Spatiotemporal Variation Characteristics of Soil Moisture and Groundwater Depth in Sand Dunes Postprint

Authors: Zhang Yuanhao, Alamusa, Jiawang Yin, Jiang Shaoyan

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Abstract

In arid and semi-arid dune regions, precipitation is scarce and evaporation is high, making water resource conditions a critical factor for ecosystem functioning. Soil water content and groundwater serve as key indicators of water resource status in these areas. Based on a vegetation coverage gradient, this study selected typical dunes (mobile dunes, semi-fixed dunes, and fixed dunes) as research objects to investigate variation characteristics of soil water content and groundwater depth under different vegetation coverage conditions and at different dune slope positions. The results indicate: (1) Dune vegetation coverage influences soil water content, with soil moisture gradually decreasing as vegetation coverage increases, showing the following order: mobile dunes > semi-fixed dunes > fixed dunes. Soil water content varies among different dune slope positions, exhibiting the trend: windward toe > leeward toe > windward middle > dune crest > leeward middle. The temporal variation characteristics of dune soil moisture are primarily controlled by rainfall processes, showing consistency with rainfall occurrence patterns. (2) Seasonal variation of groundwater level in dune areas shows a clear recovery during the non-growing season and a gradual decline during the growing season, with annual variation ranging between -0.21 and 0.18 m. Vegetation coverage affects groundwater variation characteristics, with the coefficient of variation decreasing in the order: fixed dunes > semi-fixed dunes > mobile dunes. Influenced by rainfall, when cumulative rainfall within a short period or single rainfall events exceed 30 mm, groundwater levels in dune areas show corresponding recovery, with the magnitude of recovery varying due to differences in surface vegetation coverage and slope position. (3) Groundwater may recharge deep soil moisture at dune toe positions, but no significant recharge effect was observed on soil moisture in the middle and upper dune slope areas.

Spatial and Temporal Variation Characteristics of Soil Moisture Content and Groundwater Depth in Sand Dunes

ZHANG Yuan-hao[1],[2], **Ala Musa**[1], **YIN Jia-wang**[1],[2], **JIANG Shao-yan**[3]

[1]Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, Liaoning, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Liaoning Forestry Vocation-Technical College, Shenyang 110101, Liaoning, China

Abstract

In arid and semi-arid dune regions, precipitation is scarce and evaporation rates are high, making water resource status a critical factor governing ecosystem functioning. Soil moisture content and groundwater depth serve as key indicators of water resource conditions in these areas. Based on vegetation cover gradients, this study selected typical dunes (mobile dunes, semi-fixed dunes, and fixed dunes) in the Horqin Sandy Land to investigate variations in soil moisture content and groundwater depth under different vegetation covers and slope positions. The results demonstrate that vegetation cover significantly influences dune soil moisture content, with soil moisture decreasing as vegetation cover increases. The ranking of soil moisture content across dune types was: mobile dunes > semi-fixed dunes > fixed dunes. Soil moisture content also varied by slope position, following the pattern: windward slope bottom > leeward slope bottom > middle windward slope > dune crest > middle leeward slope. Temporal variations in dune soil moisture were primarily controlled by rainfall patterns, showing consistency with rainfall distribution characteristics. Seasonal groundwater level fluctuations in the dune area exhibited a marked rise during the non-growing season and a gradual decline during the growing season, with an annual variation range of -0.21 to 0.18 m. Vegetation cover affected groundwater level dynamics, with coefficients of variation decreasing in the order: fixed dunes > semi-fixed dunes > mobile dunes. Rainfall events influenced groundwater levels; when cumulative rainfall within a short period or single rainfall events exceeded 30 mm, groundwater levels showed corresponding rises, with the magnitude of rise varying according to surface vegetation cover and slope position. Groundwater may recharge deep soil moisture at dune slope bottoms, but showed no significant replenishment effect on soil moisture in middle and upper slope positions.

Keywords: dune vegetation coverage; soil moisture content; groundwater depth

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1. Methods

1.1 Study Area Overview

The study area is located in the southwestern margin of the Horqin Sandy Land, in the Ulan Odoi region of Ongniud Banner, Chifeng City, Inner Mongolia (43°02 03.0 N, 119°38 48.0 E). The landscape is dominated by mobile dunes, semi-fixed dunes, fixed dunes, and inter-dune lowlands. The main plant species include sand-fixing shrubs such as *Caragana microphylla*, *Hedysarum fruticosum*, *Salix gordjevii*, and *Artemisia desertorum*, and herbaceous species including *Agriophyllum squarrosum*, *Bassia dasyphylla*, and *Setaria viridis*. The soil type is aeolian sandy soil, with groundwater depth in inter-dune areas ranging from 1-2 m, occasionally forming surface water accumulation. The region experiences a temperate continental semi-arid monsoon climate, with an average annual rainfall of 311.23 mm over the past decade (2009-2018). Rainfall is concentrated in July and August, accounting for approximately 81.45% of the annual total. The frost-free period is 140-160 days, and the average annual wind speed is 4.2 $\mathrm{m \cdot s^{-1}}$.

1.2 Experimental Design

Based on differences in vegetation cover, three typical dune types (fixed dunes, semi-fixed dunes, and mobile dunes) were selected as study objects (Table 1), with dune morphological characteristics kept as consistent as possible. A transect was established from the windward slope bottom to the leeward slope bottom on each dune. Groundwater observation wells were installed at the dune bottom, middle slope, and crest positions along each transect. The observation wells consisted of PVC pipes ($\Phi = 6.6$ cm), with depths reaching the groundwater table. Groundwater level changes were monitored manually, with observations beginning on October 15, 2018. During the non-growing season (November-April), measurements were taken once per month; during the growing season (May-October), measurements were taken during the early, middle, and late parts of each month, with additional observations following rainfall events. Soil moisture content was measured concurrently with groundwater observations, with sampling points adjacent to the observation wells. Samples were taken at 10 cm intervals from 0-200 cm depth, with three replicates per point. Soil moisture content was determined using the oven-drying method. Soil bulk density and capillary water holding capacity were measured using the ring knife method. Meteorological data were obtained from the Ulan Odoi meteoration station, located approximately 5 km from the study area. Vegetation surveys were conducted in 10 m × 10 m plots (measuring length, width, height, basal diameter, and branch number), with vegetation cover calculated as the ratio of plant projected area to plot area.

1.3 Data Statistical Analysis

Data analysis and graphing were performed using Origin and SPSS 21.0 software. Descriptive statistical analysis, one-way ANOVA, and bivariate correlation analysis were conducted.

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2. Results

2.1 Rainfall Characteristics During the Study Period

As shown in Figure 2, during the entire observation period (October 15, 2018 to October 15, 2019), a total of 45 rainfall events occurred, with cumulative rainfall of 320.6 mm. Individual rainfall amounts ranged from 0.1–49.3 mm, with 10 events exceeding 30 mm. Rainfall was concentrated in July and August, accounting for 81.45% of the total rainfall during the observation period.

[Figure 2: see original paper]

2.2 Effects of Vegetation and Slope Position on Soil Moisture

2.2.1 Influence of Vegetation on Spatiotemporal Variation of Dune Soil Moisture Figure 3 shows that soil moisture content in different dune types exhibited clear temporal fluctuations throughout the observation period, with variation trends influenced by rainfall distribution and increasing with rainfall amount. During periods of high cumulative rainfall (mid-July to early August), soil moisture content in all dune types reached relatively high values, while during low-rainfall periods (April–May), soil moisture content decreased to its lowest values. Correlation analysis between average soil moisture content across the entire sampling profile and rainfall revealed significant correlations for mobile and fixed dunes. Although semi-fixed dunes showed no statistically significant correlation between soil moisture and rainfall distribution, Figure 3 indicates similar variation trends.

[Figure 3: see original paper]

In addition to rainfall distribution, soil moisture content was also affected by vegetation conditions in the area. Figure 4 reveals that different dune types showed distinct vertical trends in soil moisture content. The minimum soil moisture values all occurred in the 0–10 cm layer, with specific values of 0.028 $g \cdot g^{-1}$ for mobile dunes, 0.029 $g \cdot g^{-1}$ for semi-fixed dunes, and 0.027 $g \cdot g^{-1}$ for fixed dunes. The depth of maximum values differed among dune types: 0.050 $g \cdot g^{-1}$ at 180–190 cm for mobile dunes, 0.040 $g \cdot g^{-1}$ at 80–100 cm for semi-fixed dunes, and 0.036 $g \cdot g^{-1}$ at 80–100 cm for fixed dunes. The vertical patterns were: increasing with depth in mobile dunes, initially increasing then decreasing in semi-fixed dunes, and remaining relatively stable at low levels in fixed dunes. Vegetation cover also significantly affected overall soil moisture content among dune types (Figure 4), showing the pattern: mobile dunes > semi-fixed dunes >

fixed dunes, indicating that higher vegetation cover corresponded to lower soil moisture content.

[Figure 4: see original paper]

2.2.2 Influence of Slope Position on Soil Moisture Throughout the observation period, slope position significantly affected soil moisture content, with the ranking: windward slope bottom > leeward slope bottom > middle windward slope > dune crest > middle leeward slope. The average soil moisture contents for windward slope bottom, middle slope, dune crest, middle leeward slope, and leeward slope bottom were 0.041 $g \cdot g^{-1}$, 0.038 $g \cdot g^{-1}$, 0.037 $g \cdot g^{-1}$, 0.035 $g \cdot g^{-1}$, and 0.040 $g \cdot g^{-1}$, respectively. Comparison with rainfall data shows that cumulative rainfall during observation intervals directly affected soil moisture levels. The highest cumulative rainfall occurred in mid-July, while the lowest occurred in April. Correspondingly, the highest soil moisture values in middle windward slope appeared in late July (0.046 $g \cdot g^{-1}$), while other positions peaked in mid-July, with values of 0.049 $g \cdot g^{-1}$ (windward slope bottom), 0.045 $g \cdot g^{-1}$ (middle slope), 0.045 $g \cdot g^{-1}$ (dune crest), and 0.047 $g \cdot g^{-1}$ (leeward slope bottom). The lowest soil moisture values occurred in mid-April for middle slope and dune crest (0.029 $g \cdot g^{-1}$ and 0.026 $g \cdot g^{-1}$, respectively) and mid-May for slope bottom positions (0.027 $g \cdot g^{-1}$ for both windward and leeward).

[Figure 5: see original paper]

Figure 6 shows that soil moisture at different slope positions remained relatively stable in the 0–150 cm layer without significant fluctuations. However, below 150 cm, differences became more pronounced, with slope bottom positions showing significantly higher soil moisture than other positions. The average soil moisture contents below 150 cm for windward slope bottom, middle slope, dune crest, middle leeward slope, and leeward slope bottom were 0.046 $g \cdot g^{-1}$, 0.041 $g \cdot g^{-1}$, 0.033 $g \cdot g^{-1}$, 0.041 $g \cdot g^{-1}$, and 0.049 $g \cdot g^{-1}$, respectively. This may be due to shallower groundwater depth at slope bottoms, where deep soil moisture receives groundwater recharge.

[Figure 6: see original paper]

2.3 Effects of Vegetation and Slope Position on Groundwater Fluctuation

2.3.1 Influence of Vegetation on Groundwater Fluctuation Amplitude Figure 7 shows that groundwater levels exhibited an initial rise followed by a decline throughout the observation period. The period from October 2018 to April 2019 represented a groundwater recovery phase, while May to October 2019 was a decline phase, showing an overall decreasing trend. During the recovery phase, groundwater levels rose up to 0.21 m above the initial level, while during the decline phase, they fell to 0.18 m below the initial level. Different vegetation covers caused distinct differences in groundwater fluctuation amplitude. Compared to initial water levels, semi-fixed dunes showed the greatest variation, rising up to 0.22 m during the recovery phase and falling to 0.29 m during the decline phase. Fixed dunes showed moderate variation (0.08 m rise, 0.22 m fall), while mobile dunes showed the smallest variation (0.12 m rise, 0.10 m fall).

[Figure 7: see original paper]

2.3.2 Influence of Slope Position on Groundwater Fluctuation Amplitude Slope position directly affected groundwater fluctuation patterns. As shown in Figure 8, using October 2018 groundwater levels as a baseline, all slope positions showed net declines throughout the observation period, with lower slope positions showing smaller declines. The smallest declines occurred at slope bottoms (0.03 m for windward, 0.08 m for leeward), followed by middle slopes (0.19 m for windward, 0.20 m for leeward), while dune crests showed the largest declines (0.24 m). Additionally, lower slope positions generally showed higher peaks during the recovery phase and lower troughs during the decline phase. During recovery, windward and leeward slope bottoms rose 0.31 m and 0.20 m, respectively, while middle slopes rose 0.24 m (windward) and 0.21 m (leeward), and the crest rose 0.17 m. During the decline phase, windward and leeward slope bottoms fell 0.09 m and 0.03 m, respectively, while middle slopes fell 0.24 m (windward) and 0.19 m (leeward), and the crest fell 0.17 m.

[Figure 8: see original paper]

The coefficient of variation was highest at windward slope bottom, followed by leeward slope bottom. Among different dune types, fixed dunes showed the highest coefficient of variation, followed by semi-fixed dunes, with mobile dunes showing the lowest, indicating that vegetation affects groundwater variability. The largest ranges occurred at semi-fixed dunes (0.68 m for windward slope bottom, 0.89 m for middle slope), while the maximum standard deviation occurred at fixed dunes (0.6 m at windward slope), consistent with the coefficient of variation patterns.

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3. Discussion

In arid and semi-arid regions, water is a crucial component of the ecological environment and the primary limiting factor for ecosystem functioning, serving as the essential source for all life [11]. Precipitation and groundwater are the main sources of water replenishment, with rainfall amount and groundwater depth being key determinants of soil moisture conditions [12]. Rainfall recharge of soil moisture is influenced by rainfall magnitude, soil texture, geomorphology, and vegetation [13]. This study examined the effects of different vegetation covers (dune types) and groundwater depths (slope positions) on soil moisture content. Under varying vegetation cover, we found that higher vegetation cover corresponded to lower soil moisture content, consistent with numerous studies

[14-16]. This occurs because vegetation characteristics affect rainfall interception, plant transpiration, and root water uptake processes, thereby influencing underlying soil moisture. Under different groundwater depth conditions, we found that deep soil moisture content was higher at slope bottoms with shallowest groundwater, suggesting possible groundwater recharge, while no such effect was observed at middle slopes and dune crests with deeper groundwater. Groundwater recharge of soil moisture primarily occurs through capillary rise and vapor condensation [17-18]. Capillary rise is influenced by soil physical properties; Zhou et al. [19] found that capillary water rise height in typical desert soil profiles is mainly affected by soil bulk density and clay content, with rise heights of approximately 120 cm in three typical soil types. Most studies indicate capillary water rise heights of 150–152 cm [20-21]. Groundwater vapor condensation replenishes deep soil moisture as film water [22]. In this study, groundwater depths at middle slopes and dune crests far exceeded these thresholds, while deep soil moisture at slope bottoms may receive groundwater recharge, explaining the significant differences in deep soil moisture between slope bottom and other positions (Figure 9).

[Figure 9: see original paper]

Previous research has identified numerous factors affecting groundwater fluctuations, including precipitation characteristics, annual precipitation totals, vadose zone lithology, infiltration depth, and surface morphology-vegetation development processes [23-24]. This study found that vegetation cover in dune areas primarily affects groundwater fluctuation amplitude. Fixed dunes with the highest vegetation cover showed the greatest groundwater level fluctuations and highest coefficient of variation, indicating that vegetation influences groundwater recharge processes by affecting rainfall infiltration. Several mechanisms may explain this: (1) During the growing season, high temperatures and evaporation rates cause substantial water loss through canopy interception and surface evaporation shortly after rainfall; (2) Areas with higher vegetation cover consume more soil water through root uptake and transpiration, reducing deep percolation and groundwater recharge [25]; and (3) In arid and semi-arid regions with shallow groundwater, vegetation can supplement water by absorbing groundwater [26], and fixed dunes with the highest vegetation cover consequently show the greatest variability. These processes demonstrate that vegetation is a major factor influencing groundwater fluctuations in dunes.

Additional factors affect groundwater fluctuations. Temperature decreases reduce evaporation rates [27], and during freeze-thaw periods, the insulating effect of frozen layers drastically reduces water exchange between groundwater and the atmosphere [28], causing soil moisture to continuously rise and groundwater levels to recover during the non-growing season. Rainfall also affects groundwater fluctuations; previous studies indicate that in extremely arid regions, only extreme rainfall events can cause groundwater level rises [29-30], a conclusion supported by this study. Analysis of several large rainfall events (>30 mm) revealed that groundwater levels rose or their decline slowed following substantial rainfall. However, groundwater level rise did not show a consistent increasing trend with rainfall amount (Figure 10), possibly due to varying rainfall characteristics and differences in temperature, vegetation conditions, and other factors.

[Figure 10: see original paper]

Dune slope position also influences groundwater fluctuation amplitude. As slope position increases, vadose zone thickness increases and groundwater depth becomes greater, lengthening the rainfall infiltration pathway to groundwater and creating temporal lags in recharge, thereby producing differences in groundwater fluctuation patterns. Dune slope gradient also affects fluctuation amplitude; gentler slopes facilitate vertical infiltration and groundwater recharge [31], enhancing groundwater fluctuations, while steeper slopes promote greater lateral flow during rainfall infiltration [32], slowing groundwater recharge and reducing fluctuation intensity. Research on groundwater evaporation indicates that shallow groundwater can recharge upper soil moisture through capillary rise and vapor condensation, promoting evaporation [33], and shallow groundwater receives more direct and obvious precipitation recharge [34].

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4. Conclusions

1) During the growing season, vegetation cover is a primary factor affecting soil moisture content. Higher vegetation cover corresponds to lower soil moisture, manifested as: mobile dunes > semi-fixed dunes > fixed dunes. Slope position also affects soil moisture, with slope bottoms showing higher moisture content than other positions.

2) Groundwater depth shows clear recovery during the non-growing season and continuous decline during the growing season. Different vegetation covers cause varying groundwater fluctuation patterns, with the degree of variation following: fixed dunes > semi-fixed dunes > mobile dunes. Different slope positions also cause varying groundwater fluctuations, with the degree of variation following: windward slope bottom > leeward slope bottom > middle leeward slope > middle windward slope > dune crest. When cumulative rainfall within a short period or single rainfall events exceed 30 mm, groundwater levels show slow recovery or slowed decline.

3) Deep soil moisture content at dune bottoms is higher than at other slope positions, suggesting possible groundwater recharge. The better soil moisture conditions at dune bottoms are more conducive to sand-fixing vegetation establishment, providing practical guidance for rational vegetation pattern design in sand fixation efforts.

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