Development and Evaluation of Soil Transfer Functions for the Balaguer River Basin: Postprint

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Abstract

Establishing pedotransfer functions based on soil physicochemical property data represents an important approach for indirectly obtaining soil hydraulic parameters. In this study, 102 soil samples were collected from 0–30 cm and 30–60 cm layers in the Balaguer River Basin, and indicators including particle size distribution, dry bulk density, organic matter, saturated hydraulic conductivity, and field capacity were measured. Methods such as mathematical statistics, spatial interpolation, and principal component analysis were utilized to reveal the spatial characteristics of soil physicochemical and hydraulic properties within the basin' s root zone. Taking soil saturated hydraulic conductivity (KS) as an example, the applicability of multiple soil pedotransfer function models was evaluated. The results demonstrate that: (1) Soils are predominantly sandy loam, and with increasing depth in the root zone, sandy loam content decreases while loamy sand content increases; (2) The spatial distribution of saturated hydraulic conductivity exhibits similarity across different layers, with KS values being greater in the deeper soil layer than in the surface layer; (3) The newly developed pedotransfer function for the 30–60 cm soil layer of the root zone shows favorable simulation performance, with validation parameters r, δME, and δRMSE of 0.73, 0, and 1.62, respectively; (4) The magnitude of estimation error is associated with soil type, and the newly developed PTFs are more suitable for sandy loam.

Full Text

Construction and Evaluation of Pedo-Transfer Functions in the Balager River Basin

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Abstract

Pedo-transfer functions (PTFs) based on soil physical and chemical properties are important tools for indirectly obtaining soil hydraulic parameters. In this study, 102 soil samples were collected from the grass root layer (0–60 cm) in the Balager River Basin of Inner Mongolia. Measured indices included particle size distribution, dry bulk density, organic matter content, saturated hydraulic conductivity (KS), and field water holding capacity. Mathematical statistics, spatial interpolation, and principal component analysis were employed to reveal the spatial characteristics of soil physical, chemical, and hydraulic properties in the basin' s root zone. Using KS as an example, the applicability of multiple PTF models was analyzed. The results showed that: (1) sandy loam was the dominant soil texture, with its content decreasing as soil depth increased, while loamy sand content increased; (2) the spatial distribution patterns of KS were similar across different layers, with values being higher in deeper soil layers than in surface layers; (3) the newly developed PTF for the root zone soil layers demonstrated good simulation performance, with validation parameters of r = 0.73, δME = 0, and δRMSE = 1.62; and (4) estimation error was related to soil type, with the new PTF being more suitable for sandy loam soils.

Keywords: grass root soil; hydraulic parameters; soil classification; transfer function; Balager River Basin

Introduction

Soil is a crucial component of vegetation ecosystems, and soil hydraulic properties form the basis for studies on soil water movement, solute transport, and vegetation ecology. Pedo-transfer functions (PTFs), which utilize soil physical and chemical properties such as texture, bulk density, and organic matter content to rapidly and indirectly estimate soil hydraulic parameters, have received widespread attention from scholars as an important method for estimating soil hydraulic characteristics. Researchers have established PTFs applicable to different regions and soil types based on various theories and databases, including the Huang-Huai-Hai Plain, meadow areas interspersed with sand dunes, farmland, and purple soil in hilly regions. However, studies on PTFs for the root layer of grassland basins in Inner Mongolia' s inland rivers are scarce. Therefore, this paper selects the Balager River Basin as a typical study area to systematically analyze the spatial distribution patterns of soil physical and chemical properties and hydraulic characteristic parameters, and to establish a suitable PTF for estimating saturated hydraulic conductivity (KS) in the basin' s root layer, aiming to provide a scientific basis for research on soil hydraulic characteristics and grassland ecosystems in Inner Mongolia' s inland river basins.

1. Study Area and Methods

1.1 Study Area Overview

The Balager River Basin (116°21 -119°31 E, 43°57 -45°23 N) is located in Xiwuzhumuqin Banner, Xilingol League, Inner Mongolia, covering an area of 5,350 km^2 with elevations ranging from 850 to 1,876 m. The grassland type is typical steppe dominated by *Leymus chinensis* and *Stipa* species. The region experiences a continental semi-arid climate with cold winters and hot summers, an average annual precipitation of 334 mm, annual evaporation of 1,149 mm, average temperature of 1.2 °C, maximum temperature of 37.5 °C, minimum temperature of -38.5 °C, and average wind speed of 3.5 m/s, with wind speeds reaching 15 km/h on 148 days per year.

1.2 Data Sources and Processing

According to the "Technical Specifications for Soil Environmental Monitoring" (HJ/T 166-2004) and considering the basin' s topography and vegetation cover types, 102 soil sampling points were established [Figure 1: see original paper]. At each point, surface debris was removed before excavating a soil profile. Parallel ring samples were taken from the middle of each layer to determine soil hydraulic properties, while soil bags were used for physical and chemical analysis. Soil particle size was measured using a laser particle size analyzer (HELOS OASIS type). Soil saturated hydraulic conductivity was determined using the constant head method. Saturated water content was measured by saturating ring samples wrapped with gauze at the bottom; when the weight variation was less than 0.02 g, the sample was considered saturated, and the average value was taken as the saturated water content. Soil organic matter was determined by the potassium dichromate dilution-heat method. Dry bulk density was measured using the ring knife method. Field water holding capacity was determined using the Wilcox method.

Data processing involved SPSS 22.0 for mathematical statistics, ArcGIS 10.3 for Kriging interpolation and mapping, and Excel 2010 for principal component analysis. F-tests were conducted at significance levels of $\alpha = 0.05$ and $\alpha = 0.01$.

1.3 Research Methods

Soil texture classification followed the international standard , with particle size fractions defined as: clay (<0.002 mm), silt (0.002-0.05 mm), and sand (0.05-2 mm). The mean particle diameter (d) and its standard deviation (σ) were calculated as primary input elements for PTF development to enhance model validity:

$$d = \sum_{i=1}^{n} d_i f_i$$

$$\sigma = \sqrt{\sum_{i=1}^{n} (d_i - d)^2 f_i}$$

where d_i is the midpoint of the particle size interval, and f_i is the percentage content in that interval.

Principal component analysis was applied to soil physical and chemical indicators correlated with KS. Factors with cumulative contribution rates exceeding 85% were selected as independent variables for model development. The final input variables for the 30 cm layer were silt content and standard deviation, while dry bulk density and silt content were selected for the 60 cm layer.

Model applicability was assessed using mean error (δME), root mean square error (δRMSE), and correlation coefficient (r):

$$\delta_{ME} = \frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)$$

$$\delta_{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)^2}$$

where N is the number of soil samples, y_i is the measured value, and $\hat{y}_i$ is the calculated value. An r value closer to 1 indicates better agreement between calculated and measured values; δME closer to 0 indicates less systematic bias (positive values indicate overestimation, negative values underestimation); and smaller δRMSE indicates higher accuracy.

2. Results and Analysis

2.1 Soil Texture and Spatial Distribution Characteristics

Based on the international soil texture classification standard, statistical analysis of the 102 samples revealed that soil texture in the 0–30 cm root layer was relatively uniform, with sand content exceeding 50% and clay content below

10% [Figure 2: see original paper]. Sandy loam was the dominant texture, distributed along the river channel in the central basin, covering over 60% of the area. Loamy sand was the second most common texture, dispersed at the basin boundaries and accounting for over 20% of the area. Less than 10% of the area consisted of 零星分布的 silt loam and other textures.

In the 30-60 cm layer, sandy loam remained dominant but its proportion decreased to approximately 50%, primarily distributed in the central and southern basin. Loamy sand increased to about 30%, distributed in the southeastern and northwestern regions, while silt loam and other textures accounted for less than 20% . Overall, sandy loam content decreased with increasing soil depth, while loamy sand content increased, indicating greater soil type diversity at depth [Figure 3: see original paper].

2.2 Soil Saturated Hydraulic Conductivity Characteristics

The spatial distribution of KS in the root layer showed high-value zones primarily in the upstream region and southern Chaidamu Sumu in the downstream area, appearing as 块状分布. Low-value zones were mainly distributed near the basin boundaries along both sides of the river valley [Figure 4: see original paper]. The spatial distribution patterns were similar between the 30 cm and 60 cm layers, with KS values being higher in the deeper layer than in the surface layer. High KS values occurred in low-lying valley areas along the main tributaries of the Balager River, while low values appeared on the valley sides near basin boundaries. Upstream KS values were higher than downstream values, likely related to uneven spatial distribution of precipitation, differences in grassland vegetation, and varying grazing intensities, reflecting the complexity of the basin’ s underlying surface conditions.

Statistical analysis revealed that KS in the 30 cm layer was extremely significantly correlated with silt and sand contents ($\alpha = 0.01$), significantly correlated with mean particle diameter ($\alpha = 0.05$), but not significantly correlated with dry bulk density or clay content. Therefore, silt content, sand content, standard deviation, and mean particle diameter were preliminarily selected as input variables for PTF development. In the 60 cm layer, KS was extremely significantly correlated with silt content, sand content, mean particle diameter, and standard deviation ($\alpha = 0.01$), and significantly correlated with dry bulk density and clay content ($\alpha = 0.05$). Consequently, silt content, sand content, clay content, mean particle diameter, standard deviation, and dry bulk density were selected as input variables for the 60 cm layer .

Principal component analysis extracted two main components for both layers, with cumulative contribution rates exceeding 85% . For the 30 cm layer, the first component was dominated by silt content and standard deviation, while the second component was dominated by dry bulk density. For the 60 cm layer, the first component was dominated by silt content and standard deviation, and the second component by dry bulk density and clay content. Based on this analysis, the final input variables for the 30 cm layer PTF were silt content and standard deviation, while dry bulk density and silt content were selected for the 60 cm layer.

2.3 Model Applicability Assessment

The newly developed statistical regression PTF and five traditional models (Cosby, Saxton, Campbell, Puckett, and Wosten) were used to calculate KS and evaluate their applicability . The new PTFs for both layers were:

30 cm layer:

$$K_S = 3.456\times10^{-3}\times(1.3/\rho_b-2.5\times10^{-3})\times\exp(-6.88\times10^{-4}\times\text{Silt}-3.63\times10^{-4}\times\sigma-0.025)$$

60 cm layer:

$$K_S = 0.336\times10^{-3}\times\exp(-0.323\times\rho_b+1.344\times\text{Silt}^3+(-0.477+2.846\times\rho_b^3)\times\exp(0.025-0.363\times\rho_b+0.2\times e^{-45.4\times\rho_b}+6$$

where ρ_b is soil bulk density (g/cm^3), Silt is silt content (%), C is clay content (%), and σ is the standard deviation of mean particle diameter.

Validation using 30 samples showed that the new PTF performed best for both layers . For the 30 cm layer, the new PTF achieved r = 0.73, δME = 0, and δRMSE = 1.62, significantly outperforming traditional models. The Saxton model performed second best (r = 0.68, δME = -0.21, δRMSE = 1.89), while other models showed varying degrees of underestimation [Figure 5: see original paper].

For the 60 cm layer, the new PTF also demonstrated superior performance with r = 0.81, δME = 0.01, and δRMSE = 1.43. The Saxton model again ranked second (r = 0.71, δRMSE = 1.82), while traditional models showed lower accuracy. The improved performance of the new PTF was attributed to its incorporation of locally-specific soil properties through principal component analysis.

Spatial distribution of calculation errors revealed that absolute errors for the 30 cm layer were generally less than 2 m/d, with good estimation accuracy. Errors were smaller for sandy loam soils but larger for loamy sand and silt loam soils, particularly in areas with complex terrain and mixed soil types [Figure 6: see original paper]. In the 60 cm layer, the new PTF accurately estimated KS for sandy loam soils, but showed larger errors for loamy sand and silt loam soils. Localized errors without clear patterns, such as in eastern Chaidamu Sumu, may be related to sampling location topography and underlying surface conditions not accounted for in the model.

3. Discussion and Conclusions

3.1 Discussion

Although accurate KS data can be obtained through field and laboratory measurements, these methods are time-consuming and labor-intensive, making it difficult to acquire large-scale data. Therefore, indirect calculation methods are crucial. Previous studies have compared point estimation, linear regression, nonlinear regression, and artificial neural networks, finding that nonlinear methods perform better for simulating soil hydraulic properties. This study' s selection of dry bulk density and particle composition as input variables aligns with these findings, indicating their dominant role in controlling saturated hydraulic conductivity.

The Saxton model performed better than other traditional models for this semi-arid grassland basin, consistent with previous research. However, the new PTF outperformed all traditional models because it incorporated locally-measured soil properties and used principal component analysis to select optimal input variables. The spatial distribution of KS showed similar patterns across layers, with deeper soils having higher conductivity than surface layers, consistent with findings from other studies in arid and semi-arid regions.

Estimation accuracy was influenced not only by the model structure but also by human factors during sampling, as well as terrain, slope, and vegetation cover. Analysis of Landsat 8 NDVI data for the basin revealed that vegetation coverage was relatively high, with the most 茂盛 areas in Aobao Shao Reng, southeastern Haole Tum Town, and southern Daqingbao, while vegetation was relatively sparse in northern Balagaer Sumu, Chaidamu Sumu, and Haole Tum Town [Figure 7: see original paper]. The spatial distribution of vegetation showed some correlation with KS, suggesting that incorporating vegetation indices into PTFs could potentially improve estimation accuracy.

The new PTF was also applied to estimate field water holding capacity, achieving better accuracy than for KS estimation (r = 0.78, δME = 0.02, δRMSE = 3.21), indicating that the model framework has broader applicability for other hydraulic parameters .

3.2 Conclusions

1) The Balager River grassland basin is dominated by sandy loam soils. With increasing root layer depth, sandy loam content decreases while loamy sand content increases, leading to greater soil type diversity. The spatial distribution patterns of saturated hydraulic conductivity are similar across different layers, with higher values in deeper soils than in surface soils.
2) The newly developed PTF for the deeper root zone soil layer demonstrates good performance in simulating soil hydraulic properties, with estimation errors related to soil type. The model is particularly suitable for sandy

loam soils, with larger errors occurring primarily in loamy sand distribution areas. Although the accuracy could be further improved, the new model outperforms traditional PTFs.

3) There is a certain degree of correlation between grassland vegetation spatial distribution and soil layer KS. Incorporating vegetation index data based on soil physical and chemical properties could further improve the accuracy of soil hydraulic parameter estimation.

This research provides a reference for ecosystem protection, rainfall infiltration, soil water movement, and solute transport studies in Inner Mongolia’ s inland river grassland basins, and can inform ecological management and agricultural practices for sustainable socio-economic development.

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