Inverse modeling approach for determining soil hydraulic properties as affected by application of cattle manure

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Abstract: Numerical codes are extensively used in the modeling of water and solute transport in the vadose zone. The application of these codes depends on knowledge of soil hydraulic properties such as soil water retention curve and hydraulic conductivity. Application of cattle manure to the soil can increase soil organic matter (SOM) contents. Increases in SOM associated with changes in the structure and adsorption properties of soil and, thus, their hydraulic properties. In this study the effect of cattle manure on soil hydraulic properties was investigated using inverse method. Applied inverse method was based on Levenberg-Marquart optimization algorithm to estimate hydraulic properties of soil in transient condition using C^{++} programming language along with forward model (HydroGeoSphere) as a numerical code. Nine iron cylinders of 57 cm in inner diameter and about 40 cm in height were filled with Sandy clay loam soil of 30 cm in height. Cattle manure applied at 0, 30, and 60 Mg/ha at three replications in a completely random design. One year after cattle manure application, saturated hydraulic conductivity, porosity, and water retention curve parameters (van Genuchten function, α and β) were estimated using inverse method. Statistical analysis showed that the automatic calibration is sensitive to α more than the other parameters. The results showed that porosity, saturated hydraulic conductivity, residual water content, α and β increased significantly (P<0.05) with application 30 and 60 Mg/ha cattle manure. But there was no significant difference (P<0.05) in β between application of 30 and 60 Mg/ha cattle manure. The study also indicated that α was 25.0% and 50.0% higher and β was 9.6% and 12.6% lower than control treatment in 30 and 60 Mg/ha treatments. In addition, application cattle manure showed positive effect on hydraulic parameters of soil.

Keywords: soil hydraulic property, parameter estimation, inverse method, HydroGeoSphere, unsaturated flow, cattle manure
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1 Introduction

Organic matter such as cattle manure has the potential to modify soil water regimes. Soil organic matter is important in maintaining soil structural stability, aiding the infiltration of air and water, promoting water retention, and reducing erosion[1]. Organic matter affects crops growth and yields either directly by supplying nutrients or indirectly by modifying soil physical properties such as stability of aggregates, porosity and available water capacity that can improve the root environment and stimulate plant growth[2]. Reduction in soil available water capacity is considered the foremost contributing factor in the loss of soil productivity caused by erosion. Incorporation of organic matter either in the form of crop residues or farmyard manures has been shown to improve soil structure and water retention capacity[3]. Singh et al.[4] evaluated the effect of eight treatments comprised of various combinations of green manure, wheat straw, rice straw, farmyard manure and urea alone (control) on physical and hydraulic properties of soil in a rice-wheat experiment. They reported that the use of green manure, farmyard manure and crop residues restores the damaged

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soil structure. Bauer and Black[5] showed that an increase in organic carbon concentration did not change the available water capacity in the sandy and decreased it in the medium and fine textural. Mosaddeghi et al.[6] found that tillage methods and manure applications had significant effects on bulk density and soil cone index. Rasoulzadeh and Yaghoubi[7] investigated the effect of cattle manure on coefficients of Philip's equation (Sorptivity (S) and constant coefficient (A)). They declared that the application of cattle manure did not significantly affect S but showed significant effect on A (P < 0.05). Previous investigations have consistently found that manure can increase porosity and saturated hydraulic conductivity[8,9] but decrease bulk density[9-11].

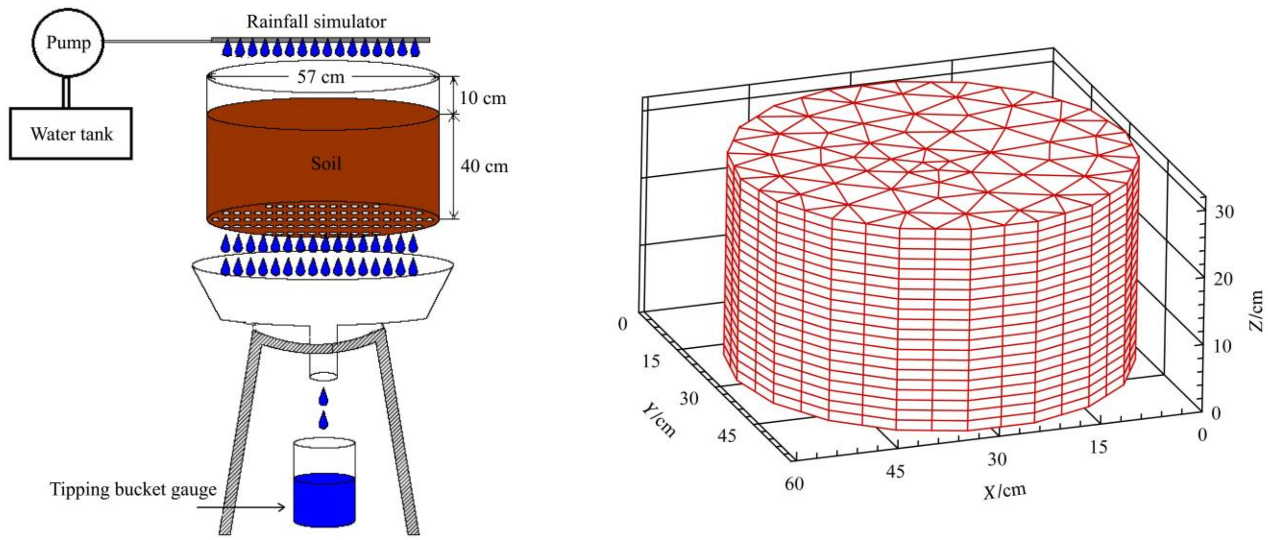
The application of cattle manure to the soil can change soil hydraulic properties. The magnitude of the changes of soil hydraulic properties is related to the rate of manure application[12]. Arriaga and Lowery[11] found a strong positive correlation between water content and total carbon content at saturation and 20 kPa tension in the surface layer. Miller et al.[13] found that manure amendment significantly increased soil water retention compared with control across the whole tension range between 0 and 1 500 kPa. In contrast, Danalatos et al.[14] and Lal[15] did not observe any effect of organic mater content on water retention, and the latter authors attributed this to the low organic matter content in their samples[12]. However, soil hydraulic properties are the essential input to water and solute transport numerical code. Direct methods for the determination of soil hydraulic parameters are time consuming and costly, and sometimes unreliable because of soil heterogeneity and experimental errors[16-18]. Also, due to hysteresis effect, soil water retention curve has two desorption and sorption branches. Ordinarily, the desorption curve is measured by gradually and monotonically extracting water from initially saturated samples in the lab[19]. But the sorption curve is essential for modeling water and solute transport in unsaturated porous media. To overcome these problems indirect methods such as the inverse method can be used to identify the basic flow and transport parameters.

The objective of this study was to determine soil hydraulic properties as affected by cattle manure using the inverse solution technique. This objective was examined by Levenberg-Marquart optimization algorithm for inverse modeling to estimate some hydraulic properties of soil in transient condition along with forward model (HydroGeoSphere) as a numerical code to simulate water flow in unsaturated porous media based on Richards' equation. First, unknown soil parameters including saturated hydraulic conductivity, porosity, and water retention curve parameters (van Genuchten function) were estimated by the inverse method. Second, the correlation between parameters, sensitivities, and the standard error was obtained for the evaluation of parameters estimation uncertainty.

2 Materials and methods

2.1 Study area and experimental device

Study area is located in northwest of Iran (Ardabil province) with the climate of cold semi-arid type with 305 mm mean annual precipitation. Most of precipitation falls as snow in the cold season. This study was carried out on a Sandy clay loam soil lack of plant in University of Mohaghegh Ardabili. Nine iron cylinders of 57 cm in inner diameter and about 40 cm in height were supplied for performance experiments. The cylinders were filled with Sandy clay loam soil of 30 cm in height (Figure 1a). Cattle manure applied at 0 (control), 30, and 60 Mg/ha at three replications in a completely random design. Note that cattle manure was air-dried and sieved through 10 mm sieve. The cylinders were outdoors (in the experimental field of the University) to be in natural condition. One year after the cattle manure application, artificial rainfall experiments were conducted on the top of the columns and free drainage from the bottom of columns was measured. Rainfall intensity was controlled by a rotary pump connected to a raindrop maker that produces water drops (Figure 1a). Applied rainfall intensities were randomly changed in the range of 0-0.12 cm/min. Drainage at the bottom of the tray was collected and measured using an electronic balance. First, a constant intensity rain (0.05 cm/min) was applied to reach the steady state condition as a constant discharge rate from the bottom was established in order to accurately define the initial condition required for the numerical simulation of unsaturated water flow. After reaching the state steady experiment, transient condition was carried out. In transient condition, the random rainfall experiment was conducted and the transient discharge rate from the bottom was continuously monitored.



a b

Figure 1 a) Experimental device and b) Numerical model mesh

2.2 Numerical model description

The following modified form of Richards' equation is used by HydroGeoSphere code[20] which describes three-dimensional transient subsurface flow in a variably-saturated porous medium:

$$-\nabla.\left(w_M q\right)+\sum\Gamma_{ex}\pm Q=w_m\frac{\partial}{\partial t}\left(\theta_s S_w\right) \qquad (1)$$

where, w_m (dimensionless) is the volumetric fraction of the total porosity occupied by the porous medium (or primary continuum). This volumetric fraction is always equal to 1.0 except when a second porous continuum is considered for a simulation, which is the case when the dual continuum option is used to represent existing fractures or macropores. The fluid flux q (L T^{-1}) is given by:

$$q=-K\cdot k_r\nabla(\psi+z) \qquad (2)$$

where, $k_r = k_r(S_w)$ represents the relative permeability of the medium (dimensionless) with respect to the degree of water saturation S_w (dimensionless); ψ is the pressure head (L); z is the elevation head (L) and θ_s is the saturated water content (dimensionless), which is assumed equal to the porosity. Fluid exchange with the outside of the simulation domain, as specified from boundary conditions, is represented by Q (L^3 L^{-3} T^{-1}), which is a volumetric fluid flux per unit volume representing a source (positive) or a sink (negative) to the porous medium system.

The hydraulic conductivity tensor, K (L T^{-1}), is given by:

$$K=\frac{\rho g}{\mu}k \qquad (3)$$

where, g is the gravitational acceleration (L T^{-2}); μ is the viscosity of water (M L^{-1} T^{-1}); k is the permeability tensor of the porous medium (L^2) and ρ is the density of water (M L^{-3}), which can be a function of the concentration C (M L^{-3}) of any given solute such that $\rho = \rho(C)$.

Water saturation is related to the water content θ (dimensionless) according to:

$$S_w=\frac{\theta}{\theta_s} \qquad (4)$$

In Equation (1), Γ_{ex} represents the volumetric fluid exchange rate (L^3 L^{-3} T^{-1}) between the subsurface domain and all other types of domains supported by the model and it is expressed per unit volume of the other domain types. Currently, these additional domains are surface, wells, tile drains, discrete fractures and dual continuum. The definition of Γ_{ex} (positive for flow into the porous medium) depends on the conceptualization of fluid exchange between the domains.

The primary variable of solution for the nonlinear flow Equation (1) is the pressure head, and constitutive relations must be established that relate the primary unknown ψ to the secondary variables S_w and k_r. The relative permeability may be expressed in terms of either the pressure head or the water saturation.

Using the van Genuchten function[21], the saturation is given by:

$$\begin{aligned} S_w &= S_{wr} + (1-S_{wr})(1+|\alpha\psi|^{\beta})^{-(1-1/\beta)} && \text{for } \psi < 0 \\ S_w &= 1 && \text{for } \psi \geq 0 \end{aligned} \tag{5}$$

and the relative permeability is obtained from:

$$k_r = \left(\frac{S_w - S_{wr}}{1-S_{wr}}\right)^{0.5}\left[1-\left((1-\frac{S_w - S_{wr}}{1-S_{wr}})^{1/(1-1/\beta)}\right)^{(1-1/\beta)}\right]^2 \tag{6}$$

where the symbols α, and β are shape parameters and S_{wr} is the residual water saturation [dimensionless].

HydroGeoSphere is a recent code taken into consideration as a forward model. HydroGeoSphere provides a rigorous simulation capability that combines fully-integrated hydrologic/water quality/subsurface flow and transport capabilities with a well-tested set of user interface tools.

HydroGeoSphere solves the pressure-head based form of Richards' equation (Equation (1)) for variably-saturated flow and the linear contaminant transport equation in up to three dimensions using a Galerkin finite element approach.

2.3 Model discretization and optimization techniques

The finite element grid was generated automatically using the pre-processor GRID BUILDER[22] as shown in Figure 1b. The discretization in the vertical direction was approximately 1.5 cm. The intent of this discretization was to be able to resolve vertical water flow with precision.

Boundary conditions for each experimental model were identical. An artificial rainfall shown in Figure 1b was applied at the top of each model. The sides of each model were considered impermeable and no flow boundary. Free drainage was considered at the bottom of each model.

Many methods for inverse modeling can be classified according to minimization algorithm, such as the Levenberg-Marquardt-genetic-algorithms. In this study, we developed an inverse method for estimating parameters using Levenberg-Marquardt[23] minimization algorithm in C++ language. The Levenberg-Marquardt minimization algorithm was found to perform well for most inverse methods. The purpose of the minimization algorithm is to find the minimum of the objective function by iteratively updating the parameters of the model. Note that in this study, the measured and simulated variable for objective function is the free drainage or flux from the bottom of experimental device.

A detailed description of the Levenberg-Marquardt minimization algorithm is given by Marquardt[23], Press et al.[24], and Daniel and Wood[25]. The description will not be repeated here. The algorithm expresses the error between observed and simulated data:

$$\Phi(b) = \sum_{i=1}^{n}(P_i^*(z,t) - P_i(z,t;b))^2 \tag{7}$$

The right hand side represents the sum of squared deviations between the measured and calculated space–time variables free drainage. Here, n is the number of measurements, $P_i^*(z,t)$ represents specific measurements at time t and depth z; $P_i(z,t,b)$ are the corresponding values simulated with a set of parameters, b.

Initial values such as matric pressure head and water content were unknown in the experimental device. So, first the model was run for a long time period to reach the pseudo steady state as the simulated discharge rate showed a good agreement with the observed discharge rate. The matric pressure head yielded from the steady state condition was used as the initial condition for the transient simulation. Some of measured free drainage data from the bottom of the experimental device were used for the automatic calibration procedure, while the rest of the data were used to test (validate) the predictive capability of the calibrated models for whole treatments. In the calibration procedure, the inverse model was used to estimate the saturated hydraulic conductivity (K_s), the saturated water content (θ_s), the residual water content (θ_r) and water retention function parameters of van Genuchten (α, β) which were unknown parameters in the unsaturated water flow. In the validation period, estimated parameters (K_s, θ_s, θ_r, α and β) by the inverse method from the calibration period was applied to simulate free drainage by HydroGeoSphere.

3 Results and discussion

Soil physical properties before applying cattle manure are shown in Table 1 as well as cattle manure properties used in the experiment are listed in Table 2.

Table 1 Physical and chemical soil properties before applying cattle manure

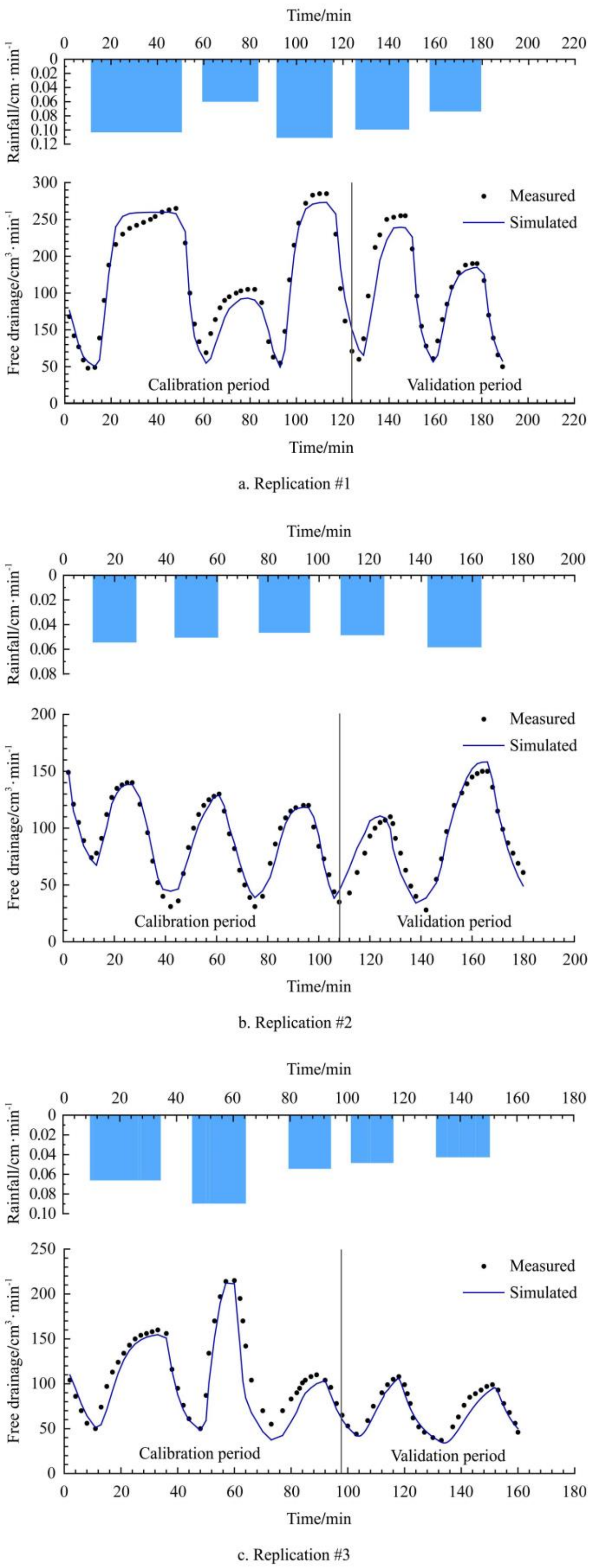
Soil texture	Organic carbon/%	Clay /%	Silt /%	Sand /%	Electrical conductivity/ds cm^{-1}	PH_e
Sandy clay loam	0.1	25	18	57	0.86	7.66

Table 2 Physical and chemical properties of cattle manure used in the experiment

PH (1:2)	C:N	Total nitrogen /%	Organic carbon /%	Electrical conductivity (1:2)/ds cm^{-1}	Bulk density /g cm^{-3}
7.36	12.73	1.65	21	8.51	0.4

Observed and simulated free drainage for automatic calibration and validation period using van Genuchten's retention functions are shown in Figures 2 to 4 for all treatments and replications. Figures 2 to 4 show that the simulated free drainage using the optimized parameters exhibits a good match with the observed free drainage for all treatments and replications. Therefore, one could conclude that Richards' equation along with estimated van Genuchten's retention functions using the inverse method can successfully describe the unsaturated water flow in all treatments.

Estimated parameters obtained from automatic calibration by the Levenberg-Marquart optimization algorithm are listed in Table 3 for control treatments and applications of 30 and 60 Mg/ha cattle manure for three replications, respectively. The standard error of the θ_r in Table 3 is significantly greater than the mean value for all treatments, implying that calibration was not sensitive to θ_r. Also, comparison between the standard error and mean values of estimated parameters (Table 3) shows that the automatic calibration is more sensitive to α than all other parameters.



a. Replication #1

b. Replication #2

c. Replication #3

Figure 2 Observed and simulated free drainage for calibration and validation period using van Genuchten's retention functions for control treatment (application 0 Mg/ha cattle manure)

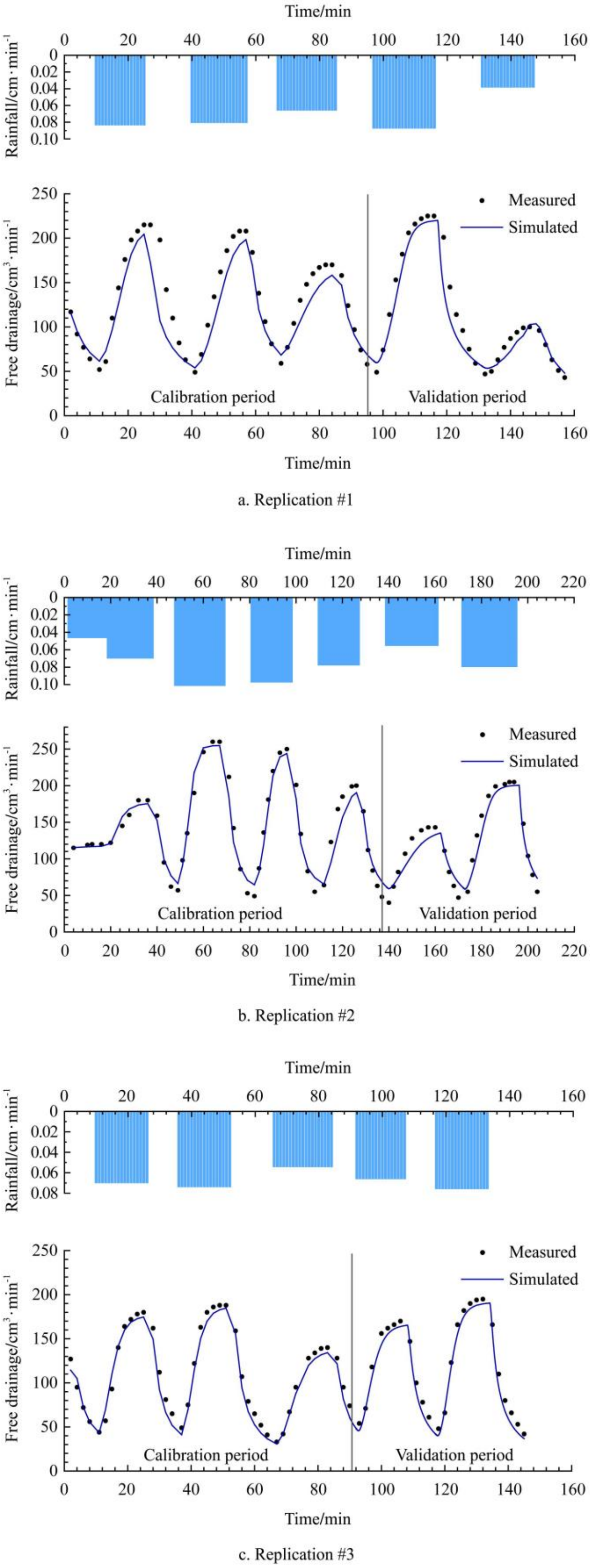


Figure 3 Observed and simulated free drainage for calibration and validation period using van Genuchten's retention functions for application 30 Mg/ha cattle manure

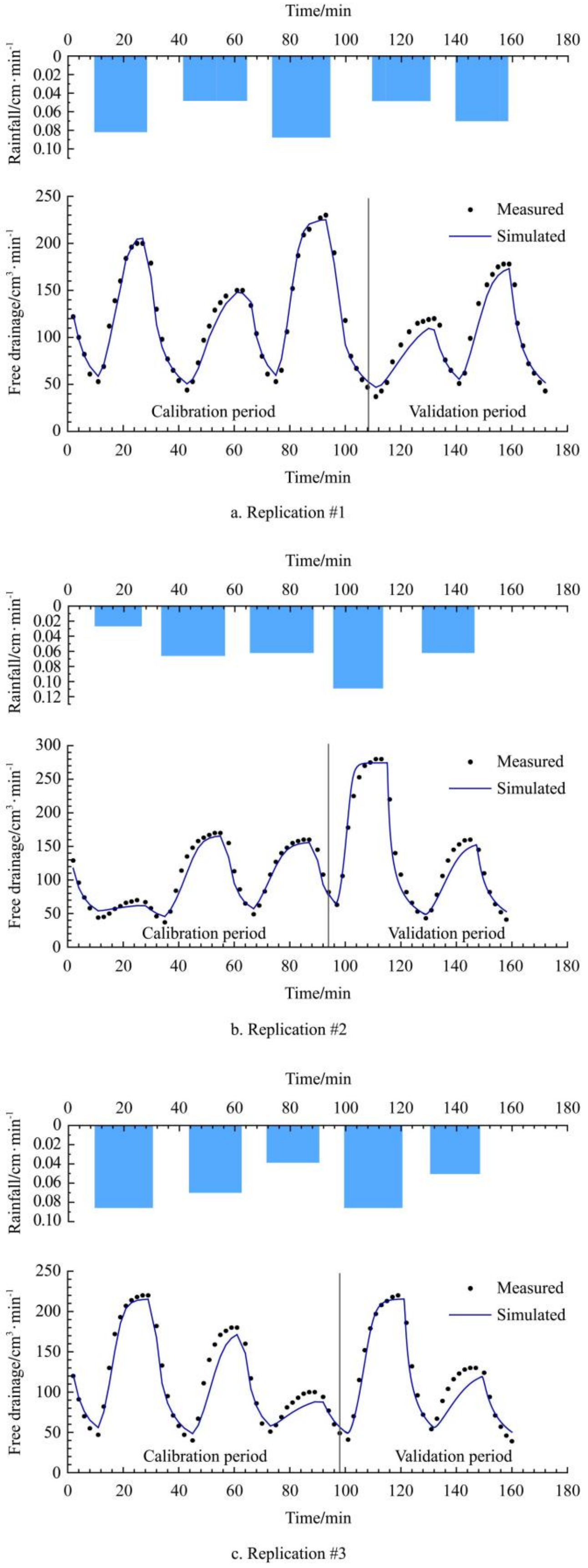


Figure 4 Observed and simulated free drainage for calibration and validation period using van Genuchten's retention functions for application 60 Mg/ha cattle manure

Table 3 Value, standard error (SE), 95 percent confidence limits (CL) of van Genuchten functions for control, application 30 and 60 Mg/ha cattle manure treatments for all replications (K_s: saturated hydraulic conductivity, θ_s: saturated water content, θ_r: residual water content, α and β: shape parameters)

Estimated parameters	Replication #1											
	Control treatment				30 /Mg ha^{-1} treatment				60 /Mg ha^{-1} treatment			
	Value	SE	CL Lower	CL Upper	Value	SE	CL Lower	CL Upper	Value	SE	CL Lower	CL Upper
K_s, Log10 (cm min^{-1})	-0.71	0.41	-1.54	0.11	-0.41	0.82	-2.08	1.25	-0.18	0.72	-1.64	1.28
θ_s, Log10 (-)	-0.37	0.24	-0.85	0.11	-0.32	0.86	-2.07	1.42	-0.31	1.19	-2.71	2.10
θ_r, Log10 (-)	-0.94	1.78	-4.52	2.65	-0.93	4.08	-9.16	7.31	-0.87	4.43	-9.81	8.07
α, Log10 (cm^{-1})	-2.39	0.34	-3.03	-1.66	-2.25	0.47	-3.20	-1.31	-2.18	0.20	-2.58	-1.79
β, Log10 (-)	0.14	0.13	-0.11	0.40	0.09	0.13	-0.16	0.35	0.08	0.08	-0.08	0.23
	Replication #2											
K_s, Log10 (cm min^{-1})	-0.84	3.61	-8.04	6.38	-0.41	0.26	-0.92	0.11	-0.19	1.32	-2.85	2.47
θ_s, Log10 (-)	-0.36	5.10	-10.56	9.82	-0.33	0.17	-0.66	0.01	-0.30	0.22	-0.74	0.15
θ_r, Log10 (-)	-0.96	12.1	-25.09	23.19	-0.93	0.78	-2.42	0.63	-0.86	2.17	-5.25	3.54
α, Log10 (cm^{-1})	-2.44	1.45	-5.34	0.45	-2.32	0.18	-2.67	-1.96	-2.31	0.29	-2.89	-1.72
β, Log10 (-)	0.13	0.91	0.77	1.95	0.09	0.04	0.021	0.17	0.07	0.06	-0.06	0.20
	Replication #3											
K_s, Log10 (cm min^{-1})	-0.53	1.64	-3.85	2.75	-0.31	0.61	-1.58	0.92	-0.12	0.53	-1.19	0.96
θ_s, Log10 (-)	-0.35	0.74	-1.84	1.14	-0.34	0.62	-1.59	0.91	-0.29	0.49	-1.29	0.71
θ_r, Log10 (-)	-0.93	3.01	-6.54	5.07	-0.89	3.26	-7.5	5.71	-0.83	1.99	-4.85	3.19
α, Log10 (cm^{-1})	-2.38	0.78	-3.77	-0.83	-2.36	0.34	-3.01	-1.66	-2.25	0.25	-2.76	-1.75
β, Log10 (-)	0.12	0.11	-0.11	0.35	0.08	0.07	-0.07	0.22	0.07	0.05	-0.03	0.16

Furthermore, the parameters must not be strongly correlated. The matrix of correlation between parameters is shown in Table 4 for the third replication of treatments. The rest of the replications showed the same results. In addition, Table 4 shows that the correlation of K_s to β is higher than the other estimated parameters.

Table 4 Correlation matrix for estimated parameters of van Genuchten functions for control, application 30 and 60 Mg/ha cattle manure treatments for third replications (K_s: saturated hydraulic conductivity, θ_s: saturated water content, θ_r: residual water content, α and β: shape parameters)

	Treatments														
	Control					30 /Mg ha^{-1}					60 /Mg ha^{-1}				
	K_s	θ_s	θ_r	α	β	K_s	θ_s	θ_r	α	β	K_s	θ_s	θ_r	α	β
K_s	1.00					1.00					1.00				
θ_s	-0.35	1.00				-0.37	1.00				-0.02	1.00			
θ_r	-0.79	0.76	1.00			-0.73	0.67	1.00			-0.79	0.61	1.00		
α	-0.76	0.35	0.73	1.00		-0.15	0.38	0.27	1.00		-0.11	0.11	0.35	1.00	
β	-0.96	0.38	0.76	0.71	1.00	-0.89	0.11	0.75	0.51	1.00	-0.92	0.08	0.45	0.28	1.00

For ease of exposition, the $\log_{10}$ of all five estimated parameters are converted to conventional units for all treatments (Table 5) and Duncan's multiple range test at 5% level of probability was used by SPSS software to test the differences between means of individual treatments[26].

The statistical results showed that saturated hydraulic conductivity (K_s) strongly increased with the applications of 30 and 60 Mg/ha cattle manure. Note that there is a significant difference between the applications of 30 and 60 Mg/ha cattle manure (P<0.05) on K_s (Table 5). Increase in the K_s due to the application of cattle manure might be attributed to the improvement in soil structural stability, the increase in organic matter content, and the biological activity of the soil. This strong increase might be the high rate of cattle manure application and the semi-arid climate. Miller et al.[13] reported that the K_s value of manure-treated soil was significantly higher than the control in a dry land zone in 1 year. Felton and Ali[27], Ohu et al.[28], Shirani et al.[29], and Hati et al.[10] reported that adding manure would increase saturated hydraulic conductivity.

Table 5 Effect of cattle manure on saturated hydraulic conductivity (K_s), saturated water content (θ_s), residual water content (θ_r), shape parameters (α and β)

Treatment	K_s /cm min^{-1}	θ_s /cm^3 cm^{-3}	θ_r /cm^3 cm^{-3}	α /cm^{-1}	β (-)
Control	0.21^{c*}	0.44^c	0.11^b	0.004^b	1.35^a
30 Mg/ha	0.42^b	0.47^b	0.13^b	0.005^{ab}	1.22^b
60 Mg/ha	0.69^a	0.50^a	0.14^a	0.006^a	1.18^b

Note: * Same letter in column indicates no significant difference (P<0.05).

The results showed that the saturated water content (θ_s) increased (P<0.05) with the applications of 30 and 60 Mg/ha cattle manure. If the saturated water content was assumed to be equal to total porosity, the cattle manure promotes total porosity of the soil as the microbial decomposition products of organic manures such as polysaccharides and bacterial gums are known to act as soil particle binding agents. These binding agents increase porosity of the soil by improving soil aggregation (after Rasool et al.[30]). Also, these results are supported by other studies[9,12,27,30]. Application of cattle manure significantly increased the residual water content (θ_r) at 0.05 level of probability but there was no significant difference (P<0.05) in θ_r between the application of 30 Mg/ha and control treatments. Miller et al.[13] found that the water retention significantly differed at 1 500 kPa tension treatments with and without manure application in irrigated land, but Zhang et al.[12] declared that this increase was not significant.

Application of cattle manure increased α and decrease β relative to the control treatment at the 0.05 level of probability. But there was no significant difference (P<0.05) in β between the applications of 30 and 60 Mg/ha cattle manure. Table 5 shows that the application of cattle manure increases soil water retention. Increasing α and decreasing β has a positive retention contribution from all pore sizes in the tension interval 0-1 500 kPa. These results are consistent with findings from other researchers who have reported positive responses of soil water retention to manure addition across a wide range of water tensions[12,31].

4 Discussion and conclusions

The soil water retention curve has two desorption and sorption branches due to hysteresis effect. In the testing of the organic matter effect on soil properties, the desorption curve is measured by gradually and monotonically extracting water from initially saturated samples in the laboratory. But the sorption curve is essential for modeling water and solute transport in unsaturated porous media. In this study to overcome these problems the inverse method was used to identify the basic flow and transport parameters. The results of the study showed that the applications of 30 and 60 Mg/ha cattle manure increased K_s, θ_s, θ_r, α and decreased β significantly at 0.05 level of probability. The saturated water contents in the 30 and 60 Mg/ha treatments were 6.8% and 13.6% higher than control treatment, respectively. Also θ_r in the 30 and 60 Mg/ha treatments was 18.2% and 27.3% higher than the control treatment, respectively. The study also indicated that α was 25.0% and 50.0% higher and β was 9.6% and 12.6% lower than control treatment in 30 and 60 Mg/ha treatments. Therefore，one could conclude that cattle manure can be used to effectively enhance physical fertility of low organic matter soils which are widely cultivated in semi-arid region. This study showed that cattle manure significantly improved hydraulic and physical properties of soil. In addition, the application of cattle manure showed positive effect on hydraulic parameters of soil.

Acknowledgements

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