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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.

ACTIVITY

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 year's 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.,

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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 plant's 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 year's 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 -26.5°C in January to the maximum of 27.3°C in July. Daily average minimum and maximum temperatures for summer and winter vary between 15 to 42 °C and -25 to 8°C. 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.°C from December to mid-March and it warmed up from mid-March to July. The average temperature reached a maximum in July of about 28.8°C. After July, temperatures decreased from 28.8°C to 5°C 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 $3m \times 3m$ 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 days' 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

the vegetated ground from June to November. This could be attributed to plant canopy, which reduced the evaporation of the soil surface in the vegetated ground. Statistical analysis of the data indicates that the surface soil moisture content is negatively correlated with the ground air temperature (T > 0) for both bare and vegetated. The two variables have an exponential relationship for T > 0 such that (see Fig. 5 and Fig. 6)

$$\theta = 37.073 \exp(-0.0452 \text{T}) \text{ R}^2 = 0.7381$$

for the bare area (1)

 $\theta = 27.527 \exp(-0.025 \text{T}) \text{ R}^2 = 0.7481$

for the vegetated area (2)

where θ the soil moisture is content on the ground (%) and *T* is the air temperature (°C).

3.2. The variation of water table

The water table is the bottom boundary of the vadose zone, and it varied over the experiment period (Fig. 7). The range of groundwater depth variation was 1.81m, from a maximum of 8.23m in early July to a minimum of 6.42m in the middle of September. Overall, the depth to the water table increased from January to June, and declined from July to December.

3.3. The variation of pressure head and total hydraulic head in the vadose zone for the non-vegetated ground

Based on the analysis of the averaged tensiometer data along the depth over 15 days, we classified six periods of the soil water pressure head distribution along the profile for the entire observation time. The 1st period is from November 2004 to 15 February 2005; the 2nd period is from 16 February to 15 March; the 3rd period is

from March 16 to Late April; the 4th period is May; the 5th period is from June to 15 August; the 6th period is from 16 August to October. Detailed descriptions of the pressure profiles and associated hydrologic processes for these periods are given in supporting material section.

Overall, these pressure profiles during the six periods reveal the followings for hydrologic processes in the bare ground plot: precipitation replenished the vadose zone during March till May; increase in temperature and evaporation during June to October only affects soil moisture at shallow depth (from the land surface to the depth about 1m), while the moisture in the rest of the vadose zone continued downward movement. The rise and fall of the water table did not significantly affect the vadose zone above. The cut off the replenishment of moisture from the land surface to the vadose zone, and the continuous downward migration of moisture explained the dry condition from 0 to 3 m depths during the first period.

Flow dynamics over the six periods. Figs. 8a and 8b show the distribution of the averaged pressure head in the vadose zone from the 1^{st} period to the 3^{rd} period and the 4^{th} to 6^{th} periods, respectively for the bare ground plot. The corresponding hydraulic head distributions for these periods are presented in Figs. 8c and 8d. The hydraulic head is the sum of pressure and elevation heads:

$$H = h + z \tag{3}$$

where *H* is the total hydraulic head, *h* is the pressure head and *z* is the elevation head. The hydraulic gradient (dH/dz) determines upward or downward flow in the vadose zone (see Yeh et al., 2015). Here, we define that *z* represent the depth, a positive value measuring from the land surface downward. Accordingly, dH/dz=0implies that there is no upward or downward flow. If dH/dz>0, the flow is upward. On the other hand, if dH/dz < 0, the flow is downward. In particular, when dH/dz = -1, the downward flow is virtually driven by gravity.

Fig. 8c shows that the zone between the atmosphere and soil, where downward infiltration (dH/dz<0) or upward evaporation (dH/dz>0) could occur, extends to about 1.2 m depth below the ground surface. Note that the soil was frozen down to 12 cm below the land surface during the 1st period and down to 22.5 cm below the land surface during the 2nd period. The red dashed line in the figure denotes dH/dz = -1, representing gravity drainage.

During the 1st period, a positive (upward) hydraulic gradient existed from 1m depth to the depth of 0.4 m below the soil surface, and then the gradient became negative (Fig. 8c) below 1 m depth. This is an inflection point. Above this inflection point, the flow is upward, and below it, the flow is downward. The inflection point is the moisture source (center of the moisture plume) in the vadose zone available for upward and downward flow. The location of this inflection point changed with time. This inflection point migrated upward to 0.4m during the second period, likely due to the thawing of the frozen soil layer. The gradients from the gravelly sand up to the inflection points are similar during these two periods; they are negative (downward flow) but less negative than the gravity drainage.

During the 3rd period, the inflection point was near the surface, and the gradient from the gravelly sand up to the soil surface became -1, indicative of gravity drainage downward flow (orange line in Fig. 8c). Below the gravelly sand, the gradients for the three periods were similar, and they were more negative than that of gravity drainage, reflecting the low permeability nature of the clay below. On the contrary, the gradients in the fine sand below the clay were less negative than the gravity drainage. The less negative gradients may be related to the high permeability of the fine sand. Notice that the drop of the water table during the 3^{rd} period made the gradient more negative.

During the 4th period, the inflection moved down from the location of the 3rd period; continued downward movement during 5th and 6th periods. The hydraulic gradient near the land surface then gradually became positive, indicative of upward flow due to evaporation (Fig. 8d). The overall gradients from the inflection points down to the water during the three periods were generally close to that of gravity drainage, although they exhibited the similar pattern as those in Fig. 8c. Overall, it is clear that moisture movement below 1m is mainly driven by gravity and downward. The effects of evaporation (upward) were limited to 1 m below the land surface. The majority of precipitations stored in the vadose zone from the 3rd and fourth periods continuously moved down by gravity. As the supply from the upper vadose zone was cut off due to frozen ground surface during the winter periods (see Figure 8c), the hydraulic gradient in the upper zone (1m to 3 m) decreased, the gradient in the clay layer below increased due to dry conditions and less permeable. Consequently, the gradient in the fine sand decreased due to less moisture availability.

3.4. The variation of pressure and hydraulic head in the vadose zone with vegetation

Next, we examine the results from vegetated ground for the same periods. The pressure head profiles during the 1^{st} and 2^{nd} periods were similar to those in the bare soil since the ground was frozen and they are not shown here. The profiles of pressure heads at different times of the 3^{rd} , 4^{th} , 5^{th} , and 6^{th} periods are illustrated in Figures. S2 a, b, c, and d, (supporting material), respectively. The averaged pressure profiles of

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each period are plotted in Figs. 9a and 9b, and the corresponding the total hydraulic head are in Figs. 9c and 9d.

The averaged pressure head profiles of the vegetated ground during the six periods (Figures 9a and 9b) bear similar trends of those in the bare ground (Figures 8a and 8b). The major difference lies in the behaviors above the depth of 3m where effects of plant roots were apparent. During the first two periods, the pressure profiles above the depth 3 m reflected moisture deficits caused by the frozen ground surface and continuous drainage as did those profiles in the bare ground plot. Moisture deficits in this zone were then replenished by precipitation during the 3rd and 4th periods similar to those in the bare ground plot. However, during the plant growth periods (5th and 6th periods), the pressures in the zone above the depth of 3 m became significantly more negative as the depth decreases due to demand of plants, but the pressures remained close to zero from depths 3m to 4m. On the other hand, the drastic change in pressure profile in the bare ground plot (due to evaporation) took place only limited to a shallow zone (between the land surface and the depth of 1m). Below this zone, the pressure remained relatively close to zero from depth 1m down to 4m. A comparison of these profiles, one can conclude that the plant root absorption in the vegetated ground unambiguously reached to the depth of 3 m where the gravel overlying on the clay layer.

This effect of root absorption may also explain the difference in the location of the inflection of the pressure profiles in the vegetated ground plot and the bare ground plot during the 1st, 2nd, and 3rd periods. Figure 9a shows the inflection point in the vegetated plot is at a depth of 4m, and is at a depth of 3m in the bare ground plot. Plots of the hydraulic heads also show upward flow from depth 3m to the land surface in the vegetated plot (Figures 9c and 9d) and from depth 1m to the land surface in the

bare ground plot (Figures 8c and 8d). Below these depths, moisture in either bare or vegetated ground plots moved predominantly by gravity. However, hydraulic characteristics of layers do modify the gradient.

These observations and qualitative analyses of the evolutions of the pressure heads, hydraulic heads, and gradients in soil profiles of bare and vegetated grounds lead to some interesting observations. That is, flow dynamics in the vadose zone is mainly driven by gravity but modified by temperature, rainfall, plants, and ground water variations. Results of the bare ground plot demonstrated that evaporation driven by high temperatures affected flow only in the shallow depth (1 m) of the vadose zone. On the other hand, the evapotranspiration due to the growth of shrubs can extract moisture from 3 m below the land surface, and was then stopped at the interface between the gravelly sand and clay layer. Below this zone of evaporation or evapotranspiration, moisture generally is driven by gravity down to groundwater, and is modified by geologic heterogeneity. Our observation shows that fluctuation of the water table did not clearly relate to the upper part of the vadose zone at this plot.

3.5. The land-atmosphere interface flux in the bare ground plot

In Figure 10, we plot the temporal variations of the estimated land-atmosphere interface flux (soil surface evaporation or rainfall infiltration rate), temperature and rainfall from April to November, 2005. This flux was estimated using Darcy's law, the hydraulic gradient in the top soil and measured hydraulic properties (Table 1). According to Figure 10, the ground surface had little evaporation before April 25, but mostly downward drainage of moisture from previous periods (negative flux). This is consistent with the interpretation based on Fig. 8c. From late April to May 20, under the influence of the dramatic change of temperature, heavy rainfall and other factors,

the interface flux fluctuated significantly in accordance with the variation of temperature. A cross-correlation analysis indicates that the interface flux responses lagged behind the temperature by about 2 to 3 days. The positive interface flux (evaporation) is likely due to the increased rainfall, sub-surface permafrost thawing, and snow melt during this period. These processes slowly increased the water content and the water storage in the surface soil and vadose zone. As the temperature had increased sharply, increase in the surface soil evaporation rate (i.e., interface flux) then followed.

From late May to late September, the temperature overall was high, and rainfall became less. Consequently, water content of the surface soil and the vadose zone declined, water storage in the soil decreased, and the surface soil evaporation relatively lessened. Nonetheless, the figure 10 shows that the topsoil evaporation increased drastically 2 to 3 days following heavy rainfall. Afterward, the surface evaporation decreased sharply then gradually until the next round of heavy rain. The exchange flux remained positive because of the rise of temperature and other factors. This process repeated itself several times during this period. The temperature started to decrease in mid-August through November. At early October, as the temperature continued to decline, the surface soil evaporation became small even there were rainfalls. The exchange flux became negative, indicating that the surface soil remained in an infiltration status.

Figure 11 shows top soil average evaporation intensity over the period. It reveals the followings: 1) Notable surface soil evaporation took place from late April to mid-September. 2) The largest amount of surface soil evaporation was from late April to May (the evaporation rate ranged from $0.17 \sim 0.56$ mm/day). 3) The topsoil evaporation rate from June to July declined from 0.42 to 0.19mm / day, and for early

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to mid-August was 0.29mm / day. 4) From late August to the end of September, the topsoil evaporation started to decline. 5) By the end of September, the average evaporation dropped to 0.13mm / day.

The ratio of the average soil evaporation intensity to the water surface evaporation intensity is illustrated in Fig. 12. This figure shows that the surface soil evaporation accounted for 2%-5% of the water surface (potential) evaporation rate. A maximum reached around 6.7%. It further suggests that soil surface evaporation intensity depends mainly on two factors. First is the evaporation capacity (the potential evaporation or water surface evaporation rate), which are determined by radiation, temperature, relative humidity, wind speed and other weather conditions. Second is the water availability of the vadose zone, which is controlled by the negative soil pressure water head distribution in the vadose zone, water content, and soil hydraulic properties $k(\theta)$ and $h(\theta)$. When the rate of water availability in the soil is less than the potential evaporation rate, the soil surface evaporation rate is constrained by the On the other hand, as the water availability is greater than the water availability rate. potential evaporation rate, the evaporation is in control. Through the analysis of the data from the study area, we find that water availability is less than the potential evaporation rate from April to May; water availability is greater than the potential evaporation intensity from June to September.

3.6. Analysis of plant root water absorption

During the period of growth, plants absorb water from the soil through roots, altering the negative pressure head distribution in the vadose zone. Differences in negative pressure head profiles in the vegetated area and those in the bare ground area thus reveal the distribution of root absorption during the period. That is, in the case of the vegetated ground, the mass balance for soil water movement is:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} + S \tag{4}$$

where θ is moisture content, *t* is time. *q* is water flux, *z* is the depth, and *S* is the root uptake rate. In the case of the bare ground, the term *S* in Eq. 4 is zero and the rate of change in moisture content is attributed to evaporation and infiltration only. Accordingly, the uptake rate was estimated using differences in the $\partial \theta / \partial t$ profiles between the bare and vegetated grounds. In order to estimate $\partial \theta / \partial t$, we took the average negative pressure data during the period of plant growth every 15 days and set this period as the time step. The calculated root absorption rate of vegetated areas is shown in Fig. 13, which reveals the followings:

(1) During the seedling period before the end of May, root absorption rate was small since plant roots were not well developed.

(2) June to August was the period of seedling, jointing and tasseling. The plant roots became gradually mature with increased water absorption ability. The plant's water demand also increased rapidly, from 0.14mm/day in early June to 2.31mm / day by the end of July.

(3) As the water in the vadose zone near the surface constantly evaporated or was absorbed by roots and moved downward by gravity, water left in the vadose zone diminished. The remaining water in the top soil no longer satisfied the demand of vegetation. The roots of the vegetation had to absorb water from deeper soil. The depth of water absorption by the roots increased from 0.3m in early June to 2.8m in July (Fig. 13). Comparing the bare soil area and vegetated areas, the negative pressure head distribution in the profile of vegetated ground thus changed significantly above 3m (see Figs. 9b).

(4) From August to September is the period of maturity and withering. At this time, plant roots became progressively aged. Thus, the water absorption ability of roots sharply decreased from 2.31mm/day in early August to 0.001mm/day by early September. This reduction in root abortion rate is also notable in the relatively small changes in the pressure head profile from the previous period in the vegetated ground.

3.7. Effective rainfall analysis

If rainfall occurs and there is no surface runoff, the groundwater recharge quantity Q by rainfall can be estimated by:

$$Q = P - \int_{0}^{z_{f}} (W_{m} - W_{c}) dz - E$$
(5)

Where Q is the quantity of groundwater recharge by rainfall (mm). P is precipitation (mm). W_m is the soil field water capacity (%), and W_c is the initial water content in soil before rain, which were estimated using measured pressure head profiles, and the moisture retention curve of the soil. Z_f is the total thickness of the soil layer, which is under moisture deficit (i.e., less than field water capacity (mm). E is the sum of the evaporation during rainfall and gravity infiltration (mm).

When precipitation infiltration was greater than the moisture deficit above zero flux planes (inflection point), the rainfall infiltrates into the vadose zone was estimated as follows:

$$q = -k(\theta)\frac{\partial H}{\partial z} \tag{6}$$

In order to have recharge to groundwater due to rainfall, the rainfall must be

$$P \ge \int_{0}^{z_f} (W_m - W_c) dz + E \tag{7}$$

The right-hand side of Eq. 7 is called the soil water demand in the vadose zone. According to Eq. 7, if we know the depth of the inflection point (zero flux surface) and the distribution of water potential on profiles at different times, then we can use this equation to estimate the demand of the vadose zone the for this period. Once the demand is determined, we say that if precipitation is greater than the demand, the excess rainfall will recharge the groundwater. Otherwise, the rainfall can only infiltrate to the surface soil and vadose zone above the zero flux surface to satisfy the demand, and ultimately is transferred to atmosphere by evaporation or plant transpiration.

Table 2 lists the soil water demand calculated from average half monthly pressure heads of 2005. As indicated in the table, the water demand during March, April, and November are zero, indicating that precipitation recharges groundwater. From May to October, the demand was greater than zero and the minimum demand was 30.7mm in October. In order to facilitate groundwater recharge, precipitation over these months must be greater than the demand. Table 2 indicates that the rainfall during the four months of March, April, June and October, accounted for 57% of the total annual precipitation. This was followed by February, May, August, September and December, which accounted for 31% of the total precipitation for the year (Table 2). However, the main rainfall intensity during all these periods was less than 5mm/day. The rest of rainfall intensity was around 5 -10mm/day, which accounted for 8.5 % of the total annual rainfall. Other rainfall intensities (6.5% of the total annual rainfall) were low in frequency, generally 1 or 2 times. As a result, the precipitation for March, April,

and November had some significance for groundwater recharge, but the precipitation from May to October did not have an impact on groundwater recharge.

4. CONCLUSIONS

In this study, we investigate the flow dynamics in the vadose zone, using observed data from a field experiment in a thick vadose zone that involved bare and vegetated grounds. Results of our analysis of observed pressure heads and soil data lead us to the following conclusions:

1. Flow dynamics in the vadose zone is mainly driven by gravity but modified by temperature, rainfall, plants, and ground water variations.

2. Results of the bare ground plot demonstrated that evaporation driven by high temperatures affected flow only in the shallow depth (approximately 1 m) of the vadose zone. On the other hand, the evapotranspiration due to the growth of shrubs can extract moisture from 3 m below the land surface, and was then stopped at the interface between the gravelly sand and clay layer. Below this zone of evaporation or evapotranspiration, moisture generally was driven by gravity downward, and modified by geologic heterogeneity as it reached the water table. Our observation indicated that fluctuation of the water table did not clearly relate to the upper part of the vadose zone at this plot.

3. According to our estimates, from the period of seedling, jointing and tasseling, the roots' water absorption ability was gradually increased and reached up to 2.31mm/day. During the period of maturity and withering, the water absorption ability of roots was sharply reduced to 0.001mm/day. The depth of water uptake by roots increased from 0.3m in early June to 3 m in July.

4. Our analysis shows that the precipitation during March, April, and November had some contribution to groundwater recharge, but the precipitation from May to October did not.

These findings about the general flow dynamics are unique since most field experiments have been conducted in relatively shallow vadose zones (one or two meters thick), where the water table is close to the surface and the root zone. Our study unambiguously shows that the root absorption ability can reach down to at least 3 m and eventually is restrained by the less permeable clay layer.

At last, we emphasize that more large-scale and long term experiments in thick vadose zone are needed in order to enhance our understanding of the ecosystems in semi-arid regions. More importantly, high-resolutions monitoring of processes and characterization of soil and plant characteristics in space and time are essential to improve our knowledge of the flow dynamics in such an ecosystem.

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Type of soil	$K_s(\mathbf{m/d})$	θ_r (cm ³ /cm ³)	θ_s (cm ³ /cm ³)	α (1/m)	п
Loam	0.2496	0.078	0.43	3.6	1.15
Find sand	0.108	0.067	0.45	5	1.41
Clay	0.0168	0.089	0.43	4	1.23
Gravelly sand	1.061	0.065	0.41	5	2.5

Table 1 The parameters of van Genuchten model derived from soil samples.

Month		Zero surface	Effective	Monthly			
		depth (m)	rainfall(mm)	Rainfall(mm/day)			
March	Second half	0	0	0.1			
	month		-				
April	First half	0	0	32.2			
	month						
	Second half	0	0	2.2			
	month						
May	First half	0.5	22.79	9.5			
	month						
	Second half	0.5	33.50	6.1			
	month						
June	First half	0.5	46.33	0.1			
	month						
	Second half	0.55	48.23	41.6			
	month						
July	First half	0.70	56.35	0.7			
	month						
	Second half	0.75	59.20	3			
	month						
August	First half	0.80	60.94 66.03 66.08	14.3			
	month						
	Second half			15.8			
	month						
September	First half			0.7			
	month Second half						
	Second half	0.68	48.41	6.8			
Ostahar	Orementh	0.5	20.72	Λς ς			
October	Che month	0.5	30.73	40.0			
November	First nam	0	0	15.2			
	monun						
V.							

Table 2.Estimated effective rainfall from March to November



Fig.1 Variation of major meteorological data in half-months at the station near the experimental site



Tensiometerlocation map

Fig. 2 Illustration of the soil stratification at the site and locations of the tensiometers below the vegetated and bare grounds



Fig. 3 Unsaturated hydraulic conductivity and pressure head relationship

for clay, fine sand, gravelly sand and loam

Ç



temperature at the experimental site



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





Fig.6 The relationship between soil moisture content and air temperature on the ground for $T \ge 0$ 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.11 The distribution of topsoil average evaporation intensity

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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