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Parameterization of the Hydric Transfer Models in Three Eucalyptus Plantations in Congo

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ABSTRACT

Quantifying soil water repartition and hydric fluxes is essential to understand soil-plant relationships. Eucalyptus plantations in Pointe-Noire region are on sandy soils, a good knowledge of water behavior in the soil is important to sustainable management of eucalyptus plantations as well as for measuring the impacts of these plantations on the region water resource. The objective of this study is to parameterize a model of hydric transfer in the soil of three, using the HYDRUS 1D software i) to compare the behavior hydric of sites and (ii) to establish the hydric settlements assessment of Eucalyptus at various stages of development. The results showed different hydrodynamic characteristics according to sites, these differences are ascribable with the geometry and the pores morphology and the farming part of the soils. The hydric statements of four development states of the plantations are established, the implication of these results is discussed.

Key words: Hydric statements, model mechanists, HYDRUS 1D, eucalyptus plantations, pointe-noire region, Congo

INTRODUCTION

Under some climatic conditions such as temperature, some trees of plantations eucalyptus would be closely related to daily atmospheric vapour pressure deficit (Yin *et al.*, 2004). Water is essential to plant growth. It is mainly drawn from the soil by roots. In the soil, many processes depend on water availability, it is a essential vector to gas transfers and matter in solution. It is middle for reactions for alteration and organo mineral and insolubility phenomena (Bourrie and Lelong, 1994). Knowledge on distribution and the water transfers in soil is very important to understand the relationship between soil, water and plant. The fast growing trees of *Eucalyptus* plantations have effects on water resources, erosion, soil nutrient status (Calder *et al.*, 1997). Under some climatic conditions such as temperature, daily sap flux density of some trees of plantations eucalyptus would be closely related to daily atmospheric vapour pressure deficit (Yin *et al.*, 2004).

There are many studies linked to eucalyptus transpiration in many scientific disciplines: In the physiology of plants, hydrology, ecology and meteorology (Prazak *et al.*, 1994; Granier *et al.*, 2000;

Lagergren and Lindroth, 2002; Daudet *et al.*, 1999; Montero *et al.*, 2001). Tree transpiration is the major pathway for both water and energy leaving the forest ecosystem (Lagergren and Lindroth, 2002; Safou Matondo *et al.*, 2005).

According to Yin *et al.* (2004) sapflow or transpiration of trees may be closely linked to plant hydraulic variables and environmental factors, especially soil types (Du and Yang, 1995; Cienciala *et al.*, 1997; Lagergren and Lindroth, 2002). There is growing evidence of higher frequency of climatic extremes as a result of global climatic change (Karl *et al.*, 1995). Yin *et al.* (2004) also affirm that Forests are more directly influenced by the variation of climate (Granier *et al.*, 2000). There has been increasing evidence on the impact of climatic factors on water fluxes (Oltchev *et al.*, 2002; Devitt *et al.*, 1997). If the environmental factors vary, sap flow can fluctuate widely.

Literature on eucalyptus in Brazil and in Congo is well documented (Bouillet*et al.*, 2002; De Dieu Nzila *et al.*, 2002; Laclau *et al.*, 2000, 2001a,b, 2003a,b; Safou Matondo *et al.*, 2005; Gonçalves *et al.*, 2008; Nouvellon *et al.*, 2008; M'Bou *et al.*, 2008; Da Silva *et al.*, 2009; Fallot *et al.*, 2009; Maurice *et al.*, 2010).

The soils of Pointe-Noire region are very sandy and little fertile; they have a weak water retention capacity (Laclau, 2001). Eucalyptus plantations are on these soils. Estimating water fluxes is a major problem in these soils, on the one hand, depth fluxes could lead to major loss of minerals and consequently pollution of tablecloth by nitrate fertilizers or weed killers. On the other hand, the high water consumption characteristics of Eucalyptus could limit the hydric resource of the soils (Dye, 1996; Scott and Smith, 1997) and reduce the renewal of the tablecloth which is essentially provided by rainwater filtering through the soil.

A good knowledge of soil behavior with respect to water seems essential to the sustainable management of these ecosystems and the impacts of these plantations on the region water resource. Hydric transfers depend on many physical, chemical and biological factors of the soil. Several approaches are possible to study water transfers in the soil. Mechanist modeling is generally preferred because the parameters are explicit and enable to generalize results easily.

In the study, we parameterize a hydric transfer model of the soil in three eucalyptus plantation using the HYDRUS 1D software ® in order to compare the hydric dynamics in the three stands and to establish a hydric statements of these stands.

MATERIALS AND METHODS

Modeling hydric statements in the soil: Modeling hydric transfers in the soil usually uses soil volumic humidity equations such as Richards' equation. The one-dimension Richards' equation is at the basis of hydraulic soils functioning. It gives the relationship between soil humidity, hydric potential and hydraulic conductivity.

By combining continuity equation leading soil volumic humidity θ and water fluxes Eq. 1:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z} \tag{1}$$

and the Darcy' Law Eq. 2:

$$q = K(\theta)\frac{\partial H}{\partial z} \tag{2}$$

The one-dimension Richards' Eq. 3 is obtained:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} - 1\right)\right] \tag{3}$$

On these equations:

- K is, proportionality constant called hydraulic constant, it varies according to soil water content (Feddes *et al.*, 1978)
- h, the hydric potential, given in water height equivalent and H, the hydraulic charge, defined by $H=h(\theta)-z$

Originally soil humidity equations used in saturated middle they was extended in non saturated one by Richards (1931).

To solve Eq. 3, soil volumic humidity must be related to hydric potential for every depth. This relationship is an important component of hydric transfer phenomena. Several authors proposed continuous mathematical formulations for it (Haines, 1930; Rogowski, 1971). The Van Genuchten (4) formulation was preferred because it is the most generic one (Guennelon, 1994):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \tag{4}$$

where α, n and m are independent parameters that were determined by statistical fitting. A dependence relationship though improves the relevance of the Van Genuchten relationship for almost all soils (Van Genuchten, 1980).

The relationship can also be analytically expressed as a function of $K(\theta)$ with a null initial moisture as initial conditions:

$$K(\theta) = K_s\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^i\left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right)^m\right]^2 \tag{5}$$

The different parameters, respectively represent:

- θ_s : Natural saturation water content ($L^3.L^{-3}$)
- θ_r : Residual water content ($L^3.L^{-3}$)
- K_s : Hydraulic conductivity in natural saturation ($L.T^{-1}$)
- α : Empirical parameter of the water retention curve (L^{-1})
- m and n : Parameters of the retention curve linked to soil structure
- I : Soil porosity related parameter set to 0.5 (Mualem, 1976)

Characterizing soils requires determining these parameters of the Richards' equation. Parameters m and n are form ones while α, θ_s and θr are scale parameters. Haverkamp *et al.* (1998) showed that scale parameters are strongly linked to soil texture and that form parameters mainly depend on soil structural properties.

***In situ* draining experiment:** Aim of these experiments is to establish relationship between soil humidity and hydric potential for every level of measurements and for every soil profile studied. In that purpose, experiments of internal drainage on two plots of land were made. These experiences experiments allow establishing the relation between the soil humidity and the potential hydric for every level of measures and every soil profile studied. Experiments of internal drainage were realized on two plots of land, Kondi R0013B and Hinda H9807 with a step daily time, respectively from March 30th to May 19th and from July 27th to September 19th, 2004. For third plot, data were taken in UR2PI data base, obtained in 2001 (Damman, 2001).

The experiments were realized in the experimental eucalyptus plantations located in the vicinity of Pointe Noire (4°South, 12°East), South West of the Republic of Congo, between the coast and the Mayombe forest mountain. Two close stands (100 meter distance between stands) were chosen on a same site of Kondi (named R0013a and R0013b), the stands are three years old, planted with two contrasted eucalyptus clones (PF1-41 and UroGrandis 1-52). The third stand (H9807) was situated on a different site distant from about 10 Km and planted with the PF1-41 clone.

On each stand, a metal ring (25 cm height, 1 meter diameter) was planted at a 10 cm depth in the soil so as to define a 0.75 m^2 zone around TDR probes that measure soil volumic humidity. A second ring surrounds the first one (same height, 2 m diameter). This second ring was installed to limit lateral flow.

Soil was saturated with water in the zone between the two rings ($4m^3m^{-2}$) and the soil was left to drain and dry in order to allow homogeneous hydric transfers around the probes. In the central ring, mercury tensiometers were installed next to TDR probes, their water input point was located next to a -800 water cm pressure.

As a consequence of the soil suction, the water contained in the probes comes to equilibrium with water in the soil. This equilibrium is quantified by the raise of a mercury manometric column (Bonneau and Souchier, 1994). During the drying process, soil volumic humidity (θ) and hydric potential (h) were measured simultaneously in regular intervals at 15, 20, 100, 150 and 200 cm depths. The installed devices were covered with a tarp in order to avoid water losses by evaporation.

The experimentally measured relationship between h and θ can be represented by a characteristic soil water curve called "soil water retention curve". The parameters of the Van Genuchten formula (4) were estimated by fitting the measured data in each depth with the HYDRUS 1D ® model.

Determining soil moisture with saturation looked difficult because the soil under these plantations was very draining. Therefore, moisture at saturation θ_s were measured in the global porosity calculated from bulk and real densities. The residual water content values θ_r were set at the seasonal observed minima, the limiting conditions for the use of the tensiometers being around 0.8 bar.

Hydric statements: The daily hydric statements can be expressed as follows:

$$\Delta wz = R - In - Lc - RET - \Delta S$$

with:

- ΔWz = Drained water flux in depth z
- R = Rainfall
- In = Interception
- St = Stemflow
- RET = Real Evapo-Transpiration that depends on Potential Evapo-Transpiration (PET) and available water
- ΔS = Soil water stock variation

Daily PET was calculated from the formula of Penman-Monteith used for soil without vegetation, soil under savanna and soil under eucalyptus plantations from meteorological data of Point-Noire station (ASECNA) Interception and streaming were estimated from formula of Laclau (2001). Root uptake (equal to real transpiration) was proportionally estimated at fine roots density and controlled by the equation from Feddes *et al.* (1978).

HYDRUS 1D software: The HYDRUS 1D software uses a finite model of elements to simulate a one-dimensional movement of water, heat and dissolved bodies in a medium varying with depth. It numerically solves the Richards equation for water leaching (Simunek and Sejna, 1996, 1998). It can use the van Genuchten model (Damman, 2001) or the Brooks and Corey model (Brooks and Corey, 1964) to estimate hydraulic parameters of the soil.

HYDRUS 1D enables: (1) To estimate water retention curve parameters and Ks from internal draining experiment values; (2) to simulate daily moisture, hydric potential and deep fluxes in different depths with the following inputs : rainfall, PET, root uptake, soil characteristics (Van Genuchten parameters) and the initial conditions (humidity on time 0).

RESULTS

Hydraulic parameters: The parameters values of the water retention curve (Table 1a-c) vary with the site and depth. The soils of the Pointe-Noire region having a homogeneous pedological profile present identical values of θ_s for the same depth in the sites of Kondi R001A and R0013B. The highest values of θ_S are observed on the surface. These values of $\grave{e}_S$ decrease with the depth.

Table 1a: Parameters α and n by plot and depth

Hinda H9807 parameters	Depths (cm) 50	100	200
θ_r ($m^3.m^{-3}$)	0.041	0.045	0.042
θ_s ($m^3.m^{-3}$)	0.357	0.362	0.362
α (m^{-1})	2.4	3.9	2.15
n (¯)	2.828	2.158	2.725

Table 1b: Parameters α and n by plot and depth

Kondi R0013B	Depths (cm)			
Parametres	15	50	100	200
θ_r ($m^3.m^{-3}$)	0.029	0.031	0.036	0.078
θ_s ($m^3.m^{-3}$)	0.446	0.436	0.39	0.39
α (m^{-1})	9.31	4.21	36.39	4.14
N (¯)	1.623	1.776	1.341	2.009
Ks ($m.j^{-1}$)	373.70	200.20	66.50	45.30

Table 1c: Parameters α and n by plot and depth

Kondi R0013A	Depths (cm)			
Parameters	15	50	100	200
θ_r ($m^3.m^{-3}$)	0.029	0.031	0.036	0.054
θ_s ($m^3.m^{-3}$)	0.446	0.436	0.39	0.361
α (m^{-1})	13.513	9.781	3.826	5.828
n (¯)	1.741	2.015	2.357	1.877
Ks ($m.j^{-1}$)	350.20	62.10	45.90	29.30

In Kondi, the values of the parameter α in site R001A are higher than in site R0013B, except from 100 cm. The values of parameter n in the two sites of Kondi are lower than those observed in the site of Hinda. The values of K_s are very high and they decrease quickly with depth. Whatever the depth and the values of K_s are higher in site R0013B than in site R001Á.

The variability of the parameters values of the Van Genuchten equation depends on soils characteristics of three studied plantations. The curves obtained in various depths and sites have typical sandy soil shapes; these curves are represented in Fig. 1 (a-d). Curves of the water retention estimated and measured have similar evolution at all depths and for the three sites.

In order to characterize well the hydric behavior of the soils under eucalyptus plantations, the field capacity in the pF = 2 (θ), the permanent withering points for pF=4,2 (θ_{wilt}) and the water reserve (WR = θ_{fc}-θ_{wil}) in each depth and for each site were calculated from the Van Genuchten equation (Table 2). The field capacity values at the site Hinda H9807 show small variations with depth. The obtained θ values increase with depth in the two sites of Kondi and are almost identical in the first 50 centimeters (0.031 and 0.034 $m^3 m^{-3}$). In the site of Hinda H9807, the values of θ are almost identical in all the profile of the soil and oscillate between 0.041 to 0.045 $m^3 m^{-3}$. The values of WR vary from a site to another and according to the depth. It is noted that the in-depths values of WR are similar in the three studied sites.

Hydric statements: The use of the parameters obtained with experiments of internal draining allows a good simulation of moistures observed whatever the depth (Fig. 2 and 3). The established hydric statements show that eucalyptus plantations consume more water than the savanna (Table 3) but this consumption depends on the age of the settlement. The consumption average of eucalyptus plantations is estimated to 64% of the rainfall average, i.e., 20% more than the savanna. The losses by superficial leaching are small, under savanna as well as under eucalyptus

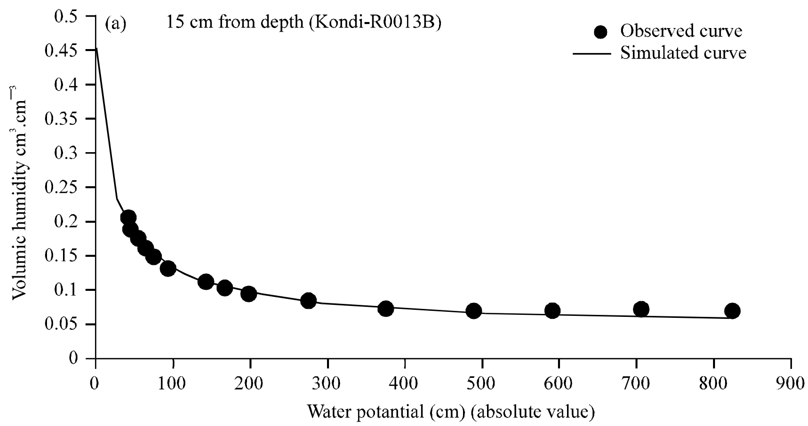

Fig. 1a: Retention curve observed and simulated from HYDRUS 1D model from 15 cm at plot Kondi-R0013B

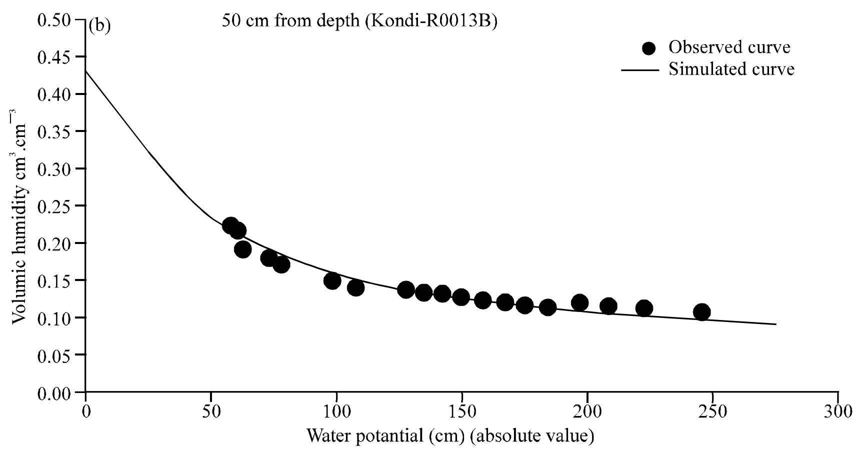

Fig. 1b: Retention curve observed and simulated from HYDRUS 1D model from 50 cm at plot Kondi-R0013B

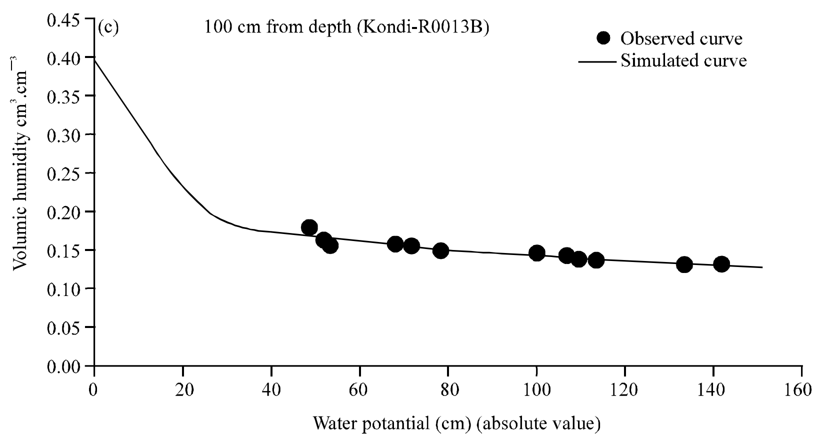

Fig. 1c: Observed curve and Estimated curve of retention from HYDRUS 1D model from 100 cm at plot Kondi-R0013B

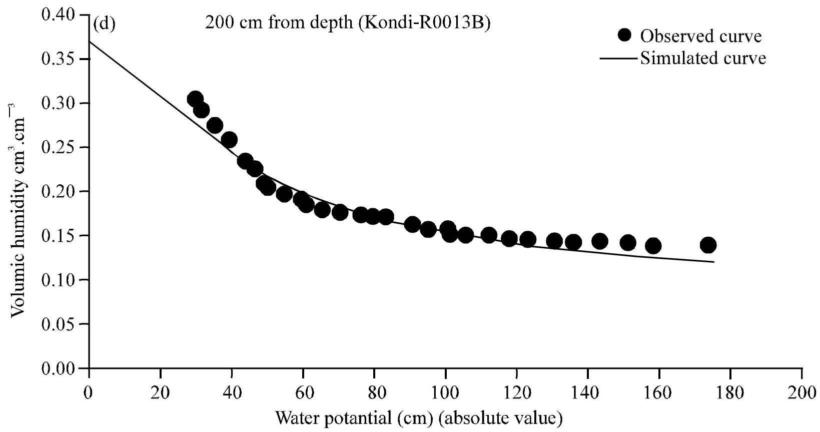

Fig. 1d: Observed curve and Estimated curve of retention from HYDRUS 1D model from 100 cm at plot Kondi-R0013B, On the Fig. 1, the observed and simulated curves represent respectively the evolution of the volumic humidity θ according to potential hydric h. The observed curve was drawn from the measures of θ and h obtained during the experiments which we made on plots Kondi-0013B, The simulated curves of θ were obtained by using HYDRUS 1D model, Both types of observed and simulated curves were made from various depths. Fig. 1 (a-d) concern respectively the depths 15, 50, 100 and 200 cm.

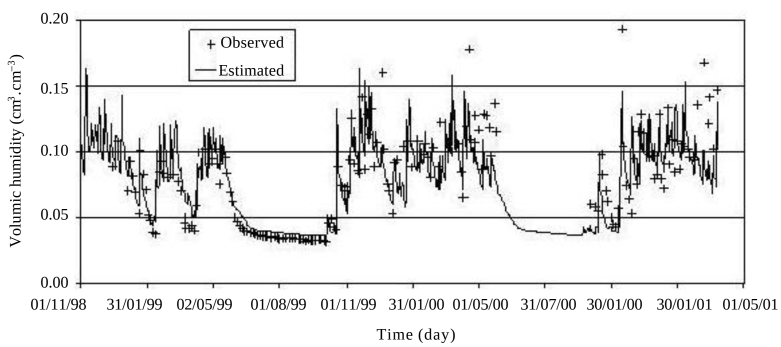

Fig. 2: Volumic humidity curve observed and simulated from 15 cm at Plot of Kondi-R00-13B, On the figure 2 are represented the daily evolutions of the observed and simulated humidity obtained from model HYDRUS 1D. These curves were made from 200 cm on plot Kondi-R0013 B. They clearly pointed out the dry seasons with minimum values of volumic humidity

plantations. We however note that the sum of RET, Streaming and Drainage can be different from the rainfall because of the stock variations in the soil.

On an average 1200 annual rainfall, the recharge of tablecloth is estimated to 520 mm year^{-1} under savanna, 680 mm year^{-1}, one year after planting, 410 mm year^{-1} for 1-2 years old plantation and 260 mm year^{-1} for 6-8 years old plantation. Over a total 7 year rotation, the average annual o f recharge is 400 mm year^{-1}, i.e., 120 mm less than under savanna.

Table 2: θ_{fc}, θ_{wilt} and WR by plot

	Plantations			
Depths (cm)	θ ($m^3.m^{-3}$)	Hinda H9807	Kondi R0013B	Kondi R0013A
15	θ_{fc},		0.132	0.09
	θ_{wilt}		0.034	0.031
	WR		0.098	0.059
50	θ_{fc},	0.102	0.16	0.071
	θ_{wilt}	0.041	0.034	0.031
	WR	0.061	0.126	0.04
100	θ_{fc},	0.109	0.14	0.092
	θ_{wilt}	0.045	0.055	0.036
	WR	0.064	0.085	0.056
200	θ_{fc},	0.119	0.15	0.13
	θ_{wilt}	0.042	0.078	0.055
	WR	0.077	0.072	0.075

Table 3: Annual hydric statements by ecosystems

Ecosystem		Rainfall	PET[1]	RET[2]	Streaming	Drainag
savannah	mm	1500	1050	820	5	660
	%[4]	100	70	55	0.3	44
Plantation (0-1 year)	mm	1170	1020	600	10	660
	%	100	87	51	0.9	56
Plantation (2-3 years)	mm	1390	1200	930	15	470
	%	100	86	67	1.1	34
Plantation (6-8 years)	mm	1500	1140	1040	25	335
	%	100	76	69	1.7	22

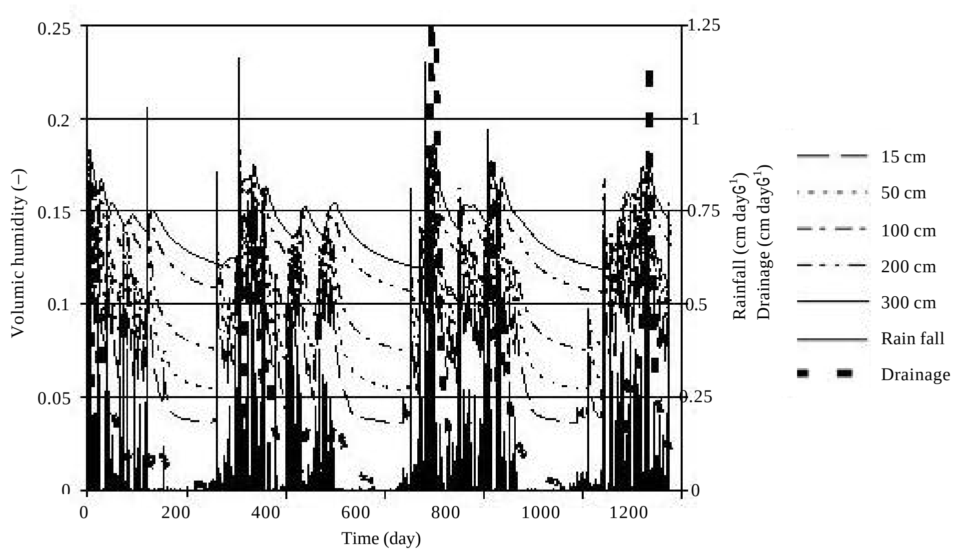

Fig. 3: Drainage estimation by using the model HYDRUS 1D, the Fig. 3 gives the simulation of the volumic humidity and the deep drainage (refill of the tablecloth) in the plot Kondi-R00-13B. The results were obtained with the model HYDRUS 1D by using the data of rainfall supplied by the station of the ASECNA at Pointe-Noire.

DISCUSSION

The soils of Pointe-Noire region have very similar physicochemical characteristics in all the studied sites (Brooks and Corey, 1964; Damman, 2001; Saint-Andre *et al.*, 2004), the hydric properties should thus also be similar. However, the estimate of the parameters which characterize the retention curve and the hydric behavior of the studied soils show variability with depth on the same site and between sites for the same depth. The spatial variability of the hydric properties of the soil was studied in some studies such as Scott and Smith (1997) and Laclau *et al.* (2001a,b).

The results obtained in this study show that the grain-size distribution (texture) cannot explain all the variability observed for the retention curves their parameters. The soils of the studied sites have the same grain-size distribution, bulk density values, organic matter content (Laclau, 2001; Laclau *et al.*, 2001a,b, 2002). The variation of the hydric parameters between sites could be due to differences in the pore size distribution and their organization, the origin of which is unknown (macro fauna of the soil, pedology, geology...) and also with the farming surface of the soils. But these characteristics were not measured, because it is difficult to measure the size of the pores and their connectivity by a direct method. In addition to these factors, the addition of the small differences of texture, bulk density, organic matter content and cations exchange capacity between sites can also contribute to the variability of the hydric behavior of the soil. For a given site, the variations of the hydric parameters with depth are coherent with the variations of texture, organic matter.

The shapes of the soil water retention curves under the three studied sites reveal that the soils of site R0013B succeeding to an original savanna can retain more water than the soils of the sites which already faced a replanting (H9807 and R001Á). Each site and each depth present a particular hydric behavior. The soils of the H9807 and R0013Á sites are more draining that the soils of site R0013B. However a similar in-depth hydric behavior is observed in all the studied sites. These soils have a significant water reserve concerning the 0-200 cm profile. Nevertheless, moisture in field capacity is never reached simultaneously on all the profile of the soils under the three studied plantations of eucalyptus (Fig. 3). These soils being very draining, the quantity of water which falls on the soil is quickly leached in-depth. In these soils, WR per unit of volume increases with depth and tends to be stabilized.

The determination of the hydric soil parameters is limited by the spatial variability from a site to another. All the studies on variability show that information obtained from a given site cannot be easily used for another. Though the objective of this study was to parameterize a model of hydric transfer transposable to any site, three distinct hydric transfer models were presented.

The mechanist model based on the physical laws of Richards (1931), characterizes well the hydric behavior of the studied soils by calculating the parameters of the Van Genuchten (1980) which links soil moisture to hydric potential. The obtained parameters show that the behavior of the soil with respect to water varies from a site to another.

The results obtained with measurements of Rainfall (R), Potential Evapo-transpiration (PET), relation between real perspiration (TR) and volumic humidity and in-depth distribution of the fine roots make it possible to simulate the evolution of the soil volumic humidity and water flows in the course of time.

Hydric statements calculated show that Eucalyptus plantations use on average 120 mm of water per year furthermore than the original savanna for the usual duration of rotation of 7 years. This increase of the water use is due to a more important transpiration of Eucalyptus, especially in dry season thanks to their deeper root system (>6 m for Eucalyptus, against <2 m for the savanna) which can reach deep layers of soil having some available water during dry season (Laclau, 2001). They also show that Eucalyptus plantations do not prevent a refill of the superficial ground waters, even if they are lesser than under savanna. The deep drainage under Eucalyptus always takes place for two reasons; (1) the annual ETP is lower on average than the annual rainfall, which explains that the climatic conditions, in particular the solar radiation, do not allow in Eucalyptus to take all the available water, (2) the soils are very filtering and in spite of a root system very developed and increasing quickly (Laclau *et al.*, 2001a,b), Eucalyptus cannot capture all soil water during heavy rainy periods.

At regional scale, ground waters refill is reduced because Eucalyptus plantations do not constitute a compact massif. Indeed, plantations are interrupted with savannas and forests gallery, though approximately a third of the territory is occupied by Eucalyptus plantations. Extrapolating results, the annual refill decrease of ground waters would be only 40 mm or less than 10% of the refill under savanna. Nevertheless it is possible that the dry years (rainfall <1000 mm), Eucalyptus plantations on ground waters are relatively more real for the populations living around plantations. The drainage decrease under Eucalyptus also can decrease the mineral elements loss risk and ground waters pollution by intrants.

These hydric statements also confirm the very good water use efficiency by Eucalyptus, because of 20% water consumption more than savanna consumption. Their annual production of biomass is twice more important (Laclau *et al.*, 2002; Saint-Andre *et al.*, 2004).

In perspective, the results of this study will allow to make on one hand (1) the simulation of the subterranean drainages using a multidimensional variable saturation model. It would be able to manage for example the infiltration the very fast in a very permeable soil and on the other hand (2) the modeling of the salt intrusion. This model will have to take into account hydrological forcing (rains, evaporation), drainage conditions upstream (in Eucalyptus plantations) and communications between various aquifers.

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