Distribution Characteristics of Surface Soil Moisture and Electrical Conductivity in the Kunes River Valley Postprint

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Abstract

Soil moisture and soil electrical conductivity are critical factors influencing vegetation growth and agricultural development. Traditional methods for measuring soil moisture and soil electrical conductivity are cost-prohibitive, leading to a paucity of research on these two soil variables at different spatial scales in mountainous watersheds based on observational data. This study employs measured surface soil moisture and electrical conductivity data, applying statistical methods to analyze the distribution characteristics and influencing factors of surface soil moisture and surface soil electrical conductivity in autumn across different spatial scales in the Kunes River Valley region of the western Tianshan Mountains. Results indicate: (1) In the Kunes River Valley, watershed-scale surface soil moisture increases significantly (P<0.01) with elevation at a rate of 10% per kilometer, but in the Alatubai small watershed, surface soil moisture first increases and then decreases with elevation; the average watershed-scale surface soil electrical conductivity is 17.51 mS · m-1, with no overall salinization in the surface soil, but electrical conductivity at some points within the 2000 ~ 2500 m elevation range exceeds 35 mS · m-1, indicating mild salinization; at the hillslope scale, significant differences exist in surface soil moisture and electrical conductivity among different slope aspects, with surface soil moisture on shady slopes (mean: 44.22%) > sunny slopes (mean: 22.83%), and surface soil electrical conductivity on sunny slopes (mean: 8.33 mS · m-1) > shady slopes (mean: 4.58 mS · m-1); (2) As spatial scale increases, environmental factors influencing soil characteristics become more complex, and the relationship between surface soil moisture and surface soil electrical conductivity gradually weakens; (3) Surface soil moisture across different land use types follows the order: grassland (mean 37.19%) > cropland (mean 37.04%) > forestland (mean 34.67%), while surface soil electrical conductivity follows: cropland (mean 17.36 mS · m-1) > grassland (mean 14.95 mS · m-1) > forestland (mean 13.81 mS · m-1). Under the influence of elevation, slope aspect, and land use type, both surface soil electrical conductivity and soil moisture in the Kunes River Valley region display moderate variability. This study is beneficial for the rational utilization of water and soil resources and ecological environmental protection in the Kunes River Basin.

Full Text

Spatial Distribution Characteristics of Surface Soil Moisture and Electrical Conductivity in the Kunes Valley

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Abstract

Soil moisture and soil electrical conductivity are critical factors influencing vegetation growth and agricultural development. Traditional measurement methods for these properties are costly, resulting in a lack of research based on measured data at different spatial scales in mountainous watersheds. This study utilizes measured surface soil moisture and electrical conductivity data, applying statistical methods to analyze the distribution characteristics and influencing factors of surface soil moisture and electrical conductivity during autumn across different spatial scales in the Kunes Valley of the western Tianshan Mountains. The results demonstrate: (1) At the watershed scale in the Kunes Valley, surface soil moisture increases significantly with altitude at a rate of <0.01 per kilometer. However, in the Alatubai small watershed, surface soil moisture first increases then decreases with altitude. The average surface soil electrical conductivity at the watershed scale is 17.51 $\mathrm{mS \cdot m^{-1}}$, indicating no overall surface soil salinization, though some points in the 2000–2500 m elevation range exceed 35 $\mathrm{mS \cdot m^{-1}}$, representing mild salinization. (2) At the slope scale, significant differences exist between aspects: surface soil moisture on north-facing slopes (mean: 44.22%) exceeds that on south-facing slopes (mean: 22.83%), while surface soil electrical conductivity on south-facing slopes (mean: 8.33 $\mathrm{mS \cdot m^{-1}}$) exceeds that on north-facing slopes (mean: 4.58 $\mathrm{mS \cdot m^{-1}}$). (3) As spatial scale increases, environmental factors influencing soil properties become more complex, and the relationship between surface soil moisture and electrical conductivity gradually weakens. (4) Across land use types, surface soil moisture follows the order: grassland (mean 37.19%) > cultivated land (mean 37.04%) > forest land (mean 34.67%); surface soil electrical conductivity follows: cultivated land (mean 17.36 $\mathrm{mS \cdot m^{-1}}$) > grassland (mean 14.95 $\mathrm{mS \cdot m^{-1}}$) > forest land (mean 13.81 $\mathrm{mS \cdot m^{-1}}$). Under the combined influence of altitude, aspect, and land use type, both surface soil electrical conductivity and moisture exhibit moderate variation in the Kunes Valley. This study provides valuable insights for rational water and soil resource management and ecological environmental protection in the Kunes River Basin.

Keywords: surface soil moisture; surface soil electrical conductivity; spatial distribution; Kunes River Basin

1. Introduction

Soil moisture and soil electrical conductivity are two essential soil attributes that influence soil productivity and environmental quality. Soil electrical conductivity is closely related to soil salinization, fertility, and pollution [1]. Soil moisture regulates material and energy exchange processes at the soil-atmosphere interface, directly affecting soil water potential, evapotranspiration, and ecosystem ecohydrological processes [2]. Therefore, studying the distribution characteristics of soil moisture and electrical conductivity is crucial for regional water and soil resource management and ecological construction.

Soil exhibits high spatial variability under natural and anthropogenic influences [3], with spatial distributions of soil physicochemical properties showing patchy or gradient patterns [4]. Research on the spatial distribution of soil moisture and electrical conductivity falls into two categories. The first category examines each property separately using geostatistical and classical statistical methods. For example, Zong et al. [5] analyzed spatial variability of soil moisture in the water source area of Hani terraces using measured data, finding that soil moisture exhibited high spatial autocorrelation, primarily influenced by land use, precipitation, and topography. Zhang et al. [6] investigated vertical variation, horizontal spatial heterogeneity, and distribution characteristics of soil moisture in alpine meadows of the Qilian Mountains, revealing close relationships with micro-topography, elevation, and distance from streams. Chai et al. [7] combined classical statistics, geostatistics, and GIS to analyze spatial variability of soil salinity around two reservoirs in the Fukang Sangong River basin of Xinjiang, showing moderate spatial autocorrelation primarily affected by human activities, micro-topography, climate, and groundwater level. Yin et al. [8] studied spatial variability of soil electrical conductivity in the Guohua karst area of Guangxi, finding arc-shaped, banded, and patchy distributions primarily controlled by vegetation coverage, geological background, and rocky desertification degree.

The second category examines soil moisture and electrical conductivity as part of broader soil physicochemical property studies. For instance, Wang et al. [9]

analyzed distribution characteristics of soil physicochemical properties under different vegetation cover conditions in the Heihe River basin, showing electrical conductivity followed the pattern downstream > midstream > upstream. An et al. [10] examined physicochemical properties of different Gobi soil types in the Hexi Corridor of Gansu, finding electrical conductivity closely related to Gobi type and groundwater depth. Diao et al. [11] studied soil physicochemical properties and spatial variability under three vegetation types on the southern slope of the Qilian Mountains, demonstrating that land use affects vertical differentiation of soil properties, with soil moisture, organic matter, and electrical conductivity showing strong spatial variability while pH showed weak variability.

These studies predominantly rely on field sampling followed by laboratory analysis. However, this approach is costly and time-consuming, limiting the number of sampling points and hindering research on soil moisture and electrical conductivity at different spatial scales in mountainous regions. Portable instruments offer advantages of compact size, rapid response, and convenient operation, substantially reducing time and labor costs compared to traditional methods, making them particularly suitable for regional-scale and mountainous applications.

The Kunes River Basin, located in the western Tianshan Mountains with complex terrain, represents the upper reaches of the Ili River—Xinjiang’ s largest inland river. Studying soil physicochemical properties in this region is significant for water and soil resource management and ecological construction in Xinjiang. Previous research has analyzed spatial distribution of soil nutrients and differences among vegetation types using traditional methods. Ma et al. [12, 13] investigated soil nutrients and their spatial heterogeneity across different grassland types in the Kunes River Basin, finding significant differences in nitrogen and phosphorus content primarily related to soil depth and altitude. However, no studies have examined the distribution characteristics of soil moisture and electrical conductivity across different spatial scales based on measured data in this region.

This study focuses on soils across an altitude gradient in the Kunes Valley of the western Tianshan Mountains. Using a portable instrument, we collected surface soil moisture and electrical conductivity data and applied classical statistical methods to analyze their spatial distribution characteristics, aiming to reveal factors influencing spatial heterogeneity of these soil properties and provide scientific basis for ecohydrological research, rational water and soil resource utilization, and ecological environmental protection in the Kunes River Basin.

1.1 Study Area Overview

The Kunes River, located in the upper Ili River Valley region of Xinjiang (Fig. 1), is one of the three major tributaries of the Ili River. Originating at the junction of the Awulale and Yilianhabierga mountains in the Tianshan range, the river source exceeds 3500 m in elevation. Flowing east to west, it enters

Xinyuan County in Ili Prefecture, joining the Tekes River west of the Kunes Sheep Farm, then converging with the Kash River at Yamadu before emptying into the Ili River. The Kunes River covers a watershed area of 4123 km^2 with an average annual flow of 50.4 $m^3 \cdot s^{-1}$, classified as a seasonal snowmelt-fed river with substantial interannual flow variation.

According to USGS DEM data, the Kunes River Basin slopes from high in the east to low in the west, with an elevation range of 700–4403 m and relative relief of approximately 3700 m. Mountains on the east, south, and north sides form a valley opening westward. The basin belongs to a temperate continental semi-arid climate zone, with annual precipitation of 270–880 mm showing uneven spatial distribution—generally greater in mountainous areas than plains, and increasing with elevation. Mean annual temperature ranges from 3.8 to 8.5°C, with significant spatial temperature variation [14].

Based on the five-year interval land ecosystem spatial distribution dataset (http://www.geodoi.ac.cn/WebCn/doi.aspx?Id=177) [15], land cover types in the study area are dominated by grassland, forest, and farmland. Along the Kunes Valley, north-facing slopes are generally forested, primarily with spruce, while south-facing slopes are predominantly grassland consisting of mountain steppe and meadow, showing clear vertical zonation of grassland types.

1.2 Data Collection

Temperature, soil moisture, and soil electrical conductivity data were measured in the field on September 18, 2018, under clear weather conditions. Measurements were conducted using an HM-WSYP portable soil temperature-moisture-salinity (electrical conductivity) meter manufactured by Shandong Hengmei Electronic Technology Co., Ltd., China. The measurement ranges were: temperature -40–100°C, soil moisture 0–100%, and electrical conductivity 0–2000 $mS \cdot m^{-1}$. During field measurements, the instrument’ s metal probe was fully inserted vertically into the soil, and readings were recorded after stabilization. Three replicate measurements were taken at each point. The probe length was approximately 6.8 cm, so measured soil moisture and electrical conductivity represent average values in the 0–6.8 cm depth range, referred to as surface soil moisture (SMC) and surface soil electrical conductivity (EC). Since the temperature sensor is located in the non-probe section, measured temperature represents surface temperature (ST). For each measurement point, a handheld GPS recorded latitude, longitude, and altitude, and land use type was documented.

To investigate spatial distribution characteristics of surface soil moisture and electrical conductivity, 1714 measurement points were collected along the valley. Based on spatial scale, data were divided into three categories: (1) **Watershed scale**: Xinyuan County to Aiken Daban, elevation range 780–3050 m, height difference approximately 2200 m, complex terrain, 400 m spacing between points, 106 measurement points; (2) **Small watershed scale**: Alatubai small watershed, a gully between Nalati Town and Xinyuan County, elevation range 1145–

1548 m, 38 measurement points; (3) **Slope scale**: North- and south-facing slopes adjacent to the Tianshan Snow Avalanche Research Station, with north-facing slope dominated by spruce (elevation 1714-1820 m, relative height 106 m, 52 measurement points) and south-facing slope dominated by grassland (elevation 1728-1820 m, relative height 92 m, 48 measurement points). At watershed and small watershed scales, the large range, complex terrain, and varying measurement times meant surface temperature was significantly affected by diurnal temperature variation; therefore, surface temperature data were only used when analyzing aspect-related differences at the slope scale.

1.3 Data Processing and Analysis

The arithmetic mean of three replicate measurements was calculated for each point. Classical statistical methods were applied for descriptive statistics, including coefficient of variation (Cv) to analyze variability. When Cv $< 10\%$, variability is weak; when $10\% \leq$ Cv $< 100\%$, variability is moderate; when Cv $\geq 100\%$, variability is strong [16].

2. Results

2.1 Watershed-Scale Spatial Distribution of Surface Soil Moisture and Electrical Conductivity

At the watershed scale, surface soil moisture ranged from 26% to 79.33%, with a mean of 43.54%. The relatively high values resulted from a heavy rainfall event on September 17, 2018, combined with good vegetation conditions and strong water retention capacity, maintaining high surface soil moisture levels. Watershed elevation ranged from 700 to 3010 m, divided into five zones: 700-1000 m, 1000-1500 m, 1500-2000 m, 2000-2500 m, and 2500-3010 m. Statistical characteristics for each zone are shown in Table 1.

Surface soil moisture increased with elevation, showing a significant positive correlation (Fig. 3). The correlation coefficient $R = 0.54$ ($p < 0.01$) indicates a significant positive relationship, with $R^2 = 0.29$, meaning elevation explains 29% of surface soil moisture variation. During sampling, local surface water accumulation was observed above 2300 m, and melting snow was present above 2500 m. Snowmelt and surface water flow from high elevations to downstream areas, while lower temperatures at high elevations reduce surface evapotranspiration, collectively causing surface soil moisture to increase with altitude.

Mean surface soil moisture values across elevation zones were: 2000-2500 m (56.21%) > 2500-3010 m (52.60%) > 1500-2000 m (40.59%) > 1000-1500 m (37.45%) > 700-1000 m (32.73%). Coefficients of variation were 12%, 29%, 42%, 38%, and 19%, respectively (Table 1), all indicating moderate variability. Variability first increased then decreased with elevation, peaking at 1500-2000 m and minimizing at 700-1000 m. The 700-1000 m zone lies in valley plains with relatively flat terrain and homogeneous soil conditions, while higher elevations have steeper slopes and more complex topography, leading to greater variability in surface soil moisture.

At the watershed scale, surface soil electrical conductivity ranged from 0.02 to 91.00 $mS \cdot m^{-1}$, with a mean of 17.51 $mS \cdot m^{-1}$, indicating no overall salinization. According to Chen et al. [17], soil is considered mildly saline when 35 $mS \cdot m^{-1} < EC < 91$ $mS \cdot m^{-1}$. Except for two sampling points in the 2000-2500 m range exceeding 91 $mS \cdot m^{-1}$, all other points showed low salinization levels (Fig. 4), with no soil salinization present overall.

Mean surface soil electrical conductivity across elevation zones was: 2000-2500 m (31.16 $mS \cdot m^{-1}$) > 1500-2000 m (18.43 $mS \cdot m^{-1}$) > 1000-1500 m (14.59 $mS \cdot m^{-1}$) > 700-1000 m (12.71 $mS \cdot m^{-1}$) > 2500-3010 m (4.58 $mS \cdot m^{-1}$). Below 2000 m, EC decreased slowly with elevation, while above 2000 m, it decreased rapidly. Coefficients of variation were 150%, 42%, 38%, 85%, and 19%, respectively, all showing moderate variability but substantially greater than for soil moisture. EC variability was highest in the 2000-2500 m range due to two points near the river with high moisture and flat terrain, causing strong salt accumulation.

2.2 Spatial Distribution of Surface Soil Moisture and Electrical Conductivity in the Alatubai Small Watershed

In the Alatubai small watershed, surface soil moisture ranged from 20.67% to 56.21%, with a mean of 38.52% and Cv of 24%, indicating moderate variability. As shown in Fig. 5, surface soil moisture first decreased then increased with elevation, with mid-elevation moisture lower than low- and high-elevation zones. This pattern occurs because precipitation is higher at high elevations than mid-elevations [18], while low-elevation moisture receives runoff from mid- and high-elevation areas [19].

Mean surface soil electrical conductivity was 15.34 $mS \cdot m^{-1}$ (range: 2.00-45.00 $mS \cdot m^{-1}$), with Cv of 65%, indicating moderate variability. Fig. 5 shows EC decreased with elevation, passing significance tests at the 0.05 level but not at the 0.01 level. At the watershed scale, soil salt content generally increases from upstream to downstream along river courses [20]. In this study, except for the 2000-2500 m zone, EC also increased from high-elevation upstream to low-elevation downstream areas. The two high EC points in the 2000-2500 m range were sampled near the river with high moisture and flat terrain, causing strong salt accumulation and resulting in the highest EC and Cv (150%) for this zone.

2.3 Surface Temperature, Soil Moisture, and Electrical Conductivity on Different Slopes

At the slope scale, north-facing slopes showed significantly higher surface soil moisture than south-facing slopes (Table 3). Surface soil moisture on north-facing slopes first increased then decreased with elevation, while south-facing slopes showed relatively flat trends. Surface temperature on north-facing slopes was significantly lower than on south-facing slopes due to stronger solar radiation on south aspects, leading to higher temperatures, greater evapotranspiration, and consequently lower soil moisture. North-facing slopes received less solar radiation, resulting in lower temperatures, reduced evapotranspiration, and higher soil moisture.

Surface soil electrical conductivity patterns mirrored moisture patterns. North-facing slope EC first increased then decreased, while south-facing slope EC showed smaller variation amplitude. Coefficients of variation for north-facing slope moisture, EC, and temperature were 42%, 85%, and 15%, respectively; for south-facing slopes they were 28%, 150%, and 9% (Table 3). Except for south-facing slope temperature (weak variability), all other variables showed moderate variability (Cv > 10%). Overall, north-facing slope variables had greater variability than south-facing slopes. North-facing slopes supported diverse vegetation types—dominant spruce with various herbaceous plants, moss, and lichen—creating complex soil characteristics. Vegetation effects varied with elevation as solar radiation changed, causing large variations in temperature and moisture between slope top and bottom. South-facing slopes had simpler vegetation dominated by grasses, resulting in smaller variability in moisture and temperature. However, south-facing slope EC showed higher variability (Cv = 150%), likely due to grazing activities affecting soil conditions.

2.4 Distribution of Surface Soil Moisture and Electrical Conductivity Across Land Use Types

Above 1500 m elevation, main land use types are grassland and forest, with farmland much less extensive. To ensure consistent comparison, grassland and forest data for this analysis were selected from the 700-1500 m range. Surface soil moisture means were: grassland (37.19%) > cultivated land (37.04%) > forest land (34.67%), differing by less than 3% due to the September 17 rainfall event that elevated moisture across all types. Forest land showed slightly lower moisture than cultivated land and grassland, with grassland highest. Forests have deeper roots and larger canopies than herbs, resulting in greater transpiration and water consumption [21]. Grassland roots concentrate in surface soil, better retaining moisture [22].

Surface soil electrical conductivity means were: cultivated land ($17.36\ \mathrm{mS \cdot m^{-1}}$) > grassland ($14.95\ \mathrm{mS \cdot m^{-1}}$) > forest land ($13.81\ \mathrm{mS \cdot m^{-1}}$), showing similar patterns to moisture but with forest land lowest. Coefficients of variation for moisture were 42% (cultivated land), 38% (forest), and 28% (grassland); for EC they were 85%, 150%, and 65%, respectively (Table 4). Both moisture and EC showed moderate variability (10% < Cv < 100%), with EC variability exceeding moisture variability. Forest land showed the highest variability for both parameters.

3. Discussion

3.1 Scale Effects on the Relationship Between Soil Moisture and Electrical Conductivity

The relationship between surface soil moisture and electrical conductivity varied by scale (Fig. 7). At the watershed scale, the coefficient of determination R^2 was 0.08. At the small watershed scale, R^2 increased to 0.41. At the slope scale, R^2 was 0.52 for north-facing slopes and 0.62 for south-facing slopes. These results show that as spatial scale decreases and environmental factors such as human activities and vegetation become more similar, the correlation between moisture and EC strengthens. At larger scales, increased spatial heterogeneity of environmental factors weakens this relationship.

3.2 Environmental Factors Influencing Spatial Variation of Soil Moisture

Environmental factors influencing soil moisture spatial variation include land use, meteorological factors, topography, soil properties, and human activities [23]. Vegetation affects soil moisture through two mechanisms: canopy interception and transpiration reduce moisture, while litter increases infiltration and reduces evaporation, and roots enhance water percolation [24]. Different plant species affect soil moisture differently. In this study, moisture followed grassland > cultivated land > forest land, with forest land lowest due to strong transpiration causing water deficits [25].

Topographic factors examined were aspect and elevation. South-facing slopes receive stronger solar radiation than north-facing slopes, resulting in higher temperatures, greater evapotranspiration, and lower soil moisture [26]. In this study, south-facing slope temperature was approximately double that of north-facing slopes, with mean moisture only 52% of north-facing slope values. Although north-facing slopes supported forest vegetation with potentially greater transpiration than grassland, the aspect effect dominated—reduced solar radiation on north-facing slopes led to lower temperatures and higher moisture, making solar radiation the primary factor controlling slope-scale moisture.

Many studies report that soil moisture decreases with increasing elevation [27, 28], contrasting with our watershed-scale finding of increasing moisture with elevation. These studies primarily focused on slope scales [29, 30], where lower slope positions receive runoff and subsurface flow from upslope areas, causing moisture to decrease with elevation. Our north-facing slope results align with this pattern—moisture at the slope top was significantly lower than at the slope bottom. However, at the watershed scale, moisture increased with elevation because: (1) precipitation increases with elevation in this region [18]; (2) during the study period, melting snow patches appeared above 2500 m, with snowmelt increasing soil moisture in the 0–30 cm layer most significantly [31, 32]; and (3) high-elevation snowmelt maintained elevated surface soil moisture.

3.3 Limitations and Future Research

This study comprehensively analyzed spatial distribution patterns of surface soil moisture and electrical conductivity across scales in the Kunes Valley, but limitations remain: short sampling period prevented analysis of seasonal variations; limited spatial sampling along linear transects restricted representation. Future research should focus on seasonal dynamics and integrate remote sensing technology to further analyze spatial distribution characteristics and influencing factors.

4. Conclusions

Based on field measurements from September 2018, this study analyzed spatial distribution characteristics of surface soil moisture and electrical conductivity and their relationships with topography and land use at watershed, small watershed, and slope scales in the Kunes Valley. Main conclusions are:

1. **Watershed scale:** Both surface soil moisture and electrical conductivity showed moderate variation (Cv). Surface soil moisture increased significantly with elevation, peaking at 2000–2500 m. Elevation explained 29% of moisture spatial variation. Electrical conductivity was highest at 2000–2500 m, decreasing with elevation at other ranges, with overall mean of 17.51 $\mathrm{mS \cdot m^{-1}}$ indicating no salinization except mild salinization at some 2000–2500 m points.
2. **Small watershed scale:** Mid-elevation moisture was lower than at low and high elevations, while EC decreased slowly with elevation. Both parameters showed moderate variation.
3. **Slope scale:** Solar radiation created large differences between aspects: temperature south > north, while moisture and EC north > south. Variation coefficients for all three variables were greater on north-facing slopes. Significant linear relationships existed between moisture and EC on both slopes, stronger than at watershed and small watershed scales.
4. **Land use effects:** Moisture followed grassland > cultivated land > forest land; EC followed cultivated land > grassland > forest land. Both parameters showed moderate variation across all land use types.

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