# Chapter 20
# A Hydrophysical Database to Develop Pedotransfer Functions for Brazilian Soils: Challenges and Perspectives

**Marta Vasconcelos Ottoni, Maria Leonor Ribeiro Casimiro Lopes-Assad, Yakov Pachepsky, and Otto Corrêa Rotunno Filho**

**Abstract** Access to soil hydrological data is vital for hydrology projects and for supporting decision-making in issues related to the availability of food and water and the forecasting of phenomena related to geomechanics. Brazil is a country of continental dimensions and has accumulated a significant body of soil information, holding a prominent position in tropical soil science. Nevertheless, a database with hydrophysical information on Brazilian soils has not been compiled so far, whereas much information is registered and analyzed. In this study we discuss the potential for the development of a Brazilian hydrophysical database and pedotransfer functions (PTFs). We present on metadata the measurement methods of soil hydrophysical

M.V. Ottoni (✉)
Department of Hydrology, Companhia de Pesquisa de Recursos Minerais (CPRM), Geological Survey of Brazil, Rio de Janeiro, RJ, Brazil

Laboratório de Recursos Hídricos e Meio Ambiente (LABH2O), Programa de Engenharia Civil, Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil
e-mail: marta.ottoni@cprm.gov.br

M.L.R.C. Lopes-Assad
Department of Natural Resources and Environmental Protection, Federal University of São Carlos (UFSCar), Araras, SP, Brazil
e-mail: assad@cca.ufscar.br

Y. Pachepsky
Environmental Microbial and Food Safety Laboratory, USDA-ARS Beltsville Agricultural Research Center, 10300 Baltimore Ave., Bldg. 173, Beltsville, MD 20705, USA
e-mail: yakov.pachepsky@ars.usda.gov

O.C. Rotunno Filho
Laboratório de Recursos Hídricos e Meio Ambiente (LABH2O), Programa de Engenharia Civil, Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa em Engenharia (COPPE), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil
e-mail: otto@coc.ufrj.br

W.G. Teixeira et al. (eds.), *Application of Soil Physics in Environmental Analyses: Measuring, Modelling and Data Integration*, Progress in Soil Science,
DOI 10.1007/978-3-319-06013-2_20, 

attributes and the characteristics of the sites where these soil properties were determined. Statistical analyses were performed to characterize the dataset according to the metadata-based data structure. A total of 8,983 datasets contains soil water retention information associated with physical or chemical properties. Besides these, 1,253 datasets with data on saturated hydraulic conductivity coupled with water retention information are also available. The results of this study suggest that it is possible to develop a representative hydrophysical database for Brazilian soils that covers most of Brazil's federative states, with a substantial volume of data and homogeneous with respect to the methods of measuring soil properties. This creates excellent prospects for PTFs development, especially for estimating water retention, at a national scale. The challenge in the development of the Brazilian soil hydrophysical database is the refinement of the dataset model that can encompass the wide range of available information and can provide answers to queries of interest to different types of users of soil information. Considering the size of the Brazilian territory, it would be of interest that the database development become a joint effort of government agencies, universities and commercial enterprises.

**Keywords** Water retention • Hydraulic conductivity • Tropical soils • Brazilian soil • Database

## 20.1 Introduction

The numerical models that simulate physical, chemical and biological processes in the vadose zone are of widely recognized importance to agricultural management, water resources, and climate change- related research and applications. Such modeling also provides technical and scientific support for the development of policies in matters related to food and water supply and earth surface phenomena that can lead to land quality reduction or even disasters, like soil loss or landslides. Typically, these models make a partition of precipitation into infiltration, runoff and evapotranspiration, and utilize soil hydraulic properties as input data to describe water and solute retention and transport in soils. The amount of these input data needed to run the models depends on the spatial and temporal resolution considered in the simulations. The higher this resolution, the greater is the volume of required measurements (Minasny and McBratney 2002). This problem indicates the need for less expensive and rapid tools to estimate soil hydraulic properties (Schaap et al. 2001).

An indirect method of determining soil hydraulic attributes consists in estimating them with pedotransfer functions (PTFs), which are based on pedological variables that can be measured routinely and easily (McBratney et al. 2002). The concept was introduced by Bouma (1989) and has been used worldwide (Wösten et al. 1999; Schaap et al. 2001; Tomasella et al. 2003; Rawls 2004; Stekauerová and Sútor 2004; Reichert et al. 2009; Makó et al. 2010; Wang et al. 2012; Mihálikovà et al. 2013).

The first PTF for water retention in Brazilian soils was proposed relatively recently (Tomasella et al. 2000). Initiatives for Brazilian PTFs development started much earlier but were limited to a specific soil class or to a certain region (Arruda et al. 1987; Silva et al. 1990; Van Den Berg et al. 1997). In the attempt to better represent the wide variety of soils in Brazil, new PTFs for Brazilian soils were created in 2003, adding to the database of Tomasella et al. (2000) with 630 samples another one with 208 samples (Tomasella et al. 2003). The PTFs presented by Tomasella et al. (2000) were used in very few studies in Brazil like Rossato (2002) and Doyle et al. (2013), but the application of PTFs from temperate regions to Brazilian soils persists, although tropical soils use to have a different mineralogy and texture than soils from temperate regions. Hodnett and Tomasella (2002) observed considerable differences between estimated parameters of the Van Genuchten (1980) equation comparing soils from tropical and temperate regions. Their analysis showed that the application of temperate PTFs for tropical soils is inadequate.

The accuracy of the numerical models depends on the PTF's performance in the simulations (Tomasella et al. 2000; Minasny and McBratney 2002; Jana et al. 2007). The accuracy of these functions requires, among other aspects, databases that present the following characteristics: (a) precise measures of soil attributes (Wösten et al. 2001; Mohanty and Shouse 2002; Perkins and Nimmo 2009; Vereecken et al. 2010); (b) various soil properties and landscape features, such as topographic parameters and terrain vegetation (Pachepsky et al. 2001; Rawls and Pachepsky 2002; Leij et al. 2004; Sharma et al. 2006) that may serve as input variables in these functions; (c) a substantial number of data distributed in relatively homogenous quantities from diverse soils and environments (Perkins and Nimmo 2009; Vereecken et al. 2010); and (d) standardization of measuring methods of soil attributes among data contained in the database (Schaap and Leij 1998; Pachepsky et al. 1999; Perkins and Nimmo 2009; Vereecken et al. 2010).

Brazil has accumulated a vast amount of soil information from pedological surveys, but most of these data is not readily available. One of the initiatives of gathering such information was the study of Cooper et al. (2005) which had its soil profile database updated by Benedetti et al. (2008) considering the second last edition of the Brazilian Soil Classification System (Embrapa 2006). Literature reviews on Brazilian soil surveys and pedological databases can be found in Chagas et al. (2004), Embrapa (2013) and Barros and De Jong Van Lier (2014, this volume).

Generally, soil survey studies in Brazil are focused on taxonomic descriptions, whereas information on hydraulic properties (water retention and hydraulic conductivity) is rarely collected. Such tendency is observed worldwide. ISRIC-WISE (Harmonized Global Soil Profile Dataset, version 3.1) (Batjes 2009), UNSODA (UNsaturated SOil DAtabase) (Leij et al. 1996; Nemes et al. 2001) and HYPRES (HYdraulic PRoperties of European Soils) (Wösten et al. 1999), were the first soil databases in which hydraulic properties associated with soil survey information were available. These datasets have (partially) satisfied the world's demand for hydrophysical information at the time.

Several soil hydrophysical data inventories have been recently developed. The latest effort resulted in the EU-HYDI (EUropean HYdropedological Data Inventory) (European Commission 2013). This initiative assembles information from soil surveys associated with hydraulic measurements from 18 European countries, including around 6,014 soil profiles and 18,682 horizons. MARTHA (Hungarian Detailed Soil Hydrophysical Database) (Makó et al. 2010) and PROPSOLO (Gonçalves et al. 2011) are examples of databases developed for Hungarian and Portuguese soils, respectively, which are included in EU-HYDI. Both were developed for building soil hydraulic PTFs.

A database with hydrophysical information on Brazilian soils has not been compiled so far. At present, diverse data are reported and analyzed in disperse publications. Assad et al. (2001), Tomasella et al. (2003), Urach (2007), Andrade and Stone (2009) and Barros et al. (2013) present examples of studies that used data on soil hydraulic attributes and carried out PTFs development. Assad et al. (2001) employed data from 373 samples from several Brazilian states, Tomasella et al. (2003) used 838 samples representing most of the Brazilian territory, Urach (2007) described 963 samples from the Southern state of Rio Grande do Sul, Andrade and Stone (2009) used more than 2,000 soil datasets, mainly from the Central-Western region of Brazil, and 786 from the Northeastern region of Brazil were collected by Barros et al. (2013). None of these studies included organizing information in a structured database that could be easily accessed, searched, and generalized. The first attempt to organize a hydrophysical database for Brazilian soils was possibly the dissertation of Silva (2005), but it is not available for public access.

Currently, the development of a soil hydrophysical database encompassing the variety of existing data in Brazil is of utmost importance. Many applications of soil hydraulic PTFs can be expected. One of them is the development of a Brazilian soil water availability map, based on the information from pedological survey studies in Brazil (Rossato et al. 1998; Cooper et al. 2005). As Brazil possesses a significant share of terrain affecting the global energy circulation, another important demand for a Brazilian PTF is in the modeling of the global energy balance for climatic forecasts.

In this context, in 2010 the Department of Hydrology of the Geological Survey of Brazil (or simply CPRM, which is the acronym for the company's official name in Portuguese: Companhia de Pesquisa de Recursos Minerais) started the "Hydrophysical Characterization of Soils" project, with the objective of developing a hydrophysical database for Brazilian soils. This project is developed by Brazilian and foreign researchers and is expected to be completed in 2016. The study consists of four stages:

1. to create an inventory of technical and scientific publications that contains hydrophysical attributes of Brazilian soils, and the corresponding data collection;
2. to define the database model;
3. to format and convert data according to the proposed model, and the corresponding data consistence;
4. to develop PTFs for the prediction of the water retention property for Brazilian soils.

In this chapter we will focus on the first of these four stages. We present an inventory of studies developed mostly in the last ten years, which address measuring hydrophysical attributes in Brazilian soils. We intend to evaluate the potential of this information to compose a Brazilian hydrophysical database, with the proposal to develop PTFs to estimate water retention for Brazilian soils.

## 20.2 Inventory of Publications and Data Survey

Relevant Brazilian publications, such as scientific papers, dissertations, theses, studies presented in soil conferences and symposia, and technical notes from the Brazilian Agricultural Research Corporation (Embrapa) were parsed for information. The study title was used as search reference considering four key words: 'hydraulic conductivity', 'hydrophysical', 'soil database' and 'water retention', as well as their equivalents in Portuguese. The studies selected to be evaluated for availability of hydrophysical data were those that included measurements of soil water retention.

In total, 1,100 studies were evaluated, from which 125 contained, in their titles, 'hydraulic conductivity', 611 'hydrophysical', 185 'soil database', and 170 'water retention'. Out of these studies, 163 contained water retention measurements and were selected for data availability analysis. The approximately 400 authors of these 163 publications were contacted and asked to provide their datasets to the CPRM, including physical, chemical and hydraulic information, and general data of the location where the soil properties measurements were made, with geographical coordinates (latitude and longitude), soil class description, methodological details of the experiments and other possibly relevant information.

For 52 of these studies, the authors made available the complete datasets, in the form of digital spreadsheets or printed material. Great differences were found in presentation format and in data quantity and quality.

Among these 52 studies with complete data availability, 14 refer to MSc dissertations, 7 to PhD theses, 10 to studies published in the Brazilian Journal of Soil Science and 21 to other sources (symposia and Embrapa technical notes). On classifying these studies into the four main topics proposed at the 2$^{nd}$ Brazilian Soil Physics Meeting/2013, the vast majority (41 out of 52) refers to "Applied soil physics: interaction between soil physics, agronomy, ecology and geosciences". Four refer to the section "Database development and pedotransfer functions", and seven others refer to "Modeling flow and transport processes in the vadose zone" and "Development of methods and instrumentation in soil physics" sections. Even though the 52 studies may not be a representative sample of the universe of publications in soil physics in Brazil, this result is an indication that, in Brazil, there seem to be few studies focused on databases, PTFs, modeling and instrumentation, compared to studies focusing on applied soil physics.

## 20.3 Development of Metadata on Soil Hydrophysical Information

Tables 20.1, 20.2 and 20.3 present the structure of the metadata on soil hydrophysical information with the example data from three publications. The soil attributes shown in Table 20.2 were chosen based on published experience of PTF development for hydraulic properties.

The geographical coordinates (latitude and longitude) of the sites of measurement were also registered in the metadata (Table 20.1). When coordinates of the sampling location were unavailable, they were taken as the center of the respective city or state. Locations with these coordinates, estimated or extracted from the original publications, were plotted on the map of Brazil in order to visually evaluate the distribution of available data by Brazilian state and by biomes.

The distribution of the total number of datasets compiled from the 52 publications across the Brazilian soils was evaluated at the level of soil order, according to the second last edition of the Brazilian Soil Classification System (Embrapa 2006).

## 20.4 Statistical Analysis

The goal of the statistical analysis was to assess the potential of the hydrophysical datasets from the 52 publications for creation of a hydrophysical database in Brazil, specifically suitable for PTFs development. In order to do so, the following aspects were evaluated: (1) total number of datasets on soil hydraulic properties; (2) scope and geographical distribution; (3) representation of soils, in terms of pedological and textural classes, as well as in terms of depth in the soil profile; (4) the variety of measuring methods of soil attributes; and (5) data characteristics for water retention PTFs development. In the latter, we intended to focus on the description of available physico-chemical attributes that can be used as PTFs predictors. Characterization of the water retention data was also done based on the frequency of measurements at different matric potential levels.

## 20.5 Summary Statistics of Soil Hydraulic data

The number of datasets with soil water retention measurements (water retention content versus matric potential) is shown in Table 20.4, together with the number of datasets including information on saturated or unsaturated hydraulic conductivity.

Comparing the data of Table 20.4 to the statistics of continental and international databases, we can conclude that Brazil is in a good position when it comes to water retention measurements, but not for the hydraulic conductivity data (Wösten et al. 1999; Nemes et al. 2001). In the European continental database HYPRES,

**Table 20.1** Metadata with hydrophysical information on Brazilian soils – part 1 ('-' symbol, indicates that the information was not reported in the study)

| | | General information of the studied area | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Study | Origin | City | State[b] | Soil class | Latitude | Longitude | Geographic coordinate information | Number of datasets | Depth |
| Assad et al. (2001)[a] | Soil dataset of the Federal University of São Carlos (UFSCAR)/SP | Many | CE, GO, MG, PR, RJ, RN, SC, SP | Many | Many | Many | Each sample has its own coordinate | 1,409 | Soil depths varying from 0 m to 9.00 m (with soil horizons description) |
| Carducci et al. (2011) | Cerrado biome | Rio Verde | GO | Latossolo Vermelho - Amarelo distrófico (1 profile) (Embrapa 2006) | 17°47′01″S | 50°57′55″W | Each sample has its own coordinate | 4 | Bw (0.80–1.00 m) |
| | | | | Latossolo Vermelho distrófico (5 profiles) (Embrapa 2006) | | | | 20 | |
| | | | | Latossolo Vermelho distroférrico (4 profiles) (Embrapa 2006) | | | | 16 | |
| Ottoni (2005) | Santa Maria and Cambiocó micro-watersheds | São José de Ubá | RJ | Cambissolo Háplico (Embrapa 1999) | 21°23′52″S | 41°55′03″W | Each profile has its own coordinate | 18 | Soil depths varying from 0.075 to 0.50 m, approximately (with soil horizons description) |
| | | | | Argissolo Vermelho-Amarelo (Embrapa 1999) | | | | 24 | Soil depths varying from 0.10 to 0.60 m, approximately (with soil horizons description) |
| | | | | Neossolo Litólico (Embrapa 1999) | | | | 6 | 0.085, 0.125, 0.185 m (with soil horizons description) |
| | | | | Gleissolo Háplico (Embrapa 1999) | | | | 16 | Soil depths varying from 0.09 to 0.60 m, approximately |

(continued)

**Table 20.1** (continued)

| | | General information of the studied area | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Study | Origin | City | State[b] | Soil class | Latitude | Longitude | Geographic coordinate information | Number of datasets | Depth |
| | | | | | | | | | (with soil horizons description) |
| | | | | Planossolo Háplico (Embrapa 1999) | | | | 16 | Soil depths varying from 0.08 to 0.60 m, approximately (with soil horizons description) |
| | | | | Luvissolo Háplico (Embrapa 1999) | | | | 4 | 0.10, 0.25, 0.37 m (with soil horizons description) |
| | | | | Extra profile | | | | 8 | 0.11,0.27, 0.47 e 0.65 (without soil horizons description) |

[a] Assad et al. (2001) used 373 datasets with water retention measurements, extracted from the UFSCAR hydrophysical database (not published) which contains 1,409 datasets as shown in Table 20.1

[b] CE – Ceará, GO – Goiás, MG – Minas Gerais, PR – Paraná, RJ – Rio de Janeiro, RN – Rio Grande do Norte, SC – Santa Catarina, SP – São Paulo

**Table 20.2** Metadata with hydrophysical information on Brazilian soils – part 2 ('-' symbol, indicates that the information was not reported in the study)

| | Soil hydrophysical property methodology | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Grain size analysis | | | | | Bulk density (BD) | Soil penetration resistance (PR) | Water retention curve | |
| Study | Method | Texture class | Organic carbon (OC) | Organic matter (OM) | Particle density (PD) | *Method; sample type[b]; sample size* | *Method; sample type[b]; sample size* | *Number of different values of matric potential* | *Matric potential values* |
| Assad et al. (2001)[a] | Embrapa (1997) | Clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm) | Modified Walkley-Black (Jackson 1982), with wet oxidation and determination by titration | OC × 1.72 | Embrapa (1997) | Volumetric ring; UN;100 $cm^3$ | - | 3 | 10, 33, 1,500 kPa |
| Carducci et al. (2011) | Pipette | Clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm) | - | - | Pycnometer | Volumetric ring; UN; 0.064 m of diameter and 0.025 m of height | Static; UN; 0.064 m of diameter and 0.025 m of height | 11 | 1, 2, 4, 6, 8, 10 kPa<br>33, 60, 100,500, 1,500 kPa |
| | | | | | | | | 19–28 | >1,500 kPa (1,500–300,000 kPa) |
| Ottoni (2005) | Densimeter | Clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm) | Modified Walkley-Black (Jackson 1982), with wet oxidation and determination by titration | OC × 1.724 | Volumetric flask | Volumetric ring; UN; 100 $cm^3$ | - | 3 | 0.006, 0.033, 1.5 Mpa |

[a]Assad et al. (2001) used 373 datasets with water retention measurements, extracted from the UFSCAR hydrophysical database (not published) which contains 1,409 datasets as shown in Table 20.1

[b]UN – undisturbed sample; D – disturbed sample

**Table 20.3** Metadata with hydrophysical information on Brazilian soils – part 3 ('-' symbol, indicates that the information was not reported in the study)

| | Soil hydrophysical property methodology | | | | |
|---|---|---|---|---|---|
| | Water retention curve | | | Hydraulic conductivity K | |
| Study | *Time of measurement* | *Method* | *Sample type*[b]*; sample size* | *K saturated; Method; sample type; sample size* | *K unsaturated; Method; sample type; sample size* |
| Assad et al. (2001)[a] | - | Pressure chamber | UN; 100 $cm^3$ | - | - |
| Carducci et al. (2011) | - | Hanging water column<br>Pressure chamber | UN; 0.064 m of diameter and 0.025 m of height | - | - |
| | | Dew point psychrometer – WP4-T | D | | |
| Ottoni (2005) | - | Pressure chamber | UN; 100 $cm^3$ | - | - |

[a]Assad et al. (2001) used 373 datasets with water retention measurements, extracted from the UFSCAR hydrophysical database (not published) which contains 1,409 datasets as shown in Table 20.1

[b]UN – undisturbed sample; D – disturbed sample

**Table 20.4** Number of datasets with soil hydraulic properties measurements

| Hydraulic properties | Number of datasets |
|---|---|
| Both water retention and saturated hydraulic conductivity | 1,253 |
| Both water retention and unsaturated hydraulic conductivity | 30 |
| Water retention data[a] | 8,983 |
| Water retention data associated with geographic coordinates information | 3,715 |

[a]Including datasets with saturated and unsaturated hydraulic conductivity

for example, there are 2,894 horizons with information on water retention and 1,136 with joint measurements of water retention and hydraulic conductivity.

The low number of datasets containing information on unsaturated hydraulic conductivity may be due to our adopted criteria for selection of publications (see Sect. 20.2). As previously noted, only those studies including water retention data were selected. Thus, publications that focused solely on unsaturated hydraulic conductivity measurements were not considered. Even though, we can affirm that few studies in Brazil determine unsaturated hydraulic conductivity, and those that do so use mostly the instantaneous profile method, the measured tension range being limited to the suction tensiometer range (0–800 cm).

From the total of 8,983 datasets containing information about water retention, 3,715 have geographic coordinates, which is a positive factor for the development of maps on soil hydraulic properties. These numbers as well as other statistics presented in Table 20.4 are, however, subject to revision after evaluating the consistency of all compiled information.

## 20.6 Scope and Geographical Distribution

The geographical distribution of the locations where hydrophysical measurements were done (52 publications) is shown in Fig. 20.1. The number of datasets containing water retention information for each Brazilian state is also indicated in Fig. 20.1 and, when inexistent, suggests that there are no measurements of this soil attribute.

The distribution of the water retention datasets (8,983) across the states and geographic regions of Brazil, with indication of data density per region (number of datasets per 100,000 km$^2$) is shown in Table 20.5.

The Southeastern region has a significant amount of datasets (2,328) and is the part of Brazil with the highest spatial density, 251 datasets per 100,000 km$^2$ (Table 20.5). Among the states in this region, São Paulo is represented by 1,176 datasets or 13 % of all water retention data. Goiás is the only state with more data quantity, with 26 %. Of the other states in the Southeast, Minas Gerais and Rio de Janeiro together present 1,110 datasets, each with relatively similar quantities of water retention measurements. The state of Espirito Santo represents only 42 datasets (~0.5 %). Figure 20.1, from Tomasella et al. (2003), shows a significant amount of datasets concentrated in the Southeastern region and might increase the percentage for this region. Currently the Tomasella et al. (2003) database can be found in the 1,561 datasets classified as 'no information' (Table 20.5).

The reason for the impressive volume of soil hydraulic information in the Southeast, especially in São Paulo, is due to the existence of large centers of soil research in this state. The Southeastern region is the second smallest region in terms of surface area, however, it represents the economic center of Brazil, with high population density, large iron ore deposits, hydro-electric power plants and ports, located between two important biomes, Cerrado and Atlantic Forest (Fig. 20.1).

In contrast to the Southeast, the Northern Brazilian region, the largest of the country and containing the richest biodiversity, surface and subsurface water resources and carbon concentration due to the presence of the Amazon Rain Forest (Fig. 20.1), is represented by only about 10 % of the entire water retention database, predominantly from the state of Amazonas, with 707 datasets (~8 %). The state of Pará, the second largest state in Brazil after Amazonas, is represented by only 16 datasets. The Northern region shows the lowest spatial density, with only 23 datasets per 100,000 km$^2$. Some of its states (Acre, Roraima and Amapá) have no water retention data at all.

Unlike the humid Northern Brazil, the Northeastern region is sub-humid to semi-arid, characterized by little rainfall. The main biome of this region is the Caatinga (Fig. 20.1), with a xerophytic vegetation and predominantly shallow and stony soils, commonly inappropriate for rainfed agriculture. This region is represented by 13 % of all database (8,983), thus being the territory with the second lowest spatial density, 75 datasets per 100,000 km$^2$. The states of Alagoas, Rio Grande do Norte and Bahia together are represented by about 1,000 datasets, 11 % of the total amount of water retention measurements. The states of Piauí and Paraíba have a low quantity of datasets (two and nine datasets, respectively). Maranhão has no water retention data at all. The remaining states of the region with hydraulic information are Ceará, Sergipe and Pernambuco, with 92, 37 and 24 datasets, respectively.

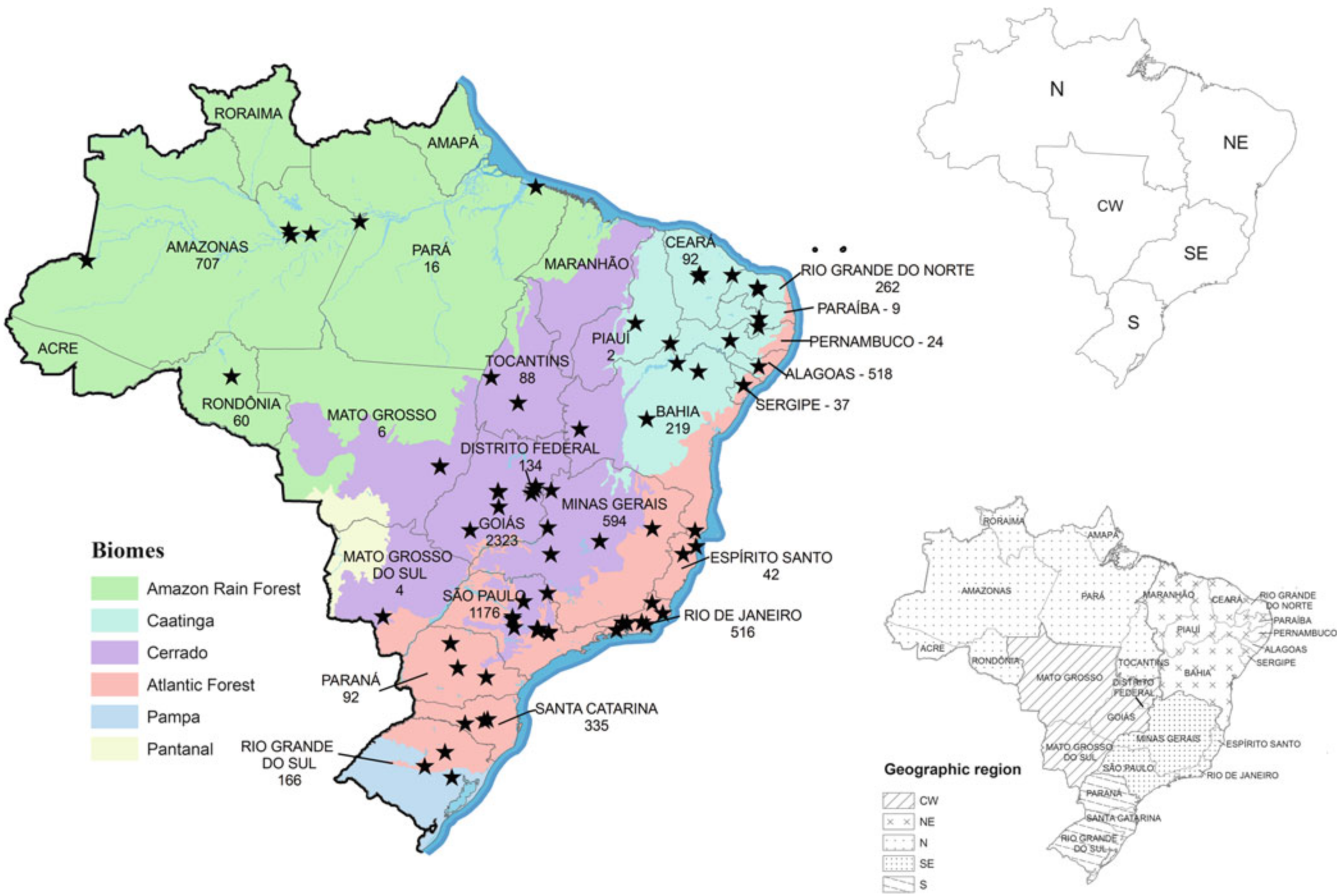


**Fig. 20.1** Distribution of used sampling locations with water retention data in Brazil; N – North, NE – Northeast, CW – Central-West, SE – Southeast, S – South. The contours of the Brazilian states and biomes were extracted from http://downloads.ibge.gov.br/downloads_geociencias.htm

**Table 20.5** Distribution of the water retention database across Brazil

| Geographic region | Data density (number of datasets per 100,000 km$^2$) | Federal states | Number of datasets | Percentages | |
|---|---|---|---|---|---|
| | | | | States | Region |
| Central-West (CW) | 94 | Goias | 2,323 | 25.86 % | 27.46 % |
| | | Distrito Federal | 134 | 1.49 % | |
| | | Mato Grosso | 6 | 0.07 % | |
| | | Mato Grosso do Sul | 4 | 0.04 % | |
| **Total CW** | | | **2,467** | | |
| Southeast (SE) | 251 | São Paulo | 1,176 | 13.09 % | 25.92 % |
| | | Minas Gerais | 594 | 6.61 % | |
| | | Rio de Janeiro | 516 | 5.74 % | |
| | | Espírito Santo | 42 | 0.47 % | |
| **Total SE** | | | **2,328** | | |
| Northeast (NE) | 75 | Alagoas | 518 | 5.77 % | 12.95 % |
| | | Rio Grande do Norte | 262 | 2.92 % | |
| | | Bahia | 219 | 2.44 % | |
| | | Ceará | 92 | 1.02 % | |
| | | Sergipe | 37 | 0.41 % | |
| | | Pernambuco | 24 | 0.27 % | |
| | | Paraiba | 9 | 0.10 % | |
| | | Piaui | 2 | 0.02 % | |
| | | Maranhão | 0 | 0.00 % | |
| **Total NE** | | | **1,163** | | |
| North (N) | 23 | Amazonas | 707 | 7.87 % | 9.70 % |
| | | Tocantins | 88 | 0.98 % | |
| | | Rondônia | 60 | 0.67 % | |
| | | Pará | 16 | 0.18 % | |
| | | Acre | 0 | 0.00 % | |
| | | Amapá | 0 | 0.00 % | |
| | | Roraima | 0 | 0.00 % | |
| **Total N** | | | **871** | | |
| South (S) | 103 | Santa Catarina | 335 | 3.73 % | 6.60 % |
| | | Rio Grande do Sul | 166 | 1.85 % | |
| | | Paraná | 92 | 1.02 % | |
| **Total S** | | | **593** | | |
| No information | | | 1,561 | 17.38 % | 17.38 % |
| **Total** | | | **8,983** | 100 % | 100 % |

The Central-Western region of Brazil overlies a significant portion of the Guarani aquifer (the second largest groundwater reserve in the world), and is covered primarily by the Cerrado biome (the second largest biome in South America). The Cerrado is characterized by savannah vegetation with grasses, shrubs and sparse trees, and by high biodiversity of plant species. This is the region with the highest concentration of datasets (2,467), although data density is not too high. Goiás alone concentrates 2,323 datasets, whereas Distrito Federal is represented by 134 measurements. Mato Grosso and Mato Grosso do Sul are represented by an insignificant number of datasets compared to the other states in the region, adding up to only 10 datasets containing water retention information. These two states represent a considerable portion of the Brazilian area and are partially covered by a major biome, Pantanal, with shallow and marshy soils. Insufficient representation of hydraulic properties of these states can be due to the unavailability of laboratories with suitable equipment for such determinations. On the other hand, the impressive volume of datasets in Goiás is explained by the presence of an Embrapa center (the Rice and Beans research center).

Finally, Brazil's Southern region, characterized in general by a subtropical climate and fertile soils, has only about 7 % of the total number of datasets, highlighting the state of Santa Catarina which has 4 %, followed by 2 % from Rio Grande do Sul and 1 % from the state of Paraná. Despite these low numbers in comparison to assessments conducted for other regions, its data frequency per 100,000 km$^2$ is the second highest. The Southern region is the home of important centers of soil research and a considerable amount of water retention data could be expected to have been measured, but much of it is currently inaccessible. Therefore, the available information for this region may not be a good overall representation.

Considering the representativeness of the 8,983 datasets for the Brazilian biomes, we found that for all but the Pantanal biome water retention measurements are reported (Fig. 20.1). According to the distribution of sampling locations shown in Fig. 20.1, there is a greater density of these sites in the Atlantic Forest biome, Cerrado and Caatinga, with little representation of the Amazon Rain forest and Pampa.

Regarding the water retention measurements in combination with saturated hydraulic conductivity data (Ksat), the number of datasets 1,253 is much lower than water retention only (Table 20.4). The geographical distribution of this database across Brazilian states and regions is shown in Table 20.6. For comparison purposes the number of datasets with data for water retention is also shown in the last column of this table.

The geographical distribution of the 1,253 Ksat datasets is quite different from the 8,983 datasets with water retention data. The Northern and Northeastern regions, for example, have in total just about 7 % of all data (Table 20.6), compared to 23 % in Table 20.5. The spatial densities of saturated hydraulic conductivity datasets in these regions are very small, especially for the Northern region, with only one dataset per 100,000 km$^2$. In both regions, most states are not subject to soil surveys including the combined determination of soil water retention and saturated hydraulic conductivity.

**Table 20.6** Distribution of the water retention and saturated hydraulic conductivity datasets across Brazil

| Geographic region | Data density (number of datasets per 100,000 km$^2$) | Federal states | Number of datasets (WR[a] + Ksat[b]) | Percentages | | Number of datasets (only WR[a]) |
|---|---|---|---|---|---|---|
| | | | | States | Region | |
| Central-West (CW) | 28 | Goias | 696 | 55.55 % | 57.86 % | 2,323 |
| | | Distrito Federal | 29 | 2.31 % | | 134 |
| | | Mato Grosso | 0 | 0.00 % | | 6 |
| | | Mato Grosso do Sul | 0 | 0.00 % | | 4 |
| **Total CW** | | | **725** | | | **2,467** |
| Southeast (SE) | 15 | São Paulo | 29 | 2.31 % | 10.93 % | 1,176 |
| | | Minas Gerais | 0 | 0.00 % | | 594 |
| | | Rio de Janeiro | 108 | 8.62 % | | 516 |
| | | Espírito Santo | 0 | 0.00 % | | 42 |
| **Total SE** | | | **137** | | | **2,328** |
| Northeast (NE) | 3 | Alagoas | 0 | 0.00 % | 3.83 % | 518 |
| | | Rio Grande do Norte | 0 | 0.00 % | | 262 |
| | | Bahia | 0 | 0.00 % | | 219 |
| | | Ceará | 48 | 3.83 % | | 92 |
| | | Sergipe | 0 | 0.00 % | | 37 |
| | | Pernambuco | 0 | 0.00 % | | 24 |
| | | Paraiba | 0 | 0.00 % | | 9 |
| | | Piaui | 0 | 0.00 % | | 2 |
| | | Maranhão | 0 | 0.00 % | | 0 |
| **Total NE** | | | **48** | | | **1,163** |
| North (N) | 1 | Amazonas | 35 | 2.79 % | 3.43 % | 707 |
| | | Tocantins | 8 | 0.64 % | | 88 |
| | | Rondônia | 0 | 0.00 % | | 60 |
| | | Pará | 0 | 0.00 % | | 16 |
| | | Acre | 0 | 0.00 % | | 0 |
| | | Amapá | 0 | 0.00 % | | 0 |
| | | Roraima | 0 | 0.00 % | | 0 |
| **Total N** | | | **43** | | | **871** |
| South (S) | 40 | Santa Catarina | 90 | 7.18 % | 18.36 % | 335 |
| | | Rio Grande do Sul | 140 | 11.17 % | | 166 |
| | | Paraná | 0 | 0.00 % | | 92 |
| **Total S** | | | **230** | | | **593** |
| No information | | | 70 | 5.59 % | 5.59 % | 1,561 |
| **Total** | | | **1,253** | 100.00 % | 100.00 % | **8,983** |

[a]WR – water retention data
[b]Ksat – saturated hydraulic conductivity

The Southeastern region concentrates only 11 % of the entire Ksat database (Table 20.6). The state of São Paulo has only 29 datasets, very few if compared to the 1,176 datasets for water retention alone. This percentage of 11 % is even lower than the percentage presented in the Southern region where this percentage is 18 %.

Brazil's Central-Western region represents the largest proportion of dataset concentration, similar to the information from Table 20.5, with about 60 % of the total number of datasets with saturated hydraulic conductivity information (1,253). The state of Goiás alone is represented by 55 %.

Datasets with both water retention and unsaturated hydraulic conductivity measurements (30) are concentrated in the state of São Paulo.

## 20.7 Soils Diversity Representation

### *20.7.1 Pedological Class*

The Brazilian soil classification system contains 13 main soil classes; the percentage of area occupied by these classes in Brazil, as well as the approximate correspondence of them to those of the FAO classification system are shown in Table 20.7.

Figure 20.2a illustrates the distribution of the number of datasets with soil water retention measurements (8,983) across the Brazilian soil classes and the corresponding data densities. In Fig. 20.2b, the distribution of the number of datasets containing water retention and saturated hydraulic conductivity (1,253) across the 13 pedological classes is also shown.

**Table 20.7** Area occupied by the main Brazilian soils and correspondence to the FAO classification system

| FAO soil class[a] | Brazilian soil class | Area/area of Brazil (%)[b] |
|---|---|---|
| Ferrasols | Latossolos | 32.14 |
| Acrisols, Lixisols, Alisols | Argissolos | 27.52 |
| Fluvisols, Leptosols, Arenosols, Regosols | Neossolos | 13.50 |
| Plinthosols | Plintossolos | 7.09 |
| Cambisols | Cambissolos | 5.37 |
| Gleysols, Solonchaks | Gleissolos | 4.79 |
| Luvisols | Luvissolos | 2.98 |
| Planosols, Solonetz | Planossolos | 2.74 |
| Podzols | Espodossolos | 2.03 |
| Nitosols, Lixisols, Alisols | Nitossolos | 1.15 |
| Chernozems, Kastanozems, Phaeozems, Greyzems | Chernossolos | 0.45 |
| Vertisols | Vertissolos | 0.21 |
| Histosols | Organossolos | 0.03 |

[a]Cited in Embrapa (2013)

[b]Source: Brazilian soil map (scale 1:5,000,000; Santos et al. 2011); in the case of associations, only the predominant soil class was considered

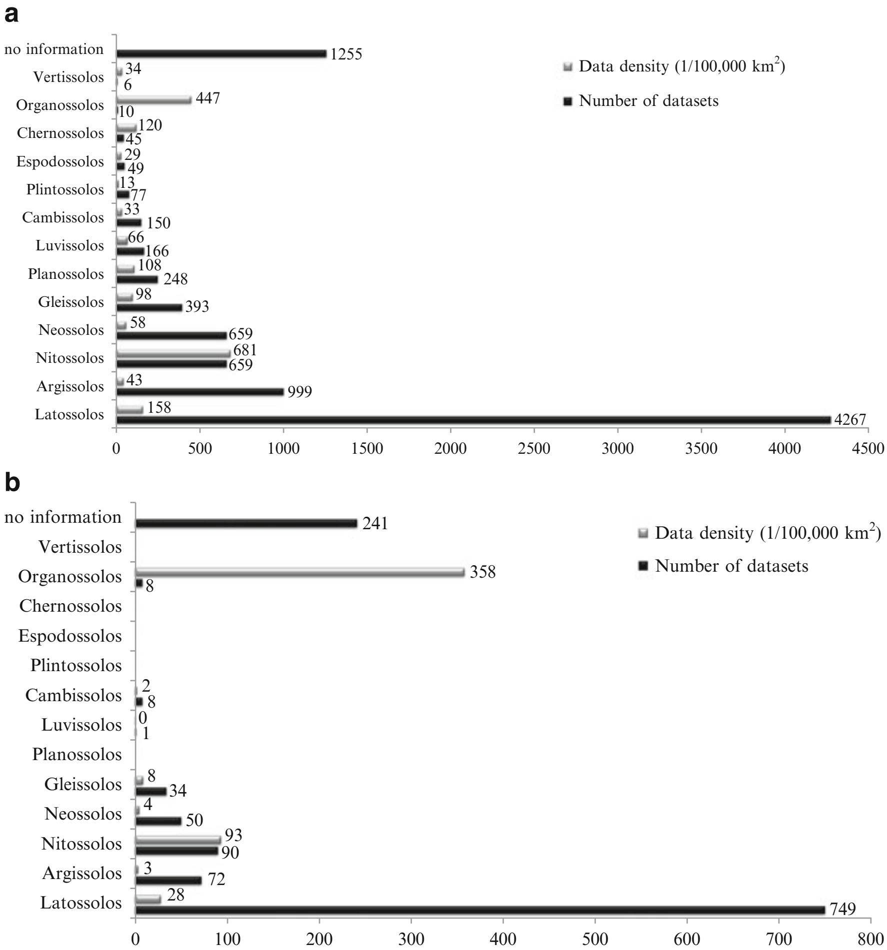


**Fig. 20.2** Distribution of the number of datasets across 13 Brazilian soils classes with available data on (**a**) soil water retention; (**b**) saturated hydraulic conductivity and water retention with corresponding datasets frequency per 100,000 km$^2$

From these figures it can be seen that the predominant soil classes, in terms of dataset concentration, are Latossolos, Argissolos, Nitossolos, Neossolos, and Gleissolos. In the case of Fig. 20.2a, all other classes are characterized. In Fig. 20.2b however, five classes do not have measurements of saturated hydraulic conductivity and water retention, and Cambissolos and Luvissolos have low representation.

In both figures, Latossolos and Argissolos together represent more than 50 % of the total number of datasets, although neither showed the highest data density (Fig. 20.2a, b). These soil classes cover, approximately, 60 % of the Brazilian territory (Table 20.7). In general, when their chemical deficiencies are remediated, they usually are very suitable for agriculture purposes, since they offer good physical and morphological conditions.

The Nitossolos, generally excellent soils for agricultural use because of their fertility and physical conditions, occupy only about 1 % of Brazil, mostly in the states of Southern Brazil. For this soil class 659 datasets are available (Fig. 20.2a), against only 90 in the case of Fig. 20.2b, thus being the class with the highest data density when considering only water retention measurements (Fig. 20.2a).

The Neossolos, which is the third more common soil class in Brazil (Table 20.7) are mostly shallow soils with inherited characteristics of the parental material, occupying mainly the Northeastern region of Brazil. These soils are represented by 659 datasets containing information about water retention. This number of datasets is about three times larger than that for Plintossolos and Cambissolos classes together, even though the latter two soils occupy almost the same area as the Neossolos (Fig. 20.2a). As for the total number of datasets containing saturated hydraulic conductivity and water retention measurements (Fig. 20.2b), 50 of them pertain to the Neossolos class, with only four datasets per 100,000 km$^2$.

The Gleissolos, which are lowland soils, covering about 5 % of the Brazilian territory, mainly in the Northern region, are represented by 393 datasets with water retention information. This is the fifth predominant soil class in term of dataset concentration (Fig. 20.2a, b). Yet, this soil class has only 34 Ksat measurements (Fig.20.2b).

The Organossolos are soils with a high organic matter content. These show a high data frequency in the two figures if considered their small geographical importance (0.03 %). Contrastingly, Chernossolos and Luvissolos, soils of high fertility and with a small geographical importance, exhibit a lower data density (Fig. 20.2a, b).

Unsaturated hydraulic conductivity data (30 datasets) represent only the Latossolos and Nitossolos classes.

### *20.7.2 Textural Class*

Out of the 8,983 datasets containing water retention information, 7,055 present particle size distribution data, distributed among textural classes as observed in Fig. 20.3a.

The prevalence of soils from the clay (C) and the sandy clay loam (SCL) classes, covering 2,963 and 1,339 datasets, respectively, can be observed in Fig. 20.3a. Classes with higher silt content (>40 %), located in the lower right corner of the textural triangle (silty clay – SiC, silty clay loam – SiCL, silty loam – SiL and silty – Si) include 432 datasets. The silt class shows the lowest percentage of all classes, with only four soils. In contrast, soils containing more than 50 % of sand found in the lower left corner of the triangle (sandy clay – SC , sandy clay loam – SCL, sandy loam – SL , loamy sand – LS and sandy – S), are represented by 3,171 datasets. The intermediate classes clay loam (CL) and loam (L) are represented by 489 datasets.

The distribution of soil samples, as shown in Fig. 20.3b, corresponds approximately to the database of Benedetti et al. (2008), who compiled 11,232

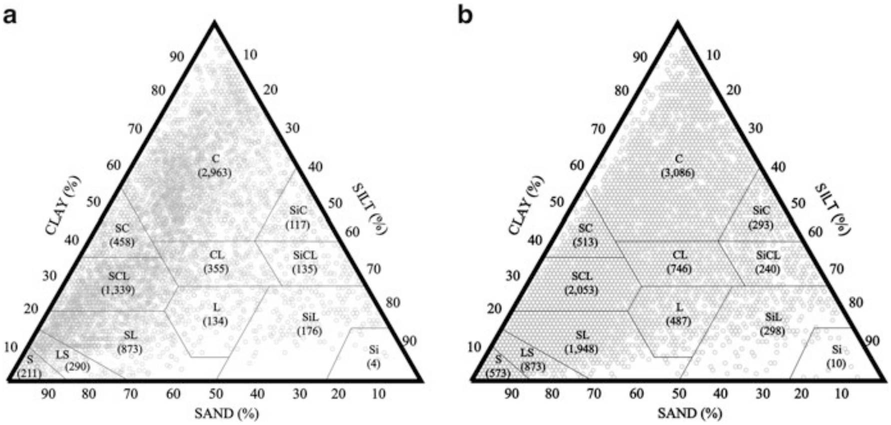


**Fig. 20.3** Distribution of the total number of datasets (**a**) compiled in this study and (**b**) from Benedetti et al. (2008) over the 12 conventional textural classes. The number of datasets for each texture class is shown between brackets below the respective abbreviation

soil horizons (Fig. 20.3b) with physical and chemical information for the entire Brazilian territory. Comparison of numbers of datasets in the same classes at Figs. 20.3a, b shows that the hydraulic property database inventoried here for Brazilian soils is representative, when it comes to their texture information.

### *20.7.3 Depth in Soil Profile*

The soil depths defined as topsoil and subsoil are represented here by depth ranges of 0–30 cm and over 30 cm, respectively. These two groups, when characterized in terms of number of datasets with water retention information (8,983) shows that about 33 % of all database are classified as subsoil, whereas approximately 55 % as topsoil and 12 % do not contain soil depth information. For the saturated hydraulic conductivity measurements (1,253 datasets), 11 % of them are classified as subsoil, 26 % as topsoil and for most datasets, about 63 %, the information is missing. As for the soils with unsaturated hydraulic conductivity measurements (30 datasets), 80 % of these datasets are from the subsoil, and only 20 % for the 0–30 cm soil depth range.

## 20.8 Measurement Methods of Soil Hydrophysical Attributes

Figure 20.4 shows the distribution of different methods for determining soil water retention for various matric potential levels. The pressure chamber and the centrifuge methods are used in about 60 % and 30 % of the water retention database (8,983),

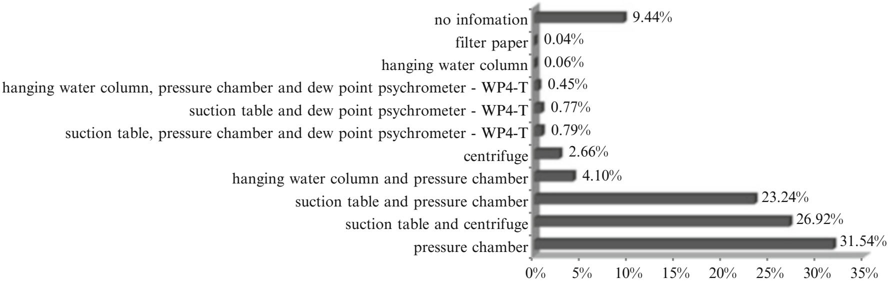


**Fig. 20.4** Distribution of different methods for determining soil water retention

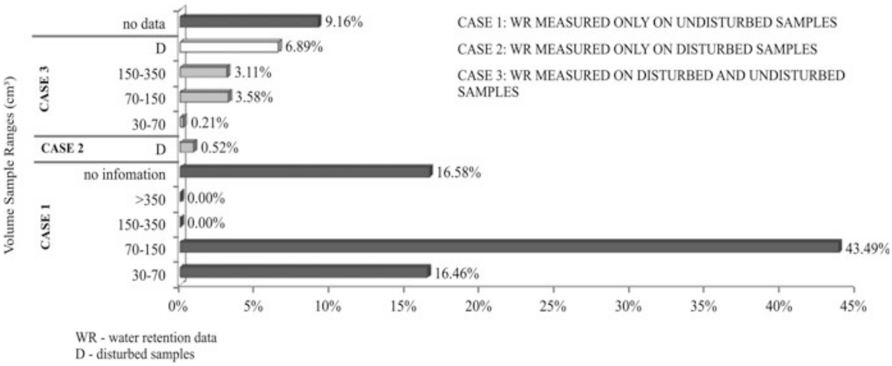


**Fig. 20.5** Distribution of sample volume ranges (cm$^3$) for measuring soil water retention in undisturbed samples (case 1), disturbed samples (case 2), or both disturbed and undisturbed samples (case 3)

respectively. Water retention data determined by the centrifuge method should be carefully interpreted, especially when grouping them together with datasets obtained by other methods for developing water retention pedotransfer functions. Nevertheless, Reatto et al. (2008) stated that for 468 soil samples from the Cerrado biome, there was a good agreement ($R^2 = 0.99$) between the water retention determination by the centrifuge and by the pressure chamber methods. An extension of this study to other types of Brazilian soils would be useful to evaluate the general reliability of this method.

About 56 % of the total number of datasets (8,983) have their water retention data measured with two or three methods (Fig. 20.4). The suction table and hanging water column are used for lower tension ranges (0–100 cm), the pressure chamber for medium (100–500 cm) and high ranges (500–15,000 cm) and the WP4-T device exclusively for high and very high tensions (>15,000 cm).

In Fig. 20.5 the distribution of sample volumes for three cases of measuring water retention content versus matric potential is shown. The first two cases (case 1 and 2) make reference to water content measurements determined only in undisturbed or disturbed samples for the entire range of matric potential, respectively, whereas the third group (case 3) refers to measurements in both sample types together. In the entire water retention database (8,983) 9,648 samples are available. In 665 datasets water retention content was measured on both undisturbed and disturbed samples (case 3) (665 disturbed samples + 665 undisturbed samples); the disturbed ones were usually employed in the highest suction range (dry range) and the undisturbed in the lowest (wet range). Taking into account case 1 and case 2 7,384 and 50 datasets have their water retention data determined exclusively in undisturbed and disturbed samples, respectively.

The most common sample size range is 70–150 $cm^3$, and 100 $cm^3$ is the most frequent single value. The range of 30–70 $cm^3$ includes almost 17 % of the total number of samples, most of them of 50 $cm^3$. About 7 % of the considered database (9,648 samples) are represented by disturbed samples.

About 74 % of saturated hydraulic conductivity measurements (1,253 datasets) were done with the constant head permeameter, 10 % using a Guelph permeameter, 8 % by the falling head permeameter method and other 8 % by using other methods. About 60 % of all 1,253 datasets have their saturated hydraulic conductivity data determined in undisturbed soil samples in the volume range of 70–150 $cm^3$, with predominant use of 100 $cm^3$, as for the water retention data. In approximately 10 % of the saturated hydraulic conductivity database, information on the sample type (disturbed or undisturbed) is unavailable, which is a restrictive factor for the use of these datasets, as hydraulic conductivity is strongly structure dependent. The unsaturated hydraulic conductivity measurements (30 datasets) were all determined in field instruments by the instantaneous profile method.

Table 20.8 summarizes the methods used to measure the particle size distribution, organic carbon content, bulk density and penetration resistance observed in the metadata, as well as the respective number of publications. The datasets compiled for most of these soil properties are not organized for immediate handling. Therefore, the observed distribution in Table 20.8 is based on the number of publications and not on the number of datasets, except for textural composition.

Two traditional methods for determining the particle size distribution stand out: the pipette and densimeter method (Table 20.8). Among these techniques, there is a predominance of measurements with the pipette, concentrating about 43 % of the database with particle size information (7,055). In some publications, the method for determining soil texture is referred to as Embrapa (1997), which, in turn, describes the methodological procedures for both methods (pipette and densimeter). In 4,739 datasets containing soil texture and water retention information (out of the 7,055 datasets), the ranges of particle size used for the clay, silt and sand fractions are described. The same range is used for all dataset (4,739): clay (<0.002 mm), silt (0.002–0.05 mm) and sand (0.05–2 mm).

In relation to organic carbon content, the modified Walkley-Black method (Jackson 1982), with wet oxidation and determination by titration, is the most popular one (Table 20.8), cited in 58 % of the studies. Measurements of the bulk density were mostly acquired by the volumetric ring method.

**Table 20.8** Methods for determining the physico-chemical attributes reported in the selected publications

| Texture | | | Organic carbon content | | | Bulk density | | | Penetration resistance | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Number of datasets | Percentage | Method | Number of studies | Percentage | Method | Number of studies | Percentage | Method | Number of studies | Percentage |
| Pipette | 3,066 | 43 % | Modified Walkley-Black (Jackson 1982), with wet oxidation and determination by titration | 30 | 58 % | Volumetric ring | 42 | 81 % | Static | 6 | 12 % |
| Embrapa (1997) | 1,820 | 26 % | Dry combustion (CHNS/O) | 3 | 6 % | Technique of gamma-ray attenuation | 1 | 2 % | Dynamic | 2 | 4 % |
| Densimeter | 1,336 | 19 % | Wet oxidation after preheating | 1 | 2 % | – | – | – | – | – | – |
| – | – | – | Modified Walkley-Black (Jackson 1982), with colorimetric determination | 1 | 2 % | – | – | – | – | – | – |
| No information | 833 | 12 % | No information | 4 | 8 % | No information | 8 | 15 % | No information | – | – |
| – | – | | No data | 13 | 25 % | No data | 1 | 2 % | No data | 44 | 85 % |
| Total | 7,055 | 100 % | Total | 52 | 100 % | Total | 52 | 100 % | Total | 52 | 100 % |

Finally, only eight studies in our inventory determined penetration resistance. Six of the sources indicated the use of the static method. The other two reported the dynamic method as the technique to determine penetration resistance.

## 20.9 Characteristics of Soil Hydrophysical Database for Development of PTFs for Water Retention Estimation

Figure 20.6 illustrates the distribution of the compiled database with information of water retention (8,983 datasets) at different levels of matric potential.

About 92 % of the water retention datasets include more than three values of matric potential, six values being the most frequent, in approximately 24 % of all cases (Fig. 20.6). In most cases, the experimental data of soil water content range from the wet range to the very dry range (60 or 100 cm to 15,000 cm suction), which can ensure greater suitability of these measurements to fit equations that represent the water retention curve.

Regarding the availability of predictors variables for PTF development for water retention (Fig. 20.7), about 63 % of the publications present data on water retention associated with particle size distribution, organic matter content (or organic carbon content) and bulk density. This percentage drops to approximately 12 % when penetration resistance is included. Figure 20.8 shows that about 58 % of the datasets that contain information on soil texture and water retention (7,055 datasets), have their particle size distribution represented by more than four size fractions. All the aspects discussed above are beneficial for the derivation of PTFs for water retention prediction.

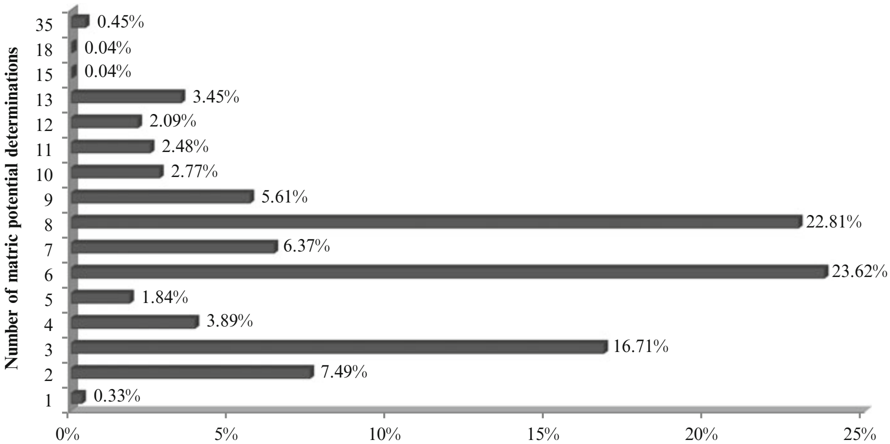


**Fig. 20.6** Distribution of the number of different measurements of matric potential per dataset over the water retention database

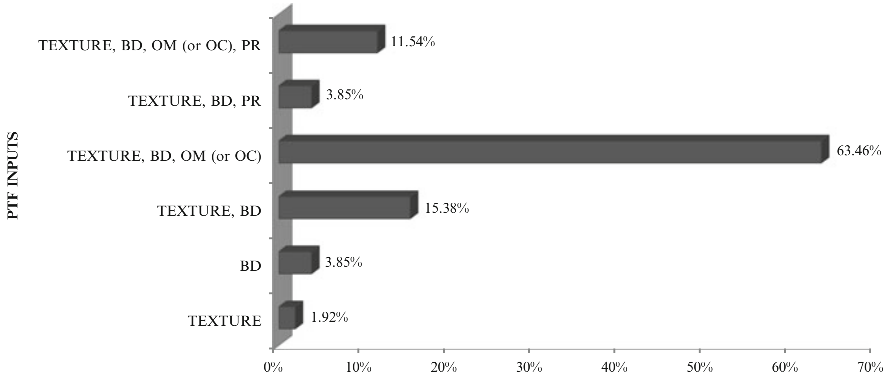


**Fig. 20.7** Distribution of publications in sets of associations of PTFs predictors

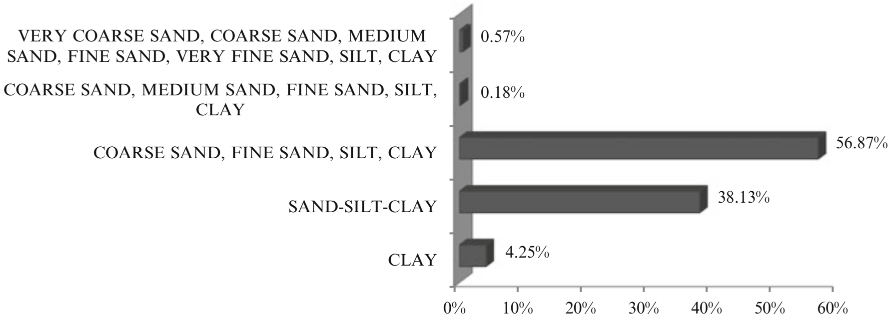


**Fig. 20.8** Distribution of the total number of datasets containing water retention and soil textural composition data among different particle size fractions associations

## 20.10 Summary and Conclusion

Access to soil hydrological data is vital for hydrologic projects and for supporting decision-making in issues related to the availability of food and water, as well as to several land surface phenomena, including natural disasters. This topic has been widely discussed at national and international forums, such as the G8 International Conference on Open Data for Agriculture and other forums related to the Global Soil Map initiative, which aim to develop global soil maps and predict soil properties at fine resolution (http://www.globalsoilmap.net/).

Brazil, a country of continental dimensions, has accumulated a significant body of soil information and holds a prominent position in the studies on tropical soils. In general, the analytical results from the Brazilian pedological survey studies are scattered and many of them do not have information on soil hydraulic properties, which represents a setback for understanding and modeling of physical and hydrodynamic processes.

In this study, the status of hydrophysical database on Brazilian soils for water retention PTFs development was discussed. We presented on metadata the measurement methods of some soil hydrophysical attributes and the characteristics of the sites where these soil properties were estimated. Statistical analyses were performed to characterize the database based on the metadata-based data structure.

A total of 8,983 datasets have soil water retention information (at various matric potential levels) associated with physical or chemical properties, such as organic matter content (or organic carbon content), particle size fractions, bulk density, and penetration resistance. A total of 63 % of the publications present data of water retention related to determinations of organic matter content (or organic carbon content), particle size distribution and bulk density.

The distribution of the water retention datasets across the Brazilian territory shows that some regions are better represented than others, especially the Southeastern and Central-Western region, with 2,328 and 2,467 datasets, respectively. The Northern region of Brazil is not represented proportional to its social and environmental importance. All Brazilian soils classes are characterized. Two dominant soil types are Latossolos (or FAO Ferrasols) and Argissolos (Acrisols, Lixisols or Alisols, according to FAO). Information on soil water retention is relatively well distributed among topsoil and subsoil. All texture classes, except those with high silt content, are well characterized. This reflects the fact that highly weathered Brazilian soils generally contain very small silt contents.

A total of 1,253 datasets containing saturated hydraulic conductivity associated with water retention measurements (at various matric potential levels) are also found. The study showed that this database can not represent all Brazilian soil classes satisfactorily, neither the Brazilian states, in particular the ones in the Northern and Northeastern regions. Only 30 datasets are found for unsaturated hydraulic conductivity data, all determined by the instantaneous profile method, with the disadvantage of making measurements only in the water-filled tensiometer range (0–800 cm).

The methods used to measure water retention versus matric potential levels, saturated hydraulic conductivity and other physico-chemical attributes, presented in the metadata, are relatively homogeneous, but the quality of measurement of these properties has not been evaluated. The homogeneity observed for methods of determining soil water retention became evident not only by the similarities in the measuring methodology itself, but also because the measurements have been performed in undisturbed samples for almost 77 % of the cases.

The inventory of water retention data shows a significant amount of measurements associated with more than three matric potential determinations, most of them characterizing the suction range from 60 (or 100 cm) to 15,000 cm. Most of the publications analyzed in this study presents measurements of water retention related to other physico-chemical properties, usually reported in the literature as potential predictors of soil water retention. Besides this, about 58 % of the database containing information on soil textural composition and water retention (7,055 datasets) have their particle size distribution represented by more than four size fractions. All these factors, along with the homogeneity of the methods for determining the soil water retention curve, and the scope and representation of such data on Brazilian soils, create excellent prospects for studies on pedotransfer functions for water retention, at the Brazilian national scale, in an attempt to obtain sufficient hydrophysical data on different scales and for several applications. This is in contrast to data on saturated and unsaturated hydraulic conductivity.

The challenge in the development of the Brazilian soil hydrophysical database for PTFs application is to define a dataset model that can encompass the wide range of available information and that meets the different kinds of queries of interest to users of soil science information. A difficulty relates to data standardization in a database model. Existing data are available in different formats. Thus, an effort will be required to make the information uniform, including the elimination of some data after data consistence analysis. The need of statistical methods for analysis and processing of the information will exist. A preliminary structure of a database to store Brazilian soil hydrophysical information is in development. Considering the size of the Brazilian territory, it would be of interest that the database development becomes a joint effort of government agencies, universities and commercial enterprises.

**Acknowledgment** The authors thank the Geological Survey of Brazil (CPRM) for the financial and technical support and all researchers and students for providing the data mentioned here.

## References

Andrade RS, Stone LF (2009) Uso do índice S na determinação da condutividade hidráulica não-saturada de solos do cerrado brasileiro. R Bras Agric Ambiental 13:376–381

Arruda FB, Zullo J, Oliveira JB (1987) Parâmetros de solo para cálculo de água disponível com base na textura do solo. R Bras Sci Sol 11:11–15

Assad MLL, Sans LMA, Assad ED et al (2001) Relação entre água retida e conteúdo de areia total em solos brasileiros. Rev Bras Agrometeorologia 9(3):588–596

Barros AHC, De Jong Van Lier Q (2014) Pedotransfer functions for Brazilian soils. In: Teixeira WG, Ceddia MB, Ottoni MV et al (eds) Application of soil physics in environmental analyses: measuring, modelling and data integration, 1st edn. Springer, p ??

Barros AHC, De Jong Van Lier Q, Maia AHN et al (2013) Pedotransfer functions to estimate water retention parameters of soils in Northeastern Brazil. R Bras Ciênc Solo 37:379–391

Batjes NH (2009) Harmonized soil profile data for applications at global and continental scales: update to the WISE database. Soil Use Manage 25(2):124–127

Benedetti MM, Sparovek G, Copper M et al (2008) Representatividade e potencial de utilização de um banco de dados de solos do Brasil. Rev Bras Ciênc Solo 32:2591–2600

Bouma J (1989) Using soil survey data for quantitative land evaluation. Adv Soil Sci 9:177–213

Carducci CE, De Oliveira GC, Severiano EC et al (2011) Modelagem da curva de retenção de água de Latossolos utilizando a equação duplo Van Genuchten. R Bras Ciênc Solo 35:77–86

Chagas CS, Carvalho W Jr, Bhering SB et al (2004) Estrutura e organização do sistema de informações georreferenciadas de solos do Brasil (sigsolos – versão 1.0). R Bras Ciênc Solo 28:865–876

Cooper M, Mendes LMS, Silva WLC et al (2005) A national soil profile database for Brazil available to international scientists. Soil Sci Soc Am J 69:649–652

Doyle ME, Tomasella J, Rodriguez DA et al (2013) Experiments using new initial soil water conditions and soil map in the Eta model over La Plata Basin. Meteorol Atmos Phys 121:119–136
Empresa Brasileira de Pesquisa Agropecuária – Embrapa (1997) Manual de métodos de análises de solo, 2nd edn. Embrapa Solos, Rio de Janeiro
Empresa Brasileira de Pesquisa Agropecuária – Embrapa (1999) Sistema brasileiro de classificação de solos, 6th edn. Embrapa Solos, Rio de Janeiro
Empresa Brasileira de Pesquisa Agropecuária – Embrapa (2006) Sistema brasileiro de classificação de solos, 2nd edn. Embrapa Solos, Rio de Janeiro
Empresa Brasileira de Pesquisa Agropecuária – Embrapa (2013) Sistema brasileiro de classificação de solos, 3rd edn. Embrapa Solos, Rio de Janeiro
European Commission (2013) European Hydropedological Data Inventory (EU-HYDI). European Commission Joint Research Centre. doi:10.2788/5936
Gonçalves MC, Ramos TB, Pires FP (2011) Base de dados georreferenciada das propriedades do solo. In: Coelho PS, Reis P (eds) Agrorrural contributos científicos. Instituto Nacional dos Recursos Biológicos I.P. e Imprensa Nacional – Casa da Moeda, S.A., Oeiras, pp 564–574
Hodnett MG, Tomasella J (2002) Marked differences between Van Genuchten soil water-retention parameters for temperate and tropical soils: a new water-retention pedo-transfer function developed for tropical soils. Geoderma 108:155–180
Jackson ML (1982) Analisis quimico de suelos. Omega, Barcelona, pp 282–309
Jana RB, Mohanty BP, Springer EP (2007) Multiscale pedotransfer functions for soil water retention. Vadose Zone J 6:868–878
Leij FJ, Alves WJ, Van Genuchten MT et al (1996) The UNSODA unsaturated soil hydraulic database. Rep. EPA/600/R-96/095. USEPA Natl. Risk Manage. Lab., Cincinna, Ohio
Leij FJ, Romano N, Palladino M et al (2004) Topographical attributes to predict soil hydraulic properties along a hillslope transect. Water Resour Res 40:1–15
Makó A, Tóth B, Hernádi H et al (2010) Introduction of the Hungarian Detailed Soil Hydrophysical Database (MARTHA) and its use to test external pedotransfer functions. Agrokém Talajtan 59:29–38
McBratney AB, Minasny B, Cattle SR et al (2002) From pedotransfer functions to soil inference systems. Geoderma 109:41–73
Miháliková M, Matula S, Doležal F (2013) HYPRESCZ – Database of soil hydrophysical properties in the Czech Republic. Soil Water Res 8:34–41
Minasny B, McBratney AB (2002) Uncertainty analysis for pedotransfer functions. Eur J Soil Sci Eur J Soil Sci 53(3):417–429
Mohanty BP, Shouse PJ (2002) Soil property database: Southern Great Plains 1997 Hydrology Experiment. Water Resour Res 38(5):1–5. doi:10.1029/2000WR000076
Nemes A, Schaap MG, Leij FJ et al (2001) Description of the unsaturated soil hydraulic database. UNSODA version 2.0. J Hydrol 251:151–162
Ottoni MV (2005) Classificação físico-hídrica de solos e determinação da capacidade de campo *in situ* a partir de testes de infiltração. Dissertação, Programa de Engenharia Civil-COPPE, Universidade Federal do Rio de Janeiro (UFRJ)
Pachepsky YA, Rawls WJ, Timlin DJ (1999) The current status of pedotransfer functions: their accuracy, reliability, and utility in field- and regional-scale modeling. In: Corwin DL, Loague K, Ellsworth TR (eds) Assessment of non-point source pollution in the vadose zone. American Geophysical Union, Washington, DC. doi:10.1029/GM108p0223
Pachepsky YA, Timlin DJ, Rawls WJ (2001) Soil water retention as related to topographic variables. Soil Sci Soc Am J 65:1787–1795
Perkins KS, Nimmo JR (2009) High-quality unsaturated zone hydraulic property data for hydrologic applications. Water Resour Res 45, W07417. doi:10.1029/2008WR007497
Rawls WJ (2004) Pedotransfer Functions for the United States. In: Pachepsky YA, Rawls WJ (eds) Development of pedotransfer functions in soil hydrology, vol 30, Developments in soil science. Elsevier B.V., The Netherlands, pp 437–447
Rawls WJ, Pachepsky YA (2002) Using field topographic descriptors to estimate soil water retention. Soil Sci 167:423–435

Reatto A, Da Silva EM, Bruand A et al (2008) Validity of the centrifuge method for determining the water retention properties of tropical soils. Soil Sci Soc Am J 72:1547–1553
Reichert JM, Albuquerque JA, Kaiser DR et al (2009) Estimation of water retention under availability in soils of Rio Grande do Sul. R Bras Ciênc Solo 33:1547–1560
Rossato L (2002) Estimativa da capacidade de armazenamento de água no solo do Brasil. INPE-(INPE-8915-TDI/809), São José dos Campos
Rossato L, Alvalá RCS, Tomasella J (1998) Distribuição geográfica da capacidade de armazenamento de água e das propriedades físicas do solo no Brasil. In: X Congresso Brasileiro de Meteorologia/VIII Congresso da FLISMET, Brasilia, Artigo HL98009 (Hidrometeorlogia), CD-ROM
Santos HG dos, Carvalho Junior W de, Dart R de O et al (2011) Mapa de solos do Brasil (in shapefiles). Escala 1:5.000.000. Embrapa Solos, Rio de Janeiro
Schaap MG, Leij FJ (1998) Database-related accuracy and uncertainty of pedotransfer functions. Soil Sci 163:765–779
Schaap MG, Leij FJ, Van Genuchten MT (2001) ROSSETA: computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J Hydrol 251:163–176
Sharma SK, Mohanty BP, Zhu J (2006) Including topography and vegetation attributes for developing pedotransfer functions. Soil Sci Soc Am J 70:1430–1440
Silva AM (2005) Banco de dados de curvas de retenção de água de solos brasileiros. Dissertação, Escola de Engenharia de São Carlos
Silva A de SS, Brito LT de L, De Oliveira CAV et al (1990) Parâmetros de solo em função da umidade na capacidade de campo em áreas irrigáveis do trópico semi-árido brasileiro. Pesquisa Agropecuária Brasileira 25:103–116
Stekauerová V, Sútor J (2004) Pedotransfer Funtions for the Rye Island – Southwest Slovakia. In: Pachepsky YA, Rawls WJ (eds) Development of pedotransfer functions in soil hydrology, vol 30, Developments in soil science. Elsevier B.V., The Netherlands, pp 465–473
Tomasella J, Hoodnett MG, 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, Pachepsky YA, Crestana S et al (2003) Comparison of two techniques to develop pedotransfer functions for water retention. Soil Sci Soc Am J 67:1085–1092
Urach FL (2007) Estimativa da retenção de água em solos para fins de irrigação. Dissertação, Universidade de Santa Maria
Van Den Berg M, Klamt E, Van Reeuwijk LP et al (1997) Pedotransfer functions for the estimation of water retention characteristics of Ferrasols and related soils. Geoderma 78:161–180
Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898
Vereecken H, Weynants M, Javaux M et al (2010) Using pedotransfer functions to estimate the Van Genuchten-Mualem soil hydraulic properties: a review. Vadose Zone J 9:795–820
Wang Y, Shao M, Liu Z (2012) pedotransfer functions for predicting soil hydraulic properties of the Chinese Loess Plateau. Soil Sci 177(7):424–432. doi:10.1097/SS.0b013e318255a449
Wösten JHM, Lilly A, Nemes A (1999) Development and use of a database of hydraulic properties of European soils. Geoderma 90:169–185
Wösten JHM, Pachepsky YA, Rawls WJ (2001) Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. J Hydrol 251:123–150