Influence Of Multimodality Soil On Their Hydrodynamic Behavior: Case Of Soils Of The Unsaturated Zone Of Allada Plateau

Soclo W. P., Igue A. M., Mwenge Kahinda J., Boukari M., Agbossou K. E

Summary: The derivative function *f* of the cumulative particle-size distribution curve of certain soils has two (02) local maxima (two modes) in weight percentage for the particle-size ranges of sand and clay (one in the range of clays and the other in the range of sands). Are referred to as bimodal soils, soils with a particle-size distribution function F having two (02) inflection points, the first in the range of clays and the second in the range of sands. Such soils are already part of multiporous soils that have multimodal behavior. Haverkamp and Reggiani (2002), have established for soils whose particle-size have a monomodal behavior a shape similarity between the cumulative particle-size distribution curve and the water retention curve h (θ). A soil whose particle-size distribution has two modes (bimodal distribution of soil particle-size) usually poses enormous difficulties to soil physicists. Indeed, this character, when already achieves two in soil (bimodal soils), results in nine (09) unknown for the same water retention curve model with mathematical-physical basic, making it very difficult if not impossible to determine hydrodynamic parameters. So, monomadal soils facilitate the study of water transfers in the soil. The hydrodynamic models are available for these types of soils and involve more than 4 unknowns. And with the initial and boundary conditions, they allow the indeterminations up without difficulty. Now the work of Tomasella and Hodnett (1998; 2000; 2002) appears to link the modal character of the soil to climate zones to which they belong. They have come to say that the monomodal soils are specific to temperate regions and bimodal soils are specific to tropical or subtropical regions. The objective of the study is to test the hypothesis of bimodality for the case of soils of the unsaturated zone of Allada plateau located in the intertropical zone and to confirm the applicability of Brooks and Corey (1964) and van Genuchten (1980) models considered in this study and which are only valid on monomodal soils. The analysis according to USDA classification of the main soils of the study area namely haplic Acrisols, umbric Fluvisols and ferric Acrisols and their representation according to the soil textural triangle with an associated bimodal zone revealed 66 % of monomodal soils and 34% of bimodal soils in the study area. The comparative analysis of results with those of similar studies of the european databases and the Maheshwaram watershed in South India (subtropical) and the Ouémé watershed (subhumid) in Benin (De Condappa, 2006; Giertz and Diekkrüger, 2003), has validated mainly monomodal soils, especially within the B horizons. Which invalidates the hypothesis of Tomasella and Hodnett for this zone and confirms the validity of hydrodynamic models mentioned in the context of this study.

Keywords: Soils of the unsaturated zone in the tropics, modality, parameters and hydrodynamic model, USDA textural triangle, Benin

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Introduction

The flow in the isotropic porous medium of the unsaturated zone is considerably influenced by multimodal behavior of soils. The multimodal character due to multiporosity of soils that are generally heterogeneous porous systems had long baffled scientists (eg., Beven and Germann, 1982; Germann and Beven, 1985; Edwards et *al*., 1988; Gerke and van Genuchten, 1993; Durner and Zurmühl, 1996). Thus, a multimodal soil is a soil whose particle-size distribution already has two (02) modes (bimodal soil). But generally and specifically in this study, it is a mixture of unimodal and bimodal character dominated by a character observed in soils because of their heterogeneity. Indeed, the bimodal character greatly affects the hydrodynamic behavior of soils (De Condappa, 2005). The multiporous systems like bimodal soils are generally associated with structural effects only, without considering the soil texture effects (eg., Nimmo, 1997). In their review, Simunek and *al*. (2003) proposed a multiporosity approach to model the heterogeneous soil, but the soil texture highly correlated with soil bimodality was not considered. Nimmo (1997), meanwhile, has divided the total porosity of the soil in two components, one relating to the soil texture (eg, distribution of the particle-size), and the other to the soil structure (eg , macropores). Several studies in literature (eg., Fiès, 1971; Christian and Bisdom, 1983; Fiès and Bruand, 1998), however, show that the texture of a soil, in addition to structural effects, can be a cause of functional hydrodynamic multimodality. The concept of multiporosity therefore has consequences on the hydrodynamic properties of soils and the Laplace capillary theory involves a multimodal retention curve, thus taking into account the texture (De Condappa et *al*., 2006). This means that the form of concept similarity between the cumulative size distribution curve and the water retention curve (Haverkamp and Reggiani, 2002), validated for monomodal soil implies that bimodal soils should theoretically present bimodal hydrodynamic properties. While most hydrodynamic soil models are monomodal, and therefore inadequate to describe the hydrodynamic behavior of bimodal soils in tropical and subtropical regions. Among these estimation parameters hydrodynamic models are those of Brooks and Corey (1964), van Genuchten (1980), Ross and Smettem (1993) and Durner (1994) etc. Moreover, it seems to be a correlation between the climatic zone and soil modality. Tomasella and Hodnett (1998; 2000 and 2002) have come to say that the monomodal soils are typical of temperate areas and bimodal soils are typical of tropical and

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subtropical regions. The work of De Condappa (2006) from data on the Maheswaram watershed in South India (subtropical), and Ouémé in Benin (subhumid region) showed the magnitude of the phenomenon of bimodalization at the genesis of soils in tropical and subtropical regions, a phenomenon not facilitating or making it impossible to estimate the hydrodynamic parameters. Similarly, the comparative analysis of various soil databases published in literature (Wösten et *al*., 2001) with the soils of Allada plateau helped identify the proportions of monomodal and bimodal soils. These databases, four in number (04), are the soil databases of UNSODA, GRIZZLY, the information system on soil of Netherlands and of IGBP-DIS. The purpose of this study is to check for Allada plateau in intertropical zone the Tomasella and Hodnett hypothesis and results of bimodal soils which have led studies in watersheds mentioned above in the same climate zone. The non-verification of the hypothesis and results of other studies supposes the validation of monomodal behavior of all the soils of the study area, and therefore the validity of the models of Brooks and Corey (1964) and van Genuchten (1980) used to determine the hydrodynamic parameters and modeling of flow in the unsaturated zone of Allada plateau.

Materials and Methods

-Analysis as classified by the USDA and representation by the textural triangle

To compare the soil textures of different sites, the size analysis results were shown in the USDA textural triangle which defines different soil texture classes (Figure 1).

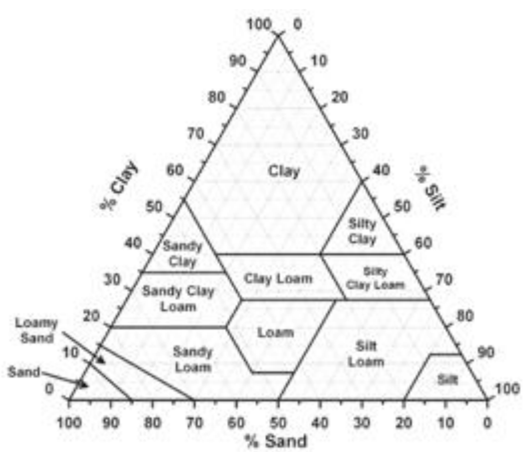


Figure 1: *Triangle textural USDA (Source: USDA, 1960)*

A soil sample of a given test site is situated in this textural triangle as sand and clay percentages of the soil. USDA classification adopted in this work, does not take into account the mass of gravel in the soil, meaning

% sable$_z$ + % limon$_z$ + % argile$_z$ = 100% [I.1]

Where % sand, % silt and % clay, respectively are mass percentages of sand, silt and clay at depth z. The textural triangle for all soils collected on surface and at depth is in Figure 6. The statistics (average, standard deviation and coefficient of variation) in depth of the results of particle size analysis has been done to analyze the variability in depth clay, sand and silt fractions of the soil samples.

- Determination of soil modality of the unsaturated zone

The concept of modality requires first, introducing the derivative of the function F defined according to the formula:

$$f(\bar{d}) = \frac{dF(\bar{d})}{d(\bar{d})}$$

This function f is a frequency distribution: it specifies the frequency of occurrence of the particle diameters with F the experimental particle-size curve.A soil is said bimodal when the following condition is satisfied between the percentages of clay, sand and silt:

$$\begin{cases} \%\ \text{sand} > \%\ \text{silt} \\ \%\ \text{clay} > \%\ \text{silt} \end{cases} \qquad [I.2]$$

For this soil, the values of f (d) in the ranges of clay and sand are larger than those in the range of silt. The curve is then shaped "camel bumps ", as illustrated in Figure 2: the curve admits two local maxima, one in the range of clays and another in that of sands, f taking relatively low values in the range of silts. This results on the curve F in a relatively high growth and the presence of the first inflection point in the clays, a relatively low growth in the silts and again a significant growth and a second inflection point in the sands. **Such soil is said bimodal.**

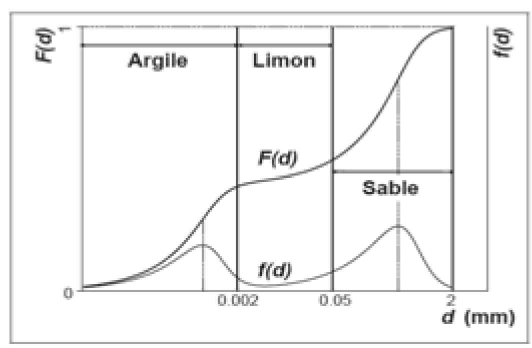


Figure 2: *Shapes of F and f curves for a bimodal soil (logarithmic scales for abscissa)*

The area of these bimodal soils, defined as [I.2] is the hatched area in the USDA textural triangle (Figure 3). It is limited by the line segment [A, G], where % sand =% silt, and the segment [G, S], where % clay =% silt, where G is the point where % sand =% silt =% clay = 100/3.

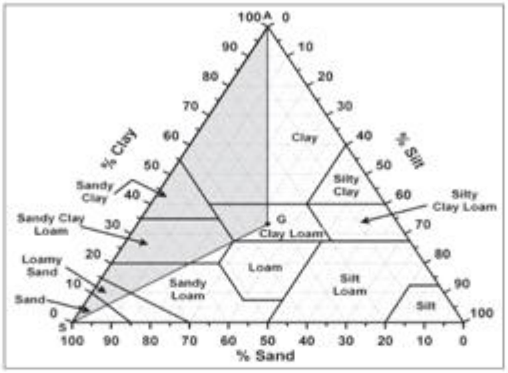


Figure 3: *Bimodal soil zone of USDA textural triangle satisfying condition [I.2] (De Condappa, 2005)*

Bimodal subfield of Figure 4 defined by [I.3] is included in the bimodal areas of Figure 3. As the large area, it can be used because of its more restrictive character (De Condappa, 2005).

$$\begin{cases} 20\% \leq \%\ \text{sand} \leq 80\% \\ 0\% \leq \%\ \text{silt} \leq 20\% \\ 20\% \leq \%\ \text{clay} \leq 80\% \end{cases} \qquad [I.3]$$

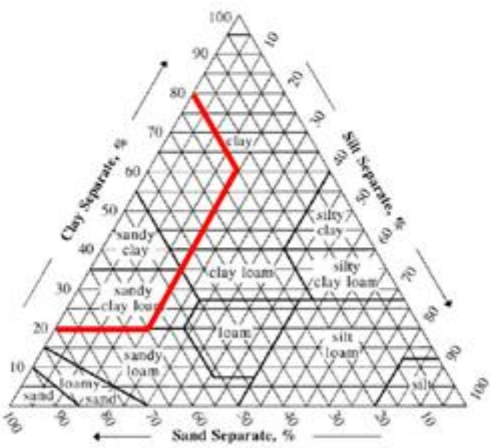


Figure 4: *Bimodal sub-defined area [I.3] (red Limits)*

The plateau of Allada

The plateau of Allada is located in South Benin, Guinean region (tropical) between longitudes 1.5 ° E and 2.3 ° E and 6.2 ° N latitude and 7 ° N. It is part of the coastal sedimentary basin of the country (BSC). Its area is about 3000 km2, or 2.6% of the national territory. The tropical climate is influenced by the double passage of the intertropical convergence zone (Sultan and Janicot, 2003). It is characterized by two rainy seasons of unequal duration: the big rainy season extends from March to July and the small rainy season is from September to November. These two rainy seasons are interspersed with a short dry season in August and a large dry season between December and February. The average annual rainfall is 1100 mm between 1951 and 2010; the average daily temperature varies between 25 ° C and 29 ° C (ALLE, 2014). The Allada plateau is almost flat topography, generally less than 3%. The soils occupying the plateau of Allada are lateritic soils called ''terre de barre''. The geological origin of ''terre de barre'' is strictly related to the presence of a particular loose sandy clay material, the Continental Terminal (Slansky, 1959). Three (03) soil classes are found to be most common on the plateau of Allada according to the classification system by FAO (FAO / UNESCO, 1974; FAO, 1990): (i) Haplic Acrisols, predominant soils of the plateau of Allada with simple and normal horizon sequences resulting from autochthonous pedogenesis on a sandy clay loose material, the Continental Terminal, (ii) umbric Fluvisols, allochthonous soils resulting from cycles of alluvial or colluvial deposits, and (iii) ferric Acrisols, uncommon soils whose lower part results from the autochthonous pedogenesis on cretaceous sandstone; the upper part resulting from the allochthonous pedogenesis on the Continental Terminal has characteristics of disturbed soil with beds of gravel or pebbles (Segalen, 1995). The soil profiles in the plateau of Allada are ABC classification, the C horizon is visible more than 2 m on the plateau of Allada.

Results

-Validation of monomodal behavior of soils in the unsaturated zone of the plateau of Allada

The validation of monomodal behavior of soils of the unsaturated zone of Allada plateau was made from the USDA soil texture triangle associated with bimodal areas. Bimodal area of the textural triangle is defined by De Condappa and Haverkamp (2005). De Condappa showed, from this tool and experimental data, that the soils of Maheshwaram watershed in South India (subtropical) and the Ouémé watershed in Benin (subhumid) are mostly bimodal soils. Meanwhile, the same exercise done on the data banks of european soils (temperate) as UNSODA, or GRIZZLY Information System on soils of the Netherlands, revealed monomodal soils. This study, by applying the same approach to the soil of the plateau of Allada located in area of tropical climate, found mainly monomodal soils. Indeed, a total of 150 samples of haplic Acrisols, ferric Acrisols and umbric Fluvisols were taken at several locations and depths (0-250cm) in the study area. The analyses were made by dry sieving and the hydrometer method. For each sample, 15 different particle diameters smaller than the diameter D = 2000 microns were determined. Silt and sand percentages were fully determined, the percentage of clay being derived from Eq. [I.1]. An example taken from the B horizon of a haplic Acrisol at 90 cm deep is given in Fig. 5. With a particle-size distribution of 10.9% clay, 20.45% silt, and 66.67% sand, the soil is classified as sandy Loam. Starting at D = 2000 microns, the cumulative curve of particle-size distribution F (D) decreases sharply as D decreases, showing an inflection point in the sand range at a particle diameter for which a local maximum in weight percent is achieved. Afterwards, it decreases gradually without another point in the silts range, showing low silt content. There are only limited data available in the clay range. But, since the clay percentage is low (i.e., 10.9%), the curve F (D) definitely decreases without another slope as D decreases. There is therefore no second inflection point in the clays range. These results clearly show a monomodal behavior of soils.

This characteristic of monomodal soils translated by the presence of a single inflection point in the sand range was observed in the majority of soils in the study area. Indeed, when the 150 soil samples were placed in the textural triangle, statistics revealed that 35.30% of the observations are in the bimodal zone defined by [I.3] (Fig.6.) and 64.70% of the observations are out of the associated bimodal zone. Nearly 65% of the soil, so the majority of soils in the study area has a monomodal behavior.

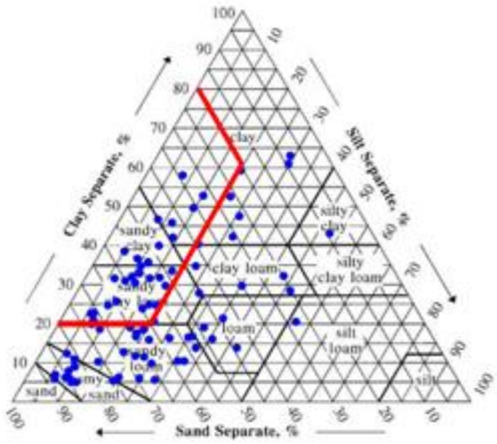


Fig.6. *Bimodal character of the soils of the plateau of Allada (All soils: 150 observations)*

Concerning the particle-size distribution curves of bimodal soils of the study area, they present the same shape as monomodal soils in the domains of sands and silts. But the fundamental differences occurred in the domain of clays. An example taken from horizon A of a ferric Acrisol at 20 cm depth gives a particle-size distribution of 32.5% clay, 10.35% silt, and 57.10% sand. This soil is classified Sandy Clay Loam. As in the case of the monomodal soils, the cumulative particle-size distribution curve F(D) beginning at D = 2000 microns, abruptly decreases as D decreases, showing an inflection point in the sand range at a particle diameter for which a local maximum in weight percent is reached. Afterwards, it decreases gradually without another point in the silts range, showing low silt content. But, since the clay percentage is high (i.e., 32.5%), the curve F (D) can certainly decrease steeply as D decreases, with a second inflection point in the clays range. These results clearly show a bimodal behavior of soils. For the three cases of soil, very few data points are available in the clays range. These results therefore recommend an extension of the particle size analysis for different types of soil (Haplic Acrisols, ferric Acrisols and umbric Fluvisols) which include the clays rang (D <2 microns).

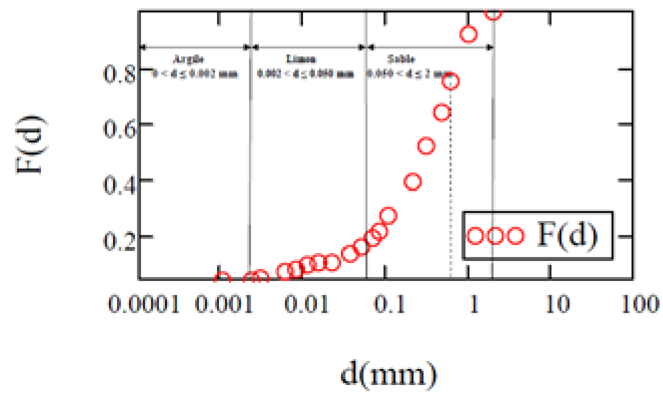
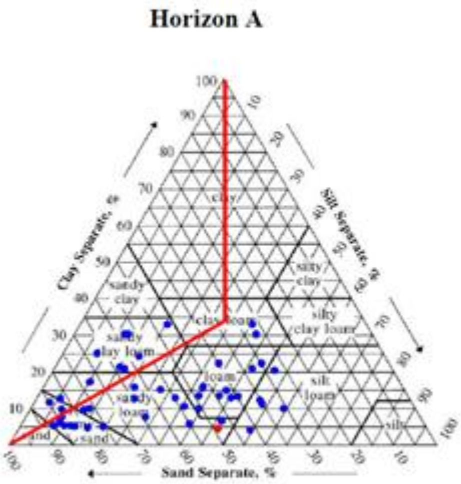
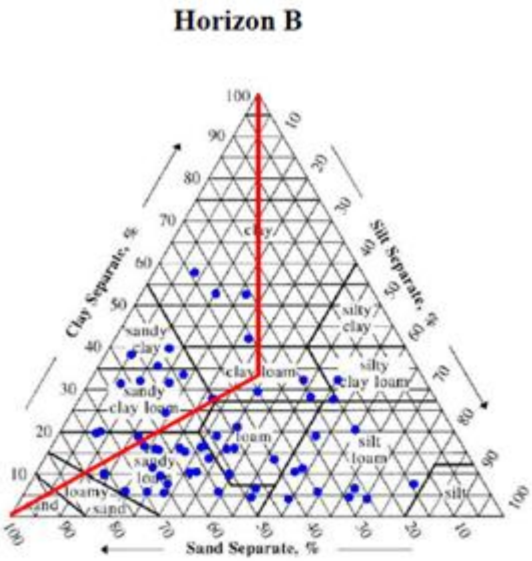


Fig.5. *Bimodal cumulative distribution of particle-size of a sandy loam with 66.67% sand, 20.45% silt and 10.9% clay. The sample is taken from the B horizon of a haplic Acrisol of the plateau of Allada (South Benin). The vertical dotted line indicates an inflection point in the sand field.*

The statistics of the particle-size distribution of 150 samples are shown in Table 1 below. Similarly, the textural classification of A and B horizons of Haplic Acrisols, ferric Acrisols and umbric Fluvisols are represented from the USDA soil textural triangle in fig. 7a and 7b, 7c and 7d and 7e and 7f. At the level of Haplic Acrisols, there is a percentage of silt loam higher than the one in Acrisols at each of the two horizons (Table 1). Most Haplic Acrisols are monomodal soils, percentages in silt, clay and sand of these soils (Table 1) do not obey the conditions of bimodality of eq. [I.3]. Which is not the case with ferric Acrisols whose sand, clay and silt fractions are in accordance with the conditions of bimodality. The ferric Acrisols, in their majority, are thus bimodal at the A and B horizons with relatively low silt contents, which specifically characterizes bimodal soils (see values of coefficients of variation in table 1). Samples from the horizon A of Haplic Acrisols are very sandy (mostly loamy sand, Fig. 7a), 80% being monomodal soils (42 samples out of 52). Samples from the B horizon are slightly less sandy and mostly sandy loam (Fig. 7b), with over 75% of monomodal soils (50 samples out of 65). Concerning the ferric Acrisols, soils from the horizon A are moderately clayey (mostly sandy clay loam, Fig. 7c), 87% being bimodal soils (31 samples out of 35). Samples from the horizon B are clayey (fine) and mostly sandy clay (Fig. 7d) with almost 100% of bimodal soils (58 samples out of 60). The silt content of horizons A and B of ferric acrisols are low compared to those in Haplic Acrisols (Table 1). As for umbric fluvisols, alluvial soil, their particule-size distribution in terms of percentages of silt, clay and sand revealed in horizon A 65% of monomodal soil and 35% of bimodal soils (Fig. 7). Samples from the A horizon of umbric Fluvisols are coarse (mostly loamy sand, fig. 7). But in the B horizon, there were a total of 45% of monomodal soils and 55% of bimodal soils. The soils of this horizon are moderately fine (clay), mostly sandy clay loam (Fig. 7f). It is noteworthy that most of the samples of horizon B are gravelly ferric acrisols (gravel weight represents about 15% of total soil sample weight). The gravel content has not been considered in this work because the gravel percentage is not a variable of the USDA soil textural triangle.



(a)



(b)

Fig.7. *Textural classification of haplic Acrisols collected from various depth in the non-saturated area of the plateau of Alladda plotted on the USDA soil textural triangle: (a) Horizon A, (b) Horizon B*

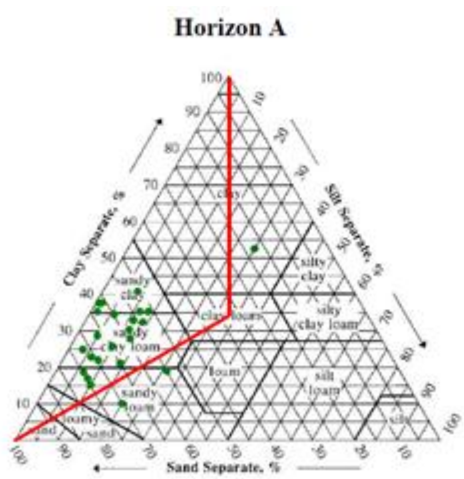
Table 1: *Average soil textures of the 150 soil samples taken from three (03) main soil classes of the plateau of Allada (the Haplic Acrisols, the ferric Acrisols and umbric Fluvisols).*

	Haplic Acrisols			
Horizons	Samples	**Silk**	**Clay**	**Sand**
	numbers	%		
A	52	14(57)	12(59)	73(17)
B	65	21(41)	23(48)	54(21)

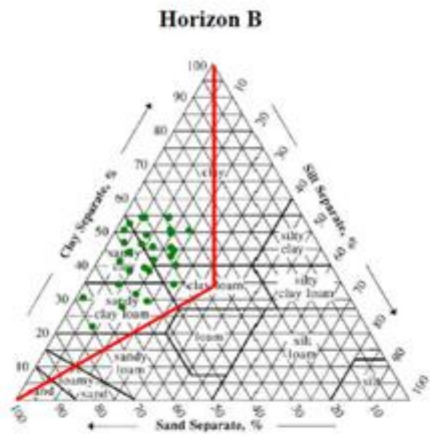
	Ferric Acrisols			
Horizons	Samples	**Silk**	**Clay**	**Sand**
	numbers		%	
A	35	11(29)	26(34)	62(14)
B	60	14(33)	40(15)	44(8)

	Fluvisols umbriques			
Horizons	Samples	**Silk**	**Clay**	**Sand**
	numbers	%		
A	22	11(54)	14(46)	75(7)
B	55	10(41)	22(31)	66(14)

In the study area, the Haplic Acrisols are the most prevalent soil with a coverage rate of about 53%. The umbriques Fluvisols and ferric Acrisols are a minority with low coverage rate of 18% and 12%, respectively. While from previous analyzes, it emerges that Haplic Acrisols are high rate monomodal soils (80%). They are followed by umbric Fluvisols 65% of monomodal soils and ferric Acrisols, soils with bimodal high rate (80%) and very poorly represented in the study area. These results show that the monomodal soils are predominant in the unsaturated zone of Allada plateau (66% of monomodal soils against 34% of bimodal soils). They are mainly present in the A and B horizons of Haplic Acrisols and umbric Fluvisols (50-200 cm deep) and are specifically loamy sand, sandy loam or loam (soil respectively very coarse, medium coarse and coarse). But with the exception that the horizon B of umbric Fluvisols, the proportions of monomodal and bimodal soils are almost equivalent (45% and 55%, respectively). As for the ferric Acrisols, the pedogenesis develops bimodal soils in A and B horizons of these soils which accumulate iron. Bimodal soils from ferric Acrisols are sandy clay loam and sandy clay textural classes (slightly fine and moderately fine soils).

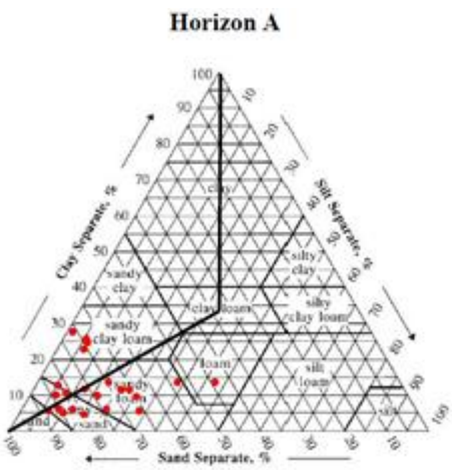


(c)

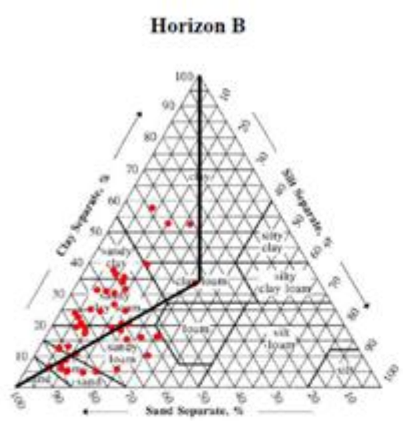


(d)

Fig.7. *Textural classification of ferric Acrisols collected at different depths in the unsaturated zone of Allada plateau plotted on the USDA soil textural triangle: (c) A Horizon, (d) B horizon.*



(e)



(f)

Fig.7. *Textural classification of umbric Fluvisols collected at different depths in the unsaturated zone of Allada plateau plotted in the USDA soil textural triangle: (e) A Horizon, (f) B horizon*

Discussions

The discussions were mainly built from the comparative analysis of the results of this study with those of two (02) watersheds and four (04) databases. These are the Maheshwaram (India) and Ouémé (Benin) watersheds and databases from temperate and tropical regions on which De Condappa, Galle, Dewandel and Haverkamp have worked in 2006.The Maheshwaram watershed of the subtropical climate zone is controlled by the periodicity of the Southwest Indian monsoon (June to October), with an average annual precipitation of 750 mm and an average annual temperature of 26 ° C. The geology of the area is relatively homogeneous and is composed of Archean granites without quartz minerals <50 microns (Dewandel et *al*., 2006). The two main taxonomic classes according to the USDA pedological classification system (Soil Survey Staff, 1960) are the Alfisols and Entisols (De Condappa et *al*., 2006). Regarding the Ouémé watershed, it is a meso-scale observation basin of the international African Monsoon Multidisciplinary Analysis (AMMA) project (Redelsberger et *al*., 2006). The area has a subhumid climate with monsoon season between April and October. The average annual precipitation is 1100 mm and the average annual temperature is 26.4 ° C. The catchment is located in central Benin on the Dahomeyan crystalline basement and the prevailing geology is granite gneiss. The dominant soils in the catchment are autochthonous "ferrugineux tropicaux lessivé" (Faure, 1977; Faure and Volkoff, 1998) according to the French soil classification and autochthonous Alfisols according to the USDA taxonomy (Soil Survey Staff, 1960).

- Comparative analysis with Maheshwaram soils

The results of De Condappa (2006) showed that the soils of Maheshwaram watershed have mostly bimodal behavior. They are mainly present in the B horizon of Alfisols (60-300 cm deep) and are specifically sandy clay loam or sandy clay (Fig. 8a), with nearly 99% of bimodal soils (66 samples out of 67). The C-horizon samples are sandier, mostly sandy loam, with 54% of bimodal soils. As for Entisols, they contain 63% of bimodal soil at the horizon E, 82% at the horizon B (Fig. 8b), and none at the horizon C (the only sample taken is a monomodal soil). But the soils of Allada plateau are an exception as they are in the same climate zone (tropics) as soils of the Maheshwaram basin, yet they are mostly monomodal soil (66% of monomodal soils against 34% of bimodal soils).

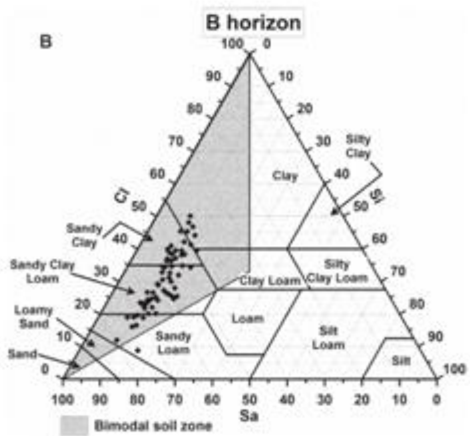


Fig.8a. *Textural classification of Alfisols collected at various depths in the Maheshwaram watershed (South India) plotted on the USDA soil textural triangle: (B) B horizon (De Condappa, 2006)*

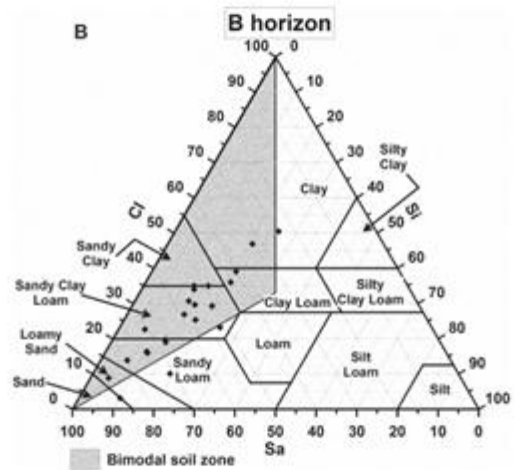


Fig.8b. *Textural classification of Entisols collected at different depths in the Maheshwaram basin (South India) plotted on the USDA soil textural triangle: (B) B horizon (De Condappa, 2006)*

Monomodal soils are mainly present in the A and B horizons of Haplic Acrisols and umbric Fluvisols (50-200 cm deep) and are specifically loamy sand, sandy loam or loam. Soils with bimodal characters were seen in ferric Acrisols which are very poorly represented in the study area. The percentage of silt which is a distinguishing criterion of monomodal soils from bimodal soils is relatively higher at the A and B horizons of Haplic Acrisols and umbric Fluvisols of Allada plateau at the level of the Alfisols and Entisols of Maheshwaram basin.

- Comparative analysis with Ouémé watershed soils

As for the case of Maheswaram basin, the Alfisols of the Ouémé basin are formed from the hydrolysis of the primary mineral, leaching of secondary clay minerals, and water erosion (Devaraj of Condappa 2006). Three (03) soil horizons A, B, and C are observable (Faure, 1977). Statistics on particle-size analyzes of horizons A, B, and C in the AMMA program (Redelsberger et *al*., 2006) and literature (Agossou, 1977; Faure, 1977; Igue 1991) gave of silt relatively low percentages in the soil profiles, about 15%, but not as low as it was observed for the Maheswaram basin. As is the case of the E horizon of the Indian basin, samples of the A horizon of Ouémé basin are very sandy, sandy loam mainly (Fig. 8c), with 24% of bimodal soils (22 samples out of 90).

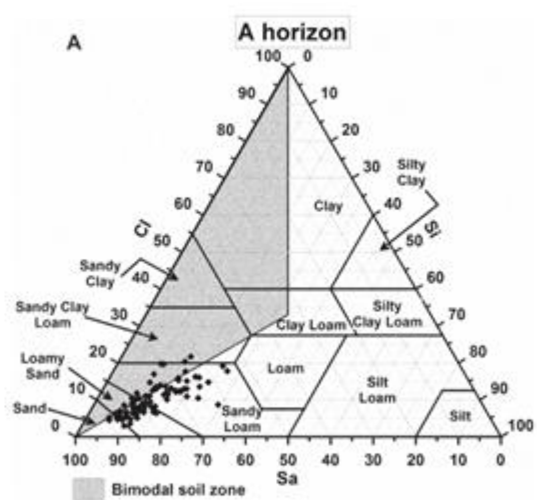


Fig.8c. *Textural classification of Alfisols collected at different depths in the basin of Ouémé (Benin, West Africa) placed in the USDA Soil textural triangle: (A) horizon A (De Condappa, 2006)*

The B horizon samples are more clayey, sandy clay loam mainly, with 83% of bimodal soils. Samples of the C horizon are even more clayey and less sandy, mostly sandy clay and sandy clay loam, with 100% bimodal soils (De Condappa, 2006). These results of Ouémé basin are consistent with those of Giertz and Diekkrüger (2003) who reported sandy clay loam in the B horizon of some soils of Ouémé basin, that is to say, soils with bimodal behavior. This is not the case of soils of Allada plateau which this study found predominantly monomodal.

- Comparative analysis with the soil databases

Previous analyzes attribute to soil of the basins of Maheshwaram and Ouémé, soils with essentially bimodal character. What seems to confirm for these basins located in the tropics, Tomasella and Hodnett's assertion (1998; 2000; 2002) that the bimodal soils are specific to tropical and subtropical regions.They are consistent with the results of Giertz and Diekkrüger (2003) but strongly disagree with the results of this study that found that the plateau soils have predominantly monomodal behavior. Boukari (1998) affirmed that the soils of the southern part of the plateau are bimodal. But his work did not pursue this aspect, they probably believed some samples of bimodal soils of the plateau or affirmations of literature that automatically classify soils of this climate zone as bimodal soils without a thorough study. The analysis of various soil databases published in the literature (Wösten et *al*., 2001) provides an opportunity to examine the issue from several angles. These databases four in number (04) are the soil databases of UNSODA, of GRIZZLY, the information system on soil of Netherlands and the one of IGBP-DIS. They contain the soils from different regions of the world. Tropical and subtropical soils are well represented in these databases. The UNSODA soil database is the first database to be compiled (Leij et *al*., 1996). It covers 780 soils providing soil basic properties such as bulk density (dry), organic matter, data on the particle-size distribution, data on the hydraulic properties of soil, and mineralogy. Most of these soils are of Europe (about 46%) and North America (45%) (Nemes et *al*., 2001). UNSODA data placed in soil texture triangle of USDA (Fig.9a) gives less than a quarter (23%) of bimodal soils, so 77% of monomodal soils (De Condappa, 2006). This shows that the bimodal zone is less represented than the monomodal area in this population of soils collected mainly in temperate regions. As the soils of Allada plateau, soils of UNSODA database have mostly monomodal character even though it contains a significant proportion of tropical and subtropical soils. The second database is the GRIZZLY database reported by Haverkamp et *al*. (1998).

Fig.9a. *A population of 666 soil samples of UNSODA database (Leij et al., 1996) plotted on the USDA soil textural triangle (De Condappa, 2006)*

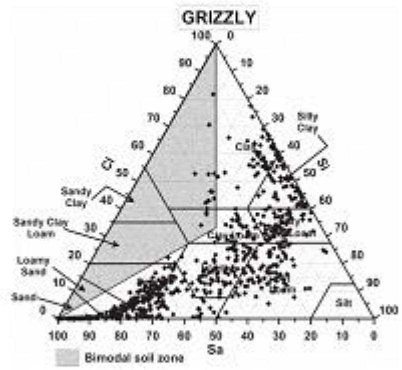


Fig.9b. *A population of 660 soil samples of GRIZZLY database (Haverkamp et al., 1998) plotted on the USDA soil textural triangle (De Condappa, 2006)*

It contains a population of 660 soils from different regions of the world, but mainly temperate climate regions of Europe (Austria, France, Hungary, Spain, and the Netherlands) and the United States. After thoroughly analyzing the population samples from the GRIZZLY soil database, the above authors found that only 12 soil samples were from the subtropics, that is to say, Morocco, Ivory Coast, Senegal, Israel and North Australia. De Condappa (2006) by placing the data of GRIZZLY database in USDA soil texture triangle found that only 16 soils (2%) are in the bimodal soils zone (Fig.9b). Almost 98% soils of this bank are monomodal, far exceeding the percentage of monomodal soils registered on the Allada plateau. The third database is a sample of the information system on soils of Netherlands. Nemes and *al*. (1999) randomly extracted 9607 soils from the database. It clearly shows that the bimodal zone is substantially less represented than the monomodal zone. The fourth database is that of Hodnett and Tomasella (2002). From the IGBP-DIS database, they chose 771 soils belonging to tropical and subtropical regions. Their Fig. 1 reproduced by De Condappa et *al*. (2006) with the bimodal zone is included here (Fig. 9c). Nearly 45% of soils belong to the bimodal soil zone, so about 55% of soils in this database are monomodal. The soils of the IGBP-DIS database are closest soil of the Allada plateau, since they come from the same climate zone.

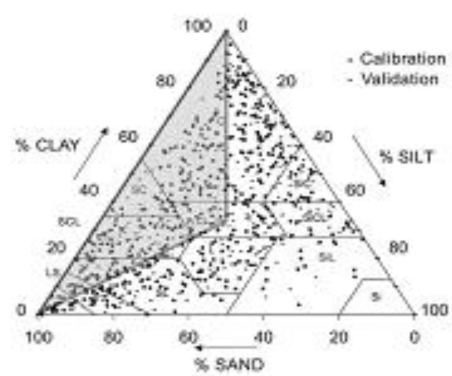


Fig.9c. *A population of 771 samples of tropical and subtropical soils extracted from the IGBP-DIS database plotted on the USDA soil textural triangle, adapted from Tomasella and Hodnett (2002). Points for calibration (492 soils) and validation (279 soils) points indicate data sets*

that Tomasella and Hodnett (2002) used to develop and validate, respectively, their pedotransfer function. Adapted and reprinted by Tomasella and Hodnett (2002) with permission of the publisher (De Condappa, 2006).

These proportions of bimodal soils and monomodal soils clearly show the extent that bimodalization phenomenon takes in these regions. The authors of this database also studied 614 soils of the Brazilian Amazon, which they described as "characterized by a very small percentage of silt (usually less than 10%), although the texture is extended from the sand to the clay "(Tomasella and Hodnett, 1998); texture triangle clearly suggests that the majority of the 614 soils is made of bimodal soils. Similar results were presented by Tomasella and *al*. (2000) for a population of 630 soil samples collected throughout Brazil. In summary, previous analyzes show that soils from these four different databases are monomodal such as soils of Allada plateau but in proportions much higher than these. They also confirm that except soils from Allada plateau predominantly monomodal, bimodal soils are (i) well represented in tropical and subtropical regions and, conversely, (ii) much rarer in regions of temperate climate.

- Bimodal soils in tropical and subtropical regions

Bimodal soils are defined as soils belonging to the bimodal zone of the USDA soil textural triangle: their percentage by weight of silt is always smaller than sand and clay percentages. To explain the existence of such soils, it is essential to consider the genesis process of these soils. The two main processes are the alteration of the bedrock and soil formation (e.g., Fanning and Fanning, 1989). Soils are the final output of the superficial alteration of the bedrock and are generated at the top of the weathering profile. Among the different pedogenic processes, physical alteration (e.g., disintegration into small pieces), hydrolysis (e.g., dissolution of minerals in the water), leaching (e.g., leaching down of the clay particles) and erosion (by wind and water) are particularly active in the genesis of soil particles (e.g., Fanning and Fanning, 1989). The hydrolysis separates and transforms the original parent rock minerals, hereinafter referred to as primary minerals, in equilibrium with the external conditions entities called secondary minerals. While some primary minerals such as olivine are highly affected by hydrolysis, others such as quartz are hardly altered at all (Tardy, 1971). Moreover, the kinetics of hydrolysis increases with the specific surface (Ss) of soil particles, defined as the ratio of area to mass, equivalent to the ratio of area to volume, which in turn is equivalent to the inverse of the particle-size diameter. Therefore, the smaller the size of a given primary mineral, the sooner it will be eliminated (e.g., Legros and Pedro, 1983). For a bedrock without quartz minerals <50 μm, the percentage of primary minerals in the soil decreases from sand to clay. Simultaneously, a new formation appears, this is the genesis of secondary minerals. Most of these secondary minerals having a size <2 μm, are called clay minerals (e.g., Buol et *al*., 2003) and contribute to the total clay content in tropical and subtropical soils. In summary, for a bedrock without quartz mineral <50 μm, the combination of clay minerals with primary sand minerals, ultimately gives bimodal soils with larger percentages of clay and sand than that of silts. For the case of a permeable surface layer of soil, leaching of the clay by the infiltrated water may also be an important process of pedogenesis. It creates in the soil profile an upper eluviation layer (E horizon) poor in secondary clay minerals and an underlying illuviation layer (B horizon) rich in secondary clay minerals (e.g., Buol et al., 2003).The B horizons of these soils are likely to show bimodal behavior.

- Consequences of the bimodal character of soils on their hydrodynamic behavior

The bimodal character of soils greatly influences the hydrodynamic behavior of soils. It is important to take this into account in the models at the parameterization step of soils (De Condappa, 2005). Indeed, the textural properties are determined from the particle size distribution of a soil sample. Conventionally, the discrete values of the particle size are shown continuously using cumulative functions of particle distribution F (D) (e.g., Haverkamp and Parlange, 1986; Buchan, 1989; Shiozawa and Campbell, 1991; Bittelli et *al*., 1999; Skaggs et *al*, 2001). According to Haverkamp and Reggiani (2002), the cumulative function of particle distribution F (D) is described by an expression similar to that of the water retention curve $h(\theta)$ where h [L] is the capillary pressure of the soil water and θ $[L^3\ L^{-3}]$ is the volumetric water content of the soil. Hence, when using a given equation (e.g., that of van Genuchten, 1980) for the function F (D), the same type of model should be used for the water retention function h (θ). This form of similar concept was used earlier by Arya and Paris (1981) and Haverkamp and Parlange (1986) to predict the water retention characteristics of soils from the texture. Besides these physical and empirical models, the cumulative function of particle-size distribution is often used to determine the hydrodynamic properties of soils through pedotransfer functions or PTFs (Bouma and van Lanen, 1987). These are generally empirical relationships which allow the hydrodynamic properties of a given soil to be predicted from experimental data, such as texture (sand, silt, and clay percentages) and bulk density. Among the many PTFs proposed in the literature (e.g., Clapp and Hornberger, 1978; Cosby et *al*., 1984; Rawls and Brakensiek, 1989; Vereecken and *al*., 1989; Schaap and *al*., 1998; Jarvis and *al*., 2002), some have been developed to predict the parameters of water-retention curve models of Brooks and Corey (1964) or van Genuchten (1980). For these PTFs, the direct conversion from particle-size shape parameters to water retention shape parameters is generally chosen. All models presented so far (either physico-empirical or PTFs) have one point in common: they consider a monomodal functional behavior of the cumulative particle-size distribution or the water retention equation. When some soils have a bimodal functional behavior, however, these models are no longer adequate (De Condappa and *al*., 2006). The concept of shape similarity between the cumulative function of particle-size distribution and water-retention curve model was validated for monomodal behavior by Haverkamp and Reggiani (2002). Assuming that the shape similarity concept is also valid for the bimodal behavior will lead to developing empirical relationships or pedotransfer functions that obey the conditions of bimodality of Eq. [2]. The modeling of flow in soils with monomodal behavior is not a problem, since the empirical relationships or pedotransfer functions that model this behavior exist. Therefore, modeling the transfer of water in the tropical and subtropical soils remains the problem to solve, as soils bimodality now requires developing other appropriate mathematical functions to the determination of the hydrodynamic characteristics of bimodal soils. The problem does not necessarily arise in this study as more than 65% of soils in the study area have monomodal behavior. The above mentioned hydrodynamic models are applicable for the soil parameterization in the study area. Something remains surprising, almost no studies were found in literature that examines the difficulties associated with the texture of bimodal soils and their effects on soil hydrodynamic (De Condappa et *al*., 2006). More detailed analysis of these specific problems should be the subject of future research.

Conclusion

This study focused on the validation of monomodal behavior of the main soils of Allada plateau, highlighting the influence of the bimodal character on their hydrodynamic behavior. The most widespread soils are in order of increasing coverage, Haplic Acrisols (53%), Umbric Fluvisols (18%) and ferric Acrisols (12%). These soils plotted on the USDA soil textural triangle revealed textures like loamy sand, sandy loam and loam in the A and B horizons of Haplic Acrisols and Umbric Fluvisols, sandy clay loam and sandy clay at ferric Acrisols. From validating the monomodal behavior of soil using textural triangle with associated bimodal zone, it appears that Haplic Acrisols monomodal rates are high (80%). They are followed by Umbric Fluvisols, 65% of monomodal soils and ferric Acrisols, soils with bimodal high rate (80%) but poorly represented in the study area. This makes all the soils of the study area 66% of monomodal soils against 34% of bimodal soils. Beyond the bimodal zone of textural triangle, the study characterized the bimodal soils by their very low content of silt and their shape marked by the presence of two local maxima (inflection points), one in the clays range and the other in the sands range. Furthermore, the study conducted a comparative analysis of the above results with those of similar studies on the watersheds of Maheshwaram and Ouémé and databases from different climatic zones. The analysis showed that the soils of the Allada plateau of the same climate zone like soils of these watersheds in the tropical zone, even mostly monomodal, encompass a significant part of bimodal soils (34%). This indicates the magnitude of the phenomenon of bimodalization at genesis of soils in this climate zone. Indeed, Alfisols and Entisols of Maheshwaram and Ouémé watershed, respectively of subtropical and sub-humid climate zones, are sandy clay loam textures, and sandy clay and mostly bimodal (De Condappa, 2006). On the contrary, global reference soil databases such as UNSODA (Leij and *al*., 1996), GRIZZLY (Haverkamp and *al*., 1998) and those of the Netherlands (Nemes and *al*., 1999) from temperate regions are monomodal. But the IGBP-DIS database (Hodnett and Tomasella, 2002) within the tropical zone account for almost 45% of soil belonging to the bimodal zone, so about 55% of soils in this database are monomodal. What seems to be in agreement with the conclusions of Tomasella and Hodnett (1998; 2000; 2002) according to which the monomodal soils are typical of temperate regions and bimodal soils are typical of tropical and subtropical regions. Giertz and Diekkrüger (2003) reported in the B horizon of some soils of Ouémé watershed, sandy clay loam soils that are bimodal, confirming the above results for the soil in intertropical regions. A challenging consequence of the texture biomodality concerns hydrodynamic properties of the soil. The cumulative particle-size distribution models are often used for PTFs. According to the concept of shape similarity between the cumulative curve of particle-size distribution and the water-retention curve, textural bimodality of soils should then be characterized by hydrodynamic characteristics of bimodal soil. Most of the models presented in literature for the determination of the hydrodynamic characteristics of the soil, however, only describe the functional monomodal behavior, and most PTFs were developed for model monomodal hydrodynamic properties. Therefore, there is a challenge to develop a new mathematical framework specific to bimodal soils in tropical and subtropical climate zones belonging to the bimodal zone of USDA textural triangle (De Condappa, 2006). In addition, the upper limit of the textural classification of soils at D = 2000 µm may be questioned. While this arbitrary limit is typically used in soil science, other disciplines such as geotechnical reflect the full domain comprising gravels (D> 2000 µm). Bimodal soils observed in the B horizons of Maheshwaram and Ouémé watersheds contain a large quantity of gravels, which can be observed in other soils in tropical and subtropical regions with similar pedogenesis. Therefore, the conventional approach that truncates the gravel range of a certain arbitrary manner may not be entirely suitable for tropical and subtropical soils.

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