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Comparison of three methods to develop pedotransfer functions for the saturated water content and field water capacity in permafrost region

Xiangsheng Yi [a,b], Guosheng Li [a,*], Yanyu Yin [a]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] Agriculture Resource Monitoring Station, Chinese Academy of Agricultural Engineering, Beijing 100125, China

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ABSTRACT

In this study, pedotransfer functions (PTFs) for predicting the soil saturated water content (SWC) and field water capacity (FWC) from basic soil properties were developed by using multiple-linear regression (MLR), artificial neural network (ANN) and Rosetta method. A soil data set ($N=488$ samples) in the Three-River Headwaters Region (Qinghai Province in China), was randomly divided into a training data set ($N_1=400$ samples) for the prediction, and a testing data set ($N_2=88$ samples) for the validation. The general performance of PTFs was evaluated based on the coefficient of determination (R^2), root mean square error (RMSE) and mean error (ME) between the observed and predicted values. Some important conclusions were obtained from this research, which mainly contained three aspects as follows. (1) The general prediction effect of the MLR method was good. The absolute value of ME and RMSE for the SWC was below 0.0509, and the R^2 was 0.9031. However, the absolute value of ME and RMSE for the FWC were bigger, and the R^2 was lower than the ANN and Rosetta method respectively. (2) The performance of ANN was the best in three methods. The absolute value of ME and RMSE for the SWC and FWC was all below the 0.0386, and their R^2 were above 0.8593. (3) The absolute value of ME and RMSE of the Rosetta method for the SWC were larger than other two methods, and the R^2 was lower than the ANN but higher than MLR. The prediction effect for the FWC was fairly good for its relatively high R^2 and low ME, RMSE. This research could provide the scientific basis for the study of soil hydraulic properties in the Three-River Headwaters Region of Qinghai Province and be helpful for the estimation of soil water retention in regional scale.

1. Introduction

The saturated water content (SWC) and field water capacity (FWC) which are defined as the maximum water content and water in the soil retained against gravity are two important soil hydraulic parameters (Hillel, 1980; Townend et al., 2001). On a plot scale, the SWC and FWC could be measured directly in the laboratory or field. If the area under investigation is relatively small or known to be quite homogeneous with respect to soil physical makeup and topography, the SWC and FWC at a reasonable number of sampling sites could be measured immediately (Carter and Gregorich, 2008), and they would provide fairly accurate estimations. However, the measurement for the soil hydraulic property is time-consuming, labor-intensive and expensive (Merdun, 2010). If the area being evaluated is large enough to exhibit substantial spatial variability of soil water availability, it is costly and time-consuming to perform adequate measurements to provide good estimates within the temporal and financial constraints of the project (Givi et al., 2004).

Recently, an alternative, indirect estimation of soil hydraulic properties from widely available or more easily measured basic soil properties using pedotransfer functions (PTFs) has attracted considerable attention of researchers in a variety of fields such as soil scientists, hydrologists, and agricultural and environmental engineers (Huang et al., 2010; Minasny and McBratney, 2002; Minasny et al., 2004). PTFs for predicting the soil hydraulic properties could be divided into two types: point pedotransfer and function pedotransfer (Acutis and Donatelli, 2003). Point pedotransfer functions estimate the water contents at fixed pressure heads, often including the water content at the FWC and the permanent wilting point (PWP) (Salchow et al., 1996) or the water content at a given matric potential (Givi et al., 2004; Pachepsky et al., 1996). Function pedotransfers predict the parameters of a closed-form analytical equation, such as the model of Brooks and Corey (Brooks and Corey, 1964) or the van Genuchten equation (van Genuchten, 1980). Though other values may be used in different countries or regions, the soil water contents at the soil water potential of 0 kPa and −33 kPa usually correspond to the SWC and FWC respectively (Carter and Gregorich, 2008). So, the SWC and FWC could be obtained by the point pedotransfer or

* Corresponding author at: Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, A11, Datun Road, Chaoyang District, Beijing 100101, China. Tel./fax: +86 10 64888338.
E-mail address: ligs@igsnrr.ac.cn (G. Li).

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function pedotransfer after some calculations. At present, there are two common methods to develop PTFs for point and/or function estimations, which are MLR method (Merdun et al., 2006; Minasny et al., 1999; Tomasella et al., 2000) and ANN method (Koekkoek and Booltink, 1999; Minasny and McBratney, 2002; Minasny et al., 2004; Sarmadian and Mehrjardi, 2008). In order to make the PTFs as widely applicable as possible, Schaap et al. (2001) developed the Rosetta software by using a large number of soil hydraulic data and corresponding predictive soil properties. Rosetta is a very popular computer program that implements some of the models published by Schaap and Bouten (1996), Schaap and Leij (1998), Schaap et al. (1998) and Schaap and Leij (2000), and can estimate the van Genuchten water retention parameters and saturated hydraulic conductivity. The Rosetta is based on neural network analyses combined with the bootstrap method, which allows the program to provide uncertainty estimations of the predicted hydraulic parameters. Therefore, Rosetta software is used widely by many scientists for the estimation of soil water retention, saturated hydraulic conductivity and unsaturated hydraulic conductivity parameters (Givi et al., 2004; Minasny et al., 2004; Schaap et al., 2001; Stumpp et al., 2009).

Although there are many studies on developing and using PTFs as listed above, there is no universal method for the prediction of soil hydraulic parameters. Moreover, the existing PTFs for the estimation of soil hydraulic properties in the literatures were not always applicable in other regions with acceptable accuracy (Cornelis et al., 2001; Nemes et al., 2003; Wagner et al., 2001). So, it is necessary to develop and evaluate the PTFs in different regions. In addition, the point PTFs in the previous studies were mainly to estimate the FWC and PWP. There were few literatures about the estimation of SWC by using the point PTFs. The function PTFs were described as a continuous curve which allowed computing the hydraulic values at selected pressures (Liu et al., 2007). Thus, the SWC and FWC could be obtained from the soil water retention curve because they can be related to the defined soil water potential respectively. Moreover, there are few studies, which compared the performance of different methods simultaneously in the development of PTFs for the SWC and FWC in the Three-River Headwaters Region of the Qinghai Province and its surrounding areas.

Therefore, the objectives of this study are (1) to develop and validate the point PTFs by using MLR and ANN method, and function PTFs by using the Rosetta method for the estimation of SWC and FWC, and (2) to compare the predictive capabilities of the three methods using some evaluation criteria in the Three-River Headwaters Region of Qinghai Province, China. If successful, this study may not only find a relatively suitable method for the prediction of SWC and FWC in the studied area, but also could provide a helpful reference for the estimation of SWC and FWC in other regions.

2. Materials and methods

2.1. Study site

The entire soil data in this study were taken from the Three-River Headwater Region of Qinghai Province, which is in the hinterland of the Tibetan Plateau (Fig. 1) and is also a typical permafrost region (Niu et al., 2012). It is composed of three principal rivers namely the Yangtze River, the Yellow River and the Lancangjiang River. The altitude in the Three-River Headwater Region of Qinghai Province ranges from 2610 to 6950 m, and the average altitude is 4500 m. The climate in the studied area is the classic plateau continental monsoon type. The annual mean temperature varies from –5.38 °C to 4.14 °C and the annual precipitation ranges between 262.2 mm and 772.8 mm.

2.2. Soil sampling and analysis

A field investigation was conducted in the July of 2009 and 2010. The 488 soil samples were taken from 99 different soil profiles at various depths in the studied area. Three undisturbed samples were taken repeatedly by the steel cylinder of 100 cm^3 at every 10 cm depth of each soil profile to determine the bulk density and water retention characteristics. The sample depths ranged from 10 cm to 120 cm, with an average of 50 cm (median 43 cm). At the same time, sub-samples about 1000 g were collected from the same soil depth for the measurement of soil texture and organic matter. All the coordinates of the sampling locations were determined with a highly accurate global positioning system (GPS).

Soil samples were air-dried in a ventilated room and cleared of roots and organic debris. The particle size analysis (Clay: <0.002 mm, Silt: 0.002–0.05 mm, Sand: 0.05–2 mm) was made by utilizing the Laser Particle Sizer (Mastersizer 2000, Malvern Company, UK), the measure range of which was 0.02–2000 μm, and the repetition measure errors were less than 2%. Sand, silt and clay contents were expressed as a percentage by mass of the fine-earth fraction (<2 mm) and soil texture was identified according to the United States Department of Agriculture (USDA) system of soil classification. The samples from the studied area were dominated by the sandy-loam and silt-loam.

Soil bulk density, SWC and FWC were measured in a series of experiments with steel cylinders. First of all, all the undisturbed soil samples along with steel cylinders of 100 cm^3 volume ($d = 53$ mm, $h = 50$ mm) were soaked in the water for 24 hours, and then they

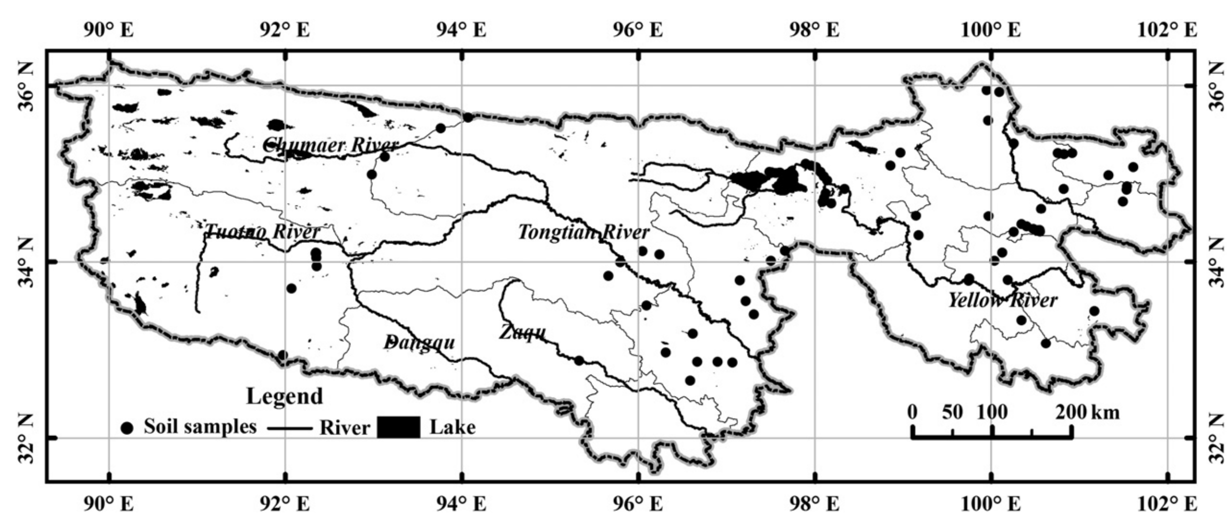

Fig. 1. Distribution of soil samples in the Three-River Headwaters Region of Qinghai Province, China.