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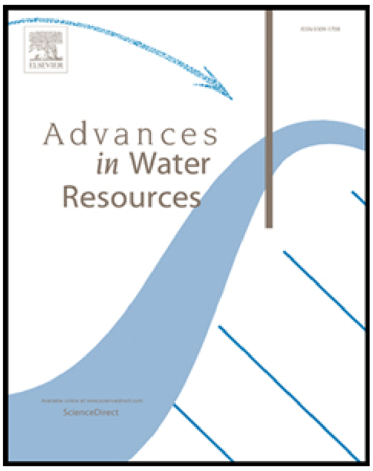

Flow Dynamics in Vadose Zones with and without Vegetation in an Arid Region

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Highlights

- ¶ Vegetation impacts on the flow dynamics 3 m deep in the vadose zone.
- ¶ Pressure head profiles in the vadose zone reflect heterogeneity distribution in the vadose zone.
- ¶ The atmospheric, water table boundary conditions and root systems of plants control the dynamics.

Flow Dynamics in Vadose Zones with and without Vegetation in an Arid Region

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ABSTRACT

Flow dynamics in a thick vadose zone in an arid region, China was investigated using a field experiment at plots with bare soils and vegetated soils. Detailed pressure head profile along a depth of 8 meters, groundwater level, soil moisture content at surface, air temperature, and precipitation were observed over one yearôs time span. The temporal and spatial variations of pressure heads and hydraulic gradients over the time span elucidate the role of air temperature, precipitation, and soil stratification, the growth of vegetation, on the flow dynamics in the vadose zone. The dynamics includes freezing and thawing of surface soils, infiltration, evapotranspiration, distribution of moisture, and groundwater recharge. Estimated hydraulic gradients based on the observed pressure heads suggest that vegetation affected flow dynamics even at 3 m below land surface during its growth seasons. The pressure head distributions at the vadose zone over the time span were found correlated well with soil stratification or heterogeneity. Afterward, we estimated the land-atmosphere interface flux, water uptake rate by the plants, and we then discussed the relationship between seasonal variation of temperature, precipitation, evaporation, plant growth, soil stratification (heterogeneity) and the flow dynamics in the vadose zone of the region.

Keywords: flow dynamics, temperature, evapotranspiration, root uptake, heterogeneity**.**

1. INTRODUCTION

Flow dynamics of the vadose zone plays an important role in groundwater recharge and ecosystems in arid and semi-arid regions (Chen et al., 2011; Wang et al., 2012, 2013, 2014, 2016), in particular, under dramatic changes in global climates. Besides, it controls migration of contaminants from the land surface to the groundwater reservoirs (Sposito et al., 1982; Goldberg and Sposito, 1984; Bourg et al., 2008; Sposito, 1998). The flow processes in the vadose zone are more complicated than those in the saturated zone are, since they involve many complex physical and dynamic processes (Sposito et al., 1977; Sposito, 1978a, 1978b, 1980, 1986; Glass et al., 1995; Bodvarsson et al., 2003; Amenu and Kumar, 2008). For example, the moisture in the vadose zone increases the plantȏs chances for survival and productivity. At the same time, the plant roots control distribution of moisture (evapotranspiration or infiltration) in the vadose zone (Sandvig and Philips, 2010; Schilling et al., 2014).

Our understanding of unsaturated flow in vadose zone are still evolving, in particular, in arid and semi-arid regions, from bare land to vegetated land, from homogenous vadose zones to stratified zones, and effects of ecological processes and groundwater (Romano et al., 1998; Scanlon et al., 2002; Skaggs et al., 2006; Twarakavi et al., 2008). Over the past few decades, numerical experiments are generally popular approaches for evaluating unsaturated flow processes and assessing sensitivity of model output to various parameters. These studies include works by, (for example, Yeh et al., 1985a, b, and c; Celia et al., 1990; Srivastava and Yeh,1992; Yeh et al., 1993; Harter and Yeh, 1996; Li and Yeh, 1998 and 1999; Yeh et al., 1993; Khaleel et al., 2002; Yeh and Simunek, 2002; Zhang et al., 2015, 2016a and 2016b). They are undoubtedly a cost-effective approach to understand the mechanism of unsaturated flow in the vadose zone. Nevertheless, numerical experiments are built upon our conceptual models of unsaturated flow and ecological processes, which may not be necessarily representative of the processes in nature.

On the other hand, some laboratory and field experiments have been conducted to gain some knowledge of the moisture, pressure head and water uptake rate by the roots (Feddeset al., 1974; Nieber et al., 1981; Kung, 1990; Rezzoug et al., 2005; Gvirtzman et al.,2008; Wang et al., 2011; Zhang et al., 2016). Complexity of the nature processes, cost of equipment and operation, along with operational difficulty, however, often restrict most field experiments to shallow depths or root zones (Kung, 1990). Very few experiments have investigated the entire profile from the ground to water table in vadose zones with 9-10 meters thick in arid and semi-arid regions. The most notable large-scale vadose zone experiments were those by Ward et al. (2000) and Gee and Ward (2001) and the results were fully analyzed by Ye et al (2005) and Yeh et al. (2005). However, these experiments aimed at investigation of effects of heterogeneity on migration of nuclear waste to groundwater reservoirs without considering interaction between surface processes (rainfall infiltration, temperature, evaporation, and plants) and groundwater. The role of large-scale geologic stratifications on the interaction between these surface processes and groundwater fluctuations has seldom explored. Understanding of flow dynamics in the vadose zone in the semi-arid regions therefore is limited. Many current knowledge has mainly been built upon our understanding of the flow mechanism in the root zone (Kung, 1990), and there is an urgent need to explore the processes at large-scale vadose zone.

Exploring flow dynamics in a thick vadose zone using observed data at plots with and without vegetation in an arid interior basin in China is the objective of this paper. Specifically, with observed pressure and hydraulic heads along profiles of 8 m deep over a yearȏs time span, we elucidate the relationship between flow dynamics and air temperature, rainfall, evapotranspiration, roots uptake, and groundwater change as well as soil heterogeneity (stratifications).

2. FIELD EXPERIMENTS

2.1. Description of the Study Area

The field experiments for this study were conducted in the deep, unsaturated stratified sediments of fine-soil in the Zhungger basin of Xinjiang Uygur Autonomous Region of China, from November 2004 to November 2005. The basin is located in the northern Tianshan Mountains, the southern part of Zhungger Basin, which is bounded by the Ganhezi River to the east, the Guertu River to the west, the Tianshan Mountains to the south, and the Gurbantunggut desert edge to the north. There are 14 inland rivers in the basin including the Urumqi River, Hutubi River, Manas River, Kuitun River, etc., which are derived from meteoric water and glacier water in the mountains, flowing northward and draining into the lakes or disappearing in the deserts. The area gently slopes from southeast to northwest with an average elevation of 450 m above the sea level, striding across multiple geomorphic types: mountains, alluvial-proluvial fan, alluvial plain, lakes and deserts. Because of the similar depositional environment, each river and the beneath groundwater system are featured by a similar hydrogeological structure from south to north. Along this direction the aquifer laminarity and layers become thinner and the groundwater depth varies from deep to shallow and finally to deep when close to the northern boundary (Qiao et al., 2005).

This study area is a major agricultural field in this region, where arid climate prevails. The major water source for plants and crops comes from river, groundwater, and rainfall. A large part of this water is transpired through the plants and crops or is evaporated from the soil. The rest percolates through the root zone and vadose zone, and ultimately recharges the groundwater. While processes of flow in the vadose zone are influenced by hydraulic properties of the vadose zone, the types of plants and crops, and the meteorological conditions of the land-atmosphere interface, their interaction with temporal and spatial flow dynamics and heterogeneity in the vadose zone have rarely been investigated. As an arid inland climate region, the annual precipitation and evaporation of the study area from 1956 to 2006 on the average are 190 mm and 2131mm, respectively. Rainfall is generally restricted to April to September, and most rainfall events occur as thunderstorms of limited areal extent with relatively short duration. Daily precipitation amounts of 2 to 10 mm are common. The rainfall from April to September accounts for 90% of the annual total. Evaporation occurs mainly from April to October, constituting more than 95% of the annual total evaporation. Average monthly temperature ranges from a minimum of -26.5Ṇ in January to the maximum of 27.3ɜ in July. Daily average minimum and maximum temperatures for summer and winter vary between 15 to 42 ɜ and -25 to 8ɜ. From November to May is the period when the upper vadose zone is in the frozen state to about 1m depth. April to October is a period for thawing.

Fig.1 shows the variation of 15-day averaged precipitation, surface evaporation, and air temperature during the period from December 2004 to November 2005, observed at the Kuitonghe weather station, located near the experimental site. The air temperature was below 0.ɜ from December to mid-March and it warmed up from mid-March to July. The average temperature reached a maximum in July of about 28.8ɜ. After July, temperatures decreased from 28.8ɜ to 5ɜ in November. The rainfall during the experiment period was restricted to early March, early April, late June and late October. Over 94% of the total evaporation occurred from April to October, correlated well with air temperature.

The sediments of the vadose zone in the area includes a sequence of alternating fine sand, sandy gravel, sandy-clay loam and clay loam. These layers are highly variable in thickness and lateral extent. The depth of water table ranges from 0 to 20m in the region.

2.2. Field experiment setup

A 3m ¦ 3m square pit of 6m deep was excavated. In order to explore the different influences of vegetation on the flow dynamics of the vadose zone and water table, the ground surface of one side of the pit was planted with small frutex (shrub) and the ground on the other side was kept as bare soil. Fig. 2 illustrates the sediment profile in the pit, which includes four major layers: loam, clay, and gravelly sand, clay, and fine sand. Soil samples of each layer were collected for laboratory measurements of moisture content-pressure relationships (using pressure plate devices), saturated hydraulic conductivity (using constant head permeameters), and particle size analysis (using sieves), as described in Klute (1986). The relationships were fitted to Mualem (1976) and van Genuchten (1980) model to derive the parameters and they are listed in Table 1.

A borehole was drilled at the bottom of the pit to 9m below the land surface for monitoring groundwater levels. Tensiometers for measuring the soil water pressure in the vadose zone were installed along the two sidewalls of the pit. One sidewall was below the ground with vegetation and the other sidewall was below the ground without vegetation. Nine tensiometers were installed along each sidewall at different depths (see Fig. 2), and they were inserted 1.2 m into the sidewall along the center of the wall. All tensiometers were connected to a data logger. To minimize the exchange of water in the vadose zone with that in air within the pit, all four sidewalls of the pit were sealed with plastic sheets. The soil moisture content on the ground was measured, using core samples taken from the soil nearby the plot to determine its gravimetric water content in the laboratory (Klute, 1986). Readings from the tensiometers, water table level and soil moisture content on the ground with and without vegetation were taken at 5 daysô intervals over the one-year experimental period. The depth of frozen ground was observed from the sides of the pit during winter periods. In the event of rain, all measurements were collected continuously for following 5 days. At the same time, meteorological data were acquired from a nearby weather station (about 3 kilometers from the field plot).

3. ANALYSIS AND DISCUSSION

This section presents experimental observations of soil water pressures and hydraulic heads in the vadose zone of experimental plots with and without vegetation.

3.1. The variation of soil moisture content on the ground at the experiment site during the experimental period

The variations of soil moisture content and air temperature near the ground surface from November 2004 to October 2005 at the experimental site for the bare and vegetated areas are shown in Fig.4. It indicates that the surface soil moisture content varied between 0 and 30% within the experiment period. Surface soil moistures at bare soil and vegetated soil were at about 18.2% in November 2004 and decreased slightly in mid-February, 2005 and reached the maximum about 28% in May, and then decreased sharply till early July. Afterward, it decreased slowly till mid-September and then increased till November, 2005. From mid-April to 15 September, the soil moisture content fluctuated downward 4.8%-20%. After September 15th, the soil moisture content increased again.

The soil moisture content on the ground in the bare ground was slightly higher than in the vegetated ground from December 2004 to late May, 2005. The soil moisture content on the ground in the bare ground then became slightly lower than in

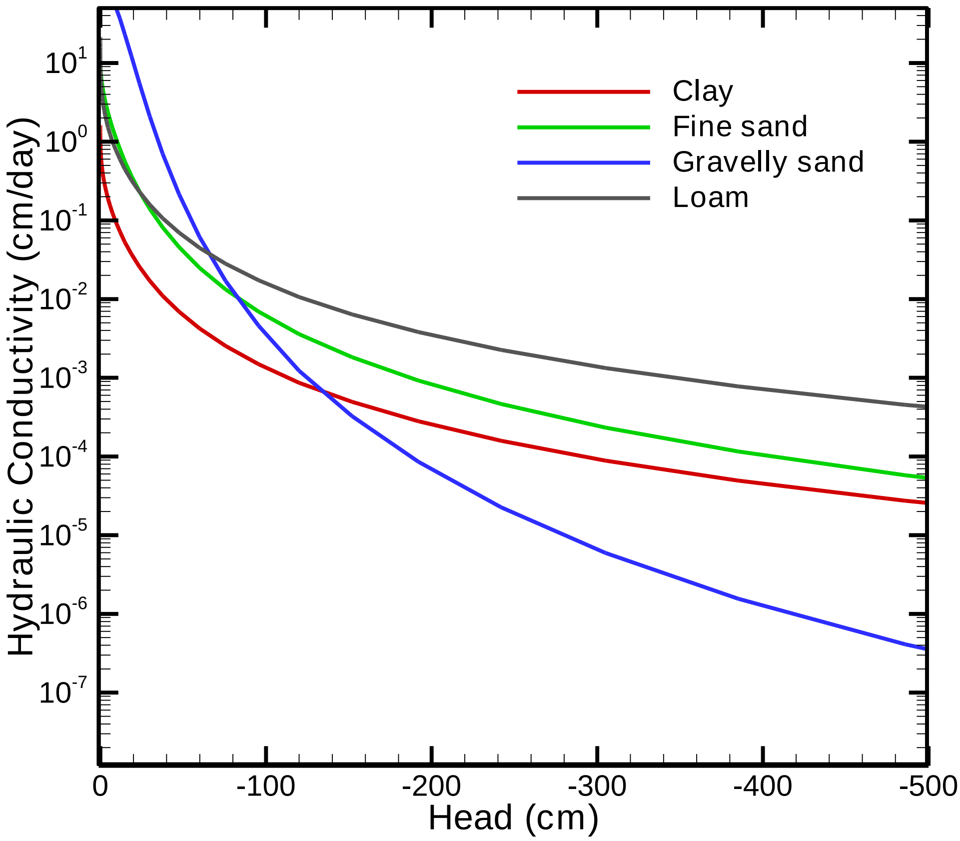

Fig. 3 Unsaturated hydraulic conductivity and pressure head relationship for clay, fine sand, gravelly sand and loam

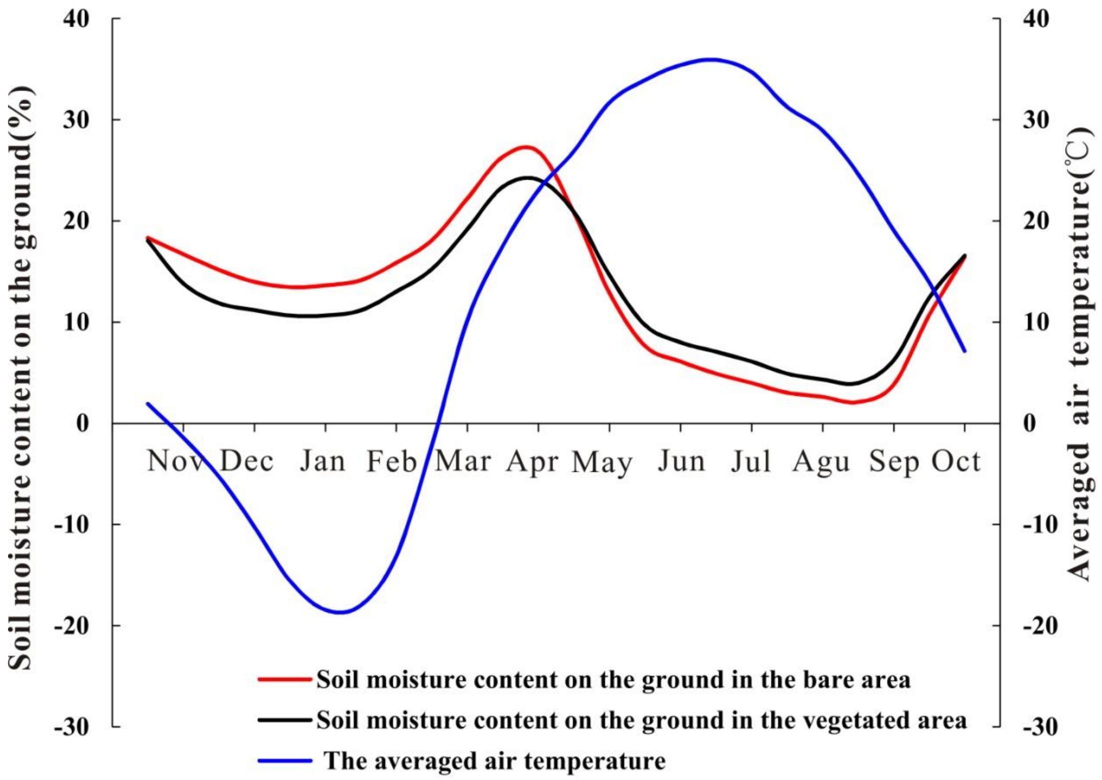

Fig.4 Surface soil moisture content on the bare and vegetated grounds, and soil surface temperature at the experimental site

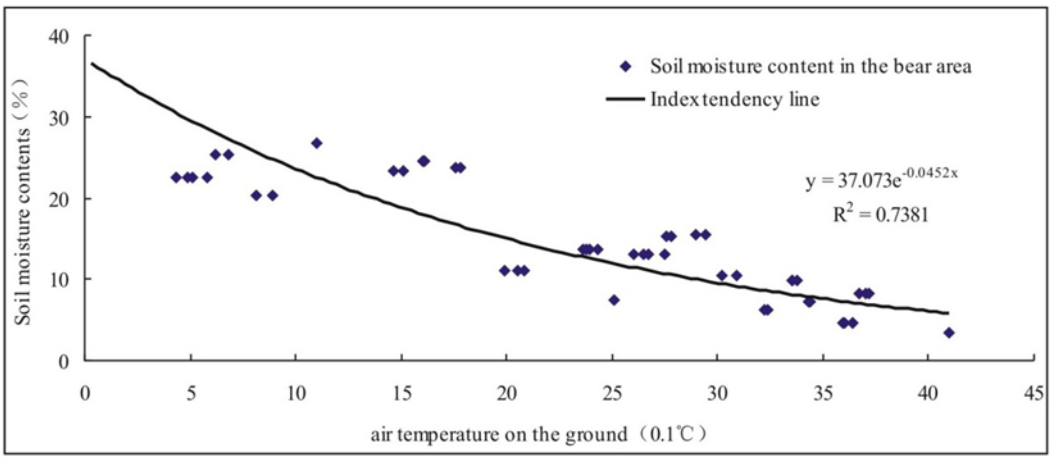

Fig.5 The relationship between the soil moisture content and air temperature on the ground for $T \geq 0$ for the bare ground

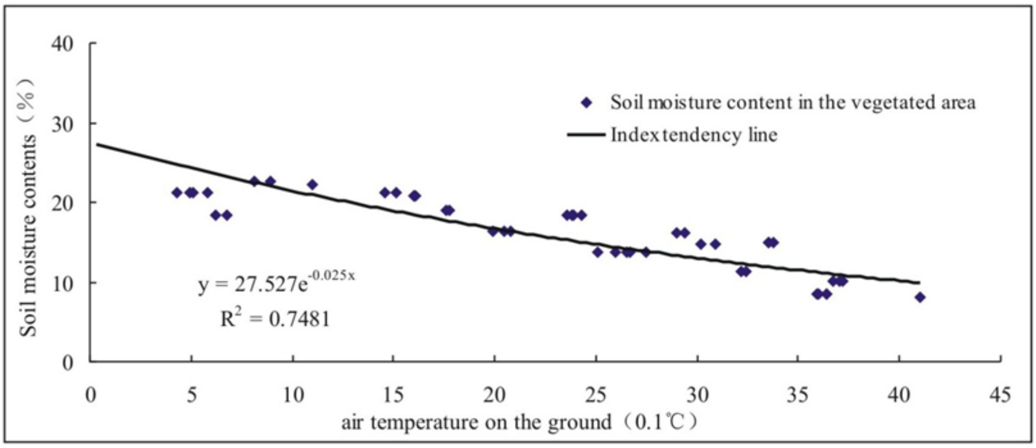

Fig.6 The relationship between soil moisture content and air temperature on the ground for $T \geq 0$ for the vegetated ground.

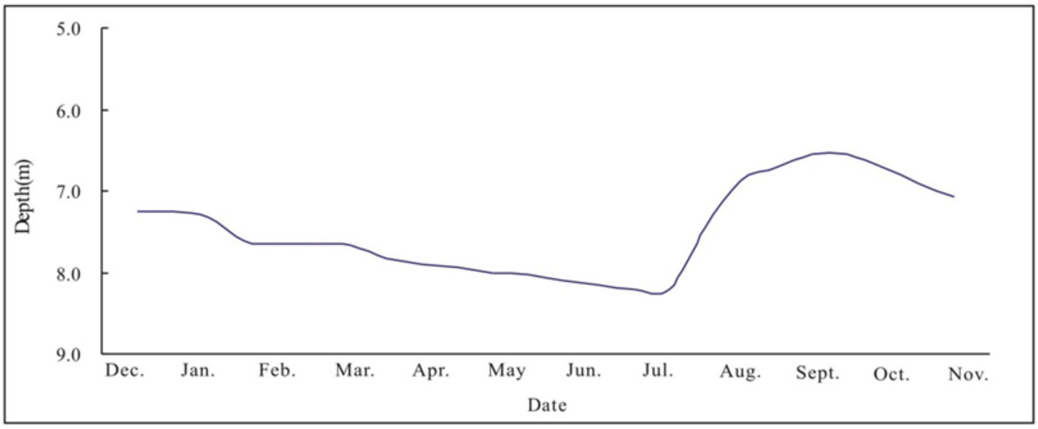

Fig. 7 The variation of groundwater depth during the experimental period at the test site.

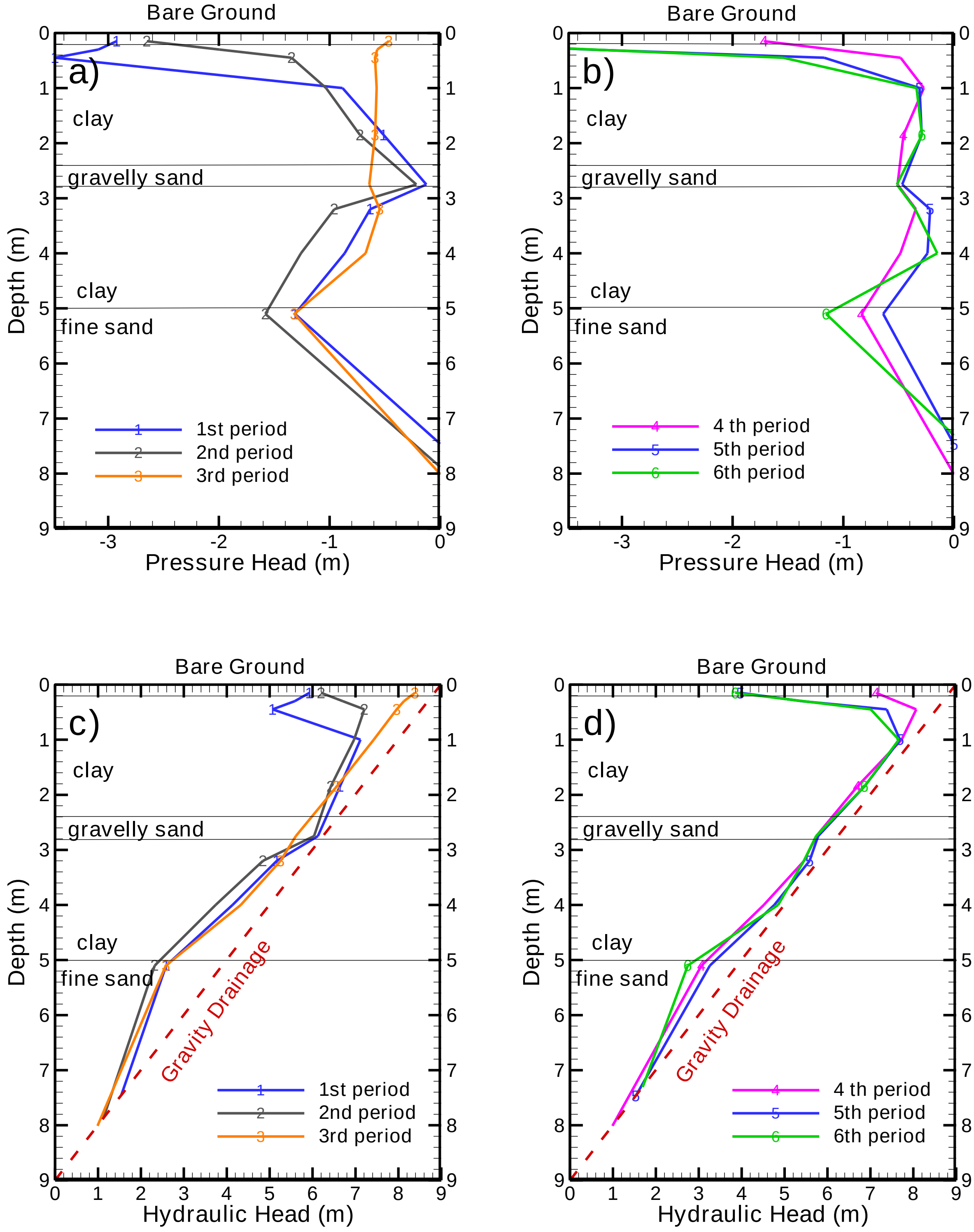

Fig. 8 The averaged pressure head distributions (a and b) and hydraulic head distributions (c and d) along the profile of the vadose zone for six periods in the bare ground plot.

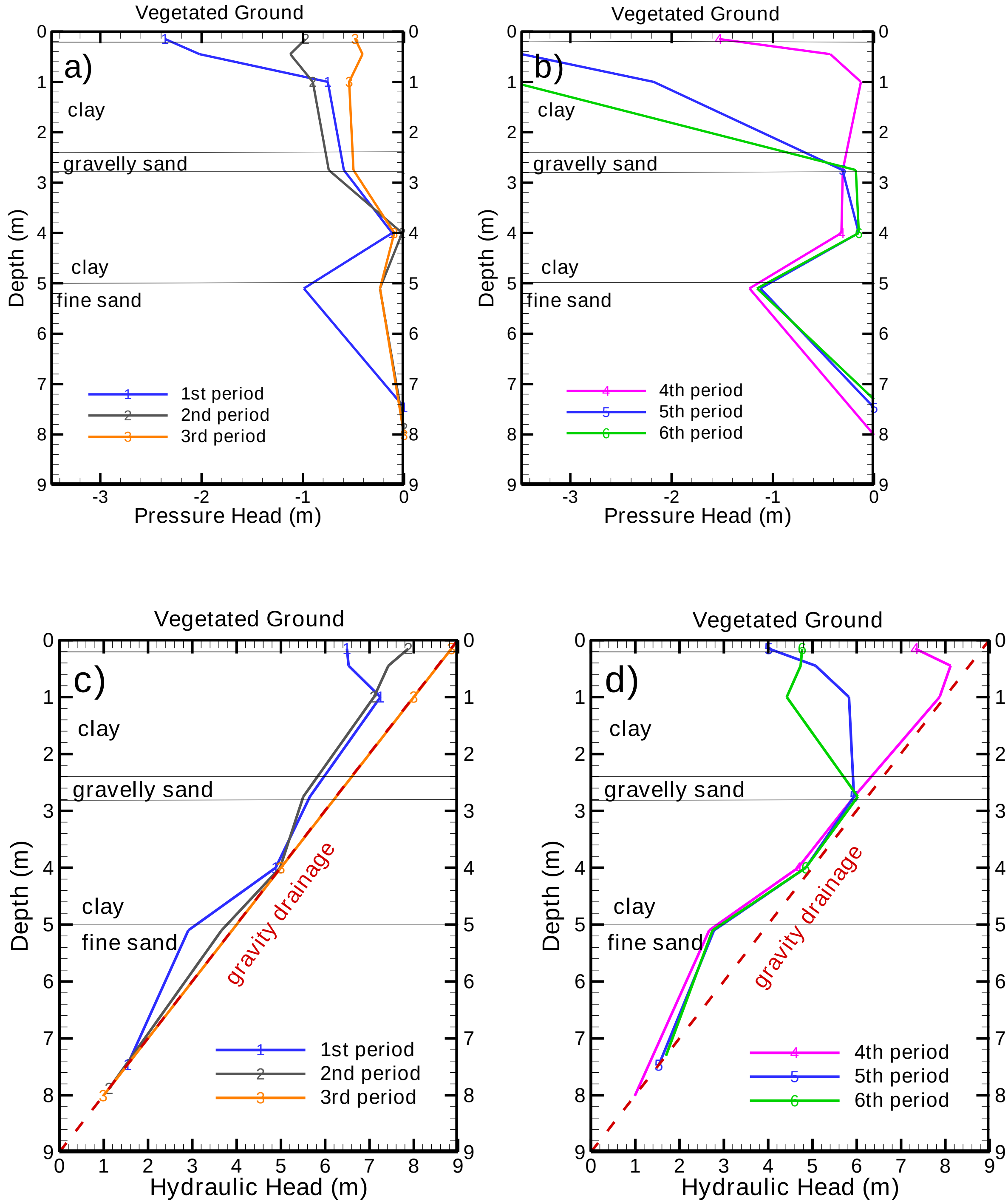

Fig.9 The distribution of average pressure head (a) and total hydraulic head (b) for each period for the vegetated area

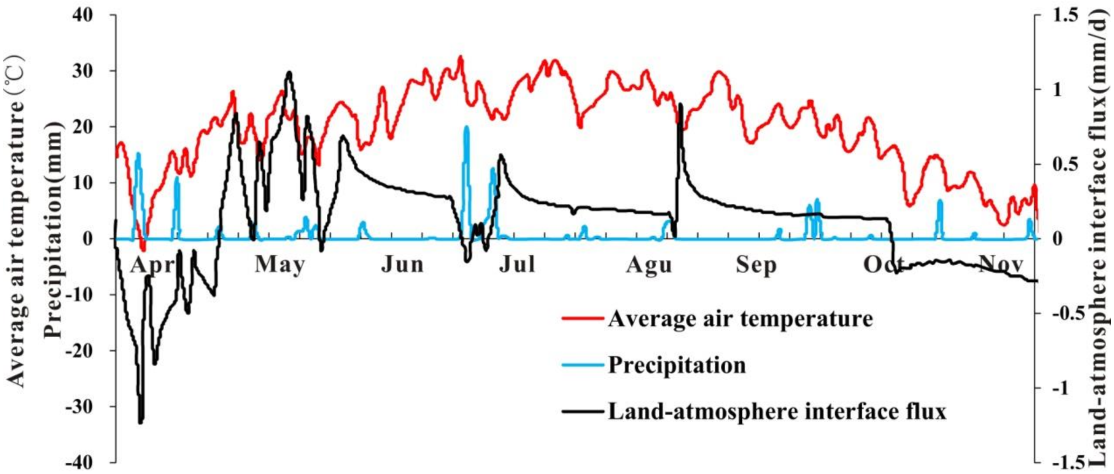

Fig.10 Estimated the land-atmosphere interface flux, air temperature, and rainfall (The flux is positive number means evaporation; negative number means rainfall infiltration)

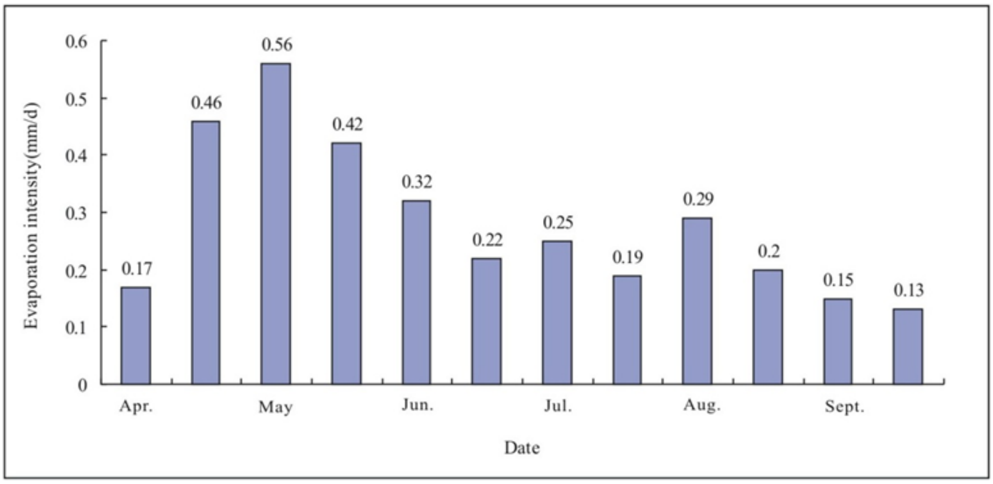

Fig.11 The distribution of topsoil average evaporation intensity

Fig.12 The percentage of topsoil to water surface average evaporation intensity

Fig.13 The changing trends of plant root water absorption intensity and water absorption depth at the test points