ESTIMATION OF WATER RETENTION AND AVAILABILITY IN SOILS OF RIO GRANDE DO SUL(1)

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SUMMARY

Dispersed information on water retention and availability in soils may be compiled in databases to generate pedotransfer functions. The objectives of this study were: to generate pedotransfer functions to estimate soil water retention based on easily measurable soil properties; to evaluate the efficiency of existing pedotransfer functions for different geographical regions for the estimation of water retention in soils of Rio Grande do Sul (RS); and to estimate plant-available water capacity based on soil particle-size distribution. Two databases were set up for soil properties, including water retention: one based on literature data (725 entries) and the other with soil data from an irrigation scheduling and management system (239 entries). From the literature database, pedotransfer functions were generated, nine pedofunctions available in the literature were evaluated and the plant-available water capacity was calculated. The coefficient of determination of some pedotransfer functions ranged from 0.56 to 0.66. Pedotransfer functions generated based on soils from other regions were not appropriate for estimating the water retention for RS soils. The plant-available water content varied with soil texture classes, from 0.089 kg kg^{-1} for the sand class to 0.191 kg kg^{-1} for the silty clay class. These variations were more related to sand and silt than to clay content. The soils with a greater silt/clay ratio, which were less weathered and with a greater quantity of smectite clay minerals, had high water retention and plant-available water capacity.

Index terms: pedotransfer functions, texture class, water retention curve, mineralogy.

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RESUMO: *ESTIMATIVA DA RETENÇÃO E DISPONIBILIDADE DE ÁGUA EM SOLOS DO RIO GRANDE DO SUL*

Informações dispersas sobre retenção e disponibilidade de água em solos podem ser agrupadas em bancos de dados para gerar funções de pedotransferência. Os objetivos do trabalho foram: gerar equações de pedotransferência para estimar a retenção de água a partir de atributos do solo de fácil obtenção; avaliar a eficiência de pedofunções existentes para várias regiões para a estimativa da retenção de água em alguns solos do RS; e estimar a disponibilidade de água em função da distribuição do tamanho das partículas dos solos. Dois bancos de dados com atributos do solo, incluindo retenção de água foram organizados: um a partir de dados da literatura (725 dados) e outro de solos de um sistema de monitoramento e manejo de irrigação (239 dados). Com o banco da literatura foram geradas funções de pedotransferência, avaliadas nove pedofunções disponíveis na literatura e calculado o teor de água disponível. As equações de pedotransferência geradas tiveram coeficientes de determinação entre 0,56 e 0,66. Equações de pedotransferência geradas com solos de outras regiões não foram adequadas para estimar a retenção de água de alguns solos do RS. O teor de água disponível variou em função da classe textural do solo, desde 0,089 kg kg^{-1} para a classe areia, a 0,191 kg kg^{-1} para a classe argilo siltosa. As variações foram mais dependentes das frações areia e silte do que da argila. Os solos com maior relação silte/argila, menos intemperizados e com maior quantidade de argilominerais do grupo das esmectitas, tiveram maior retenção e disponibilidade de água.

Termos de indexação: pedofunções, classe textural, curva de retenção de água, mineralogia.

INTRODUCTION

Plant-available water in the soil is essential for adequate crop growth and development and depends on the soil properties. For plants under water stress, the molecular and physiological processes are impaired (Ramos et al., 1999), which reduces crop development and yield. Plant-available water is measured directly, by the determination of gravimetric soil water content in a laboratory drying-oven or by indirect methods, with equipments such as the neutron probe and reflectometers. The accuracy of these methods is good, but they are very time-demanding or require the availability of expensive equipment, creating barriers to a large-scale use. To overcome these difficulties, some researchers have proposed mathematical models to estimate soil water retention (Meng et al., 1987; Arruda et al., 1987; Bell & van Keulen, 1995; van den Berg et al., 1997; Pachepsky & Rawls, 1999; Saxton & Rawls, 2006), known as pedotransfer functions or equations (pedofunctions).

These models estimate water retention by means of soil properties that are more easily measurable or available in the literature and related to water retention, and which are generally related to capillarity and water adsorption phenomena (Rawls et al., 1991). The water retention curve expresses the soil water content based on its energy state at a given potential. The water retained at lower tensions has a greater relation to soil structure, while at higher tensions it is related to particle size distribution and soil mineralogy. Thus, pedotransfer functions may be generated when the particle size distribution, density, porosity and/or mineralogy of the soil are known (Rawls et al., 1991).

The available models were developed for temperate regions (Gupta & Larson, 1979; Rawls et al., 1982; Saxton et al., 1986), where the edaphoclimatic properties are different, so their application in tropical regions may be unfeasible (Tomasella et al., 2000). In Brazil, some pedotransfer functions have already been established for estimating soil water retention (Arruda et al., 1987; Masutti, 1997; Giarola et al., 2002; Oliveira et al., 2002), but their validity for soils different from those of the database has been poorly investigated, making the degree of efficiency of a generalized use of these equations rather questionable.

The objectives of this study were: to generate pedotransfer functions to estimate soil water retention at different tensions based on easily measurable soil properties; to evaluate the efficiency of pedotransfer functions generated in other regions for the estimation of water retention in soils of Rio Grande do Sul (RS); and to calculate plant-available water capacity based on soil particle-size distribution of RS soils.

MATERIAL AND METHODS

The pedotransfer functions for the Rio Grande do Sul (RS), Brazil, soils were generated from data obtained from the literature (Kochhann, 1971; Righes, 1971; Cogo, 1972; Gomes, 1972; Curi, 1975; Abrão, 1977; Scopel, 1977; Cintra, 1980; Farias, 1981; Reichert, 1988; Salton, 1991; Costa, 1993;

Vasconcellos, 1993; Carpenedo, 1994; Barcelos, 1996; Albuquerque, 1998; Rojas, 1998; Schäfer, 1999; Lima, 2001; Leitzke, 2002; Giarola et al., 2002; Peraza, 2003; Collares, 2005; Silva et al., 2005). These studies were based on samples collected from various representative soil classes and horizons in different regions of the State, resulting in a total of 725 datasets, which include water retention curves, organic matter, clay, silt and sand content, and bulk and particle density.

Data of water retention were available for the tensions of 1, 6, 10, 33, 100, 300, 400, 500, 900, 1,000, and 1,500 kPa. In some studies the retention curve was determined for up to eight tensions, while in others there is only one tension for water retention. The water retained at the tension of 10 kPa was denominated as field capacity and that of 1,500 kPa as permanent wilting point. The option was made to standardize the estimation of water retention at 10 kPa, determined in the laboratory, although the concept of field capacity for a given tension is questionable, as laid out by Hillel (1998), who argues that, in addition to soil properties such as texture and mineralogy, the effects of slope, sequence of the layers or horizons and other soil properties influence water retention as well.

For all samples, the particle size distribution (clay, silt and sand fractions) data is available, but in some studies the data are incomplete regarding organic matter content, bulk density, particle density or total porosity. In figure 1 the ample distribution of particle sizes in the dataset can be visualized, with samples in all textural classes, except for the silt textural class. There was a greater concentration in some classes such as loam, sandy loam, clay loam and clay.

Based on the database, multiple regression analyses were performed for the pedofunctions using the "stepwise" option (SAS, 1997). This method selects the independent variables: sand, silt, clay, organic matter, bulk density, particle density and the sum of the clay fractions plus silt (soil properties) and generates the respective coefficients that compose each pedofunction to estimate the water content retained by the soil at the tensions of 6, 10, 33, 100, 500 and 1,500 kPa. Pedofunctions to estimate water retention for the tensions of 10, 33 and 1,500 kPa were also generated based on particle size distribution data only, which is necessary for databases that do not include the organic matter content and the bulk and particle densities.

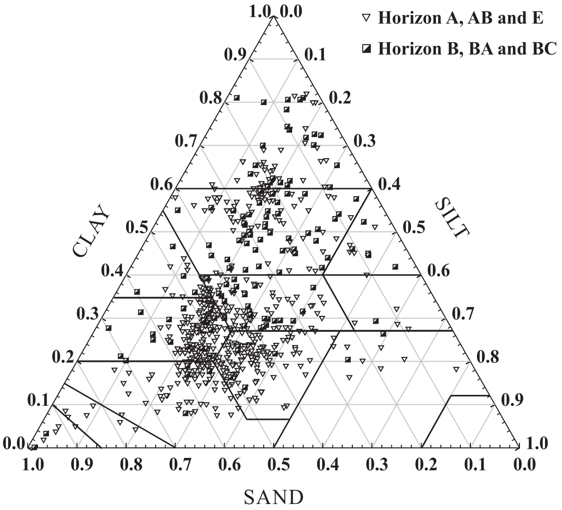

Figure 1. Soil textural classification used for derivation of the pedofunctions.

For the determination of the multiple regressions, the complete database was used, because the separation in subsets did not improve the accuracy of the equations. Oliveira et al. (2002) also observed that the division of data into subsets based on the textural class, the activity of the clay fraction, or the degree of soil weathering did generally not improve the accuracy of the pedofunctions. Nevertheless, other researchers observed greater accuracy when separating soil groups in classes of soil texture, clay activity or pedogenetic horizons (van Genuchten, 1980; Wösten et al., 1995; Pachepsky & Rawls, 1999).

The pedotransfer functions were tested by comparing the water content estimated by the proposed equations and those estimated by the pedofunctions proposed by Oliveira et al. (2002) and Masutti (1997) (Table 1). In addition, a dataset of an irrigation scheduling and management system (www.sistemairriga.com.br) was used, different from that used to generate the pedofunctions, so as to evaluate the accuracy of the estimations by the equations generated. This database contains the properties particle size distribution and water retention at the tensions of 33 and 1,500 kPa.

To evaluate the accuracy of other available equations, those that estimate the gravimetric soil water content were used, such as those proposed by Arruda et al. (1987), Oliveira et al. (2002), Bell & van Keulen (1995) and Masutti (1997), and others that estimate the volumetric soil water content, as those proposed by Gupta & Larson (1979), Rawls et al. (1982), Saxton et al. (1986), van den Berg et al. (1997), and Giarola et al. (2002) (Table 1), with data of organic matter, bulk density and clay, silt and sand content. The estimated soil water content for each model was correlated with the one measured.

Water content at field capacity (-10 kPa), at the permanent wilting point (-1,500 kPa) and plant-available water capacity (between -10 and -1,500 kPa) were calculated for each sample. The results were grouped by textural class and the mean of each class was presented in a textural triangle. For these properties, regression analysis was performed using program SAS (1997) and path analysis with the program Genes (2007), with result interpretion according to Cruz (2006). In this analysis, the data were submitted to descriptive statistics, Pearson correlation analysis and multicollinearity. Variables

Table 1. Equations from the literature used to estimate water content of the soils from the database that gave origin to the proposed model

Literature source	Soils	Tension	Model	Obs	R^2
		kPa			
Gupta & Larson (1979)	USA	10	$\theta\ (m^3\ m^{-3}) = 0{,}00502*Sand + 0{,}00855*Silt + 0{,}00883*Clay + 0{,}00497*OM - 0{,}242*\rho b$	(2)	0,96
		33	$\theta\ (m^3\ m^{-3}) = 0{,}00308*Sand + 0{,}00589*Silt + 0{,}00804*Clay + 0{,}00221*OM - 0{,}143*\rho b$	(2)	0,96
		1,500	$\theta\ (m^3\ m^{-3}) = 0{,}000059*Sand + 0{,}00114*Silt + 0{,}00577*Clay + 0{,}00223*OM - 0{,}0267*\rho b$	(2)	0,95
Rawls et al. (1982)	USA	10	$\theta\ (m^3\ m^{-3}) = 0{,}412 - 0{,}003*Sand + 0{,}0023*Clay + 0{,}0317*OM$	(2)	0,81
		33	$\theta\ (m^3\ m^{-3}) = 0{,}258 - 0{,}002*Sand + 0{,}0036*Clay + 0{,}0299*OM$	(2)	0,87
		1,500	$\theta\ (m^3\ m^{-3}) = 0{,}026 - 0{,}005*Clay + 0{,}016*OM$	(2)	0,80
Saxton et al. (1986)	USA	10	$\theta\ (m^3\ m^{-3}) = \exp\left[\frac{(2.032 - LnA)}{B}\right]$ where:		
			$A = \exp[-4{,}40 - 0{,}0715*Clay - 4{,}88.10^{-4}*Sand^2 - 4{,}28.10^{-5}*Sand^2*Clay]*100$	(2)	0,99
			$B = -3{,}14 - 2{,}22.10^{-3}*Clay^2 - 3{,}48.10^{-5}*Sand^2*Clay$	(2)	0,99
Arruda et al. (1987)	SP - Brazil	33	$\theta\ (g\ 100g^{-1}) = 3{,}074 + 0{,}629*(Silt+Clay) - 0{,}003438*(Silt+Clay)^2$	(1, 2)	0,91
		1,500	$\theta\ (g\ 100g^{-1}) = 1{,}074 + 0{,}2712*(Silt+Clay)$	(1, 2)	0,95
Bell & van Keulen (1995)	México	1,500	Model 1 $\theta\ (g\ 100g^{-1}) = -0{,}992 + 0{,}351*clay + 0{,}47*OM$	(2)	0,85
			Model 2 $\theta\ (g\ 100g^{-1}) = -1{,}62 + 0{,}436*CEC_{pH7} + 0{,}436*OM$	(2)	0,90
Van den Berg et al. (1997)	Tropical soils	10	$\theta\ (m^3\ m^{-3}\ .10^2) = 10{,}88 + 0{,}347*Clay + 0{,}211*Silt + 1{,}756*OC$	(2)	0,86
		1,500	$\theta\ (m^3\ m^{-3}\ .10^2) = 3{,}83 + 0{,}272*Clay + 0{,}212*Silt$	(2)	0,80
Masutti (1997)	PE - Brazil	33	$\theta\ (g\ 100g^{-1}) = -1{,}569 + 0{,}429*(Silt+Clay)$	(2)	
		1,500	$\theta\ (g\ 100g^{-1}) = -0{,}530 + 0{,}301*Silt + 0{,}0928*Clay$	(2)	
Giarola et al. (2002)	RS e SC Brazil	10	$\theta\ (m^3\ m^{-3}) = 0{,}081 + 0{,}005*Silt + 0{,}004*Clay$	(2)	0,79
		1,500	A Horizon $\theta\ (m^3\ m^{-3}) = -0{,}031 + 0{,}005*Silt + 0{,}003*Clay$	(2)	0,81
		1,500	B Horizon $\theta\ (m^3\ m^{-3}) = 0{,}024 + 0{,}005*Silt + 0{,}003*Clay$	(2)	0,81
Oliveira et al. (2002)	PE - Brazil	33	$\theta\ (kg\ kg^{-1}) = 0{,}00333*Silt + 0{,}00387*Clay$	(2)	0,96
		1,500	$\theta\ (kg\ kg^{-1}) = -0{,}00038*Sand + 0{,}00153*Silt + 0{,}00341*Clay - 0{,}0309*\rho b$	(2)	0,95

(1) The silt fraction has a diameter between 2 and 20 µm. (2) Organic matter (OM), organic carbon (OC), sand, silt and clay in g 100 g^{-1}. Bulk density (ρb) in kg dm^{-3}. CEC in $cmol_c\ kg^{-1}$.

with high and severe multicollinearity were not included in the path analysis.

RESULTS AND DISCUSSION

Soil physical properties and water retention

Clay contents varied from 0.01 to 0.82 kg kg^{-1}, silt from 0.01 to 0.78 kg kg^{-1} and sand from 0.01 to 0.99 kg kg^{-1}. The organic matter content was 0.01 - 0.10 kg kg^{-1} and bulk density 0.86 - 1.85 kg dm^{-3} (Table 2). This ample variation is favorable and necessary for the generation of pedotransfer functions (Pachepsky & Rawls, 1999). Thus, water retention also varied, as exemplified for the tension of 1,500 kPa, with levels of 0.01–0.48 kg kg^{-1}. These differences reflect the parent material and the degree of weathering, and consequently the physical, chemical and mineralogical properties of the soil.

Water retention is positively correlated with the clay content (Table 3), because this fraction favors the occurrence of micropores and menisci that generate capillary forces. In addition, clay increases the specific surface area of the soil matrix and, consequently, water adsorption (Hillel, 1998). These two phenomena, capillarity and adsorption, determine the matric potential and are responsible for soil water retention. Consequently, soils whose constituents or structure favor the appearance of these two phenomena will retain a greater amount of water.

Table 2. Descriptive statistics of the variables that compose the database used to generate the pedotransfer functions for RS soils

Soil property	n(6)	Minimum	Maximum	Mean	Standard deviation
Clay (kg kg^{-1})	725	0.01	0.82	0.33	0.17
Silt (kg kg^{-1})	725	0.01	0.78	0.26	0.10
Sand (kg kg^{-1})	725	0.01	0.99	0.41	0.16
Clay + Silt (kg kg^{-1})	725	0.01	0.99	0.59	0.16
OM(1) (kg kg^{-1})	366	0.00	0.10	0.02	0.02
ρb(2) (kg dm^{-3})	693	0.86	1.85	1.43	0.21
ρp(3) (kg dm^{-3})	725	1.96	3.22	2.63	0.11
ϕt(4) (m^3 m^{-3})	693	0.29	0.68	0.46	0.08
θg 6 kPa(5) (kg kg^{-1})	607	0.05	0.87	0.27	0.09
θg 10 kPa (kg kg^{-1})	358	0.04	0.77	0.26	0.10
θg 33 kPa (kg kg^{-1})	684	0.02	0.63	0.23	0.08
θg 100 kPa (kg kg^{-1})	645	0.02	0.52	0.20	0.07
θg 500 kPa (kg kg^{-1})	313	0.01	0.53	0.18	0.07
θg 1,500 kPa (kg kg^{-1})	685	0.01	0.48	0.17	0.06

(1) OM: Organic matter. (2) ρb: Bulk density. (3) ρp: Particle density. (4) ϕt: Total porosity. (5) θg: Gravimetric soil water content at different tensions. (6) n: number of samples with available data.

Table 3. Pearson correlation analysis between water retention at the tensions of 6, 10, 33, 100, 500 and 1,500 kPa with particle size distribution (clay, silt and sand), organic matter (OM), bulk density (ρb), particle density (ρp) and total porosity (ϕt)

Soil property	θg 6(1)	θg 10	θg 33	θg 100	θg 500	θg 1,500
Clay	0.49** (607)(2)	0.61** (358)	0.56** (684)	0.58** (645)	0.59** (313)	0.57** (685)
Silt	0.21** (607)	0.29** (358)	0.13** (684)	0.18** (645)	0.15** (313)	0.01 ^{ns} (685)
Sand	-0.64** (607)	-0.73** (358)	-0.68** (684)	-0.70** (645)	-0.69** (313)	-0.66** (685)
Silt + clay	0.64** (607)	0.73** (358)	0.68** (684)	0.70** (645)	0.69** (313)	0.66** (685)
OM	0.38** (253)	0.40** (298)	0.29** (325)	0.39** (296)	0.28** (251)	0.29** (339)
ρb	-0.73** (603)	-0.67** (354)	-0.57** (652)	-0.49** (641)	-0.35** (313)	-0.43** (653)
ρp	-0.01 ^{ns} (607)	0.02 ^{ns} (358)	-0.23** (684)	0.07 ^{ns} (645)	0.18** (313)	-0.14** (685)
ϕt	0.74** (603)	0.67** (354)	0.58** (652)	0.50** (641)	0.38** (313)	0.44** (653)

(1) θg: Gravimetric soil water content. (2) The number of data pairs used for calculation and correlation is indicated in brackets: **, * and ns: significant at 1 and 5 % and non significant.

Estimation of water retention and validation of pedofunctions

Due to the existence of soil variables in the RS soil database with direct and indirect relationships to water retention, it was possible to estimate water retention by pedotransfer functions (Table 4), as shown in figure 2. The independent variables included in the equations were the same as the model presented by Gupta & Larson (1979) and Rawls et al. (1982), and the coefficient associated with bulk density also had a negative signal, as in the cited study, which is due to the fact that sandier soils, with low water retention, are denser. In the model of van den Berg et al. (1997), the clay and silt contents better explained variation in water retention, which are variables also present in the model of Aina & Periaswamy (1985) and Arruda et al. (1987) to describe water retention in tropical soils. This shows that some variables are frequently related in studies of estimation of soil water retention, of which clay is the principal variable (Wösten & van Genuchten, 1988).

The coefficients of determination of the proposed pedofunctions varied from 0.56 at a tension of 500 kPa to 0.67 at tensions of 6 and 10 kPa, all significant at the 1 % level. Nevertheless, there are overestimates for low tensions and underestimates for high tensions,

Table 4. Pedofunctions generated to estimate the gravimetric soil water content (kg kg^{-1}) from data of Rio Grande do Sul soils, with all soil properties for the tensions of 6, 10, 33, 100, 500 and 1,500 kPa and with data from particle size distribution for the tensions of 6, 10 and 1,500 kPa, by multiple regression analysis

Equation	R^2 Adjusted	Pr > F	n
Equations generated using all soil properties			
θges 6 = 0.415 + 0.26 x (Clay+Silt) + 0.61 x OM –0.207 x ρb	0.67	0.01	249
θges 10 = 0.268 + 0.05 x Clay + 0.24 x (Clay+Silt) + 0.85 x OM – 0.127 x ρb	0.67	0.01	294
θges 33 = 0.106 + 0.29 x (Clay+Silt) + 0.93 x OM – 0.048 x ρb	0.62	0.01	293
θges 100 = 0.102 + 0.23 x (Clay+Silt) – 0.08 x (Silt+Sand) + 1.08 x OM	0.64	0.01	296
θges 500 = 0.268 - 0.11 x Silt – 0.31 x Are + 1.28 x OM + 0.031 x ρb	0.56	0.01	251
θges 1500 = - 0.04+ 0.15 x Clay + 0.17 x(Clay+Silt) + 0.91 x OM + 0.026 x ρb	0.62	0.01	307
Equations generated using particle sizes			
θges 10 = 0.037 + 0.38 x (Clay+Silt)	0.54	0.01	358
θges 33 = 0.366 - 0.34 x Sand	0.46	0.01	684
θges 1500 = 0.236 + 0.045 x Clay – 0.21 x Sand	0.44	0.01	685

R^2: adjusted coefficient of determination of the equation; Pr: significance level; n: number of data pairs used to generate the equation; θges: estimated gravimetric soil water content.

differences expressed in the angular coefficient, always < 1, with variation from 0.56 to 0.67 (Table 5). The underestimation of the equations at high tensions was caused primarily by the presence of soils with a wide variation in mineralogy, since that to generate the pedofunctions all data collected in the literature were included. This same observation was reported by Tomasella et al. (2000) when establishing pedotransfer functions to estimate the coefficients of the van Genuchten equation, and by Williams et al. (1983) in a study of Australian soils.

The coefficients of determination of pedofunctions generated only with data of particle size distribution were 0.44 and 0.54 (Table 4), less than those of the equations that also use organic matter and bulk density, but which may be used when particle size distribution data are available.

Soil samples with high water retention at a tension of 100 kPa were from horizons A and A/C of a Gleysol and horizon B from a Vertisol. According to Kämpf et al. (1995), in Vertisols from the plateau region of RS, located in lower areas in the catena, the clay mineralogy is composed of montmorilonite-beidellite, whereas in more elevated areas, kaolinite, smectite and smectite with aluminum hydroxide predominate between layers. These authors also observed considerable differences in the cation exchange capacity of clay in the Vertisol horizons, from 56 $cmol_c$ kg^{-1} in the C to 18 $cmol_c$ kg^{-1} in the A horizon. The role of mineralogy in water retention was already discussed by Woodruf (1950), based on the particle diameter of the different minerals. Therefore, in addition to particle size distribution, water retention is highly dependent on soil mineralogy, which varies among soils and horizons. Baumer & Brasher (1982) considered the effect of mineralogy in studies of soil water retention as an important variable. In a study by Puckett et al. (1985) in soils with similar mineralogy, the variables particle size distribution, bulk density and porosity were adequate to estimate water retention, while in soils with great mineralogical variation Hodnett & Tomasella (2002) affirmed that mineralogy is a variable that significantly influences soil water retention and, when available, must be considered in the generation of pedotransfer functions.

Evaluation of pedofunctions from the literature

The equations generated with soil samples collected in Brazil, as well as the expression of van den Berg et al. (1997), which included soils from Brazil and from other tropical climate countries, are presented in figure 3a. Of these five models, that of Masutti (1997) at a tension of 33 kPa and of Oliveira et al. (2002) at tensions of 33 and 1,500 kPa, were those that estimated water retention best, in spite of underestimating water retention at greater tensions. The model of Arruda et al. (1987) presents a gravimetric soil water content estimated at approximately 0.32 kg kg^{-1} at the tension of 33 kPa, while the measured contents are much higher. All models underestimate water retention at high tensions, which may be observed by the b coefficient of the proposed equation, which frequently has a value of < 0.5. In figure 3b, results of the estimations with models developed with soils from Mexico and the USA were presented. Of these, the model of Bell & van Keulen (1995) estimated the retention measured for

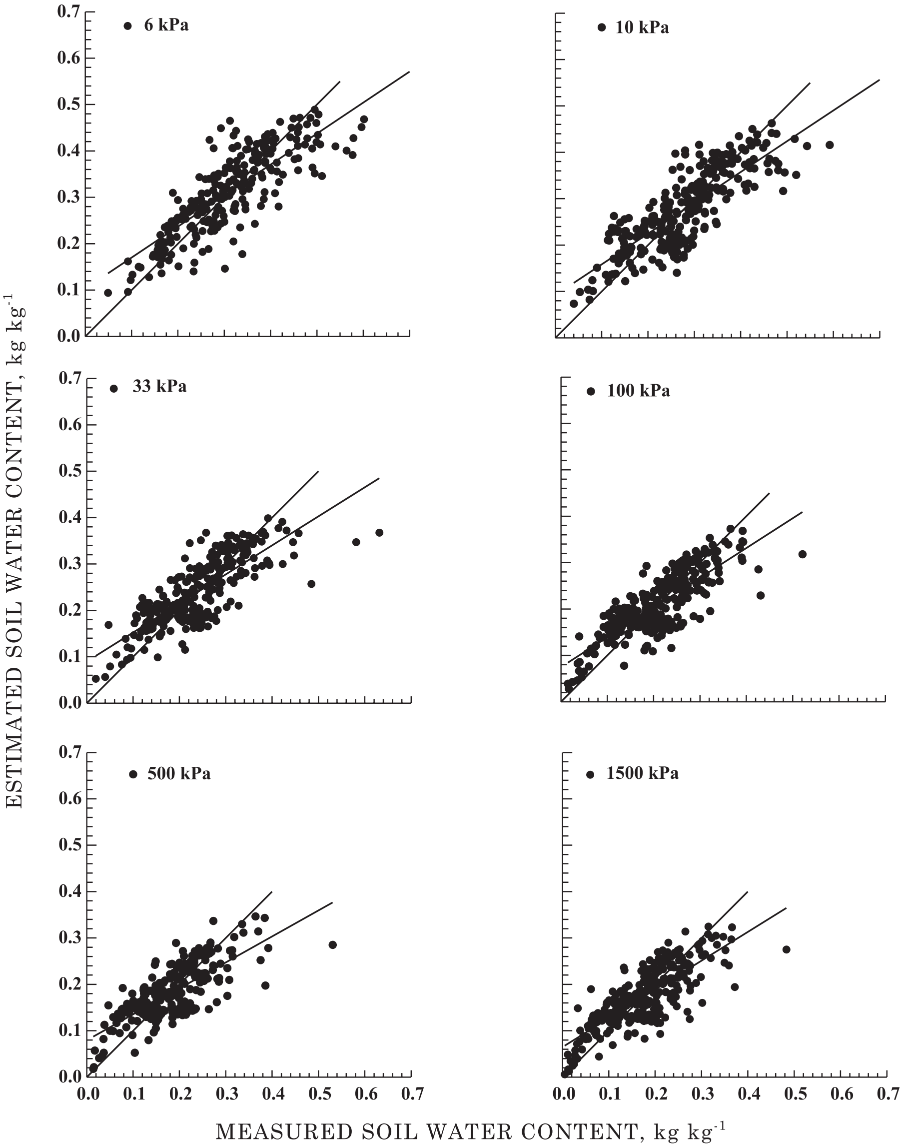

Figure 2. Relationship between the soil water content estimated by the pedofunctions proposed in table 4 and the soil water content measured in the laboratory for the tensions of 6, 10, 33, 100, 500 and 1,500 kPa in some RS soils. The straight line from the origin represents the 1:1 relation.

the soils of Rio Grande do Sul with greater accuracy. Nevertheless, the b coefficient of the equation was 0.61 (Table 5), different than 1 from the straight line 1:1. This indicates an underestimation of water retention at low tensions.

Models developed from soils of the temperate climate region, such as those of Gupta & Larson (1979), Rawls et al. (1982) and Saxton et al. (1986), also under or overestimated water retention; nevertheless, dispersion was high (Figure 3b). With the exception of the model of Saxton et al. (1986) at a tension of 33 kPa, the other models had lower coefficients of determination than the models developed for soils in tropical regions. This may be due to differences in mineralogy between the soils in tropical and temperate climate regions.

The observations based on analysis of the models from the literature and of the model proposed in this study, clearly show the need for specific equations for soils with more homogeneous characteristics, as described by Arruda et al. (1987), Vereecken et al. (1989), Wösten et al. (1995), Salchow et al. (1996), and Pachepsky & Rawls (1999). Nevertheless, for the data available, the grouping of soils by texture classes did not increase the coefficients of determination between water retention and soil properties (data not shown). Thus, mineralogy, which is quite variable in terms of soil classes and horizons, should be better studied, as emphasized by Baumer & Brasher (1982), in order to quantify its relationship with water retention.

To evaluate the accuracy of the model proposed, the estimated results were compared with those

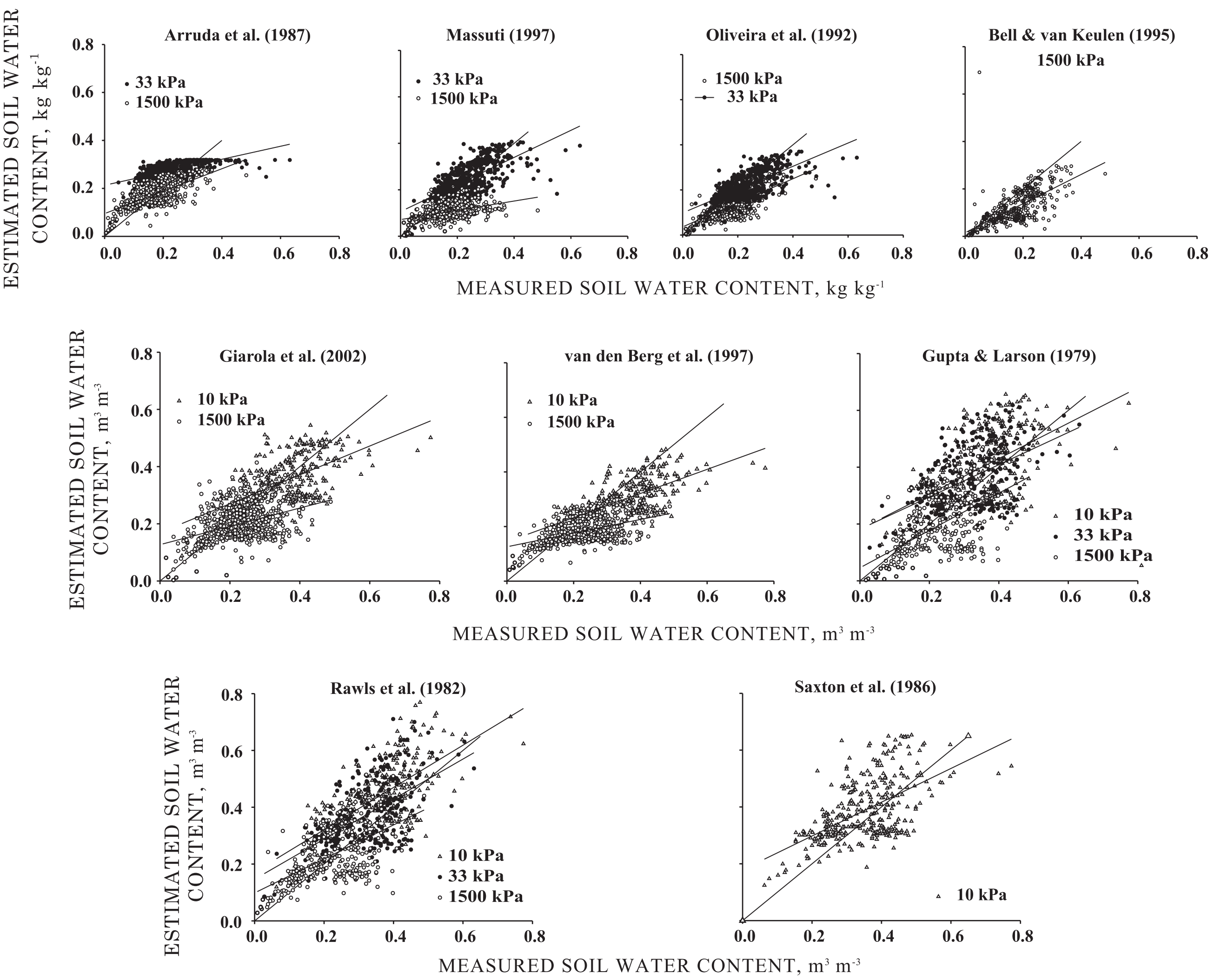

Figure 3. Comparison between soil water content estimated from published pedofunctions (Table 1: Arruda et al., 1987; Giarola et al., 2002; Masutti, 1997; Oliveira et al., 2002; van den Berg et al., 1997), based on soils from Brazil and of tropical climate, and from published pedofunctions (Table 1: Bell & van Keulen, 1995; Gupta & Larson, 1979; Rawls et al., 1982; and Saxton et al., 1986), based on soils from México and USA, and soil water content measured in soils of Rio Grande do Sul. The straight line is the 1:1 line.

estimated by the models of Oliveira et al. (2002) and of Masutti (1997), which were generated with data from the State of Pernambuco. The water retention estimated by the proposed model, compared to that estimated by the model of Oliveira et al. (2002) has an elevated coefficient of determination (0.93 for 33 kPa to 0.92 for 1,500 kPa), but the model proposed overestimates water retention at the tension of 1,500 kPa (Table 5 and Figure 4). For the model of Masutti (1997), the coefficients of determination were 0.46 at 33 kPa and 0.94 at 1,500 kPa. In addition, the angular coefficient at 1,500 kPa was only 0.42, very different from the unit value, which indicates a significant underestimation.

With the objective of making equations available when there is only information regarding particle size distribution, three water retention equations were generated for the tensions of 10, 33 and 1,500 kPa (Table 4). For the tensions of 33 and 1,500 kPa, it was possible to evaluate the equations with the data available for soils from an irrigation system. It was observed that at a tension of 33 kPa, the coefficient of determination between the estimated and the measured soil water content was 0.73, but 0.76 at 1,500 kPa (Figure 5). For soils with low water retention, the estimated is greater than the measured soil water content. In addition, the slope of the straight line is different from the 1:1 line. For retention at 1,500 kPa the estimated is greater than the measured soil water content in all samples. This may be the case because the soils underlying the proposed model have a mineralogy containing oxides, kaolinite and smectite, while in the database with the soils of the irrigation system the mineralogy consists

Table 5. Statistical parameters and equations for the data and adjustments expressed in figures 2 to 5

Adjusted equation	n(1)	R^2	MSE	Pr > F	Pr > T Intercept = 0	Pr > T Slope = 1
Figure 2						
θges 6 = 0.103+0.67x θgme 6 (2)	249	0.67	0.0028	0.01	0.01	0.01
θges 10 = 0.092+0.66x θgme 10	294	0.67	0.0024	0.01	0.01	0.01
θges 33 = 0.090+0.63x θgme 33	293	0.63	0.0019	0.01	0.01	0.01
θges 100 = 0.075+0.64x θgme 100	296	0.65	0.0015	0.01	0.01	0.01
θges 500 = 0.080+0.56x θgme 500	251	0.56	0.0015	0.01	0.01	0.01
θges 1500 = 0.065+0.62x θgme 1500	307	0.62	0.0015	0.01	0.01	0.01
Figure 3a						
θgAr 33 = 0.213+0.27x θgme 33	684	0.38	0.0007	0.01	0.01	0.01
θgAr 1500 = 0.095+0.47x θgme 1500	685	0.43	0.0011	0.01	0.01	0.01
θvGi 10 = 0.169+0.50x θvme 10	354	0.37	0.0046	0.01	0.01	0.01
θvGi 1500 = 0.127+0.32x θvme 1500	653	0.16	0.0030	0.01	0.01	0.01
θgMa 33 = 0.106+0.58x θgme 33	684	0.46	0.0024	0.01	0.01	0.01
θgMa 1500 = 0.072+0.20x θgme 1500	685	0.18	0.0007	0.01	0.01	0.01
θgOl 33 = 0.098+0.52x θgme 33	684	0.46	0.0019	0.01	0.01	0.01
θgOl 1500 = 0.036+0.53x θgme 1500	653	0.40	0.0016	0.01	0.01	0.01
θvBer 10 = 0.144+0.44x θvme 10	294	0.41	0.0031	0.01	0.01	0.01
θvBer 1500 = 0.126+0.25x θvme 1500	653	0.19	0.0015	0.01	0.01	0.01
Figure 3b						
θgBe 1500 = 0.015+0.61x θgme1500	339	0.53	0.0021	0.01	0.01	0.01
θvGu 10 = 0.181+0.62x θvme 10	294	0.28	0.0109	0.01	0.01	0.01
θvGu 33 = 0.181+0.57x θvme 33	293	0.26	0.0091	0.01	0.01	0.01
θvGu 1500 = 0.046+0.66x θvme 1500	307	0.31	0.0087	0.01	0.01	0.01
θvRa 10 = 0.172+0.74x θvme 10	294	0.41	0.0088	0.01	0.01	0.01
θvRa 33 = 0.145+0.70x θvme 33	293	0.34	0.0085	0.01	0.01	0.01
θvRa 1500 = 0.098+0.60x θvme 1500	307	0.32	0.0068	0.01	0.01	0.01
θvSa 10 = 0.179 + 0.59x θvme 10	354	0.32	0.0078	0.01	0.01	0.01
Figure 4						
θgOl 33 = -0.026+1.01x θges 33	334	0.93	0.0004	0.01	0.50	0.01
θgOl 1500 = -0.030+0.94x θges 1500	334	0.92	0.0003	0.01	0.01	0.01
θgMa 33 = -0.040+1.17x θges 33	334	0.94	0.0005	0.01	0.01	0.01
θgMa 1500 = 0.036+0.42x θges 1500	334	0.46	0.0008	0.01	0.01	0.01
Figure 5						
θges 33 = 0.027+0.90xθgmI 33	239	0.73	0.0008	0.01	0.01	0.01
θges 1500 = 0.065+0.83xθgmI 1500	239	0.76	0.0004	0.01	0.01	0.01

(1) n: number of data pairs to generate the equation; R^2: coefficient of determination; MSE: mean squared error; Pr > F: significance level for F test; Pr > T: significance level for T test. For the intercept, a significance level > 0.05 indicates that the parameter "a" of the equation of the straight line does not differ from zero. For the slope, a significance level > 0.05 indicates that the parameter "b" of the equation of the straight line does not differ from 1. (2) θges: Estimated gravimetric soil water content; θgme: Measured gravimetric soil water content; θvme: Measured volumetric soil water content; θgAr: Estimated gravimetric soil water content by the model of Arruda et al. (1987); θvGi: Estimated volumetric soil water content by the model of Giarola et al. (2002); θgMa: Estimated gravimetric soil water content by the model of Masutti (1997); θgOl: Estimated gravimetric soil water content by the model of Oliveira et al. (2002); θvbr: Estimated volumetric soil water content by the model of van den Berg et al. (1997); θgBe: Estimated gravimetric soil water content by the model of Bell & van Keulen (1995); θvGu: Estimated volumetric soil water content by the model of Gupta & Larson (1979); θvRa: Estimated volumetric soil water content by the model of Rawls et al. (1982); θvSa: Estimated volumetric soil water content by the model of Saxton et al. (1986); θgmI: Measured gravimetric soil water content from the irrigation database.

predominantly of kaolinite and iron oxides. Nevertheless, the estimation of soil water retention at 33 kPa, depending less on soil mineralogy and more on structure, was satisfactory.

Therefore, dispersion is greater and accuracy of water retention lower when we use equations generated from the database with predominance of soils of certain classes, or soils with characteristics that differ considerably from the soils where the model is being evaluated. Thus, the equations will only efficiently express water retention for soils that are similar in regard to their genesis and mineralogy (Williams et al., 1983; Mecke et al., 2002). When using pedotransfer functions created in other countries, Bonilla & Cancino (2001) observed a low accuracy for Chilean soils. To overcome this limitation, it is necessary to work with a large database to allow a division of the soils into more homogeneous classes.

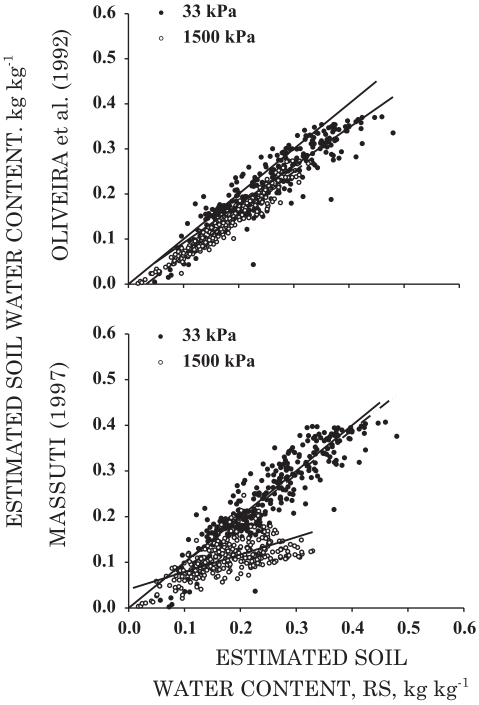

Figure 4. Relationship 1:1 between the gravimetric soil water content estimated by the proposed model (θges) and that estimated by the model of Oliveira et al. (2002) (θgOl) and Masutti (1997) (θgMa), for the tensions of 33 and 1,500 kPa.

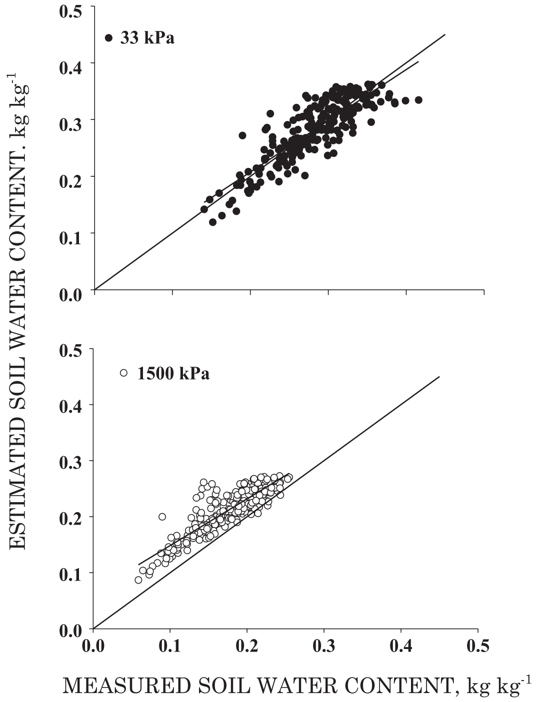

Figure 5. Ratio between the gravimetric soil water content measured for the soils of the irrigation system (θgmI) and that estimated by the proposed model (θges) for soils with particle size distribution information.

Plant-available water for RS soils.

Using path analysis, the direct and indirect effects of soil properties on water retention were evaluated (Table 6). For water retention at field capacity (10 kPa), direct and positive effects of clay and silt are observed, and a negative effect of bulk density. The direct effect of clay (R = 0.71) is greater than its total effect (R = 0.62) due to its indirect effect through the silt content (R = -0.23). In the more clayey soils, the silt content had a negative relationship with clay (R = -0.42) and the lower direct contribution of the silt fraction to water retention (R = 0.54) diminishes the total effect of clay in that retention.

The total effect of bulk density was negative (R = -0.65), a result of its direct effect (R = -0.27) and indirect effect via the clay content (R = -0.34). In denser soils, the volume of larger pores diminishes, affecting water retention at field capacity. With an increase in sand content, bulk density increased (R = 0.51); thus in the denser and sandier soils, water retention was less, which resulted in an indirect effect of particle size distribution in reducing field capacity in the denser soils. Therefore, sandier and denser soils with greater macroporosity and less microporosity than the clayey soils have a lower capacity for water retention (Casaroli & Jong van Lier, 2008); however, in soil without variation of particle size distribution, compaction generally reduces total porosity and the volume of larger pores (Araujo et al., 2004). As shown by Klein & Libardi (2002), soil cultivation in dryland and irrigated farming, compared to forest soil, generally increases water retention between tensions of 6 and 1,500 kPa, in the plant-available range, and also water retention in tensions > 1,500 kPa, unavailable to plants.

The organic matter content had a total positive effect on water retention at field capacity, with a correlation coefficient of 0.41. The direct effect was low (R = 0.14), but indirect effect of clay (R = 0.04), silt (R = 0.15) and bulk density (R = 0.09) were responsible for the total effect (Table 6). This indicates that in soils with a greater clay plus silt content there is more organic matter (R =0.22), soil fractions that contribute to the additive effect on water retention by organic matter, as also observed by Bell & van Keulen (1995) for soils in Mexico. Bauer & Black (1992) affirmed that organic matter increases water retention more in sandy soils than in clayey soils.

Similar effects to those discussed for field capacity were observed for the permanent wilting point, however with different correlation coefficients (Table 6), primarily due to the lower direct effect of the silt fraction. Furthermore, for bulk density, the negative effect on water retention (R = -0.44) was principally indirect via clay content (R = -0.33) and from organic matter (R = -0.04).

The water content retained at field capacity varied from 0.141 kg kg^{-1} in the sand class to 0.477 kg kg^{-1}

Table 6. Correlation coefficients considering the direct and indirect effects obtained by path analysis between the contents of clay, silt, organic matter (OM), bulk density (ρb) and particle density (ρp), with the gravimetric soil water content retained at field capacity (10 kPa), at the permanent wilting point (1,500 kPa) and the plant-available water capacity (retained between 10 and 1,500 kPa)

Soil properties	R total[(1)]	R – Direct effect	R – Indirect effect				
			Clay	Silt	OM	ρb	ρp
			Field capacity				
Clay	0.62	0.71		-0.23	0.01	0.13	0.00
Silt	0.27	0.54	-0.29		0.04	0.00	0.00
OM	0.41	0.14	0.04	0.15		0.09	0.00
ρb	-0.65	-0.27	-0.34	0.00	-0.04		0.00
ρp	-0.06	0.01	0.05	-0.06	-0.02	-0.05	
			Permanent wilting point				
Clay	0.58	0.69		-0.16	0.01	0.01	-0.01
Silt	0.11	0.39	-0.29		0.03	0.00	0.01
OM	0.29	0.12	0.04	0.11		0.01	0.02
ρb	-0.44	-0.03	-0.33	0.00	-0.04		-0.03
ρp	-0.15	-0.14	0.05	-0.04	-0.01	0.00	
			Available water				
Clay	0.06	-0.02		-0.10	0.00	0.15	0.00
Silt	0.22	0.23	0.01		0.01	0.00	-0.01
OM	0.19	0.04	0.00	0.06		0.10	-0.01
ρb	-0.30	-0.30	0.01	0.00	-0.01		0.01
ρp	-0.03	0.06	0.00	-0.02	0.00	-0.06	

(1) Correlation coefficient.

in the silty clay class, while the permanent wilting point varied from 0.050 kg kg^{-1} in the sandy loam textural class to 0.286 kg kg^{-1} in the silty clay textural class (Figure 6). Both the field capacity and permanent wilting point increased in similar magnitude with the increase in clay content, which caused little changes in the plant-available water capacity with the increase of soil clay content (Figure 7). An exception was observed in the case of low clay contents, in the sand textural class, with less plant-available water capacity. Consequently, the plant-available water capacity increases when the clay content increases to near 0.15 kg kg^{-1}, and remains constant thereafter (Figure 7).

The mean plant-available water capacity for the evaluated soils was 0.130 kg kg^{-1}, with less retention in the sand textural class and greater in the silt clay textural class (Figure 6). Other classes with greater retention were the silty clay loam (0.158 kg kg^{-1}) and silty loam (0.176 kg kg^{-1}). In the other textural classes, the plant-available water capacity varied little with the particle size distribution, from 0.116 kg kg^{-1}, in sandy clay loam, to 0.137 kg kg^{-1}, in sandy clay soil. The lower plant-available water capacity in the sand textural class is related to the low specific surface area of these soils, while the greater availability in the silt clay class is related to the greater presence of clay and silt, with a larger specific surface area. When the three classes with greatest retention are analyzed, it is observed that these soils are less weathered and with a greater silt clay ratio and, therefore, greater contribution to water retention with 2:1 type minerals.

The path analysis showed that the plant-available water capacity had a positive total correlation with the silt content (R = 0.22) and organic matter (R = 0.19), and a negative total correlation with bulk density (R = -0.30). For the silt content and bulk density, the effects were direct, while for organic matter, the direct effect was small (R = 0.04) and the total effect was related to the indirect effects via the silt content (R = 0.06) and bulk density (R = 0.10) (Table 6). Soils with greater organic matter content were those with greater silt content (R = 0.22); thus, the greater water retention of these soils was also via silt. Low correlation coefficients among soil properties and plant-available water capacity have frequently been reported (van den Berg et al., 1997; Giarola et al., 2002), probably due to the interactions with positive and negative effects among the soil properties, as verified by path analysis.

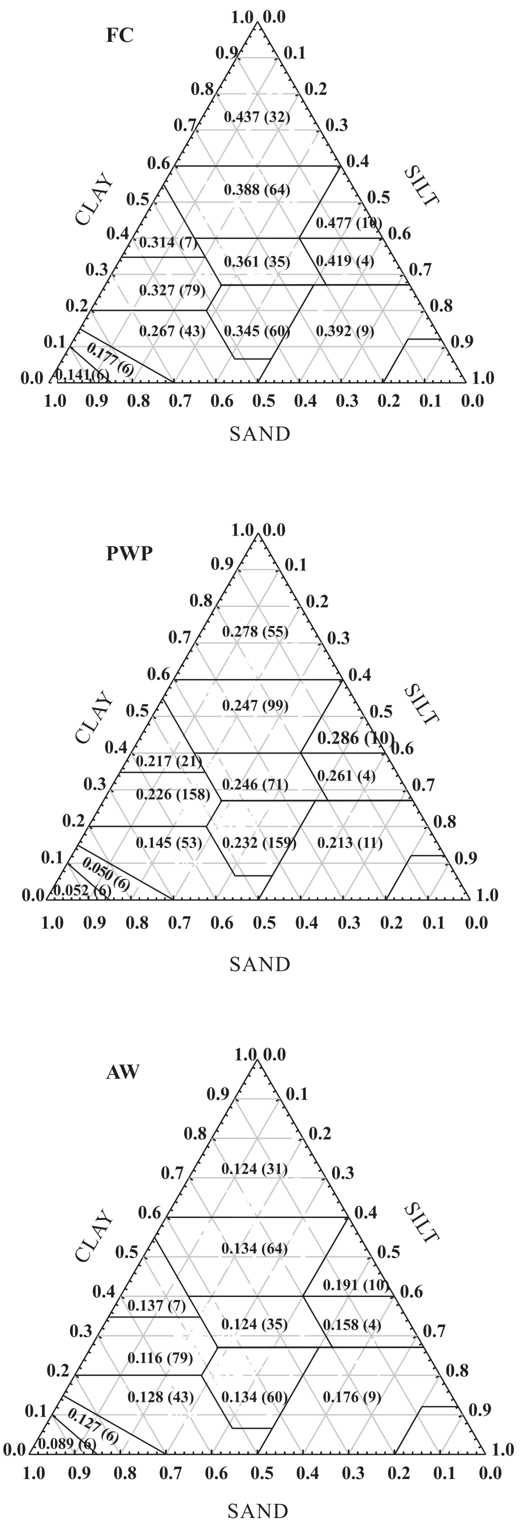

Figure 6. Water content (m^3 m^{-3}) retained at the tensions of 10 kPa (FC) and 1,500 kPa (PWP) and plant-available water capacity retained between the tensions of 10 and 1,500 kPa (AW), at the mean of each soil textural class, calculated from measured data. In brackets is the number of samples available for calculating each mean.

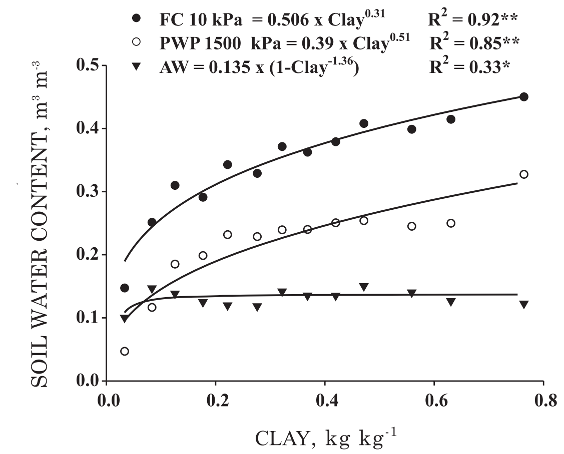

Figure 7. Relationship between the clay content in the soil and the water content at field capacity (FC = 10 kPa), at the permanent wilting point (PWP = 1,500 kPa) and the plant-available water capacity (AW = different between water content at 10 and at 1,500 kPa) for the RS soils.

CONCLUSIONS

1. Pedotransfer functions generated from soils of other geographical regions are not adequate for estimating water retention of the soils of RS.

2. The proposed equations generally include the variables organic matter, bulk density and clay plus silt fractions.

3. The contents of clay, silt and organic matter had a total positive correlation with soil water content at field capacity and at the permanent wilting point, whereas bulk density had a negative correlation with water content at field capacity. Part of the correlation was due to an indirect effect, as a consequence of interrelationships which exist among soil properties.

4. The level of plant-available water capacity was lowest in the sand textural class due to the low specific surface area, while the greatest level was observed in the classes with a greater silt content and, therefore in those with a greater silt/clay ratio, indicating less weathered soils with a greater quantity of 2:1 type clay minerals.

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