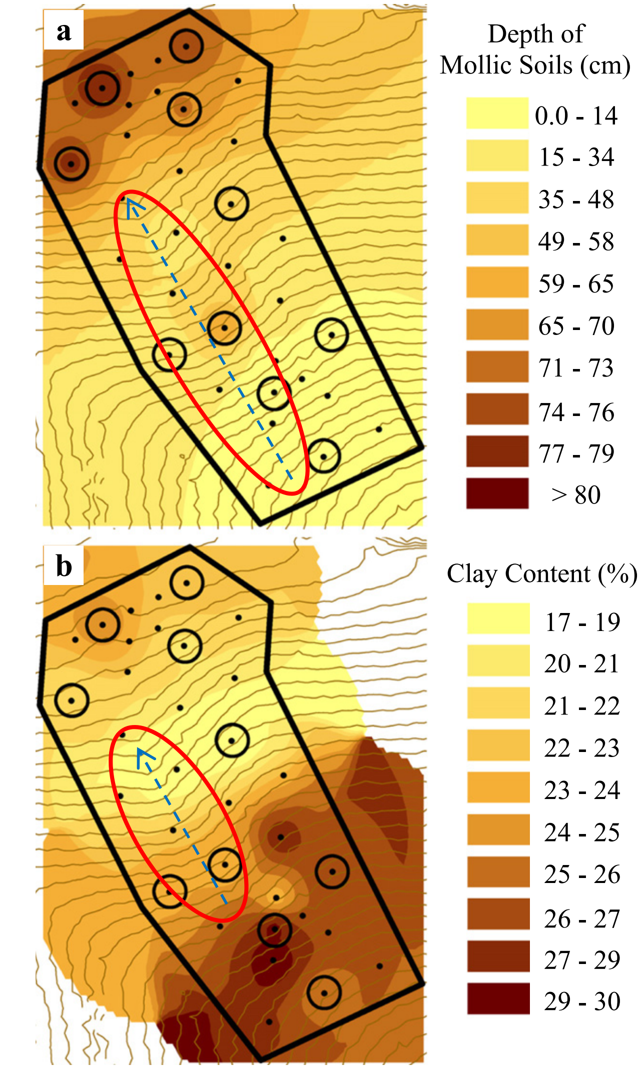

Fig. 7. Variation of the soil texture in CRP hillslope due to land erosion: (a) depth of mollic soils; (b) clay content within the soil surface horizon in the CRP. The large red ovals in the CRP reflect the areas of depleted mollic soil layers and clay content in the main drainage-way with high K_{sat} values, while the blue dashed line reflects the drainage way.

scale (1:15,840) (Burras et al., 2005; Iowa Department of Agriculture and Land Stewardship, 2002). Additionally, most landscapes have inclusions of minor soils, but it was up to the judgment of the soil surveyors to include them based on their impact on soil properties, which was often not the case (Iqbal et al., 2005; Leenhardt et al., 1994; Soil Survey Staff, 1993). The lack of correspondence between measured and published maps is generally not problematic for the traditional uses of soil surveys (McCormack and Wilding, 1969). However, it can be substantial for the purposes of infiltration prediction, and watershed modeling (Arnold et al., 1998; Elhakeem et al., 2014).

3.3. Correlation and analysis of variance

Table 4 summarizes the statistical parameters and results for the tested variables of the surface horizon, which include soil texture (described by contents of clay, silt, and sand), bulk density, CEC, pH, and OM. Fig. 8 shows the Pearson correlation coefficients (ρ) between Log (K_{sat}) and the different variables. The low to moderate values imply that none of the variables can describe K_{sat} independently and that more than one variable should be considered in the PTFs for adequately predicting K_{sat}. The analysis also shows that K_{sat} is negatively correlated to all the variables, except sand content and OM.

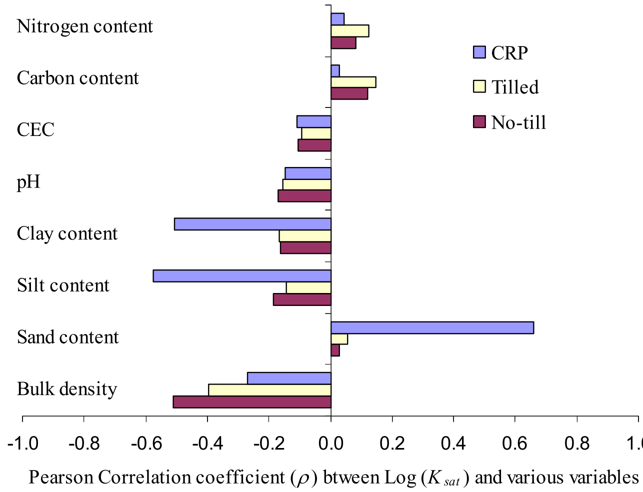

Fig. 8. Correlation between K_{sat} and different soil properties for the three hillslopes.

The positive correlation of K_{sat} with sand content and negative correlation with other variables, such as bulk density, agree well with the expected responses of the soils and has been well documented in the literature (Brakensiek et al., 1984; Cosby et al., 1984; Risse et al., 1995; Saxton et al., 1986; Vereecken et al., 1990). The positive correlation between K_{sat} and OM has also been reported by Lado et al. (2004) and is attributed to the organic matter increasing the aggregate stability of soils and hence, minimizing shrinking and swelling of the soil (Elliott, 1986; Emerson, 1977; Leroy et al., 2008; Papanicolaou et al., 2009).

When comparisons are made across the three different hillslopes, Fig. 8 shows low correlation between K_{sat} and sand content in the tilled and no-till hillslopes, which is attributed to the overall low sand content (about 5%) in these fields (see Table 4). Conversely, the correlation between K_{sat} and sand content was relatively higher in the CRP due to its higher sand content of about 16% (see Table 4). The higher sand content in the CRP relative to the cropped fields is attributed to the significant erosion along the main hillslope drainage-way, which washed away part of the fine material from the field as reported by Oneal (2009) leaving exposed the coarser sand particles. The correlation between K_{sat} and sand content is found to have significant effect on other soil fractions, namely silt and clay. As can be seen from Fig. 8, when sand exhibits high correlation with K_{sat} (see the CRP correlations), silt and clay also exhibit high correlation with K_{sat} and vice versa (see the till and no-till correlations).

The second variable that also exhibits relatively higher correlations with K_{sat} compared to the other variables is bulk density. Bulk density in the cultivated hillslopes has a higher correlation with K_{sat} than the correlations between soil texture and K_{sat}. In the case of the CRP hillslope, soil texture exhibits higher correlation with K_{sat} than the other variables. It appears that the effects of land management (i.e., compaction during cultivation) are best reflected through bulk density, as it has a higher correlation with K_{sat} for the cultivated hillslopes, while the effects of erosion are best reflected through changes in texture, based on its higher correlation with K_{sat} for the CRP. This means that, soil texture controls infiltration in soils with higher sand content and low agriculture activity. Bulk density dominates infiltration in soils with lower sand content and high agriculture activity. Other variables such OM, CEC and pH, which affect the soil structure, are also found to somewhat affect K_{sat} but the effects are minimal compared to soil texture and bulk density in this study. Similar findings have been reported by other investigators (Alberts et al., 1995; Lin et al., 2014; Nearing et al., 1996; Price et al., 2010).

An ANOVA confirms the observed differences in the three hillslopes are not triggered by uncertainty in the measurements or measuring techniques. The validity of the "null" hypothesis, which assumes that there are no differences between the values from the three sites, is examined using the p-value (Draper and Smith, 1998) as the measure of significance. The null hypothesis is rejected when p is less than 0.05. All parameters, except for clay content and CEC, are found to be significantly different across the three sites as seen with the p-values listed in Table 4. These differences between the tested fields are due to the inherent soil properties, land use, and management practice. The shared lack of significance for clay content and CEC is attributed to the interdependence of the two variables.

3.4. Pedo-transfer functions

It is shown from the correlation analysis that soil texture and bulk density are the most important soil properties affecting K_{sat} in the intensively managed, agricultural, silt loam soils of the semi-humid Midwest. It is therefore not surprising that they are considered the most important input parameters in many PTFs (Brakensiek et al., 1984; Campbell and Shiozawa, 1994; Cosby et al., 1984; Dane and Puckett, 1994; Jabro, 1992; Schaap, 1999; Saxton et al., 1986). Other parameters, such as CEC and OM may be important for certain soil series and are also considered in a few PTFs (Onstad et al., 1984; Risse et al., 1995; Vereecken et al., 1990; Wosten et al., 1999).

The mean and range of the predicted K_{sat} values are obtained using twelve representative PTFs with the collected soil data from the three hillslopes and are compared to the harmonic mean and the range of the measured K_{sat} values (Fig. 9). It can be seen from the figure that many PTFs produce K_{sat} values close to the harmonic mean, which again confirms the earlier findings of this study that it is the most representative mean. A few PTFs (Fig. 9) are able to capture either the lower or upper bound of the range of measured K_{sat} values, but not both. The PTFs are not able to reproduce the range of the measured K_{sat} values showing a narrower range for K_{sat}.

The predictions of the PTFs of Cosby et al. (1984) and Rosetta — Schaap (1999) are the closest to the harmonic mean of the measured values of K_{sat}, while the predictions of the PTFs of Campbell and Shiozawa (1994) and Vereecken et al. (1990) are the closest to the measured minimum and maximum values of K_{sat}, respectively. Although this evaluation is, to some degree, subjective, it can help the hydropedologic community by providing the steps necessary for selecting the best PTFs for representing the pedologic and hydrologic properties of a study location.

4. Conclusions

In this study, detailed field experiments were conducted using semi-automated double ring infiltrometers to examine the effects of land use and management practices on K_{sat} variability at three hillslopes in southeast Iowa with different agricultural management practices, namely Conservation Reserve Program (CRP), no-till and conventional till.

Two distinct patterns were observed in the constructed K_{sat} spatial distribution maps for the three hillslopes. The CRP map depicted a "strip pattern" for the spatial distribution of K_{sat} reflecting the presence of the drainage-way in contrary to the maps of the cultivated fields, which depicted a "mosaic pattern" for the spatial distribution of K_{sat}.

The strip pattern in the CRP was due to the significant erosion and exposure of a sandy substratum that occurred along the main drainage-way of the CRP field prior to being withdrawn from crop production. An outcome of this severe erosion was the texture variation between the drainage-way and the side slopes, which produced higher K_{sat} values in the drainage-way. The mosaic pattern in the no-till and tilled cultivated fields was attributed to the mixing of soil from cultivation during crop rotations.

The developed maps from the K_{sat} measurements showed clearly significant spatial variability in K_{sat} within the hillslopes when compared to the ISPAID maps, which were not able capture the spatial variability at the hillslope scale showing fairly homogenous soils and thus less variability in K_{sat}. This difference provided an interesting example of the impacts of past land management and soil erosion activities on K_{sat} spatial variability although it was recognized that it is quite possible that the low spatial resolution of the ISPAID maps may have camouflaged some degree of the spatial variability of soil properties.

The correlation analysis between K_{sat} and different soil properties suggested that soil texture dominated the infiltration process in soils with relatively higher sand content (>15% sand) and low agriculture activity, while bulk density dominated the infiltration process in soils with low sand content and high agriculture activity (i.e., high degree of compaction) due its high correlation with K_{sat}. The performed ANOVAs showed that the observed differences in the three hillslopes were true differences and not triggered by the uncertainty and errors in the measurements or measuring techniques.

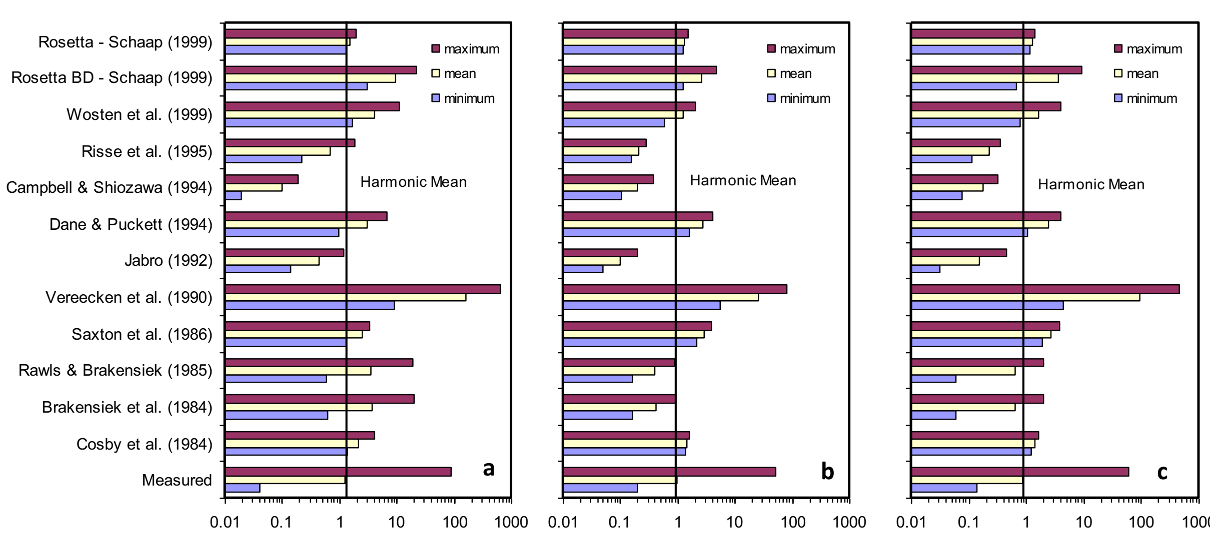

Fig. 9. Comparison between measured K_{sat} values and the predicted values from different PTFs: (a) CRP; (b) tilled hillslope; (c) no-till hillslope. The vertical line in each graph represents the harmonic mean of the measured K_{sat} values.

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