Response and Stability of Soil Moisture to Rainfall at Different Depths in the Loess Hilly and Gully Region (Postprint)

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Abstract

Through a point-area integrated methodology, this study analyzes the spatiotemporal variations of soil moisture at different depths under rainfall influence in the Loess Plateau region, extracting relative "invariance" from the complex "variability" of soil moisture. Results demonstrate that: soil moisture in the upper 20 cm exhibits no discernible regularity, making it difficult to characterize soil moisture differences among different vegetation types or spatial locations; rainfall events less than 30 mm essentially do not induce noticeable fluctuations in soil moisture below 40 cm; at a depth of 100 cm, soil moisture at each sampling point can remain at a stable value for several months, showing a stepwise increase after heavy rainfall exceeding 46 mm, before returning to a stable state; deeper soil layers exhibit more pronounced spatiotemporal stability of soil moisture, which can better characterize soil moisture differences across various vegetation types or spatial locations. This study, conducted from the perspective of soil moisture stability, holds practical application value for ground sampling design and spatiotemporal prediction of soil moisture in the Loess Plateau.

Full Text

Soil Moisture Response and Stability to Rainfall at Different Depths in the Loess Hilly-Gully Region

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Abstract

This study employs a point-area integration approach to analyze spatiotemporal variations of soil moisture at different depths under rainfall influence in the Loess Plateau, extracting relative "invariance" from complex soil moisture "variability." Results demonstrate that soil moisture above 20 cm depth exhibits frequent fluctuations without clear patterns, making it difficult to characterize differences across vegetation types or spatial positions. In the 40–80 cm layer, rainfall events less than 30 mm produce minimal response, while soil moisture among different vegetation types shows stable relative differences that persist throughout the rainy season. At 100 cm depth, soil moisture remains stable for months, with only heavy rainfall exceeding 46 mm causing stepwise increases, after which moisture levels stabilize at a new equilibrium. Spatial stability also increases with depth: locations with high soil moisture before the rainy season remain high afterward, and low locations remain low. This temporal stability of spatial patterns becomes particularly pronounced below 80 cm. These findings indicate that deep soil moisture measurements are essential for reliably comparing soil water conditions across different land-use types or spatial positions. The study provides practical guidance for ground-based sampling design and temporal-spatial prediction of soil moisture in the Loess Plateau.

Keywords: soil moisture; stability; precipitation; Loess Plateau

1. Study Area Overview

The study area is located in the Yangjuangou small watershed north of Yan' an City, Shaanxi Province, representing a typical Loess hilly-gully region [Figure 1: see original paper]. The watershed covers approximately 2 km^2 and experiences a semi-arid continental monsoon climate with a mean annual precipitation of 535 mm, concentrated between June and September and characterized by heavy storms. Soils are predominantly loessal silt (loess parent material) with poor erosion resistance and severe water loss. Natural vegetation has been largely destroyed, resulting in high cultivation intensity. Land use consists mainly of slope farmland, terraced cropland, orchards, grassland, artificial sea buckthorn forest, and artificial locust forest [cite].

2. Experimental Design

2.1 Monitoring Sites and Instrumentation

Five typical land-use type plots were established (TABLE:1), each equipped with a soil moisture monitoring system (5TE Soil Moisture and Temperature Monitoring System). Soil moisture sensors were installed at depths of 10 cm, 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm, recording volumetric water content every 10 minutes. A rain gauge was installed in the watershed for synchronous precipitation monitoring. The plots have slopes of approximately 20° with west-facing aspects. Monitoring point locations are shown in [Figure 1: see original paper].

Plot vegetation conditions: - **Locust forest:** Artificial forest with *Robinia pseudoacacia* trees spaced at 2.5 m × 3.0 m - **Shrubland:** Dense *Spiraea pubescens* with scattered locust trees - **Grassland 1:** Dominant species *Artemisia gmelinii* with mosaic patches of bare ground and grass - **Grassland 2:** Dominant species *Bothriochloa ischaemum* (natural succession after farmland abandonment) - **Farmland:** Corn (*Zea mays*) cultivated in dam land at gully bottom

Data from June to September 2015 were analyzed, covering the period with most rainfall and greatest soil moisture variation. Although data from locust forest and cornfield were interrupted due to instrument failure, sufficient rainfall events occurred during normal operation periods to observe soil moisture responses.

2.2 Spatial Sampling Design

To investigate spatial pattern stability, a typical hill within the watershed was selected. Five transects were established radiating from hilltop to footslope in different directions [Figure 1: see original paper]. Along each transect, sampling points were spaced at 5 m intervals. At each point, 100 cm deep boreholes were drilled to determine gravimetric soil water content at different depths using the oven-drying method. Soil bulk density was measured simultaneously to convert to volumetric water content. Sampling was conducted once at the beginning and once at the end of the rainy season.

3. Results

3.1 Temporal Variation of Soil Moisture Under Rainfall Influence

During the rainy season, 11 significant rainfall events occurred (TABLE:3). Soil moisture in the 10–20 cm layer responded to all rainfall events, showing rapid increases followed by gradual decreases under evapotranspiration. The relative ranking of soil moisture among different vegetation types frequently changed, indicating poor temporal stability [Figure 2: see original paper].

In the 40–80 cm layer, soil moisture response to rainfall decreased markedly. Only 3 rainfall events (with amounts >30 mm) caused noticeable increases. Despite multiple high-intensity rainfall events, the relative ranking of soil moisture among farmland, grassland, and shrubland remained unchanged throughout the rainy season. With increasing depth, the stability of relative differences among vegetation types became more pronounced.

At 100 cm depth, soil moisture stability was most prominent. Only 2 rainfall events (June 27, 76 mm; August 8–9, 58 mm) caused significant increases. Notably, without heavy or continuous rainfall, soil moisture at this depth remained stable for months. After heavy rainfall replenishment, soil moisture increased stepwise and maintained stability at the new level until the next heavy rainfall event [Figure 2: see original paper].

Pearson correlation analysis between pre- and post-rainy season soil moisture revealed correlation coefficients increasing from 0.60 at 20 cm to 0.92 at 100 cm ($P<0.01$), confirming that spatial patterns of soil moisture maintain good stability, which becomes more pronounced with depth.

3.2 Spatial Variation of Soil Moisture Under Rainfall Influence

In layers above 20 cm, soil moisture was highly sensitive to meteorological factors, fluctuating frequently under rainfall-evaporation influences. The relative differences among plots were unstable, making surface soil moisture measurements unsuitable for representing long-term conditions or comparing different spatial positions and vegetation types. Therefore, remotely sensed surface soil moisture should be used cautiously for small-patch land-use patterns in the Loess Plateau.

In the 40–80 cm layer, soil moisture was less affected by rainfall, with only events >30 mm causing significant changes. The relative ranking among vegetation types became stable. Spatial stability increased with depth, consistent with previous research [cite].

At 100 cm depth, only 2 rainfall events (>46 mm) caused significant changes in all plots. After each change, soil moisture remained stable at the new level for extended periods. Spatial stability was particularly evident: sampling points with high pre-rainy season moisture (e.g., points 1, 6, 11) remained high afterward, while low-moisture points (e.g., points 28, 29, 31) remained low. This "high stays high, low stays low" pattern was most pronounced below 80 cm, providing a valuable reference for spatial prediction of soil moisture.

4. Discussion and Conclusions

This study reveals that soil moisture below 40–100 cm can relatively stably characterize differences among vegetation types and spatial positions. For example, at 100 cm depth, soil moisture can maintain a stable state for months without continuous heavy rainfall. Accordingly, in practical sampling, measurement frequency for soil below 100 cm can be reduced to several-month intervals. This provides scientific justification for the widely used intermittent manual soil sampling method in the Loess Plateau.

Previous international research on soil moisture temporal stability employed numerous monitoring devices across small watersheds, ranking each point' s moisture relative to the watershed mean to identify stable representative sites [cite]. While effective, this approach is costly and spatially limited. In China, large-scale soil moisture surveys still predominantly rely on manual drilling methods with limited sampling frequency [cite]. The temporal stability analysis in this study helps simplify and rationalize manual sampling schedules. The findings have practical value for optimizing ground-based soil moisture monitoring and provide a reference for hydrological modeling and prediction in the Loess Plateau.

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