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Deep soil water recharge response to precipitation in Mu Us Sandy Land of China

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Abstract

Soil water is the main form of water in desert areas, and its primary source is precipitation, which has a vital impact on the changes in soil moisture and plays an important role in deep soil water recharge (DSWR) in sandy areas. This study investigated the soil water response of mobile sand dunes to precipitation in a semi-arid sandy area of China. Precipitation and soil moisture sensors were used to simultaneously monitor the precipitation and the soil water content (SWC) dynamics of the upper 200-cm soil layer of mobile sand dunes located at the northeastern edge of the Mu Us Sandy Land of China in 2013. The data were used to analyze the characteristics of SWC, infiltration, and eventually DSWR. The results show that the accumulated precipitation (494 mm) from April 1 to November 1 of 2013 significantly influenced SWC at soil depths of 0−200 cm. When SWC in the upper 200-cm soil layer was relatively low (6.49%), the wetting front associated with 53.8 mm of accumulated precipitation could reach the 200-cm deep soil layer. When the SWC of the upper 200-cm soil layer was relatively high (10.22%), the wetting front associated with the 24.2 mm of accumulated precipitation could reach the upper 200-cm deep soil layer. Of the accumulated 494-mm precipitation in 2013, 103.2 mm of precipitation eventually became DSWR, accounting for 20.9% of the precipitation of that year. The annual soil moisture increase was 54.26 mm in 2013. Accurate calculation of DSWR will have important theoretical and practical significance for desert water resources assessment and ecological construction.

Keywords: Mu Us Sandy Land; Sandy land; DSWR; Precipitation; Wetting front

1. Introduction

In semi-arid sandy lands, water is a scarce resource and a key factor restricting the vegetation growth (Rodríguez-Iturbe and Porporato, 2005). In semi-arid areas with low amounts of precipitation, high evaporation, and low sandy soil water content (SWC), soil moisture becomes a primary factor influencing vegetation growth and composition (Laio et al., 2001), and it determines the occurrence or reversal of land desertification (Imeson, 2012). As precipitation is the main source of recharge to soil moisture in semi-arid sandy areas (Pye and Tsoar, 1987), understanding the relations between precipitation and soil moisture in those areas is significant to the efficient use of limited water resources, as well as land desertification prevention and control.

Scientists have conducted a large amount of research on the relations between precipitation and soil moisture in sandy land ecological systems (Qiu et al., 2001; Wang et al., 2006). The case study of the Horqin Sandy Land of China shows that soil moisture of mobile dunes at depths of 40−300 cm is closely associated with the amount of precipitation that occurred in

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previous months (Katoh et al., 1998; Li et al., 2009). A precipitation amount of about 4 mm can affect soil moisture as deep as 20 cm (Liu et al., 2006), and subsequent moisture transport can also affect the change of soil moisture at depths of 20−60 cm. However, even in a wet year with a precipitation amount of 450 mm, the potential recharge of the precipitation to groundwater is extremely weak. Laboratory experimental results from sandboxes (Liu et al., 2006) showed that soil moisture at depths of 20−140 cm was highly variable under the influence of precipitation. The soil moisture distribution at depths greater than 140 cm was relatively stable. Specifically, when the depth was greater than 200 cm, evaporation completely ceased, and the precipitation-induced infiltration eventually recharged the groundwater system. A precipitation amount of 13.4 mm in one event was the threshold for generating measurable deep soil water recharge (DSWR) below 140 cm. The field experiment conducted at the Mu Us Sandy Land showed that an event with a precipitation amount of larger than 15 mm generates noticeable DSWR (Yang et al., 2014). This 15-mm precipitation threshold in the field was only slightly greater than the 13.4-mm precipitation threshold in the laboratory study for DSWR generation. There have already been many studies on the influence of precipitation on soil moisture in sandy areas (Li et al., 2004). For instance, a study on mobile dunes showed that soil moisture at a depth of 100 cm or a depth of 140 cm was not affected by evaporation (Zhang et al., 2008). Some studies have suggested that the precipitation threshold in a single event that can penetrate a 200-cm soil layer (thus making direct contribution to DSWR) is 15 mm (Ayalon et al., 1998). Some other studies have indicated that the precipitation threshold in a single event that can penetrate a 30-cm soil layer (but cannot penetrate a 200-cm depth) is 8 mm or 13.4 mm (Dekker and Ritsema, 1994). These findings are debatable (Pan and Mahrt, 1987), and they did not address the issue of how the SWC in the pre-precipitation period can affect the infiltration process in the soil (Jin et al., 2009).

However, there is a lack of in situ observations on deeper soil moisture dynamics and recharge effects in arid and semi-arid regions. The existing studies often report different and sometimes contradictory conclusions on the wetting front of mobile dunes, with the wetting front defined as the lowest position at which SWC is greater than the field capacity (Cassel and Nielsen, 1986). It is also unclear how much precipitation can recharge deeper soil water.

The objective of this study was to use in situ experiments to investigate deep infiltration processes or DSWR in the Mu Us Sandy Land of China. This study tried to answer the following questions:

(1) What is the soil moisture distribution in different soil layers under different precipitation events in sandy land?

(2) With different SWCs during the pre-precipitation period, how long will it take for precipitation to infiltrate into a soil layer at a depth of 200 cm?

(3) How can precipitation-induced recharge to the groundwater system be evaluated and what percentage of precipitation can eventually become DSWR?

2. Materials and methods

2.1. Overview of study area

The study area is located on the northeastern edge of the Mu Us Sandy Land of China. This area is part of Chagan Nur Gacha (39°5′N, 109°36′E), Ejin Horo Banner, in the Inner Mongolia Autonomous Region of China. The location of Ejin Horo Banner is 38°56′N to 39°49′N, and 108°58′E to 110°25′E. It is in the southeastern part of Ordos City, with an elevation between 1070 m and 1556 m above mean sea level (MSL), and a water table usually 5 m below the sandy land surface (Zhang et al., 2012). The area has a typically temperate continental monsoon climate, with a wind speed of 3.6 m/s, 2900 h of sunlight (Xu et al., 2015), a relative humidity of 52%, precipitation of 358.2 mm, and potential evaporation of 2563 mm, which is about 7.2 times the precipitation amount, all measured in annual averages. The annual average temperature is 6.2°C, and the frost-free period lasts for 127−136 d. Soil types in this area include dark loess soil, loess soil, chestnut soil, and aeolian soil.

The Ordos Basin is a large groundwater basin, which can be divided into an open shallow groundwater circulation system and a closed deep groundwater system. The shallow groundwater circulation system includes a strong groundwater exchange belt, a half-open runoff belt, and a weak runoff belt. The Cenozoic loose rock pore aquifer system and the upper portion of the Carboniferous-Jurassic clastic rock fissure aquifer system have a circulation depth of about 300 m. The Cambrian-Ordovician carbonate karst aquifer system has a maximum circulation depth of 1800 m. The Cretaceous clastic rock fracture aquifer system can reach up to 1200 m. The closed deep groundwater system mainly refers to the stagnation of groundwater, including the Cambrian-Ordovician carbonate rock karst aquifer system and the lower portion of the Carboniferous-Jurassic clastic rock aquifer system. The boundary between the shallow groundwater circulation system and the deep groundwater system in the Ordos Basin is basically the boundary between fresh water (including brackish water) and salt water. Precipitation is the main recharge source of groundwater in the Ordos Basin. There is a hydraulic relationship between the shallow and deep aquifer systems. Interaction of surface water and shallow groundwater occurs in various locations. In the Ordos Basin, precipitation and condensation water are the only two sources of recharge to deep soil water in this region. Groundwater can only discharge through evaporation and/or baseflow to surface water. Within the Ordos Basin, groundwater generally flows from the inner basin area to the boundary of the basin, where the Yellow River and its tributaries serve as the discharge channel of the groundwater.

2.2. Experimental design

On September 1, 2012, a mobile sand dune within the study area was chosen as the monitoring plot, located at 39°5′16″N,