Spatial Variability and Simulation of Soil Hydraulic Parameters in the Northwestern Arid Region: Postprint

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Abstract

To investigate the spatial distribution characteristics of soil hydraulic parameters in the arid region of Northwest China, 107 sampling sites were established in the Xinjiang region to obtain data for the surface layer (0–5 cm), including Ks (soil saturated hydraulic conductivity), FC (field capacity), and PWP (permanent wilting point). Classical statistics and geostatistics were employed to analyze the spatial variability characteristics of soil hydraulic parameters, and stepwise regression and pedotransfer functions were used to simulate Ks, FC, and PWP. The results showed that the mean values of Ks, FC, and PWP in the Xinjiang region were 10.999 mm・h-1, 0.162 g・g-1, and 0.077 g・g-1, respectively, with coefficients of variation ranging from 39.88% to 96.07%, all exhibiting moderate variability. At the regional scale, Ks, FC, and PWP exhibited strong spatial dependence, with ranges of 97 km to 291 km. Compared with pedotransfer functions constructed through independent variable data transformation, the multiple stepwise regression equations demonstrated higher prediction accuracy for soil hydraulic parameters and were more convenient to use. The multiple stepwise regression equations based on land use, bulk density, soil texture, organic carbon content, and slope aspect yielded coefficients of determination (R2) of 0.290, 0.494, and 0.491 for predicting Ks, FC, and PWP, respectively, with root mean square errors (RMSE) of 2.540 mm・h-1, 0.039 g・g-1, and 0.023 g・g-1, respectively. The establishment of these equations facilitates rapid estimation of soil hydraulic parameters in the arid region of Northwest China and can provide critical parameters for agricultural irrigation and eco-hydrological models in this region.

Full Text

Spatial Variability and Simulation of Soil Hydraulic Parameters in Arid Northwest China

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Abstract

Soil saturated hydraulic conductivity (Ks), field capacity (FC), and permanent wilting point (PWP) are important soil hydraulic parameters and critical factors in bio-hydrological models. To understand the regional-scale spatial variability of these hydraulic parameters, Ks, FC, and PWP data from the 0–5 cm soil layer were obtained from 107 sampling sites in Xinjiang. Both traditional statistics and geostatistics were used to explore the spatial variations of Ks, FC, and PWP. Estimations of these parameters were further conducted using multiple stepwise regression (MSR) and pedotransfer functions (PTFs). The results indicated that the mean values of Ks, FC, and PWP were 10.999 mm • h ^{1}, 0.162 g • g ^{1}, and 0.077 g • g ^{1}, respectively. These three hydraulic parameters varied moderately with coefficients of variation (Cv) ranging from 39.88% to 96.07%, and exhibited strong spatial correlations with ranges of 97–291 km in Xinjiang. MSR performed better than PTFs in estimating soil hydraulic parameters. Based on land use, bulk density, soil texture, soil organic carbon content, and slope aspect as predictors, the determination coefficients (R^2) of the MSR models for Ks, FC, and PWP were 0.290, 0.494, and 0.491, respectively, and the root mean square errors (RMSE) were 2.540 mm • h ^{1}, 0.039 g • g ^{1}, and 0.023 g • g ^{1}, respectively. The development of these equations is beneficial for rapid estimation of soil hydraulic parameters and can thus provide key parameters for agricultural irrigation and eco-hydrological models in arid Northwest China.

Keywords: soil saturated hydraulic conductivity; field capacity; permanent wilting point; regional scale; multiple stepwise regression; Xinjiang

1 Introduction

Soil saturated hydraulic conductivity (Ks), field capacity (FC), and permanent wilting point (PWP) are fundamental soil hydraulic properties that control water movement and availability in soils. These parameters serve as critical inputs for bio-hydrological models and are essential for agricultural water management and ecological restoration in arid regions. Previous studies have demonstrated significant spatial variability in these parameters across different scales. For instance, Zhang et al. [2] investigated the distribution of Ks on the northern Loess Plateau, while Chen et al. [9] examined Ks variability in typical grassland ecosystems. Qiao et al. [11] developed pedotransfer functions for estimating FC and PWP in the Loess Plateau' s critical zone. Wang and Zhao [7,8] mapped the spatial patterns of Ks using digital soil mapping techniques. However, most existing research has focused on the Loess Plateau region, with limited attention to the vast arid and semi-arid areas of Northwest China, particularly Xinjiang. The extreme climatic conditions, diverse land uses, and complex topography of Xinjiang create unique challenges for characterizing soil hydraulic properties at regional scales. This study aims to: (1) characterize the spatial variability of Ks, FC, and PWP across Xinjiang using geostatistical methods; (2) develop predictive models using both multiple stepwise regression and pedotransfer functions; and (3) compare the performance of these modeling approaches for estimating soil hydraulic parameters in arid environments.

2 Materials and Methods

2.1 Study Area

The study was conducted in Xinjiang Uygur Autonomous Region, located in Northwest China (34°22 -49°33 N, 73°22 -96°21 E). The region encompasses diverse landscapes including mountains, basins, deserts, and oases. The climate varies from temperate arid to semi-arid, with mean annual precipitation ranging from 25 mm to 200 mm and mean annual temperatures from -4°C to 14°C, depending on elevation and location. Land use types include cropland, grassland, forest, and desert.

2.2 Data Collection

Soil samples were collected from 107 sites across Xinjiang during the growing season. At each site, undisturbed soil cores were taken from the 0–5 cm surface layer to measure Ks using the constant-head method. Soil water characteristic curves were determined using pressure plate apparatus at pressures of -1/3 bar (for FC) and -15 bar (for PWP) [1,13]. Soil texture was analyzed using the pipette method after sieving through 0.25 mm and 1 mm meshes. Soil organic carbon content was measured by the dichromate oxidation method. Bulk density was determined using the core method. Slope aspect and land use type were recorded at each sampling location.

2.3 Statistical Analysis

Classical statistical analysis was performed using SPSS 20.0 to calculate descriptive statistics including mean, standard deviation, coefficient of variation (Cv), and skewness. Pearson correlation analysis was conducted to examine relationships between soil hydraulic parameters and environmental factors.

Geostatistical analysis was performed using GS+ 9.0 to model spatial autocorrelation. Semivariograms were calculated using the formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where h is the lag distance, $N(h)$ is the number of sample pairs at lag h, $Z(x_i)$ is the measured value at location x_i, and $Z(x_i + h)$ is the value at location $x_i + h$. The semivariogram parameters—nugget (C), sill (C + C), and range—were fitted to theoretical models (spherical, exponential, or Gaussian). Spatial dependence was classified according to Cambardella's criteria [16]: strong spatial dependence when C /(C +C)   25%, moderate when 25% < C /(C +C) < 75%, and weak when C /(C +C)   75% [2,7].

Multiple stepwise regression (MSR) models were developed with Ks, FC, and PWP as dependent variables and land use, bulk density, soil texture fractions, soil organic carbon, and slope aspect as independent predictors. Model performance was evaluated using determination coefficient (R^2) and root mean square error (RMSE). Pedotransfer functions from previous studies [7,11,17] were applied for comparison. Spatial interpolation was performed using kriging in ArcGIS 10.6 to generate prediction maps.

3 Results

3.1 Descriptive Statistics

The descriptive statistics for soil hydraulic parameters are summarized in Table 1. The mean values of Ks, FC, and PWP were 10.999 mm · h ^{1}, 0.162 g · g ^{1}, and 0.077 g · g ^{1}, respectively. Ks exhibited the highest variability with a Cv of 96.07%, followed by FC (39.88%) and PWP (48.14%). The Cv values indicated moderate to high variation for all three parameters. Ks values ranged from 0.019 to 549.17 mm · h ^{1} across the study area, showing substantial spatial heterogeneity. FC and PWP showed relatively narrower ranges of 0.048–0.342 g · g ^{1} and 0.037–0.174 g · g ^{1}, respectively.

Table 1 Descriptive statistics of soil hydraulic parameters

Parameter	Mean	Min	Max	Cv (%)
Ks (mm · h ^{1})	10.999	0.019	549.17	96.07
FC (g · g ^{1})	0.162	0.048	0.342	39.88
PWP (g · g ^{1})	0.077	0.037	0.174	48.14

3.2 Spatial Variability

Geostatistical analysis revealed strong spatial autocorrelation for all three hydraulic parameters. The semivariogram models showed ranges of spatial correlation between 97 km and 291 km, indicating that samples separated by distances greater than these ranges were spatially independent. The spatial dependence classification showed that Ks had moderate spatial dependence (C /(C +C) = 29.0%), while FC and PWP exhibited strong spatial dependence with ratios of 49.40% and 49.10%, respectively.

3.3 Model Performance

The MSR models outperformed PTFs in predicting all three soil hydraulic parameters. For Ks, the MSR model achieved an R^2 of 0.290 and RMSE of 2.540 $mm \cdot h^{1}$, which was superior to existing PTFs [7,8,13]. The FC model showed better predictive capability with $R^2 = 0.494$ and RMSE = 0.039 $g \cdot g^{1}$, while the PWP model performed best with $R^2 = 0.491$ and RMSE = 0.023 $g \cdot g^{1}$. The predictor variables selected by the stepwise procedure included sand content, silt content, clay content, soil organic carbon, bulk density, and slope aspect, with land use type as a categorical factor.

4 Discussion and Conclusion

This study characterized the spatial variability of three critical soil hydraulic parameters across Xinjiang and developed predictive models using both geostatistical and regression approaches. The moderate to high coefficients of variation observed for Ks, FC, and PWP reflect the diverse soil types, land uses, and climatic conditions in the region. The strong spatial correlation ranges (97–291 km) suggest that regional-scale processes such as climate, parent material, and land use patterns dominate over local-scale factors.

The superior performance of MSR compared to PTFs indicates that locally developed models incorporating regional environmental variables provide more accurate predictions for arid Northwest China. The relatively low R^2 values for Ks prediction highlight the persistent challenge of modeling this parameter, which is influenced by complex macropore structures and dynamic soil processes that are difficult to capture with static predictors.

The developed regression equations offer practical tools for rapid estimation of soil hydraulic parameters in data-scarce regions. These models can be integrated into agricultural irrigation scheduling and eco-hydrological modeling frameworks to improve water resource management in arid environments. Future research should incorporate additional predictors such as remote sensing-derived vegetation indices and topographic attributes to further enhance model performance.

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