Field examination of the hydrological behaviour of a typical vertisol in a cropped area

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in

Santini A. (ed.), Lamaddalena N. (ed.), Severino G. (ed.), Palladino M. (ed.).
Irrigation in Mediterranean agriculture: challenges and innovation for the next decades

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 84

2008
pages 115-123

Field examination of the hydrological behaviour of a typical vertisol in a cropped area

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Abstract. The site was selected in a cropped area on a typical vertisol, fairly uniform in depth, down to about 2.5 m. It was difficult to install anchored rods and piezometers at different depths (0.2-0.3-0.4-0.5-1-1.5-2 m and 2.5 m for piezometers).

Soil moisture was monitored for a certain time by drilling the ground and soil samples were dried in an oven.

Cases studied were: (A) a period of dry months with severe drought (10.4 mm in 132 days);(B) a second period with exceptionally uniform precipitation (about 3.5 mm/day during 2 months). These seasonal conditions permitted the following observations: for (A) the swelling of the soil in the lower extreme cannot be strictly compared to Philip's (1969) concept of a free expansion of the water ponding on soil due to the overburdening of different conditions; for (B) the expected tendency to begin a stationary water flux depends strongly on the water regime in the previous period. In a dry period, the water accumulates in the deepest piezometers, being fed by water from the upper source at a progressively increasing rate of water rise. The regime of stable water flux is therefore delayed. The hydraulic conductivity changes in different soil layers according to the water content.

Keywords. Piezometers – Swelling soil – Vertisol – Water table.

Observations de terrain du comportement hydrologique d'un vertisol dans un champ cultivé

Résumé. *Les sols gonflables sont caracterisés par des phénomènes de distribution des efforts entre la phase solide et liquide. L'ouvrage aborde plus particulièrement les difficultés de l'implantation verticale des tiges de métal et des piézomètres à différentes profondeurs (0,2-0,3-0,4-0,5-1-1,5-2 m pour les tiges de métal et 2,5 m pour les piézomètres) dans un vertisol. L'humidité a été quantifiée pendant deux ans en perforant le terrain et, la mesure directe de la teneur en eau des échantillons a été faite par séchage.*

On a examiné deux situations météorologiques différentes. (A) une saison caracterisée par une période sèche (10,4 mm de pluie en 132 jours) et (B) une saison humide avec une pluviosité exceptionnellement uniforme (3,5 mm de pluie par jour pendant deux mois). Ces conditions climatiques ont permis les observations suivantes : dans la phase sèche (A) le gonflement des argiles est nettement différent par rapport au schéma de libre expansion proposé par Philip (1969), à cause de la présence d'une nappe phréatique d'environ 2.5 m de profondeur ; dans la phase humide (B) le flux des eaux n'est pas stationnaire et dépend avant tout du régime hydraulique au début de la période des pluies. Dans ce contexte, en période sèche l'eau s'accumule dans les piézomètres les plus profonds, alimentés par l'eau dérivant de la source supérieure à un taux croissant de rémontée. Ce phénomène se produit lentement initialement, et s'accélère avec de l'infiltration de l'eau. La conductivité hydraulique change dans les différentes couches du sol en fonction de leur humidité.

Mots-clés. *Piézomètres – Sol gonflable – Vertisol – Nappe phréatique.*

I – Introduction

The contribution of the soil swelling process to the distribution of the total mechanical stress between solid and liquid phase according to a load factor is considered under field conditions. The field observation of a swelling soil rich in clay (vertisol) is not common due to certain organizational issues such as finding an agricultural area with this kind of pedology (Talsma, 1974) or the possibility to install equipment required by the research and then verify if there is an underground water accumulation. Under these conditions researchers have found difficulties in monitoring the water balance in the profile, which would be useful to better understand and rationalize the cropping system in the area.

For these reasons, notwithstanding some organizational drawbacks, it was decided to install some instruments to start a first examination of the hydrology of these swelling soil systems in a cropped area.

II – Material and methods

The experimental area considered is situated on the Emilia-Romagna plain. The soil is a vertisol classified as “Ustic endoaquerts fine mixed mesic”, series Risaia del Duca (Benciolini, 1996), Eutric Vertisols according to the FAO classification. The initial profile of the considered soil surface is given in Fig.1. The soil is very deep, apparently fairly uniform, and rich in slickenside formation at least in the upper part of the profile. It was considered to have had deep underground water (“suolo di valle”) in the past. The usual tillage depth is about 0.35 m. The rainfall regime was recorded by a weather station 100 m far from the experimental site. During the rainy season (winter) the surface soil becomes sticky and access to the experimental area is difficult; in the dry season (summer) visible cracks remained on the soil surface for a depth of 0.2-0.4 m.

Figure 1. Distance from the left side of the field.

The succession of crops grown in the area were wheat, maize, barley, and sugarbeet, never irrigated during the experimental period (Fig. 2). The main characteristics of the tilled soil (0.35 m) are: 72.8 % clay (< 0.002 mm) and 26.8 % silt (0.02-0.002 mm); moisture θ_g at wilting point, 1500 kPa, 27.8 % and at field capacity, 33 kPa, 38.6 %; clay minerals are smectite 31 %, illite 54 %, kaolinite 9 % and chlorite 6 %; lime 18 %, pH (1:5) 8.2.

The plot was 41 m long x 1.5 m wide and accommodated two randomized replications of anchored rods and piezometers (Fig. 3 a,b,c) along the top line of a field transversally shaped as a near elliptical surface (mean transversal height difference 0.4 m between borders of lateral drainage ditches).

The bores for the installation of the rods and piezometers were drilled on October 17 of 2001 by the firm GEOTEA of Bologna. At the same time the cores of the deepest bores (approximately 2.5 m from soil surface) of both replications (a, b) were taken for sections roughly corresponding to 0.50 m. The soil parameters given by the firm suggest that the bottom of the considered soil profile should be quite near to a lower water table (somewhat deeper than 2.5 m) and that the soil properties change adequately. Immediately after cutting, the sections from the cores were put in impermeable cases and then taken to the DiSTA laboratory. Each section was divided into two parts and on each of them textural analysis (pipette method) and gravimetric soil moisture determinations were performed.

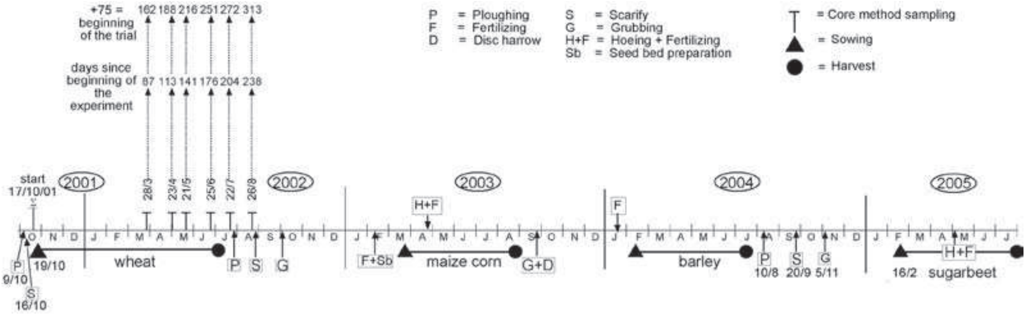

Figure 2. Distribution of crops and cultural operations during the experimental period.

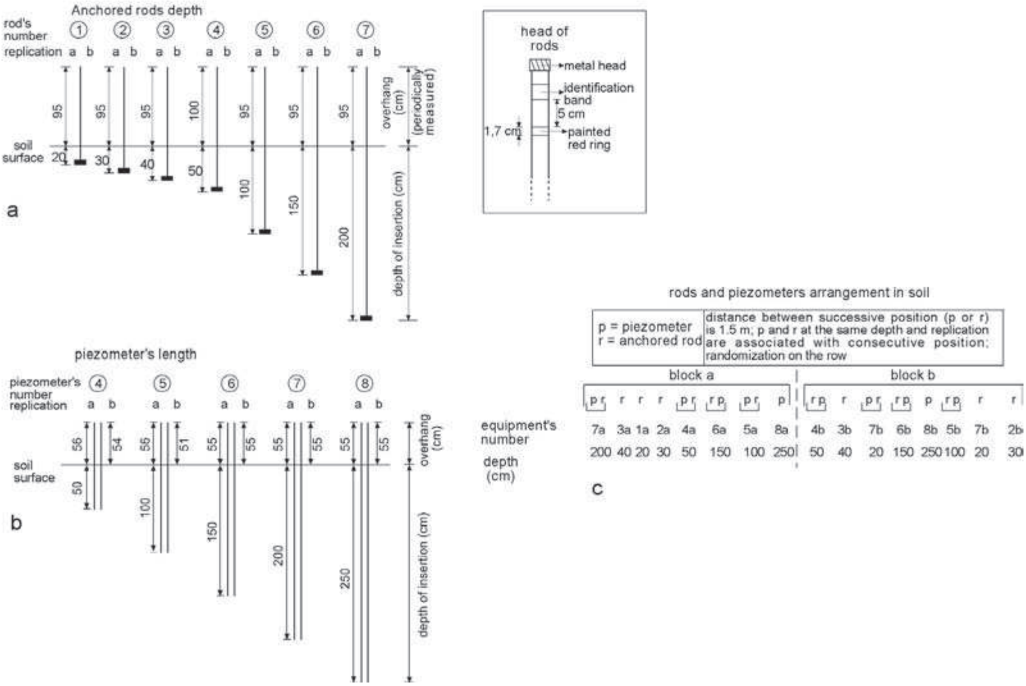

Figure 3. Depths of the rods (a), piezometers (b) and their randomization (c).

A representation of the clay fraction (less than 0.002 mm) variation along the profile of both replications, as well as their mean, is shown in Fig. 4. The analogous variation of moisture content as θ_g (as $m^3\ m^{-3}$ of dry soil) is shown in Fig. 5. Examination of fig. 4 shows that the mean clay content (%) remains fairly uniform along the soil profile and shows relative minimum (52.5-57.5%) at a depth of 1.53 m and maximum (70.0% - 71.5%) near the soil surface at about 0.13 m depth. The role of both moisture and clay content on the dry bulk density can be only analysed taking the approximated dry bulk density as a dependent variable and θ_g and clay as independent variables for a multiple regression. The data from both replications show a high correlation (R^2= 0.99) with the dominant effect of the moisture θ_g (Fig. 6) and a lower effect of the clay content in this range.

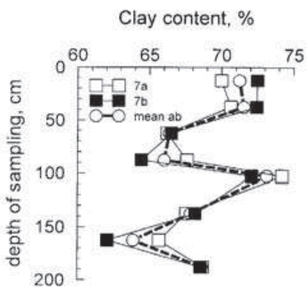

Figure 4. Clay content function of depth.

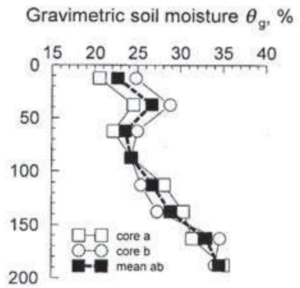

Figure 5. Water content in the soil profile.

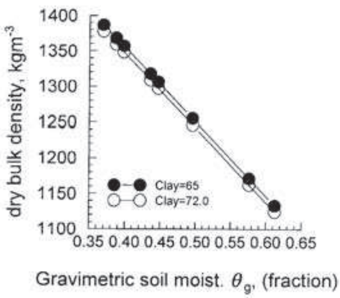

Figure 6. Gravimetric moisture function of depth.

Under the conditions of this experiment a deeper underground water table was suspected for which the anchoring system suited to a rigid soil (as Talsma and Van der Lelij, 1976) was inadequate; it was therefore decided to fix the a metal disc (0.08 m diameter and 0.02 m thick) to the lower end of the rods. The distances of the rods from the soil surface were: 0.2-0.3-0.4-0.5-1.0-1.5-2.0 m.

The piezometers consisted of plastic tubes (0.08 m diam.) extending out of the soil surface 0.5 m, with the lower end of the piezometers at the following depths: 0.5-1.0-1.5-2.0-2.5 m.

1. Moisture monitoring

For the evaluation of the moisture along the soil profile and its change throughout the trial, fifteen profiles were investigated during the wheat and maize growing season from 27/11/2001 to 6/11/2003. Each profile was perforated at a lateral distance not less than 1.5 m from the alignment of the rods and piezometers (2 or 4 replications monthly) using an auger (5.5 cm diam.) and taking samples at selected depth intervals. The soil water content of the samples was determined gravimetrically in an oven at 105 C°.

A first precaution was that in order not to disturb the successive observations all auger holes were perforated under the nearby wheat or maize plants. Otherwise the moisture determinations could have been vitiated due to the uptake of water from the crop plants to meet the evapotranspiration and any rainfall in the upper layer.

The second, more general risk was that a compression effect by the auger could squeeze out part of the soil water content from the soil sample. It was considered that assuming no residual air content when the soil saturation was reached, the water content (θ_g, fraction) of a sample could only be valid if there was in the soil before sampling:

$$\theta_g \leq \rho_l \left(\rho_b^{-1} - \rho_s^{-1}\right) \quad (1)$$

where ρ_l, ρ_s are respectively the mass per unit volume (kg m^{-3}) for water and solids and ρ_b is the dry bulk density. This limit is wide in the present case, where the maximum θ_g found in the lower soil levels is about 0.59 and the corresponding ρ_b is 1149 or less for a wetter soil.

The analysis of variance of the data from both replications was performed according to the classical design of randomized blocks.

III – Results

2. Moisture variation

Fig. 7 shows the tendency of the moisture to increase when moving downwards. From the evaluation at intermediate times there was for all depths a constant deviation from a linear regression line. Given the apparent correspondence at certain times and depths it seems that there must be some reasons to explain the higher moisture at about 1.80 m compared to the values at local 2.00 m. This rather surprising behaviour is not confirmed by the clay and moisture variation as in Fig. 4 and Fig. 5. As described in Fig. 7 (b and c), these anomalies appeared mainly when the determinations of moisture were extended to 5 different depths.

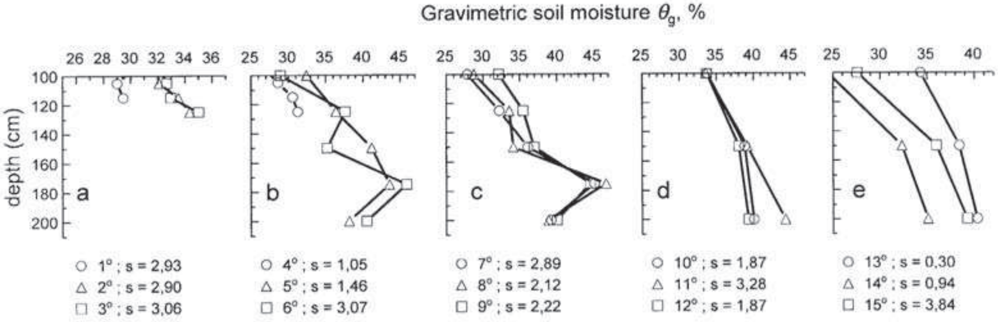

Figure 7. Gravimetric soil moisture at different depth and time.

2. Displacements of rods

Fig. 8a demonstrates that the alignment of the rods is still usually evident and seems to suggest that the process did not appreciably change along the transept. If we analyse in detail the change in time (Fig. 8b) of the top soil (about 1 m), it is evident that the curvature is upward; on the contrary the curvature is not so for the lower layers at about 2 m.

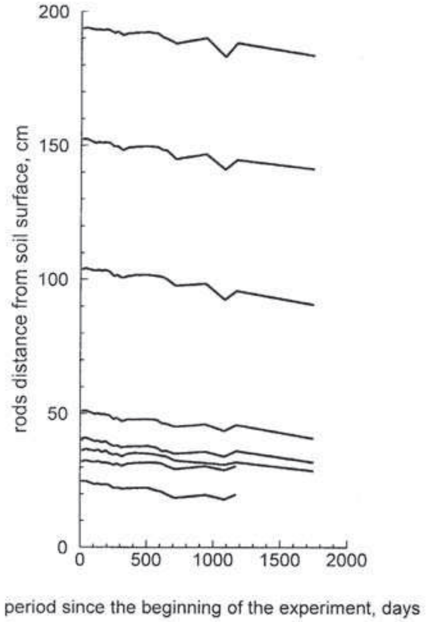

Figure 8a. Variation of the rods height.

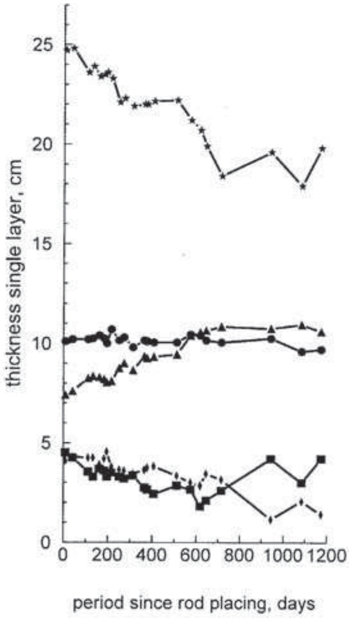

Figure 8b. Differences between layers in the first period.

3. Piezometers examination

The data recorded for each piezometer, after averaging between two replications, are synthesized in Fig. 9. A discontinuous perched water table is evident inside the upper 0-0.50 m layer. It includes 4 episodes with high water levels in the piezometer readings. Their water table only exceptionally reaches the surface soil (possible ponding) in the 2^{nd} and 4^{th} episode. In the 2^{nd} episode a connection with the lower aquifer occurred. The piezometers measure the "submersion potential" at the point reached by the lower opening of the tube; this potential includes

$$\varphi = P + z \tag{2}$$

where Φ is the submersion potential (in m), *P* is the hydraulic pressure (in m) at that point, and ***z*** is the gravitational component (in m). It is interesting to note that an upper piezometer often starts before the lower piezometers and reaches its basis, which demonstrates that the water is flowing from above. The graphs of the lower piezometers are often more skewed. In most cases the level of water in the lower piezometers does not reach the level of the water in the upper piezometers (there is a difference of submersion potential) showing a potential gradient promoting the descent of the water. The excursion of the submersion potential is mostly greater, the deeper the piezometers are inserted. These considerations prompted us to evaluate the speed of water rise in the piezometers (differences of values at consecutive registration (d*h*) divided by the difference in time of registration (d*t*); this means the derivative d*h*/d*t*). Fig. 10 shows that this speed increases appreciably with the piezometer depth. In the deepest piezometers the graph is continuous and shows a periodicity similar to that of the rainfall. The greater speed in the fluctuation of the lower piezometers suggest a higher hydraulic conductivity in these layers. This could be explained by higher θ_v content (less probable for some reduced porosity). The first explanation seems more acceptable and implies that the moisture θ_g increases downwards along the profile (Fig. 5).

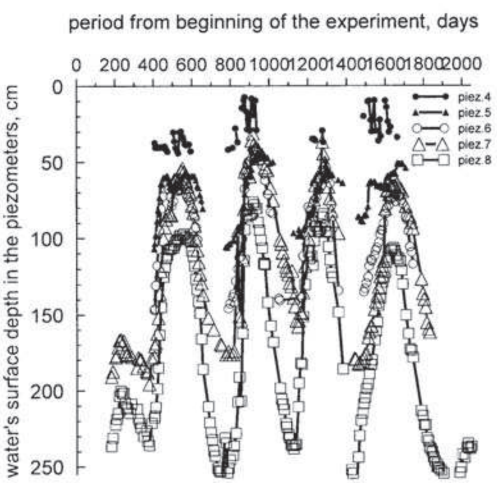

Figure 9. Superimposed water level in the piezometers at different depth.

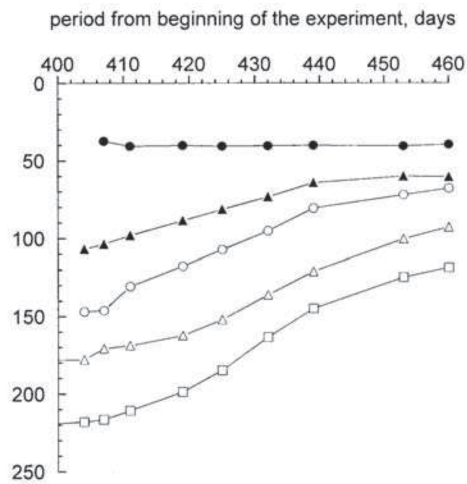

Figure 10. Variation of water levels in the piezometers (phase B).

IV – Discussion

It is notable that the variability of the pressure in the piezometers is minimum in the more superficial piezometers and greater for the deeper layers at 2.5 m (Fig. 11).

The empirical observations clearly show how complex are the processes involved in the practical conditions mostly dominated by the meteorological fluctuations (Fig. 12). Among the experimental times two occasional meteorological periods were found to promote interesting discussion. Period A, in which an initial prolonged time of severe drought occurred from the beginning of the observations (17 October 2001; 10.4 mm in 132 days) and period B characterized by a daily rainfall of 3.5 mm.

In the first rainless period the soil system apparently moved gradually towards a near static water condition. In effect it is well known (Childs 1969) that for given constant potential evaporation in the air (I_p), the effective loss of evaporation from a water table (W.T.) under the surface of a uniform soil decreases with increasing depth of the W.T., though more with coarser soils. This means that during the conditions for model A the water in the soil profile should tend gradually to approach a static equilibrium, though not rigorously so, as recognised by Talsma *et al.* (1974). These latter authors define "apparently stable conditions", such as those taken at single traits of this static model (Fig. 12). When analysing the first period A, a simplification of the model is useful assuming the texture and the fine structure to be vertically uniform. This hypothesis is assumed valid down to depth 0.35 m previously analysed (Cavazza *et al.*, 2006). At the lower boundary of the model a fixed W.T. level is to a depth of 2.5 m (the end of the deepest piezometers). This can represent a W.T. connected to a wide area. Assuming that Fig. 12 represents the state of equilibrium expected, starting from the lower boundary one expects to find a swollen soil and a somewhat reduced solid constant. If the W.T. increases the soil water content should increase due to the possible entering of water from interconnected W.T. but there is a reduction owing to the manifestation of the overburden component of water in this soil that reduces upwards. When waterlogging exists, there are conditions of continuity up to the water-air surface boundary so that the soil material can freely expand up to its swelling capacity (including colloidal suspension; Fig. 12); in the present model, on the contrary, the soil swelling is limited by the local Ω component.

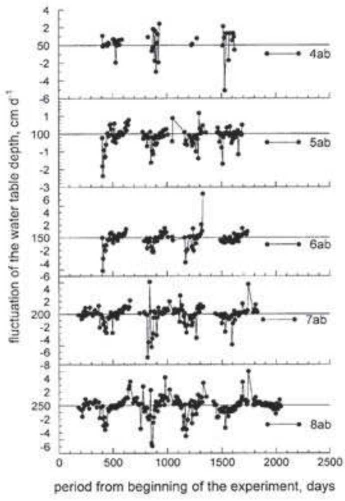

Figure 11. Fluctuation of water in piezometers.

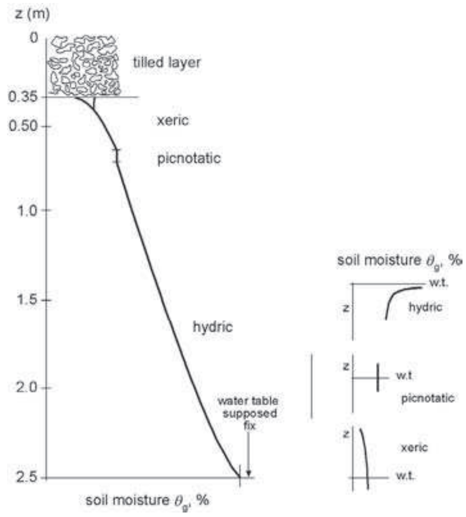

Figure 12. Diagram of the water potential in a soil with water table.

The equilibrium conditions for the total water potential Φ in the case of model A were therefore:

$$\Phi = z + \psi + \Omega \tag{3}$$

where z is the gravitational potential (≥ 0) measured from the W.T.; ψ is the matric potential (< 0) corrected by the height (i.e. as given by common techniques); Ω is the overburden potential (indicated by Talsma, 1974, as apparent steady flow):

$$\Omega = \alpha \int_{z}^{0} g\, \rho_{\mathrm{bw}}\, \mathrm{d}z, \tag{4}$$

where α is the fraction of the mechanical load (the integral part of the equation) being $\alpha = 0$ for dry soil and 1 for saturated soil; under the integral g is the gravity constant (9.81 m s^{-2}) and ρ_{bw} is the wet bulk density which is a function of the distance along the path from z to the 0 m depth.

According to equation 3, z increases with increasing distance from the W.T. and consequently $\Omega > 0$ reduces; $\Psi < 0$ also decreases so that θ_g (kg kg^{-1}) also decreases (see Fig. 12). This reduction of Ψ corresponding to an increase of z from the W.T. changes the water profile which according to Philip (1969) shifts from the hydric to the picnotatic and then to a xeric profile (see insert in Fig. 12). These profile changes are expected to occur in the higher part of the model. When the xeric profile is reached the solid particles at a certain moisture can be subject to a *stretching* (as evidenced by Chertkof, 2005) so that with further decrease of θ_g under the tillage layer cracks can form in the soil with much more complex physics. The whole water and solid content are slightly different from that of Smiles(2000), notwithstanding Talsma's (1974) caution.

In the second period B it happened that daily rainfall was fairly constant (mean 3.5 mm/day) and this suggested the possibility of a gradual increase of the water flux capacity of the soil. This implies a shift of the soil entry through the surface towards a final stationary water flux. These manifestations are expected to vary greatly with the water feeding intensity at the soil surface. An extremely low water accumulation and W.T. rise at the end of the surface feeding makes the column profile not saturated. A maximum flux through the soil column is expected on the contrary when all pores are completely saturated along the profile and the real stationary condition can be realized only through a fairly short water path before dispersion.

When the W.T. rises or the piezometers indicate that a certain level of water air boundary is formed the total water potential Φ (known as "subsidence potential") is more simpler expressed as:

$$\Phi = z + P \tag{5}$$

where P is now the hydraulic pressure and $\boldsymbol{z}$ the W.T. of the level reached by the piezometers. Under this surface there is not the matric potential (water-air interaction), nor an overburden water potential. This simplifies the examination of equilibrium between different piezometers.

V – Conclusive considerations

As a whole it is evident that the hydrology of this soil classified as typical vertisol can be better understood as a soil comprised of two hydrological sources: meteorological fluctuations and that artificially created by underground water sources. This strictly depends on the meteorological variability and the cropping use of the soil and the basic underground water table which might have very variable conditions. The upper soil layer including the tilled layer and part of the lower layers is more or less affected by the development of the root rhizosphere (about 1 m) and often has somewhat stronger competition so that the water from above is more widely retained, creating an almost suspended water layer. Along most of the lower layers down to the basic water table, the water is held in a quasi-equilibrium to the basic water level. This water moves less freely according to the meteorological regime and follows the superimposed water change.

Irrigation should take these facts into account (which are not often simple to examine). The possibility to observe two particular situations have shown that there were hydrological laws responsible for most of the apparent irregularities between these lower water tables.

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