

PEDOLOGIE

Overprint from *Pedologie* 1989/2

International bulletin edited by the Belgian Society of
Soil Science

PLANOSOLS IN THE "CHAMPAGNE HUMIDE"
REGION, FRANCE
A MULTI-APPROACH STUDY

D. BAIZE

Abstract

This article is devoted to acid soils with strong differentiation that have developed in sedimentary clay material of the early Cretaceous period (Champagne Humide, France).

Macro and micromorphological, granulometric, physico-chemical and mineralogical studies were conducted on seven profiles selected from an initial 60 pits. Also, the soil water regime was investigated in situ over a 5-year period by simple procedures using piezometers, tensiometers and neutron measuring devices; 200 to 420 mm of rainfall are removed annually by lateral flow as a temporary shallow water-table.

Four isoquartz balances were established, indicating that these soils became differentiated as a result of the lateral translocation of clay minerals from the upper horizons without significant accumulation in the deeper layers. Initial homogeneity of the parent material was determined by various methods, so that these soils can be defined as "pedomorphic planosols" whose formation is not related to a particular climate, but to two combined site factors : a slowly permeable clay parent material and a subhorizontal topography. Unlike sandy or silty materials, the clay materials studied here showed an essentially lateral natural drainage.

Key-words

Planosols, pedogenesis, clay materials, France.

D. Baize - Service d'Etude des Sols et de la Carte Pédologique de France, INRA - Départ. Science du Sol, Centre de Recherches d'Orléans, Ardon, F-45160 Olivet, France.

1. INTRODUCTION

1.1. Purpose and approach

This paper presents the main approaches and major results of an extensive overall study of the highly acid planosols of Champagne Humide (southern Paris Basin) which have developed from cretaceous clay deposits (Baize, 1983). Details on the methods employed and on general results are given in the three following articles : study of particle size distribution (Baize, 1980a), isoquartz balances (Baize, 1980b) or soil water regime (Baize, 1984).

The research was conducted by following a "multi-approach" procedure. First, the greatest possible number of independent methods have been used. In preference, the more comprehensive methods (such as soil survey) and those for investigating the soil mantle in situ have been employed. Each independent approach yielded basic data. After critical examination, the latter served to elaborate partial syntheses. The relevant combination of these syntheses (i.e. taking into account any apparent contradiction between existing phenomena and results of earlier processes) led to reliable final conclusions.

Table 1 shows in part the approaches followed and the methods and material used. The various study methods have been applied to a relatively large number of selected representative profiles. A sizeable amount of data has therefore been collected. It is also evident to which point these methods differ in terms of site (field or laboratory) and scale of observations (from micrometre to kilometre). For such an article, it was also necessary to condense the obtained results to a great extent. This is why each chapter contains only an indication of these methods used and an outline of the major results and partial conclusions.

1.2. Planosols - Previous works

The name planosol was introduced in the 1938 USDA Soil Classification. This designation is now widespread, especially after its use at the highest taxonomic level in the legend of the FAO-UNESCO Soil Map of the World (1974).

Dudal (1973) summarized all the studies carried out in the world until 1971 concerning planosols or related soils. Since that time, several surveys can be mentioned. Most of them have taken place in Africa or in South America, a few in Europe (Carvalho Cardoso and Teixeira Bessa, 1973; Conea et al., 1973; Trashliev et al., 1975; Feijtel et al., 1988).

Morras (1979), after a book-review, states that the only consistent feature of all planosols appears to be their seasonal waterlogging; this may be related to climatic conditions, topographic posi-

Table 1.

The "multi-approach" proceeding applied to planosols of Champagne Humide : questions, methods and material.

QUESTION TO BE SOLVED	METHODS USED	STUDY MATERIAL
1. What is the morphology of these soils, their constituents, their water regime?	. medium-scale mapping . soil descriptions; particle-size and chemical analysis . X-ray diffraction	. about 40,000 ha . 60 pits both described and sampled . 7 profiles
2. Are there pedomorphologic or lithomorphologic planosols?	. arguments relating to mapping . particle-size distribution study . test area study . heavy minerals study	. >1500 auger borings . 282 sampled horizons . 12 ha, 8 profiles . 2 profiles
3. Are there evidences of illuviation?	. microscopic examination of thin sections	. 21 horizons from 5 profiles
4. What are the factors and conditions of the soil water regime?	IN SITU : . piezometer and tensiometer readings; neutron scattering	. 2 sites for five years
	. bulk density and weight soil moisture measurings LABORATORY MEASUREMENTS ; . solid density . relationship moisture/pF	. samples from the two sites
5. Do material losses from the E horizons accumulate within the S horizons, in invisible form?	. isoquartz balances	. 4 profiles
6. What is the composition of waters in the subsurface runoff?	. chemical analysis of waters and suspended particles	. 11 water samplings from one site (brook)

tion or slow permeability of the parent material. Thus, the morphology of planosols appears to result from convergence, different soil-forming processes and mechanisms occurring according the case.

In France, the term planosol was first applied by Favrot and Legros in 1972. In this particular case, these were "lithomorphic" planosols in which a heterogeneous double layer material existed, previous to soil formation. At the same time, Begon and Jamagne (1973) described planosols and planosolic soils corresponding to the ultimate stage of "sols lessivés dégradés", in which the slowly permeable horizons result from considerable clay illuviation. Planosols formed directly from homogeneous clay material have been reported, for the first time, in the Paris Basin (Baize, 1976; Begon et al., 1976; Isambert, 1984).

2. THE ENVIRONMENT : THE "CHAMPAGNE HUMIDE" REGION

The "Champagne Humide" is located in the southeastern Paris Basin, France. It is clearly differentiated from the wine growing Champagne because it is strictly confined to the outcropping of sedimentary strata of the early Cretaceous period. The present study is only concerned with a part of this region (areas near Chaource, St. Florentin and Auxerre).

The stratigraphic sequence (Barremian to Cenomanian) displays abrupt vertical and lateral lithological variations, but clay deposits remain dominant. Many parent materials result directly from clay sedimentation. In addition, several materials that did not initially consist of clays were converted into clay materials due to moderate weathering processes; for instance, the "green sands" of the Albian period were transformed by disintegration of glauconitic pseudosands and the Cenomanian marls by simple decarbonation.

Several lithological facies can be distinguished among parent materials : marls, glauconitic or non-glauconitic calcareous clays, non calcareous glauconitic clays and continental variegated clays. From a granulometric point of view, four categories can be recognized in the field : heavy clays, clays with a silty skeleton, clays with a fine sand-sized skeleton and sandy clays. Thus, there is a great diversity of materials exposed to pedogenetic processes, and this diversity is increased by the variety in mineralogical compositions (see below).

The "Champagne Humide" is a gently plain at low altitudes (120-130 m). Most soils are temporarily waterlogged and show strong acidity. For this reason, the vegetation consists chiefly of forest stands and permanent pastures.

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Local climate is characterized by moderate annual rainfall (630-770 mm), well distributed throughout the year. Mean annual temperature is close to 10.5° C. This predominantly oceanic climate, affected by western and southwestern winds, has rather mild winters and temperate summers. Temperature in Auxerre averages 2.5° C in January (coldest month) and 18.6° C in July (warmest month).

3. SOILS

The initial basic knowledge was derived from medium-scale mapping (Baize, 1976). Material is described in table 1.

3.1. Morphology of the profiles

The studied soils always show horizons poor in clay (silty or sandy) that overlie clay or sandy-clay horizons. In addition, they exhibit a strong textural differentiation and an abrupt nearly-horizontal transition between the two types of horizons.

During field mapping, the upper clayey horizons had been presumed to be structural horizons rather than the result of illuviation. This hypothesis was to be tested. Thus, the sequence of horizons can be designated as : A, E, Eg, S, SC, C (new French nomenclature, Référentiel Pédologique, 1988; E = previously A₂ and S = previously (B)).

Some variations exist nevertheless, depending on type of humus, podzolic evolution in the A horizon, thickness of coarse-textured E horizons (widest range of 20 to 90 cm; usual range of 35 to 45 cm), waterlogging intensity and hydromorphic properties of the Eg horizons, aspect and importance of "morphological degradation" phenomena (Jamagne, 1978; Pedro et al. 1978) at the textural contact, and presence or absence of a clay "bulge" (highest clay content in the S horizon);

Hydromorphic features of the Eg horizons vary with each profile. In dry periods (June through November), the following features can be observed : streaks combining light colours and rust-brown colours, bleached spots or mottling and ferro-manganic nodules of variable size. In humid periods (January through April), waterlogging occurs due to temporary subsurface watertables, giving the coarse-textured upper horizons a nearly sludge state and ephemeral greyish or greenish colours (gleying is weakly expressed due to the lack of iron).

"Morphological degradation" at the top of the S horizons is evidenced by both discoloration and local alteration of the texture. Volumes of soil material of varying size become differentiated at the top of the clay horizons. These volumes contain much less clay

(hence their greater porosity and looser structure) and much less iron (hence their whitish colours) than the remainder of the S horizons. Morphological degradation only occurs in one solum out of two : it is not a general phenomenon. When clearly visible, such degradation fluctuates between two extremes. At last, there are thin skeletons coating the ped surfaces over the upper 5 to 8 cm of the S horizon (designated as Sd sub-horizon). As a maximum, degradation affects 20 to 60 % of the volume of the Sd horizon, which may be from 10 to 30 cm thick. These degraded volumes are, however, preferentially oriented : they extend more deeply along the vertical faces of the prismatic peds. This type of glossic-like degradation is encountered mainly in the soils richest in silt-sized skeletal grains. This last facies is very similar to that observed in the "sols lessivés dégradés" (CPCS, 1967) on medium-textured materials.

The S horizons are characterized by : heavy clay or sandy-clay textures; cubic and/or prismatic structures, which are finer in the upper part of the horizon; presence of many ochre or rust-coloured spots that are clearly visible on the beige, grey or green matrix; moderate and constant humidity contrasting with the winter water-logging of the E horizons. Other features can also be observed in some exceptional profiles : slanted slickensides, few thin reddish or brownish clay coatings, and grey coatings.

The C horizons consist of slightly weathered cretaceous sediments that have been little affected by soil-forming processes. There are four criteria of field identification. If the parent-rock contains CaCO_3 , the C horizons are not fully decarbonated and show frequently a calcic Cca sub-horizon in their upper part. The passage from S to C horizons is sometimes gradual and is characterized by loss of structure. The C horizons have only a coarse and weakly developed prismatic structure. Whatever the season, these deep horizons appear to be dry. Lastly, the clayey geological sediments become clearly recognizable on the base of their colour (blackish, brownish or slate-coloured) and of their "soapy" or "rubbery" touch. It is only at this depth that the glauconitic green sands maintain their sandy texture, the glauconite grains being intact and well individualized.

3.2. Mineralogical data of the clay fraction

The parent rock shows a diverse mineralogical composition. Within each profile, few qualitative differences are noted between E, S and C horizons. A more thorough study (separating clay fraction into granulometric sub-fractions) points to three main statements :

- the E horizons exhibit a relative accumulation of the coarsest clays (0,2 - 2 μm) and of quartz, kaolinite and titanium minerals;

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- from the bottom to the top of the glauconiferous profiles, the finest glauconites show a geochemical evolution : progressive opening of the layers with acquisition of swelling properties ("transformation smectites", Robert and Barshad, 1973) and along with a loss of potassium, magnesium and iron;

- concerning the Flogny profile, vermiculitization of the illites has been established, a significant loss of potassium affecting the finest particles. The genesis of "transformation smectites" seems to have been inhibited in the Eg horizon by the fixation of probably aluminous ions.

The clay minerals currently found in planosols of the Champagne Humide are mainly inherited from cretaceous sedimentation. Only those clay minerals that result from the transformation or neof ormation are of pedogenetic significance, but it is difficult to point them out as they remain a minority "drowned" in the original heritage.

Planosolization is not related to one type of phyllite mineral in particular, although it affects 2:1 minerals much more than kaolinite. The 2:1 minerals seem nevertheless to be more weatherable and/or smaller and/or more mobile.

3.3. Major analytical data

The forested planosols of the Champagne Humide show an acid or strongly acid pH in water. All A and E horizons as well as most deeper horizons are below pH 5.5. The highest acidity level is found in the "podzol-like" humus-rich A horizons (pH in water < 4.0). Base saturation values remain lower than 65 % in the A and E horizons (usually < 30 %), and range from 8 to 100 % in the S horizons, depending on the parent material (table 2).

CEC values obtained for the clay fractions show a systematic decrease in the E horizons. This might be due to the interlayer position of aluminous compounds blocking a number of exchange sites.

Ratios of total iron to clay content suggest a relative accumulation of iron in the Eg horizons. Furthermore, the highest total iron levels are usually encountered in Sd or S horizons. Consequently, there is some absolute accumulation of iron in the uppermost S₁ horizon.

Ratios of free to total iron clearly indicate that weathering increases from the bottom to the top of the profiles. The same applies to ratios of Al extracted with Tamm's reagent to total Al levels. The horizons closest to the abrupt textural change (Eg, Sd or S₁) contain the highest amount of exchangeable aluminium. Finally, Al³⁺ plays a dominant part in the E horizons where its

level exceeds that of basic cations.

A major gradient therefore exists between (i) slightly acid (sometimes calcareous), saturated or weakly desaturated, slightly weathered C horizons devoid of free aluminium; (ii) clayey, acid, more or less desaturated, increasingly weathered S horizons containing considerable amounts of exchangeable and "free" aluminium; (iii) coarse-textured, highly acid (organic protons and Al^{3+}), strongly desaturated and highly weathered A and E horizons.

Table 2.

Some physico-chemical data of planosols in the Champagne Humide. (Note : nothing is mentioned concerning the C horizons because of their large variability).

Horizons	Clay content (%)	CEC of the horizon* (me/100g)	Base saturation (%) (forest)	CEC of the clay fraction (me/100g)
A, E & Eg	5 to 26 mostly 10 to 18	1 to 8	10 to 65 mostly 10 to 30	5 to 39 mean = 14
Sd, S & SC	32 to 60	8 to 24	8 to 100	16 to 56 mean = 36
* at pH 7, saturation with NH_4Ac				

3.4. Additional field data

During soil survey and profile pit examination, several major facts have been registered. First, an everyday field observation from December to May showed temporary shallow watertables circulating above slowly permeable clay layers. Not only is waterlogging visible in any pit or hole, but also water circulation does (rather fast in spite of the slight slopes). For instance, the deeply rutted forest tracks become small active brooks.

Secondly, during summertime, the clayey S horizons, although located at small depth, are never dry and show no obvious shrinkage. In fact, these horizons are sheltered from evaporation because they are under tree cover, thick litter and silty or sandy surface layers.

3.5. Conclusions

It is obvious that the above-described soils correspond exactly

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to the concept of planosol (Dudal, 1973; FAO-UNESCO, 1974) because of their morphology and of their peculiar type of temporary subsurface waterlogging.

4. LITHOMORPHIC OR PEDOMORPHIC PLANOSOLS?

A prerequisite to a pedogenetic interpretation was to find out whether the strong textural differentiation was due to some initial abrupt lithological discontinuity (cretaceous sedimentation or recent deposit), or to a particular soil-forming process in situ. In the first case, it would be possible to speak of "lithomorphic" planosols (Favrot and Legros, 1972); in the second case, these soils could be referred to as "pedomorphic" planosols. To elucidate this point, arguments relating to mapping or particle size distribution have been used.

4.1. Arguments relating to mapping

A first qualitative argument was provided by medium-scale mapping. During the survey, the textural variations of the E horizons were shown to be well correlated with the lithological facies of the geological layers appearing in successive outcrops (fig. 1).

In fact, field surveys on E horizons show rapid textural variations, on a decametric scale. The observed textures range continuously from pure medium sand to sandy silt loam. This excludes the hy-

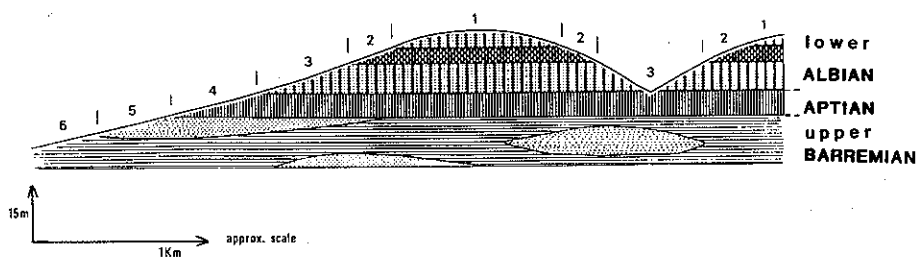


Fig. 1.

Textural variations of the Eg horizons are well correlated with the lithological facies appearing in successive outcrops (schematic presentation) :

- 1 and 3 = medium sand over glauconitic "green sands"
- 2 = silty sand over grey clays with a fine-silty skeleton;
- 4 = sandy silt loam over slightly calcareous yellow clays;
- 5 = fine sand over variegated sandy clays;
- 6 = sandy silt over variegated clays with a fine-silty skeleton.

pothesis of a shallow deposit of remote origin. Furthermore, the details of these variations can only be understood in relation to the detailed facies variations of the geological sequence. For example, sandy-textured surface horizons (n° 1 and 3, fig. 1) always overlay deep green sandy-clay horizons, whereas silty loamy textures overlay the aptian yellow clays (n° 4).

Rapid variations within the cretaceous sedimentation are the only cause of granulometric variability in surface horizons. This is a major argument in favour of the rather strict autochthony of the A and E horizons. Consequently, the latter seem to have had the same parent material as the deeper clay horizons.

4.2. Study of "granulometric skeletons"

This study (Baizé, 1980a) was conducted on a large number of samples (282 horizons), with the interest exclusively been oriented towards the sand and silt fractions. The clay fraction was excluded by calculation because the $< 2 \mu\text{m}$ fractions are more mobile (vertical or lateral translocation), more sensitive to geochemical degradation, and because they may occur within the horizons as a result of the in situ weathering of coarser particles (disintegration of glauconitic pseudo-sands or micro-division of the fine silt-sized illites). Six granulometric fractions could be used (table 3). These values, expressed as a percentage of their sum, served as a basis for comparing horizons of the same profile ("vertical" comparisons, fig. 2) or horizons of different sites ("horizontal" comparisons).

Table 3.

Calculation of the "écart brut" (Eb) between two horizons, i.e. the sum of differences of the six granulometric fractions (absolute values in per cent). Example : Héry profile.

Hori- zon	LF (2-20 μm)	LG (20-50 μm)	SF1 (50-100 μm)	SF2 (100- 200 μm)	SG1 (200- 500 μm)	SG2 (500- 2000 μm)	
Eg	14.1	13.0	37.1	28.1	6.8	0.9	
Sd	17.5	12.3	42.0	24.1	3.4	0.8	
=/=	3.4	0.7	4.9	4.0	3.4	0.1	Eb=16.5

As a first qualitative approach, diagrams were constructed, For the purpose of simplification, they only compared the Eg and Sd or S₁ horizons of each profile (two samples vertically close, but

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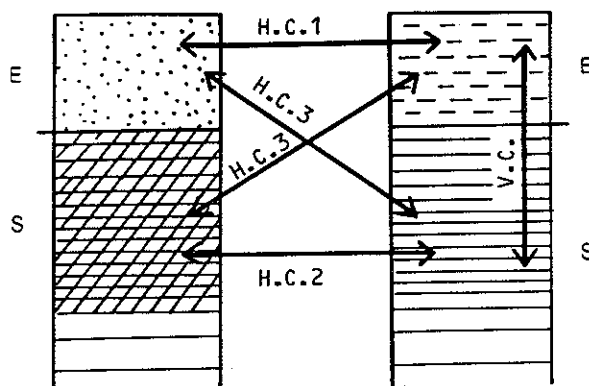


Fig. 2. Comparisons between "granulometric skeletons" (V.C. = vertical comparisons; H.C. 1, 2, 3 = horizontal comparisons).

placed on either side of the abrupt textural change). Among the 55 studied pairs, similar material was found in 53 cases besides 1 doubtful case, and 1 certain case of heterogeneity.

Afterwards, a quantitative index termed "écart brut" (Eb) was calculated (table 3). Many treatments were applied to this index, but only one result will be mentioned, namely the distribution of the "écart brut" obtained by vertical comparison within the 55 profiles. Some forty sites showed Eb indices lower than 20. It was felt that this result indicated a good homogeneity in particle size distribution. For the other profiles, however, there are no clear answers due to the lack of references for this kind of index.

4.3. Study of a small test area

This study was made in three steps : mapping over 95 ha, sampling of 17 E horizons, and then sampling of 8 profiles located within a 12-ha polygon. In order to examine the 8 E and S pairs, the 120 "écarts bruts" that distinguish the "granulometric skeletons" of the 16 horizons have been calculated. The E and S horizons of a same profile generally showed rather low Eb indices, lower than those calculated between two horizons of two distinct profiles. This, however, is not an absolute rule : the two horizons most similar in terms of particle size distribution are derived from eluviated horizons of two remote sites. Then, the profiles were geographically relocated in relation to each other in order to compare spatial proximity with mathematical proximity. Of the 15 relations examined in this way, 14 show that the E and S horizons of the same profile are more similar than the E and S horizons in closely spaced profiles.

In conclusion, there is a variability from one site to another over very small distances but a relatively strong genetic link within each profile.

4.4. Heavy minerals

A study of the heavy minerals in four profiles pointed to the cretaceous nature of all E and S horizons. This fact, once again, excludes the hypothesis of an allochthonous deposit of remote origin.

4.5. Conclusion - New question

The cretaceous sedimentation appears to be quite heterogeneous with abrupt field variations, especially in particle size distribution. All qualitative and quantitative arguments converge to one and the same conclusion : the rapid and substantial changes from one site to the next contrast with the close similarities between horizons of a same profile located on either side of the abrupt textural change ("planic contact"). A number of technical and pedologic difficulties were encountered. A good initial uniformity in particle size distribution could however be demonstrated in over fifty profiles, hence in the majority of the soils considered. Differentiation of the surface horizons poor in clay is therefore not related to some original sedimentary discontinuity or recent deposit, but results from soil formation in situ. This had to be elucidated before pursuing any research on the evolution of this type of planosol. We are dealing with pedomorphic planosols.

The above considerations lead to a further question : does the strong textural differentiation result from relative clay accumulation in a S horizon, or does it result from absolute clay accumulation in a BT horizon due to argilluviation?

5. MICROMORPHOLOGY

Regarding the distribution of clay, observations of thin sections in five profiles revealed a nearly total lack of argillans and ferriargillans (usually indicating clay illuviation) in the clayey S horizons. The few cutan-like features seem rather to be diffusion or stress cutans, but they are of little importance considering the textural differentiation of the soils. The very few typical illuviation cutans were found in the Eg and Sd horizons rather in the clay-rich S horizons.

In addition, thin section examination allowed recognition, at the microscopic level, of some features already observed in the field,

e.g. conversion of glauconite grains into yellow-greenish poorly limpid plasma, stress cutans and vo-sepic plasmic fabric along fissures corresponding to slickensides, iron impregnation and nodulation representing the rust-coloured spots typical of waterlogging or weathering, and "morphological degradation" at the top of the S horizons associated with the disappearance of the clayey plasma.

Consequently, the planosols of Champagne Humide do not appear to have undergone significant clay illuviation. Additional evidences must, however, be provided in support of this statement (see chapter 7).

6. WATER REGIME

Two forested sites have been selected in order to understand the water dynamics under the best possible natural conditions. Several independant in situ methods were used from May 1977 to January 1982, as well as laboratory tests (table 1). The results obtained on both the HERY and PONTIGNY sites were in good agreement, except for a few slight differences. For lack of room, only the main results will be presented here. Any reader interested by more detailed results can refer to Baize (1983; 1984).

Climatic water balances were calculated. They indicate a considerable soil water deficit in 1978 (July to November), a smaller one in 1979 (July to September), a slight shortage in September 1980 and 1981, and no deficit in 1977. Winter water surplusses were determined as being 178 mm, 306 mm, 217 mm, 282 mm and > 162 mm respectively for each winter period. In summer, natural drainage may have occurred in August 1977. In June 1981, a considerable water surplus is pointed out by calculation : 45 mm during the first 10-day period, 11 mm during the third.

The presence of water in short piezometers pointed to the existence of a subsurface watertable, hence to waterlogging of the coarse-textured E horizons. This shallow watertable appears every year in January, February and March. It was observed once in late December 1980, in May 1979, on 10 June and 10 August 1981, but was not detected in April nor during the other months. It could not be determined whether the watertable is continuously present in winter. Three long periods of watertable existence have nevertheless been identified : 20 days from 24 January to 14 February 1979; 63 days from 9 January to 14 March 1980 and 22 days in January 1981. The shallow watertable was present for less than 8 days in May 1979, March 1980 and December 1980.

The absence of a subsurface watertable may be as ephemeral as its presence, e.g. it could be observed on 27 December 1980

and 1 January 1981 but not on 30 December 1980.

81 neutron moisture measurements have been carried out between May 1977 and January 1982, i.e. an average of one every 21 days for nearly 5 years. To study variations in the course of time, the raw readings have been expressed in a standard form as a percentage of the total variation throughout the 81 measurements for each horizon (0 % = min. reading; 100 % = max. reading). In such a way, the horizons can exhibit four different states :

- dry (raw readings < 30 %);
- wet (raw readings > 65 %);: very close to field capacity;
- transitional : rewetting or drying;
- waterlogged (raw readings exceeding 80 %) : excess of water saturating all the voids, especially packing voids, channels and macropores.

There was a good correlation between these raw values and the presence of a subsurface watertable detected with the short piezometers.

Temporary waterlogging was only encountered at depths of 15, 25 and 35 cm in the two sites (A and E horizons). At these depths, the wet state corresponds to raw data ranging from 65 to 80 %, whereas the waterlogged state would be evidenced by higher percentages. None of the horizons occurring under the "planic contact" exhibits a waterlogged state which differs from the wet state.

After calibrating the raw data and converting them into volumetric moisture amounts, the soil moisture contents could be calculated for each measuring date (expressed in mm). Table 4 shows which is possibly a favourable period. Between 10 November 1978 and 24 January 1979, 142 mm of rainfall were recorded. It may be assumed that 103 mm of water rewetted the soil and that 39 mm were removed laterally (or evapotranspired) because they did not reach the C horizons. From 24 January 1979 till May 1979, 335 mm of rainfall were recorded. Of these 335 mm, 15 mm are assumed to have contributed to the soil rewetting, whereas 320 mm were laterally drained, evapotranspiration being probably negligible at this period, under deciduous trees.

Various field and laboratory measurements were used in establishing some kind of volumetric balance at extreme moisture contents (assuming that the total porosity remained constant). Such balances demonstrate :

- the large water capacity available in the E horizons (> 24 %);
- the small water capacity available in the S horizons (7 to 8 %) and their high content of strongly retained water;
- the very small volumes occupied by air during periods of maximum moisture content (1.5 and 4 % in the S horizons; 3 to 7 % in the E horizons). At these times, aeration is there-