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# Deep soil water infiltration and its dynamic variation in the shifting sandy land of typical deserts in China

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Soil moisture is the key resource constraint in arid ecosystems, and has been a focus of research on restoration. However, quantitative studies on the contribution of rainfall to deep soil rainfall infiltration are lacking. In this study, we used the YWB-01 Deep Soil Infiltration Water Recorder which had been invented by ourselves to measure the quantity of rain infiltration into deep soil, 150 cm below ground, in four locations in China: Mu Us Sandy Land and Ulan Buh, Tengger, and Badan Jilin deserts over a 2-year period. We found: (1) Deep soil rainfall infiltration decreased progressively from east to west and from semiarid to arid areas, with two locations completely lacking rainfall infiltration. Heavy rain was important to deep soil infiltration in shifting sandy land of arid and semiarid areas. (2) Seasonal variation of infiltration was correlated with rainfall, with a time lag that was less apparent in areas with more rainfall. (3) For single intense rainfall events, infiltration maximums occurred 40–55 h after the rainfall, during which the infiltration rates increased rapidly before reaching a peak, and then decreased slowly. Continuous infiltration could last about 150 h. Rainfall infiltration was determined by the combined action of intensity, quantity and duration. Rainfall with low intensity, long duration, and large quantity was most favorable for deep soil infiltration. Our results can be used in water resource assessments and protection during eco-restoration in the arid and semiarid areas in China.

**deep soil water infiltration, dynamic variation, rainfall, shifting sandy land, arid and semiarid areas**

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Desertification is a serious eco-environmental problem faced globally. Moisture in the form of soil water is the most important limiting factor in the desert ecosystem as soil water is the material basis for plant survival, and restricts germination and growth. Soil water content and dynamics are decisive in the formation and reversal of desertification (Li, 2011; Zhu et al., 2012). In the desert where underground water is deep, soil water is mainly replenished by rainfall. He et al. (2008) showed that in Korqin shifting sandy land in semiarid areas, the humidity of soil 40–300 cm below the surface correlated with rainfall from the previous month. Zhao et al. (2002) found that interannual variation of underground water in sandy areas in the east, north and west of China was closely related to rainfall. A separate study in Mu Us Sandy Land revealed that rainfall greater than 15 mm could replenish underground water (Yuan 2002). As the key variable influencing water movement and equilibrium in sandy lands, deep-soil rainfall infiltration is an important factor to consider in the management of water resources (Lei et al., 1999).

Based on the effect of rainfall infiltration on vertical var-

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iation of soil water in sandy lands, Liu et al. (2006) classified soil into three layers: a superficial dry-sand layer (0–20 cm), a variable layer influenced by precipitation (20–140 cm), and a deep, stable layer (below 140 cm). Studies on rainfall infiltration and water content variation in the first two layers (Huang et al., 2004; Ye et al., 2005; Wei et. al, 2008; Liu J S et al., 2010) have revealed characteristics under different site conditions, such as landform, morphology and vegetation (Wang et al., 2003; Shi et al., 2007; Wang X P et al., 2008; Zhao et al., 2010) as well as the processes, dynamics and limiting factors (Han, et al., 1996; Wang et al., 1998; Liu et al., 2011). Seasonal variation in soil water was classified into the consumption, replenishment and stable stages (Chen et al., 2000). However, studies on the dynamic equilibrium of soil water and the rainfall infiltration process in the third layer are few (Yuan et al., 2002; He et al., 2008) and there have been few long-term systemic observations and comparative research of the deep soil rainfall infiltration process in all three layers (Zhao, 2009). Therefore, issues concerning the provenance and process of underground water replenishment in the desert lack comprehensive data. For example, water provenance of scattered lakes in the interior Badan Jilin Desert is still under debate. Liu (2010) stated that the water source of the lakes and underground water in the Badan Jilin Desert was mainly underground water replenishment from the middle and upper reaches of the Heihe River, as well as precipitation and snowmelt from the Qilian Mountains. Qian (2005) suggested that underground water in this area may also come from local precipitation and lateral water seepage from the eastern Badan Jilin Desert. In view of ecological degradation caused by soil desiccation and continuous water table decline in arid and semiarid areas of China, it is important to conduct systemic studies on deep soil water infiltration.

Instruments and methods for calculating rainfall infiltration include the ring sampler, double ring sampler, lysimeter, artificial rainfall plot, soil water flux, and the soil water tracer (Meng, 2006; Liu et al., 2006; Zhang, 2006; Zhou, 2007; Wang et al., 2010). The quantity of deep soil rainfall infiltration can also be estimated using mathematical models (Finch, 1998; Liu et al., 2002; Gogolev et al., 2002). However, there is a shortage of methodologies to directly monitor the quantity of infiltrated water. The soil water flux method can calculate this; however, detailed data on soil water potential and water content over a relatively large area are essential for its use. Such data are difficult to acquire and the effect of temperature on soil water movement is neglected in the calculation (Zhang, 2006). A lysimeter can directly measure infiltrated water, but is not feasible for large-scale use owing to its high cost (Wang, 2008). Likewise, the isotope tracer can only indirectly calculate the quantity of water replenishment (Yang, 1999) and cannot achieve accurate results at small temporal scales (Wang, 2008).

To overcome the shortcomings, the authors had invented the YWB-01 Deep Soil Infiltration Water Recorder which was authorized as a national patent (Yang et al., 2011). It can be used to measure the quantity of infiltration water (the water infiltrated into certain-deep soil under the gravitational force in unit time, being denoted with mm). This instrument is digital and can automatically collect the data and undergo consecutive observations. We used this instrument to conduct real-time monitoring of deep soil (150 cm below the surface) water infiltration in sandy land of arid and semiarid areas with variable precipitation. We quantitatively analyzed temporal and spatial variations and evaluated the provenance and dynamic equilibrium of underground water. Our results provide methodologies for elucidating water source and assessing the process of underground water replenishment, both of which are now under intense debate in scientific circles. Our results also provide a resource for evaluating water resources in desert ecosystem restoration.

## 1 Materials and methods

### 1.1 Study site

We selected three arid and one semiarid site in China: Wushen Banner (semiarid, in the hinterland of Mu Us Sandy Land), Dengkou (arid, at the southeast fringe of Ulan Buh Desert), Alxa Left Banner (arid, at the northern fringe of the Tenggeli Desert), and Alxa Right Banner (arid, at the southern fringe of Badan Jilin Desert). See Figure 1 for locations and Table 1 for characteristics. All sites have a continental climate. Annual precipitation decreases from east to west, with an average rainfall of 360.8 mm in Wushen Banner, 152.7 mm in Dengkou, 110.6 mm in Alxa Left Banner, and 72.4 mm in Alxa Left Banner.

### 1.2 Measurements

The YWB-01 deep soil infiltration water recorder was used for real-time monitoring, with a resolution of 0.2 mm and precision ±2%. Installation of the instrument is seen in Figure 2. After the observation plot was selected, a 267-cm-deep pit was dug (150 cm observation depth + 68 cm of the maximum height of capillary water + 49 cm high bucket for catching infiltrated water). Then, the upper mouth position (150 cm deep) was determined, and the pit was adjusted with a gradienter. The instrument was tested before being installed in the pit. Measurements were taken one month later, when the physical properties of the soil in the bucket were similar to the original state. Data were recorded at 30-min intervals from June 2010 to May 2012. In this paper, infiltrated water refers to rain water that reached 150-cm depth by gravitational force.

The EC-5 soil water sensor was used to monitor soil water content on a layer basis, above where the deep soil infiltration water recorder was installed, with a resolution ratio of ±0.06% and calibrated soil precision ±2%.

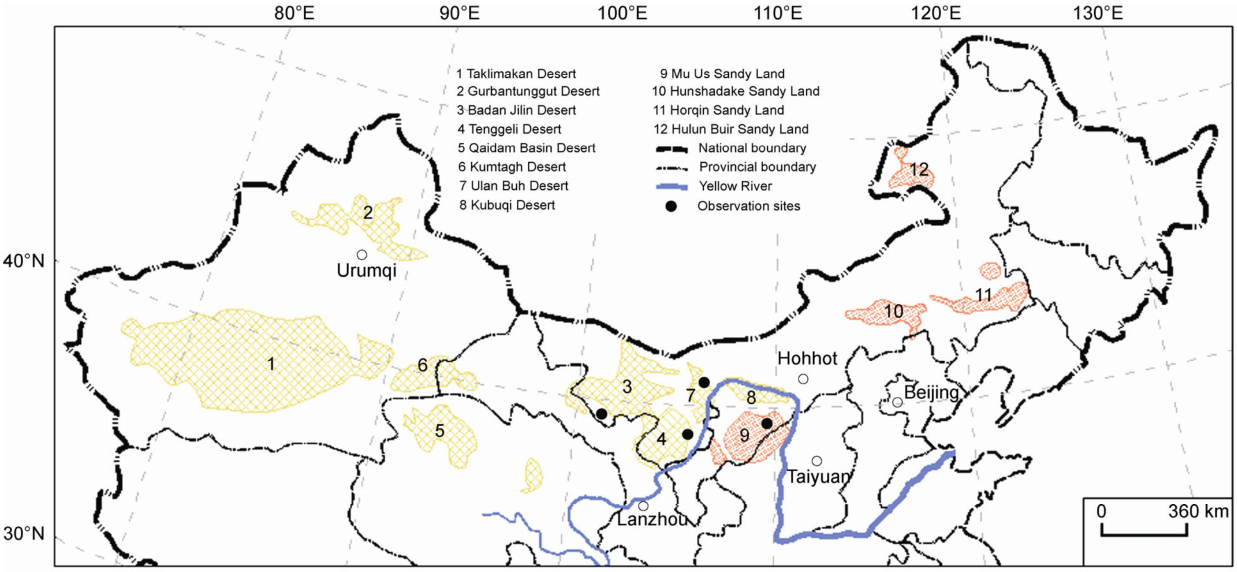


**Figure 1** Location of observation sites.

**Table 1** Actual conditions at the four study sites

| Observation sites | Wushen Banner | Dengkou | Alxa Left Banner | Alxa Right Banner |
|---|---|---|---|---|
| Location | 40°28′N, 106°46′E | 40°28′N, 106°46′E | 38°41′N, 105°35′E | 39°14′N, 101°40′E |
| Elevation (m) | 1306 | 1050 | 1386 | 1595 |
| Annual average temperature (°C) | 6.4 | 7.4 | 7.4 | 8.3 |
| Precipitation (mm) | 360.8 | 152.7 | 110.6 | 72.4 |
| Wet season | July–Sep. | June–Aug. | July–Sep. | July–Sep. |
| Annual average evaporation (mm) | 2592 | 2327 | 3100 | 4000 |
| Dryness | 1.4 | >4.0 | >4.0 | >4.0 |
| Geomorphology | Dominated by mobile sand dunes, 6–12 m in height | Dominated by mobile sand dunes, 2–5 m in height | Dominated by mobile sand dunes, 4–5 m in height | Dominated by mobile sand dunes, 6–8 m in height |
| Soil texture | Medium and fine aeolian soil, with sand particles 0.1–0.5 mm, bulk weight 2.63 g mm$^{-3}$, homogeneous. | Medium and fine aeolian soil, with sand particles 0.1–0.5 mm, bulk weight 2.71 g mm$^{-3}$, homogeneous. | Medium and fine aeolian soil, with sand particles 0.1–0.5 mm, bulk weight 2.68 g mm$^{-3}$, homogeneous. | Medium and fine aeolian soil, with sand particles 0.1–0.5 mm, bulk weight 2.67 g mm$^{-3}$, homogeneous. |
| Water table (m) | 5.4–6.1 | >7 | >8 | >10 |

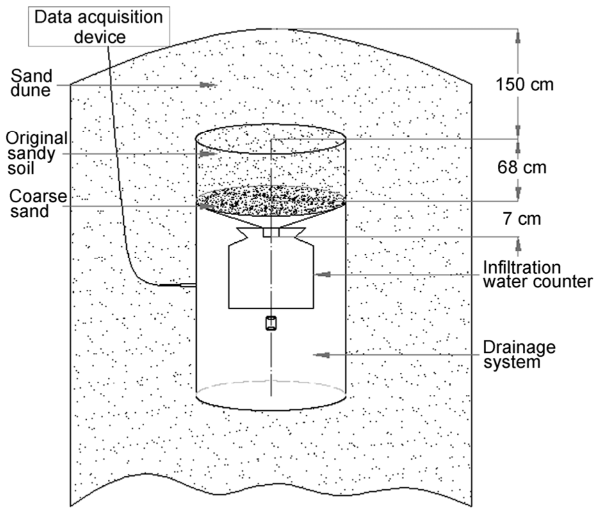


**Figure 2** Schematic diagram of the installation of YWB-01 Deep Soil Infiltration Water Recorder.

To measure rainfall quantity, we used the AV-3665R rainfall sensor (Avalon, USA) with a resolution ratio ±0.2 mm and precision ±2%. Times, duration, intensity and quantity of rainfall were recorded.

## 2 Results and analysis

### 2.1 Spatial distribution of deep soil water infiltration in sandy lands

Infiltrated water at the four study sites was correlated with spatial distribution, specifically precipitation, with a trend of decreasing infiltration from east to west and semiarid to arid. Deep soil water infiltration in the semiarid areas was substantial, whereas in the typical arid areas there was little to none. Data on the amount of rainfall and deep soil water infiltration at the four study sites are listed in Table 2.

Wushen Banner, a typical semiarid area, had the greatest

**Table 2** Rainfall and deep soil water infiltration at the four study sites during the observation period

| Sites | Observation period | Rainfall (mm) | Infiltration | | Remarks |
|---|---|---|---|---|---|
| | | | Total (mm) | Proportion of the concurrent rainfall (%) | |
| Wushen Banner | Oct. 6–Dec. 5 | 870 | 508.4 | 58.4 | Heavy rain July 1–2, 105 mm |
| | 2011 | 519 | 352.3 | 67.9 | |
| Dengkou | Oct. 6–Dec. 5 | 171.6 | 23.8 | 13.9 | Normal rainfall |
| | 2011 | 72.6 | 10.9 | 15.0 | |
| Alxa Left Banner | Oct. 6–Nov. 6 | 82.4 | 0.8 | 1.0 | Normal rainfall |
| Alxa Right Banner | Oct. 6–Nov. 12 | 33.8 | 0.0 | 0.0 | Normal rainfall |

deep soil rainfall infiltration, 508.4 mm in the total observation period and 352.3 mm in 2011, composing 58.4% and 67.9% of the total precipitation. Dengkou, at the transitional zone between semiarid and arid areas, had 23.8 mm during the observation period and 10.9 mm in 2011, representing 13.9% and 15.0% of the total precipitation. Alxa Left and Right Banners, both typical arid areas, had neither deep soil infiltration nor any intense rainfall events during the observation period.

## 2.2 Temporal distribution of deep soil water infiltration in sandy lands

Figures 3 and 4 show monthly variation of deep soil water infiltration from June 2010 to May 2012 in the sandy lands of Wushen Banner and Dengkou. In Wushen Banner, deep soil water infiltration occurred in all months except January and February, and was highest during July–September, with a peak in July. Infiltrated rainfall from July to September 2011 was 246.2 mm, with 119.8 mm in July, constituting 70% and 34% of infiltrated water at that year. In Dengkou, there was almost no water infiltration during November–February, and the main infiltration was in March–August/September. There was no record of infiltration during March–May 2012 because of instrument failure. The infiltration peak was not in the month of greatest rainfall, but in March, at 2.8 mm, which was due to the fast soil freeze-thaw process (Wang et al., 2006). The effects of rainfall on the seasonal variations of deep soil water infiltration in the two plots were consistent. There was little or no infiltration in winter, and infiltration ceased in January when the soil is frozen.

Because of the infiltration time lag, days with infiltration were 3–5 times more numerous than days of rainfall. Additionally, the daily quantity and days of infiltration varied strongly among the sites (Table 3). In Wushen Banner, there

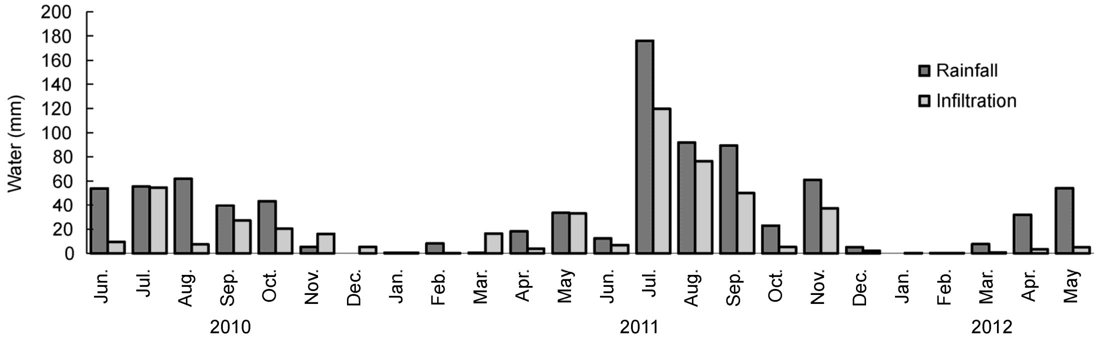


**Figure 3** Monthly variation of deep soil infiltration water from June 2010 to May 2012 in the shifting sandy land in Wushen Banner.

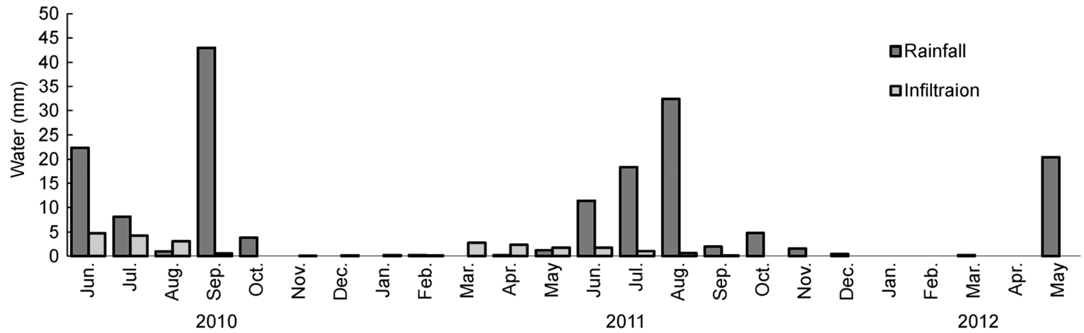


**Figure 4** Monthly variation of deep soil infiltration water from June 2010 to May 2012 in the shifting sandy land in Dengkou.

**Table 3** Days of rainfall and infiltration during observation period at the four study sites

| Sites | Total observation days | Precipitation | | | | | | Infiltration | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total days | Daily maximum precipitation (mm) | Days with different quantity of rainfall (d)/ accumulated rainfall (mm) | | | | Total days | Daily maximum infiltration (mm) | Days with different infiltration quantity (d)/ accumulated infiltration quantity (mm) | | | |
| | | | | ⩽5 mm | 5–15 mm | 15–25 mm | ⩾25 mm | | | ⩽1 mm | 1–5 mm | 5–10 mm | ⩾10 mm |
| Wushen Banner | 731 | 171 | 78.8 | 125/140.6 | 30/279.4 | 9/194.2 | 7/255.4 | 617 | 51.35 | 532/154.5 | 69/158.4 | 12/112.7 | 4/82.8 |
| Dengkou | 731 | 58 | 24.2 | 45/43.6 | 12/103.6 | 1/24.2 | 0/0 | 234 | 0.25 | 234/23.8 | 0/0 | 0/0 | 0/0 |
| Alxa Left Banner | 395 | 36 | 13.8 | 31/39.2 | 5/43.2 | 0/0 | 0/0 | 11 | 0.12 | 11/0.8 | 0/0 | 0/0 | 0/0 |
| Alxa Right Banner | 579 | 96 | 1.4 | 96/33.8 | 0/0 | 0/0 | 0/0 | 0 | 0.0 | 0/0 | 0/0 | 0/0 | 0/0 |

were 617 infiltration days, 304 of which were in 2011, representing 84.4% and 83.3% of the total days. In Dengkou, there were 234 infiltration days, 133 of which were in 2011, making up 32.1% and 36.4% of the total days. Both maximum daily infiltration and average infiltration rates in Wushen Banner were high, 51.35 mm $d^{-1}$ and 0.95 mm $d^{-1}$, ~200 times and 10 times the amount recorded in Dengkou. Daily infiltration in Dengkou was less than 1 mm, and there were 225 days in which infiltration was less than 0.2 mm, making up 96.2% of the total infiltration days and 90.8% of the total infiltration quantity. In Wushen Banner, daily infiltration was 0.06–51.35 mm and there were 532 days on which it was less than 1 mm, representing 86.2% of the total infiltration days and only 31% of the total infiltration quantity. There were 85 days on which daily infiltration exceeded 1 mm, making up only 16.4% of the total infiltration days and 69% of the total infiltration quantity. There were 81 days on which daily infiltration was 1–10 mm, constituting 53.3% of the total infiltration quantity, and there were only four days on which daily infiltration was greater than 10 mm. These figures demonstrate that heavy rain was critical to deep soil infiltration.

## 2.3 Effect of rainfall pattern on infiltration process and quantity

Rainfall is the main water source in sandy lands. Quantity, duration, intensity and temporal distribution are key influences on the quantity and process of deep soil water infiltration (Meng, 2006; Du et al., 2009; Liu et al., 2009; Liu et al., 2011). Our four study sites are in different climatic zones, and exhibit distinct spatial differences in rainfall pattern (Table 3). In the typical arid areas in Alxa Left Banner and Alxa Right Banner, rainfall is rare, normally less than 15 mm and mostly less than 5 mm. Sparse rainfall only infiltrates the superficial soil layer or is lost to evaporation, thus there was almost no infiltration into the deep soil 150 cm belowground. Dengkou is in the transitional zone between semiarid and arid areas and the quantity and intensity of rainfall is slightly higher; however, 77.6% of the rainfall was less than 5 mm. Maximum rainfall was 24.2 mm $d^{-1}$. This relatively heavy rain was effective for deep soil water infiltration; however heavy rain days were sparse. During the observation period, there was only 23.8 mm infiltrated water, accounting for 13.9% of total rainfall. Wushen Banner had more heavy rains, with nine rainfalls exceeding 15 mm and seven exceeding 25 mm, for a total rainfall contribution of 51.7%. Infiltrated water reached 508.4 mm, making up 58.4% of rainfall. Heavy precipitation can effectively replenish deep soil water through infiltration, whereas light precipitation can only saturate the uppermost layers of the soil (Li, 2011). We found a nonlinear relationship between rainfall and infiltration. For example, rainfall in Wushen Banner was seven times that in Dengkou in 2011, but infiltration was 35 times greater. Moreover, maximum rainfall in Wushen Banner was seven times that in Dengkou, while infiltration was 200 times greater (Table 3).

We performed a Pearsons correlation analysis of deep soil infiltration and rainfall in Wushen Banner and Dengkou during the observation period. It was found that monthly deep soil infiltration and monthly rainfall in Wushen Banner were significantly and positively correlated ($R^2$=0.782, $P$<0.01), whereas in Dengkou rainfall was not correlated with infiltration ($R^2$=0.024, $P$>0.05). In areas with plentiful rain, the effect of rainfall on deep soil infiltration was more strongly correlated and interannual dynamic variations of infiltration and rainfall were more similar. This suggests a minimum critical rainfall quantity for deep soil infiltration.

Figure 5(a)–(c) shows infiltration after three major rain events from July to September in Wushen Banner. There was no rain in the 10 days before these events, and there was only a small difference in soil water content before the rains (Table 4). Thus, these events may illustrate a typical pattern of infiltration in a semiarid sandy land. The rain event of September 20, 2010, with a quantity 24 mm and an intensity 8.0 mm $h^{-1}$, lasted 3 h. Infiltration rate increased 39 h after the rain and peaked after 54 h, at 0.21 mm $h^{-1}$. The average infiltration rate was 0.13 mm $h^{-1}$ and it gradually decreased after 54 h. Infiltration lasted 159 h and made up 64.2% of the total precipitation.

The rain on July 7, 2010, with quantity 31 mm and intensity 1.88 mm $h^{-1}$, lasted 16.5 h. The infiltration rate increased 33 h after the rain and reached a peak after 42 h, with maximum 0.43 mm $h^{-1}$. The average infiltration rate

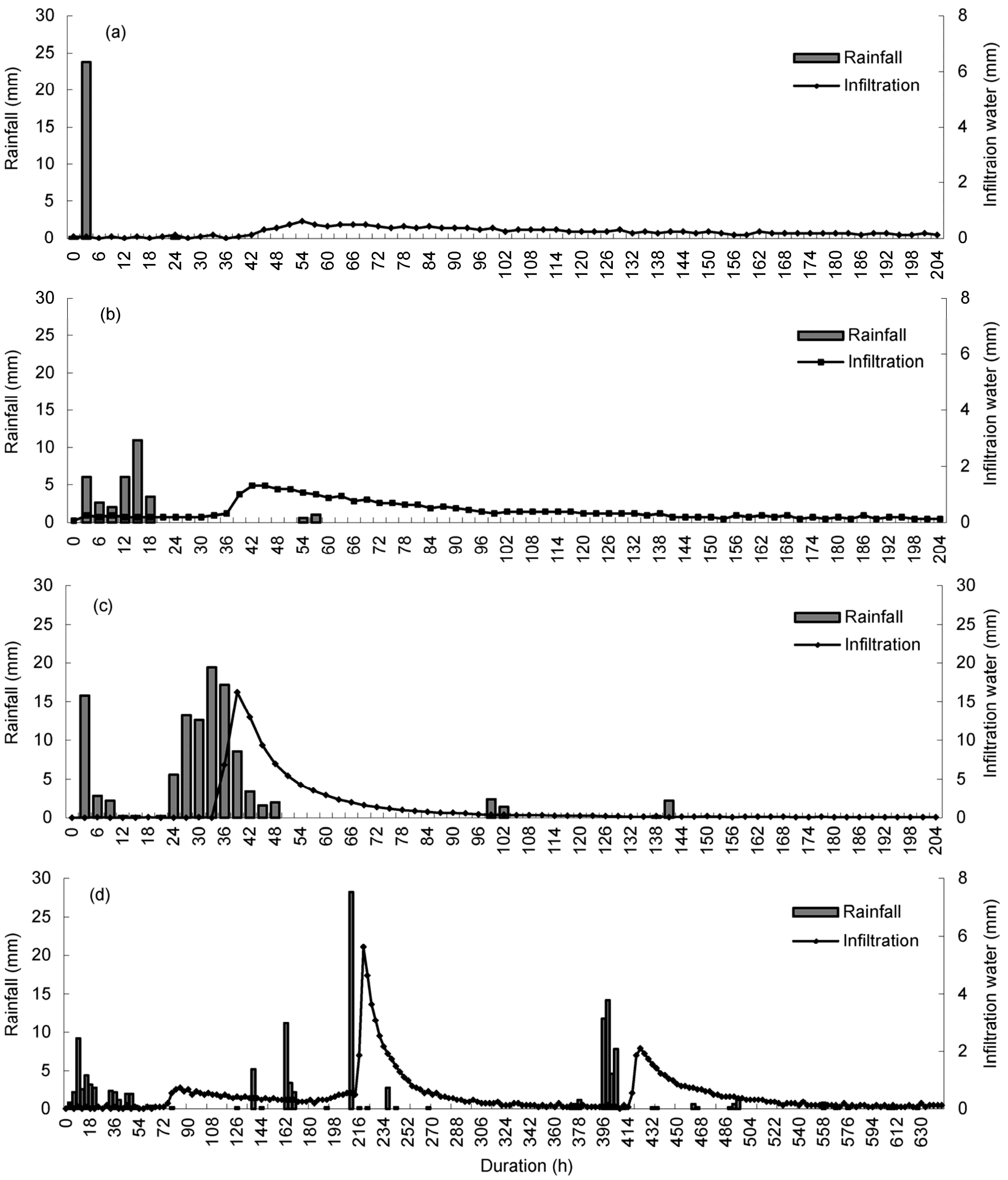


**Figure 5** Deep soil Infiltration process under different rain events in shifting sandy land in Wushen Banner. (a) The infiltration process of 24 mm rain event on Sep. 20, 2010, with rainfall intensity 8.0 mm $h^{-1}$ and duration 3 h. (b) The infiltration process of 31 mm rain event on July 7, 2010, with rainfall intensity 1.88 mm $h^{-1}$ and duration 16.5 h. (c) The infiltration process of 105 mm rain event on July 1 to 2, 2011, with rainfall intensity 2.26 mm $h^{-1}$ and duration 46.5 h. (d) The infiltration process of several rain events from Aug. 17 to Sep. 3, 2011.

**Table 4** Soil water content (%) before rains in Wushen Banner

| Date | Soil water content (%) at different soil depths | | | | |
|---|---|---|---|---|---|
| | 40 cm | 80 cm | 120 cm | 160 cm | Average soil water content |
| July 6, 2010 | 9.5 | 10.3 | 11.7 | 7.2 | 9.7 |
| Sept. 19, 2010 | 10.9 | 9.9 | 10.8 | 7.0 | 9.7 |
| June 30, 2011 | 9.9 | 10.7 | 11.5 | 8.0 | 10.0 |
| Aug. 16, 2011 | 5.0 | 10.5 | 9.8 | 8.0 | 8.3 |
| Aug. 24, 2011 | 16.7 | 8.2 | 7.0 | 5.3 | 9.3 |
| Sept. 2, 2011 | 11.5 | 9.7 | 9.7 | 7.4 | 9.6 |
| Sept. 3,2011 | 16.6 | 10.2 | 9.7 | 7.2 | 10.9 |
| Sept. 8, 2011 | 10.9 | 14.4 | 14.3 | 11.8 | 12.9 |

was 0.29 mm h$^{-1}$ and it gradually declined after 45 h. Infiltration lasted 138 h and made up 75.8% of the total precipitation. The rain on July 1–2, 2011, with quantity 105 mm and intensity 2.26 mm h$^{-1}$, lasted 46.5 h. The infiltration rate increased 33 h after the rainfall and maximized after 39 h, at 5.41 mm h$^{-1}$. Average infiltration rate was 3.85 mm h$^{-1}$ and gradually decreased after 39 h. The infiltration lasted 150 h and made up 82.6% of the total precipitation. These three events indicate that rainfall quantity is the key influence on deep soil infiltration. Heavier rains produced higher deep soil infiltration rates, greater infiltration amounts, and a higher proportion of infiltration to total rainfall. However, the relationship is nonlinear. The infiltration coefficient increased much more slowly than rainfall quantity, suggesting the existence of a maximum critical value for infiltration coefficient. The infiltration is under the combined force of rainfall quantity, intensity and duration. During the consecutive rainfall infiltration, the infiltration rate reduced with the increase of soil water content. When the rainfall intensity was less than the infiltration rate, the infiltration increased with the intensified rainfall, and *vice versa*. When the rainfall intensity approximated to the infiltration rate, the infiltration reached the optimum. When the rainfall was concentrated and the rainfall intensity was high, the runoff took into form easily as the infiltration rate was far less than rainfall intensity. Although the rainfall quantity was high, the infiltration rate was unexpectedly low, which showed the rainstorm with high intensity and short duration was not favorable for rainfall infiltration. As a result, the rainfall with low intensity, longer duration and intensified individual rainfall was more favorable for deep-soil infiltration. This is consistent with Yuan et al. (2010).

Figure 5(d) shows the dynamic process of deep soil infiltration caused by several high intensity rain events over a short period. From August 17 to September 3, 2011, there were four heavy rains and several lighter rains, with rainfall quantity totaling 136.4 mm. The rain on August 17 totaled 24.8 mm. The infiltration rate peaked (0.25 mm h$^{-1}$) after 84 h because the soil water content was low, an average of 8.3% before the rain (Table 4). Infiltration made up 65.4% of the total precipitation. Two consecutive rains, on August 23 and 25, totaled 14.6 mm and 28.2 mm. The first rain lacked a distinct infiltration peak (Table 4) and the second peaked after 9 h. The percentage of total rainfall that made up deep soil infiltration during the two rains combined was 94.4%. The September 2–3 rain was heavy, totaling 38.4 mm. The infiltration rate peaked (0.7 mm h$^{-1}$) after 30 h and the total amount made up 84.3% of the total rainfall. This suggests that deep soil infiltration was facilitated by consecutive rains.

### 2.4 Effect of freeze-thaw on deep soil infiltration

The seasonal freeze-thaw process contributes to the dynamic variation in deep soil infiltration in sandy land of arid and semiarid areas (Wang et al., 2006). Wushen Banner and Dengkou shared a similar pattern of seasonal variation (Figures 6 and 7). In late October, the sandy land began to freeze and deep-soil water infiltration decreased with the deepening of frozen soil. In January, the frozen depth was near its maximum in Wushen Banner and Dengkou at 91 cm and 87.6 cm, and infiltration almost ceased. The frozen soil began thawing by the end of February and was 20 cm deep around March 13. Stagnant water in the frozen layer began to infiltrate to 150 cm, and infiltrated water increased with the thaw. The thaw layer reached 30 cm depth around March 19, when infiltration peaked (3.95 mm d$^{-1}$ in Wushen Banner and 0.25 mm d$^{-1}$ in Dengkou). Infiltration declined sharply after 2–4 days. The frozen soil thawed completely by the end of March, and infiltration became slight again (Figure 8). Under the freeze-thaw action, there was a small peak of deep soil water infiltration in mid-March. In April, there was scarce rainfall and minimal deep soil infiltration.

## 3 Discussion and conclusion

Deep soil water infiltration varied in response to rainfall characteristics and was correlated with spatial variation at

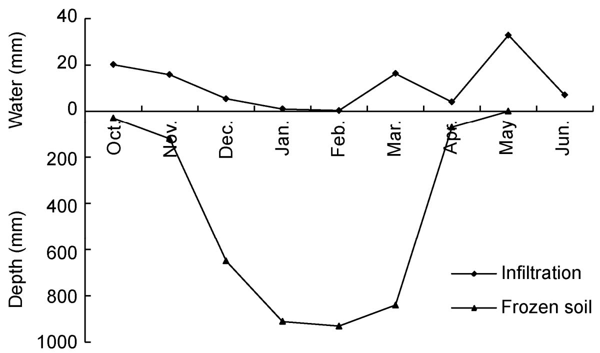


**Figure 6** Effect of freeze-thaw process on the deep soil infiltration in shifting sandy land in Wushen Banner.

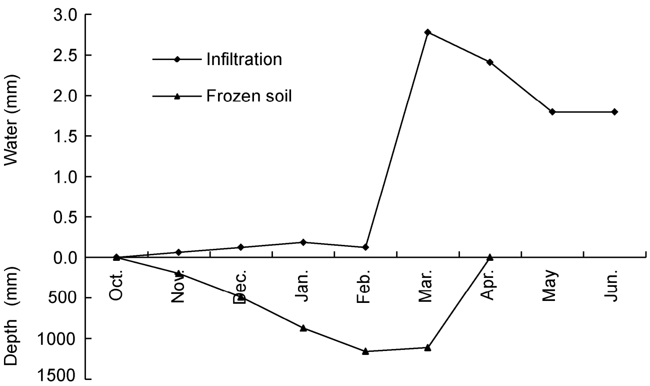


**Figure 7** Effect of freeze-thaw process on the deep soil infiltration in shifting sandy land in Dengkou.

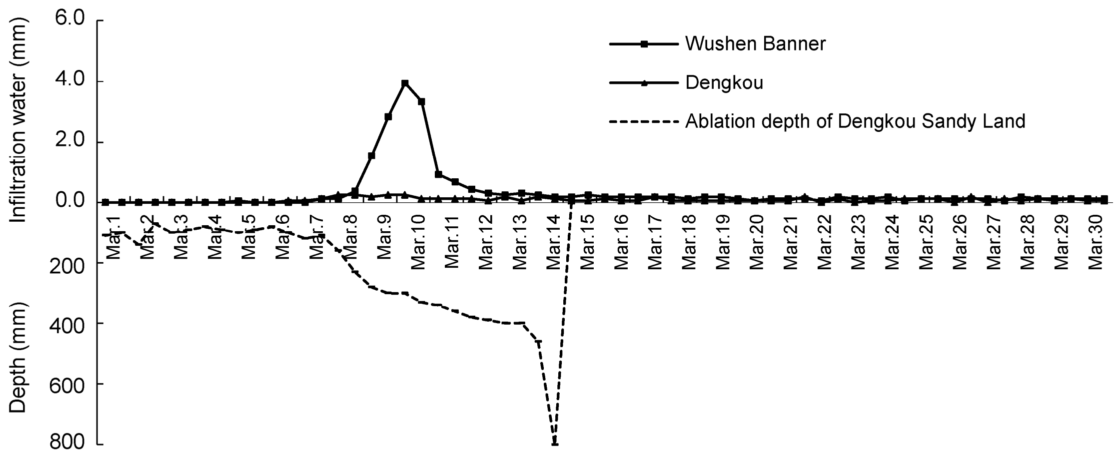


**Figure 8** Effect of thaw process on the deep soil infiltration in shifting sandy land in Wushen Banner and Dengkou.

our four sites. There was more rain in typical semiarid areas, where deep soil water infiltration commenced when rainfall exceeded 15 mm, and infiltration made up nearly 60% of concurrent rainfall. In the transitional zone between arid and semiarid areas, water infiltration was slight, representing less than 14% of total rainfall. Rain was rare in typical arid areas and could only replenish the topmost soil layers, with almost no deep soil water infiltration. Our results support previous studies that rainstorms are the most important water source in Northwest China (Li, 2003). Between 1960 and 2012, Alxa Left Banner and Alxa Right Banner only had 39 and 20 rainfall events that exceeded 25 mm (China Meteorology Data Sharing Network). Studies on deep-soil infiltration caused by heavy rains contribute to the dialogue on water provenance in arid regions and may inform important eco-restoration or water-management decisions. For example, underground water downstream of Ejina Basin comes from several sources, including replenishment from the Heihe River, local rainfall and lateral seepage of underground water from the Badan Jilin Desert to the east (Qian et al., 2005). Water in lakes in the southeast and underground water at the southern fringe of that desert mainly come from local rains during the rainy season and from infiltrated water in low mountains on the southern fringe (Ma et al., 2008). However, rainfall is the main source of water, and rainfall infiltration is the only source of deep soil water in deserts and sandy land in China. Interannual variation of infiltration is consistent with the seasonal variation of rainfall, with a slight lag. Areas with plentiful rainfall had similar interannual variation and rainfall trends. The seasonal dynamics of deep soil infiltration reveals that there are two steps to deep soil water infiltration: storage and conduction. When rain infiltrates the soil, part is stored, and the surplus infiltrates further, forming a moist peak. In April and May or during periods of drought, the soil is relatively dry and soil water content is low. A rainfall event during these times leads to a large portion of rain being stored but if the rain event is too brief, only a small amount of water will infiltrate into the deeper soil layer.

In the rainy season when soil water content is high, rainfall is the key factor leading to dynamic variation in infiltration. Replenishment causes fluctuation of infiltration rate whereby if the quantity of an individual rainfall event is high, the infiltration peak appears a short time after the rain. The combined action of low intensity, long duration and large quantity rainfall is most favorable to deep soil infiltration in sandy lands. The seasonal freeze-thaw process has a direct effect on the seasonal variation of deep soil water infiltration in the shifting sandy lands of arid and semiarid areas. During the frozen soil period of November–February, deep soil water infiltration declined with deepening of the frozen layer, and ceased in December and January. There was also a small infiltration peak in March indicative of thawing, which was higher than the peak in April.

In this study we conducted real-time monitoring of deep soil water infiltration, and offered a method for accurate evaluation of the effect of rainfall. Because infiltration is a complex process influenced by various factors, we suggest that more effort be made toward long-term monitoring and systemic research.

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