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ORIGINAL ARTICLE

The response of infiltration depth, evaporation, and soil water replenishment to rainfall in mobile dunes in the Horqin Sandy Land, Northern China

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Abstract To understand the relationships among rainfall–infiltration–evaporation–replenishment in mobile dunes in the semi-arid areas of China, we used the Container of Water Distribution (100 × 100 × 120 cm^3) to examine rainfall infiltration, soil water redistribution, and soil surface evaporation under natural and simulated rainfall conditions. The results showed that infiltration depth was linearly related to rainfall amount and intensity. Rainfall amounts larger than 13.4 mm, could replenish soil water at 60 cm depth after redistribution, while with rainfalls larger than 39.8 mm, infiltration depth could exceed 120 cm. Rainfall amounts larger than 50 mm produced saturated soil water at 120 cm depth, and replenishment amount accounted for 40.4 % of the total amount of rainfall. Soil surface evaporation exhibited a relatively minor change with increases in rainfall when rainfall was larger than 11.8 mm. The amount of evaporation and soil water content were significantly correlated at 0–60 cm soil depth, but not below. These results suggest that the maximum effective depth of evaporation is 60 cm below the ground surface, and that rainfall of 13.4 mm is a threshold distinguishing effective from ineffective rainfall in the mobile dunes of the Horqin Sandy Land.

Keywords Mobile dunes · Infiltration depth · Evaporation · Soil water replenishment

Introduction

Soil water is one of the critical factors affecting plant growth, plant density, species number, and plant distribution patterns in semi-arid regions (Li et al. 2004; Karie et al. 2006; Wang et al. 2008; Liu et al. 2009). Rainfall is the only source of soil water replenishment and the limiting factor for vegetation cover in desert ecosystems (Wang et al. 2007). Infiltration rates and soil water distribution are significantly influenced by vegetation characteristics, soil texture, and soil physical properties (Wang et al. 2007; Itzhak et al. 2008). Vegetation establishment decreases the area of desertification and prevents soil wind erosion in mobile dune areas, but it also aggravates water scarcity and soil desiccation (Chen et al. 2008). Mobile dunes play an important landscape-level role in rainfall redistribution (Berndtsson et al. 1996); their eco-hydrological functions are very important for plant growth and survival as mediated by rainfall infiltration and replenishment (Liu et al. 2009). A previous study indicated that 20–30 % of annual rainfall recharges groundwater in mobile dunes by rainfall infiltration; accordingly, a stable level of groundwater can be retained in the lowlands among the mobile dunes; this favors vegetation growth in mobile dune ecosystems (Zhao et al. 2007b).

Accurate estimation of replenishment in mobile dunes is useful for water resource management and modeling efforts. However, accounting for the variability in replenishment, resulting from the spatial and temporal variability in precipitation, is challenging. Furthermore, the processes of rainfall infiltration and distribution of soil water, and

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their associations with rainfall characteristics, remain poorly understood in mobile dunes. Hence, quantification of the changes in rainfall infiltration, soil water dynamics, and evaporation in mobile dunes will close this information gap.

Application of time domain reflectometry (TDR) provides relatively exact and rapid method for monitoring of soil water content (Topp et al. 1980; Kachanoski et al. 1992; Timlin and Pachepsky 2002; Wang et al. 2008). The measurement technology has been used to study rainfall infiltration and patterns of soil water redistribution in different conditions of surface cover and in the presence of individual shrubs (Martinez-Meze and Whitford 1996; Dunkerley and Booth 1999; Wang et al. 2007).

The Horqin Sandy Land is a desert area in the southeast part of Inner Mongolia. This area has become one of the most severely affected by desertification in northern China due to long-term overgrazing, reclamation, gathering of fire wood, and excessive utilization of water resources (Gomes et al. 2003; Zhao et al. 2006, 2010). Landscape is characterized by different kinds of sand dunes alternating with gently undulating lowland areas. Mobile dunes are one of the main dune types in this region. Experimental data relating to the characteristics and processes of rainfall infiltration and soil water redistribution in mobile dunes in this semi-arid region are limited. The purpose of this study was to (a) estimate infiltration depths and soil water characteristics after rainfall events; and (b) examine the quantitative relationships of rainfall, evaporation, and replenishment in mobile dunes of the Horqin Sandy Land.

Materials and methods

Study site

The study was conducted in the south-western part (42°55′N, 120°42′E; 360 m elevation) of the Horqin Sand Land, Inner Mongolia, China. The climate is temperate, semi-arid, continental, and monsoonal. The area receives 357 mm of precipitation annually, with 75 % of precipitation in the growing season from June to September. Individual rainfall amounts in this region range from 0.1 to 116.1 mm, and rainfall intensity ranges from 0.1 to 63.2 mm h^{-1}. The average length of the dry interval was 11.3 days; the maximum duration of the dry interval averaged 23 days, and the minimum was 0.6 day in the growing season, based on unpublished data obtained at the Naiman station from 1985 to 2013. The mean annual potential evaporation is about 1,935 mm, and the mean annual temperature is about 6.8 °C. The annual frost-free period is 130–150 days. The average annual wind speed is 3.4 ms^{-1}. Soils are sandy, light yellow, have loose structure, and are particularly susceptible to wind erosion (Zhao et al. 2007a). Moving dunes are the most typical feature in this area; depth to groundwater is between 12 and 15 m, therefore, groundwater is unable to supply surface soil water.

Experimental design

The experiment was conducted in three Containers of Water Distribution (CWD) with the size of 100 cm (length) × 100 cm (width) × 120 cm (height), from June 1 to September 3, 2004. The three CWDs were made of a steel plate with a thickness of 5 mm. Eleven holes were drilled on one side, which were used to install the probe of a time domain reflectometer (TDR) (TRIME-FM-P3, IMKO Micromodultechnik, Ettlingen, Germany) in a horizontal position.

Soil water contents were monitored in 10 cm increments from 10 to 110 cm soil depth at different time intervals. The CWDs were buried underground, and an observation area was excavated to measure soil water content and percolating water. The bottom of each CWD was fitted with a drainage tube with a diameter of 5 cm to collect percolating water (Fig. 1). Soils from different depths of the mobile dune were placed in CWDs in 10 cm layers. Physical properties of soils in the 0–120 cm depth are shown in Table 1.

Rainfall was measured by three rain gauges placed at the side of the CWDs. There were 11 rainfall events during the study period; 10 were produced by a rainfall simulator, and 1 was natural (11.8 mm, 20.29 mm h^{-1}). Artificial rainfall was designed to reproduce characteristics of the local natural rainfall amount and intensity; thus, rain amount ranged from 5.7 to 110.1 mm, and intensity from 7.56 to 61.17 mm h^{-1}. The artificial rainfall simulator consisted of three systems: water supply, water spraying, and decompression, and was equipped with three fixed V-Jet nozzles. The nozzle spacing was 3 m (Fig. 1). The simulator could be adjusted through nozzle sizes and water pressure to precisely deliver the desired rainfall amount and intensity. The calibrated rainfall intensity of the simulator was 7.56–60.17 mm h^{-1}; simulator's rainfall uniformity coefficient exceeded 0.90, which was similar to natural rainfall in raindrop distribution and size, and there were no significant differences in rainfall characteristics between natural and artificial rainfall. Before testing, the rainfall simulator was placed above the ground at 3.0 m. Tap water was used for this experiment, and the rainfall simulator was operated at water pressure of 75 kPa.

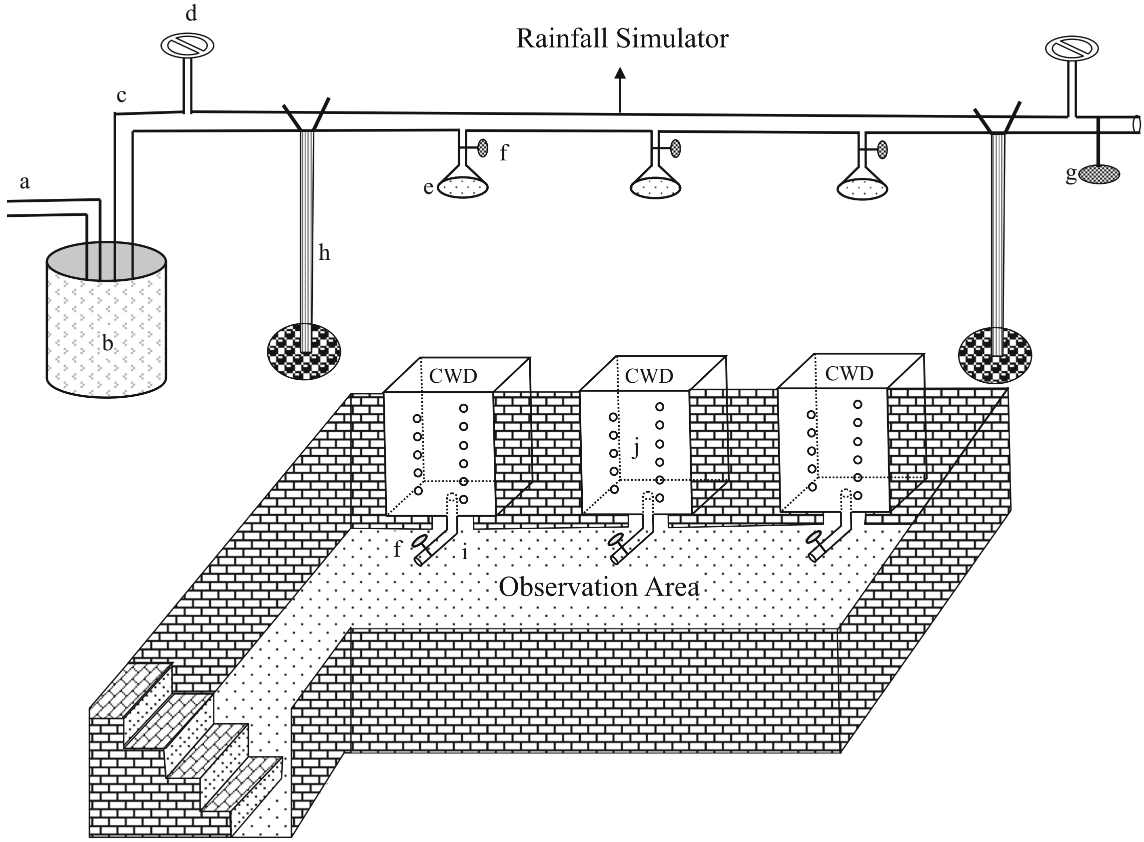

Fig. 1 A schematic representation of the experimental setup. **a** Tap water, **b** Water supply system, **c** Water tube, **d** Water pressure gauge, **e** V-Jet nozzles, **f** Water valve, **g** Reducing pressure valve, **h** Support frame, **i** Drainage tube, **j** TDR probe

Table 1 Soil physical properties at the 0–120 cm soil depth in mobile dunes

Soil physical properties	Depth (cm)					
	0–20	20–40	40–60	60–80	80–100	100–120
Bulk density (g cm^{-3})	1.59 ± 0.03^{a}	1.61 ± 0.03^{a}	1.61 ± 0.03^{a}	1.58 ± 0.03^{a}	1.58 ± 0.02^{a}	1.56 ± 0.01^{a}
Field water holding capacity (gg^{-1}, %)	11.28 ± 2.45^{a}	9.96 ± 0.51^{a}	11.75 ± 1.00^{a}	12.37 ± 1.32^{a}	12.73 ± 0.63^{a}	13.43 ± 0.46^{a}
Saturated water holding capacity (gg^{-1}, %)	22.21 ± 1.32^{a}	19.35 ± 1.10^{a}	21.5 ± 1.51^{a}	21.47 ± 0.85^{a}	20.11 ± 0.91^{a}	22.23 ± 0.74^{a}
Coarse sand (2–0.25 mm, %)	37.62 ± 9.98^{a}	$23.97 \pm 3.62^{b,c}$	$22.27 \pm 6.96^{b,c}$	25.66 ± 13.26^{b}	$23.15 \pm 11.76^{b,c}$	15.18 ± 9.15^{c}
Fine sand (0.25–0.1 mm, %)	59.59 ± 9.96^{a}	$72.89 \pm 4.17^{b,c}$	$74.42 \pm 8.59^{b,c}$	71.76 ± 13.24^{b}	$73.81 \pm 11.86^{b,c}$	81.23 ± 8.00^{c}
Very fine sand (0.1–0.05 mm, %)	0.99 ± 0.45^{a}	$1.44 \pm 0.70^{a,b}$	$1.88 \pm 1.69^{a,b}$	$1.51 \pm 0.39^{a,b}$	$1.62 \pm 0.45^{a,b}$	0.45 ± 2.36^{b}
Silt + clay (<0.05 mm, %)	1.76 ± 0.50^{a}	$1.70 \pm 0.86^{a,b}$	$1.48 \pm 0.74^{a,b}$	1.06 ± 0.23^{b}	$1.41 \pm 0.85^{a,b}$	$1.22 \pm 0.76^{a,b}$

Values are mean ± SD. Values with the same letters within rows are not significantly different at $P < 0.05$

Measurements

Soil physical properties in mobile dunes were determined before the experiment. Three random soil pits were excavated to collect soil cores with a stainless steel cylinder (50 cm^3) from each depth at 20 cm increments down to a depth of 120 cm. We determined soil bulk density, field water holding capacity, and saturated water holding capacity. A total of 18 soil cores were collected at each depth; six of these were used to measure soil bulk density, and the others were used to determine field and saturated water holding capacity. Briefly, soil cores, covered at one end with a fine mesh and left open at the other end, were saturated with water for 12 h. The resulting soil water content represented gravimetric saturation water capacity. Excess water was then drained by placing samples on the surface of a sand bed for 12 h, and field water holding capacity was determined. Soil samples were composited by depth to measure soil particle size distribution; for this analysis, soil samples were air-dried and sieved through a 2-mm screen to remove roots and other debris. Soil particle size distribution was determined by the wet sieving method (ISSCAS 1978).

Soil water content was determined with time domain reflectometry (TDR). The TDR is capable of measuring volumetric saturations between 0 and 100 %, with an accuracy of $\leq \pm 2.0$ %. The wetting front can be detected by the changes of soil water content in a soil profile (Noborio et al. 1996). In our experiment, soil water contents at different depths were measured at 5 min intervals during rainfall events. Between rainfall events, soil water contents were measured at 10, 20, and 30 min, and then at 1, 2, 3, 4, 6, and 9 h, depending on the movement of the wetting front; the maximum time interval between measurements was 12 h.

Soil surface evaporation after a rainfall was measured with Micro-lysimeters (Boast and Robertson 1982; Daamen et al. 1993). Generally, measurements taken from the same Micro-lysimeter and natural environment under the same conditions are comparable (Wang et al. 2004a, b). Micro-lysimeters were made of PVC pipes that were 30 cm high, and consisted of an inner pipe of 7 cm in diameter and an outer pipe of 8 cm in diameter. After a rainfall, intact soils in CWD were collected with the inner pipe, the bottom of which was closed with adhesive tape, and the outer pipe was set up in CWD with its brim parallel to the soil surface. Soil and the inner pipe with the tape were weighed together on an electronic scale (precision 0.01 g) before the soil was placed in the outer pipe. Evaporation amounts from surface soil at 0–30 cm depth were determined from the changes in the weight of the soil columns (1 g change accounted for 0.260 mm of evaporation). Soils in inner pipes were replaced every 48 h, and weighed at 7:00 and 19:00 every day.

Calculations of infiltration rate and amount of replenishment

The replenishment coefficient is the ratio between the amount of replenishment and rainfall in a certain time interval. According to the principle of soil water balance, rainfall can be separated into the components of runoff, infiltration, and evaporation; in bare soils in mobile dunes, no runoff occurred on the soil surface during the observation period, and the relationship among replenishment, rainfall, evaporation and soil water content can be defined mathematically as:

$$P_{\mathrm{r}} = P - \sum_{i=1}^{11} (\theta_{\mathrm{ei}} - \theta_{\mathrm{ti}}) \times Z_i - E \qquad (1)$$

where P_{r} is replenishment of rainfall infiltration (mm), P is rainfall (mm), θ_{ti} is initial volumetric soil water before the rainfall event (cm^3 cm^{-3}), θ_{ei} is volumetric soil water at the end stage (cm^3 cm^{-3}), Z_i is soil depth (cm), i is soil layer, E is the amount of evaporation from the soil surface (mm). Based on the result of Eq. 2, replenishment coefficient can be defined as:

$$\alpha = P_r / P \qquad (2)$$

where α is replenishment coefficient (%).

Data analysis

Primary statistical analysis was performed using the SPSS software (version 13.0; SPSS Inc., Chicago, IL, USA). Multiple-comparison and one-way analysis of variance (ANOVA) procedures were used to compare the differences among soil properties and soil water content in different depths. Least significant difference (LSD) tests were performed to determine the significance of the evaporation amount. Pearson correlation coefficients were used to evaluate relationships between rainfall, soil water content at different depths, and amount of evaporation (Zhao et al. 2011).

Results

Rainfall characteristics and infiltration depth

During the study period, the minimum rainfall was 5.7 mm with rainfall intensity of 7.56 mm h^{-1}, while the maximum rainfall was 110.1 mm with rainfall intensity of 61.17 mm h^{-1} (Fig. 2). Runoff generation or surface ponding was not observed in the mobile dunes. Infiltration depth increased with the increase in rainfall amount. Soil water content at 10 cm depth was significantly different before and after the rainfall of 5.7 mm ($F = 1327.69$, $P < 0.01$). However, soil water content from 20 to 40 cm depth increased only slightly, and no significant differences were found before or after rainfall ($P > 0.05$) (Fig. 3a). The maximum infiltration depths were 50, 60, and 50 cm, after rainfall events of 11.8, 13.4, and 20.4 mm, respectively (Fig. 3b, c, d). Changes in soil water at the 60 cm depth were noticeable when rainfall was 13.4 mm with higher intensity (40.1 mm h^{-1}) (Fig. 3c). However, infiltration depth reached 50 cm only after a rainfall of 20.4 mm, due to lower intensity (36.06 mm h^{-1}) and rapid evaporation from the soil surface (Fig. 3d). Moreover, at least 13.4 mm

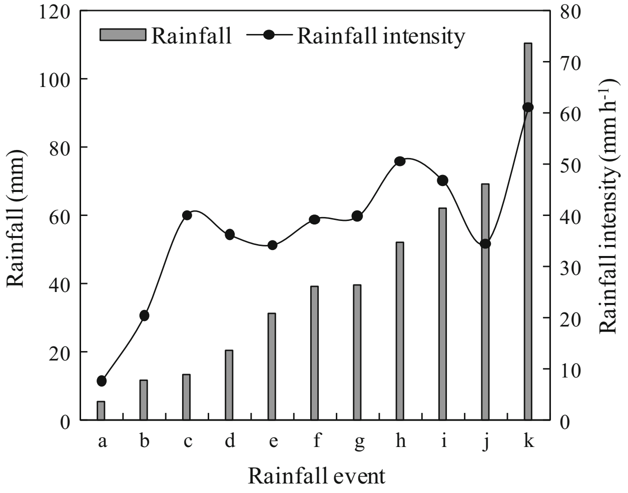

Fig. 2 Rainfall characteristics during the experimental period. **a** 5.7 mm, **b** 11.8 mm, **c** 13.4 mm, **d** 20.4 mm, **e** 31.4 mm, **f** 39.3 mm, **g** 39.8 mm, **h** 52.3 mm, **i** 62.1 mm, **j** 69.1 mm and, **k** 110.1 mm

of rainfall was required for rainwater to reach the depth of 60 cm and replenish soil water in mobile dunes (i.e., 40.1 mm h^{-1} in Fig. 3c). Additionally, when rainfall was 31.4 mm, infiltration reached only 80 cm depth (Fig. 3e), while with a rainfall larger than 39.8 mm, infiltration depth could exceed 120 cm (Fig. 3f). When rainfall was larger than 52.3 mm, infiltration depth could reach 120 cm, generate saturated seepage, and then increase soil water content in deep soil layers.

When rainfall intensity was 40.1 mm h^{-1} (13.4 mm), it took 0.33 h for the wetting front to reach the depth of 20 cm (Fig. 3c). In contrast, when rainfall intensity was 34.3 mm h^{-1} (31.4 mm), it took at least 0.58 h for the wetting front to reach the same depth (Fig. 3e). Rainfall events of 52.3 mm (50.7 mm h^{-1}) and 69.1 mm (34.6 mm h^{-1}) showed a similar response of infiltration depth to rainfall intensity, even though the rainfall amount of the latter was higher than that of the former (Fig. 3 h, j). When the rainfall amount was 11.8 mm with rainfall intensity of 20.3 mm h^{-1-1}, it took 15 h for the wetting front to reach a depth of 50 cm. However, for the rainfall of 31.4 (34.3 mm h^{-1}), 52.3 (50.7 mm h^{-1}), and 110.1 mm (61.2 mm h^{-1}), it took 3.5, 1.5, and 0.6 h, respectively, for the wetting front to reach the same depth. The wetting front decreased linearly when rainfall was 110.1 mm, and it took 2.5 h to reach a depth of 120 cm, while rainfall of 52.3 mm needed 85 h to reach the same depth (Fig. 4).

Soil surface evaporation after rainfall events

The total amount of soil surface evaporation after rainfall events in mobile dunes is presented in Table 2. The amount of evaporation from the soil surface for a 5.7 mm rainfall was 4.15 mm within 11 days, accounting for 72.8 % of the total rainfall. Furthermore, the ratios of soil evaporation and total rainfall amount showed a clear tendency to decrease with an increase in rainfall amount. When rainfall amounts were larger than 20.4 mm, the total amounts of soil surface evaporation ranged from 8.26 to 9.02 mm within 11 days (Table 2). Meanwhile, rainfall amounts were not significantly correlated with cumulative evaporation amounts ($R = 0.558$, $P > 0.05$). Moreover, the amounts of daily evaporation were significantly correlated with the soil water content at the 10–60 cm depth (R ranged from 0.812 at the 10 cm depth to 0.437 at the 60 cm depth, and $P < 0.01$ or 0.05). In contrast, no significant correlations were found in the 70–110 cm depth ($P > 0.05$). Evaporation on the first day was 35.3 % of total evaporation after a 5.7 mm rainfall. Furthermore, when rainfall amounts were >11.8 mm, the mean soil evaporation could exceed 50 % of total evaporation on the first day after rainfall, decreasing gradually in the following days. Percent evaporation on the first day was 60.6, 64.9, 50.4, 67.2, and 61.6 % of the total evaporation after rainfall events of 11.8, 20.4, 39.3, 52.3, and 110.1 mm, respectively (Fig. 5).

The response of soil water replenishment to rainfall event

Soil water content at the 0–10 cm depth was significantly influenced by a rainfall of 5.7 mm (Fig. 3a), and at depths of 0–30 cm, it was replenished after a rainfall of 11.8 mm (Fig. 3b). Significant differences were found in soil water content at the 0–40 cm depths before and after rainfall amounts of 13.4 and 20.4 mm ($P < 0.05$). Additionally, the wetting front could reach 110 cm depth after a rainfall of <39.8 mm, but soil water could not infiltrate into the layer below 120 cm. In other words, soil water content of this layer did not exceed field water holding capacity (20.95 ± 0.72 %). When the amount of rainfall reached 52.3 mm, soil water could infiltrate into the layer below 120 cm, and the amount of replenishment was 21.13 mm, accounting for 40.4 % of the total rainfall. Similarly, the amounts of replenishment were 28.75, 34.27, and 60.31 mm, after rainfall amounts of 62.1, 69.1, and 110.1 mm, respectively. The coefficients of soil water replenishment ranged from 40.4 to 54.8 % (Table 2).

Discussion

In semi-arid areas, the processes of rainfall infiltration in mobile dunes are mainly affected by rainfall characteristics, soil properties, and by runoff (Leonard and Andrieux

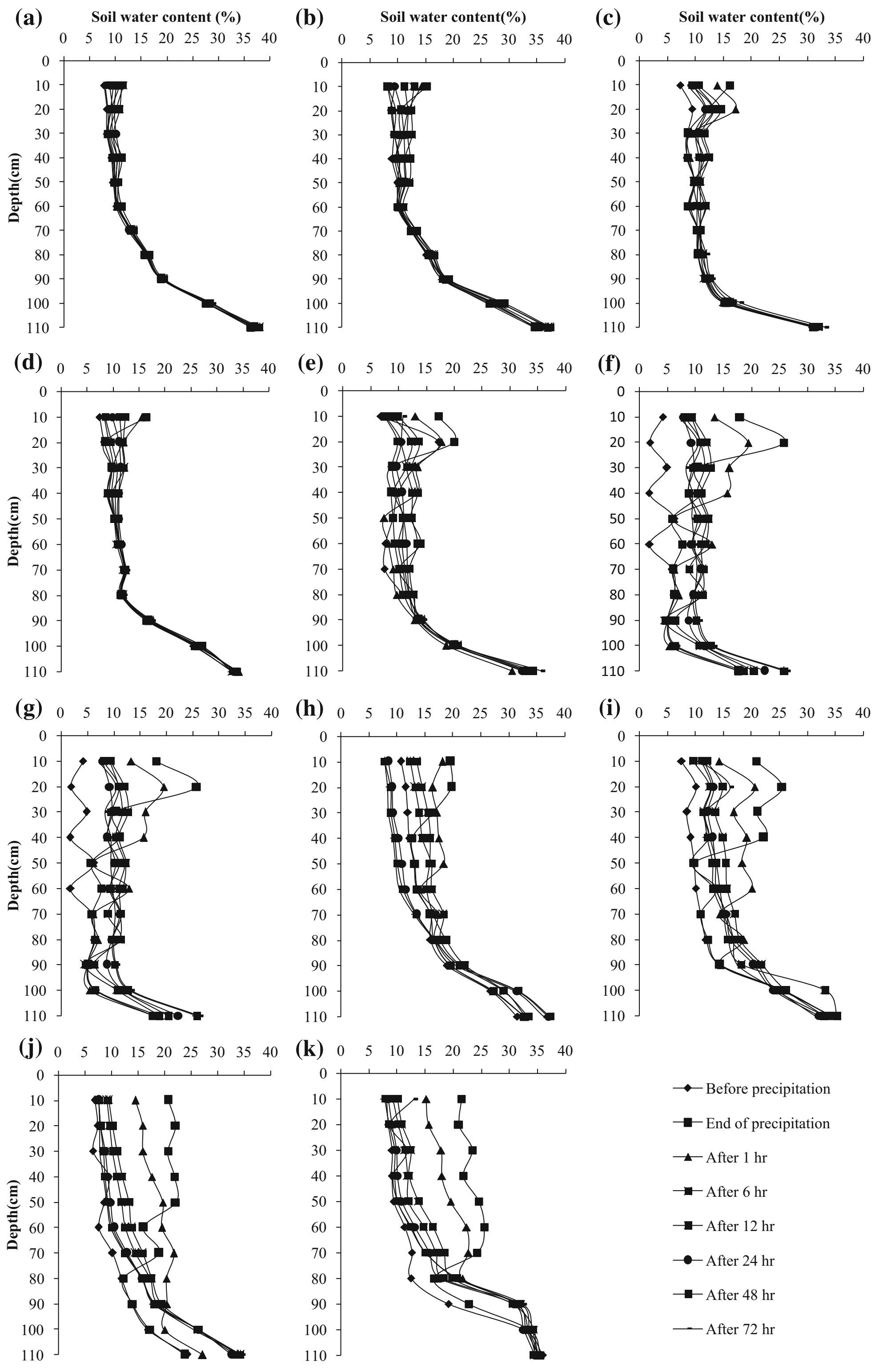

Fig. 3 Changes in soil water content with depth as a result of rainfall infiltration into the soil after rainfall events of **a** 5.7 mm, **b** 11.8 mm, **c** 13.4 mm, **d** 20.4 mm, **e** 31.4 mm, **f** 39.3 mm, **g** 39.8 mm, **h** 52.3 mm, **i** 62.1 mm, **j** 69.1 mm and **k** 110.1 mm

1998; Wythers et al. 1999; Zhang et al. 2008; Katra et al. 2007; Jose and Juan 2009). Rainfall characteristics such as amount, frequency, and intensity significantly affect soil water content and infiltration depth (Reynolds et al. 2004; Harper et al. 2005; Heisler-White et al. 2008; Yaseef et al. 2010; He et al. 2012). In our study, infiltration depth increased with the increase in rainfall amount and intensity (Fig. 3). This may be attributed primarily to the fact that

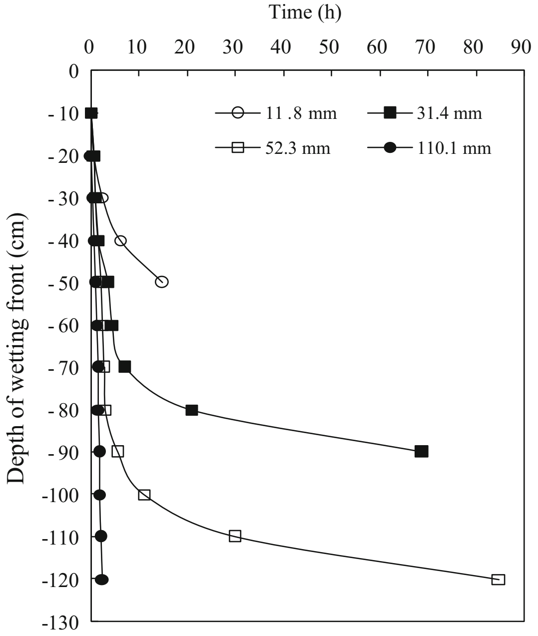

Fig. 4 The wetting front advances of four individual rainfall events

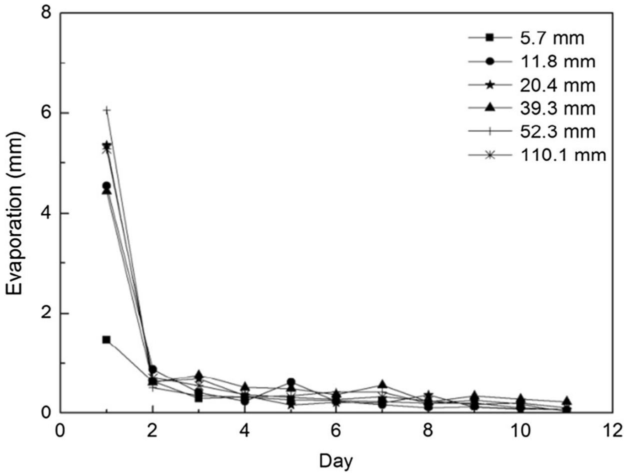

Fig. 5 Daily evaporation from soil surface after rainfall events

higher rainfall intensity could decrease infiltration time for a given depth. In contrast, rainfall events with lower intensity are easier to evaporate from the soil surface due to a limited infiltration depth. This is consistent with the findings from other studies which showed that soil water in mobile dunes is affected by rainfall amount and intensity (Yang et al. 2008; Hao et al. 2008). Additionally, studies have shown that increased soil water content decreases rainfall infiltration, and higher initial soil water content causes larger wetting pattern sizes in all directions (Wangemann et al. 2000; Hawke et al. 2006; Trumana et al. 2011). Loss of infiltrated rainfall is correlated with the antecedent soil water content and not with the total amount of rainfall as well as the rainfall intensity (Mikio et al. 1988). Higher antecedent soil water content leads to higher initial infiltrability but lower steady state infiltration rate (Liu et al. 2011). Wang et al. (2008) indicated that infiltration rates varied greatly with individual rainfall amount and antecedent soil water content, with drier soil profile facilitating infiltration. Hao et al. (2008) also suggested that precipitation is the primary factor of infiltration depth, while antecedent soil water content and precipitation intensity is the secondary and tertiary, respectively. In the present study, antecedent soil water content had less influence on rainfall infiltration because total initial volumetric soil water in different rainfall events showed a relatively small change (Table 2). However, it should be noted that one limitation of this study is lack of sufficient consideration of the influence of antecedent soil water content on infiltration depth of rainfall, which will be studied in future to obtain more comprehensive results of factors that influence infiltration depth in mobile dunes.

A previous study has indicated that small differences in water content result in large differences in hydraulic conductivity, and irregular wetting patterns and preferential

Table 2 Calculations of water balance for 11 rainfall events

P (mm)	E (mm)	P_r (mm)	$\sum\theta_{ti}$ (mm)	$\sum\theta_{ei}$ (mm)	ΔS (mm)	E/P (%)	P_r/P (%)
5.7	4.15	0	98.7	100.2	1.5	72.8	0
11.8	7.51	0	112.6	116.8	4.2	63.6	0
13.4	7.66	0	104.8	110.5	5.7	57.2	0
20.4	8.26	0	113.5	125.6	12.1	40.5	0
31.4	8.67	0	107.2	129.9	22.7	27.6	0
39.3	8.79	0	101.6	132.1	30.5	22.4	0
39.8	8.53	0	103.5	134.7	31.2	21.4	0
52.3	9.02	21.13	112.3	134.4	22.1	17.2	40.4
62.1	8.94	28.75	106.1	130.5	24.4	14.4	46.3
69.1	8.83	34.27	108.8	134.8	26.0	12.8	49.6
110.1	8.58	60.31	115.4	156.6	41.2	7.8	54.8

P rainfall amount, E cumulative evaporation from the soil surface within 11 days, P_r amount of replenishment, $\sum\theta_{ti}$ total initial volumetric soil water, $\sum\theta_{ei}$ total end volumetric soil water; ΔS soil water increment flow may occur in heterogeneous field soils (Ritsema and Dekker 1994). However, rainfall infiltration into homogeneous isotropic soil could be simply regarded as one-dimensional infiltration process, and the wetting front is nearly parallel to the soil surface and moves down vertically during rainfall infiltration and soil water redistribution (Chen et al. 2006). Arbel et al. (2005) also documented that low-slope angled dunes do not favor lateral flow and the wetting depth has been found to be quite uniform over the whole area. In this study, the backfilled soils in CWDs were taken from the nearby mobile dunes that are almost homogeneous isotropic soil, thus, the movement of wetting front could be regarded as one-dimensional infiltration process. We have taken the lateral movement into consideration and mainly concentrated on the vertical movement of soil water in this study due to the limitation of equipment. Nevertheless, this study surely indicated that soil water in mobile dunes is mainly affected by rainfall amount and intensity.

Clearly, soil water replenishment is particularly important because it determines surface water cycle and vegetation pattern (Ding 1992); further, it can be used to evaluate soil moisture dynamics and the risk of drought. Rainfall is the primary influencing factor of soil water replenishment, and the two exhibit positive correlation (Hao et al. 2008). Our results showed that the depth of soil water replenishment increased with an increase in rainfall amount; rainfall >52.3 mm could effectively replenish soil water at 120 cm depth. Li et al. (2013) reported a similar result in the Inner Mongolia region of northern China, in which noticeable increases in soil water recharge were observed at 100 cm soil depth after a rainfall event of 56 mm. However, small rainfall events are prone to greater losses of soil water due to evaporation from the soil surface (Wythers et al. 1999); this affects the depth of soil water recharge (Ludwig et al. 1997). In this study, we found that rainfall <5.7 mm played a trivial role in replenishing soil water in the Horqin Sand Land (Fig. 3a), and rainfall amounts from 5.7 to 20.4 mm could influence soil water at depths of 0–60 cm (Fig. 3b, c, d). The main reason for this is that evaporation from the soil surface has the greatest impact on the water content in the upper soil layers, and the influencing depth of evaporation is limited to 40–60 cm. This is consistent with the results of He and Zhao (2002); Yao et al. (2013)also investigated the influencing layer of evaporation in the mobile dunes of the Horqin Sand Land. In addition, our results also indicated that at least 13.4 mm of rainfall was required for rainwater to reach a depth of 60 cm at the mobile dunes, and to replenish soil water. A previous study has shown that the depth of 40–60 cm was the lower limit of evaporation loss in arid sandy lands (Feng and Cheng 1999). Wang et al. (2008) also reported that the soil water storage increased significantly when rainfall infiltrated to the depth below 60 cm. Our results further showed that soil water content below 60 cm depth maintains a relatively stable state, suggesting that rainfall <13.4 mm with rainfall intensity of <40.1 mm h^{-1} is ineffective for soils in mobile dunes because all rainfall is consumed by evaporation from the soil surface in the period without rainfall events. In contrast, when the rainfall was >13.4 mm, it could replenish soil water in deep soil after rainfall redistribution. This contrasts with previous research results from the Tengger Desert, in which rainfall of 6.4 mm with intensity of 0.7 mm h^{-1} was effective for soil water replenishment in a bare sand dune area (Berndtsson et al. 1996; Wang et al. 2008). This difference may be attributed primarily to the higher infiltration capacity and higher content of coarse sand in the sand dunes of the Tengger Desert.

In semi-arid regions, evaporation from bare soil constitutes a large fraction of the total soil water loss, and it can account for 40–70 % of annual precipitation (Gill and Jalota 1996; Wallace et al. 1999; Aydin et al. 2005). As potential evaporation is as high as 1,937 mm in this region, rainfall dominates the evaporation process (Berndtsson et al. 1996). Evaporation from the soil surface was very high immediately after individual rainfall events (White et al. 1997; Wang et al. 2004c). Our study showed that the percentage of evaporation and total rainfall significantly decreased with the increase in rainfall amount when the rainfall was >11.8 mm (Table 2). Meanwhile, rainfall amounts were not significantly correlated with the cumulative evaporation amounts. In addition, the maximum influencing depth of evaporation was 60 cm, and no significant differences were found at 70–110 cm depth between the soil water content and daily evaporation amount. The main reason for this may be that the smaller individual rainfall events (<13.4 mm) are more easily consumed by soil surface evaporation due to limited infiltration depth. However, for rainfall events >20 mm, evaporation amounts exhibit relatively small changes with increases in rainfall because soil water at the evaporation layer (above 60 cm) can reach field capacity for rainfall ≥20 mm. With evaporation lasting several days, soil water content at the evaporation layer maintains a similar level for different rainfall events; a dry sand layer gradually develops, resulting in a gradual decrease in soil evaporation. A drying effect can be formed at a depth of 2 cm after 2 h of continuous rainfall (Fohrer et al. 1999), and 80 % of soil water is lost through transpiration and first-stage evaporation before a quasi-steady state is reached (Liu et al. 1995). The dry sand layers become a limiting factor for soil water evaporation when their thickness is ≥5 cm in mobile dunes (Liu et al. 2006). Due to lack of a vegetation cover and a rapid formation of a dry sand layer in mobile dunes after rainfall, evapotranspiration is less than that in sand dunes with vegetation cover (Alamusa et al. 2005; Gong et al. 2012).

Conclusions

Small rainfall events are prone to evaporation from the soil surface, whereas large rainfall events can infiltrate into deep soil layers and even replenish ground water. Furthermore, infiltration depth increases with increases in rainfall amount, and higher rainfall intensity causes deeper infiltration under the same rainfall amount. Rainfall of 13.4 mm in our study was the critical event which separated the effective from ineffective rainfall in mobile dunes; thus, all rainfall events <13.4 mm will be more easily consumed by soil evaporation due to limited infiltration depth (<60 cm). Rainfall amount >50 mm produced saturated soil water conditions at 120 cm depth, then further infiltrated into deeper soil layers, and the replenishment amount was 21.13 mm accounting for 40.4 % of total rainfall. The daily evaporation amounts were significantly correlated with the soil water content at soil depths of 10–60 cm; in contrast, no significant correlations were found at depths of 70–110 cm. These results suggest that the maximum influencing layer of evaporation is the depth of 60 cm below ground surface in mobile dunes of the Horqin Sandy Land. At rainfall amounts $\geq$11.8 mm, soil surface evaporation exhibited a small change with the increase in rainfall. Meanwhile, rainfall amounts were not significantly correlated with the cumulative evaporation amounts. Our results support dune restoration efforts in the mobile dunes of the Horqin Sandy Land because they form the basis for estimating soil water replenishment and making informed decisions about planting time and depth of vegetation when planting native shrubs and herbs.

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