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Study of Shrinkage and Swelling Phenomena in Clay Soils of Fanaye (Middle Senegal River Valley): Simulation of Water Transfers in a Soil Column

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Abstract

Soil degradation due to shrinkage and swelling of these clay soils is a problem for agriculture. To understand the physical properties of the soils in this agricultural area, we will use an undisturbed soil monolith 60 cm high and 23 cm in diameter in the laboratory. This study quantified the swelling and shrinkage of these soils during a 10-month experiment. The determination of the hydrodynamic parameters of this monolith made it possible to simulate water transfers in a soil of constant volume and a water transfer in a soil of variable volume. The results of this simulation show significant differences between these two cases, hence the need to integrate the variations in soil volume into the simulation processes of water transfers.

Keywords

Clay, Swelling, Shrinkage-Sampling, Wetting-Drying, Hydrodynamic Parameters

1. Introduction

Drought has generated shrinkage phenomena in many clay soils. These phenomena are mainly translated by the modification of the physical properties of the soil which directly influences agriculture [1] [2] [3] [4]. These physical properties are related to the microporal volume of clay particles and their modeling depends on the size and type of sample [4]-[10].

In the Senegal River valley, simulation tests of water and solute transfers and the study of the hydro-saline functioning of the soils of the delta and the middle valley have been carried out [11] [12] [13]. These authors have shown that shrinkage and swelling phenomena are related to the nature of the soils and the circulation of water in these soils.

In recent years, this agricultural area has experienced sodization and alkalinization of the soils, which has led to a decrease in agricultural yields.

In order to understand the shrinkage and swelling phenomena, a simulation of water transfers on a column of undisturbed soil was undertaken.

These physical characteristics of the soil are often unfavorable to cultivation [10] [14] [15] [16] [17]. This is the case in Fanaye, an area known for its agriculture in the middle valley of the Senegal River. In this area, the shrinkage and swelling phenomena would be related to the nature of the soils and the circulation of water in these soils. To better understand the phenomena of shrinkage and swelling of these soils, a simulation of water transfers on a column of undisturbed soil was undertaken in the laboratory.

2. Materials and Method

2.1. Presentation of the Study Area

The study area is located in Fanaye, in the middle valley of the Senegal River. This site is located about 165 km from the city of Saint-Louis at 16˚32' North and 15˚12' West. It is drained by the Ngalenka, a defluent of the Senegal River (Figure 1).

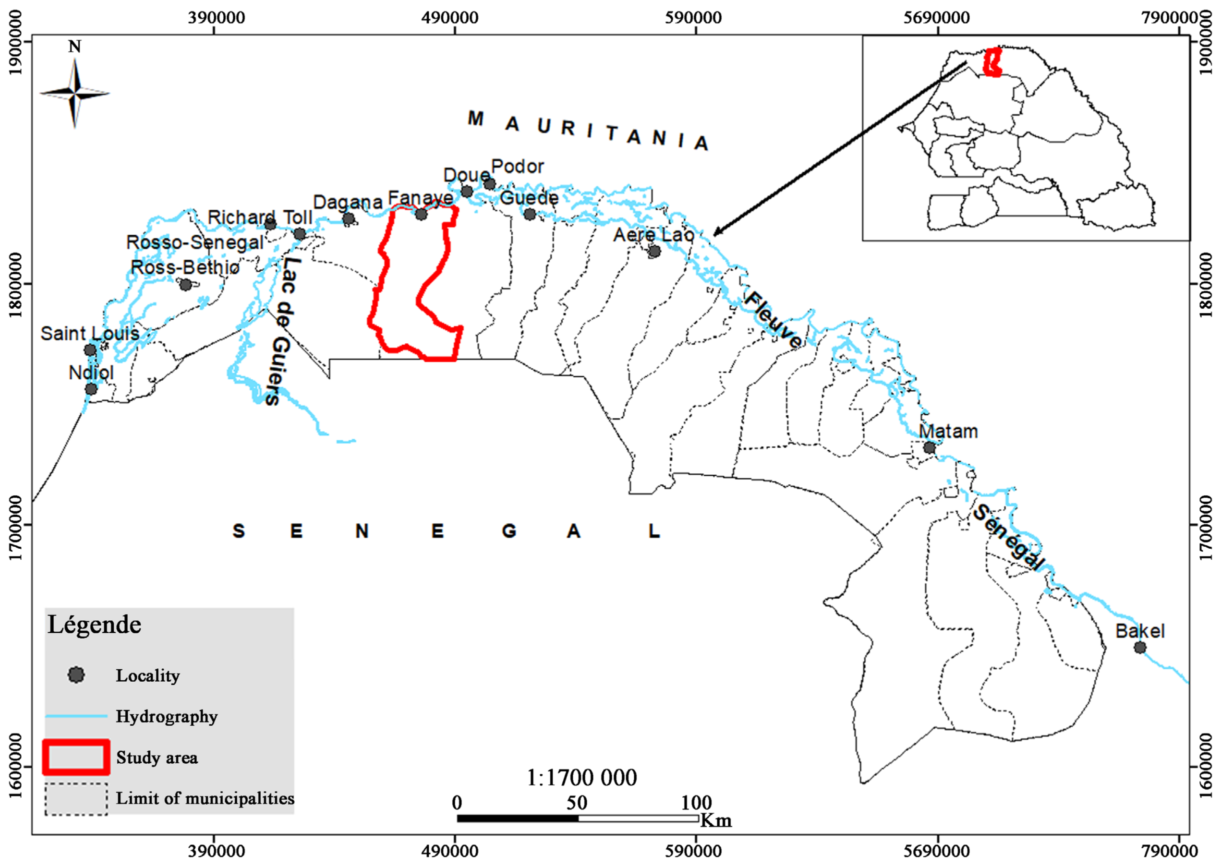

Figure 1. Location map of the Fanaye area.

2.2. Site Characteristics

The Senegal River Valley is an arid zone where the dry season lasts from November to July and the winter season from July to October. Temperatures vary between 35˚C and 45˚C.

The advance in desertification has led to the formation of shrub and tree steppes composed mainly of *Acacia adansonii*, *Balanites aegyptiaca*, *Vetiveria nigritana*, *Chloris prieurii* and *Schoenefeldia gracilis* [18].

The hydrographic network is essentially constituted by the Senegal River and its tributaries: the Bafing and the Bakoy.

The average annual rainfall varies around 200 mm/year [18].

The Senegal River valley belongs to the Senegal-Mauritania Basin. It has undergone numerous climatic and marine variations that have shaped it during the Quaternary period. This valley is characterized by alluvial and colluvial deposits. The marine transgression of the Nouakchottian period was at the origin of deposits of mud, marine, or lagoon sands but also of the formation of a system of levees and settling basins.

More recent sediments dated from the Post-Nouakchottian period have formed high sandy-silt levees, small sandy-loamy-clay levees, and fluvio-deltaic deposits.

The high parts rarely submerged are levees constituted by not very evolved soils of hydromorphic and vertic contribution. The lowest parts are occupied by settling basins constituted by vertic soils and hydromorphic soils with swelling clays of montmorillonite type (**Figure 2**) [19] [20].

3. Method

The experiment was carried out on a monolith of undisturbed soil taken from Fanaye in the middle valley of the Senegal River. This monolith is 60 cm high and 23 cm in diameter. The experiment was conducted in two phases: a wetting

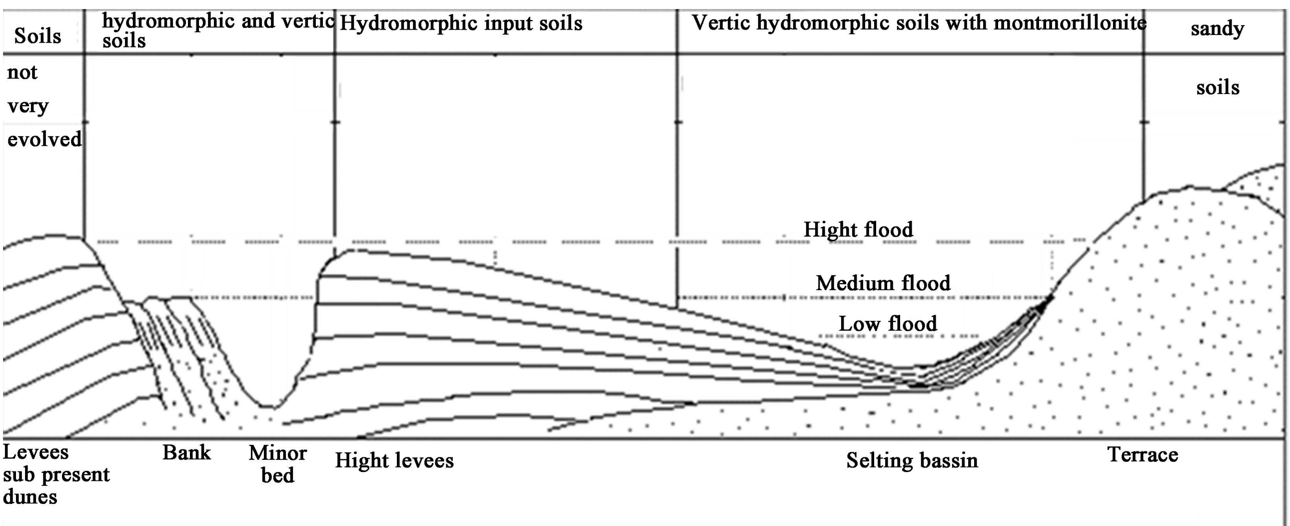

Figure 2. Schematic section of the Senegal river valley [20].

phase and a drying phase [21] [22] [23].

3.1. Experimental Phase

On the sample are placed three types of measuring instruments:

- Time Domain Reflectometry (TDR) which measures soil water content;
- Pressure sensors which measure the pressure potential of the soil and;
- Displacement sensors that measure the displacement in the soil.
- These instruments are placed at −10 cm; −20 cm; −30 cm; −40 cm; −50 cm so that there is one TDR, one pressure sensor, and one displacement sensor for each level.

There are two scales that measure respectively the weight of water that infiltrates and the weight of the soil column. In order to have continuous and regularly distributed measurements in time, all these measuring devices are connected to a data acquisition system consisting of three computers.

3.2. Determination of Hydrodynamic Parameters

The knowledge of these parameters is necessary for the simulation of water transfers. They are determined with the help of the curves $\theta(h)$ and $K(\theta)$.

3.2.1. Tracing the Curves θ(h)

Several equations allow obtaining the hydraulic conductivity curve $K(\theta)$ from the retention curve. But the most used are that of [24] and that of [25].

The Brooks and Corey equation gives unreliable results when the soil texture is fine [26], so we chose the Van Genuchten equation.

The curves allow us to better see the relationship between the soil pressure potential and the water contents: these curves were drawn with "Sigma plot", a very practical software for iterative calculations and graphical representations [27] [28].

The relationship $h(\theta)$ is one of the most important in the study of water transfers in unsaturated media. In a saturated medium, the total potential remains constant, but in an unsaturated medium, the pressure potential h varies with the water content which allows a better description of the retention curve for water content values close to saturation.

The equation of Van Genuchten was used for the adjustment of the tracing curves because it made it possible to calculate the new values of water contents, and to find the parameters which enter these formulas.

These parameters are constant for each level but they vary from one level to another:

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

Thus, for each level studied, the parameters of the Van Genuchten equation were calculated:

θ_s = water content at saturation.

θ_r = residual water content.

h = pressure potential.

n and m = empirical constant the constraints for these calculations are: $\theta_r > 0$ and $\theta_s > \theta_r$ with $n > 1$.

3.2.2. Drawing of Curves $K(\theta)$

The development of the curves $K(\theta)$ requires the values of hydraulic conductivity K and water content θ. The water contents used in the latter calculations are those calculated by the Van Genuchten equation.

The hydraulic conductivity at saturation is given by the formula which is deduced from Darcy's law generalized to one-dimensional flow:

$$q = -K\frac{\mathrm{d}h}{\mathrm{d}z}K = -q\frac{\mathrm{d}z}{\mathrm{d}h}$$

Moreover, the continuity equation imposes:

$$\frac{\mathrm{d}q}{\mathrm{d}z} = \frac{\mathrm{d}\theta}{\mathrm{d}t}q = \frac{\mathrm{d}\theta}{\mathrm{d}t}\mathrm{d}z - q_0 \quad \text{with} \quad q_0 = \frac{P}{ST}$$

K_s = the saturation hydraulic conductivity.

Q = the flux through the soil sample.

q_0 = the flux at the surface of the soil column.

P = weight of the soil column during drying.

S = cross-section of the soil column.

T = Time.

After these calculations in Excel, the values of K and θ are entered into the *sigma plot*. The curves are fitted using the Van Genuchten equation which gives new values of K as well as those of the parameters used in the equation. The curves $K(\theta)$ with the newly found hydraulic conductivities are plotted and compared to the first ones.

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

K = hydraulic conductivity.

K_s = hydraulic conductivity at saturation.

θ_s = saturation water content.

θ_r =residual water content.

m and n are empirical constants.

$$m = 1 - \frac{1}{n}$$

These curves $\theta(h)$ were $K(\theta)$ based on the results of water content, pressure potential, displacement, and weight acquired during the drying phase.

These calculations will be carried out with water contents where either a constant or a variable volume of soil is considered.

These operations will allow us to find the hydrodynamic parameters of the sample in these two cases and compare them in the case of a simulation.

3.3. Simulation of Water Transfers

The development of numerical modelling in all fields of research is justified because it allows us to anticipate a project, a problem, and consequently avoid it or bring the best solution.

It is with this in mind that soil scientists have been working on modelling water and solute transfers in agricultural environments.

3.4. Description of the Hydrus-2D Model

Several models are used to simulate water and solute transfers in soil, but the Hydrus-2D model was used in this work. This model is developed by the *U.S. Salinity Laboratory, U.S. Department of Agriculture, Agriculture Research Service*. It simulates water, temperature, and solute transfers in 2D. It uses the Richards equation which allows following the water transfer in an unsaturated medium:

$$div\left(Kgrad\left(h+z\right)\right)-c\left(h\right)\frac{\mathrm{d}h}{\mathrm{d}t}=0$$

Hydrus-2D allows the prediction of temperature and/or solute transfers, and studying a limited number of samples, it also allows the extrapolation of these transfers in space and time and for other types of soil.

Hydrus-2D includes several modules:

Hydrus-2D, the main program;

Project Manager, the module that allows you to create a project, open, rename;

Meshgen 2D, which allows the 2D discretization of the transfer area into an unstructured triangle and the definition of boundaries and internal curves;

Boundary, the module that specifies the initial and boundary conditions of the area chosen for the transfer, defines the spatial distribution of other parameters that characterize the transfer area;

Hydrus 2, the module that allows the implementation of the simulation;

Graphics allow the presentation of the results of the simulation in the form of maps, figures, and curves.

3.5. Simulation Process

The Hydrus-2D program is provided with the following information necessary for the simulation: the type of transfer (vertical water transfer); the geometric information (transfer on a column of 60 cm height and 23 cm diameter); the duration of the simulation (45 days); the hydraulic model used (Van Genuchten). Finally, the hydrodynamic parameters are introduced and the boundary conditions are defined (constant pressure at the surface and free drainage at the lower boundary).

4. Results and Discussion

The results are presented as curves for the wetting and drying phases.

4.1. The Wetting Phase

4.1.1. The Height of Infiltrated Water

Figure 3 shows that the height of infiltrated water increases with time.

4.1.2. The Variation in Height of the Column

Figure 4 shows that the height of the column varies around 2.75 cm during the first twenty days of wetting and then stabilizes over time.

4.2. The Drying Phase

4.2.1. Water Content Variations

Figure 5 shows that between the surface and 20 cm depth, the water content in

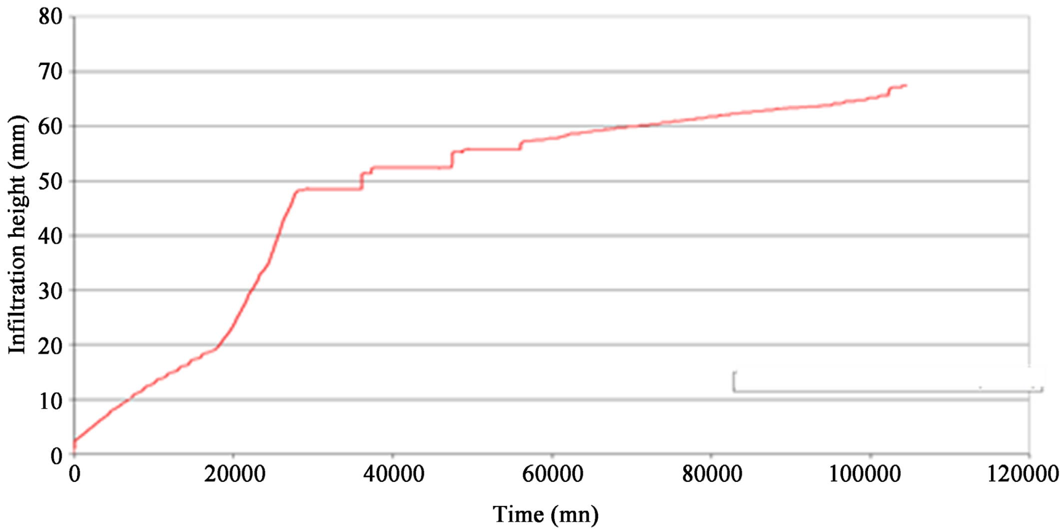

Figure 3. Evolution curve of the infiltrated water height during infiltration.

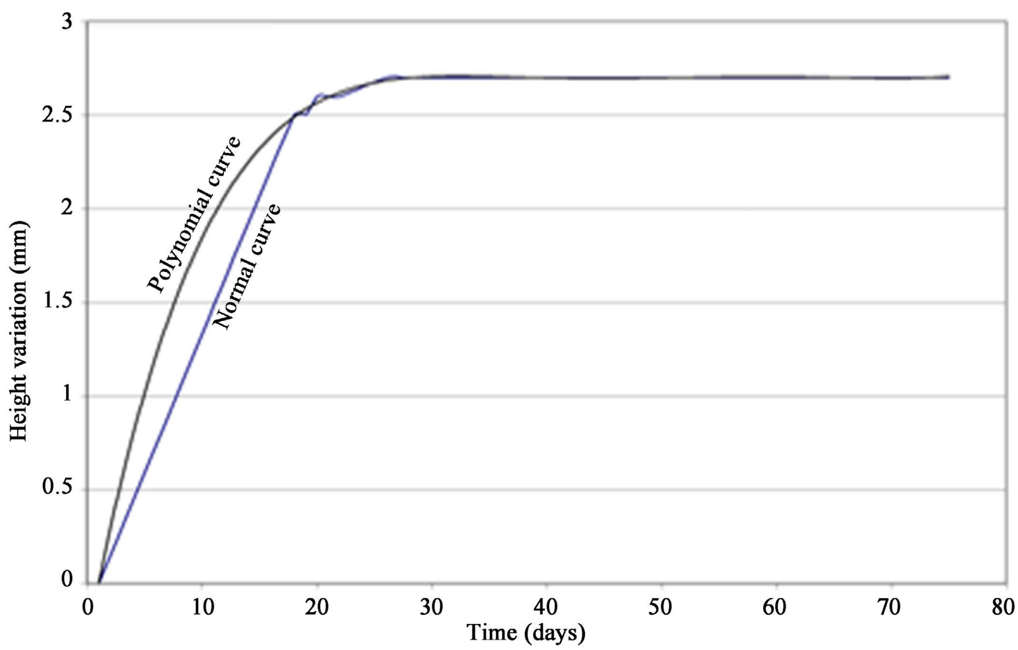

Figure 4. Curve of the column height evolution during the infiltration.

the column varies significantly from the beginning of the drying to the end of the experiment. However, at the bottom of the column, between 40 and 60 cm in depth, the water contents hardly vary. We do not have data from the fourth level (−40 cm) for which the TDR could not work properly.

4.2.2. Pressure Potential Variations

The variations of the pressure potential inside the column are shown in Figure 6 below. It shows that the pressure potential varies over the whole column during the drying process, with notable differences when moving from one level to another. The variation of the pressure potential is important at the surface (−900 mb) and very rapid during the drying time. The greater the depth, the smaller this variation is and it tends to stabilise from the surface towards the deep levels from about 330,000 minutes. This stabilization time increases with depth.

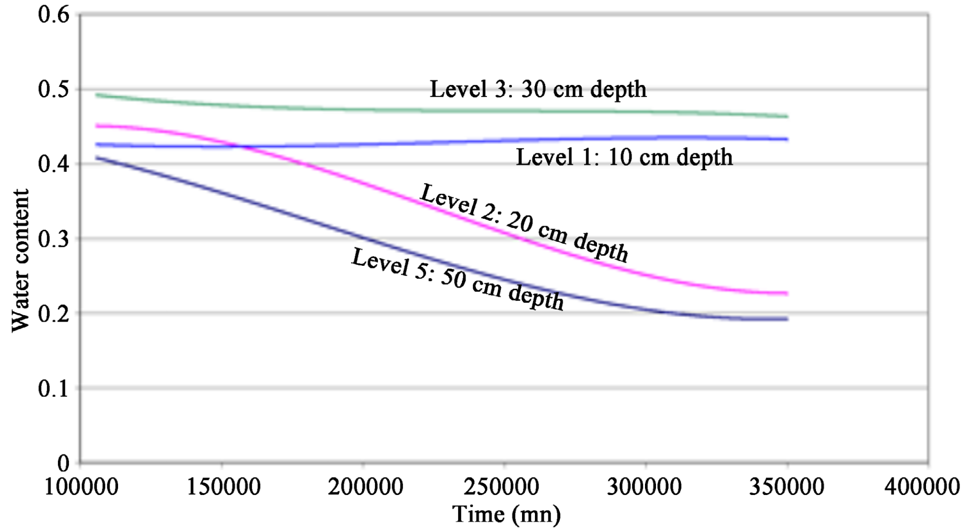

Figure 5. Water content variation curve during drying.

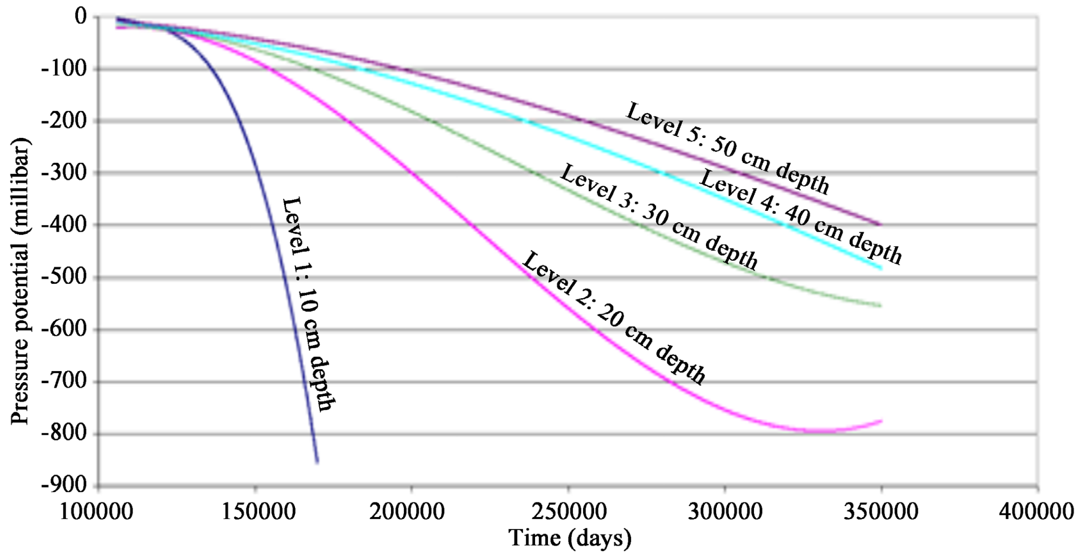

Figure 6. Change in pressure potential during drying.

4.2.3. Displacement Variations in the Column

These variations can be vertical as well as lateral.

1) The vertical displacement

Figure 7 shows a reduction in height of about 2 cm during drying. It shows that the displacement is more important at the surface and that the measurement of a height variation of the whole column is not sufficient to quantify the displacement in the soil.

Soil movement in the first three levels decreases as the drying time increases while the last levels do not move.

The variation in soil volume is more significant at the surface (levels 1 and 2), where there is a reduction of about 10 mm for the first level and about 5 mm for the second, which does not affect the bottom of the column (Figure 8).

These figures show that the displacement is not uniform in the soil during drying: it is more important on the surface and the measurement of a variation in height of the whole column is not sufficient to quantify the displacement in the soil.

4.2.4. The Variation of the Weight of the Column

The weight of the column was monitored throughout the drying process and its evolution is shown in Figure 9 below. This figure shows that the weight of the column has strongly decreased from 75 kg at the beginning of the experiment to 71.3 kg at the end of the experiment; that is to say a weight loss of 3.7 kg which allows calculating the evaporation flux. More than weight loss, water content, and pressure potential are important data in that a relationship can be established between these two parameters by plotting the $\theta(h)$ curves for each level

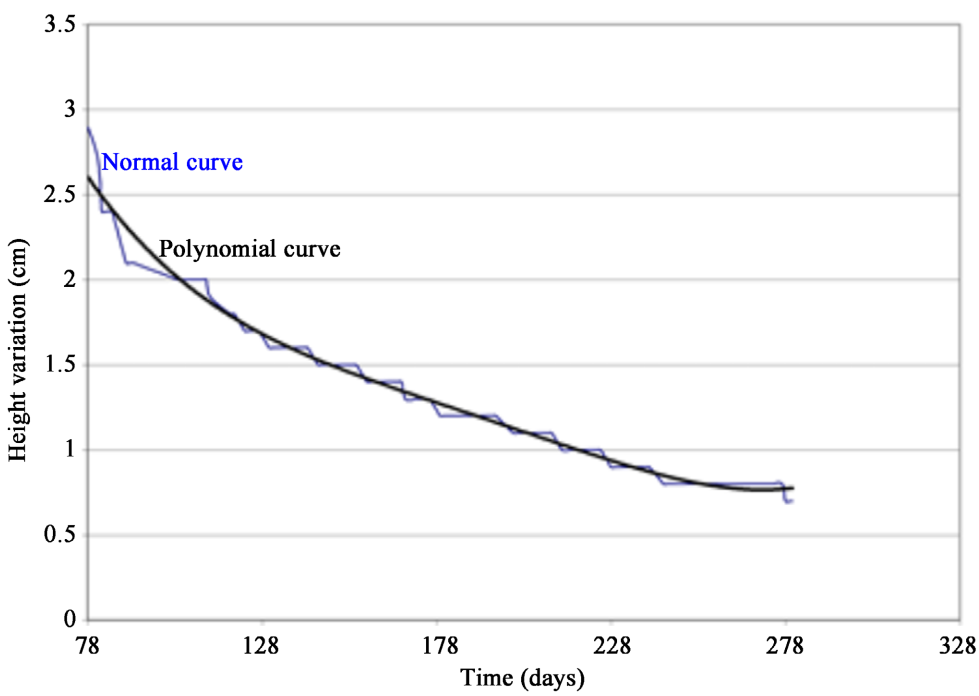

Figure 7. Variation of the height of the column.

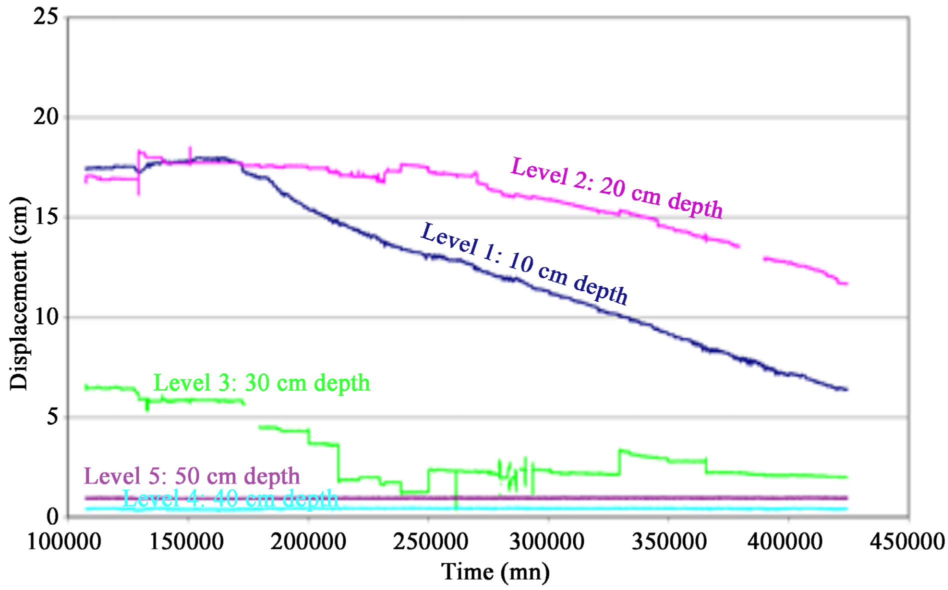

Figure 8. Variation of vertical displacement in the soil column.

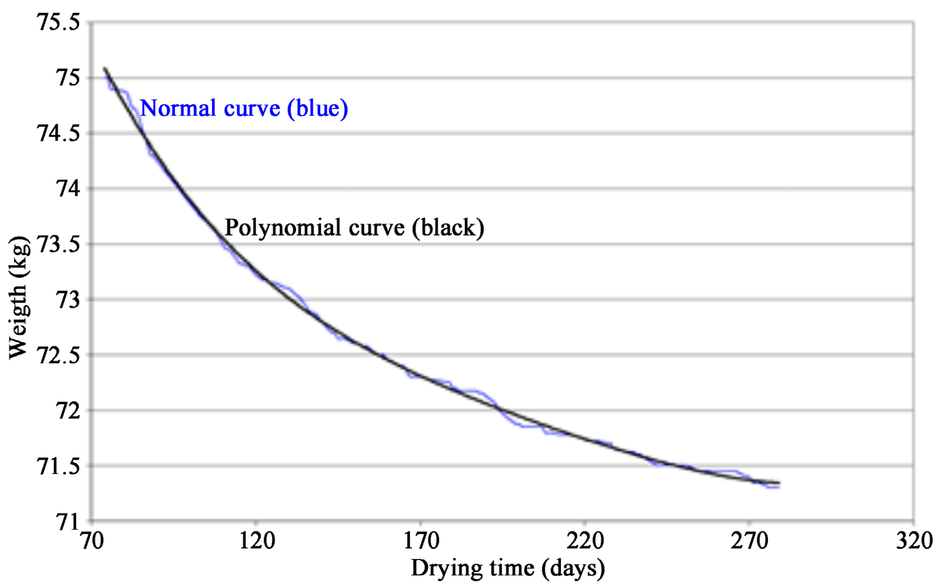

Figure 9. Evolution of the weight of the column during the drying phase.

during drying.

4.3. Digital Modeling

4.3.1. Determination of Hydrodynamic Parameters

Without volume variation

Curves $h(\theta)$ and $K(\theta)$ at 10 and 20 cm depth (Figure 10 and Figure 11)

The parameters in Table 1 were obtained by curve fitting $\theta(h)$ (of the experimental data) with the Van Genuchten Equation (a):

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

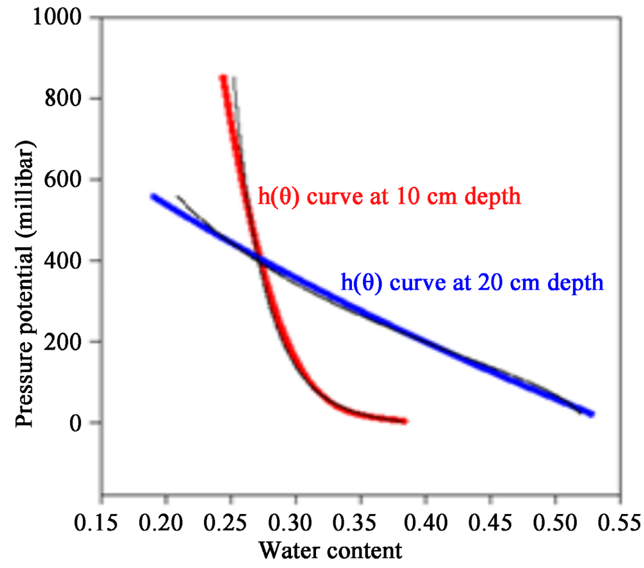

Figure 10. The $h(\theta)$ curve.

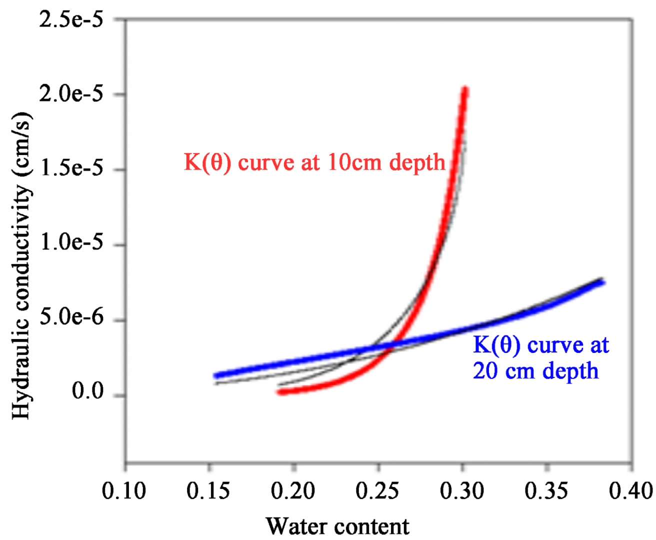

Figure 11. The $K(\theta)$ curve.

Table 1. Hydrodynamic parameters for an assumed constant soil volume.

Parameters	Level 1	Level 2
θ_r	$5.203 * 10^{-9}$	$2.4746 * 10^{-9}$
θ_s	0.3065	0.3911
K_s (cm/s)	$1.805 * 10^{-5}$	$1.495 * 10^{-5}$
α	0.0765	$4.22 * 10^{-3}$
n	1.113	1.989

With volume variation

Curves $h(\theta)$ and $K(\theta)$ at 10 and 20 cm depth (Figure 12 and Figure 13)

The hydrodynamic parameters of the soil column (Table 1 and Table 2) show

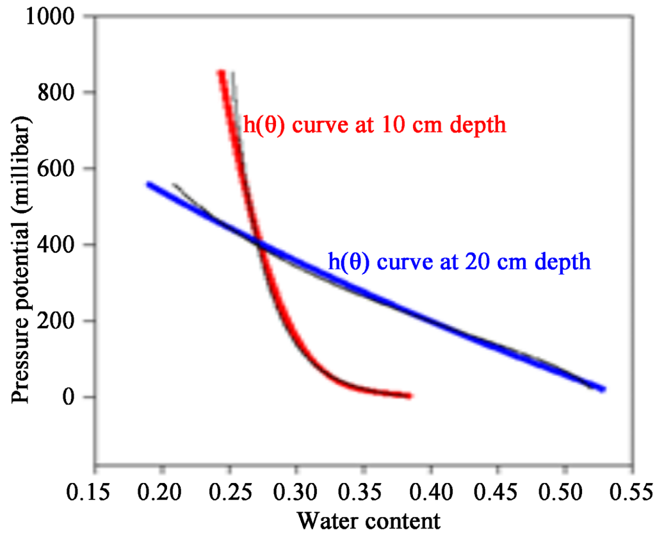

Figure 12. The $h(\theta)$ curve.

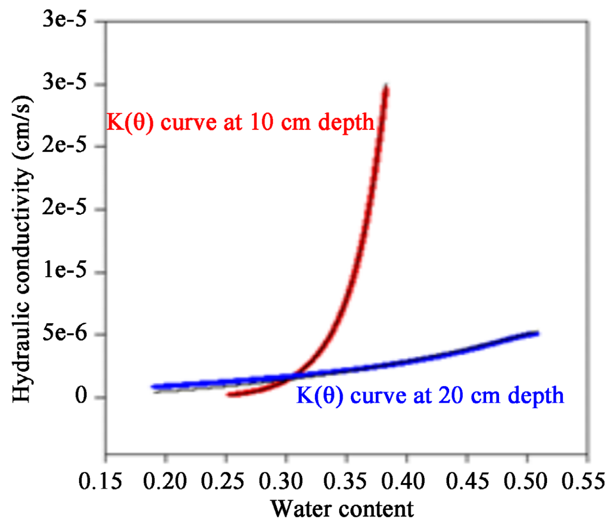

Figure 13. The $K(\theta)$ curve.

Table 2. Hydrodynamic parameters for a variable soil volume at 10 cm and 20 cm.

Parameters	Level 1	Level 2
θ_r	$5.767 * 10^{-9}$	$3.339 * 10^{-9}$
θ_s	0.3912	0.5215
K_s (cm/s)	$3.8 * 10^{-4}$	$2.887 * 10^{-5}$
α	0.1035	$4.237 * 10^{-3}$
n	1.097	1.964

a difference between the two cases considered. They will be used for the numerical modelling of water transfers in the soil column. Our results give higher hydraulic conductivities at saturation when the variation in soil volume is taken into account. The modeling was done with the drying data of the first two levels.

4.3.2. The Results of the Simulation

A constant soil volume

If we consider a constant volume over time (Figures 14-19), the curves obtained by the Hydrus-2D model show a decrease in the pressure potential which stabilizes and is cancelled out from the thirtieth day of infiltration at the surface and around the thirty-fifth day for the deeper levels (Figure 14).

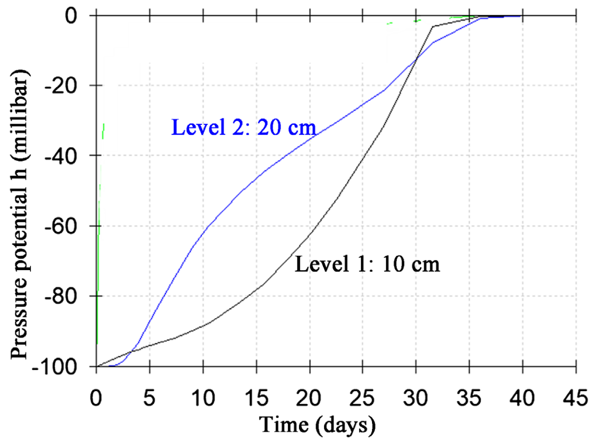

Figure 14. Variation in pressure potential.

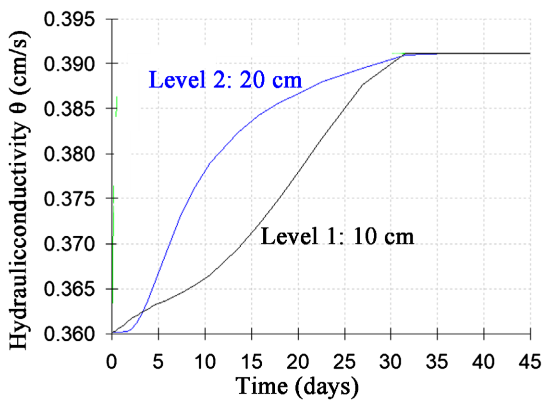

Figure 15. Variation in water content.

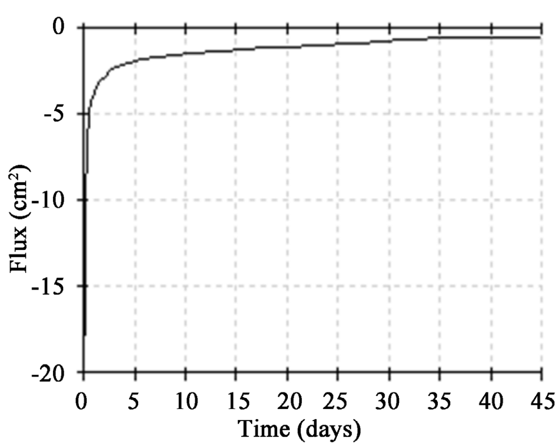

Figure 16. Variation of input flow.

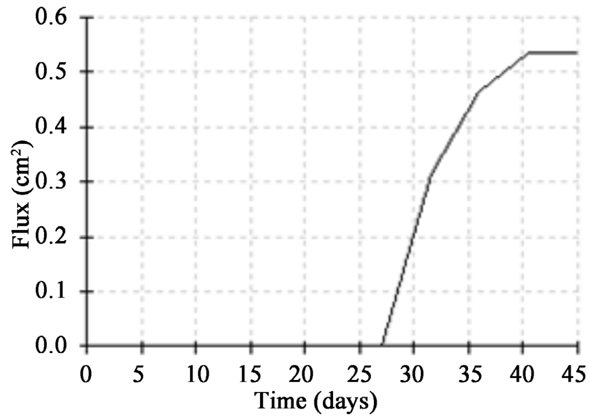

Figure 17. Variation of the output flow.

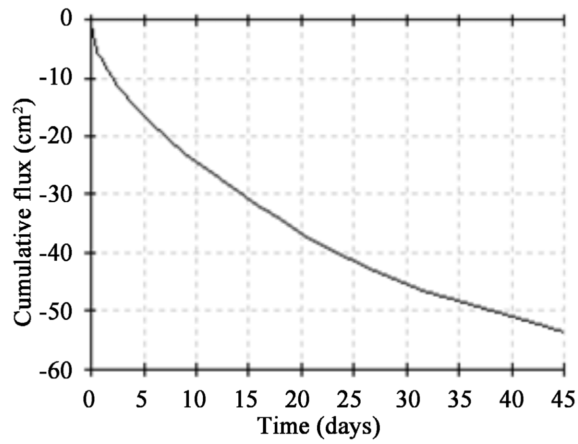

Figure 18. Cumulative input flow.

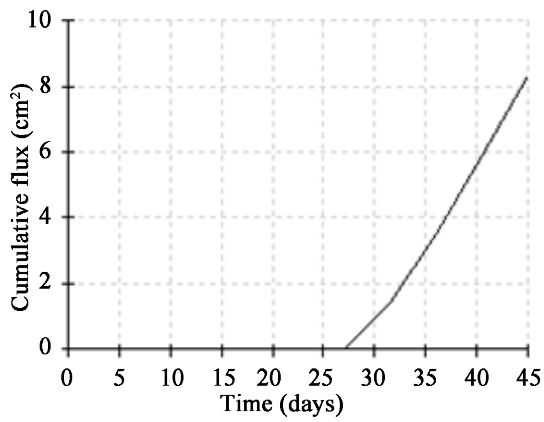

Figure 19. Cumulative output flow.

The retention curves show that the reduction of the pressure potential in the soil (Figure 14) is related to an increase in the water content.

Water content increases during infiltration and stabilizes when the sample is saturated from day 30 onwards (Figure 15).

The infiltrated fluxes vary very rapidly from the first day of infiltration and tend towards equilibrium over time. This infiltrated flow stabilizes at a low value from the thirtieth day of infiltration (Figure 16).

However, the outflow is not materialized until day 27 and reaches values of 0.5 cm/day at the end of the simulation (Figure 17).

The cumulative fluxes during the 45 days of infiltration are 55 cm^2 and 8.5 cm^2 respectively for the inflow and outflow (Figure 18 and Figure 19).

If we consider a variable volume of soil, which is more reflective of reality, we also have a decrease in pressure potential (Figure 20) accompanied by an increase in water content (Figure 21). However, the time required for the stabilization of the system is shorter; it is 20 days for the saturation of the sample which is manifested by very low to zero pressure potentials and high water contents (Figure 20 and Figure 21).

The values of the inflow are larger (of the order of 90 cm^2) for the whole duration of the simulation (Figure 22 and Figure 24).

This is also the case for the outlet flows which are not only more important (with values of 25 cm^2) but also the drainage time which is shorter. In fact, we note an outlet flow from the twentieth day of infiltration (Figure 23 and Figure 25).

The analysis of the simulation results shows a difference in the time required for the saturation of the soil sample, a difference in the start of drainage, and a

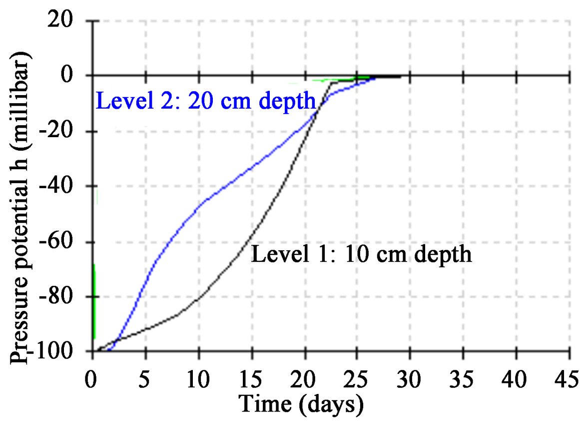

Figure 20. Variation in pressure potential.

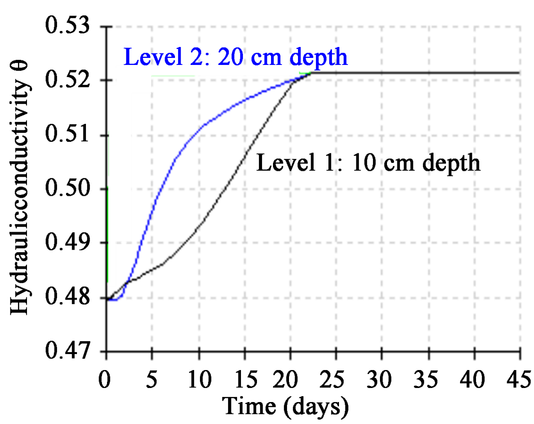

Figure 21. Variation in water content.

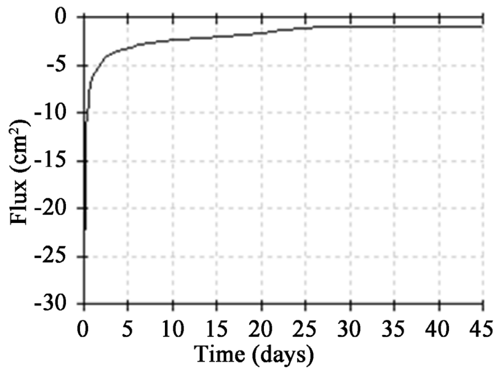

Figure 22. Variation of the input flow.

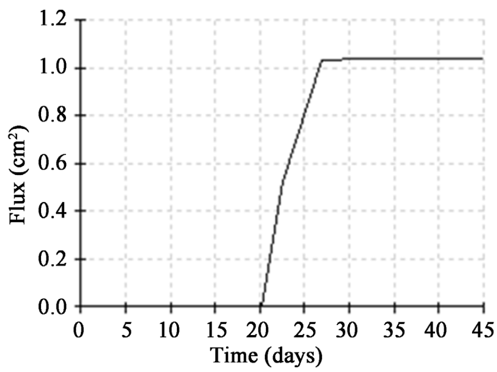

Figure 23. Variation of the output flow.

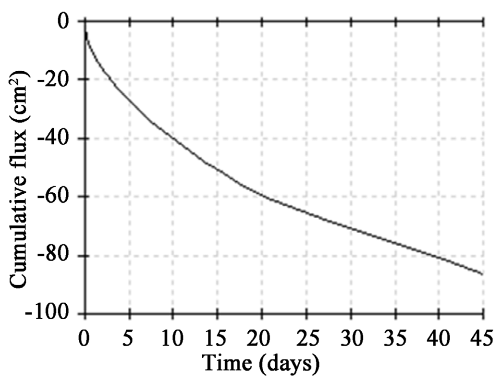

Figure 24. Cumulative inflow.

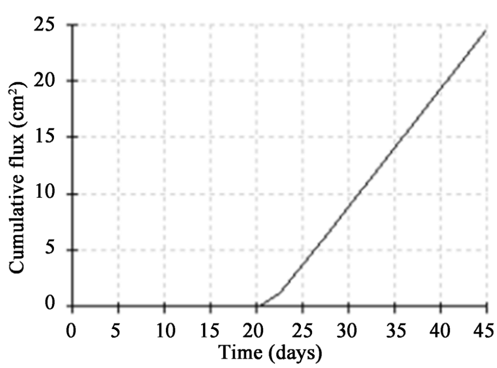

Figure 25. Cumulative outflow.

difference in the quantification of the infiltrated and drained flows.

The determination of the error on the quantification of the input and output flow can be done as well as on the drainage time:

$$\frac{\Delta F}{F} = \frac{90-55}{90} * 100 = 39\% \quad \text{and} \quad \frac{\Delta t}{t} = \frac{27-20}{27} \times 100 = 26\%$$

These errors are not negligible, hence the need to take into account the variation in soil volume when simulating water transfers, as recommended by authors such as [29] in the modelling, not of water transfers, but of the shrinkage curve.

The studies carried out, therefore, show the importance of soil shrinkage and swelling phenomena in the simulation of water transfers in this agricultural area. These results confirm [9] who showed that a high soil swelling shrinkage capacity makes it difficult to grow plants because their roots can break.

The interest of our study is also illustrated by [30], who shows that the taking into account the phenomena of shrinkage-swelling and cracking, at the time of the infiltration of water in clayey soils, makes it possible to improve the prediction of the water balance in this type of soil. [11] showed that the hydraulic conductivity decreased when the clay content increased in depth.

This experiment on an undisturbed soil monolith of this size confirmed the variability of soil volume and hydrodynamic parameters along the profile.

5. Conclusions

The exploitation of the data acquired in the laboratory showed the relationships between the variations of water content, pressure potential, and displacement. Thus, the volume variation of the soil sample occurs both vertically and laterally during infiltration and during drying. It takes place at the surface as well as at depth and ultimately the calculated hydrodynamic parameters change from one level to another in the soil column.

The analysis of the curves of variations in water content, pressure potential, weight, and horizontal and vertical displacement shows the relationship between the variation in water content and the variation in the volume of the soil sample. This loss of water during drying is a very slow process and only affects the first three levels. It is accompanied by an increase in the pressure potential of the soil which is felt at all levels of the soil column. The resulting shrinkage occurs both vertically and horizontally. For a correct determination of the hydrodynamic parameters necessary for a numerical simulation, it is important to integrate the volume variations of the soil.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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