# Soil Hydraulics Properties Estimation by Using Pedotransfer Functions in a Northeastern Semiarid Zone Catchment, Brazil

Lúcio Flávio Ferreira Moreira

A. M. Righetto

V. M. de A. Medeiros

# Soil Hydraulics Properties Estimation by Using Pedotransfer Functions in a Northeastern Semiarid Zone Catchment, Brazil

**L. F. F. Moreira, A. M. Righetto and V. M. de A. Medeiros[a]**

[a]*Programa de Pós-graduação em Engenharia Sanitária/ Universidade Federal do Rio Grande do Norte Natal/RN Brasil 59072-970*

**Abstract**: Hydrological modeling of the unsaturated soil zone fluxes allows the transfer processes simulation through the hydrological active soil zone. The pedotransfer functions (FTP) are useful tools in the modeling process. They contain analytical functions derived through statistic optimization process using a large amount of soil information data. This paper aims to analyze the level of reliability of two different pedotransfer functions [Wösten et al. (2001); Hodnett and Tomasella (2000)] by using field measurement of soil properties and experimental infiltration data through a disc infiltrometer in an experimental catchment at northeastern semi arid zone of Brazil. FTP's used in this study were derived on previous studies by taking into account soils of different origins. The former FTP considers a large range of soil classes from temperate climate regions; the latter was derived through a selection of soils from tropical climate regions. The use of these pedotransfer functions showed a large variation between calculated soil hydraulic parameters. The tropical climate function seemed a better adjustment to the experimental data. Van Genuchten parameters and experimental infiltration data allowed the derivation of the unsaturated hydraulic conductivity and soil pore-water tension functions. The derived soil hydraulic parameters showed spatial and temporal variation within the catchment.

***Keywords:*** *Pedotransfer function; tropical soils; reliability*

## 1. INTRODUCTION

Hydrological models are important tools in physical processes research particularly in the unsaturated media called hydrological active zone of soils. However, the task of modeling normally one supposes previous soil hydraulics parameters determination. Modeling normally requires derivation of input parameters that characterize retention and flow capacity at soil vadose zone. They can translate soil hydraulic behavior in function of soil physical, chemical and biological properties. According to soil hydraulic behavior, flow through the vadose zone is highly dependent of the temporal and spatial variability in its characteristics. Actually, one of the questions concerning the pedotransfer functions (PTF) development by many researchers deals with its capacity to predict accurately soil hydraulic properties. Accuracy implies a high level of correspondence between measured and predicted data set from which a PTF was derived.

In this sense, pedotransfer functions are very useful tools in modeling application. PTFs are analytical functions derived through statistical optimization involving a wide variety of information of different soil types. Such information consists of soil hydraulic properties database, grouping a large number of soil horizons throughout the world. These data are obtained directly in the field by experiments and bulk analysis on laboratory: soil composition, structure, bulk density, percentage of silt, clay and organ matter and pH.

The great advantage of PTFs use is the possibility of predicting soil hydraulic parameters directly. The derived parameters are commonly used to express soil water retention and hydraulic conductivity as functions of water volume content [van Genuchten and Mualen (1992), Brooks and Corey (1964)]. These functions can be incorporated into hydrologic distributed models because they can be able to simulate spatial soil hydraulic behavior variation through the watershed.

PTFs can be derived by two approaches: class PTF and continuous PTF. Class PTF is developed separately for each group individually [Wösten et al (1990)]. Many researchers have developed methods to group soils, taking into account some soil properties. On the other hand, continuous PTF is developed without grouping the data, but using all data set to derive equations. Actually, it has been discussed the accuracy of each type of

PTF [Hodnett and Tomasella (2002)]. For example, use of class PTF can give good results if soil mineralogical characteristics of the soils as well as textural class are similar.

Usually, relationships to predict soil properties deal with many parameters related one to another in an undirected relation. This explains the low level of agreement of these relations. They are obtained by using mathematical methods involving a number of soil properties. That procedure generates some errors that can lead to limited relations in terms of accuracy. Despite of the use of regression analysis, this technique has shown a limited capacity to translate the whole shape of dependence between parameters. The development of statistical methods has permitted to improve the level of accuracy. Actually, artificial neural networks have become a common technique used by many authors because of its ability to work with complex systems.

In practice, PTF is an empirical relationship. So, its use must be limited by the range/type of soils from the data used to derive it. Most of the PTFs developed to predict Brooks and Corey (1964) and van Genuchten (1980) parameters were derived using data sets from soils of temperate regions. Hodnett (1995) warned that PTFs developed for temperate soils should be applied with caution to tropical soils. Tomasella *et al.* (2000) tested a PTF derived from Brazilian soil data and concluded that it had better results than using temperate soil PTF. They concluded that there might have functional differences between temperate and tropical soils caused by some factors other than texture.

Hodnett and Tomasella (2002) derived a PTF using a data set of soils from tropical regions, which was contained in IGBT-DIS soil database. The data was checked and reduced to 771 horizons from 21 tropical countries. They were divided into two groups to be used in parameter calibration and PTF validation. These data contained eight pairs of points that defined the observed water release curve for each soil, volumetric soil water content ($m^3/m^3$) in function of soil matric potential (kPa). These data was used to derive van Genuchten parameters ($\alpha$, n, $\theta_s$ and $\theta_r$) using a nonlinear least squares fitting routing, resulting in a good level of fitting (91% had $R^2$ >0,97).

Wösten *et al.* (2001) compared the use of 21 different PTFs. They applied them to predict water content at –33 kPa and –1500 kPa by using a measured dataset from Oklahoma. The tests showed many types of discrepancies between them, which may confirm the fact that PTF is an empirical relationship. In this sense, reliable predictions must consider the fact that its use is valid only for soil horizons that fall in the same texture range as the horizons for which they have been developed. In this study, a PTF obtained by Tomasella and Hodnett (2002), derived from a data set composed by 614 tropical soil horizons, showed a partially good fitting for low water content ($\Psi$=-1500 kPa) and failing for high water content ($\Psi$=-33 kPa).

Hodnett and Tomasella (2002) found significant differences in soil characteristics between temperate and tropical soils. A comparison of soil textural class distribution between tropical and temperate datasets showed great difference in distributions, especially in clay class (far higher in tropical sets). A comparison of soil samples properties showed that, in general, tropical soils had less mean bulk density for each class than temperate soils. On the same way, a comparison of van Genuchten parameters derived for tropical and temperate soils showed significant differences. The values of parameter $\alpha$ for sand in temperate soils were more than twice higher than values obtained for tropical soils. For clay class, differences showed that both soil texture and mineralogy are important factors to be considered. The mean values of fitted $\theta_s$ for tropical dataset were higher than for the temperate data for all classes. On the same way, $\theta_r$ mean values in the tropical dataset showed to be higher than for the temperate soils. This difference between soils properties from tropical and temperate datasets explains the occurrence of marked differences between water release curves.

## 2. FUNCTIONS FOR WATER RETENTION CHARACTERISTICS

In unsaturated porous media, Darcy law defines flow as a result of soil capacity of transmission (hydraulic properties) and the action of an energy gradient, as follows,

$$V = -K_{ns}\,\nabla\phi \qquad (1)$$

where

$$K_{ns} = f_1(\psi)\ ;\ \ K_{ns} = f_2(\theta)\ ;\ \ \nabla\phi = \nabla(\psi - Z)$$

$k_{ns}$ is unsaturated soil hydraulic conductivity (cm/s), $\Psi$ is soil matric potential (cm), $\phi$ is total energy head, z is measured vertical distance from soil surface (cm), $\theta$ is volumetric soil water content ($cm^3/cm^3$).

Hydraulic gradient is the energy used by flowing water. Solutions of problems governed by (1) involve functions that express relations of soil water retention and hydraulic conductivity with soil water content. Richards equation (1931) describes flow in unsaturated soil as a combination of Darcy law and conservation of mass law, as follows,

$$\frac{\partial}{\partial y}\left(K(\psi)\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \phi}{\partial z}\right)=\theta^{*}\frac{\partial \phi}{\partial t} \qquad (2)$$

where $\theta^{*}=\frac{\partial \theta}{\partial \psi}$. $\theta^{*}$ can be derived by soil water release curve. Flow equation solution involves two analytical functions: soil hydraulic conductivity, $k=f_1(\psi)$, soil matric potential, $\psi=f_2(\theta)$. The relation $\psi=f_2(\theta)$ can be described empirically by a number of equations. Brooks-Corey equation (1964) is defined by the following expression,

$$S=\left(\frac{\psi_b}{\psi}\right)^{\lambda} \quad \text{where} \quad S=\frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad (3)$$

S is soil saturation level, $\theta_s$ is volumetric soil water content at saturation ($cm^3/cm^3$) and $\theta_r$ is residual water content ($cm^3/cm^3$), defined as the water that can be extracted from soil at high temperatures. $\psi_b$ is the air entry pressure head and $\lambda$ is the pore distribution index, both empirical fitting parameters.

Van Genuchten equation (1980) is a reference in its ability to characterize flow condition in unsaturated soil. It has shown good results for a variety of soils, and is defined as follows,

$$S=\frac{1}{\left[1+(\alpha|\psi|)^{n}\right]^{m}} \quad , \quad \psi \le 0 \qquad (4)$$

Relationship between parameters $m$ and $n$ is $m=1-\frac{1}{n}$

where $n$ is a dimensionless parameter that determines the steepness of the water release curve.

The parameter $\alpha$ is equal to the inverse of $\Psi$ at the point where the curve is steepest.

Flow capacity in unsaturated soil zone can be well characterized with a model proposed by van Genuchten and Mualen (1992), using van Genuchten parameters, defined as follows,

$$K(S)=K_{sat}S^{0,5}\left[1-(1-S^{n/(n-1)})^{(1-1/n)}\right]^{2} \qquad (5)$$

This work aims to study the level of reliability of Hodnett and Tomasella PTF in its application to soils of semiarid regions. For this purpose, it will be used data from soil sample analysis on laboratory and measured hydraulic conductivity at saturation from infiltration experiments on 8 locations within an experimental catchment in Brazilian northeastern semiarid zone, state of Rio Grande do Norte.

## 3. METHODS

The study area is located approximately 300 km west from Natal, state of Rio Grande do Norte. It is located within the Espinharas river watershed in northeastern semiarid zone. The catchment area is 3,82 $km^2$ (Fig. 1). It has been environmentally protected for many years by IBAMA (Brazilian Institute for Environmental Protection) Administration, Brazilian government. It is topographically located at the Espinharas watershed boundary. Research area relief is partially hill slope; a topographically closed basin presents an alluvium area located upstream a reservoir used to storage water for human consumption.

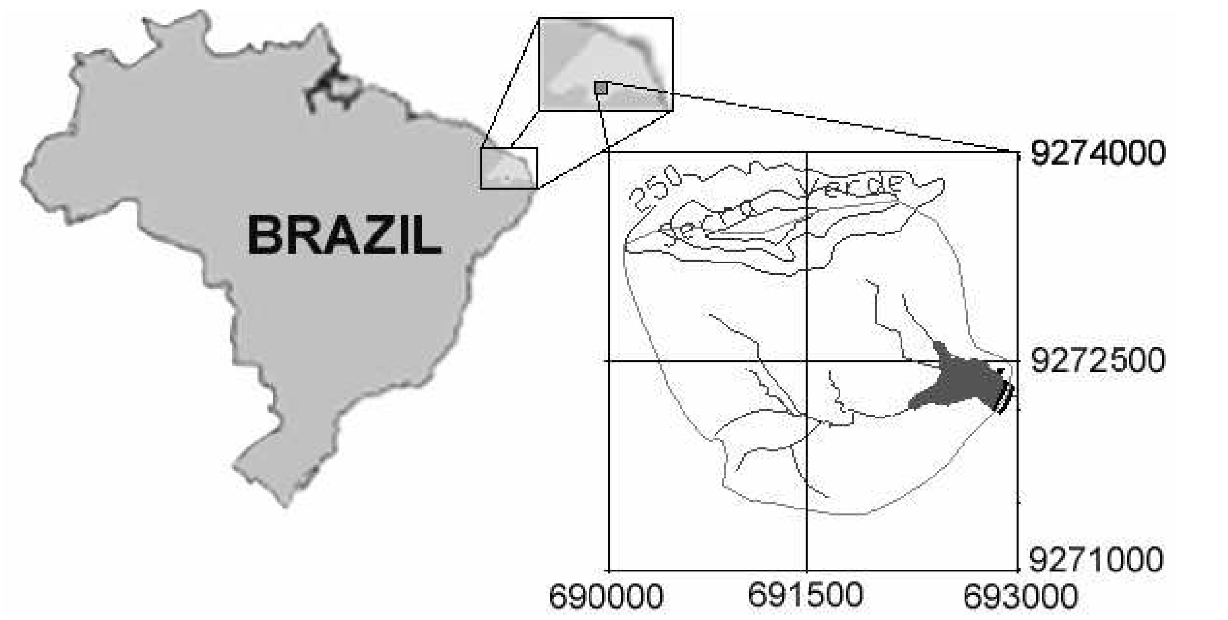


**Figure 1.** Geographical coordinates of catchment area

Survey measurements showed that soil depth ranges from 0,2 m to 1,2 m; geological rock formation appears on the surface area at some points. At the midland part of the catchment, soil surface erosion is produced by the action of a potentially high overland flow on flat areas. On these areas, the existence of pebbles and cobbles rest on soil surface indicates that: a. sediment was eroded from the surface; b. soil grain size distribution is bimodal; c. soil horizon is well consolidated.

Natural drainage network presents, in most area, boulder formation along an ephemeral stream talweg. It indicates that most part of sediment yield may occur on the drainage network upstream, where local scour erosion process is caused by channel flow.

Soil samples were collected at 0,15 m depth in 8 different points covering the most part of the basin area. Laboratory measurements included grain size analysis, gravimetric water content, bulk density and textural classification. Sample grain size distribution analysis showed that most of them are poorly sorted and bimodal (fine and coarse modes present in the mixture), except the alluvium soil formation. Bulk density and porosity of soil samples fall to a range of 1,53 to 1,75 g/cm$^3$ and 0,20 to 0,35 respectively. Measured hydraulic conductivity at saturation ranges from 1,34 x $10^{-4}$ to 4,5 x $10^{-3}$ cm/s (Table 1). Infiltration experiments were performed in 8 measurement locations within the catchment by using a constant head disc infiltrometer. This method allows obtaining accurate estimates of field saturated hydraulic conductivity, $k_{sat}$ (cm/s).

Water was supplied to the soil at a positive head by using a disc infiltrometer. It allows the air entrance to a reservoir (PVC tube with a 0,15 m diameter), with water liberation to a ponded soil surface. Steady state soil water flow is the result of integration of gravitational effect, constant ponded head influence and capillary forces. Two metallic rings were carefully inserted into the ground to a depth of approximately 3 cm without removing any natural vegetation. When measurement started, ground area between rings was ponded in order to prevent lateral flow because it misrepresents vertical infiltration). At each location, infiltration experiments were performed until steady state infiltration was attained. The time required for attaining this condition varied in function of soil hydraulic characteristics, with 40 minutes on average. At steady state condition, measured infiltration remained approximately constant in function of time. Measured curves showed variations in soil hydraulic behavior. In three experiments, it was verified a marked dispersion of infiltration capacity in function of time, indicating the existence of preferred flow pathways for infiltrating water (vertical and cylindrical pores) or local biological activity into the soil. The other five experiments resulted in a well-shaped downward curve before infiltration attained steady state condition and a horizontal configuration could be observed.

## 4. RESULTS AND DISCUSSION

Measured soil properties and hydraulic conductivity at field-saturated condition data was used in Hodnett and Tomasella (2002) and Wösten *et al*. (2001) PTFs to obtain soil hydraulic parameters. Soil hydraulic parameters $\alpha$, n, $\theta_s$, $\theta_r$ and $k_{sat}$ obtained by using these PTFs are listed in Tables 2 and 3. The level of reliability of Hodnett and Tomasella (2002) PTF can be evaluated by comparing soil hydraulic parameters obtained from IGPB/T database with those parameters derived from using the same PTF and measured properties of soil samples collected within the catchment. For this purpose, the comparative analysis was made considering soil parameters derived for each soil texture class.

In every case, the mean values of field bulk density were higher than the IGBP/T data set for each texture class, with differences ranging from 17% (sandy clay) to 41% (loamy class).

The mean $\alpha$ values derived by using Hodnett and Tomasella (2002) PTF to the field soil samples were compared with those obtained for the IGBP/T data set. The differences between $\alpha$ values were less for loamy texture (12%) and higher for clay (33%). Higher differences were observed for the $\theta_r$ parameter, especially for sandy clay and clay classes, 43% and 56% respectively. For the mean n values, the differences were less, ranging from 1,3% to 10%.

In a second stage, a comparison was made between Wösten *et al.* (2001) and Hodnett and Tomasella (2002) PTFs by using measured soil sample data as input. There was a marked difference between soil parameters derived by these two functions, ranging from 43% to 98%. The mean $\alpha$ and $\theta_s$ values are overestimated by Hodnett and Tomasella (2002) PTF for every class, with the higher difference for sandy loam class. Wösten *et al.* (2001) $k_{sat}$ parameter was compared to the field saturated hydraulic conductivity data for each soil class. These values were overestimated by Wösten *et al.* (2001) function for every class, ranging from 12% (clay) to 65% (loamy class). Marked differences between parameters obtained by these two PTFs indicate that soils from different climatic conditions show hydraulic differences that may be reflected in the derived parameters [Wösten *et al.* 2001].

| Soil sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Bulk density ($g/cm^3$) | 1.75 | 1.74 | 1.67 | 1.64 | 2.03 | 1.88 | 1.67 | 1.93 |
| Porosity | 0.31 | 0.31 | 0.34 | 0.35 | 0.20 | 0.26 | 0.34 | 0.24 |
| $q_{initial}$ ($cm^3/cm^3$) | 0.029 | 0.034 | 0.025 | 0.063 | 0.054 | 0.079 | 0.02 | 0.066 |
| K sat ($x10^{-4}$cm/s) | 12 | 7.3 | 15 | 17 | 1.3 | 4 | 43 | 15 |
| Soil texture | Sandy loam | Sandy loam | Sandy clay | Sandy clay | Loam | Sandy loam | Clay | Sandy loam |

**Table 1.** Measured soil hydraulic properties at 8 locations within the catchment.

| Soil sample | $\alpha$ | n | $\theta_{sat}$ | $K_{sat}$ |
|---|---|---|---|---|
| A1 | 0.151 | 2.465 | 0.322 | 7.395 |
| A2 | 0.111 | 2.510 | 0.330 | 7.871 |
| A3 | 0.272 | 2.619 | 0.331 | 6.574 |
| A4 | 1.117 | 2.510 | 0.330 | 7.871 |
| A5 | 0.188 | 3.037 | 0.391 | 9.902 |
| A6 | 0.193 | 2.478 | 0.316 | 5.754 |
| A7 | 0.191 | 2.750 | 0.348 | 6.410 |

**Table 2.** Soil hydraulics parameters obtained by Hodnett and Tomasella PTF (2002) application.

| Soil sample | $\alpha$ | n | $\theta$ sat | $\theta$ r |
|---|---|---|---|---|
| A1 | 0.292 | 1.398 | 0.569 | 0.140 |
| A2 | 0.260 | 1.361 | 0.570 | 0.153 |
| A3 | 0.359 | 1.502 | 0.566 | 0.112 |
| A4 | 0.411 | 1.542 | 0.561 | 0.117 |
| A5 | 0.290 | 1.375 | 0.579 | 0.163 |
| A6 | 0.321 | 1.467 | 0.588 | 0.112 |
| A7 | 0.307 | 1.442 | 0.587 | 0.119 |
| A8 | 0.303 | 1.437 | 0.587 | 0.119 |

**Table 3.** Soil hydraulics parameters obtained by Wösten *et al.* PTF (2001) application.

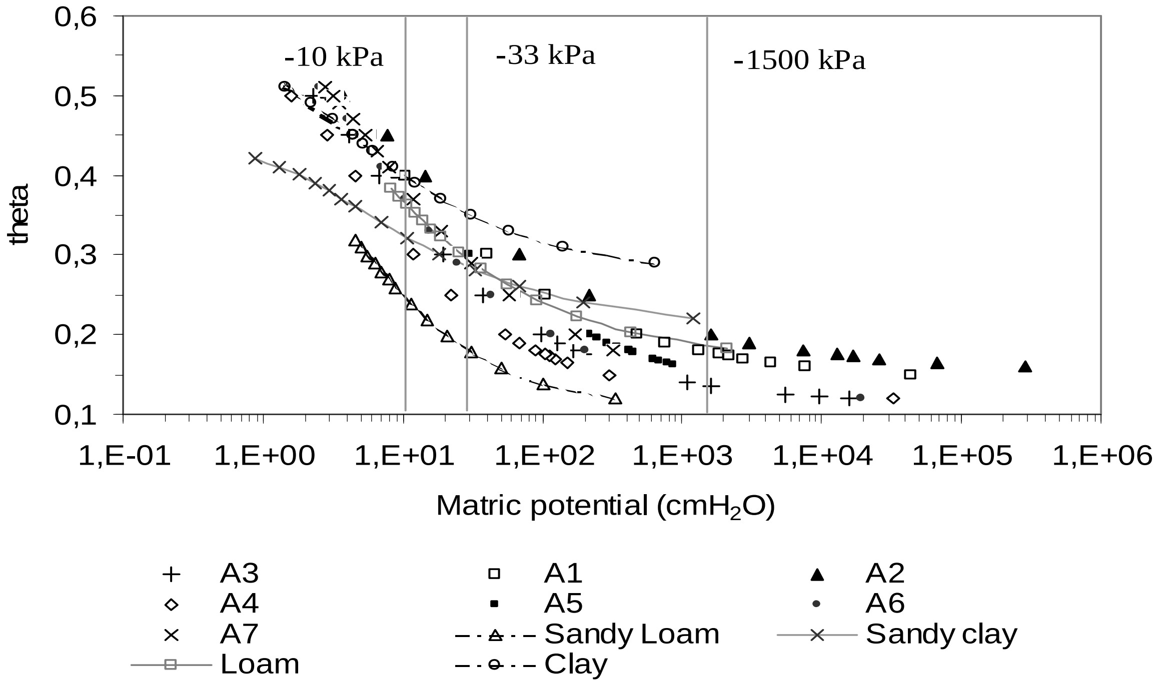


**Figure 2**. Water release curves for field sample soils and IGPB/T soil data set

Different geographic regions around the world exhibit important variations in structural soil characteristics that must be considered by PTFs. Regional specificity of a PTF can be clearly emphasized when results obtained by PTFs from tropical and temperate data sets are compared.

Hodnett and Tomasella (2002) PTF and van Genuchten parameters generated from IGBP/T data for each textural class were used to construct the water release curves for the soil classes found in study area (Figure 5). Although it shows a reasonable agreement with the curves obtained for each soil sample, the scatter between curves from the same textural class reflects limitations for reproducing water release curve for these soils. This limitation may be due to some factors: a. functional differences between soils from IGBP/T data and soils from study area; b. specific soil hydraulic behavior in semiarid region areas that may need to be better understood on further investigations; c. the effect of the bimodality on soil hydraulic functioning was not considered; d. use of regression analysis to derive relationships has a limited capacity to represent a complex system.

## 5. CONCLUSIONS

IGBP/T data set used by Hodnett and Tomasella (2002) to derive a tropical PTF was composed of a large range of tropical soils. However, it was limited to regions represented by those data. IGBP/T data set didn't cover all types of soil mineralogy of tropical regions. In this study, a comparison was made between soil parameters from IGBP/T data set and field samples within a study area located in a semi arid region. Results showed some important differences. Although differences were not significant when compared with Wösten *et al*. (2001) temperate PTF, they emphasize the specificity of semi arid regions soils behavior. The differences may be explained by some factors related to specificity on soil hydraulic functioning in these regions, accuracy level of relationships between soil properties and predicted parameters, among other factors.

Despite of these limitations, calculated differences between parameters showed a reasonable agreement with the same trend, what is shown in water release curves for field sample soils and IGPB/T soil data set shown in Figure 2.


## 6. ACKKONWLEDGEMENTS

This research was supported by CT-HIDRO/FINEP Brazilian Government through the IBESA Project – Implementation of Experimental Catchment in Brazilian Semi Arid Region.


## 7. REFERENCES


Brooks, R.H. and Corey, A.T., 1964. Hydraulic properties of porous media. Hydrologic paper Nº 3, Civil Engineering Dept., Colorado State University, Fort Collins, CO.

Van Genuchten, M.Th., 1980. A closed form equation for predicting hydraulic conductivity in unsaturated soils. Soil Sci. Soc. Am., J. 44, 892-898.

Tomasella, J., Hodnett, M.G., and Rossato, L., 2000. Pedotransfer functions for the estimation of soil water retention in Brazilian soils. Soil Sci. Soc. Am., J. 64, 327-338.

Tomasella, J., Hodnett, M.G., 1998. Estimating soil water retention characteristics fron limited data in Brazilian Amazonia. Soil Science, 163, 190-202.

Hodnett, M.G. and Tomasella, J., 2002. Marked differences between van Genuchten soil water retention parameters for temperate and tropical soils: a new water retention pedotransfer functions developed for tropical soils. Geoderma, 108, 155-180.

Wösten, J.H.M., Pachepsky, Ya. A. and Rawls, W.J., 2001. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. Journal of Hydrology, 251, 123-150.

Dong, W., Yu Z. and Weber, D., 2003. Simulations on soil water variation in arid regions. Journal of Hydrology, 275, 162-181.

Wösten, J.H.M., Schuren, C.H.J.E., Bouma, J. and Stein, A., 1990. Functional sensitivity analysis of four methods to generate soil hydraulic functions. Soil Sci. Soc. Am., J. 54, 832-836.

Hodnett, M.G., Pimentel da Silva, L., da Rocha, H.R. and Cruz Senna, R., 1995. Seasonal soil water storage changes beneath central Amazonian rainforest and pasture. Journal of Hydrology, 170, 233-254.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics, 1, 318-333.