

Measuring and Estimating Saturated and Unsaturated Hydraulic Conductivity in Steady and Transient States on Sloping Lands

¹Majid Raoof, ²Amir Hosein Nazemi, ²Ali Ashraf Sadraddini, ³Safar Marofi and ⁴A. Pilpayeh

¹Faculty of Agriculture, University of Mohaghegh, Ardabili, Ardabil, Iran

²Department of Water Engineering, University of Tabriz, Tabriz, Iran

³Department of Water Engineering, University of Bu Ali Sina, Hamadan, Iran

⁴Department of Water Engineering, Parsabad Moghan Branch, Islamic Azad University, Parsabad, Iran

Abstract: The aim of this study was to compare soil hydraulic conductivity on lands with different slope gradients and under steady and transient flow conditions. Field experiments were conducted in a homogeneous loamy soil with different slope gradients in the Gonbad research station, Hamadan, Iran. Soil surface slope gradients of 0, 10, 20, 30 and 40 degrees were selected. For each slope gradient, water infiltration experiments were carried out using a double ring and a tension infiltrometers at 0, 6, 9 and 15 cm tensions, in three replications. Totally 60 water infiltration experiments were carried out. Results indicated that the cumulative infiltration (I) decreased with increasing capillary tension from bottom to top, h, for h=0, 6, 9 and 15 cm. The hydraulic conductivity values for both steady state and transient flow procedures decreased with increases in tension and slope gradient. In steady and transient state, with increase of slope gradient from 0 to 40 degrees, decreasing rate of hydraulic conductivity in 0 tension was 4.1 and 3.7 times more than those in 15 cm tension, respectively. In all experiments, values of relative difference of hydraulic conductivity (RDHC) in both steady state and transient flow procedures were less than 7% that indicated good fitness between two procedures.

Key words: Double ring and tension infiltrometer • Saturated and unsaturated hydraulic conductivity • Steady and transient states

INTRODUCTION

Hydraulic conductivity, one of the most important hydraulic properties, affects water flow and solute transport in saturated and unsaturated soils. In many parts of the world, most of lands are sloping. Significant amounts of precipitation and snowmelt runoffs take place on sloping lands. Several researchers have reported that land slope influences soil properties such as moisture distribution, infiltration rate, cumulative infiltration and saturated and unsaturated hydraulic conductivity [1, 2, 3 and 4]. Few measurement techniques and instruments exist for determining soil hydraulic properties on sloping lands [5]. These include the use of excavated trenches [6], excavated trenches along the contour line [7], tracers, piezometers, tensiometers and suction lysimeters [8] and hillslope infiltrometer [9]. Under field conditions, these methods are time consuming, laborious and destructive,

also hillslope infiltrometer instrument is not produced in commercial scale [5]. Double ring infiltrometer [10] and tension infiltrometer [11] are simple, fast, convenient and useful instruments for determining soil hydraulic properties based on in situ infiltration experiments. Double ring infiltrometers have been widely used for estimation of saturated hydraulic conductivity under ponding conditions [10]. Also, tension infiltrometers have been proven useful for characterizing unsaturated hydraulic conductivity [12-14], sorptivity coefficient [15], mobile and immobile water content [16] and water conducting porosity [17-19]. Water infiltration from a tension infiltrometer placed at a sloping landscape can be simulated with various disk diameters, water pressures applied at the soil surface and sloping degrees. The Richards' equation for three dimensional water flow in a homogenous and isotropic soil at a sloping land may be expressed as [20]:

$$C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left\{ -K(h) \left(\frac{\partial h}{\partial x} - \sin \delta \right) \right\} + \frac{\partial}{\partial y} \left\{ -K(h) \frac{\partial h}{\partial y} \right\} + \frac{\partial}{\partial z} \left\{ K(h) \left(\frac{\partial h}{\partial z} + \cos \delta \right) \right\} \quad (1)$$

Where $C(h)$ is the soil water capacity [$L^3 L^{-4}$], h is the water pressure head [L], $K(h)$ is the hydraulic conductivity at tension h [LT^{-1}], δ is the angle of the slope in radian, t is the time [T] and x, y, z are the axes of the Cartesian coordinate system [L]. The saturated and unsaturated hydraulic conductivity in steady and transient states can be estimated using cumulative infiltration, which is measured by double ring and tension infiltrometer.

Transient State Infiltration Experiment: In transient flow, the amount of water flowing through the voids of soil changes and the infiltration rate reduces with time. In this state, Philip's two-term infiltration equation can be used to determine the soil hydraulic properties such as hydraulic conductivity by taking advantage of cumulative infiltration data obtained from double ring and tension infiltrometer. This equation has been defined as [21]:

$$I = C_1 t^{\frac{1}{2}} + C_2 t \quad (2)$$

Where I is the cumulative infiltration [L], $C_1 [LT^{-\frac{1}{2}}]$ and $C_2 [LT^{-1}]$ are empirical parameters and t is the time [T]. C_2 can be related to soil hydraulic conductivity by [15]:

$$C_2(h) = A K(h) \quad (3)$$

Where A is a dimensionless coefficient and h is the tension value of the infiltrometer used during the infiltration experiment ($h \leq 0$). By estimating the parameter A , the hydraulic conductivity can be determined in different water pressure heads. In transient state, determination of the saturated and unsaturated hydraulic conductivity requires soil hydraulic functions such as soil retention function ($\theta(h)$) and hydraulic conductivity function ($K(h)$). The hydraulic characteristics of the soil under consideration showed better fitness with van Genuchten's hydraulic functions. van Genuchten's retention function is described as [22]:

$$S_e(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + \{\alpha h\}^n \right]^{-m} \quad (4)$$

Where

$$m = 1 - \frac{1}{n}, \quad n > 1 \quad (5)$$

And the corresponding hydraulic conductivity function reads:

$$K(h) = K_{sat} S_e^{0.5} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (6)$$

Where θ_r and θ_s are the residual and saturated water contents, respectively, n and $\alpha [L^{-1}]$ are parameters defining the shape of $S_e(h)$ and $K(h)$ curve and K_{sat} is the saturated hydraulic conductivity [LT^{-1}]. The hydraulic conductivity coefficient (C_2) is obtained by fitting the cumulative infiltration data with Philip's infiltration equation (eq.(2)). Then soil hydraulic conductivity can be determined by:

$$K(h) = C_2 / A \quad (7)$$

The dimensionless coefficient A changes slightly during infiltration experiment, which can be neglected and assumed constant. Zhang [15] established following empirical relationships for A as function of soil retention parameters, infiltrometer parameters and initial water content, which are compatible with Eq.(4) and (6).

$$A = \frac{11.65(n^{0.1} - 1) \exp[2.92(n - 1.9)\alpha h]}{(\alpha r_0)^{0.91}}, \quad n \geq 1.9 \quad (8)$$

$$A = \frac{11.65(n^{0.1} - 1) \exp[7.5(n - 1.9)\alpha h]}{(\alpha r_0)^{0.91}}, \quad n < 1.9 \quad (9)$$

Where n and α are the retention parameters, $h[L]$ is the pressure head of the infiltrometer in each experiment ($h > 0$), r_0 is the radius of the infiltrometer [L], θ is the water content at h and θ_i is the initial water content.

Steady State Infiltration Experiment: In steady state method for a deep soil profile, a unit hydraulic gradient is assumed and the steady state infiltration rate equals saturated hydraulic conductivity, i. e.,

$$Q^\infty = K_{sat} \quad (10)$$

Where q_∞ is the steady state infiltration rate [LT^{-1}] (while $t \rightarrow \infty$) and K_{sat} is the saturated hydraulic conductivity [LT^{-1}]. Equation (10) neglects the effects of hydrostatic

pressure of surface water and capillarity on infiltration rate although the calculation is very simple. Therefore, this equation overestimates the K_{sat} value. An analysis of steady ponded infiltration in the double-ring method, which takes into account soil hydraulic parameters, ring radius, depth of ring insertion and depth of ponding, was given by Reynolds *et al.* [23]. The K_{sat} can be obtained from quasi-steady-state infiltration rate through a double-ring as [23]:

$$K_{sat} = \frac{q_s}{\left(\frac{H}{c_1 d + c_2 r}\right) + \left(\frac{1}{\alpha(c_1 d + c_2 r)}\right) + 1} \quad (11)$$

Where q_s is the steady state infiltration rate [LT^{-1}], H is the depth of water in the inner ring [L], d is the depth of rings insertion into the soil [L], r is the radius of the inner ring [L], $c_1 = 0.316\pi$ and $c_2 = 0.184\pi$ are dimensionless coefficients, α is the soil parameter [L^{-1}] and K_{sat} is the saturated hydraulic conductivity [LT^{-1}]. Most calculating methods of unsaturated hydraulic conductivity, $K(h)$, in steady state are based on Wooding's [24] analysis for unconfined steady state infiltration from a disk

$$q(h) = \pi r^2 K(h) + 4r\varphi(h) \quad (12)$$

Where $q(h)$ is the steady state infiltration rate [L^3T^{-1}] at the water pressure head h , r is the radius of the infiltrometer disk [L], $K(h)$ is the unsaturated hydraulic conductivity [LT^{-1}] and $\varphi(h)$ is the matric flux potential, defined as:

$$\varphi(h) = \int_{h_i}^h K(h) dh \quad (13)$$

Where h_i is the initial soil water pressure [L] and h is the applied pressure head in each infiltration experiment. Several methods exist to determine the unsaturated hydraulic conductivity, for example, those proposed by White and Sully [12], Smettem and Clothier [13] and Ankeny *et al.* [14].

The method of White and Sully requires estimation of infiltration rate and coefficient of sorptivity during early times of experiment [25], which is difficult. Additionally in this method, reliable determination of S (sorptivity coefficient) for calculation of the hydraulic conductivity requires that the soil be quite dry before infiltration experiment in each pressure head [26, 27]. Alternatively, the measurements must be done at different locations, resulting in increased variability because of spatial

variations of hydraulic properties and antecedent water content. Smettem and Clothier's method requires using two or more diameters of infiltrometer disk. For two various diameters of disk, the Wooding's equation has two unknowns with two equations, which can be solved easily. Also this method requires measurements at different locations to show sensitivity of hydraulic properties to spatial variation. Therefore, this method can not be applied extensively. In order to reduce the possible error, Ankeny *et al.* [14] started with Wooding's equation (equation 12) and measured infiltration rates at two water pressure heads, which led to two equations and four unknowns:

$$q(h_1) = \pi r^2 K(h_1) + 4r\varphi(h_1) \quad (14)$$

$$q(h_2) = \pi r^2 K(h_2) + 4r\varphi(h_2) \quad (15)$$

They assumed a constant ratio between K and φ and an approximate value for $\Delta\varphi(h)$, $\varphi(h_1) - \varphi(h_2)$. Then they obtained three equations with three unknowns that could be solved for two unsaturated hydraulic conductivity values as follow:

$$K(h_1) = \frac{q(h_1)}{\pi r^2 + 2r(h_1 - h_2) \left\{ 1 + \frac{q(h_2)}{q(h_1)} \right\} / \left\{ 1 - \frac{q(h_2)}{q(h_1)} \right\}} \quad (16)$$

$$K(h_2) = \frac{q(h_2)}{q(h_1)} K(h_1) \quad (17)$$

After measurement of steady state infiltration rate at two different pressure heads, the unsaturated hydraulic conductivity could be determined by Ankeny *et al.* [14] method.

Gardner's Exponential Model: The Wooding's algebraic approximation (equation (4)) can also be written as:

$$q(h) = \pi r^2 K(h) \left[1 + \frac{4}{\pi r \alpha} \right] \quad (18)$$

The value of h will normally be negative corresponding to a tension at the water source, however it can also be zero. It is assumed that the unsaturated hydraulic conductivity of soil, $K(h)$, varies with matric potential, h , as proposed by Gardner [28]:

$$K(h) = K_{sat} \exp(\alpha h) \quad (19)$$

Where K_{sat} is the saturated hydraulic conductivity [LT^{-1}] and α is the soil parameter [L^{-1}]. With tension infiltrometer one measures the volume of water entering the soil per unit time through the porous membrane at a minimum of two tensions, e. g. h_1 and h_2 . By combining equations (18) and (19) and after substitution of h_1 and h_2 , respectively, for h in the combined equation one obtains:

$$q(h_1) = \pi r^2 K_{sat} \exp(\alpha h_1) \left[1 + \frac{4}{\pi r \alpha} \right] \quad (20)$$

$$q(h_2) = \pi r^2 K_{sat} \exp(\alpha h_2) \left[1 + \frac{4}{\pi r \alpha} \right] \quad (21)$$

Where h_1 and h_2 are known and $q(h_1)$ and $q(h_2)$ are measured for various slope gradients. By solving equations (20) and (21), α and K_{sat} can be computed. Once α and K_{sat} are known, their values can be substituted in the Gardner's exponential equation (equation (19)), yielding the relationship between hydraulic conductivity and tension for the soil. This relationship can be used to calculate the unsaturated hydraulic conductivity at the desired tensions.

In this study hydraulic conductivity values of a homogeneous loamy soil have been measured in lands with various slope gradients and different water pressure heads under steady and transient flow conditions. The experimental results also compared to those obtained from some existing empirical models.

MATERIALS AND METHODS

Description of Study Area: This study was conducted at the Gonbad research station, Hamadan, Iran ($48^\circ 42.14' N$ lat., $34^\circ 41.74' W$ long. and 2170 m elevation from sea level.). The research area consists of 740 ha land with an average annual precipitation of 560 mm and an average land slope of 28.8 degree. A soil pedon with 1.5 m length,

1.5 m width and 2 m depth was excavated. Soil layer was homogenous and no abrupt changes in soil texture were observed. To determine the soil physical and chemical properties in different slopes, for each slope three disturbed and three undisturbed samples (0.05 m in diameter and 0.05 m in height) were taken from areas next to the measurement sites. Bulk density, particle density and porosity were estimated using Flint and Flint [29] method. Sand, silt and clay percentages were also determined using the hydrometer method. Soil in the experimental site is loamy textured (Table 1). The residual soil water content at 33 and 1500 K Pa tensions were measured by a pressure plate instrument.

Slope Treatments: Five various soil surface slope gradients including 0, 10, 20, 30 and 40 degrees were selected in the area. For each slope gradient, water infiltration experiments were carried out by a double ring and a tension infiltrometers at tensions of 0, 6, 9 and 15 cm of water in three replications. For saturated condition ($h=0$) the cumulative infiltration was obtained by a double ring infiltrometer and for unsaturated conditions ($h=-6, -9$ and -15 cm) was obtained by a tension infiltrometer. Totally 60 water infiltration experiments were carried out in five different surface slopes, four tensions and three replications.

Field and Laboratory Experiments: When the amount of water entered into the soil did not change with time for three consecutive measurements taken at 5-minute intervals, steady state flow was assumed and the corresponding infiltration rate was calculated based on the last three measurements. Generally, steady state flow was achieved within 30 to 60 min for the tension infiltrometer and within 60 to 120 min for the double ring infiltrometer. To estimate saturated hydraulic conductivity, a double ring infiltrometer with inner and outer rings of 0.2 and 0.3 m in diameter, respectively,

Table 1: Some selected soil physical and chemical properties of the experimental site

Parameter	Slope gradient (degree)				
	0	10	20	30	40
Bulk density (gr/cm^3)	1.66	1.67	1.68	1.68	1.69
Particle density (gr/cm^3)	2.58	2.57	2.57	2.57	2.58
Sand (%)	39.3	38.4	38.9	38.1	40.2
Silt (%)	38.1	37.2	37.6	39.2	38.5
Clay (%)	22.6	24.4	23.5	22.7	21.3
Porosity (%)	35.66	35.02	34.63	34.63	34.5
O. M. content (%)	0.6	0.3	0.6	0.5	0.6
PH	7.9	7.9	7.8	7.9	7.8
SAR ($m\ mol/lit^{0.5}$)	28.03	28.21	27.95	28.12	28.15
$Ec_e(dS/m)$	0.46	0.45	0.45	0.47	0.45
Initial water content(-)	0.12	0.122	0.123	0.121	0.123

was used at a constant head [23]. Steel rings were pushed into the soil concentrically to a depth of 0.05 m approximately with minimum soil disturbance. Then the inner cylinder and between two cylinders were filled with water to 0.1 m water head. Water level falling in the inner cylinder during the experiment was recorded by pointer. Water level in the outer ring was maintained exactly at the same height as that in the inner ring. To estimate unsaturated hydraulic conductivity, a tension infiltrometer with a 0.2 m diameter disk (soil measurement systems, Tuscon. Az) was used. At first the location of experiment was selected and then a thin layer (5×10^{-3} m) of moist fine sand was applied over the prepared surface at each measurement location in a circular area with a diameter equal to the diameter of infiltrometer disk. The hydraulic conductivity of testing sand must be more than that of the experimental soil. Applying the fine sand has two advantages as follow [5]:

- The sand prevents tearing the nylon mesh attached to the infiltrometer disk.
- This smoothes out any irregularities of the soil surface and ensures good contact between the soil surface and the infiltrometer membrane.

After preparation of the experiment location, tension infiltrometer instrument was regulated in given tension and was placed on it. The amount of infiltration into the soil was measured by recording the water level falling in the graded reservoir tower as a function of time. Using known values of the residual soil water content at 33 and 1500 K Pa tensions, sand, silt and clay percentages and bulk density, four parameters of the van Genuchten soil hydraulic functions (residual soil water content $[\theta_r]$, saturated soil water content $[\theta_s]$ and empirical shape factors $[n]$, $[\alpha]$) were estimated by artificial neural network method. On the other hand, for different slope gradients and tensions, values of the coefficient C_2 were obtained by fitting cumulative infiltration data with Philip's two-term infiltration equation using a maximum neighborhood method [30]. Then hydraulic conductivity values for different slope gradients and tensions were determined by equation (7), [15]. For double ring experiments (saturated condition), steady infiltration rate is equal to water level falling in the inner ring when the amount of water entered into the soil did not change with time. Equation (11), Reynolds *et al.* [23] was used to determine the saturated hydraulic conductivity in steady state. The steady state infiltration rate in unsaturated condition, $q(h)$, was also

measured from the water level falling in the reservoir tower of the tension infiltrometer. Equations (16) and (17) [14] were also used to determine the unsaturated hydraulic conductivity in steady state. The saturated and unsaturated hydraulic conductivity values were calculated by Matlab software.

Values of hydraulic conductivity in steady and transient states were compared using Eq.(22):

$$RDHC = \frac{\sqrt{(K_{ss} - K_T)}}{K_G} \times 100 \quad (22)$$

Where $RDHC$ is the difference in hydraulic conductivity (%) measured in steady state and transient flow procedures and K_{ss} , K_T and K_G are the hydraulic conductivity values calculated by steady state flow procedure, transient flow procedure and the Gardner exponential equation, respectively. The same criterion for estimating the difference between hydraulic conductivity values in level and sloping lands was used as follows:

$$RDHC_{L,S} = \frac{\sqrt{(K_L - K_S)^2}}{K_L} \times 100 \quad (23)$$

Where $RDHC_{L,T}$ is the difference between the measured values of hydraulic conductivity in sloping and level lands (%) and K_L and K_S are the values of hydraulic conductivity at a given tension for level and sloping lands, respectively.

RESULTS

Table 1 gives the soil physical and chemical properties such as bulk density, particle density, sand, silt and clay percentages, porosity, organic matter content, pH, sodium adsorption ratio (SAR) and electrical conductivity (EC_e) in different slopes at 0-20 cm of its depth. To compare the steady and transient state results, the statistical parameters $RDHC$ and to compare the hydraulic conductivity values in different slopes the statistical parameter $RDHC_{L,S}$ were used in this study.

Transient and Steady State Flow: Figures 1 and 2 illustrate the cumulative infiltration versus time for different tensions in 0- and 40 degree slope gradients. The trend of hydraulic conductivity changes with increase in applied tension at different slope gradients has been illustrated in Figure 3. In transient state the range of variation of hydraulic conductivity in saturated condition is greater than those in unsaturated condition.

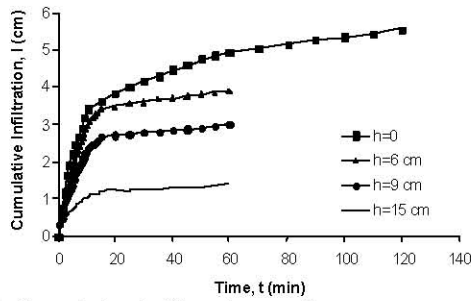


Fig. 1: Cumulative infiltration vs. time (0 degree of slope gradient)

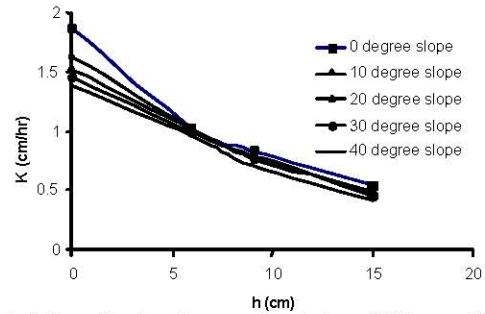


Fig. 3: Mean hydraulic conductivity, $K(h)$ at different slope gradients in transient state

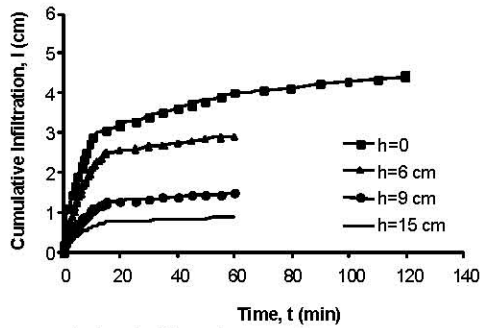


Fig. 2: Cumulative infiltration vs. time (40 degrees of slope gradient)

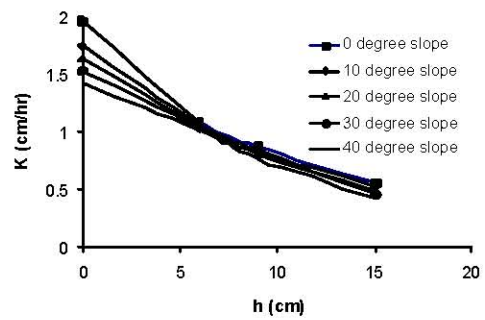


Fig. 4: Mean hydraulic conductivity, $K(h)$ at different slope gradients in steady state

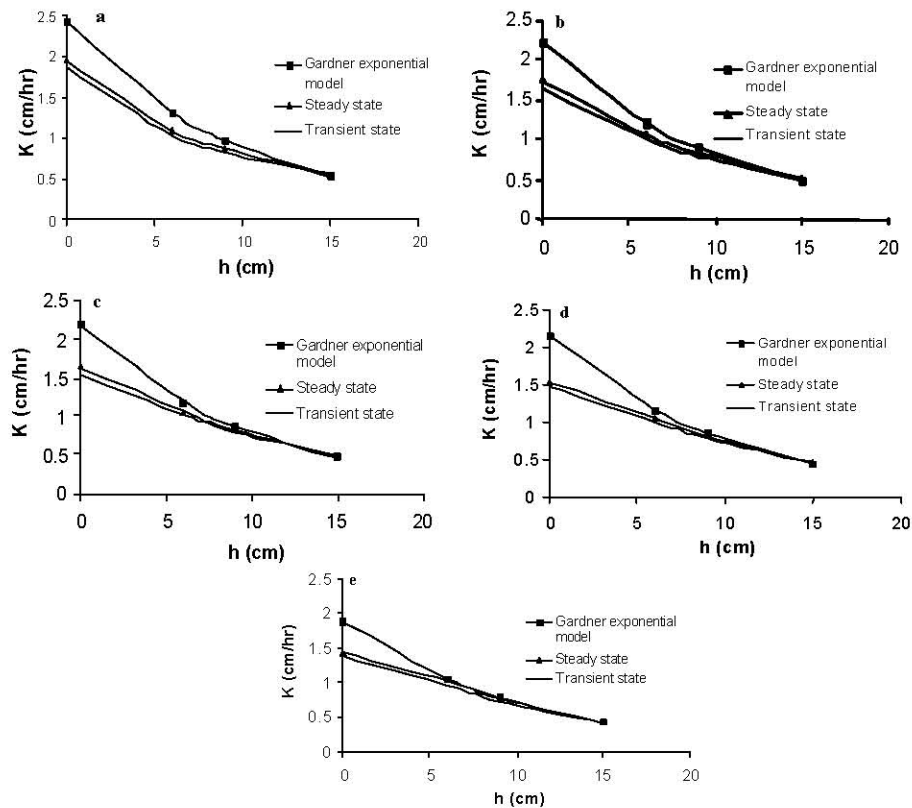


Fig. 5: Comparing The Gardner's exponential model, steady state and transient flow procedures at different slope gradients (a)0 degree, b)10 degrees, c) 20 degrees, d) 30 degrees and e) 40 degrees)

Table 2: Relative Difference Hydraulic Conductivity between steady state and transient flow procedures ($RDHC$) for different slope gradients and tensions (%)

Tension (cm)	Slope gradient (degree)				
	0	10	20	30	40
0	3.52	5.05	4.73	3.23	2.01
6	4.64	3.79	3.16	4.22	5.53
9	3.87	5.00	3.98	3.05	6.45
15	2.43	3.21	3.55	1.38	3.12

Table 3: Relative Difference Hydraulic Conductivity of sloping land with respect to level land ($RDHC_{L,S}$) for different tensions (%), in steady state

Tension	Slope gradient (degree)				
	0	10	20	30	40
0	0	11.11	16.67	22.22	27.41
6	0	2.08	3.2	4.38	6.92
9	0	3.83	5.89	8.05	12.74
15	0	7.49	11.85	16.22	23.64

Table 4: Relative Difference Hydraulic Conductivity of sloping land with respect to level land ($RDHC_{L,S}$) for different tensions (%), in transient state

Tension	Slope gradient (degree)				
	0	10	20	30	40
0	0	13.03	18.39	22.39	26.13
6	0	0.74	1.08	3.43	6.98
9	0	4.89	5.81	7	14.77
15	0	8.23	12.88	15.39	24.29

Figure 4 illustrates the trend of hydraulic conductivity changes with tension increase at different land slope in steady state. In steady state the same remarks of transient state can be mentioned on the variation of hydraulic conductivity values.

Comparison of Steady State and Transient Flow Procedures: Hydraulic conductivity values obtained from steady state infiltration experiment were closely fitted with those of transient state. The Gardner's [28] exponential equation coefficients were also determined for different slope gradients. Therefore, the hydraulic conductivity values in different slope gradients and tensions were calculated by the Gardner exponential equation. Figure 5 illustrates the trends of hydraulic conductivity changes with tension increments in different slope gradients. In this figure steady state flow and transient state flow have been compared together. Also the hydraulic conductivity values estimated from the Gardner's exponential model have been shown in fig. 5. Table 2 illustrates the $RDHC$ values in different slope gradients and tensions.

The $RDHC_{L,T}$ calculated for each tension. Table 3 and 4 illustrate the $RDHC_{L,S}$ values in different tensions for steady state and transient flow procedure, respectively.

DISCUSSION

Figures 1 and 2 show that for a given land slope, the cumulative infiltration, I , decreases with increasing capillary tension, h , for $h=0, 6, 9$ and 15 cm. It is also seen that for a given tension, the cumulative infiltration is smaller for higher land slope, indicating the inverse effect of steep slope on amount of the infiltrated water. Both transient and steady states underestimate the hydraulic conductivity values in saturated and unsaturated condition. In transient state, hydraulic conductivity values decrease with increase in tension values. In transient state decreasing rate of hydraulic conductivity in low tensions was greater than that in high tensions. With increase of slope gradient from 0 to 40 degrees, decrease of hydraulic conductivity in 0 tension (saturated condition) was 3.7 times more than that in 15 cm tension. The results of transient state experiment correspond to those of other researches such as Casanova *et al.* [31], Bodhinayake *et al.* [5] and Zhang [15], that have been studied in slope gradient less than 9 degree (20%). In steady state, as illustrated in Figure 4, the hydraulic conductivity decreases with increasing tension and increasing slope gradient. Figure 4 also indicate that, with

increase in surface slope gradient, the decreasing rate of hydraulic conductivity of the saturated condition ($h=0$) is higher than that of the unsaturated condition. In steady state, with increasing slope gradient from 0 to 40 degrees, decreasing rate of hydraulic conductivity in 0 tension (saturated condition) was 4.1 times more than that of 15 cm tension. Results obtained in this case are also agreed with the findings of other researchers such as Casanova *et al.* [31] and Bodhinayake *et al.* [5], that have been also studied in slope gradient less than 9 degree (20%). The reasons for decrease of hydraulic conductivity with increase of slope gradient can be explained as follow:

- In steep slopes, the downslope component of each soil particle weight causes slight compression of soil and decrease of pores dimensions. Therefore, the amount of flow through the soil decreases with decrease of pores dimensions due to increase of slope gradient.
- Soil particles arrangement in sloping surface is different from that in level surface [17, 32, 31]. In sloping surface soil particles arrangement has higher regularity than that in level surface. Therefore, total porosity in sloping land is less than that in level land which causes reduction in hydraulic conductivity value.

The hydraulic conductivity values calculated from the Gardner exponential model show more accordance with steady state flow procedure than transient one. The steady state results are more reasonable than those of the transient state, because the effect of sorptivity decreases and the effect of gravity increases during the experiments. The effect of sorptivity in transient state is greater than that in steady state, whereas in steady state gravity plays more important role in flow. The $RDHC$ values in all experiments are less than 7% that indicate well closeness between steady state and transient flow procedures. In both steady state and transient flow procedures, maximum value of the $RDHC_{Lr}$ were obtained for saturated condition illustrating that, decreasing of hydraulic conductivity in saturated condition is more than that in unsaturated condition.

REFERENCES

1. Sinai, G., D. Zaslavsky and P. Golany, 1981. The effect of soil surface curvature on moisture and yield-Beer Sheba Observations. *Soil Sci.*, 132: 367-375.
2. Zebarth, B.J. and E. de Jong, 1989a. Water flow in a hummocky landscape in central Saskatchewan, Canada. I. Distribution of water and soils. *J. Hydrol.*, 107: 309-327.
3. Zebarth, B.J. and E. de Jong, 1989b. Water flow in a hummocky landscape in central Saskatchewan, Canada. III. Unsaturated flow in relation to topography and land use. *J. Hydrol.*, 110: 199-218.
4. Philip, J.R., 1991. Hill slope infiltration: Planar slopes. *Water Resour. Res.*, 27: 109-117.
5. Bodhinayake, W.L. and B.C. Si Xiao, 2004. New method for determining water-conducting macro- and mesoporosity from tension infiltrometer. *Soil Sci. Soc. Am. J.*, 68: 760-769.
6. Dunne, T. and R.D. Black, 1970. An experimental investigation of runoff production in permeable soils. *Water Resour. Res.*, 6: 478-490.
7. Mosley, M.P., 1982. Subsurface flow velocities through selected forest soils, South Island, New Zealand. *J. Hydrol. (Amsterdam)*, 55: 65-92.
8. Torres, R., W.E. Dietrich, D.R. Montgomery, S.P. Anderson and K. Loague, 1998. Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment. *Water Resour. Res.*, 34: 1865-1879.
9. Mendoza, G. and S.T. Steenhuis, 2002. Determination of hydraulic behavior of hillsides with a hill slope infiltrometer. *Soil Sci. Soc. Am. J.*, 66: 1501-1504.
10. Bower, H., 1986. Intake rate. Cylinder infiltrometer. P. 825-843. In A. Klute (ed.) *Methods of soil analysis*. Part 1. Physical and mineralogical properties. 2 nd. Ed. ASA. Madison, WI.
11. Perroux, K.M. and I. White, 1988. Design for disc permeameters. *Soil Sci. Soc. Am. J.*, 52: 1205-1215.
12. White, I. and M.J. Sully, 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resour. Res.*, 23: 1514-1522.
13. Smettem, K. and B. Clothier, 1989. Measuring unsaturated sorptivity and hydraulic conductivity using multi-disc permeameters. *Soil Sci. Soc. Am. J.*, 40: 565-568.
14. Ankeny, M., M. Ahmed, T. Kaspar and R. Horton, 1991. Simple field method for determining unsaturated hydraulic conductivity. *Soil Sci. Soc. Am. J.*, 5: 467-470.
15. Zhang, R., 1997. Determination of soil sorptivity and hydraulic conductivity from disk infiltrometer. *Soil Sci. Soc. Am. J.*, 61: 1024-1030.

16. Angulo-Jaramillo, R., J.P. Vandervaere, S. Rolier, J.L. Thony, J.P. Gaudet and M. Vauclin, 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments. *Soil Tillage Res.*, 55: 1-29.
17. Watson, K. and R. Luxmoore, 1986. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. *Soil Sci. Soc. Am. J.*, 50: 578-782.
18. Dunn, G.H. and J.R. Philip, 1991a. Macroporosity of a well-drained soil under no till and conventional tillage. *Soil Sci. Soc. Am. J.*, 55: 817-823.
19. Cameira, M.R., M.R. Fernando and L.S. Pereira, 2003. Soil macropore dynamics affected by tillage and irrigation for a silty loam and irrigation for a silty loam alluvial soil in southern Portugal. *Soil Tillage Res.*, 70: 131-140.
20. Russo, D., E. Bresler and U. Shani and J.C. Parker, 1991. Analysis of infiltration events in relation to determining soil hydraulic properties by inverse problem methodology. *Water Resour. Res.*, 27: 1361-1373.
21. Philip, J.R., 1957. The theory of infiltration 4. Sorptivity and algebraic infiltration equations. *Soil Sci. Soc. Am. J.*, 84: 257-264.
22. Van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic properties of unsaturated soils. *Soil Sci. Soc. Am. J.*, 44: 892-898.
23. Reynolds, W.D., D.E. Elrick and G. Youngs, 2002. The soil solution phase. Single ring and double- or concentric – ring infiltrometers. P 821-826. In J H Jane and G C Topp(ed) *Methods of soil analysis: part 4. Physical methods*. SSSA. Madison WI.
24. Wooding, R., 1968. Steady infiltration from a shallow circular pond. *Water Resour. Res.*, 4: 1259-1273.
25. Logsdon, S. and D. Jaynes, 1993. Methodology for determining hydraulic conductivity with tension infiltrometers. *Soil Sci. Soc. Am. J.*, 57: 1426-1431.
26. White, I. and K.M. Perroux, 1987. Use of sorptivity to determine field soil hydraulic properties. *Soil Sci. Soc. Am. J.*, 51: 1093-1101.
27. White, I. and K.M. Perroux, 1989. Estimation of unsaturated hydraulic conductivity from field sorptivity measurements. *Soil Sci. Soc. Am. J.*, 53: 324-329.
28. Gardner, W. R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from water table. *Soil Sci. Soc. Am. J.*, 85: 228-232.
29. Flint, L.E. and A.L. Flint, 2002. The soil solution phase Porosity. P 241-254. In J.H Dane and G.C. Topp (ed.) *Methods of soil analysis: Part 4. Physical methods* SSSA. Madison WI.
30. Marquardt, D.W., 1963. An algorithm for least squares estimation of nonlinear parameters. *J. Soc. Ind. Appl. Math.*, 11: 431-441.
31. Casanova, M., I. Messing and A. Joel, 2000. Influence of aspect and slope gradient on hydraulic conductivity measured by tension infiltrometer. *Hydrol. Processes*, 14: 155-164.
32. Wilson, G.V. and R.J. Luxmoore, 1988. Infiltration, macroporosity and mesoporosity distributions on two forested watersheds. *Soil Sci. Soc. Am. J.*, 52: 329-335.