Optimal disc tension infiltrometer estimation techniques for hydraulic properties of soil under different land uses

Zhou Beibei[1], Wang Quanjiu[1,2*], Wu Xiangbo[3]

(1. *State Key Laboratory of Eco-Hydraulic Engineering, Institute of Water Resources and Hydro-electric Engineering, Xi'an University of Technology, Xi'an 710048, China*; 2. *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Northwest A & F University, Yangling 712100, Shaanxi, China*; 3. *Inner Mongolia Water Resources and Hydropower Survey and Design Institute, Hohhot 010020, China*)

Abstract: Different land use, and associated variations in agricultural or silvicultural practices, can cause substantial variations in soils' hydraulic properties. Thus, the optimal method for measuring these properties may vary, even among neighboring sites. In this study these variations were examined by comparing measurements of hydraulic properties of soil in fields used for poplar, alfalfa and wheat cultivation obtained with two steady flow methods (the White and Sully, and single disc with multiple tension methods) and two transient flow methods (the single disc with single tension, and multiple tensions with multiple disc radius methods). The fields were all located in Changwu municipality, a major grain-producing area in Shaanxi Province, China. Disc tension infiltrometers were used to measure unconfined, unsaturated infiltration over a range of supply pressure heads (h = −9 cm, −6 cm, −3 cm and 0) at the soil surface. Intact soil cores were sampled near the surface to determine bulk density and soil water retention curves at potentials ranging from −0.15 kPa to −100 kPa. Unsaturated hydraulic conductivity values over the range of supply pressure heads were estimated using Wooding's equation for steady-state flow from a disc source. The van Genuchten water retention model was fitted to experimental data to estimate the parameter values. The results indicated that land use affects soils' saturated and unsaturated hydraulic conductivity. Further, steady state flow methods are most appropriate for measuring hydraulic properties of soils under poplar and wheat, due to their high organic contents and saturated hydraulic conductivity. However, for soils supporting alfalfa (which are more homogeneous), instant methods provide better results, in addition to substantial time and labor savings.

Keywords: soil property, hydraulic conductivity, land uses, disc tension infiltrometer

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1 Introduction

Hydraulic properties of soil strongly influence both vertical and lateral movements of water through it. Thus, they are highly important for characterizing many associated processes, such as rain infiltration and runoff, migration of nutrients, pesticides and contaminants through the soil profile, as well as the design and monitoring of irrigation and drainage systems[1-3]. Previous studies showed that changes in land use can cause changes in soil hydraulic properties over time due to associated changes in tillage, fertilization, crop rotation and other various practices[4,5]. Notably, Vos and Kooistram[6] found that physical properties of soil used for long-term pasture or minimal-tillage were much more favorable for growing crops than soil at the same site under conventional (high-input) or integrated (reduced N-fertilization, and biocide use, with shallower tillage) cultivation systems. Similarly, Noellemeyer et al.[7]

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Biographies: Zhou Beibei, PhD, research interests: soil physics, water saving irrigation, Email: happyangle222@aliyun.com; **Wu Xiangbo**, graduate student, research interests: soil physics, Email: wuxb.lucky@163.com.

***Corresponding author: Wang Quanjiu,** PhD, Professor, research interests: soil physics, soil water and nutrient loss on the slope. Institute of Water Resources and Hydro-electric Engineering, Xi'an University of Technology. Tel: +86-13359268666, Email: wquanjiu@163.com.

found that soil organic carbon contents and aggregation rapidly decreased after three years of cultivation of former permanent pastures, and hydraulic properties of the soil were affected in the longer term. Furthermore, Schwartz et al.[8] noted that the pore structure of soil in cropland converted to pasture had still not fully recovered from effects of tillage ten years after the conversion. Thus, land use can profoundly affect soils' hydraulic properties in both short and long terms.

Since the 1990s, tension disc infiltrometers have been widely used for measuring hydraulic properties of soil at or near the surface[9-12]. Use of these infiltration-based devices is particularly suitable for quantifying changes in near-surface hydrology resulting from soil management activities such as tillage[13]. Numerous techniques have been applied for interpreting disc infiltration data[9-11]. Each published technique has both advantages and disadvantages. For example, non-linear regression, based on the Wooding Equation[14] of unsaturated infiltration measurements at multiple tensions can provide quick and stable hydraulic estimates without soil moisture data, but it has to adjust the three water heads at least which is a little difficult and labor consuming. However, less research is about the other appropriate methods for characterizing specific types of soils under specific land uses. Thus, the objectives of this study were to evaluate the effects of different land uses (poplar, alfalfa and wheat cultivation) and management practices on soils hydraulic properties, and identify appropriate methods for analyzing data acquired using disc infiltrometers in soil supporting different land uses.

2 Materials and methods

2.1 Field site description

The study was conducted at the Changwu agricultural and ecological experimental station (35.28°N, 07.88°E; 1200 m elevation) located on the Loess Plateau of China. The climate at the field site is semiarid, with an average annual temperature of 9.2°C, and annual evaporation from a free water surface of 1565 mm. Average annual rainfall amounts to 555 mm, with 73% falling during the maize growing season. The area is rain-fed, and the primary cropping system consists of one maize or wheat crop harvested per year. The soils at the site are Cumuli-Ustic Isohumosols[15], which are loess-derived and thus easily eroded. The pH of the top 20 cm of the soil at the study site was 8.4.

The study focused on soils in fields at the site that had been supporting three land uses for at least 15 years: cultivation of poplar *(Populus simonii)*, alfalfa (*Medicago sativa*) or wheat (*Triticum aestivum*). As shown in Table 1, the particle size distributions in the fields supporting the three crops were similar, with 10%-13% sand particles, 72%-74% silt particles and 15%-16% clay particles. Soil in all three cases is classified as loam according to international standard. The bulk density is also similar under all these three land uses, ranging from 1.22 g/cm^3 to 1.29 g/cm^3, however the organic matter contents of the soil varies substantially, being much higher under poplar than that under alfalfa or wheat (Table 1).

Table 1 General characteristics of the surface soil under the three land uses

Land use (crop)	Clay /kg·(100 kg)$^{-1}$	Silt /kg·(100 kg)$^{-1}$	Sand /kg·(100 kg)$^{-1}$	Bulk density /g·cm^{-3}	Organic matter /g·kg^{-1}
Poplar	15.2	72.2	12.6	1.29	5.5
Alfalfa	15.8	71.9	12.3	1.23	3.2
Wheat	16	73.1	10.9	1.22	2.9

The disc infiltration measurements were made on fields with three different land uses. The measured area for each field was about 100 m^2. The criteria for selecting these three fields were the close spatial arrangement of the fields and the types of land used represented in the fields. All the selected three land use fields have growth duration of 15 years. Furthermore, it should be noted that for alfalfa land, wheat land and Poplar land management activities were adopted only at the seeding or planting periods followed by alfalfa cutoff one or two times a year. In 2009, alfalfa was not cut until the completion of our infiltration measurement. Therefore, three of the fields were less affected by human activity during the experimental process.

2.2 Sampling and measurement

To account for possible seasonal hydraulic changes, different disc infiltration measurements were acquired in each of the fields under each land use between May and August 2009. As mentioned above, management activities were applied only during the seeding or planting periods and harvesting or cutting periods, and in 2009 the alfalfa was not cut until after our infiltration measurements. Thus, no management treatments were applied between samplings. In each set of infiltration measurements two disc infiltrometers (10 cm and 15 cm diameters, both with a reservoir tube radius of 1.7 cm) were used to determine infiltration rates under four pressure heads, increasing in the order −9 cm, −6 cm, −3 cm and 0 at eight locations.

The eight measurement locations in each field were spaced in a 30 cm×30 cm grid, with adjustments to allow selection of sites with bare soil surfaces between the dominant vegetation. For the first set of infiltration measurements, an unsmeared cleared soil surface was prepared by using a knife to remove the top 1-2 mm of surface soil. The bare soil was covered with a certain sand layer (according to different measure methods) to ensure good hydraulic contact between the disc and the soil. For each infiltration measurement, cumulative infiltration was recorded every minute until it reached a steady state. Soil near each measurement location was sampled to determine the initial soil content, and after infiltration the soil under the sand layer was sampled to determine the final water content. Each method has four replications.

2.2.1 Basic theory

Several techniques can be used to estimate hydraulic properties using data obtained from either single-disc or multiple-disc infiltrometer infiltration measurements. However, the main methods can be divided into steady state and transient flow methods. Two of both types were applied and compared in this study, as described below.

2.2.2 Steady state flow methods

1) White & Sully Method (WS, using discs with a single radius and one tension)

Data obtained from infiltration measurements by infiltrometers with a single radius can be analyzed in terms of sorptivity (S) in initial stages, assuming equivalence to one-dimensional water flow[16,17], using the Equation (1):

$$I(t) = St^{\frac{1}{2}} \tag{1}$$

where, I is cumulative intake per unit area; t is time, and S is the slope of I versus $t^{1/2}$. For long times, Wooding's[14] Equation applies:

$$\frac{Q}{\pi r_0^2} = K + \frac{4\lambda S^2}{\Delta\theta\pi r_0} \tag{2}$$

where, Q is the flow rate; r_0 is the radius of the disc infiltrometer; K is the hydraulic conductivity value corresponding to the water supply potential, and λ is the macropore capillary length. White and Sully[9] showed that λ is a function of sorptivity and hydraulic conductivity, expressed as:

$$\lambda = \frac{bS^2}{(\theta_0 - \theta_i)(K_0 - K_i)} \tag{3}$$

where, θ_0 is the moisture content at the supply potential; θ_i is the initial moisture content; K_0 and K_i are the conductivity values corresponding to the supply potential and initial water content, respectively, and b is a constant approximately equal to 0.55.

2) Single disc radius with Multiple tensions (MP)

Another approach based on Wooding's solution can be applied when steady state flow rates are known for two or more r_0 values, as follows.as Equation (2) can then be solved for the two unknowns (K_0 and λ). With Q_1 and Q_2 corresponding to flow rates observed in discs r_1 and r_2, respectively, λ is given by,

$$\lambda = \frac{\pi}{4}\left[\frac{Q_1 - Q_2}{\frac{Q_2}{r_1} - \frac{Q_1}{r_2}}\right] \tag{4}$$

where, Q_1, Q_2 are flow rate; r_1, r_2 are the discs radius.

The same principle can be applied for measurements obtained using discs with a single radius and multiple pressures[10], assuming validity of the Gardner relationship[17]:

$$k = K_s\exp(\alpha h) \tag{5}$$

where, h is the metric potential expressed as a length; K_s is saturated hydraulic conductivity, and α a constant equivalent to λ^{-1}. Thus Wooding's Equation (2) can also be expressed as:

$$\frac{Q}{\pi r_0^2} = \left(1 + \frac{4}{\alpha\pi r_0}\right)K_s\exp(\alpha h) \tag{6}$$

Measurement of steady state flow for pressures at the same site, yields Equations, each with two unknowns of K_s and α.

2.2.3 Transient flow methods

1) Single disc with single tension (ST)

Smettem et al.[18] presented the following model, accounting for both three-dimensional (3D) and one-dimensional (1D) infiltration:

$$I_{3D} - I_{1D} = \frac{\gamma S^2}{r_0\left(\theta_0 - \theta_i\right)} \tag{7}$$

where, the subscripts 3D and 1D refer to axially symmetric 3D and 1D processes, respectively. γ is 0.75 when gravity can be ignored.

Haverkampa et al.[19] extended Equitation (8) and obtained:

$$I_{3D} = St^{\frac{1}{2}} + \left[\frac{2-\beta}{3}K + \frac{\gamma S^2}{r_0\left(\theta_0 - \theta_i\right)}\right]t \tag{8}$$

where, β is a constant value between 0 and 1, and is generally approximately equal to 0.55.

2) Multiple tensions with multiple disc radii (MR)

Vandervaere et al.[20] developed a hydraulic model based on multiple disc radii and multiple tensions, expressed as follows,

$$C_{2A} = \frac{\gamma S_0^2}{R_A\left(\theta_0 - \theta_n\right)} + \frac{2-\beta}{3}K_0 \tag{9}$$

$$C_{2B} = \frac{\gamma S_0^2}{R_B\left(\theta_0 - \theta_n\right)} + \frac{2-\beta}{3}K_0 \tag{10}$$

Combining Equations (9) and (10) gives:

$$K = \frac{3}{2-\beta}\left[\frac{C_{2A}R_A - C_{2B}R_B}{R_A - R_B}\right] \tag{11}$$

As already stated, an objective of the study was to identify suitable methods for assessing hydraulic properties of the soils under the three focal land uses. For this purpose, the accuracy of results obtained using the four methods described above was evaluated by comparing them to results obtained using the non-linear regression method based on theoretical analysis of 3D quasi-steady-state water fluxes in an infiltrometer[14], showing as follows

$$\frac{Q}{\pi r_0^2} = \left(1 + \frac{4}{\alpha \pi r_0}\right)K_s \exp\left(\alpha h\right) \tag{12}$$

where, K_s is the calculated saturated hydraulic conductivity, α is the Gardner's value.

3 Results and discussion

3.1 Saturated hydraulic conductivity of soil

To assess the applicability of the four methods for estimating hydraulic properties of the soil under each of the land uses, saturated hydraulic conductivities determined using them were compared with reference values. The results from the transient flow methods were close to the reference values, with deviations as low as 1.71%, but the values obtained using a single disc radius are generally higher than those obtained using multiple radii (see Tables 2-4, showing results obtained with a water head of 0). The steady-state flow methods generally provide lower (and less accurate) saturated hydraulic conductivity values than the transient flow methods.

Table 2 Saturated hydraulic conductivities calculated with the four assessed methods and reference method

	Saturated hydraulic conductivities/cm·s^{-1}				
	Method	Diameter/cm	Poplar land	Alfalfa land	Wheat land
Transient flow methods	ST	15	3.26E-03±0.075	4.03E-03±0.085	1.16E-03±0.012
		10	2.22E-03±0.023	4.18E-03±0.045	4.23E-04±0.071
	MR	15	4.39E-03±0.012	4.89E-03±0.015	9.29E-04±0.004
		10	2.72E-04±0.062	4.77E-03±0.021	4.64E-04±0.047
Steady state flow methods	WS	15	1.36E-03±0.064	3.34E-03±0.087	9.09E-04±0.012
		10	5.62E-03±0.075	4.18E-03±0.045	3.57E-04±0.035
	MP	15	1.16E-03±0.032	1.25E-03±0.042	7.85E-04±0.008
		10	2.00E-03±0.043	1.39E-03±0.024	6.64E-04±0.074
	Reference method		2.1E-03±0.025	4.12E-03±0.045	9.9E-04±0.065

Note: Water head: 0. ST: single disc radius with single tension; MR: multiple disc radii with multiple tensions; WS: White and Sully method; MP: Single disc with multiple tensions.

Table 3 Errors of saturated hydraulic conductivity values, relative to reference values, obtained using the assessed methods

			Relative error/%		
	Methods	Diameter/cm	Poplar land	Alfalfa land	Wheat land
Transient flow methods	ST	15	55.2	−1.71	43.2
		10	5.71	1.95	−47.8
	MR	15	109	19.3	14.7
		10	−87.0	16.3	−42.7
Steady state flow methods	WS	15	−35.0	−18.6	12.3
		10	167	2.05	−18.9
	MP	15	−44.8	−69.6	−3.09
		10	−4.55	−66.2	−18.0

Note: Water head: 0. ST: single disc radius with single tension; MR: multiple disc radii with multiple tensions; WS: White and Sully method; MP: Single disc with multiple tensions.

More detailed inspection of the data in the tables shows that the ST and MP methods provided the best results for the soil supporting poplar. However, the ST method should not be used when the surface is dry[14], and there should be at least three repetitions, to avoid potentially negative results. Similar results have also been found by Hussen[12] which could be mainly attributed to lateral rather than vertical soil water movement. In soil with high organic contents (such as the field with poplar, Table 1), the accuracy of the transient flow method could be substantially affected by such water movement. Thus, the MP steady state flow method may generally provide the most accurate results for poplar field.

For the wheat field, the results from the transient flow methods deviated from the reference values considerably more than results from the static flow methods. This can be attributed to effects of the more intense management practices (notably weeding and plowing) on the soil's characteristics and structures. Infiltration does not reach steady state in short transient flow experiments, thus they cannot accurately reflect the soil's hydraulic characteristics after intense human disturbances (weeding, plowing). Hence, the steady flow WS method is strongly recommended for characterizing the soil under wheat cultivation.

The soil under alfalfa is far less disturbed than under wheat, in a closer to natural state, with relatively homogenous water content and soil particle composition. Consequently, as shown in Table 3, the ST method provided very accurate results (relative errors as low as 1.71%), so this transient flow method could be reliably applied, which is highly advantageous as it is also rapid. Using steady state flow methods the hydraulic conductivity cannot be estimated until infiltration is stable, which takes almost 45 min in loamy soil with a −9 cm water head, and ca. 25 min with a-3 cm water head. However, data acquired at any time can be used in calculations with the transient flow method, without waiting for a steady state to be attained, significantly reducing the measuring time.

3.2 Unsaturated hydraulic conductivity

The land use was the major factor accounting for the variability in $K(h)$, especially at the large supply water head. Therefore, before applying and comparing the four assessed methods, the unsaturated hydraulic conductivities in each of the experimental fields was measured using the reference method, with pressure heads ranging from −9 cm to 0. As shown in Figure 1, in all three cases the unsaturated hydraulic conductivity increased with increases in the negative potential. However, the increase from −9 cm to −3 cm was significantly lower in the alfalfa field than in the other two fields, possibly due to soil compaction, structural damage and destruction of macrospores arising from overgrazing or cultivation. However, when the negative pressure changed from −3 cm to 0, the increase was much sharper. In contrast, in the wheat field $K(h)$ increased strongly from −9 cm to −3 cm, but only slightly from −3 cm to 0, which could be associated with the low frequency of macropores or weak connectivity/continuity of macropores in wheat soil. Figure 1 also shows that the variation in $K(h)$ is three and two times higher under alfalfa than under poplar and wheat, respectively, in accordance with results presented by Jarvis and Messing[21].

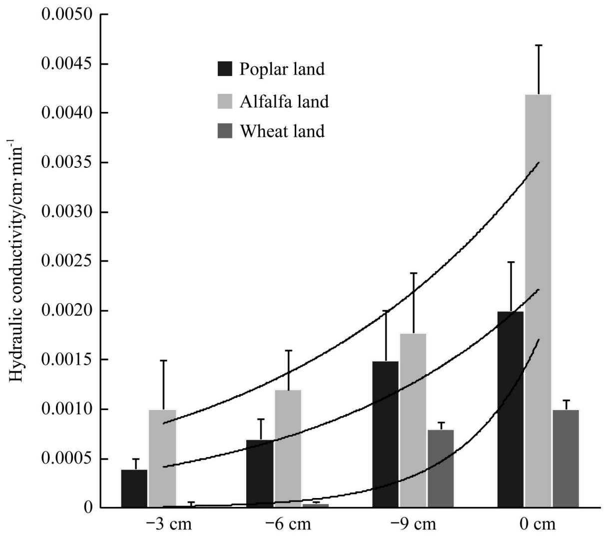

Figure 1 Differences in unsaturated hydraulic conductivity under three land uses

Previous studies have indicated that some methods that often provide rapid and reliable measurements of soil's hydraulic properties are unsuitable for some sites due to the complex relationships of the properties with soil structure parameters and human practices. Application of the MP method can effectively avoid the need to measure the soil water content in order to account for spatial variations of soil, allowing multiple measurements at the same point. In contrast, once sorptivity estimates are required the soil water content must be measured, which is laborious and destroys the measured points. However, the MP method can only be applied when soil water infiltration rates have become stable. In order to solve this problem, the transient flow formulae were developed. The ST transient flow method requires the acquisition of estimates of both the initial and final soil moisture contents, which will inevitably influence subsequent measurement results, while errors may arise from the differences in measuring locations when using the MR method.

In order to compare and optimize the calculation results, the error results of the four methods compared to the reference method were also calculated, as shown in Table 4. The coefficient of linear fitting and discrete degree between calculated value by different methods and reference value are also listed in Table 4.

Table 4 Relative errors in hydraulic conductivity estimates provided by each of the methods (deviations from reference values) and linear regression coefficients between the estimates and reference values

Land use	Methods	C	R^2	SD
Poplar cultivation	WS	1.58	0.97	3.2
	MP	1.33	0.98	4.1
	ST	0.91	0.91	6.4
	MR	1.28	0.99	7.4
Alfalfa cultivation	WS	1.24	0.95	2.2
	MP	0.90	0.82	3.1
	ST	1.29	0.87	3.3
	MR	1.10	0.97	3.3
Wheat cultivation	WS	1.10	0.97	4.2
	MP	0.83	0.99	3.9
	ST	0.90	0.96	5.5
	MR	1.01	0.98	8.1

Note: ST: single disc radius with single tension; MR: multiple disc radii with multiple tensions; WS: White and Sully method; MP: Single disc with multiple tensions. C is equal to the calculated data with the other four methods/ calculated data with standard method; SD is standard deviation.

In order to compare the results provided by the four methods, and identify the most appropriate in each case, the deviations in the results from values obtained with the reference method (relative errors) were also calculated, as shown in Table 4. Coefficients of linear regression between the results and reference values are also listed in the table.

The soil in the alfalfa field has a relatively natural undisturbed, uniform structure, with little spatial variation, so transient flow methods provide the best results for it, potentially saving substantial time and labor. For the soil supporting poplar, results obtained with the WS method have large errors, while the transient flow methods provide highly variable results, so the MP method seems to be most suitable (Table 4). The soil in the wheat field was most strongly affected by management practices, including tillage and mechanical compaction, both of which have marked effects on pore sizes, numbers and connectivity. Hence, the spatial variation is largest under wheat, as demonstrated by the standard deviations of hydraulic conductivity estimates. Thus, the optimal method for soil of this type is the steady flow WS method or the reference method.

4 Conclusions

The optimal method for estimating the soil hydraulic properties should be carefully considered. Results of this study confirmed that land use could strongly affect both saturated and unsaturated hydraulic conductivity. For soil under poplar is substantial lateral water movement due to its high organic contents and saturated hydraulic conductivity, transient flow methods are most suitable to avoid acquisition of negative rates. For the fields with wheat, in which the soil varies strongly due to effects of management practices and compaction by machinery, steady-state flow methods are much more appropriate. The soil structure is more homogenous and the water moves predominantly vertically in the field with alfalfa, consequently transient flow methods are most suitable.

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