Shallow Soil Moisture Variation and Its Influencing Factors in the Alpine Region of the Upper Heihe River Basin (Postprint)

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Abstract

Soil water constitutes the foundation of vegetation ecosystems. Employing statistical and correlation analysis methods, this study investigated shallow soil moisture and its influencing factors across different ecological grassland types in the upper reaches of the Heihe River. The results indicate that under natural conditions, precipitation in the upper Heihe River basin determines the spatial distribution of soil moisture content; however, agricultural cultivation activities enhance infiltration, reducing soil moisture content in the 30 cm soil layer while increasing water content in deeper layers. Analysis of the primary influencing factors across different soil layers reveals that precipitation exerts a strong influence on fluctuations in surface 0–20 cm soil moisture during the plant growing season. Additionally, the 20 cm soil layer exhibits maximum water content due to precipitation interception by plant stems and dense root distribution. Conversely, temperature variations affect soil temperature and predominantly influence soil moisture during the non-growing season and below the 30 cm soil layer, leading to an extended vegetation growing season and shortened freezing period in the study area, thereby altering the regional hydro-ecological environment.

Full Text

Preamble

Changes in Shallow Soil Moisture and Its Influencing Factors in the High Mountain Areas of the Upper Heihe River

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Abstract

Soil water constitutes the foundation of vegetation ecosystems. Using statistical and correlation analysis methods, we analyzed shallow soil moisture and its influencing factors across different ecological grassland types in the upper reaches of the Heihe River. The results demonstrate that under natural conditions, precipitation determines the spatial distribution of soil moisture content in the upper Heihe River basin. However, agricultural cultivation activities enhance infiltration, reducing soil moisture content in the 30 cm soil layer while increasing water storage in deeper layers. Analysis of the main influencing factors for soil moisture at different depths reveals that precipitation exerts a strong influence on the fluctuation of surface soil moisture (0–20 cm) during the plant growing season. The 20 cm soil layer exhibits the highest water content due to precipitation interception by plant stems and dense root distribution. Temperature variation affects soil temperature and primarily influences soil moisture below the 30 cm layer during the non-growing season, leading to extended vegetation growth periods and shortened freezing periods in the study area, thereby altering the regional hydro-ecological environment.

Keywords: Alpine region; Soil moisture; Influencing factors; Climate change

Introduction

Soil water, defined as water stored in soil pores, serves not only as the material basis for ecosystem existence but also as a driving factor in the hydrological cycle [1]. Soil moisture is comprehensively influenced by precipitation, temperature, vegetation, soil properties, and topography, exhibiting distinct distribution characteristics across temporal and spatial scales [2-6]. Climate change alters soil water-heat processes, and soil moisture in alpine cold regions, affected by frigid climates and slope conditions, displays even more complex spatiotemporal patterns [7-8]. Investigating soil hydrological processes in high-altitude mountainous areas represents a core component for understanding hydrological cycles in alpine runoff generation zones and ecological environment changes, constituting a critical focus of soil-hydrology-atmosphere research against the backdrop of global climate change. While existing studies have achieved certain results regarding the spatiotemporal heterogeneity of soil moisture [9-10], research on influencing factors of moisture variation in each soil layer remains limited, making studies on shallow soil moisture changes in alpine mountainous areas particularly significant.

The upper Heihe River region belongs to a high-altitude, cold ecosystem, characterized by extensive natural alpine grasslands and forest-grassland transition zones. However, in the eastern areas suitable for human habitation, agro-pastoral transition grasslands influenced by agricultural cultivation are also distributed [11]. In recent years, climate change has induced alterations in water-heat processes of alpine ecosystems. The high-altitude, cold region of the upper Heihe River is sensitive to climate change and ecologically fragile, attracting widespread attention to hydrological research in the Heihe River basin [12-13]. Chen et al. [14] conducted quantitative analysis of the hydrological cycle and water-heat coupling processes in the upper Heihe River mountainous area through systematic observation and mathematical modeling. Peng et al. [15-16] studied the eco-hydrological effects of forest growth states through observations in the upper Heihe River. Liu et al. [17] analyzed seasonal precipitation across the entire basin and its impact on runoff. Wang et al. [18] and Tang et al. [19] examined the relationship between soil moisture and vegetation spatial variability and conducted single-factor analysis of soil saturated hydraulic conductivity. Bai et al. [9] analyzed the influence of vegetation characteristics on soil moisture in the upper Heihe River. However, current hydrological process research in the Heihe River basin primarily focuses on large-scale, single-factor, and easily observable hydrological processes and their ecological effects, with limited investigation into influencing factors of shallow soil moisture changes under human activity impacts.

This study focuses on the alpine ecosystem—the primary runoff generation ecological type in the upper Heihe River—employing geostatistical methods to analyze hydro-thermal factors directly affecting shallow soil moisture changes in vegetation ecosystems. The research investigates soil moisture variation processes in each layer under the influence of climate warming and human cultivation activities, providing a theoretical basis for further study and analysis of alpine grassland hydrological cycle processes, effective evaluation of mountain water resource dynamic balance, and construction of alpine hydrological models against the backdrop of global climate change.

1.1 Study Area

The study area is located in the alpine grassland and agro-pastoral transition zone of the upper Heihe River, with three typical plots representing different grassland types selected for experimental observation . The Biandukou agro-pastoral transition grassland experimental site is situated on a slope in the Qilian Mountains within Minle County, flanked by pastures and dry farmland. The Dayekou forest-grassland transition plot is established on a flat platform between cold alpine forests and grasslands in Sunan Yugur Autonomous County. The Kangle alpine grassland plot is located on a piedmont slope, serving as a winter pasture that was fenced for one year prior to observation. The study area is dominated by arid and semi-arid vegetation with plant heights ranging from 5–30 cm and root systems distributed primarily in the 0–30 cm soil layer, with fibrous roots mainly concentrated in 0–10 cm. Gramineae and Cyperaceae vegetation are widely distributed. Kangle grassland has the lowest vegetation coverage at 30%, dominated by *Agropyron cristatum* and *Carex*. Biandukou and Dayekou have vegetation coverage of 95% and 60%, respectively. In addition to dominant

Agropyron cristatum and *Carex* species, they also contain considerable amounts of *Stellera chamaejasme* and species from Rosaceae and *Potentilla chinensis*. Soil and meteorological factors were independently observed and recorded at each experimental site. The three grassland type plots are distributed from east to west in the upper Heihe River, showing distinct type differences, designated as agro-pastoral transition zone, forest-grassland transition zone, and alpine grassland.

1.2.1 Data Collection

In each of the three typical grassland types in the upper Heihe River, observation plots were selected in relatively flat areas with natural ecological conditions and representative characteristics. Instruments were installed at the center of each plot for experimental observation and data collection. Collected data included: (1) soil property data: clay, silt, sand, saturated hydraulic conductivity, and bulk density; (2) primary meteorological data: precipitation and air temperature; and (3) hydro-thermal data: soil volumetric water content within 40 cm below the surface and corresponding soil temperatures. Meteorological data were automatically collected by a self-recording weather station (Model: WatchDog 2000, Spectrum Technologies, USA), including net radiation, 2 m air temperature, relative humidity, rainfall, wind speed, and wind direction at 30-minute intervals. Soil moisture and temperature data were continuously and automatically collected using ECH2O 5TE sensors (Decagon Devices, USA) with probes installed at four depths (0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm). Each group simultaneously collected soil moisture and temperature at 30-minute intervals. The experimental observation period was from January to December 2018. Concurrently, soil profiles were excavated within the study plots, and soil samples were collected at corresponding depths using cutting rings for laboratory testing of soil property data for each layer.

1.2.2 Research Methods

Soil saturated hydraulic conductivity was measured using the constant head method, dry bulk density by oven-drying and weighing, and soil particle size by a Mastersizer 2000 laser particle size analyzer. The coefficient of variation (Cv) was used for spatiotemporal variability analysis, and Pearson two-tailed correlation tests were employed to analyze relationships among influencing factors. Statistical analysis was performed using SPSS 25.0 software, and figures were created using Origin 2018 software.

2.1 Soil Characteristics

Analysis of underlying surface factor characteristics for the three typical grasslands in the upper Heihe River reveals that surface soils are primarily silt loam [Figure 1: see original paper]. Biandukou agro-pastoral transition grassland soil is silty, Dayekou forest-grassland transition grassland is silty (sandy) clay loam, and Kangle alpine grassland is silty (sandy) soil. Below 30 cm, the forest-grassland transition grassland soil is primarily gravel detritus layer, with internal soil structure affecting saturated hydraulic conductivity, bulk density, soil permeability, and other properties.

Biandukou grassland has 95% vegetation coverage, with the highest silt proportion (84.4%) and lowest sand proportion (9.5%). Its soil saturated hydraulic conductivity increases with depth in the 0–30 cm layer but decreases sharply at 40 cm. Agricultural activities have led to relative enrichment of organic matter in the 10 cm layer, resulting in the lowest soil bulk density. With increasing depth, organic matter content decreases while bulk density increases, reaching 1.1 $g \cdot cm^{-3}$ at 40 cm. Dayekou grassland has 60% vegetation coverage, with decreasing silt content and increasing sand content compared to the agro-pastoral transition grassland (73.6% and 19.9%, respectively). The difference between maximum and minimum saturated hydraulic conductivity across soil layers is only 0.05 $m \cdot d^{-1}$, indicating generally consistent shallow soil structure in the forest-grassland transition zone, while bulk density shows a clear increasing trend from 10–20 cm. Kangle alpine grassland has the lowest vegetation coverage (30%), with the highest sand content and lowest clay and silt contents (27.9%, 67.2%, and 4.91%, respectively). Its overall saturated hydraulic conductivity is relatively small but varies significantly among soil layers, with the surface 10 cm layer being approximately three times that of the 40 cm layer. This indicates that alpine grassland soil texture and structure show obvious differences with increasing depth. Bulk density is higher in the surface 10 cm and deep 40 cm layers than in the intermediate 20 cm and 30 cm layers, suggesting surface soil erosion and desertification in alpine grasslands. Higher vegetation coverage facilitates soil water storage and infiltration through dense root networks and soil organic matter, providing stronger precipitation buffering capacity. Silty soil structures are relatively loose with low sand content, high porosity, good connectivity, and strong water conductivity. In contrast, soils with low silt and high sand content have dense structures with poor water storage and conductivity, resulting in low vegetation coverage.

2.2 Soil Moisture Characteristics

Soil moisture is a primary environmental factor and major component of soil. Its variation is influenced by soil properties, vegetation, and atmospheric conditions, showing certain variability in spatiotemporal distribution. Analysis of spatiotemporal distribution and variability of shallow soil moisture in the study plots reveals that the 20 cm soil layer has the highest moisture content, while the 40 cm layer has the lowest in upper Heihe River grasslands. Dayekou forest-grassland transition grassland shows the highest soil moisture content during the growing season but lower content than Biandukou agro-pastoral transition grassland during the freezing period. Biandukou agro-pastoral transition grassland shows the smallest difference among soil layers, with an annual daily average soil moisture content of only 3.1% in 2018 and 3.5% during the growing season. The

10 cm layer in Biandukou agro-pastoral transition and Kangle grasslands shows the highest variation coefficient during the growing season, while the 30 cm layer in Dayekou and Kangle grasslands shows the lowest variation coefficient.

2.3.1 Precipitation

The upper Heihe River belongs to an alpine climate type, but regional differences in geographical location, elevation, and underlying surfaces among plots cause spatial variation in rainfall intensity, though overall precipitation patterns are consistent. Monthly rainfall at the three typical plots is shown in [Figure 2: see original paper]. In 2018, the study area experienced low total precipitation and relatively low maximum rainfall intensity, with the plant growing season and rainy period concentrated from April to September. Biandukou agro-pastoral transition grassland received the highest total precipitation (430.0 mm) with a maximum daily precipitation of 26.2 mm. Dayekou and Kangle grasslands received similar annual precipitation (290.3 mm and 257.3 mm, respectively) with maximum daily precipitation of 18.3 mm and 24.4 mm. Biandukou and Dayekou grasslands had the most abundant precipitation in July (113.3 mm and 84.3 mm, respectively), decreasing from August with no precipitation in December and January. Kangle alpine grassland had maximum precipitation in August (93.7 mm), showing a temporal delay.

2.3.2 Air Temperature and Soil Temperature

Temperature variation affects evapotranspiration intensity and soil temperature, influencing land surface hydrological cycles and soil water storage and transport. The upper Heihe River has a consistent climate type with small spatial temperature variation . In 2018, Biandukou and Kangle grasslands had higher annual daily average air temperatures, with soil temperatures significantly higher than air temperature. Dayekou grassland had the lowest air temperature, with soil temperature essentially equal to or slightly higher than air temperature. During the growing season, Dayekou grassland had the highest air temperature but the lowest soil temperature, with only the 10 cm layer slightly higher than air temperature while deeper layers were cooler. Biandukou grassland had the lowest air temperature but relatively high soil temperature. Daily maximum air temperatures occurred on July 25 at all sites (23.0°C, 20.7°C, and 19.6°C for Biandukou, Dayekou, and Kangle, respectively), while daily maximum soil temperatures occurred later, with increasing delay at greater depths. Daily average air temperature began showing negative values on October 19, while daily average soil temperature showed negative values later, with Dayekou soil temperature dropping below 0°C earliest and Biandukou latest, with longer delays at greater depths. Soil temperature shows significant positive correlation with air temperature , weakening with depth and decreasing during the growing season, except for an increase in the 20 cm layer at Kangle grassland.

3.1 Interaction Between Precipitation and Soil Moisture

Analysis of precipitation and soil moisture content at typical plots in the study area [Figure 3: see original paper] shows that the three study regions belong to the alpine zone of the upper Heihe River, where soil freezing occurs in winter. During the freezing period, soil moisture conditions change with low water content, and solid precipitation has weak direct interaction with soil moisture due to low winter precipitation. In early March, rising temperatures cause soil thawing and gradual, stable increases in soil moisture until the rainy season arrives in July, when high-intensity, high-frequency precipitation induces strong fluctuations in soil moisture.

Analysis indicates that soil moisture in the upper Heihe River originates primarily from precipitation and seasonal frozen soil thawing [20], with spatial precipitation distribution largely determining the overall level and fluctuation patterns of soil moisture [21]. In Dayekou and Kangle grasslands unaffected by human production activities, precipitation fluctuations strongly influence only the surface 20 cm layer, with variation amplitudes of 14.2% and 11.2% in the 10 cm layer and 18.3% and 9.1% in the 20 cm layer during the growing season. The 20 cm layer, with dense plant roots, shows the highest water content (19.3% and 10.8%) due to precipitation interception by vegetation and stemflow. Below 20 cm, soil moisture gradually accumulates through replenishment from previous precipitation and stabilizes, showing weak short-term response to individual rainfall events and small variation amplitude. Due to uneven spatial precipitation distribution, Kangle grassland receives low annual precipitation, affecting the vegetation ecological environment, resulting in the lowest vegetation coverage and dense soil structure that limits soil water storage and transport, leading to significantly lower soil moisture than Dayekou forest-grassland transition grassland .

However, human agricultural activities have altered the 30 cm soil layer structure and composition, improving soil hydraulic conductivity. This causes strong, consistent fluctuations in the 30 cm layer at Biandukou agro-pastoral transition grassland under precipitation variation [Figure 3: see original paper], while the 40 cm layer shows weak fluctuation due to higher water content from upper layer replenishment and soil regulation. Although Biandukou receives the most abundant precipitation, human activities have reduced its 30 cm layer moisture content below that of Dayekou grassland, with maximum differences of 2.3% in the 10 cm and 20 cm layers. Conversely, the 40 cm layer shows significantly higher moisture content than Dayekou (5.1% difference), primarily because crop growth consumes substantial surface soil moisture and altered soil structure enhances surface infiltration, creating a spatial distribution pattern that differs from precipitation distribution. In precipitation-deficient Kangle alpine grassland, severe water shortage and soil desertification have altered local plant growth conditions, resulting in the lowest vegetation coverage and overall soil moisture content, with the 20 cm layer reaching only 10.8% and shallow precipitation influence.

In summary, the upper Heihe River is a semi-arid region where precipitation is the key factor determining soil moisture spatial distribution and short-term fluctuations [23]. Spatially, precipitation shows an east-west decreasing trend, with its spatiotemporal variation determining the overall level of soil moisture distribution—higher precipitation corresponds to higher soil moisture content. However, human activities strongly influence soil profile moisture distribution, reducing moisture in the 30 cm layer while enhancing shallow infiltration and deep layer accumulation. Under global climate change, increasing precipitation in the upper Heihe River [13] will raise soil moisture content, promoting deep soil water storage in agricultural areas, improving agricultural productivity, ecological environment, and living standards, and fostering harmonious human-nature coexistence. In precipitation-deficient areas, increased precipitation will promote plant growth, alleviate soil desertification, improve soil structure, directly affect local soil-vegetation hydrological cycles, and consequently alter regional hydrological cycles and spatiotemporal patterns of water resources in inland river basins.

3.2 Relationship Between Soil Temperature and Soil Moisture

Based on 2018 data of soil temperature and moisture variation processes across different underlying surfaces in the upper Heihe River, Pearson correlation analysis was conducted [FIGURE:4, TABLE:5]. During the growing season, soil moisture in the 30 cm and 40 cm layers correlates well with soil temperature, while the surface 20 cm layer, despite strong fluctuation, shows no significant correlation with soil temperature [24]. This occurs because during the growing season, rising temperatures, crop growth, and precipitation create complex interactions, making the effect of soil temperature on shallow moisture weak. The regulation effect of upper soil layers allows deeper soil moisture to show stronger correlation with weak temperature fluctuations. Across different seasons, soil moisture shows significant positive correlation with soil temperature, weakening with depth and becoming weakest at 40 cm. This indicates that during cold winters, soil temperature changes driven by air temperature are the primary factor affecting soil moisture, while in summer, complex factors influence soil moisture variation, with air temperature effects on deep soil being more pronounced than on surface soil but generally weak overall.

Temperature, as an important driver of soil water migration, affects soil water redistribution by influencing water occurrence forms and activity intensity [25]. The upper Heihe River has similar climate types with small temperature differences (0.28°C annually and 0.35°C during the growing season). However, differences in vegetation coverage and human activities cause substantial variation in soil temperature. Dayekou forest-grassland transition grassland, minimally affected by human activities with good ecological conditions, has the lowest soil temperature, closest to air temperature. During the growing season, the 30 cm layer shows the largest soil moisture difference (1.05°C), with abundant water content regulating both soil temperature and regional hydrological cycles, resulting in the best correlation between soil moisture and temperature . Although Kangle alpine grassland has low surface vegetation coverage, the presence of surface crust provides insulation and water retention, making soil temperature significantly higher than air temperature (minimum 2.8°C difference at 40 cm). Limited interaction between surface soil moisture and the atmosphere strengthens the correlation between soil moisture and temperature with depth. Agricultural activities at Biandukou have created a surface layer with abundant residual plant roots that limit energy transfer, altering local soil water-heat exchange processes that mainly affect the cold non-growing season . Surface infiltration has increased the relative water content in the deeper 40 cm layer, with only 3.5% difference between the 20 cm and 40 cm layers during the growing season. Under ongoing global warming, rising temperatures in the upper Heihe River directly increase soil temperature, advancing shallow soil thawing time and delaying freezing [26], shortening the freezing period and reducing frozen depth. This increases soil moisture loss through evapotranspiration and subsurface flow, potentially decreasing shallow soil moisture content and altering soil water-heat exchange intensity and processes. These changes affect alpine cold region land surface hydrological cycles, impact the security and stability of original ecosystems, and influence regional hydrological processes and spatiotemporal water resource distribution.

Conclusions

Based on analysis of shallow soil moisture and its influencing factors across different grassland ecological types in the upper Heihe River high mountain area, the following conclusions were drawn:

(1) Under natural conditions, soil moisture distribution in the upper Heihe River is determined by precipitation, showing an east-high, west-low trend. However, human production activities alter shallow soil structure and basic properties, reducing moisture content in the surface 30 cm layer while enhancing infiltration capacity and increasing water content in deeper layers.

(2) Analysis of main influencing factors reveals that in the upper Heihe River alpine region, air temperature primarily affects soil moisture during the non-growing season and below the 30 cm layer, while precipitation strongly influences fluctuations in surface soil moisture (0–20 cm) during the growing season.

(3) Climate change will accelerate alterations in soil water-heat processes, leading to extended vegetation growth periods and shortened soil freezing periods. These changes modify soil hydrological cycling processes, further affecting spatiotemporal distribution of vegetation ecosystems and water resource conditions.

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