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Discriminant pedological factors of in situ specific moisture and available water content of African soils

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Abstract – The management of groundwater and crop-available water requires the knowledge of the hydrological behaviour of soils. A study was carried out from North to South Senegal on about 5 degrees of latitude, which cover a large range of pedological factors and various climatic, geologic and geomorphologic conditions. 1387 layer samples of 103 soils were taken from the surface to 2 m depth by 0.1 m-deep increments. The studied pedological properties were clay + silt content, bulk density, exchangeable Na⁺ and pH. The hydraulic properties were the minimum moisture content, the field capacity and the available water content. Principal component analysis shows that the main factors, the texture, the minimum moisture content and field capacity, the available water content and the pH were in a decreasing order of importance. A good agreement between predicted and measured values of the minimum moisture content and the field capacity data, except for the available water content, was found for all mixed layers, for soils grouped according to their layers and for two soils (Arenosol and Ferralsol). However, the available water content can be calculated by statistical calculation by the grouping of textural classes for each layer.

West-Africa / minimum moisture content / field capacity / available water content / arid to tropical climates / discriminant equations

1. INTRODUCTION

The management of ecosystems and the use of groundwater require the knowledge of the hydrological behaviour of soils. The prediction of the response of soils under various hydrological conditions is important for farming in arid to tropical climates. Indeed, the hydrological state of a soil controls physical and chemical phenomena such as erosion, sediment transport, runoff, percolation, draining off, salt leaching and accumulation [40, 43, 71, 75]. These phenomena can be modelled using specific moisture and/or available water content of the soils [3, 24]. Over the last few years, many models have been developed which deal with erosion [73], soil surface transport of contaminants from soils to water layers [5], biomass production, the Nitrogen cycle and plant growth [15, 31, 51], agrogeological zoning [23, 38], water balance [17], land evaluation systems and good irrigation practices [27].

The minimum moisture content and the field capacity are the most important points of the water retention curve of unsaturated soil. These two values are required to compute the available water content [63]. In Europe and America, soil databases have been used to assist with planning the sustainable use of land since the beginning of the 70s. In the 1990s, the databases of pedological properties were extended to predict the hydraulic characteristics of soils and to explain the movement and retention of water in unsaturated soils. Maps of pedological characteristics have been drawn by Wösten et al. [76] for Euro-

pean soils, by Kern [33] and De Jong and Schields [22] for USA soils and by Valet [58] for soils of the Ivory coast.

The concept of available water content is based mainly on laboratory measurements, except for some measurements realised directly in the field [13, 41]. It has been demonstrated that the measurement of moisture at the upper and lower limits of retention made in the laboratory gives limited results [48, 49, 54]. These experimental values have to be calibrated with field data [52]. Pedotransfer functions (PTF) describe the relationship between values of water retention and other parameters such as van Genuchten parameter distribution [10]. For European soils, pedotransfer functions have been estimated from field measurements for a range of minimum moisture content and field capacity values and for different cases of hydraulic conductivities and infiltration processes [67]. These functions are variable both in heterogenous and homogeneous soil [35]. The coefficients of variation (CV_s) of these functions may rise from 75% to 1000%. The precise values of the specific van Genuchten parameters are very difficult to obtain in a large range of American and African soils [16, 28]. Tietje and Tapkenhinrichs [56] concluded that the 13 pedotransfer functions applied to 1118 soil samples cannot produce a precise relationship between hydraulic and pedological properties, because the van Genuchten parameters exhibit too large a variability.

However, field and laboratory measurement of these parameters are time- and money-consuming and therefore difficult to realise [30]. Other methods have been developed to

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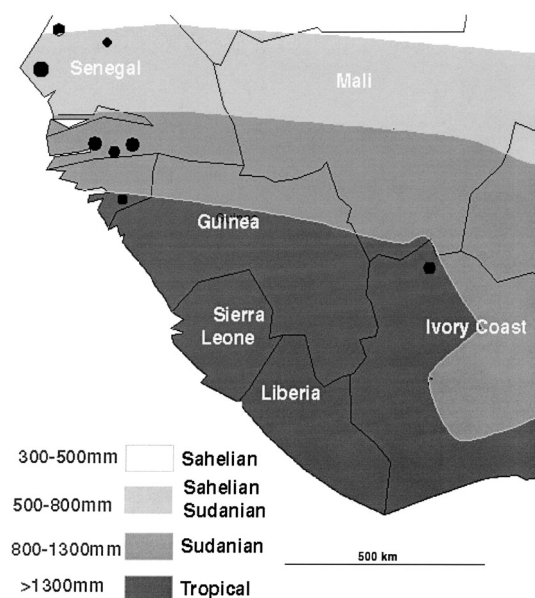


Figure 1. Map of African climates with annual rainfall isohyets (mm). The location of sampling sites is marked with a circle.

predict hydrological flow in [45, 68]. Predictive equations of these hydraulic characteristics have been proposed based on usual easily measurable soil properties [74]. These predictive equations are based on known relationships between water content and pedological properties [66]. The different equations differ in the number of applied pedological variables, among which there are particle density, pore size distribution, soil morphology, structure and clay mineralogy [32, 69, 72]. The effect of the silt amount is also important [32]. Colloidal minerals and organic compounds increase water retention [34]. High Na^+ concentration and pH (sodicity and alkalinity characteristics) can also lower the infiltration and the water retention [63]. The large number of these models shows that they are not universal and that they are specific to the analysed material and to the studied climates [6]. The problem of the extension of these models arises on a regional scale and the application in other soils. So it is necessary to elaborate new models for other soils and regions.

In arid to tropical regions, data on hydrological soil behaviour are scarce. In this study, predictive equations of soil in situ specific moistures and available water content of arid to tropical regions are proposed. These equations are built from classical pedological properties measured in Senegal, as has been done elsewhere by Dane and Hruska [19] and Valet [63].

2. PRESENTATION OF THE DATA SET

2.1. Studied areas

The studied areas are located from North to South Senegal on about 5 degrees of latitude. The area of Ferkessedougou, which is in the North of the Ivory Coast, has been added (Fig. 1). These areas cover a large range of pedological factors depending on climatic, geologic and geomorphologic condi-

tions. The climate ranges from arid (precipitation lower than 250 mm y^{-1}) to wet tropical (precipitation above 1350 mm y^{-1}). These soils can be classified into poorly-weathered soils, Arenosols (with Dieri as the local name), Acrisols, Cambisol, Ferralsols and azonal soils such as Fluvisols, Regosols and Histosols [9]. This North-South pedological zoning and the climatic gradient are correlated.

2.2. Methodology

The data were compiled from Vachaud et al. [57] and from unpublished reports of the CIRAD (Centre International de Recherche en Agronomie et Développement) [18, 60], of ISRA (Institut Sénégalais de la Recherche Agronomique) [46, 61, 62] and from the ORSTOM (Office de la Recherche Scientifique et Technique de l'Outre Mer, now called Institut de Recherche et Développement) [78]. The classical methods of analysis were applied to 103 soils. Samples were taken to 2 m depth at 0.1 m deep increments at each site. A total of 1387 layers were analysed.

In the field, the soil bulk density (g cm^{-3}) was measured by two methods: (1) by a densitometer, and (2) by a gammaden-simeter. Both methods have a similar error lower than 0.5%. Moisture retention was obtained by the Müntz method (immersion of two ring basins of 1 and 5 m^2) [41]. The moisture content was measured by a neutron probe and hand auger.

Classical pedological analysis was done by the CIRAD, the ORSTOM and the ISRA-Bamby laboratories. The fraction of organic carbon was measured by the Walkley and Black [70] method. The concentration of exchangeable Na^+ was estimated by the method of cobalthiexamine chlorur. The pH was measured by a glass electrode in a 1/2.5 soil/water ratio [39]. The clay and silt content was determined by the "pipette Robinson" method after dispersal with sodium hexametaphosphate [21].

Basic and elementary statistics and Principal Component Analysis were performed to find multivariate structure-property relationships. Principal Component Analysis was applied to the complete data set. This method is useful for discriminating the main variables and the correlation between variables in a given data set. Axes are defined by principal physical and hydric components. Data are grouped along these axes. Principal Component Analysis is widely used for finding the underlying dominant features in a matrix with data reduction [25]. Principal Component Analysis consists of finding the eigenvalues and eigenvectors (termed principal components) in the matrix between individual observations. Principal components are linear combinations of the observed variables and are orthogonal (uncorrelated) to each other. The principal component that corresponds to the largest eigenvalues explains most of the variation within data. The sign and magnitude of the coefficient contained in a principal component reflect the relationships between observed variables. They assess the variance of the data in function of the three main axes to maximise the explained variance of the data. Then, the multivariate functions were found by elaboration of multiple predictive equations for 1387 layers of the 103 soils. The set of equations introduces step by step all pedological and hydric variables whose determination coefficient is higher than 1%. This was applied to vertical soil grouping (between 0.2–0.5, 0.5–1, 1–1.5 and 1.5–2 m), to each soil type and to epipedons

Table I. Mean, median, standard deviation and variation coefficient of 1387 layers (103 soils).

Variables	Mean	SD%	CV%	Median	Student test	Distribution
Clay + silt	22.4	11.0	49.3	22.3	75.69	N
OC%	2.45	1.05	42.9	2.46	86.62	N
pH	6.06	0.49	8.02	6.0	465.3	N
Na ⁺	0.29	0.11	48.7	0.27	76.06	LN
BD	1.49	0.06	4.17	1.48	895.3	N
MMC	7.82	5.1	65.0	7.5	57.5	LN
FC	19.0	5.31	28.6	19.1	138.6	N
AWC	11.2	3.4	30.17	11.2	122.5	N

OC%: organic carbon; pH: acidity/alkalinity; exch. Na⁺: BD: bulk density; MMC: minimum moisture content; FC: field capacity; AWC: available water content; distribution: N: normal; LN: log-normal; SD: standard deviation.

(0.1–0.2 m). The linear relationship between predicted and measured water contents was elaborated to estimate the quality of correlation. Finally, we used the Snedecor F test on quality of slopes and intercepts to test the validity of the functions.

3. RESULTS AND DISCUSSION

3.1. Variability of soil properties

The analysis of the statistical moments of each variable is shown in Table I. The coefficients of variation (CV_s) range between 4.2 and 65%. All variables, except minimum moisture content and Na⁺ concentration, were found to be normally distributed. The database is large enough to be statistically representative of the soil properties' distribution. The values of the statistical moments show that the population is quite homogeneous. This low variability has also been observed for a large range of the soils in the USA [50], in France [29] and in Niger [63].

The correlation matrix shows a strong correlation between the textural variables and the moisture contents. The coefficient of correlation is 0.84 between texture and minimum moisture content and 0.82 for the field capacity (Tab. II). These two properties are strongly correlated ($R^2 = 0.80$). The available water content is not correlated with any of the variables.

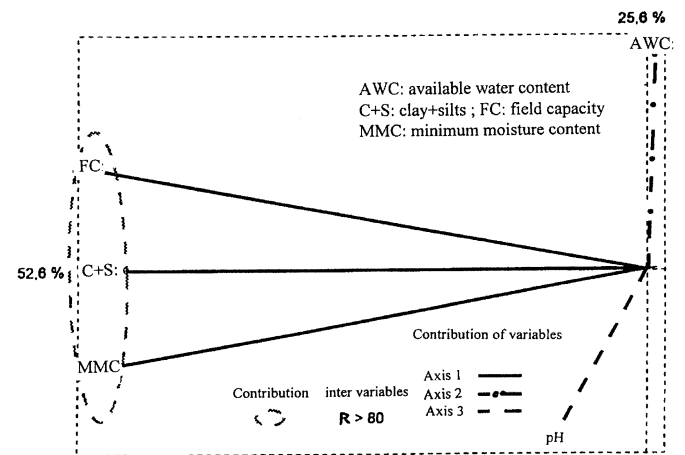
3.2. Identification and classification of the significant variables

Principal component analysis underlines relationships between structures and hydraulic properties. It indicates a correlation between measured variables such as clay + silt content and pH on the one hand, and the five studied pedological variables and minimum moisture content, field capacity and available water content of in situ hydraulic properties on the other hand. The first three principal components (PCs) explain 96.7% of the total inertia of the data. The remaining variation in the

Table II. Correlation matrix of pedological and hydrological properties of 1387 layers (103 soil profiles).

	Layers	Cl+S	BD	OC%	Na ⁺	pH	MMC	FC	AWC
Layers	1								
Clay + silt	0.33	1							
BD	0.09	-0.29	1						
OC%	-0.48	0.50	-0.12	1					
Na ⁺	-0.45	0.14	-0.18	0.38	1				
pH	-0.35	0.10	0.095	-0.29	-0.11	1			
MMC	0.54	0.84	-0.22	-0.14	-0.13	0.12	1		
FC	0.20	0.82	-0.28	0.11	0.14	0.38	0.80	1	
AWC	-0.42	0.24	-0.12	0.38	0.45	-0.12	-0.26	0.38	1

Cl + S: clay + silt; OC%: organic carbon; pH: acidity/alkalinity; exch. Na⁺: BD: bulk density; MMC: minimum moisture content; FC: field capacity; AWC: available water content.

**Figure 2.** Plot of the first principal component (horizontal axis) versus the second principal component (vertical axis) from analysis of hydrological and physico-chemical soil variables.

data could be due to noise, to measurement and sampling precision or to untreated structural variables such as clay type and pore radius. The first PC contributes to 52.5% and the second to 25.6%. The first two PCs were only conserved for the graphical representation (Fig. 2). Coefficients of the first PC reveal no opposition between texture, minimum moisture content and field capacity. This observation is in agreement with those given for different soils using moisture retention at different matrix potentials. Figure 2 shows that the first PC is better explained by texture than field capacity and minimum moisture content, PC2 by available water content and PC3 by pH. So physically, the first principal component can be interpreted as an "axis of textural property and water retention curve" where soils exhibit an increasing amount of these three properties. This analysis shows the similarity of hydrological behaviour for the different soil types from arid to tropical zones.

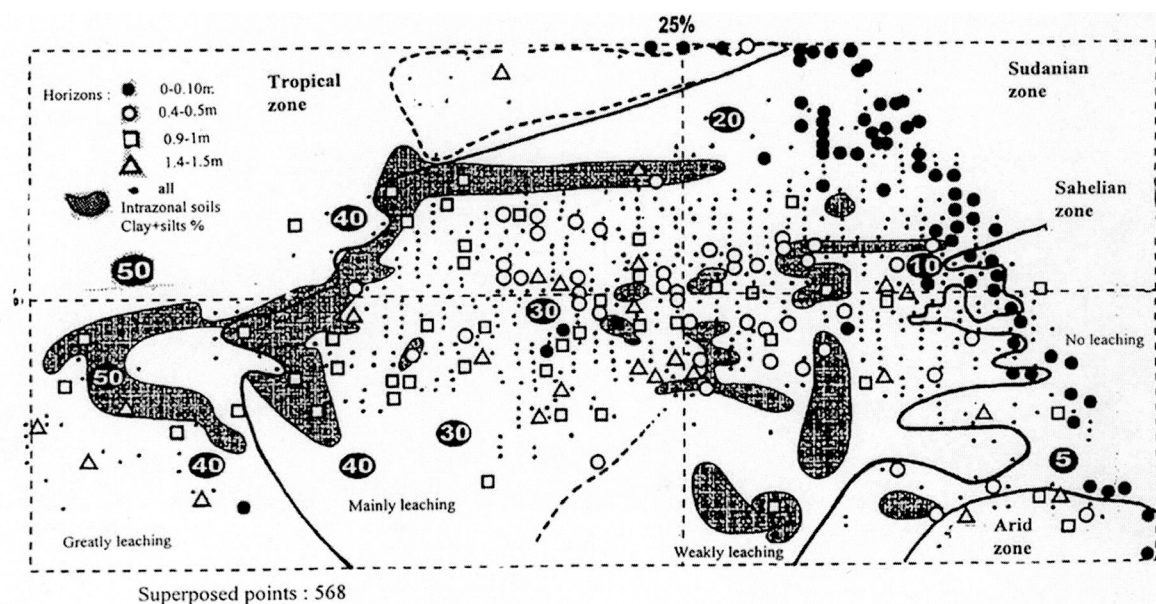


Figure 3. Plot of the first principal component (horizontal axis) versus the second principal component (vertical axis) from analysis of 1387 layers (103 soil profiles).

The exchangeable Na^+ which discriminates the soils of the Niger valley [63] has no importance in our case due to its low concentration. Plotting the scores of the first PC versus the second PC computed for the 1387 layers shows that the soils are grouped by soil families from Ferralsols to Arenosols according to a gradient of clay content from 52.5% to 10% along the “textural axis” (Fig. 3). The transition from one family to the other is progressive. The first axis is thus the pedological axis, which reflects the decrease in climatic alteration of the bedrock as climatic zonation. Plateau soils, and linear and footslope soils are distributed inside soil families according to their clay + silt content. PCA provides some visualisation of the difference in the physical and hydrological behaviour between epipedons (0–0.1 m) and other layers. The eroded epipedons which lose clay + silt are localised close to the positive pole of data except when the soil contains more clay. These soils have undergone a granulometric sorting due to wind, water and slope effects, and anthropic practices [14, 37, 55]. The specific moisture content increases with the amount in clay + silt along the first axis. Available water content increases along the second axis until 20.6 mm. Along the third axis the pH is 7.5 for Cambisol soils and decreases to 5.65 for the leached Ferrallitic soils. This axis can be called the “lixiviation axis”. This axis position correlated with the soil’s geographical zonation reflects the increase in the genesis of clay, iron liberation and cation lixiviation from north to south due to the weathering actions. This has also been observed in India with the same climate gradient and a similar increase in climatic drainage, which explains the pH decrease [11]. The pedogenesis effect is more sensitive in tropical than in arid climates due to rain and temperature enhancement.

These five variables (clay + silt, pH, minimum moisture content or field capacity and available water content) are suf-

ficient to classify soil types according to their physical and hydrological properties.

3.3. Discriminant regression equations

Multiple linear stepwise regression was developed to predict soil in-situ moisture contents for all the soils using independent variables. Three models were studied: (1) for all the layers; (2) for the layers grouped into epipedons 0.2 m thick and layers 0.5 m thick, and (3) for each soil type.

3.3.1. Equation for all the layers

The coefficients of determination for 1387 layers were assessed to determine if the measured values contributed significantly to the prediction of the soil hydraulic properties for all grouped soils (Tab. III). The coefficients of determination (R^2) are 0.74 for minimum moisture content, 0.70 for field capacity and 0.26 for available water content (Tab. IIIA, B1 and C). If field minimum moisture content values are taken into account in the equation of field capacity, as done by Rawls et al. [47], the determination coefficient increases to 0.78 (Tab. IIIB2). However, this variable is seldom included in databases. These results confirm the major effects of clay plus silt with high specific surface on water retention. The predictive results based on texture only show a good reliable prediction, as Baver [8] and Valet [63] have demonstrated for a wide range of soils.

3.3.2. Epipedon and layer grouping

The correlation between minimum moisture content, field capacity and available water content and pedological properties is very low for the epipedon (0–0.1 and 0.1–0.2 m) (Tabs. IVA and VA). From 0 to 0.20 m the soil carbon effect decreases

Table III. Intercept, slope coefficient, sd, R^2_s , mean and probability test of pedological variables in equations for predicting specific moisture content and available water content (mm) of 103 soils (0–2 m). Each column represents the best equation for the lowest number of independent variable sets.

Moisture content	A- Minimum moisture content	B1- Field capacity	B2- Field capacity with Minimum moisture content	C- Available water content
Clay + silt		0.672	0.672	
Clay + silt ²	0.71		0.011	
Exch. Na ⁺	0.013	0.0236	0.043	0.189
OC%	0.016		0.011	0.058
Minimum moisture content	-	-	0.037	
Intercept	3.55	8.46	5.66	6.73
F (Snedecor)	1337.1*	1578.1*	952.1*	238.9
σ	2.583	2.94	2.53	2.90
R²	0.74	0.70	0.78	0.26
Mean ⁽¹⁾	7.5		19.13	11.2
σ	5.10		5.3	3.4

**, * indicate significance at the 0.01 and 0.05 probability levels, respectively. ⁽¹⁾ Field measured values.

when clay + silt increases (from 0% to 20 to 37%) (Tabs. IVA and VA). This can be due to the effects of various conditions such as farming systems, the existence of savannah or farmer practices. Valet [63] has demonstrated for African soils that the difference in minimum moisture content measured in the field and in the laboratory increases according to the type of plants which grow on the given soils, and to the texture. Chiselling and ploughing induce crusting growth and organic and mineral particle sorting, transport by runoff and sequestration by runoff for Cambisol, Ferralsol [64] and Oxisol [65]. Bauer and Black [7] in Nigeria proved that stubble-mulch tillage increases organic matter and water retention. At the surface, the role of sand (probably coarse and very coarse sand), which significantly reduces water retention, should be taken into account. For sandy soil, Meng et al. [42] showed the water retention reduction due to fine to very coarse sand. Aina and Periaswamy [1] demonstrated for Nigerian soils that water retention is highly correlated to sand content.

The layers located from 0.2 to 0.5 m have better coefficients of determination than the surface layers with $R^2 = 0.50$ and 0.55 for minimum moisture content and field capacity when bulk density is less than 1.54 and $R^2 = 0.97$ and 0.70 when bulk density is more than 1.54 (Tabs. IVB and VB). The increase in the determination coefficient could be explained by the decrease in the sand effect with depth. Aina and Periaswamy [1] demonstrated that the role of sand decreases significantly until 0.42 m depth and Meng et al. [42] suggested that the increase in clay content could increase water retention at a specific moisture content in sandy soils. This could explain the increasing

Table IV. Intercept, slope coefficient, sd, R^2_s , mean and probability test of pedological variables in equations for predicting minimum moisture content (mm) of layers (0–0.2 m) for different sets (103 soils). Each column represents the best equation for the lowest number of independent variable sets.

Layers m	A		B		C	D	E
	0–0.1	0.1–0.2	0.2–0.5		0.5–1	1–1.5	1.5–2
Bulk density			<1.54	>1.54			
Clay + silt	0.017	0.195	0.44	0.038	0.731		
Clay + silt ²			0.012	0.884		0.77	0.74
Clay + silt ³	0.13	0.022	0.014	0.014	0.011		0.034
Bulk density	0.04	0.084	0.011				0.041
Exch. Na ⁺	0.021	0.029			0.017	0.016	
pH	0.02	0.043	0.028	0.052			
OC%		0.19	0.019	0.003		0.028	
Intercept	-16.63	-22.92	-19.5	4.03	1.65	1.33	70.8
F (Snedecor)	11.54	11.53	53.7**	272.1**	514.7**	335.7**	203.1**
σ	1.24	1.55	1.77	0.88	2.00	2.31	2.3
R²	0.42	0.37	0.50	0.97	0.76	0.80	0.81
Mean ⁽¹⁾	0.985	2.69	5.43	4.86	9.69	10.49	11.1
σ	1.57	1.91	2.49	4.44	4.07	5.32	5.3
Number	103	103	268	41	495	234	143

**, * indicate significance at the 0.01 and 0.05 probability levels, respectively. ⁽¹⁾ Field measured values.

Table V. Intercept, slope coefficient, sd, R^2_s , mean and probability test of pedological variables in equations for predicting field capacity (mm) of layers (0–0.2 m) for different sets (103 soils). Each column represents the best equation for the lowest number of independent variable sets.

Layers m	A		B		C	D	E
	0–0.1	0.1–0.2	0.2–0.5	0.5–1	1–1.50	1.50–2	
Bulk density			<1.54	>1.54			
Clay + silt	0.299	0.37	0.438	0.632	0.67	0.749	0.73
Clay + silt ²	0.18	0.11	0.116				
Clay + silt ³		0.010	0.046				
Bulk density							0.058
Exch. Na ⁺	0.017			0.034	0.013	0.048	
pH							0.012
OC%	0.023		0.025	0.013	0.019		
Intercept	–1.54	3.69	3.76	5.09	7.96	8.83	82.0
F (Snedecor)	24.0*	31.85*	164.2**	7335**	422.9**	273.9**	188.3**
S	3.15	2.87	2.58	3.41	2.74	2.70	2.01
R²	0.52	0.49	0.55	0.70	0.72	0.78	0.85
Mean ⁽¹⁾	16.0	15.62	17.47	15.61	20.6	20.33	19.81
σ	4.60	3.97	3.84	6.17	5.17	5.73	5.03
Number	103	103	268	97	495	235	143

**, * indicate significance at the 0.01 and 0.05 probability levels, respectively. ⁽¹⁾ Field measured values.

effect of clay + silt below 0.5 m. The best agreement was obtained between pedological variables and specific moisture content (minimum moisture content and field capacity) except for available water content R^2_s . Determination coefficients increase from 0.72 to 0.85 (Tabs. IV and V, C, D and E). However, available water content values can be statistically obtained by grouping the layers according to five texture classes from bulk density <1.54 to bulk density >1.54 (Tab. VI). The coefficients of variations are generally less than 20/25% except for the sandy epipedon (0–0.2 m) where it reaches 63% due to erosion and farmer practice effects. In the sandy epipedon, clay + silt plays a less effective part than organic carbon, negatively correlated to bulk density. The soil organic carbon with mud and vetch/oat mixture manure [26] improves significantly both the carbon sequestration and the available water content. Bruand et al. [12] showed this effect too for French soils. The available water content increased by two times when bulk density decreased from 1.8 to 1.2. Bauer and Black [7] point out that in Nigerian sandy and moderately fine surface epipedons, the organic carbon concentration decreases with bulk density increase. This effect accounts for about 75% of the variation of both minimum moisture content and field capacity. The available water content values increase with clays + silts from 0 to 1 m depth and then decrease to 2 m at each texture class. The bad correlation between available water content and clay + silt is perhaps due to trapped soil air and fine capillarity structures which hinder water circulation [63].

Table VI. Mean, CV and 25, 50 and 75% quartiles of available water content deducted from measured specific moisture content according to textural classes (available water content = field capacity–minimum moisture content) (103 soils). CV: coefficient of variation.

Layers m	Probability	Clays + silts				
		<6%	6–18%	18–25%	25–35%	>35%
0–0.2	Mean	6.7	14.4	17.2	15.7	13.7
	CV%	63.47	23.26	20.49	13.46	22.60
	Q25%	2.8	12.2	15.2	12.3	11.0
	Q50%	6.0	14.7	16.6	15.7	11.2
	Q75%	7.8	16.8	18.8	17.1	12.0
0.2–0.5	Mean	5.0	11.4	12.3	13.1	11.5
	CV%	20.49	24.5	13.3	13.35	22.66
	Q25%	3.8	9.8	11.0	11.4	9.7
	Q50%	5.2	11.5	12.0	13.0	11.6
	Q75%	5.2	13.1	13.3	14.6	12.8
0.5–1	Mean	5.6	10.2	11.6	11.8	10.6
	CV%	18.59	31.9	20.47	20.75	19.98
	Q25%	5.7	7.9	10.4	10.2	9.2
	Q50%	5.9	10.1	11.5	11.7	10.8
	Q75%	6.0	12.0	13.1	13.3	12.1
1–1.5	Mean	5.3	9.0	10.3	11.0	9.2
	CV%	20.27	19.9	22.44	17.27	27.39
	Q25%	6.0	7.8	8.4	9.5	7.0
	Q50%	6.4	8.4	10.7	11.4	8.5
	Q75%	7.0	10.0	12.1	12.6	11.2
1.5–2	Mean	6.7	7.3	9.7	9.5	7.6
	CV%	23.8	44.76	23.93	27.60	37.74
	Q25%	5.5	7.4	7.7	6.9	5.6
	Q50%	6.4	7.8	9.6	9.5	6.7
	Q75%	6.7	9.4	10.9	11.7	8.0

3.3.3. Taxonomy classification grouping

The prediction of minimum moisture content, field capacity and available water content was done for soils classified according to pedogenetic criteria. For the region of central Senegal and the North of the Ivory Coast, the coefficients of determination are high and of the same magnitude for each variable for Arenosol (Dieri) and Ferralsols. They have the highest R^2 , more than 0.90 for minimum moisture content and field capacity only (Tab. VII). The correlation with available water content is always lower than 0.62, except for Arenosol (Dieri) and Ferralsols ($R^2 > 0.81$). The result for these two soils can be explained in the following way. These two soils exhibit no horizon with a high bulk density value due to the highest degree of alteration for Ferralsol and a homogeneous eolian bedrock for Arenosol. These results show that the main factors of variance of specific moisture and available water content are organic carbon in surface soil and clay + silt under 0.10 m depth. In contrast, continuous and class pedotransfer functions calculated from 4030 layers of 11 European soil classes (HYPRES database) gave limited site-specific information. Indeed, R^2_s of θ_s

Table VII. Intercept, slope coefficient, sd, R^2_s , mean and probability test of pedological variables in equations for predicting minimum moisture content, field capacity and available water content (mm) of two types of soils, Arenosols and Ferralsols (0–2 m). Each column represents the best equation for the lowest number of independent variable sets.

Soils	Arenosol (Dieri)			Ferralsol		
	MMC ⁽¹⁾	FC	AWC	MMC	FC	AWC
Clay + silt				0.883	0.44	
Clay + silt ²	0.15			0.17	0.21	
Clay + silt ³	0.67		0.012			0.037
Bulk density			0.017			0.011
Ech. Na ⁺	0.099	0.06				
pH	0.012	0.79	0.212	0.017		0.02
OC%		0.05	0.791	0.90	0.06	
Intercept	-12.37	-19.6	4.41	-2.12	17.5	7.11
F (Snedecor)	64.6**	82.3*	50.2*	115.8**	190.4**	16.0**
σ	0.35	0.68	0.56	1.79	1.87	1.78
R²	0.93	0.90	0.83	0.93	0.96	0.72
Mean ⁽²⁾	2.11	8.05	5.94	11.09	19.7	8.6
σ	1.03	1.94	1.29	6.42	8.48	3.6
Number		35			30	

⁽¹⁾ MMC: minimum moisture content; FC: field capacity; AWC: available water content.

** , * indicate significance at the 0.01 and 0.05 probability levels, respectively. ⁽²⁾ Field measured values.

(field capacity) were 0.76%, but for van Genuchten parameters R^2_s were about 12 to 54% and K (hydraulic conductivity) equalled 19% [76]. But these authors assert that the results based on these horizon data are sufficient to be used in the derivation of pedotransfer functions and to predict both retention and hydraulic conductivity. Tietje and Tapkenhinrichs [56] have demonstrated that for one Netherland soil class, with 88 soil profiles, prediction of van Genuchten parameters was better and R^2 rose to 42% and 63%. So reasonable adjustments can be made to pedotransfer functions in order to improve the prediction. Considering these uncertainties in the measurements, the overall predictive ability of the given models of pedotransfer functions would need other soil parameters such as pore radius, particle-size distribution and clay type [4, 20]. Valet [63] demonstrated that field values of minimum moisture content and field capacity of a wide range of soils in Niger are more accurate than laboratory values, which gave hydraulic values with CVs of about 4 to 86%. These CV values are better than van Genuchten parameters and functions' CVs. The laboratory or field CVs of minimum moisture content, field capacity and K rise from 100 to 1000% due to using small experimental parcels or core [36, 44, 53].

3.4. Model calibration

The performance of the models can be assessed by a comparison of the predicted with the measured values. The pre-

Table VIII. Validation equations of measured and predicted specific moisture and available water content (1387 layers from 0 to 2 m).

Moisture content	A- Minimum moisture content	B- Field capacity	C- Available water content
Slope	0.74	0.70	0.26
Intercept	2.0	5.79	8.21
F (Snedecor)	4017.1**	3159.3*	687.1
σ	2.21	2.46	1.26
R²	0.74	0.695	0.332
Mean ⁽¹⁾	7.81	18.97	11.16
σ	4.38	4.44	1.54

** , * indicate significance at the 0.01 and 0.05 probability levels, respectively. ⁽¹⁾ Field measured values.

dicted values of minimum moisture content and field capacity show a good agreement with the measured values at the 0.05 probability level significance for all soils (Tab. VIII) and for grouped layers except between 0.2 and 0.5 m depth with bulk density <1.54 (Tab. IX). When the soils are grouped into two taxonomic classes (Arenosol and Ferralsol), good correlations are obtained between minimum moisture content, field capacity and available water content and pedological properties at the same probability level (Tab. X). The coefficient of determination values of these regressions vary from 0.695 (1387 layers) to 0.90 (35 layers). The predicted standard deviation values (σ), which are two times less than the measured values, underline the accuracy of these equations.

In this study, two to four variables were retained for African soil predictive equations. This number of variables is lower than the variables used by many authors to predict moisture contents on heterogeneous soils [4, 13, 63, 77]. The results indicate that the moisture prediction is acceptable on a regional scale larger than 1:500000. In contrast, the pedotransfer functions calculated from 4030 layers of eleven European soil databases (HYPRES) indicate that they can be used to derive soil hydraulic function for large areas of land when working on a scale smaller than 1:10000000 [76]. However, concerning these results, imprecision can arise at epipedons if the equations are not locally adjusted. The spatial variability of texture is high on large scales and can vary according to the soils and the geographical position [42]. This variability can be increased by local runoff or runoff effects and landscape position [2, 64]. However, this study opens possibilities for the use of the pedological database to predict specific moisture contents and available water content on a field to regional scale. These possibilities concern the hydrological behaviour of soils and construction of pedotransfer equations. These functions can be used for the control of water supply of plants, in the risk estimation of environmental risks such as erosion, pollution and drought effect, and agroecological zoning [45, 59].

4. CONCLUSIONS

The study showed the feasibility of accurate discriminant factor identification and the appraisal of minimum moisture

Table IX. Specific moisture and available water content predicted and measured correlation at soil depth (0.2–0.5 m with bulk density <1.54; 0.2–0.5 m with bulk density >1.54; 0.5–1; 1–1.5; 1.5–2 m) (1387 layers from 0 to 2 m of 103 soils).

Predicted hydraulic characteristics	Layers m	A		B	C	D
		0.2–0.5	0.2–0.5	0.5–1	1–1.5	1.5–2
		Bulk density BD < 1.54		BD > 1.54		
Minimum moisture content	Slope	0.54	0.95	0.759	0.804	0.81
	Intercept	2.69	0.18	2.33	2.04	2.14
	F	272.7*	1178.2*	1550.5*	955.55*	618.2*
	σ	1.23	0.78	1.74	2.11	2.05
	R²	0.506	0.968	0.759	0.804	0.806
	Mean ⁽¹⁾	5.41	4.81	9.69	10.43	11.0
Field capacity	σ	1.75	4.30	3.54	4.76	4.7
	Slope	0.55	0.876	0.693	0.751	0.836
	Intercept	7.79	1.83	6.35	5.12	3.21
	F	329.6*	272.9*	1112.1*	698.55*	769.8*
	σ	1.91	2.31	2.26	2.39	1.83
	R²	0.553	0.875	0.723	0.750	0.837
Available water content (deducted from noticeable moistures)	Mean ⁽¹⁾	17.46	14.7	20.72	20.52	19.79
	σ	2.86	6.47	4.08	4.76	4.6
	Slope	0.36	0.62	0.137	0.28	0.239
	Intercept	7.68	3.75	9.51	7.25	6.50
	F	152.8	60.73	64.78	74.47	36.91
	σ	1.32	1.86	1.01	1.27	1.36
	R²	0.365	0.609	0.116	0.234	0.202
	Mean ⁽¹⁾	12.06	9.85	11.06	10.09	8.55
	σ	1.66	2.94	1.08	1.45	1.52
	Number	268	41	495	235	148

⁽¹⁾ Field measured values; **, * indicate significance at the 0.01 and 0.05 probability levels, respectively.

content, field capacity and available water content on the field to the regional scale using previously calibrated deterministic models that take into account the variation of a few pedological properties such as clay and silt content, organic carbon, bulk density, extractable Na⁺ and pH. Continuous hydraulic multivariate equations according to soil taxonomic classification are accurate for only two soil types grouped by sandy and clayey homogenous soils (Arenosols and Ferralsols). For all soils, the class multivariate equations were used to generate minimum moisture content, field capacity and available water content. The predicted minimum moisture content, field capacity and available water content matched the measured values with an acceptable accuracy by grouping all samples and layers. The available water content values were calculated from measured or predicted specific moisture content at different probability levels, grouped by texture and horizon. Spatial extrapolation is possible because of the wide pedological differentiation of the soils in a large climatic area. Geographic ori-

Table X. Specific moisture and available water content predicted and measured correlation of two homogenous soils, Arenosols and Ferralsols (0–2 m).

Predicted hydraulic characteristics	Soil types	ARENOSOL	FERRALSOL
		(Dieri)	
Minimum moisture content	Slope	0.9	0.93
	Intercept	0.21	0.78
	F	284.4*	374.4*
	σ	0.32	1.66
	R²	0.896	0.930
	Mean ⁽¹⁾	2.10	11.10
Field capacity	σ	0.98	6.20
	Slope	0.89	0.95
	Intercept	0.897	0.90
	F	262.9*	615.2*
	σ	0.61	1.75
	R²	0.888	0.956
Available water content (deducted from specific moistures)	Mean ⁽¹⁾	8.05	19.68
	σ	1.83	8.26
	Slope	0.829	1.21
	Intercept	1.02	0.546
	F	160.0*	70.28*
	σ	0.49	2.81
	R²	0.829	0.715
	Mean ⁽¹⁾	5.95	10.98
	σ	1.17	5.17
	Number	35	30

⁽¹⁾ Field measured values. **, * indicate significance at the 0.01 and 0.05 probability levels, respectively.

gin did not seem to be a discriminant factor because the correlation between the hydrologic properties (minimum moisture content, field capacity and available water content) and the pedological properties (clay+silt) was the same at each latitude. The approach developed in this study can be applied to any other weakly-pedologically differentiated soil. It is clear that these functions should not be applied to organic soils (OC > 5%), to sodic/alkali soils or to soils with very small bulk density (bulk density <1.1). Provided the above restrictions are respected, these equations should be sufficiently accurate in a functional sense to be used in modelling specific soil water content on field, regional and national scales. However, knowledge of spatial variability is required. These discriminant equations need to be tested for other African soils of different countries. A major obstacle to the wider application of these models is the lack of easily accessible and representative in situ or sieved soil hydraulic properties. Further research may be initiated to elaborate a pedological database which contains hydrologic properties, such as was done for different soils in two continents

(European HYPRES and US NATSGO databases). This database could then be used to derive a set of predictive equations of African soil field hydraulic properties.

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