Effect of soil texture on water infiltration in semiarid reclaimed land

Wenmei Ma, Xingchang Zhang, Qing Zhen and Yanjiang Zhang

ABSTRACT

The infiltration of water and its influencing factors in disturbed or reclaimed land are not well understood. A better understanding would provide essential information for assessing the hydrological processes in disturbed ecosystems. We measured the infiltration of water in soils from loamy and sandy reclaimed land. The relationships between infiltration and soil properties were analyzed based on three models: the Kostiakov, Philip, and Green–Ampt equations. Our objectives were to understand water infiltration in reclaimed land with a variety of soil textures and to establish the dependence of water infiltration on soil properties. Both the rate of infiltration and the cumulative infiltration were higher in sandy than in loamy soils. The rate of infiltration and the cumulative infiltration decreased with soil depth in undisturbed land. The sorptivity rate (S) from the Philip equation, empirical coefficient (K) from the Kostiakov equation, and the saturated hydraulic conductivity (Ks) from the Green–Ampt equation were 22%, 16%, and 7.1% higher, respectively, in sandy than in loamy soils. The Ks increased significantly with Ks (saturated hydraulic conductivity) in both sandy and loamy soils. These indicated that the Green–Ampt equation can be used to describe Ks and the characteristics of infiltration for soils on disturbed land.

Key words | reclaimed land, saturated hydraulic conductivity, soil texture, water infiltration

INTRODUCTION

The infiltration of water into soil is an important process of the hydrological cycle in terrestrial ecosystems, particularly in arid and semiarid ecosystems, that are limited by the availability of soil water. Infiltration into soils has been widely investigated in both field and laboratory studies. The saturated hydraulic conductivity has previously been evaluated by field infiltration experiments over a period of years (Matula 2003). Yang et al. (2006) described the behavior of infiltration in laboratory experiments, and the process has been well described and modeled. The Green–Ampt equation, an early conceptual model of infiltration, was defined in 1911 (Green & Ampt 1911). Hsu et al. (2002) evaluated three models of infiltration, the Philip, Green–Ampt, and Horton models, with several types of soil. A study conducted in a cultivated field and a grazed pasture showed that the cumulative infiltration was not affected by the type of land use (Bharati et al. 2002). The disruption of soil structure and channels under conventionally tilled farmland led to a lower infiltration rate compared with an untilled treatment (Azooz & Arshad 1996). Laboratory studies have demonstrated that the fine-particle content of soils determined water infiltration and can be used to estimate infiltration rates (Agassi et al. 1982; Bharati et al. 2002).

The empirical Kostiakov equation was widely used in early studies to describe water infiltration (Mezencev 1948; Kincaid et al. 1969; Gilley 1984; Wilmes et al. 1993). Mishra et al. (2003) indicated that the Kostiakov equation was unable to provide detailed information about the infiltration process because its physical meaning was not robust. The Green–Ampt and Philip equations are therefore now used to model infiltration. McCuen et al. (1981) showed that the Green–Ampt model can well describe infiltration in
agricultural land. Shahsavar et al. (2010) successfully predicted water infiltration using the Philip equation in 12 soil series on the Saveh plain in Iran.

These experiments and modelings were mostly conducted with soils collected from undisturbed land with natural vegetation and with soils from farmland under various tillage practices. Water infiltration in disturbed land, due to changes in land use, or in reclaimed land, however, has rarely been reported. The soil structure and profile characteristics of disturbed or reclaimed land differ greatly from those of undisturbed land. The destruction of soil structure in disturbed or reclaimed land will change soil bulk density (BD) and soil pore size distribution, which might vary with soil depth. The change of soil texture, driven by laws of physics, combined with model parameterization to represent the pore-size distribution, etc., can affect the infiltration model to not be so applicable. The modeling of water infiltration in disturbed land thus differs greatly from the modeling of undisturbed land, which could decrease the accuracy of the modeling by the various mathematical methods. Understanding infiltration in disturbed land is therefore essential for a better understanding of hydrological processes and for assessing the results of modeling in disturbed ecosystems.

Infiltration is generally influenced by soil texture, which determines BD, pore size, soil organic-matter (SOM) content, initial soil-moisture content, and the type of land use (Mcginty et al. 1978). However, the effects of soil texture on infiltration and the dependence of influencing factors on infiltration in disturbed or reclaimed land have not been well investigated. Moreover, researchers previously focusing on the influence of tillage on infiltration (Khan et al. 2001; Nyamadzawo et al. 2007), vegetation cover, management systems, and soil organic matter (Radke & Berry 1993; Akintoye et al. 2012) and layered soil (Corradini et al. 2000; Huang et al. 2011), have not investigated these issues in disturbed or reclaimed land. Understanding such dependencies would provide a useful guide for predicting infiltration in soil.

In this study, 42 soil cores from loamy and sandy soils were collected to a depth of 140 cm at reclaimed land on the Northern Loess Plateau in China. Soil properties and water infiltration were measured. Three models were used to describe the infiltration processes, and the relationships between infiltration and soil properties were analyzed. The objectives were to understand water infiltration in reclaimed land with different soil textures and to establish the dependence of water infiltration on soil properties.

MATERIALS AND METHODS

Study sites and soil sampling

Soil samples were collected from the reclaimed land in the HeiDaiDou Open Pit Coal Mine on the Northern Loess Plateau. The soil in this area has been reclaimed since 1998, and the depth of the reclaimed soil was at least 150 cm. After the new dump formed, the soil was not disturbed until we collected it. The elevation of the site ranges between 1,025 and 1,302 m, the mean annual temperature is 7 °C, and the mean annual precipitation is 400 mm.

Soil samples were collected from reclaimed areas with sandy soil and loamy soil from 0–20, 20–40, 40–60, 60–80, 80–100, 100–120, and 120–140 cm layers in July 2012. The 20 cm of undisturbed soil from each layer was collected with a column 7 cm in diameter and 25 cm in length for measurements of saturated hydraulic conductivity and for the water-infiltration experiments. An additional soil sample from each site was collected for the measurement of soil particle size distribution, SOM content, and BD. The dominant vegetation at the loamy sites was Stipa bungeana (profile 1), Bothriochloa ischaemum and S. bungeana (profile 2), and Aspen trees (profile 3), while the dominant vegetation at the sandy sites was Medicago sativa and S. bungeana (profile 4), Robinia pseudoacacia and S. bungeana (profile 5), Medicago sativa and S. bungeana (profile 6).

Laboratory analysis

The particle size analysis was based on the method proposed by Bouyoucos (1927). SOM content was determined by the titration method (Walkley & Black 1934). BD was measured by a method proposed by Brasher et al. (1966).

For the infiltration experiments, deionized water at a temperature of 24 ± 1 °C was applied to the surface of the columns from Mariotte bottles, a constant 4.5 cm head of water was applied, and the head was constant during the
infiltration. The whole progress of the wetting front was recorded. For the first 6 min, it was recorded every 30 s. Then, it was recorded every 1 min for the following 20 min. For the next 30 min, it was recorded every 2 min. After that, it was recorded every 5 min for 50 min. Finally, it was recorded every 10 min until the wetting front disappeared. Once the wetting front had reached the base of the soil column, the outflow was collected with a fraction collector continuously every 30 min, and the volume accrued in each 30 min interval was measured until the flow rate became constant. This point determined the saturated hydraulic conductivity ($K_s$).

The $K_s$ of the soil column were calculated from the infiltration data using Darcy’s law (Marshall & Holmes 2003):

$$k_s = \frac{v}{t} \frac{L}{H}$$  \hspace{1cm} (1)

where $v/t$ is the volume of water flow per unit time (mL min$^{-1}$), $L$ is the length of the soil column (cm), $A$ is the area of the soil column (cm$^2$), and $H$ is the difference between top and bottom water level (cm).

Data analysis

A two-way analysis of variance was used using SAS software (SAS Institute 1999) to analyze the effects of soil texture and soil depth on the variables. Correlation analysis was used to evaluate the relationships between $K_s$ and parameters of the equation. The Kostiakov, Philip and Green–Ampt equations were used to describe the infiltration of water into the soils.

The Kostiakov (1932) equation is expressed as:

$$I = K_i t^{-\alpha}$$  \hspace{1cm} (2)

where $I$ is the cumulative infiltration (cm), $t$ is time (min), and $\alpha$ and $K_i$ are empirical coefficients.

The Philip (1957) equation is expressed as:

$$I = St^{1/2} + At$$  \hspace{1cm} (3)

where $I$ is the cumulative infiltration (cm), $t$ is time (min), $S$ is the sorptivity (cm min$^{-1/2}$), and $A$ is the steady-state infiltration rate (cm min$^{-1}$).

The Green & Ampt (1911) equation is expressed as:

$$q = K_s \left[ 1 + \frac{H_m}{L_f} \right]$$  \hspace{1cm} (4)

where $q$ is the infiltration rate (cm min$^{-1}$), $K_s$ is the saturated hydraulic conductivity (cm min$^{-1}$), $H_m$ is the effective pressure head at the wetting front (cm), and $L_f$ is the generalized moist wetting front (cm).

Wang et al. (2002) showed the matric potential plays a major role in a relatively limited infiltration time and the Green–Ampt equation is expressed as:

$$i = k_d \frac{h_f}{z_f}$$  \hspace{1cm} (5)

where $i$ is the infiltration rate (cm min$^{-1}$), $K_d$ is the satiated hydraulic conductivity (cm min$^{-1}$), $h_f$ is the average suction wetting front (cm), and $z_f$ is the generalized moist wetting front (cm).

The Green–Ampt infiltration model includes two parameters, $K_d$ and $h_f$: $K_d$ is determined by the experimental conditions, whereas $z_f$ is determined by the cumulative infiltration:

$$I = (\theta_1 - \theta_i)z_f$$  \hspace{1cm} (6)

where $I$ is the cumulative infiltration (cm), $\theta_s$ is the saturated water content (cm$^{-3}$ cm$^{-3}$), and $\theta_i$ is the initial soil-moisture content (cm$^{-3}$ cm$^{-3}$).

RESULTS AND DISCUSSION

Soil properties

As shown in Table 1 and Figure 1(a), BD and $K_s$ were not significantly ($P = 0.05$) influenced by soil texture and soil depth in this study. Sand content, however, was significantly higher in the sandy than in the loamy soils across the profile, as expected (Figure 1(d)). The SOM is shown in Figure 1(c). The difference in SOM between the two soils was greater at 0–40 cm and 120–140 cm depths than other soil depths, which might lead to the significant interaction. SOM
content was generally higher in loamy than in sandy soils in all soil layers. $K_s$ was higher in sandy than in loamy soils in the 0–60 cm layer but similar change was found in the two soils below 60 cm (Figure 1(b)).

### Water infiltration

The extent of cumulative infiltration increased with time for both the sandy and the loamy soils in each layer. The infiltration of water in the disturbed soils varied with soil texture (Figure 2). These results were consistent with those from other studies conducted in undisturbed land (Jorgenson & Gardner 1987; Chong & Cowsert 1997; Shrestha et al. 2005). The infiltration rate and cumulative infiltration were higher in sandy than in loamy soils for each soil layer (Figure 2). For example, the infiltration rate and cumulative infiltration averaged 0.28 cm min$^{-1}$ and 2.29 cm in sandy soils, respectively, but averaged 0.21 cm min$^{-1}$ and 1.99 cm in loamy soils, respectively, in soils collected from the 0–20 cm layer. The infiltration rate and cumulative infiltration averaged 0.24 cm min$^{-1}$ and 2.53 cm in sandy soils, respectively, but averaged 0.18 cm min$^{-1}$ and 2.46 cm in loamy soils, respectively, in the 60–80 cm layer. The infiltration rate and cumulative infiltration averaged 0.35 cm min$^{-1}$ and 2.38 cm in sandy soils, respectively, but averaged 0.27 cm min$^{-1}$ and 2.97 cm in loamy soils, respectively, in the 120–140 cm layer.

The progress of the wetting front in different soil textures showed a trend similar to that of the extent of infiltration (Figure 3). For example, the wetting front in sandy soil was always deeper than in loamy soil in each soil layer. The wetting front was deeper in the sandy soils collected from the 120–140 cm layers than in soils from the 0–20 and 60–80 cm layers. The wetting front in loamy soil, however, was similar in the different layers (Figure 3). These results were expected because the higher sand content and porosity of sandy soil provide lower soil water potential and higher $K_s$ compared to loamy soil, which favors the infiltration of water in sandy soil. These results were consistent with the relatively lower infiltration rates in fine-textured than in coarse-textured soils observed in both farmland (Návar & Synnott 2000) and land with natural vegetation (Mbagwu 1997). In the clayey soil, the bulk density was higher in the more compacted soil than that in non-compacted soil (Neves et al. 2003). Thus in the water infiltration process, the wetting front moved in the loamy soil more slowly than in the sandy soil.

Infiltration rate and cumulative infiltration have been found to decrease with soil depth in undisturbed land. For example, the infiltration rate in field and laboratory experiments with soils collected from seven natural sites decreased with increasing soil depth throughout a 0–160 cm profile (Zettl et al. 2011). In our study, however, infiltration rate and cumulative infiltration did not vary with depth in both sandy and loamy soils due to the relatively homogeneous distribution of soil properties along the soil profile in the disturbed land, consistent with the

<table>
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*The degree of freedoms of soil texture, soil depth, and interaction were 1, 6, and 6.
lack of variation in sand content and $K_s$ with depth in both sandy and loamy soils (Figure 1(b)). Similarly, Chu & Mariño (2005) found little difference in water infiltration among the layers of layered soils. We therefore concluded that infiltration was not dependent on soil depth in either the disturbed or the reclaimed land.

Across the 0–140 cm soil profile, $S$ derived from the Philip equation, $K$ derived from the Kostiakov equation and $K_{sl}$...
derived from the Green–Ampt equation were relatively higher in sandy than in loamy soils (Figure 4). The averaged $S$, $K$, and $K_{sl}$ were 22%, 16%, and 7.1% higher, respectively, in sandy than in loamy soils. These results were consistent with the relatively higher infiltration rate in sandy than in loamy soils (Figures 2 and 4). The profile distribution of $S$, $K$, and $K_{sl}$, however, varied with soil texture. We observed no increase or decrease in $S$, $K$, or $K_{sl}$ with soil depth in either sandy or loamy soils. These results conflict with those from undisturbed land with natural vegetation or from farmland whose surface layer was only lightly tilled. For example, Dijck & Asch (2002) reported that $S$ and infiltration rate were higher in the topsoil than in the subsoil in land with natural vegetation. Wang et al. (2011) reported the $K_s$ in the 0–10 cm layer higher than below 30 cm under a dense cover of vegetation in an alpine meadow. The independence of $S$, $K$, and $K_{sl}$ on soil depth in the reclaimed land in our study was likely due mainly to the disturbance of the soil structure along the profile. The depth of disturbance of the soil structure was generally 140 cm, which provided a high homogeneity of soil properties along the profile.

The dependence of water infiltration on soil properties

$K_s$ increased with sand content ($K_s = 0.031 + 0.002^*\text{sand}, r = 0.273, n = 54, P = 0.0457$). These relationships were expected because lower sand content produced lower porosity and higher soil water potential. These results were consistent with observations in disturbed/reclaimed and undisturbed land. SOM content was assumed to be positively correlated with $K_s$ because SOM can stimulate soil aggregation, which lowers BD and increases porosity in the sandy soil (Wang et al. 2009; Chaudhari et al. 2013). SOM and sand contents can therefore be used to predict $K_s$ in disturbed soils following reclamation or changes in land use. Sand content and BD can therefore also be used to predict $K_s$ in disturbed soils.

$K_{sl}$ increased significantly with $K_s$ in both sandy and loamy soils. The results indicated that the Green–Ampt equation could successfully describe $K_s$ and the characteristics of infiltration for the soils from disturbed land. $K$, however, was not significantly correlated with $K_s$ (Figure 5(a)). These results agreed with other findings in both undisturbed and reclaimed land. Based on their results from field and
laboratory tests on soils from coarse sand to fine clay, Mishra et al. (2003) suggested that the Kostiakov equation could not provide detailed information about the infiltration process, and the physical meanings of the model were not robust. Sir et al. (1988) observed poor predictive ability with the Philip model for some soil. Oku & Aiyelari (2014) also indicated that the Philip model was better than the Kostiakov equation in predicting infiltration in inceptisols of the humid forest zone of Nigeria. Mbagwu (1997) reported that the Philip model cannot predict the infiltration model when the assumptions of model were not met during the infiltration process.

The Green–Ampt equation is one of the most widely used equations for modeling one-dimensional vertical flow of water into soil (Liu et al. 2008). The values for Kd and S were both significantly correlated with Ks, the result suggesting that both the Green–Ampt and Philip equation are the best alternatives to soil infiltration under different soil texture conditions (Figure 5). However, the S with a value of coefficient of association correlate was lower than Kd, which indicates the Green–Ampt equation is closer to soil infiltration than the Philip. A comparison was also made between the Philip and Kostiakov equations, and based on these results, the K was not significantly correlated with Ke (Figure 5(a)), and the S proved to be estimated closed to the Ks (Figure 5(b)). These showed that the Phillip performs better than the Kostiakov equation. Through these equations, the Kd was found to increase significantly with Ke in both sandy and loamy soils. Our analysis confirmed that the Green–Ampt model can well describe infiltration processes in reclaimed land, consistent with findings from other field and laboratory experiments (Chu 1978; Rawls et al. 1982; Liu et al. 2008; Gowdish & Carpena 2009; Ma et al. 2010). For example, Chu (1978) extended the Green–Ampt model to describe infiltration during intermittent rainfall for a homogeneous soil profile. Ma et al. (2010) successfully described water infiltration through a five-layered stony soil column 300 cm in length using a modified Green–Ampt model. In our study, Kd explained nearly 100% of the Ke for both soils (Figure 5(c)). We therefore recommend the Green–Ampt equation for describing water infiltration in disturbed/reclaimed land.

CONCLUSIONS

The extent of cumulative infiltration in the reclaimed land increased with time in both sandy and loamy soils in all soil layers and varied with soil texture. The infiltration rate and cumulative infiltration were higher in sandy than in loamy soils in each soil layer. The progress of the wetting front with soil texture showed a trend similar to that of the extent of infiltration. Infiltration rate and cumulative infiltration decreased with soil depth. The averaged S (the sorptivity rate), K (an empirical coefficient), and Kd (saturated hydraulic conductivity) were 22%, 16%, and 7.1% higher, respectively, in sandy than in loamy soils and varied with soil texture. Kd increased significantly with Ke in both sandy and loamy soils. Kd explained nearly 100% of the Ke in both soils. These results indicated that the Green–Ampt equation can successfully describe Ke and the characteristics of infiltration for the soils from disturbed land.

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REFERENCES


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