Soil Water Characteristics and Maximum Capillary Rise Height of Aeolian Sandy Soils at the Southern Margin of the Gurbantunggut Desert (Postprint)

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Abstract

To determine the maximum rising height of capillary water in the deep groundwater burial area at the southern edge of the Gurbantunggut Desert and provide a theoretical basis for partitioning water sources of sand-fixing vegetation, soil water content in the 0–10 m soil layer of the experimental site was monitored using the neutron probe method from March 2016 to November 2018. The seasonal variation of soil water content at different slope positions of sand dunes was analyzed, and the maximum rising height of capillary water at the experimental site was determined using the curve intersection method between maximum molecular water holding capacity and soil water content. The results showed that: soil water content in the 0–130 cm soil layer at different slope positions of sand dunes was significantly influenced by external meteorological factors, with obvious seasonal variation patterns; the soil layer from below 130 cm to 570–760 cm was a dry sand layer with relatively stable soil water content; while soil water content in the soil layer below 570–760 cm was mainly affected by groundwater table fluctuations and capillary rise water, and the upper boundary of its water content variation could be regarded as the maximum rising height of capillary water. The maximum molecular water holding capacity of the experimental site was 0.026 1 $cm^3 \cdot cm^{-3}$, and the maximum rising height of capillary water at different slope positions of sand dunes ranged between 250–290 cm.

Full Text

Maximum Height of Capillary Rising Water and Characteristics of Soil Moisture at the Southern Edge of the Gurbantunggut Desert

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Abstract

To determine the maximum rising height of capillary water in areas with deep groundwater tables at the southern edge of the Gurbantunggut Desert and provide a theoretical basis for identifying water sources of sand-fixing vegetation, we conducted observations from March 2016 to November 2018 using a neutron probe to monitor soil moisture in a 0–10 m profile. Seasonal variations in soil water content were analyzed across different dune positions, and the intersection method between maximum molecular moisture holding capacity and soil water content curves was employed to determine the maximum capillary rise height. Results showed that soil water content in the 0–130 cm layer at different dune positions was significantly influenced by meteorological factors and exhibited clear seasonal patterns. The soil layer between 130 cm and 760 cm constituted a stable dry sand layer with relatively constant moisture content. Below 760 cm, soil water content was primarily affected by groundwater table fluctuations and capillary rise water, with the upper boundary of moisture content change representing the maximum capillary rise height. The maximum molecular moisture holding capacity at the test site was 0.0261 cm^3/cm^3, and the maximum capillary rise height across different dune positions ranged from 250 cm to 290 cm. Based on the root distribution characteristics of *Haloxylon ammodendron* and *Haloxylon persicum*, we preliminarily conclude that these constructive species in the Gurbantunggut Desert can utilize groundwater through capillary rising water.

Keywords: maximum molecular moisture holding capacity; capillary rise; soil water content; soil moisture characteristic curve

Introduction

Water is the primary limiting factor for vegetation restoration and sand control in arid and semi-arid regions, as well as a crucial environmental factor affecting desertification areas. Capillary water represents one of the main water sources for plants, and if capillary rise water can reach the active root zone of psammophytes, it establishes hydraulic connectivity between the plants and groundwater, providing favorable conditions for groundwater utilization. This connection enables plants to avoid water stress, maintain their capacity for natural regeneration, and sustain their sand-fixing ability. Consequently, studying the rising height of capillary water in sandy areas is essential.

Current methods for determining capillary water rise height primarily include the capillary apparatus method, soil column method, monolith method, water content distribution curve method, and direct observation in test pits. The water content distribution curve method includes both the plastic limit intersection method and the maximum molecular moisture holding capacity intersection method. Previous studies have investigated capillary rise in sandy soils, such as Jia et al.' s work using radioactive ^{131}I to examine capillary water movement patterns in loose sandy soil under different groundwater depths. Wei studied capillary water movement in aeolian sand columns with groundwater depths of 80–200 cm, while Chen and Gao et al. investigated the hydraulic properties of desert aeolian sand. Kan examined the effects of water-retaining agents on capillary rise in sandy soils, and Li and Dong studied the influence of water quality on capillary water movement characteristics. However, these studies were primarily laboratory experiments with relatively shallow groundwater depths, and there remains a lack of understanding regarding capillary rise heights in sandy soils with deep groundwater tables around 600 cm.

Building upon previous research, this study focuses on semi-fixed dunes at the southern edge of the Gurbantunggut Desert. Three monitoring points were established at the west slope foot, east slope foot, and interdune lowland to simultaneously monitor groundwater depth and soil moisture. Using the intersection method between maximum molecular moisture holding capacity and soil water content curves, we investigated the maximum capillary rise height in aeolian sandy soil to provide a theoretical basis for identifying water utilization pathways of sand-fixing plants.

1 Study Area and Methods

1.1 Study Area Description The study area is located at the Beishawo test site on the southern edge of the Gurbantunggut Desert (44°22.63 N, 87°55.21 E). The aeolian landforms are dominated by dendritic sand ridges 10–20 m in height, with relatively gentle flowing sand belts approximately 150 mm wide. The sand ridge tops have slopes of 6–8°, while the west slope inclines at 16–28° and the east slope at 22–36°. The regional mean annual temperature is 6.6 °C, with annual precipitation of 150 mm and stable snow cover for 160 days.

Maximum snow depth reaches 20 cm. The soil is typical desert aeolian sand with a dry bulk density of 1.65 $\mathrm{g \cdot cm^{-3}}$, and the groundwater table ranges from 570–760 cm. Vegetation is dominated by *Haloxylon ammodendron* and *Haloxylon persicum*, accompanied by *Ephedra distachya*, *Ceratocarpus arenarius*, *Artemisia desertorum*, and numerous ephemeral plants.

1.2 Determination of Capillary Rise Height This study employed the water content distribution curve method to determine capillary rise height. Based on previous research, the maximum molecular moisture holding capacity intersection method can be used for sandy soils. Using soil water content data measured by neutron probe, we plotted soil water content distribution curves with sampling depth as the vertical axis and soil water content as the horizontal axis. The maximum molecular moisture holding capacity line and average groundwater depth line were then marked. The distance from the intersection point of the maximum molecular moisture holding capacity line and soil water content distribution curve to the groundwater table represents the maximum capillary rise height.

1.3 Soil Moisture Measurement In the deep groundwater table area at the southern edge of the Gurbantunggut Desert, three soil moisture monitoring points were arranged along the dune cross-section at the west slope foot, east slope foot, and interdune lowland. From March 2016 to November 2018, a neutron probe was used to measure soil moisture at these points, with measurement depths of 10 cm, 20 cm, 30 cm, and so on down to below the water table. The interval between adjacent measurements was typically 10–15 days, with three readings taken at each depth and averaged as the observation value. Aluminum neutron access tubes were installed to depths of 1010 cm, 840 cm, and 890 cm at the three monitoring points, respectively, with elevations of 398.40 m, 399.04 m, and 400.95 m.

1.4 Groundwater Depth Measurement Groundwater observation wells were installed approximately 0.5 m from each soil moisture monitoring point at the west slope foot, east slope foot, and interdune lowland, with monitoring synchronized with soil moisture measurements.

1.5 Soil Water Characteristic Curve Determination Soil samples were collected from the three monitoring points, and the pressure membrane method was used to determine soil water characteristic curves.

1.6 Data Processing Soil water content data from 2016–2018 for each slope position were statistically analyzed using Excel 2016. The Van Genuchten model parameters were fitted to calculate maximum molecular moisture holding capacity, and Origin 2018 software was used for plotting.

2 Results and Analysis

2.1 Seasonal Variation of Soil Moisture Figure 2 shows the temporal variation of soil water content at the west slope foot, east slope foot, and interdune lowland of a fixed dune at the Beishawo test site. Spring (March–May) represents the most rapid period of soil moisture change in the Gurbantunggut Desert. Due to slow temperature rise, relatively low soil evaporation, and recharge from snowmelt and spring precipitation, soil water content remains relatively high. After May, rapid temperature increase intensifies soil evaporation, and the germination of desert ephemeral plants consumes substantial soil moisture, causing overall water content to decline continuously. During summer (June–August), enhanced solar radiation and evaporation with minimal rainfall cause rapid depletion of surface soil moisture, forming a stable dry sand layer. Except for minor rapid fluctuations from precipitation events, soil water content remains consistently low. In autumn and winter (September–February), decreasing temperatures reduce evaporation, while seasonal rainfall and snowfall replenish surface soil moisture, increasing water content again. By early November, snow cover and soil freezing stabilize soil water content.

Surface soil moisture at all three monitoring points is profoundly affected by meteorological factors such as atmospheric precipitation and evaporation, with influence depths ranging from 0–130 cm. Deeper soil layers, particularly below 130 cm, are minimally affected by meteorological factors, and their water content changes likely result from groundwater table fluctuations and soil capillary rise water. The upper boundary of water content change in deep soil layers can be considered the maximum capillary rise height.

2.2 Soil Water Characteristic Curve and Maximum Molecular Moisture Holding Capacity The soil profile mechanical composition at each monitoring point was relatively uniform, with sandy soil texture at all locations (Table 1). The relationship between deep soil volumetric water content and soil water suction at the west slope foot, east slope foot, and interdune lowland was fitted using the Van Genuchten model:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha \cdot S)^n]^m}$$

where θ is soil volumetric water content ($\mathrm{cm}^3/\mathrm{cm}^3$), θ_s is saturated water content ($\mathrm{cm}^3/\mathrm{cm}^3$), θ_r is residual water content ($\mathrm{cm}^3/\mathrm{cm}^3$), α is an empirical constant whose reciprocal is often considered the air-entry pressure, S is soil water suction (cm H_2O), and m and n are empirical shape coefficients.

Nonlinear regression using Origin 2018 yielded the following parameters:

$$\theta = 0.0162 + \frac{0.4285 - 0.0162}{[1 + (0.0203 \cdot S)^{1.3692}]^{0.2695}}$$

Maximum molecular moisture holding capacity is a soil water constant representing the sum of hygroscopic water and film water when film water reaches its maximum amount, corresponding to a soil water suction of 6,375 cm H_2O. Substituting $S = 6,375$ cm H_2O into the equation yields a maximum molecular moisture holding capacity of 0.0261 cm^3/cm^3.

2.3 Capillary Water Rise Height Using soil depth as the vertical axis and average soil water content as the horizontal axis, water content curves were plotted for the west slope foot, east slope foot, and interdune lowland. The maximum molecular moisture holding capacity line was then marked (Figure 4). The intersection point between the maximum molecular moisture holding capacity line and the soil water content curve represents the vertex of capillary rise, and the distance from this point to the groundwater table indicates the maximum capillary rise height.

At the west slope foot, with an average annual groundwater table of 1010 cm, the intersection point occurred at 760 cm depth, yielding a maximum capillary rise height of approximately 250 cm. At the east slope foot, with a groundwater table of 840 cm, the intersection occurred at 570 cm depth, giving a maximum capillary rise height of about 270 cm. At the interdune lowland, with a groundwater table of 890 cm, the intersection at 600 cm depth produced a maximum capillary rise height of approximately 290 cm. These results are consistent with the deep soil moisture variation patterns shown in Figure 2, demonstrating that the maximum molecular moisture holding capacity intersection method can effectively determine maximum capillary rise height.

Variations in maximum capillary rise height among the three positions may relate to factors such as soil texture in deeper layers. Figure 2 shows increased soil water content at 800–950 cm depths at the west and east slope feet (except at the interdune lowland), likely due to finer-textured loam interlayers. Loam soils, having smaller pores than sand, generate greater capillary forces that draw water from underlying sand layers. The better water-holding capacity of loam increases soil moisture in these layers. Since the loam interlayer thickness is less than the maximum possible capillary rise height in that soil, capillary water can continue moving upward through the interlayer, increasing the overall capillary rise height.

3 Conclusions

1) Soil water content in the 0–130 cm layer at different dune positions is significantly affected by snowmelt, atmospheric precipitation, and soil evaporation, showing clear seasonal patterns. The layer between 130 cm and 760 cm constitutes a dry sand layer with relatively stable water content. Below 760 cm, soil water content is primarily influenced by groundwater table fluctuations and capillary rise water, with the upper boundary of water content change representing the maximum capillary rise height.

2) Based on the Van Genuchten soil water characteristic curve model, the maximum molecular moisture holding capacity in the study area was determined to be 0.0261 cm^3/cm^3.

3) Using the maximum molecular moisture holding capacity intersection method, the maximum capillary rise height at the test site was preliminarily determined to range between 250 cm and 290 cm. The root depth of *Haloxylon ammodendron* in this region approaches approximately 3.0 m, with main roots extending to about 5.0 m, while *Haloxylon persicum* root depths can exceed 8.33 m, with main roots reaching the groundwater table. With the groundwater table at 570-1010 cm and maximum capillary rise heights of 250-290 cm, we conclude that constructive species such as *Haloxylon ammodendron* and *Haloxylon persicum* at the southern edge of the Gurbantunggut Desert can utilize groundwater through capillary rising water.

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Note: Figure translations are in progress. See original paper for figures.