



Land use-dependent variation of near-saturated and saturated hydraulic properties in calcareous soils

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Abstract

Land use change may differently affect soil hydraulic properties at different applied tensions (ψ). In comparison to soil physico-chemical properties, long-term effects of land use types on soil hydraulic properties particularly measured at different applied tensions and calculated using different approaches have been evaluated in rare cases. Therefore, the present study aimed to evaluate the effects of long-term land use types including annual cultivated field (ACF), perennial alfalfa field (PAF) and orchard field (OF) on near-saturated and saturated hydraulic conductivity (K_{ψ}), sorptive number (α) and pore size classes contributing to water flow within calcareous soils and to compare the near-saturated hydraulic conductivity determined using the variable and constant alpha approaches in the soils of different land uses. A total of 75 in situ infiltration measurements were made using a tension disk infiltrometer (25 replications for each land use) at 6 tensions of 0–15 cm. K_{ψ} were determined using variable alpha ($K_{A\psi}$) and constant alpha ($K_{G\psi}$) approaches. $K_{A\psi}$ in PAF was 1.10–2.69 times greater than that of ACF. Meanwhile, $K_{A\psi}$ in PAF was 2.15–2.35 times greater than that of OF. $K_{A\psi}$ and $K_{G\psi}$ were equal at ψ of 5 cm. Furthermore, $K_{A\psi}$ was higher than $K_{G\psi}$ at $\psi < 5$ but was lower than $K_{G\psi}$ at $\psi > 5$ cm. In the ACF, the average relative proportion of the ‘pore classes’ to ‘flow’ was 2 (micropores):7 (mesopores):6 (macropores). However, the proportions were 1:6:6 for PAF and OF land uses. The total values of water flow in micro- and mesopores were 1.5, 1.2, and 1.2 times greater than that of macropores in ACF, PAF and OF land uses, respectively. The results are useful for describing more accurately the hydraulic properties in modeling the water flow and the pollutant/chemical transport within soil environment.

Keywords Annual cultivated field · Infiltrometer · Near-saturated hydraulic conductivity · Orchard field · Perennial alfalfa field · Sorptive number

Introduction

Soil degradation is commonly known as a great threat to most natural environments (Ostovari et al. 2020; Mozaffari et al. 2021). Most scientists believe that it is the major reason for low agricultural productivity (Ostovari et al. 2021) and rapid changes in ecosystems (Reed et al. 2011; Batunacun et al. 2019). These changes are notoriously caused by global warming, environmental pollution, the decline in biodiversity, followed by lower amounts of soil organic matter (OM)

and the deterioration of soil fertility (Doran et al. 1996). Agricultural activities are often the main destructive factors that lead to soil degradation, but they can play protective roles in the maintenance of soils if they are carried out scientifically. Land use is one of the most common ways by which humans interfere with environmental processes, and it can either intensify or reduce soil degradation (Zheng et al. 2011). Soil and crop managements include conventional practices such as tillage, use of fertilizers and irrigation methods which play important roles in the sustainability of agricultural and natural resources and can influence the soil attributes differently (Paz-Gonzalez et al. 2000; Rahmati et al. 2018; Castellini et al. 2021).

Increased environmental awareness has led scientists to pay particular attention to water movement and its redistribution in soils (Mallants et al. 1997) in which soil hydraulic characteristics (saturated and nearly saturated hydraulic parameters) play key roles. The mentioned properties are key input parameters in many water flow models and solute/

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contaminant transport systems within the soil profile (Baker and Ellison 2008).

Soil structure (Kodešová et al. 2011), particles size distribution, PSD (Nasta et al. 2013), pore size distribution (Villarreal et al. 2020), bulk density, BD (Castellini et al. 2020) and OM (Dexter et al. 2008) are the most significant factors that can affect the mentioned soil hydraulic properties. These factors are strongly influenced by soil management and land use practices (Zhou et al. 2008). It has been reported that appropriate farming systems have important effects on the physical properties of soils. Such improvements can happen due to enhanced soil structures as reinforced by root hairs and fungal hyphae, higher rates of microbial carbohydrate production and the modification of water and soil relationships (Gregory et al. 2012).

So far, many studies have evaluated the effects of land use on the physico-chemical properties of soils (Bauer and Black 1981; Franzluebbbers et al. 2000; Bronson et al. 2004; Moradi et al. 2016; Kaur and Bhat 2017; Zahedifar 2017; Zahedifar and Moosavi 2017; Liu et al. 2018; Tellen and Yerima 2018). However, in comparison to physico-chemical properties, effect of land use changes on hydraulic characteristics, especially near field-saturated hydraulic properties (e.g., hydraulic functions and hydraulic properties as a function of matric potential) has been studied in fewer cases. For instance, Bodhinayake and Si (2004) reported that near-saturated hydraulic conductivity, K_{ψ} (measured at ψ of -0.3 kPa) in surface meadows and grasslands soils are 2–3 times higher than that in cultivated soils with wheat and canola in rotation with fallow. They also showed that the mean value of field-saturated hydraulic conductivity (K_0) in meadows and grasslands soils is 4 times higher than that in cultivated soils. Their results showed that land use alters the water balance in the region via changes in runoff and water storage. Scheffler et al. (2011) reported that forest to pasture conversion reduces infiltrability and K_0 . They also stated that pasture-soybean conversion can increase infiltrability and create various effects on K_0 at different soil depths. Pirastu et al. (2014) in a semi-arid Mediterranean environment revealed that K_0 of the maquis soil was higher than that of the grassy soil. Hu et al. (2009) reported no significant differences between hydraulic properties (except on K_{ψ} at ψ of -15 cm) by different land uses when dealing with Bunge needlegrass, alfalfa, soybean and Korshinsk peashrub farming. Furthermore, Bormann and Klaassen (2008) showed that the type of land use can have significant effects on hydraulic and hydrological characteristics. They stated that some soil attributes such as BD, K_0 , water infiltration into soils and field capacity water content (FC) can be significantly different when selecting from a variety of land uses. Different trees (e.g., pear, grape and pine) and their roots have been observed to have various effects on water infiltration into the soil (Kazemi-Zadeh and Sepaskhah 2016). They reported that

water infiltration into the soil under the canopy of trees is higher than that of outside the canopy because of root channels. In addition, Papanicolaou et al. (2015) showed that K_0 values ranged from 0.15 to 360 mm h^{-1} on three hill slopes with different agricultural management practices in Iowa.

Field evidence identifies the existence of macropores, hence preferential flow in soils. The change of hydraulic conductivity (K_{ψ}) is mainly affected by the changes of soil structure. Simultaneously, the contribution of pore size classes to water flow changes with soil structure. Obviously, knowledge of changing pore class contributions to water flow with land use management would better facilitate the understanding of underlying reasons for changing K_{ψ} as affected by land use. Unfortunately, most studies concerning effects of land use on K_{ψ} did not refer to the pore size contribution to water flow in soil when they presented explanations for changes of K_{ψ} (Hu et al. 2009).

Soil hydraulic properties are main parameters in soil and environmental modeling (Ventrella et al. 2019). These parameters are strongly dependent upon the matric potential of soil and land use change. The mentioned issues can significantly improve our understanding and modeling of the hydrological process (Picciafuoco et al. 2019; Tashayo et al. 2020). As Bormann and Klaassen (2008) stated, catchment models and hydrological site models are mostly structured according to the use of a constant soil hydraulic model parameterization. The models often consider small-scale spatial variability of soil attributes, but their parameterization does not differ when dealing with various types of land use and does not vary in time. To the best of our knowledge, although the changes in land use can have different effects on physico-chemical properties of soils, there is a lack of information on how change in land use tend to affect hydraulic properties of calcareous soils especially at different tensions. To this end, there are several approaches to the calculation of near-saturated hydraulic parameters using the tension disk infiltrometer data regardless of soil type (Ankeny et al. 1991; Reynolds and Elrick 1991; Jarvis and Messing 1995; Bodhinayake et al. 2004). These may result in different outputs in different soil conditions.

According to abovementioned descriptions, the effects of long-term management practices and land use types including annual cultivated field (ACF), perennial alfalfa field (PAF) and orchard field (OF) on soil hydraulic parameters (e.g., saturated and near-saturated hydraulic conductivity) at different applied tensions which are key parameters in hydrological modeling and water flow and material transportation within soil profile have been not studied in the literature. Furthermore, pore size contribution to water flow in the mentioned different land uses and comparing the near-saturated and saturated hydraulic conductivities determined using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches did not investigate in the

previous studies. The mentioned issues are the novel aspects of the present paper. Therefore, the objectives of the present study were (i) to evaluate the effects of different land uses including annual cultivated field (ACF), perennial alfalfa field (PAF) and orchard field (OF) land uses on hydraulic parameters of calcareous soils when measured at different tensions, (ii) to compare the near-saturated hydraulic conductivity determined using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches in the soils of different land uses, and (iii) to investigate pore size contribution to water flow in the different land uses.

Materials and methods

Site description and basic physico-chemical properties of soils

The study area that ranged across nearly 3700 ha is located in the Bajgah region, Shiraz, Fars province, Iran. The location has an altitude of 1810 m above sea level and is situated in the geographic coordinates 29° 44' 7" to 29° 45' 18" N, 52° 32' 53" to 52° 35' 55" E. The study area has a mean annual precipitation and potential evaporation of about 400 and 2000 mm, respectively. It is characterized by a thermo-Mediterranean climate, located about 15 km north of Shiraz city. The soils of different land use types were developed on relatively similar parent materials of calcareous alluvium and had geological formations of Asmari, Jahrom and Sachoon (Geological Survey and Mineral Exploration of Persia 2017). The soils consisted of three long-term (> 20 years) land use types including (i) annual cultivated field, ACF, with different rotations of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), corn (*Zea mays* L.) and canola (*Brassica napus* L.) by the fallow system; (ii) orchard field, OF, (pear, *Pyrus communis* L.) and (iii) perennial alfalfa field, PAF, (*Medicago sativa*) as schematically described in Fig. 1. According to the Soil Taxonomy (Soil Survey Staff 2014), the soils of all land uses that are studied herein pertain to Inceptisols (Fine, mixed, mesic, and Xerochrepts). Each studied land use was sampled for soil from 25 experimental points on a relatively regular square grid of 5 × 5 m. This is noteworthy to mention that the hydraulic properties are very dynamic and can be affected significantly by time (Zhou et al. 2008). Therefore, in the present study, the infiltration tests were done continuously and intensively over 21 days for all studied 75 points (1 week for each studied land use) to avoid the effects of temporal variation on the studied hydraulic properties (application of more than one infiltrometer or reducing the number of replications also may be considered to minimize temporal variation). In the vicinity of each experimental point, a composite sample of about 2 kg was

taken from a depth of 0–30 cm. The samples were air-dried and passed through a 2 mm sieve, before being transferred to the laboratory for further analysis. Some physico-chemical properties of the samples were measured using common standard methods including bulk density (BD) using core sampler method (Arshad et al. 1996); soil primary particles size contents (sand, silt and clay contents based on USDA classification) using wet-sieving and sedimentation method using hydrometer (Gee and Bauder 1986); electrical conductivity (EC_e) using conductometer in saturated extract (Rhoades 1996); soil organic matter (OM) using wet combustion method (Nelson and Sommers 1996); soluble sodium (Na^+) in saturated extract by flame photometry (Helmke and Sparks 1996); soluble magnesium (Mg^{2+}) and calcium (Ca^{2+}) in saturated extract using titration with EDTA (Richards 1954); and sodium adsorption ratio (SAR) using $SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$ equation in which concentrations of Na^+ , Ca^{2+} and Mg^{2+} are in $meq L^{-1}$ unit and SAR is in $[(meq L^{-1})^{0.5}]$ unit (Table 1).

Infiltration experiments and determination of soil hydraulic properties

Saturated hydraulic conductivity (K_0) and sorptive number (a)

Infiltration experiments were conducted using a single-disk tension infiltrometer of 20 cm diameter over the growing season in the second and third months of spring (May and June). At the time of measurements, wheat and alfalfa crops had been planted in the ACF and PAF, respectively. Similar to what Moosavi and Sepaskhah (2012a, b) did in Bajgah region, Fars province, Iran, at each experimental location, grass and plant residues were removed from the soil surface while flattening the surface without altering the soil structure. To ensure an appropriate hydraulic contact between the disk membrane and the soil, a thin (nearly 5 mm thickness) contact layer of fine sand (0.1–0.25 mm diameter) was placed on the soil surface between the disk membrane of the infiltrometer and the soil surface. The infiltrometer was pushed slightly onto the sand layer.

After filling the device reservoir with fresh water of nearly $0.6 dS m^{-1}$ electrical conductivity (EC) and $0.5 mol^{0.5} L^{-0.5}$ sodium adsorption ratio (SAR), the maximum desired tension (i.e., 15 cm in our study) was set by air tower and Marriott tube (Tension disk operating instruction 2008). In other words, the vertical distance between the level of water and the bottom of the Marriott tube plus 1.5 (calibration coefficient) was considered equal to the desired tension. After setting the tension, infiltration tests were carried out at successive applied tensions of 15,



Fig. 1 A schematic view of the studied land use types **a** annual cultivated field (ACF), **b** perennial alfalfa field (PAF), and **c** orchard field (OF)

Table 1 Mean values ($N=25$) of the measured physico-chemical properties in soils of the studied land use types at 0–30 cm depth

Soil attributes	Land uses		
	Annual cultivated field (ACF)	Perennial alfalfa field (PAF)	Orchard field (OF)
Bulk density, BD (g cm^{-3})	1.24	1.27	1.27
Sand (%)	3.9	5.14	19.6
Silt (%)	56.5	61.53	54.6
Clay (%)	39.6	33.33	25.8
Textural class	Silty clay loam	Silty clay loam	Silt loam
Electrical conductivity of saturated extract, EC_e (dS m^{-1})	0.34	0.467	0.575
Organic matter, OM (%)	2.44	2.39	3.75
Soluble sodium, Na^+ (meq L^{-1})	0.58	0.17	1.21
Soluble magnesium, Mg^{2+} (meq L^{-1})	4.18	2.66	4.29
Soluble calcium, Ca^{2+} (meq L^{-1})	2.59	3.36	4.11
Sodium adsorption ratio, SAR ($(\text{meq L}^{-1})^{1/2}$)	0.236	0.101	0.599

10, 7.5, 5, 2.5, and 0 cm. The aforementioned descending sequence of tensions was used for preventing hysteresis (Jarvis and Messing 1995). In each of the applied tensions, after moistening the layer of sand (nearly 30 s), water infiltration into the soil was manually recorded at time intervals of 15 s for the first 300 s, and then was recorded every 60 s until steady-state conditions were met. Conditions were considered as steady state when at least five successive readings of the infiltrated flow rate became similar (Angulo-Jaramillo et al. 2000).

Hydraulic properties of the soils were determined by applying the infiltration data based on the analytical solution of the variably saturated water flow equation presented by Wooding (1968). As proposed by Gardner (Gardner 1958) in Wooding’s approach, it is assumed that K_ψ varies with ψ as an exponential model (Eq. 1) when water infiltrates into the soil from a circular source of radius r with a constant pressure head at the soil surface (Wooding 1968; Simunek et al. 1998):

$$K_\psi = K_0 \exp(\alpha\psi) \tag{1}$$

where K_0 is the saturated hydraulic conductivity ($L T^{-1}$), α is the sorptive number (L^{-1}), which is equal to the inverse of macroscopic capillary length, λ [L] (Philip 1969). The analytical solution was derived by Wooding (1968) and is given by

$$Q_{\psi_i} = \pi r^2 K_\psi + \frac{4\pi r^2 K_\psi}{\pi r \alpha} = \pi r^2 K_\psi \left(1 + \frac{4}{\pi r \alpha}\right) \tag{2}$$

where Q is the volume of water entering the soil per unit time ($L^3 T^{-1}$) at steady-state infiltration conditions and r is the radius (L) of the infiltrometer disk. Although Eq. (1) can be used for unsaturated and ponded infiltration, Eq. (2) applies only for $\psi \geq 0$. The first and the second terms on the right hand of Eq. (2) represent the effect of gravitational and capillary forces, respectively. Substituting Eq. (1) in Eq. (2) resulted in the following equation:

$$Q_{\psi_i} = \pi r^2 K_0 \exp(\alpha\psi) \left(1 + \frac{4}{\pi r \alpha}\right) \tag{3}$$

$$q_{\psi_i} = \frac{Q_{\psi_i}}{\pi r^2} = K_0 \exp(\alpha\psi) \left(1 + \frac{4}{\pi r \alpha}\right) \tag{4}$$

where q is the flux of water entering the soil ($L T^{-1}$). α and K_0 are the unknown parameters to be calculated using linear or nonlinear regression approaches (Logsdon and Jaynes 1993; Bodhinayake et al. 2004). In the present study, the linear regression method was used. That way, Eq. (4) linearized as the following equation:

$$\ln(q_{\psi_i}) = \alpha \psi_i + \ln\left(K_0 + \frac{4K_0}{\pi r \alpha}\right) \tag{5}$$

$\ln(q_{\psi_i})$ versus ψ_i was plotted for each experimental point to give a straight line. The slope and the intercept of the curve were determined and taken as α and $\ln\left(K_0 + \frac{4K_0}{\pi r \alpha}\right)$, respectively. According to the intercept and by the obtained α and K_0 , value was calculated.

There are several approaches to analyze the tension disk infiltrometer data (Ankeny et al. 1991; Reynolds and Elrick 1991; Jarvis and Messing 1995; Bodhinayake et al. 2004). In the present study, the following methods proposed by Gardner (1958) and Ankeny et al. (1991) were used for determining the near-saturated hydraulic conductivity:

Determining near-saturated hydraulic conductivity using constant alpha approach (Gardner 1958), $K_{G\psi}$

After determining the α and K_0 parameters using the approach as mentioned above, values of the applied tensions (ψ) entered the Gardner exponential relation (Eq. 1), resulting in the corresponding values of near-saturated hydraulic conductivity at the tensions.

Determining near-saturated hydraulic conductivity using variable alpha approach (Ankeny et al. 1991), $K_{A\psi}$

According to the approach proposed by Ankeny et al. (1991) using Wooding’s solution for unsaturated conditions, steady-state fluxes were obtained with the same disk infiltrometer at different tensions, e.g., ψ_i and ψ_{i+1} . By replacing K_ψ with $K_0 \exp(\alpha\psi)$ and by substituting ψ_i and ψ_{i+1} in the combined equation yields, we arrive at the following:

$$Q_{\psi_i} = \pi r^2 K_0 \exp(\alpha\psi_i) + \frac{4\pi r^2 K_0 \exp(\alpha\psi_i)}{\pi r \alpha} \quad i = 1, 2, \dots, n - 1 \tag{6}$$

$$Q_{\psi_{i+1}} = \pi r^2 K_0 \exp(\alpha\psi_{i+1}) + \frac{4\pi r^2 K_0 \exp(\alpha\psi_{i+1})}{\pi r \alpha} \tag{7}$$

$i = 1, 2, \dots, n - 1$

In the mentioned approach, α parameter of the Gardner’s exponential model is assumed constant over the interval between two adjacent applied tensions of ψ_i and ψ_{i+1} .

It should be noted that the homogeneous, isotropic and uniform initial soil water contents are applied as assumptions in Wooding’s analytical solution, and when these limiting assumptions are not effectively satisfactory, the analysis often leads to negative K_ψ values (Vandervaere et al. 2000, and references therein). Solving Eqs. (6) and (7)

simultaneously, resulted in the following equations (Ankeny et al. 1991):

$$K_{\psi_i(1)} = \frac{Q_{\psi_i}}{\pi r^2 + 2\Delta\psi r \left(1 + \frac{Q_{\psi_{i+1}}}{Q_{\psi_i}}\right) / \left(1 - \frac{Q_{\psi_{i+1}}}{Q_{\psi_i}}\right)} \quad (8)$$

$$K_{\psi_i(2)} = \frac{Q_{\psi_{i+1}} K_{\psi_i(1)}}{Q_{\psi_i}} \quad (9)$$

The present study was carried out based on an approach proposed by Ankeny et al. (1991). Five equations were solved simultaneously, using ψ values of 0 and 2.5, 2.5 and 5, 5 and 7.5, 7.5 and 10, and 10 and 15 cm. Ankeny et al. (1991) defined the best estimate of K_{ψ} as the arithmetic mean of the available estimates, where K_{ψ_i} is calculated from the (ψ_i, ψ_{i+1}) rate pair ($K_{\psi_i} = \frac{K_{\psi_{i+1}} + K_{\psi_i}}{2}$). The following equations reveal how K_{A0} , $K_{A2.5}$, K_{A5} , $K_{A7.5}$, K_{A10} and K_{A15} are actually calculated (Ankeny et al. 1991):

$$K_{A0} = K_{A0} (0, 2.5) \quad (10)$$

$$K_{A2.5} = (K_{A2.5} (0, 2.5) + K_{A2.5} (2.5, 5))/2 \quad (11)$$

$$K_{A5} = (K_{A5} (2.5, 5) + K_{A5} (5, 7.5))/2 \quad (12)$$

$$K_{A7.5} = (K_{A7.5} (5, 7.5) + K_{A7.5} (7.5, 10))/2 \quad (13)$$

$$K_{A10} = (K_{A10} (7.5, 10) + K_{A10} (10, 15))/2 \quad (14)$$

$$K_{A15} = K_{A15} (10, 15) \quad (15)$$

Determining the contribution of pore classes to water flow

According to the capillary theory (Miller and Miller 1955), infiltration at the applied tensions of 2.5, 5, 7.5, 10 and 15 cm excludes pores of an equivalent radius greater than 1.2, 0.6, 0.4, 0.3 and 0.2 mm, respectively, from the flow path (Ghiberto et al. 2007). Therefore, the following five classes of pore ranges were defined (Hu et al. 2009):

- i. pores with equivalent radius greater than 1.2 mm (macropores),
- ii. between 1.2 and 0.6 mm (mesopores 1),
- iii. between 0.6 and 0.4 mm (mesopores 2),
- iv. between 0.4 and 0.3 mm (mesopores 3),
- v. between 0.3 and 0.2 mm (mesopores 4),
- vi. smaller than 0.2 mm (micropores).

It should be pointed out that the idea for such pore size classification initiated from those proposed by Hu et al. (2009). After determining the contribution of each pore class to the total infiltration flow, we calculated the percentage of flow (Watson and Luxmoore 1986; Ghiberto et al. 2007):

$$\%flow = \frac{K_{A\psi_i} - K_{A\psi_{i-1}}}{K_{A0}} \times 100 \quad i = 1, 2, \dots, n \quad (16)$$

where i is the number of measurements performed in a sequence, ψ is the applied tension (L), $K_{A\psi_i}$ and $K_{A\psi_{i-1}}$ are the near-saturated hydraulic conductivity ($L T^{-1}$) obtained for two consecutive applied tensions, and K_{A0} is the saturated hydraulic conductivity ($L T^{-1}$).

Statistical analysis

Soil hydraulic properties including sorptive number (α), hydraulic conductivity determined using variable alpha, $K_{A\psi}$ (Ankeny et al. 1991), and constant alpha, $K_{G\psi}$ (Gardner 1958) approaches and contribution of pore classes to water flow were analyzed in terms of statistical moments of the empirical distribution functions. General statistical parameters including the minimum, maximum, mean, variance, coefficient of variation, skewness and kurtosis coefficients were calculated for each soil property. Before the statistical comparison, a normal distribution of each soil property was checked using the Kolmogorov–Smirnov (KS) normality test (after Razali and Wah 2011). In the test of normality, the null hypothesis (of normal distribution) was tested by calculating the KS statistics and then comparing it with tabulated values at probability levels of 5% and 1%. In all cases, the data that did not follow normal distribution, the data were checked for outliers (values that are either extremely high or low in the data set) using the box plot. In almost all cases, excluding the maximum 3 outlier data led to a normal distribution for further statistical analysis.

Statistical analyses were performed using EXCEL version 2013 (Calberg 2014), SPSS version 19 (Gray and Kinnear 2012), and SAS (SAS Institute Incorporated 1990) software packages. In present study, treatments were arranged in a randomized complete design. The mean values of the measured hydraulic properties of the studied land uses at each applied tension were also statistically compared based on LSD test using SAS software packages. It should be noted that since most agriculture fields in the world are annually cultivated fields with different crop rotations, the annual

cultivated field (ACF) is considered as the control group of land use in the present study.

Results and discussion

Summary statistics

In the soils of ACF and PAF land uses, among all measured values of $K_{A\psi}$ or $K_{G\psi}$, the highest coefficient of variation (CV) pertained to K_0 (Table 2). In the case of OF land use, however, the highest CV values pertained to $K_{A7.5}$ and K_{G0} . In general, for most of the measurement sets, variations in K_{ψ} tended to increase in response to a decrease in applied tension (positive values) or increase in applied matric potential (negative values). The results of ACF and PAF land uses were in close agreement with the findings of Moosavi and Sepaskhah (2012c) and Hu et al. (2009) who stated that the highest CV was obtained for the measured $K_{A\psi}$ at the lowest applied tension (0 cm). However, Mohanty et al. (1994) stated that the CV value of $K_{A\psi}$ between rows that are compacted by wheel traffic tend to be greater at 15 cm than at the lower applied tensions, which could be due to larger homogeneous pores as a result of soil structure degradation by the wheel traffic. Furthermore, $K_{A\psi}$ and $K_{G\psi}$ by the ACF land use had CV values of 48.2–183% and 51.1–131%. These belonged to the high variability classes based on the classification proposed by Wilding (1985). Wilding (1985) indicated that an attribute with the CV of < 15%, 15–35% and > 35% usually belongs to low, moderate and high variability classes, respectively. Meanwhile, $K_{A\psi}$ and $K_{G\psi}$ by the PAF land use had CV values of 16.8–32.5% and 15.3–29.3%, respectively, and belonged to the moderate variability classes. Furthermore, $K_{A\psi}$ and $K_{G\psi}$ by OF land use had CV values of 32.5–47.9% and 28.9–43.8%, respectively, and belonged to the moderate to high variability classes (Table 2). The results were in agreement with those reported by Kilic et al. (2004). Furthermore, the other investigators concluded that the measured hydraulic properties indicate moderate (CV of 16–35%) to high (CV > 36%) variability (Moosavi and Sepaskhah 2012c), whereas physico-chemical properties indicate low (CV < 15%) to moderate (CV of 16–35%) variability (Moosavi and Sepaskhah 2012c; Moosavi et al. 2021).

In general, the measured hydraulic properties (α , $K_{A\psi}$, and $K_{G\psi}$) showed the most and the least values of heterogeneity by the ACF and PAF land uses, respectively (Table 2). This could be explained by high and low variations in cropping management strategies and practices in ACF and PAF land uses, respectively.

Among the soil properties studied herein, the hydraulic and physical properties generally resembled the most and the least heterogeneous variables in all the land uses

(data not presented). This could be related to a high inherent variability and a high susceptibility of hydraulic soil properties to managerial practices and human activities. Pore system of soils and consequently their physical and hydraulic properties changes due to soil deformation (Alaoui et al. 2011) as a result of agricultural practices. Furthermore, other investigators reported that the measured K_{ψ} at tensions of 1 and 4 cm varied temporally due to the tillage, wetting/drying, and plant growth (Murphy et al. 1993) and those measured at tensions of 0–11 cm decreased during the growing season due to the structural breakdown by rain and surface sealing (Messing and Jarvis 1993).

The Kolmogorov–Smirnov (KS) test indicated that except α and K_{G15} all of the studied hydraulic properties ($K_{A\psi}$ and $K_{G\psi}$) of the ACF land use with high negative or positive skewness and kurtosis values do not significantly follow normal distribution, whereas opposite results were found in the case of other land uses (Table 2). For instance, the probability distributions of the measured hydraulic conductivity at different applied tensions (ψ) were obtained using the constant alpha approach, $K_{G\psi}$ (Gardner 1958) with/without outliers in ACF are summarized along with the fitted normal distribution curves (Fig. 2). It should be pointed out that, the cracks and termite nests were observed near to outlier points which can directly affect hydraulic conductivity due to much macropores. Therefore, the mentioned outliers cannot be representative for soil hydraulic conductivity in ACF and with removing the outliers in ACF, the normal distribution of hydraulic properties was achieved. Mohanty et al. (1994) also reported that the distribution of near-saturated hydraulic conductivity ($K_{A\psi}$) at different tensions under various cropping conditions were not normal. However, Shouse et al. (1995) and Moosavi and Sepaskhah (2012c) measured physico-chemical and hydraulic soil properties which almost followed a normal distribution. These differences that exist between our findings and those of previous researchers could be a result of different soil conditions.

Sorptive number

Sorptive number (α) is the sole parameter in the Gardner's exponential (or the quasi-linear) hydraulic conductivity function (Eq. 1). It is linked to the pore size distribution. High values of α ($0 < \alpha \leq 1 \text{ cm}^{-1}$) show a dominance of gravity over capillarity that is typically found in the highly structured porous media (Reynolds et al. 2002). While, low values of α ($\alpha < 0.01 \text{ cm}^{-1}$) indicate dominance of capillarity over gravity that is found in many poorly structured porous media (Di Prima et al. 2020). It is also interpreted as the inverse of the macroscopic capillary length (λ), capillary fringe or the air-entry pressure value (Russo 1988). It should be pointed out

Table 2 Summary of statistics for the measured soil hydraulic properties at different applied tensions in the studied land use types and normal distribution fitting parameters ($N=25$ for each land use)

Hydraulic attributes [†]	Land uses			Orchard field (OF)														
	Annual cultivated field (ACF)			Perennial alfalfa field (PAF)				Orchard field (OF)				Orchard field (OF)						
	Mean	CV	VC	SK	KR	KS ^{††}	Mean	CV	VC	SK	KR	KS	Mean	CV	VC	SK	KR	KS
α	0.070	33.3	Moderate	1.50	3.60	0.179 ^{ns}	0.121	19.1	Moderate	1.37	3.22	0.162 ^{ns}	0.080	27.6	Moderate	0.952	0.771	0.139 ^{ns}
K_{A15}	12.0	54.0	High	1.49	1.16	0.342 ^{**}	25.2	21.2	Moderate	-0.247	-0.553	0.155 ^{ns}	8.00	32.5	Moderate	0.408	-0.742	0.210 ^{ns}
K_{A10}	16.8	48.2	High	2.43	7.18	0.319 [*]	38.4	18.7	Moderate	0.648	0.662	0.123 ^{ns}	10.9	36.4	High	1.041	1.91	0.200 ^{ns}
$K_{A7.5}$	23.3	65.7	High	3.60	14.5	0.380 ^{**}	60.9	16.8	Moderate	0.892	1.53	0.117 ^{ns}	16.9	47.9	High	1.37	2.00	0.164 ^{ns}
K_{A5}	34.1	87.7	High	2.90	8.92	0.350 ^{**}	103	18.1	Moderate	0.876	1.52	0.124 ^{ns}	30.2	41.5	High	0.645	-0.383	0.126 ^{ns}
$K_{A2.5}$	52.5	97.4	High	3.34	12.7	0.300 [*]	183	20.2	Moderate	1.22	2.08	0.137 ^{ns}	56.1	31.9	Moderate	-0.254	-0.690	0.134 ^{ns}
K_{A0}	94.4	183	High	4.69	22.7	0.386 ^{**}	348	32.5	Moderate	2.29	7.11	0.239 ^{ns}	104	37.9	High	0.063	-0.198	0.106 ^{ns}
K_{G15}	15.6	51.1	High	1.90	3.87	0.249 ^{ns}	33.1	20.1	Moderate	-0.080	-1.40	0.154 ^{ns}	14.8	28.9	Moderate	-0.376	-0.163	0.146 ^{ns}
K_{G10}	23.2	70.3	High	2.92	9.75	0.289 [*]	59.9	15.3	Moderate	0.399	0.384	0.103 ^{ns}	22.1	29.2	Moderate	-0.431	-0.551	0.121 ^{ns}
$K_{G7.5}$	28.5	82.7	High	3.32	12.4	0.321 ^{**}	81.0	15.5	Moderate	0.675	1.40	0.132 ^{ns}	27.1	31.1	Moderate	-0.246	-0.835	0.085 ^{ns}
K_{G5}	35.3	97.0	High	3.64	14.8	0.326 ^{**}	110	18.2	Moderate	1.06	1.51	0.136 ^{ns}	33.4	34.2	Moderate	0.100	-0.670	0.085 ^{ns}
$K_{G2.5}$	44.1	113	High	3.91	16.8	0.332 ^{**}	150	22.9	Moderate	1.55	2.82	0.158 ^{ns}	41.2	38.5	High	0.529	0.019	0.085 ^{ns}
K_{G0}	55.4	131	High	4.12	18.4	0.343 ^{**}	205	29.3	Moderate	2.01	5.02	0.196 ^{ns}	51.0	43.8	High	0.959	1.04	0.113 ^{ns}

* and ** show significant differences with normal distribution (departure from normal distribution) at the probability levels 1 and 5%, respectively

[†] α , $K_{A\psi}$, and $K_{G\psi}$ show sorptive number (cm^{-1}), near-saturated hydraulic conductivity ($\times 10^2$, cm h^{-1}) determined using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches, respectively

^{††} Mean, CV, VC, SK, KR and KS are the mean, coefficient of variation, variability classes according to Wilding (1985), skewness coefficient, kurtosis coefficient and the statistics of Kolmogorov–Smirnov normality test, respectively

^{ns} Means lack of significant difference with normal distribution

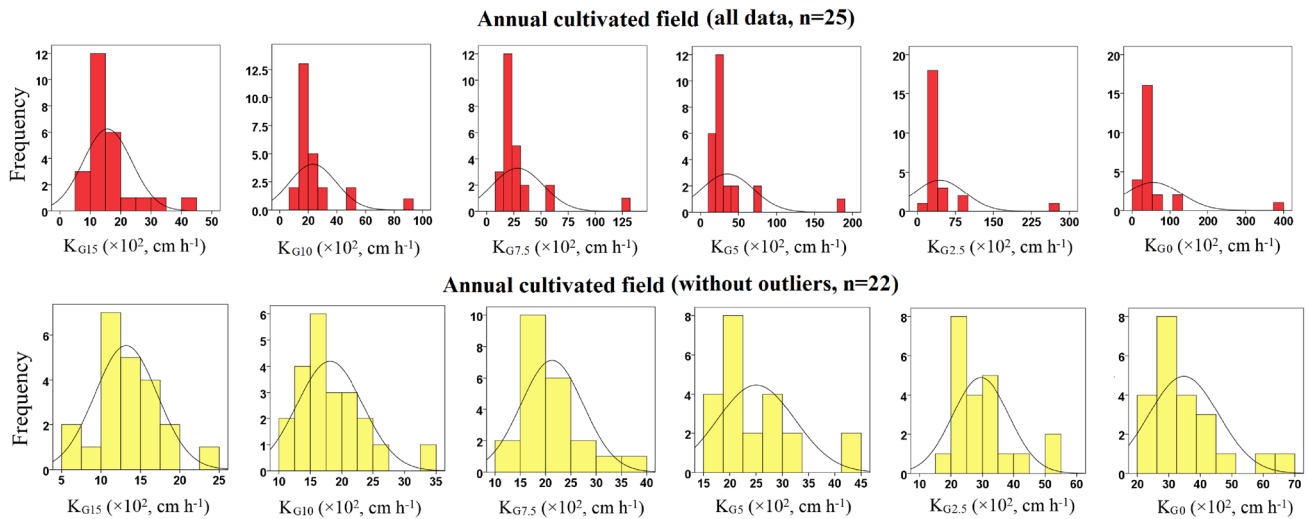


Fig. 2 Probability distribution of the measured hydraulic conductivity at different applied tensions (ψ) using constant alpha approach, $K_{G\psi}$ (Gardner 1958), along with the fitted normal distribution curve in annual cultivated field (ACF)

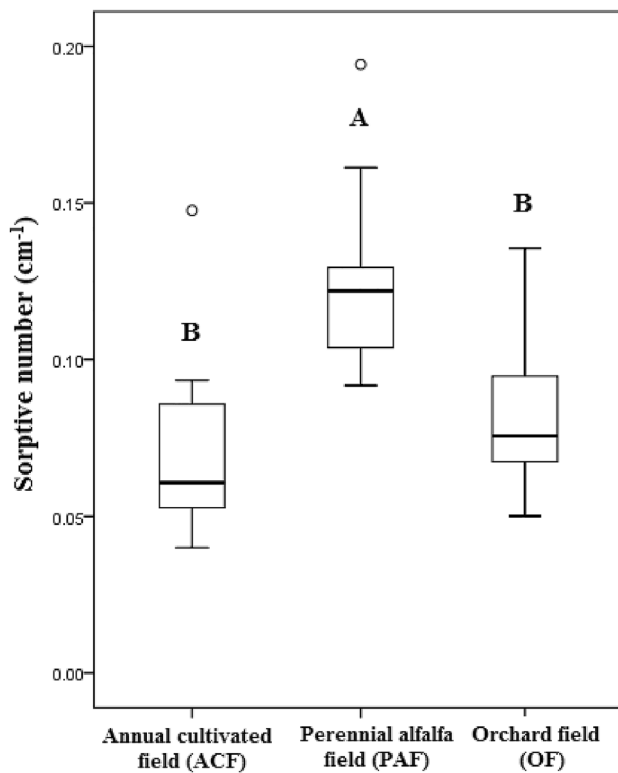


Fig. 3 The measured sorptive number (α) at different land uses (in each case, the mean values of the box plots followed by the same capital letters are not significantly different based on LSD test ($p < 0.05$))

that the present study involved using the approach proposed by Gardner (1958), whereby the average value of α parameter was determined on all applied tensions. The results revealed

that the studied land uses have significant effects on the α parameter (see Appendix Table 4). For instance, α in soils of the PAF land use was significantly higher than those of soils in ACF and OF by nearly 72% and 52% (Table 2). However, there was no significant difference between the α parameter in soils of the ACF and OF land uses (Fig. 3). Short-term plowing operation may increase macropores and cause more infiltration rate. While, in long-term, plowing operation can compact the soil, decrease surface macropores and destruct soil structure (Hernández et al. 2019). Formation of well aggregates takes time and need to cementation agents. Plowing causes decomposition of organic matter be done with high rate (Arshad et al. 1999). In addition, Nath and Lal (2017) in the North Appalachian Region, USA reported the values of wet stable aggregates (WSA) and wet mean weight diameter of aggregates (MWD_{wet}) in no-tillage operation system were greater than conventional tillage operation system of corn cultivation land use and consequently there are more macropores in lands with no-tillage operation system compared to lands with conventional tillage operation system. Overall, tillage in short term may increase macropores but in long term (> 10 year) decreases macropores because of compaction, destruction of soil structure and help to decompose organic matter with high rate (Hernández et al. 2019). In the present study, the higher values of α in soils of PAF land use, as compared to other land uses, could be related to good soil structure and higher surface macropores resulting from (i) long-term no-plowing conditions, (ii) positive effects of alfalfa root systems, (iii) high organic matter content and (iv) less machine activity and fewer livestock on PAF land use than on other land uses.

Near-saturated hydraulic conductivity

In general, the variance analysis revealed that changes in land use, in applied tensions and in their interactions had significant effects ($p < 0.01$) on all studied hydraulic parameters (See Appendix Tables 4 and 5). Changing the land use from ACF to OF significantly reduced the measured the $K_{A\psi}$ at the applied tensions (ψ) of 15 and 10 cm by 50% and 54%, respectively (Fig. 4a). However, there was no significant difference between the measured $K_{A\psi}$ at the other applied tensions (i.e., ψ of 7.5, 5, 2.5, and 0 cm) in soils of the ACF and OF land uses. Furthermore, there was no significant difference between the measured $K_{G\psi}$ among the different groups of applied tensions in the ACF and OF land uses (Fig. 4b). The values of both $K_{A\psi}$ and $K_{G\psi}$ at each of the applied tensions in the soil of PAF land use were significantly higher than those measured in the soils of the other land uses. For example, K_{15} , K_{10} , $K_{7.5}$, K_5 , $K_{2.5}$ and K_0 in the soil of PAF land use were 1.10, 1.06, 1.61, 2.02, 2.49 and 2.69 times higher (based on $K_{A\psi}$) and 2.11, 2.58, 2.84, 3.11, 3.40 and 3.69 times higher (based on $K_{G\psi}$) than those of ACF. In addition, the mentioned values of K_{ψ} in the soil of PAF land use were 2.15, 2.53, 2.60, 2.41, 2.26 and 2.35 times higher (based on $K_{A\psi}$) and 2.23, 2.71, 2.99, 3.29, 3.63 and 4.01 times higher (based on $K_{G\psi}$) than that of OF land use, respectively (Fig. 4a and b).

According to the results, the differences between both $K_{A\psi}$ and $K_{G\psi}$ in the soils of ACF, PAF and OF land uses increased as the soils became saturated (i.e., the applied tension became near to 0 cm). Soil hydraulic conductivity is a consequence of several physical properties such as bulk density, porosity and aggregate stability (Li and Shao 2006). Therefore, with compacting the coarse aggregates, the abundance of macropores

is decreased. Of course, other soil properties such as organic matter and microorganism activity affect the soil bulk density, aggregate stability and porosity (Moreno-Barriga et al. 2017). These changes could indirectly alter soil hydraulic conductivity. Soil pores and soil macropores in particular tend to accelerate water infiltration into the soil and have decisive roles in determining the amount of water drainage from the soil, soil aeration and root penetration into the soil.

Cultivation and soil management practices affect soil hydraulic properties. In this regard, Baranian Kabir et al. (2020), Zhipeng et al. (2018), and Kazemi-Zadeh and Sepaskhah (2016) reported that the type of land use can significantly affect soil water infiltration characteristics, including hydraulic conductivity when measured at different applied tensions. Furthermore, Schwartz et al. (2003) stated that land use operations can affect water flow into the soil more than natural processes do. Picciafuoco et al. (2019) showed that saturated hydraulic conductivity (K_0) varies significantly from 12 mm h⁻¹ in grassy fields to 34.5 mm h⁻¹ in arable fields. Moreover, the K_0 values of 63, 7, and 8 mm h⁻¹ have been reported as descriptions of forest, managed lawns and pastures, respectively, in the southern Blue Ridge Mountains, North Carolina, USA (Price et al. 2010).

In the present study, K_{ψ} values that describe soils by the PAF land use were higher compared to other land uses at each applied tension, particularly at ψ of 0 cm (saturated conditions). This difference could be related to long-term no-plowing conditions and also because of positive effects caused by alfalfa root systems, high amounts of organic matter content in the soil structure, and consequently, surface macropores. In other words, PAF improves soil structure. Furthermore, machinery and livestock traffic on PAF land use tend to be lower compared to other land uses. It seems that reducing the

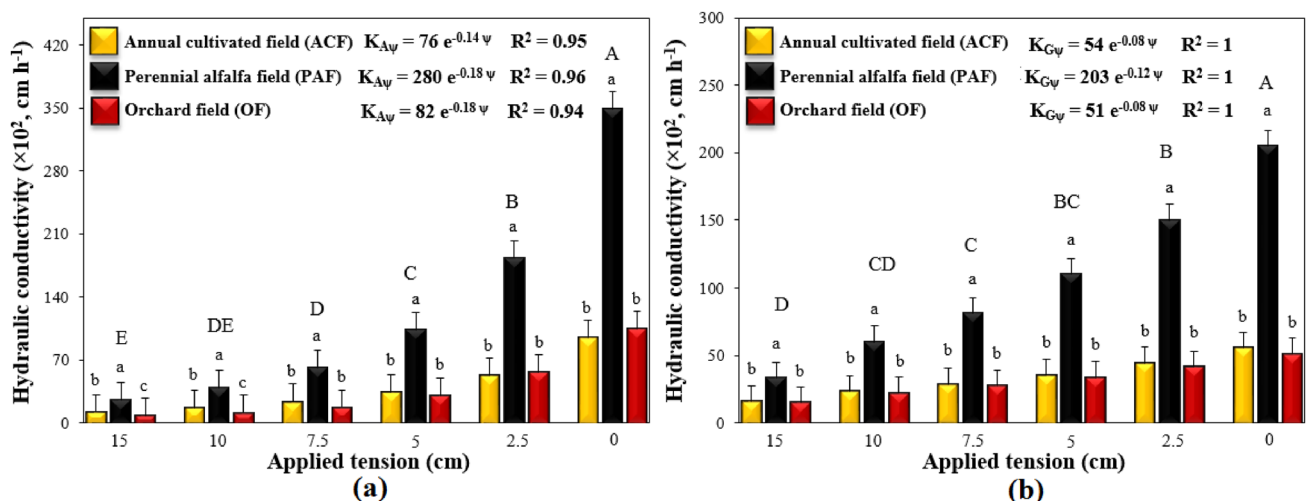


Fig. 4 The measured hydraulic conductivity at different applied tensions (ψ) using **a** variable alpha approach, $K_{A\psi}$ (Ankeny et al. 1991) and **b** constant alpha approach, $K_{G\psi}$ (Gardner 1958) along with their regression relationships in different land uses. (In each tension, col-

umns followed by the same lowercase letters are not significantly different based on LSD test at the probability level of 5% and similar capital letters indicate no significant difference between the measured K_{ψ} at different tensions)

abundance of machinery/livestock traffic can lead to a better soil structure and can increase macropores when considering the PAF land use. In this regard, Huang et al. (2019) in Qinghai-Tibetan Plateau reported that long-term cultivation of PAF (7 years) can significantly increase the alpine soil water infiltrability in comparison with 2- and 4-year cultivation of PAF. They also stated that soil water infiltrability of PAF were significantly more than that of corn cropland. On the other hand, frequent soil tillage—a common practice in ACF—resulted in the loss of macropores in the soil, and consequently, reduced hydraulic conductivity, especially at near-saturated conditions. Despite the highest organic matter content in OF compared with ACF and PAF (Table 1), the values of K_{ψ} at all tensions are lower than those in PAF. According to Table 1, the values of soluble sodium in OF is 2.1 and 7.1 times more than that in ACF and PAF, respectively, which is due to excessive use of manure fertilizers (especially cow manure) in OF. Sodium can destroy soil structure and consequently low surface macropores due to high hydrated radii, and consequently, dispersion of soil particles (Tajik et al. 2003). Furthermore according to local ranchers, the livestock traffic in OF was extremely higher than PAF and ACF. Therefore, these two important issues can justify the lower values of K_{ψ} in OF than PAF.

Certain land uses can have significant effects on K_{ψ} (Borrmann and Klaassen 2008; Zhou et al. 2008). The results of the present study are in close agreement with those reported by Hu et al. (2009) that K_{ψ} values differ significantly when measured at 15 cm tension in the soils of different land uses, i.e., Bunge needlegrass, alfalfa, soybean and Korshinsk peashrub farming. Contrary to our results, the mentioned research claimed no significant difference between the measured K_{ψ} values at other applied tensions (i.e., 6, 3 and 0 cm). Furthermore, Hu et al. (2009) found no significant difference in K_{ψ} values among different land use types, except for the K_{15} . The researchers concluded that the lack of significant difference may be related to the following reasons: (i) no significant influence of land use on the measured physico-chemical properties that are generally believed to influence K_{ψ} ; (ii) relatively homogeneous hydraulic conductivities among different land uses because of similar hydrological processes and weather conditions as a result of close spatial alignments among farm fields; and (iii) relatively small sampling numbers (i.e., six replications). Licht and Al-Kaisi (2012) reported that long-term tillage operation can reduce water infiltration into the soil by suppressing macropores. Conservation and no-tillage systems compared to conventional tillage can conserve soil organic matter, decrease soil erosion, increase soil infiltration, water stable aggregates, and microbial biomass (Arshad et al. 1999). According to Nath and Lal (2017) results, there are greater aggregates in no tillage than conventional tillage operation systems in corn cultivation land use. According to the finding by present study and mentioned researchers, tillage operation can reduces soil surface macropores.

Furthermore, in each type of land use, $K_{A\psi}$ increased in response to a decrease of the positive values of applied tensions (Fig. 4a). In other words, $K_{A\psi}$ increased as exponential equations with the coefficients of determination, R^2 of 0.95, 0.96 and 0.94 as ψ neared zero in the soils of ACF, PAF and OF land uses, respectively (Fig. 4a). The results showed that the mean value of $K_{A\psi}$ over all land use types also increased by nearly 92, 88, 81, 69 and 46% when ψ decreased from 15, 10, 7.5, 5 and 2.5 cm to 0 cm, respectively (Fig. 4a). Similar to the values of $K_{A\psi}$ for each land use type, $K_{G\psi}$ increased in response to a decrease in the applied tension (positive values of tensions). In the soils of ACF, PAF and OF land uses, the $K_{G\psi}$ values at zero cm tension were 3.5, 2.4, 1.9, 1.6 and 1.3 times higher; 6.2, 3.4, 2.5, 1.9 and 1.4 times higher; 3.4, 2.3, 1.9, 1.5 and 1.2 times higher than those measured at 15, 10, 7.5, 5 and 2.5 cm tensions, respectively (Fig. 4b). In other words, $K_{G\psi}$ increased as exponential equations with the coefficients of determination, R^2 of 1 as ψ became close to zero in the soils of all studied land uses (Fig. 4b). Besides, results depicted that the mean value of $K_{G\psi}$ over all land use types also increased by nearly 80, 66, 56, 43, and 24% when ψ decreased from 15, 10, 7.5, 5 and 2.5 cm to 0 cm, respectively (Fig. 4b). These were the least sharp trends of increase in ACF land use, while those of the OF and PAF land uses were almost similar. This indicated that pores in the soil of ACF land use are more homogeneous with a narrower range of pore diameter variation as compared with those in the other land uses. This may be a result of fragmentation effect of soil tillage and disturbance in ACF land use. The results are in close agreement with the findings of Moosavi and Sepaskhah (2012c) and Kelishadi et al. (2014) who reported that the hydraulic conductivity values decreases with the increase in applied tensions (positive values of tensions). Results showed that both the measured $K_{A\psi}$ and $K_{G\psi}$ at applied tension of 15 cm in each of the three studied land uses were close to each other, whereas an increase in the applied tension caused a greater difference between the measured $K_{A\psi}$ and $K_{G\psi}$ among the soils of the studied land uses. At the applied tensions of 15, 10, 7.5, 5 and 2.5 cm, the soil pores with diameters of less than 0.2, 0.3, 0.4, 0.6 and 1.2 mm are likely to have different effects on water flow through the soil. Therefore, the least difference between K_{15} of the studied land uses (Fig. 4a and b) revealed that the abundance of pores with <0.2 mm diameter is relatively similar among the soils of these studied land uses and that the pores are least susceptible to agricultural practices while being abundant in compacted soils. Furthermore, the difference among the measured K_{ψ} at the other applied tensions in the soils of PAF land use, as compared with those of the other land use types, increased parallel to the increase in applied tensions. This revealed that as the pores became larger, their susceptibility to agricultural practices and machine/livestock induced greater compaction.

The results indicated that the values of $K_{A\psi}$ measured at tensions zero to less than 5 cm in the soils of PAF and OF

land uses were significantly higher than that of $K_{G\psi}$. There was no significant difference between the measured $K_{A\psi}$ and $K_{G\psi}$ at tensions of 5 cm in the mentioned land uses. At applied tensions greater than 5 cm, however, an opposite trend was obtained and $K_{G\psi}$ became significantly higher than $K_{A\psi}$ in the mentioned land uses (Fig. 5). In the case of ACF land use, results depicted that the K_{A0} was significantly higher than K_{G0} by nearly 70%. There was no significant difference between the measured $K_{A\psi}$ and $K_{G\psi}$ at 2.5, 5, and 7.5 cm tensions. However, at applied tensions greater than 7.5 cm, the trend changed and the measured $K_{G\psi}$ at tensions of 10 and 15 cm became significantly higher than that of $K_{A\psi}$ by nearly 31% and 39%, respectively (Fig. 5). According to the results, both the variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches resulted in the

same values of near-saturated hydraulic conductivity at the applied tensions of 2.5 to 7.5 cm for ACF and 5 cm for PAF and OF land uses. Therefore, the quantification and interpretation of saturated and near-saturated hydraulic conductivity strongly depends on the methods used for their calculation (Verbist et al. 2013).

Contribution of pore classes to water flow

The contribution of six pore classes, including macropores, four classes of mesopores and micropores to water flow through the soils of the studied land uses are summarized in Table 3 and Fig. 6. In the ACF land use, the relative proportion of flow on average was 2, 1, 1, 2, 3 and 6 in micropores, mesopores I, mesopores II, mesopores III, mesopores IV

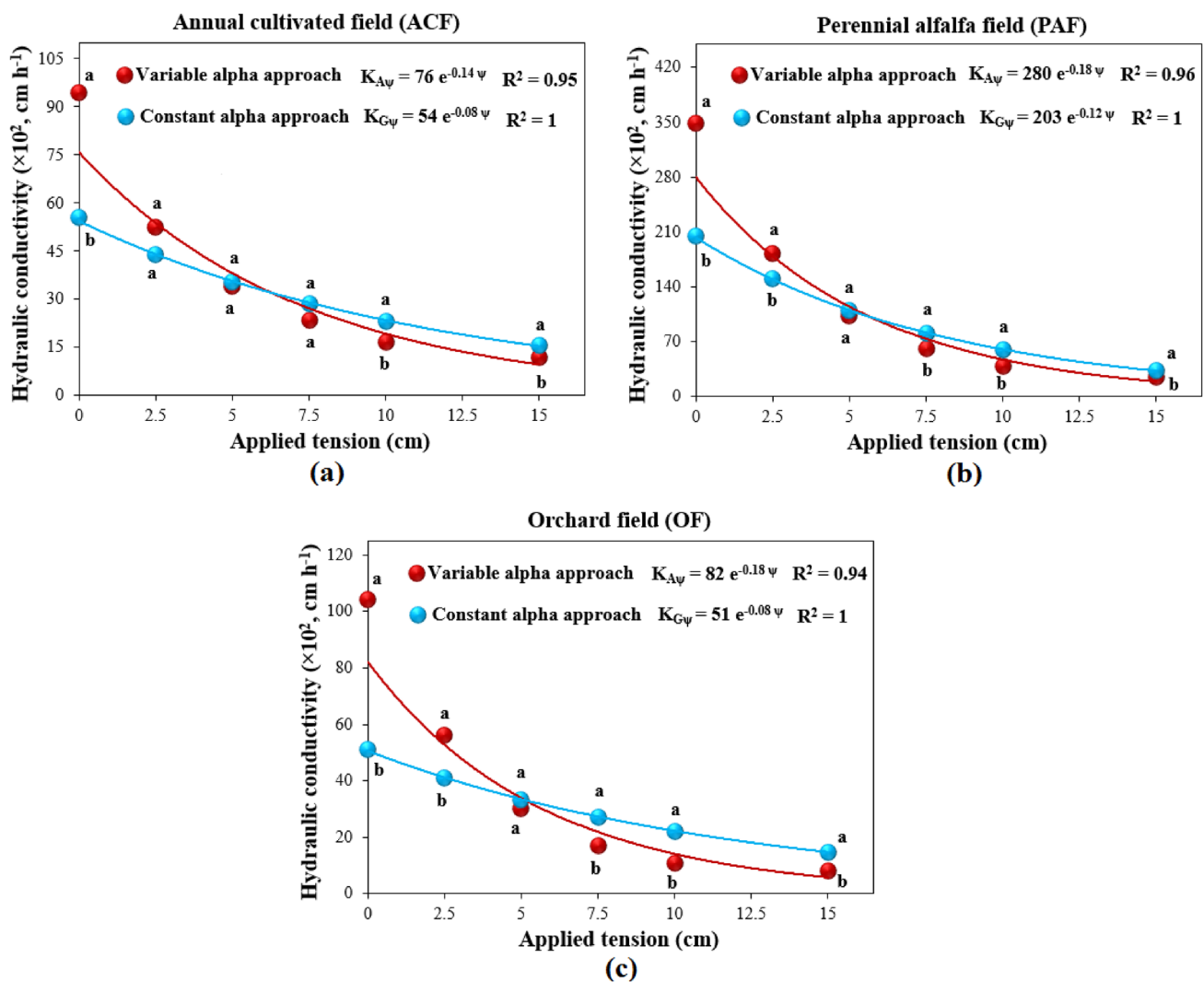


Fig. 5 A comparison of the measured hydraulic conductivity as determined at different applied tensions (ψ) using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches ($K_{A\psi}$ and $K_{G\psi}$ respectively) in **a** annual cultivated field (ACF), **b** perennial

alfalfa field (PAF), and **c** Orchard field (OF) along with their regression relationships. (At each tension, values followed by the same lowercase letters are not significantly different based on LSD test at the probability level of 5%)

Table 3 The mean relative proportion of water flow in different pore classes of the studied land use types

Pore class [†]	Land use		
	Annual cultivated field (ACF)	Perennial alfalfa field (PAF)	Orchard field (OF)
Micropores (<0.2 mm)	2	1	1
Mesopores IV (0.3–0.2 mm)	1	0	0
Mesopores III (0.4–0.3 mm)	1	1	1
Mesopores II (0.6–0.4 mm)	2	2	2
Mesopores I (1.2–0.6 mm)	3	3	3
Macropores (> 1.2 mm)	6	6	6

[†]Pores were classified after Hu et al. (2009)

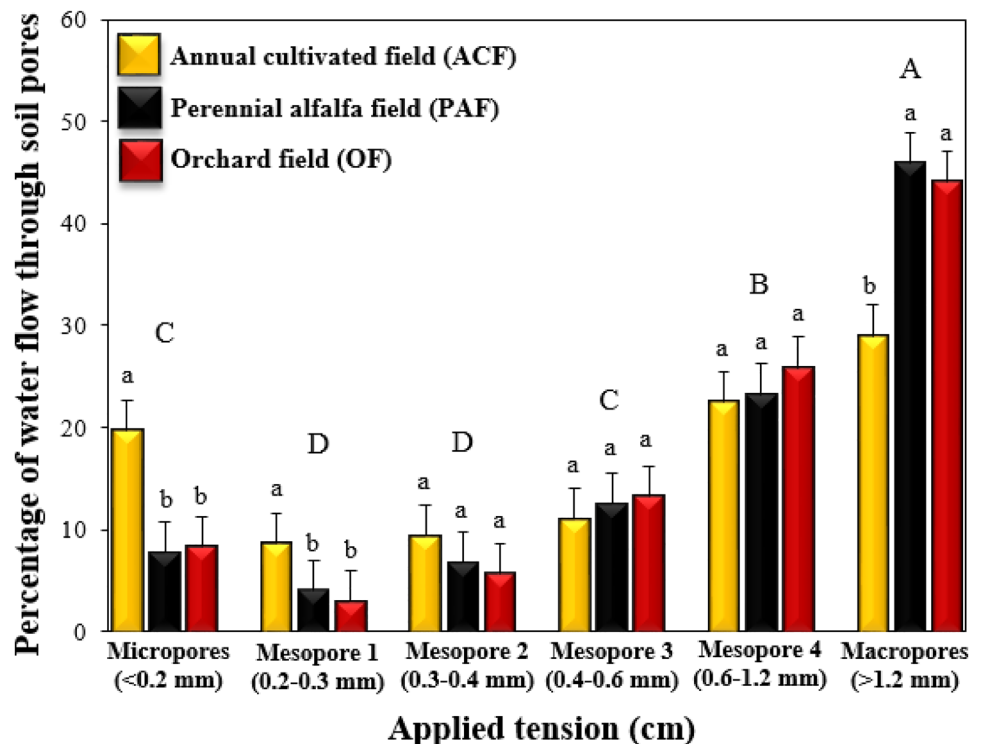
and macropores, respectively. However, the mentioned proportions were 1, 0, 1, 2, 3 and 6 in PAF and OF land uses, respectively. In our study area, this indicates that the total water flow in micropores and mesopores is relatively high, being 1.5, 1.2 and 1.2 times higher than that of macropores in ACF, PAF and OF land uses, respectively. These ratios revealed that the contribution of macropores to water flow in the soils of PAF and OF land uses is higher than that in the ACF land use. The results are in close agreement with the findings of Hu et al. (2009) who reported that the

contribution of macropores and mesopores is low (50% of the total flow) in their studied land uses. However, opposite results were reported by Vita et al. (2007), stating that the contribution of macropores to water flow in the soil is higher than the contributions of micropores and mesopores.

Conclusions

Soil hydraulic properties are of great importance with regard to many aspects of water flow through the soil. In this study, three types of land use (annual cultivated field, ACF, perennial alfalfa field, PAF and orchard field, OF) were studied. Our observations revealed that the values of $K_{A\psi}$ and $K_{G\psi}$ at all applied tensions and α in PAF were found to be significantly higher than those in the other land uses. According to the obtained results, even in a small area, constant soil hydraulic parameters cannot be used for modeling and the land use-dependent variations, along with the spatio-temporal variations should be considered. The findings also revealed that near-saturated hydraulic conductivity can be determined using both the variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches, as these values were equal at ψ of 5 cm. At $\psi < 5$ cm, $K_{A\psi}$ was higher than $K_{G\psi}$ but, at $\psi > 5$ cm, $K_{G\psi}$ was higher than $K_{A\psi}$. Therefore, it can be concluded that different methods may result in different values of saturated and near-saturated hydraulic conductivity. The average relative proportion of the ‘pore classes’ to ‘flow’ was 2 (micropores):7 (mesopores):6 (macropores) for ACF

Fig. 6 Contribution of each pore class to water flow in different land uses (in each case, columns followed by the same lowercase letters are not significantly different based on the LSD test at the probability level of 5% and similar capital letters indicate there is no significant difference between water flow in different pore classes)



and 1:6:6 for PAF and OF. Furthermore, the total values of water flow in micro and mesopores were 1.5, 1.2 and 1.2 times greater than that of macropores in ACF, PAF and OF, respectively. In conclusion, the findings can be applied for accurate monitoring of liquid flow and the pollutant/chemical transportation within soil environment. As take-home messages, it may be recommended that the farmers should always keep the organic matter and plant residues on soil surface to form greater and more stable aggregates; substitute conventional tillage by the minimum and no-tillage practices; considering alfalfa cultivation in crop rotation for several consecutive years in lands with poor soil structure to form macropores and to achieve more infiltration rate and reduce soil erosion.

Appendix

See Tables 4 and 5

Table 4 Results of two-way variance analysis, ANOVA for the effect of land use type on the studied soil hydraulic properties

Variation source	Degree of freedom, DF [†]	Mean squares		
		$\alpha^{\dagger\dagger}$	$K_{A\psi}$	$K_{G\psi}$
Tension	5	–	302,531*	68,110*
Land use	2	0.018*	389,013*	272,060*
Tension × land use	10	–	65,860*	20,090*
Error	432	0.001	2683	904
Total	449			

*Show significant at the probability level of 1 %

[†]The mentioned DF values correspond to $K_{A\psi}$, and $K_{G\psi}$ parameters and in the case of α , the DF for the land use, error, and total sources of variation are 2, 72, and 74, respectively

^{††} α , $K_{A\psi}$, and $K_{G\psi}$ show sorptive number (cm^{-1}), near-saturated hydraulic conductivity ($\times 10^2 \text{ cm h}^{-1}$) determined using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches, respectively

Table 5 Results of variance analysis, ANOVA for the effect of land use type on the studied soil hydraulic properties

Source of variation	Degree of freedom, DF	Mean squares of hydraulic properties at different applied tensions (cm)					
		15	10	7.5	5	2.5	0
$K_{A\psi}^{\dagger} (\times 10^2, \text{ cm h}^{-1})$							
Land use type	2	2035*	5248*	14,128*	42,219*	137,875*	516,812*
Error	72	25.7	44.2	135	468	1435	14,797
Total	74						
$K_{G\psi} (\times 10^2, \text{ cm h}^{-1})$							
Land use type	2	2650*	11,567*	23,586*	47,636*	95,636*	191,437*
Error	72	42.1	131	262	569	1306	3117
Total	74						

*Show significant at the probability level of 1 %

[†] $K_{A\psi}$ and $K_{G\psi}$ show near-saturated hydraulic conductivity ($\times 10^2 \text{ cm h}^{-1}$) determined using variable alpha (Ankeny et al. 1991) and constant alpha (Gardner 1958) approaches, respectively

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Author contributions HM carried out the experiment, analyzed the data, and wrote draft of the manuscript. AAM supervised the research, wrote, and edited the manuscript. ARS was adviser of the research and edited the manuscript.

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Availability of data and material Data will be available based on the request.

Code availability Not applicable.

Declarations

Conflict of interest There is no conflict of interest.

Ethics approval All the authors confirm that this manuscript has not been published elsewhere and is not under consideration by another journal and confirm that all ethical issues have been considered.

Consent to participate All the authors have approved the manuscript and confirmed their contributions, and the mentioned order of authors in the submitted manuscript.

Consent for publication All the authors confirm that the manuscript has not been published elsewhere and is not under consideration by another journal and agree with submission to Environmental Earth Sciences.

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