ATLANTIC ZONE PROGRAMME

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Field Report No. 110

SOIL PHYSICAL PROPERTIES OF A FERTILE, POORLY DRAINED SOIL AND THEIR ADEQUACY FOR USE IN QUANTIFIED LAND EVALUATION

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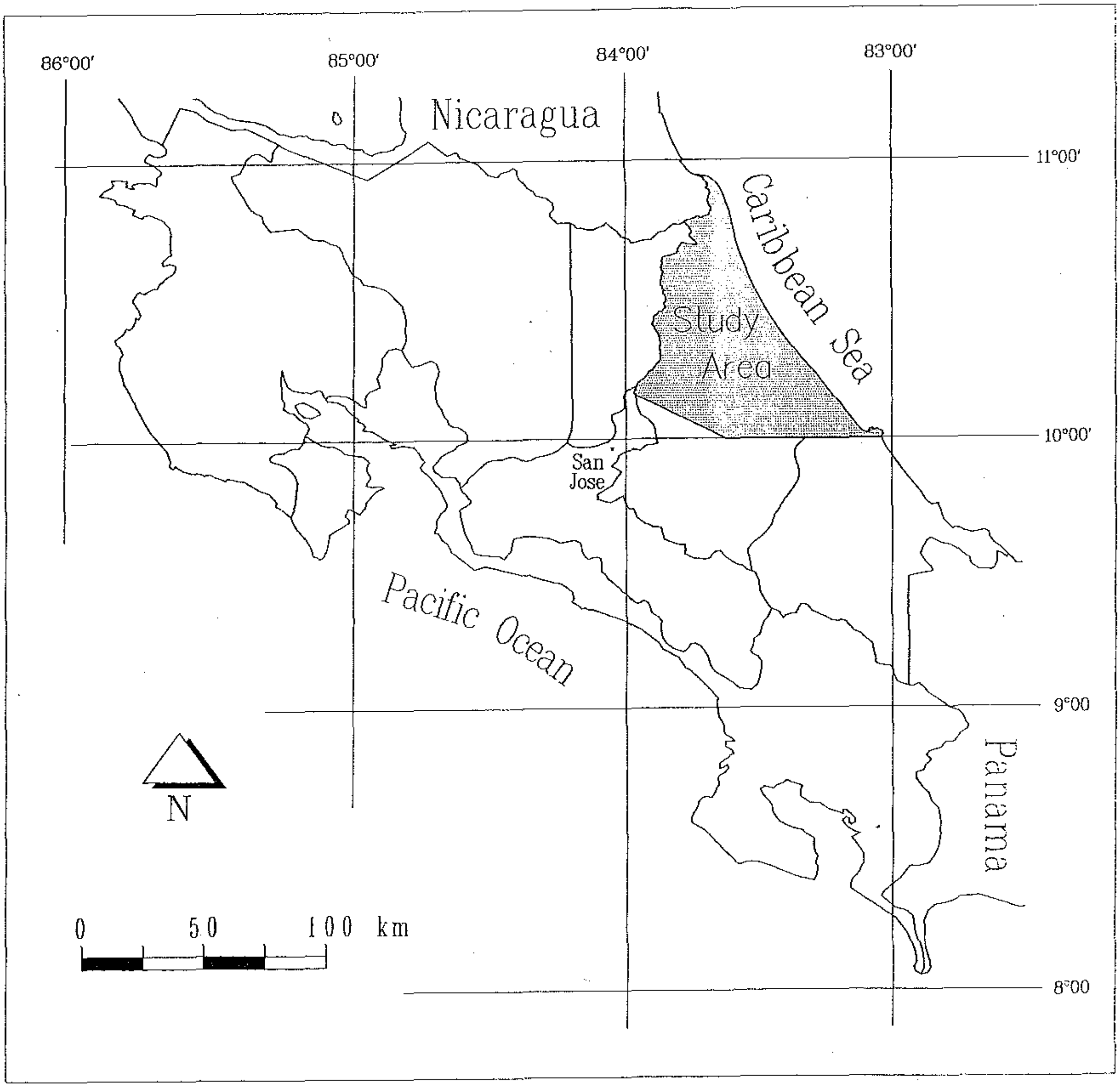
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PREFACE

In its second phase, the Atlantic Zone Programme focuses on the development of a methodology for land use planning on a sustainable basis. The methodology comprises three successive steps. First relevant combinations of land utilization types and land units are identified, followed by an analysis of these systems and finally the definition of a scenario. On the basis of this scenario the optimal distribution of land use systems over the area is determined. During the first step three main land units are identified:

- fertile, well drained soils,
- fertile, poorly drained soils, and
- unfertile well drained soils.

The analysis of land utilization types on these land units takes place by studying actual systems found in the area, but also by defining water limited, nutrient limited and potential alternatives. The productions of these alternative systems have to be determined on the basis of crop growth simulation.

This report describes the soil physical measurements on the fertile, poorly drained soils which will form the basis for the crop growth simulation. It includes a description of the functionality of the measured values to the production of a maize crop.

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ACKNOWLEDGEMENTS

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Stephan Mantel.
Wageningen, June 1993.

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1. INTRODUCTION

From June to September a study was carried out in the Atlantic Zone of Costa Rica. For modelling three broad categories of soil have been distinguished in the zone; the (1) fertile and (2) unfertile, well drained soils and the (3) fertile, poorly drained soils. For this study descriptions and physical characterisations were made of the poorly drained soil group; physical data were not yet available for this group. Physical characterization of the fertile, well drained soil has been done by Leummens (1993), under banana, and Weitz (1992), under four different forms of land use. The soil data obtained, together with daily climate data from the area, were used for crop growth simulations with the PS123N-model.

For writing the paragraphs about geology and about hydrology parts were used from a report by P. Maebe ("Drainage observations in the poorly drained soils", Internal report Programma Zona Atlantica, LUW-CATIE-MAG).

1.1 MATERIAL AND METHODS

Soil descriptions were made and soil physical measurements done along a transect. Augerhole descriptions were made every hundred metres from river to river. Special attention was given, in addition to the 'standard soil description', to mottling patterns. Three representative sites were selected to describe the soil profile in a pit. From these pits undisturbed samples were taken, with 300 cc cores, from two layers (0-15 cm and 15-30 cm) and from a slowly permeable silty layer at a depth of approximately 2.50 m. Additional samples were taken for bulk density measurements (100 cc cores). See the tables in appendix 9 for results of bulk density and organic matters content measurements. Hydraulic conductivity was measured along the transect following the augerhole method of Hooghoudt-Ernst. Close to the soil pits hydraulic conductivity of the upper layers was determined using the column-method. In the laboratory one-step measurements were done, estimating physical parameters as input for crop growth simulations with the PS123N-model.

1.2 LOCATION

The area under study is located in the northern part of the Atlantic zone of Costa Rica, Province of Limon. The transect, along which nearly all observations were taken, was located between two rivers; the Río Tortuguero and the Río Palacios. Some 40 Kms North of Guápiles and about two kilometres from a small town called Quatro Esquinas. See App. 1.

1.3 GEOLOGY AND PHYSIOGRAPHY

1.3.1 Costa Rica

Costa Rica is an extremely varied country, both geographically and ecologically, despite its small size of about 1.4 times the size of The Netherlands. One reason is that the country is divided in two parts by a chain of mountains; the Cordillera Central, running parallel to the Pacific coast and extending from the Mexican border to Costa Rica and following a more dispersed pattern into Panamá (R. van Seeters, 1992). In the highlands a central plain is situated, called meseta central. Costa Rica's five large cities are situated in this central plain, between about 1000 and 1500m in height. The highlands reach 3820 metres at the Chirripó

Volcano. Many ecological habitats correspond with altitude. On either side of the Cordillera Central coastal lowlands stretch away; they differ greatly in character (R. Rachowiecki,1991). See appendix 2.

1.3.2 The Atlantic Zone

The study area is located in the Atlantic-Caribbean lowland of Costa Rica, in the north of Limon province. This lowland is part of a large tectonic unit formed by subduction of the Cocos plate under the Caribbean plate.

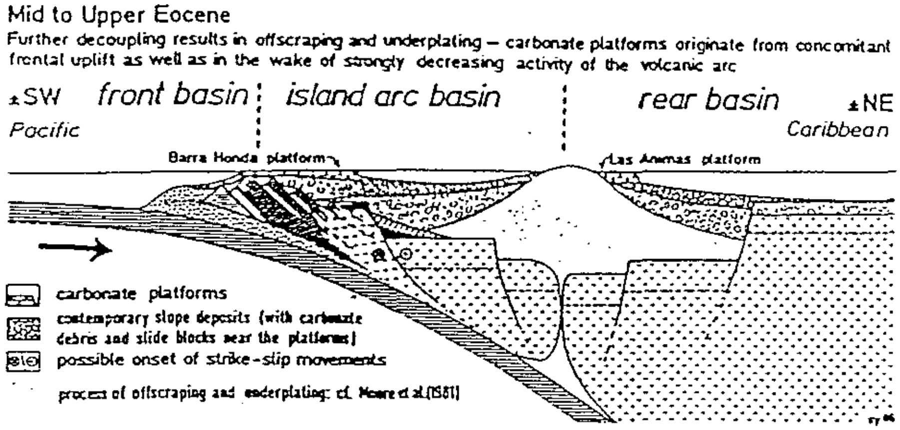

Fig. 1. Geological cross-section of Costa Rica (Shipley & Moore, 1986).

Two morphological features are prominent in the study area: an island arc and a back-arc basin. The island arc is a chain of strato volcanoes, formed by melted parts of the subduced plate. Behind the island-arc a back-arc basin is formed by crustal thinning, due to the faster rate of sinking of the subducting plate than the forward motion of the overriding plate. This crustal thinning may even lead to the rise of basaltic magma; examples of this in the Atlantic Zone are the basaltic volcanoes in the centre of the basin 'Lomas de Sierpe' and the 'Cerro del Tortuguero'. The Atlantic-Caribbean lowland is a sedimentation area since the early Tertiary . The still subsiding region is intersected by many rivers draining the Cordillera Central in a radial pattern, like the Toro Amarillo-Tortuguero system is an example (van Seeters, Skinner and Porter in van Seeters, 1992).

Most soils in the Atlantic zone are andosols or soils with 'andic' properties. The soils in the area were mapped and classified in the first part of the research programme. The soils were grouped to three broad categories:

I - Young holocene soil depostits with good drainage properties and high fertility.
II - Young holocene soil depostits with poor drainage properties and high fertility.
III- Old pleistocene soil deposits with good drainage properties and reduced fertility.

See appendix 3 for a set-up of distinguished soil types and their relation with development stage and physical environment.

1.3.3 The study area

The area between Río Tortuguero and Río Palacios consists of alluvial sediments. Slopes are < 2%, except for some isolated hills that are remnants of an older landscape, consisting of weathered, homogeneous soils of the Neguev-type. Most fluvial deposits in this area are Holocene deposits with textures ranging from coarse sand (old river beds) to silty and loamy, but finer textures predominate.

In a study dated august 1992 on geomorphology, mineralogy and geochemistry of river systems in the Atlantic Zone of Costa Rica, R. van Seeters stated that: "The geomorphology of the Río Toro-Amarillo/Río Tortuguero watershed is a result of short-lasting periods of series of disastrous events in which large amounts of sediment are deposited, separated by long-lasting relatively calm periods in which sediments become weathered, reworked and transported. The short-lasting disastrous periods coincide with reactivation of Irazú and Turrialba volcanoes. Eruptions of ash and lava, lahars, sheetfloods, landslides and floods result in enormous sediment deposits and in enormous increases of sediment discharge of the rivers draining these volcanoes. During these periods rivers change their course and inundations occur. In the long-lasting calm periods landslides, floods and inundations occur too, but do not have the same dramatic effect as do the short-lasting periods. Río Tortuguero once in time has been a branch of Río Toro Amarillo. Presently Río Tortuguero is a small, nearly straight, brook that runs in its old riverbed, that has been filled up completely". The sediments of Río Tortuguero have a high content of heavy metals. This is especially the case for Cu, Zn and Ba (Kroonenberg, pers. comm.).

The soil is fertile. In some part of the study area old, deeply weathered soils are found with clay loam textures and deep homogeneous profiles. The soils of this type, locally classified as Neguev, are unfertile and have "P-fixing" properties. Neguev soils are found on small hills in the area. To which depth the fluvial deposits extend is not clear, but from descriptions of deep wells in the area (Anon., 1992), it can be concluded that the alternation of sandy and clayey alluvial sediments could extend to a depth of more than 40 metres.

1.4 CLIMATE

The Atlantic Zone has a tropical rainy climate (A) and has no distinct dry season (f); the driest months have more than 60 mm of precipitation. According to the classification of Köppen (1923) this climate is an Af-climate; a hot climate with no cool season, and an average monthly temperature over 18 °C. The climate is typical for areas of lowland tropical rain forest. The, usually not very strong, winds, measured in Limon by the 'National Meterological Institute' (1972) are mainly north, north-west and south-west. Occasionally there are strong eastern and southeastern winds.

There is a gradient of rainfall from the coast to the Cordillera Central. Although no distinct dry season can be distinguished there are two periods with rainfall maxima (July and Nov/Dec). In this study, data from two weather stations were used; "Hacienda El Carmen" (banana plantation) and Puerto Limon (Sea Port). The average monthly rainfall (1970-1991) gauged at these stations show that, no month has less precipitation than 155 mm. See fig.2-3. The average rainfall in July on "Hacienda El Carmen" is 452 mm! Yearly average (1982) is 4049 mm for Carmen, 3773 mm for Limon, 4413 mm for La Mola. Showers can be very heavy. Four days of little or no rain can be followed by a day with 260 mm, that falls in one or two showers of a few hours! Two kinds of showers are distinguished: 1) so-called temporals; showers caused by invading cold air from northern regions (mainly in November-May), accompanied by light to moderate winds, 2) Heavy downpours, which are more local than temporals, of short duration and can be very intens (mainly occurring from May till October) (van Seeters, 1992).

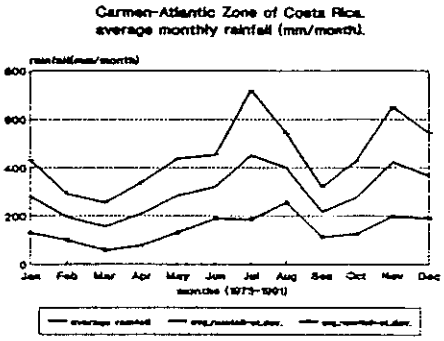

Fig. 2: average rainfall El Carmen.

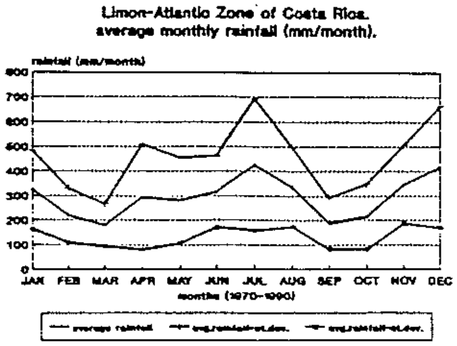

Fig. 3: average rainfall Limon.

Cumulative, potential evapotranspiration rates (El Carmen, 1982) vary between 10 cm/month (Dec) and 14 cm/month (March-May) and cumulative, potential evaporation varies between 11 cm/month (Dec) and 16 cm/month (March-May). Average relative humidity is 0.6. Winds are not very strong in the Atlantic Zone. The average wind speed in sea port Limon is somewhere between 4.5 and 5.5 km/h throughout the year. Hacienda El Carmen has a lower average wind speed; i.e. between 3.5 and 4.5. The number of sun hours does not differ greatly between the two stations. From January to May the number of sun hours per day is about 5.5. For the rest of the year it varies between 4 and 5. See Appendix 4 for climate data.

1.5 LAND UTILIZATION TYPES

1.5.1 Introduction

Some 25 years ago the north-eastern part of the Atlantic Zone of Costa Rica was completely covered with primary forest. Due to the high pressure on the land elsewhere in the country settlers began to move in to clear the land. Both government guided and spontaneous settlers colonized the region. Between 1966 and 1989, 28 % (847.000 ha) of Costa Rica's forests were cleared (Repetto, 1992). At present, natural forest is still found in the extreme north-east of the country (mainly natural reserve area). Poorly drained conditions predominate in most of the remaining forest areas. Logged out parts of the forest remain scattered over the area (Nieuwenhuyse, 1988). The current land use on poorly drained soils in the Atlantic Zone is predominantly extensive cattle farming, mainly for meat production. The area under pasture in the Atlantic Zone of Costa Rica has increased sixfold in the last two decades; a strong relation with deforestation is suspected (P.Paap, pers. comm.). The settlers have little experience with agriculture under the biophysical conditions of the Atlantic Zone. North-East of boomtown Cariari the roads are in very poor condition; in Cariari the paved road changes into an all-weather road which can only be used by 4-wheel drive vehicles. The poor infrastructure and the low grade of organisation among the farmers make that supply of and removal of agricultural goods are difficult. Extensive cattle farming is a low input, low technology and relatively low risk form a agriculture. Unlike harvested agricultural goods, cattle poses little problems in terms of storage (animals can be kept alive until slaughter) or quality loss of the product during transport (the animals are slaughtered in the vicinity of the market). Other forms of agriculture require a higher level of knowledge and skills and need more input (including labour).

Soil compaction seems to be a major problem incurred in cattle farming (Nieuwenhuyse, 1988). Extensive cattle farming is efficient in the sense that cattle can be kept on soils that are unsuitable to arable farming. But when extensive cattle farming is practised in parts that are suitable to arable farming (or can be made suitable) it is questionable, with the present scarcity of land and the rate of deforestation, whether this is an ecologically sound and sustainable way of land use.

1.5.2 LUT grassland

Pasture improvement and introduction of better grass species and nitrogen fixing species are needed. One of the most common grass species used for pasture in the Atlantic Zone is Ratana (Ischaemum ciliare) and pasto natural (natural grass species); both low productive grass species. Some farmers, however, try to improve their pastures by introducing better grass varieties. The cattle kept is either the Indian Brahman type, the local criollo type or a crossbreed; often a Brahman bull is kept for breeding with a criollo cow. Most constraining to this type of land use are the quality of the pastures and weeds (types that grow well under swampy conditions; f.i. arum). Farm size, in terms of heads of cattle, varies between 5 to 100 (Nieuwenhuyse, 1988). On the average about 20 heads of cattle are kept per farm, which means 0.8 heads per hectare. In other parts of the Atlantic Zone (Siquirres) cattle breeding farms of 3500 ha with some 7000 heads of cattle are found (Ruthenberg, 1980). In most cases the system is sylvopastoral with dispersed trees and/or living fences. Dispersed trees are isolated trees that have regrown or that were not cut or burnt during clearing. Trees that are planted as supports for barbed wire are called living fences. They can be multi-functional; additionally providing fodder and poles for new planting (but in low quantities). Most living fence trees are leguminous, local names: poro, madero negro (P.Paap, pers.comm.). Most cattle farmers work off-farm; on banana plantations during the week and on his own farm in the afternoon and on sundays.

1.5.3 LUT Maize

Maize is usually sown in December or January and harvested in April or May, after a period of a month (or more) in which the stalks are doubled over in order to dry and to protect the ears from molds and diseases. All labour is done by hand; on most farms fertilizers are not used, but herbicides are used frequently. To reduce planting time, maize is sown in small clusters of 3 to 5 plants. On the better soils maize yields of approximately 2000-3000 kg grains/ha are obtained. (Nieuwenhuyse, 1988).

1.5.4 Alternative forms of Land Use

It would be interesting to know if, and in what way, (some of the) poorly drained areas can be drained and used for other land uses; f.i. cultivation of crops. And what would be the production potential of maize or another crop? Some cattle farmers have tried to grow green peppers (chilies) and this seems to be economically quite attractive. In some ponded parts aquaculture might be a possibility.

1.6 HYDROLOGY

1.6.1 General

In the area between Río Tortuguero and Río Palacios a rather thick layer of low permeability is found deeper than 2 metres. We have augered down to 4 metres, but could not get through. It is suspected that this layer occurs in many parts of the poorly drained soil unit. Random observations outside the study area (in the direction of the Tortuguero park) in the poorly drained soil unit support this assumption. On the other side of Río Tortuguero, seen from the study area, the area is planted to banana by the GEEST-company. After the area was cleared from vegetation, deep drainage channels were dug. In these large channels it is clearly visible that water flows over the impermeable silty layer (see photo. no.1). In one of these "freshly" dug channels a profile was studied and described, see appendix 10, profile no.4.

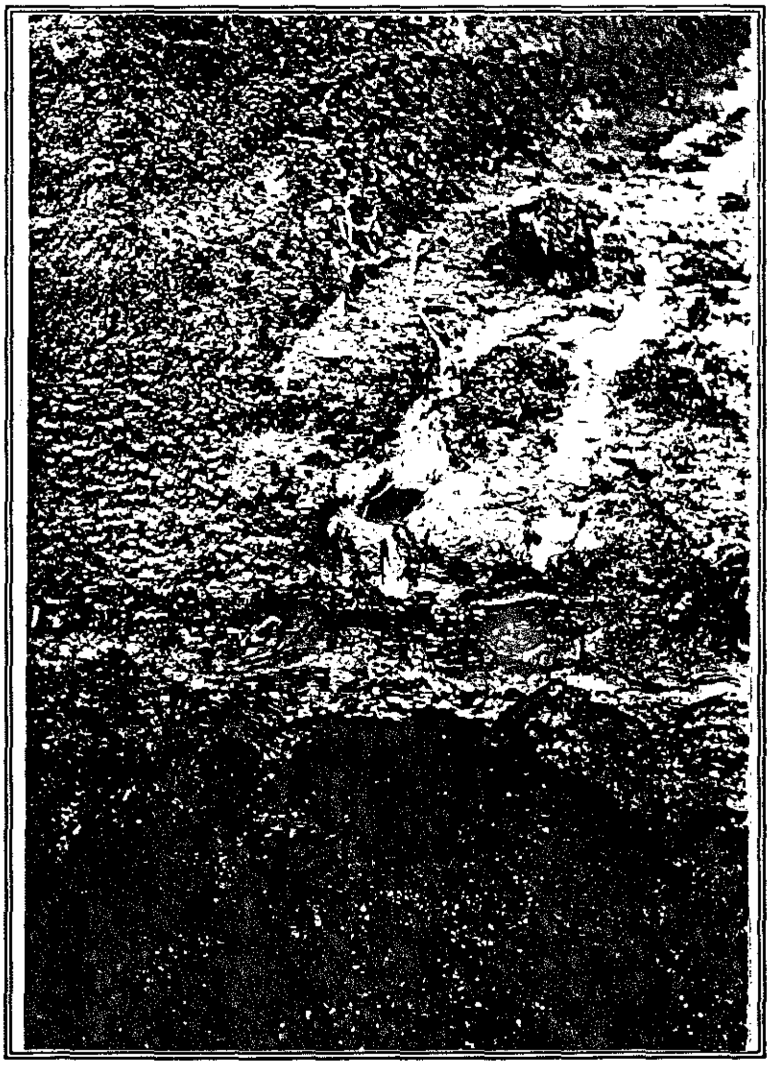

Photo 1. Wateroutflow over slowly permeable silty layer in drain on GEEST-Bananaplantation (see descr. profile no. 4).

1.6.2 Hydrogeology

In a study of Pascal Maebe, Int. rep. 1992, water-levels were observed for a period of four months in piezometers that were placed along the same transect used for this study. The corrected outflow rates of the various wells are listed by date hereafter:

Table 1: Corrected outflow rates (mm/day) of wells listed by end-date of the outflow-period, the mean water level (m) in piezometer 3 and the mean daily precipitation P (mm/ day), at banana-plantation Banagro (8 km from study area). Negative values indicate water-table rise (source: Maebe, 1992).

date	well 1	well 2	well 3	well 4	well 5	depth#3	P
10/4	-	3.2	1.4	-	2.2	2.12	0.2
23/4	-	-0.7	-2.4	-	-2.6	1.95	2.2
28/5	23	-	22.5	9.8	19.8	2.52	0
01/6	5	-	5.7	1.6	5.4	2.34	0
22/6	6	7	6.4	-0.7	10.0	2.40	0
24/6	6	5	7.9	-0.7	10.0	2.30	0
02/7	0.6	2	-4.5	-4.0	-8.4	2.28	1.8

In appendix no. 5, the distances between the piezometer reading and the elevation, at ground-surface are given for each piezometer. The water levels are expressed relative to the bed of Río Tortuguero. Table 1 suggests, that outflow in wells #1, #2, #3 and #5 are similar and that ground-water discharge at low water-table positions is around 2 mm/day; 5-7 mm at medium water-table positions and around 20 mm a day at high water-table positions. The question is, whether this amount can be drained perpendicularly to the two rivers. The river levees are sandy (up to 200-300 m) and are > 3 m thick. Conductivities in these deposits are high (about 8-12 m/d). In the rest of the area between the two rivers the deposits above the silty layer are mainly loamy and have a saturated hydraulic conductivity of about 0.5 to 5 m/d.

Maebe (1992) calculated theoretical water-profiles. To simplify calculations, he assumed: 1)horizontal flow only 2)the water potential of the river is extending down to the impermeable layer 3)a homogeneous aquifer. He further assumed the impermeable layer to be located at the same depth all over the cross-section and at a position lower than the bottom of the Río Tortuguero. Steady state was assumed which permitted to use the following equation to calculate the ground-water-table-position between the two rivers:

$$H^2=\frac{x}{L}(H_2^2-H_1^2)+H_1^2+\frac{N}{K}x(L-x) \qquad (1)$$

with L : distance between the two rivers (m);
N : natural recharge over the cross-section (m/day);
K : hydraulic conductivity of the aquifer system (m/day);
x : distance from any point in the cross-section to the first river (m);
H_1 : water-potential at the first river, x=0 (m);
H_2 : water-potential at the second river, x=L (m);
H : water-level at any point x (m).

The theoretical water-table position was calculated assuming the natural recharge N of 0.003 m/day and a hydraulic conductivity K of 5 m/day. The water-depth in both rivers was set to 0.3 m. These calculations were repeated for three cases: 1) the impermeable layer at 1 m below the Río Tortuguero bed (D +1), 2) at 5 m (D +5) and 3) 10 m (D +10) below the base. This implies that H_1=3.42 m and H_2=1.3 m for the first case, H_1=7.42 and H_2=5.3m for the second case and H_1=12.42 m and H_2=10.3 m for the third case. A fixed potential was taken at x = 1300 m, because it was observed that the water-level at piezometer site #4 was always lower than in the surrounding piezometers indicating a constant ground-water flow towards this piezometer. Close to piezometer at site #4 a gully was found with standing, or slowly flowing, water most of the time. The drainage capacity is calculated for the best possible scenario; the slowly permeable silty layer is taken lower (1 m, 5 m and 10 m resp.) than the bottom of the Tortuguero river, where in reality the top of this layer is situated at the same level as the river bottom or higher, resulting in a better drainage capacity. The results of these calculations are given in Appendix 6 (fig.1 and fig. 2); the water-profile was fitted with the piezometer-levels observed during a wet period (day 103).

1.6.3 Results

Maebe found in his study that the calculated water table profiles were higher than the topography, indicating that the aquifer system cannot drain 3 mm/day under the given assumptions. However, the piezometer outflow curves show that the mean ground water discharge is at least 3 mm/day and probably even around 6 mm/day. This leads to the conclusion that an important part of the ground-water flow is not perpendicular to the two rivers. It is not very probable that much ground-water infiltrates the silty layer and percolates to a deeper aquifer, because of the hydraulic properties of this layer and because Maebe assumed a greater thickness of the upper aquifer than the field situation for his calculations. Another possibility is that part of the ground-water recharge flows parallel to the rivers, although this will not be more than the amount of water that flows perpendicular to the rivers, as the slope in this direction is small (± 7 m/5 km). More probable is that some water drains away through small gullies, parallel to the rivers, with the result that the distance between two drains is smaller. This possibility is also illustrated in appendix 6, figure 2, for the section between the intermediate point at 1300 m and Río Tortuguero.

1.6.4 Conclusions

It is not clear how the ground-water is discharged. In many parts of the study area the hydraulic conductivity above the impermeable layer (0 to appr. 2m) is quite high; the flat topography and the considerable distance between the drains are thought to be causing this soil to be poorly drained. Although not many gullies could be found, a probable explanation is that part of the water is discharged through small gullies parallel to the river.

2. SOIL PHYSICAL MEASUREMENTS

2.1 AUGERHOLE METHOD

2.1.1 Introduction

The augerhole method was used, alongside the column method, to get a fair number of observations along the transect in a relatively short time and to obtain results with a reasonable accuracy. Moreover, a comparison could be made could be made between the two methods. While a better impression was obtained of the gradient and variability in the hydraulic conductivity along the transect. Another advantage of having augerhole data in addition to the column data is that the conductivities measured with the augerhole method represent horizontal conductivity (in contrast to the vertical conductivities of the column method) and the two methods yield data from different depths; the column method concerns the upper 30 cm of soil, whereas the augerhole method yields the saturated hydraulic conductivity of the subsoil. There are advantages and disadvantages to both methods, which will be discussed below. Bouma (1983), gives an overview of methods available for determining K_{sat}, evaluating the accuracy of measurements and time needed for measuring.

If the augerhole method is applied, a hole is made with an auger to below the water-table. Water is pumped out and the inflow of water is measured by recording the speed of the water table rise. The test arrangement and the geometric and hydraulic parameters are shown in fig. no.4.

The diameter of the augerhole should be at least 0.08 m. and the depth below the water table (H) should be more than 0.5 m. Augerhole test are generally carried out in duplicate or in triplicate and often at two depths (H = 0.5 m. and H = 1 to 1.5 m.) below the water table. Water is removed from the hole after an equilibrium is reached with the surrounding ground-water. Ground-water seeps in to replace the water removed. Measurement starts immediately after water is removed from the hole. Reading may stop when the total rise is 0.25 of the initial drawdown $h(t_1)$. Two to four readings are taken on the same auger hole. Often, particularly in sticky soils, the second test gives better results (sealing effect). In unstable soils, e.g. most sandy soils, the hole collapses when water is removed and a filter must be used.

Landon (1991) states that the augerhole method gives the average permeability of the soil layers extending from the water-table to a few decimeters below the bottom of the hole. He also states that the radius of the column of soil of which the permeability is measured is about 30 to 50 cm. This seems rather small, however; it might be somewhat more, especially in more permeable soils. The use of the augerhole method is limited to areas with a high ground water table (GWT), at least during part of the year and to soils where a bore hole of a known shape can be maintained throughout the test.

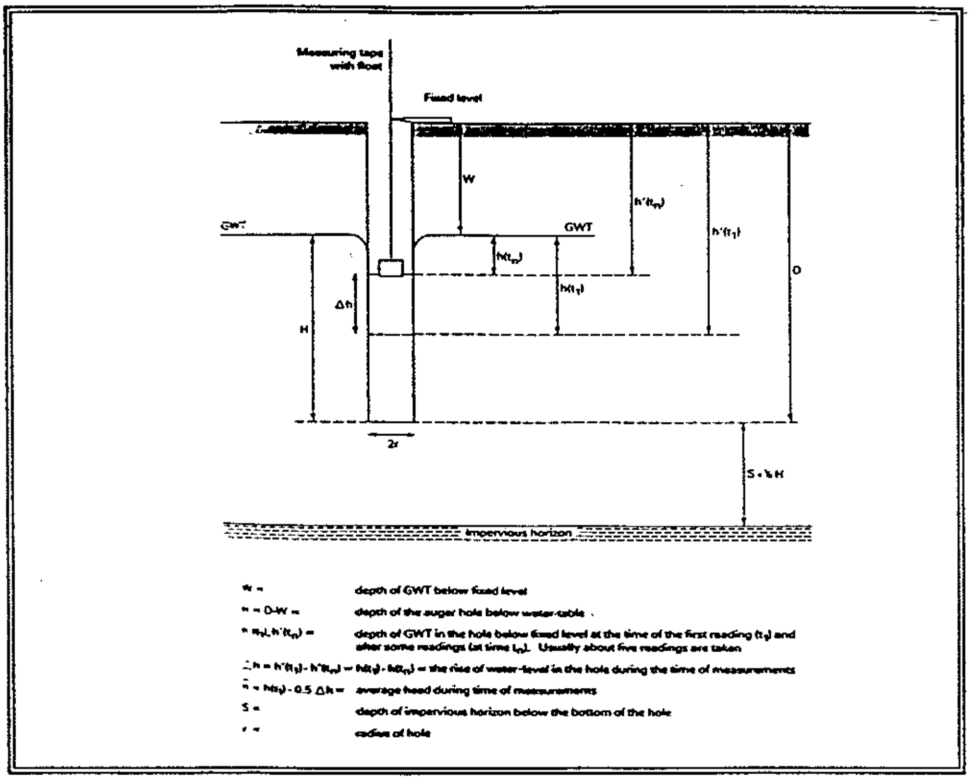

Fig. 4: set up augerhole method (van Beers, 1976, In: Landon (1991).

The relation between the hydraulic conductivity of the soil and the flow of water into the augerhole depends on the boundary conditions; the numerically derived equation for this is given by Ernst (1950) as:

$$K = \frac{(4000 * r^2 * \Delta h)}{(H + 20r) * (2 - hl/H) * hl * \Delta t} \qquad (2)$$

In which:
K = hydraulic conductivity (m/day).
h1 = distance between ground-water level and the average level of the water in the hole for the time interval t (cm).
H = depth of the hole below the GWT (cm).
r = radius of the augerhole (cm).
S = depth of the impermeable layer below the bottom of the hole or layer, which has a permeability of about 1/10 or less than the permeability of overlying layers.

This formula is empirical; the value of K will be sufficiently accurate (maximum error is about 20%) if the following conditions are met (Landon, 1991): $3 < r < 7$cm, $20 < H < 200$ cm, $h1 > 0.2$ H, $D > H$, $\Delta h < 0.25h(t1)$.

This formula holds for a homogeneous profile with an impermeable layer at a depth $S \geq 0.5$ H.

2.1.2 Results and discussion

Table 2: Values for saturated hydraulic conductivities measured with the augerhole method:

Observ.	K-sat value
1	1.14
2A	12.35
2B	4.84
2C	7.67
3	1.08
4	0.13
5	1.02
6	1.35
7A	2.44
7B*	1.15

Observ.	K-sat value
8A	4.29
8B*	1.67
9A	4.49
9B*	1.88
10A	1.67
10B	10.00
10C	6.08
11	1.31
12	5.05
13	5.41
14	3.76

Observation one is done approximately 150 m. from Río Tortuguero. The observations are all done along the transect with 100-150 m. distance between them. The last observation, no. 14, was done approximately 200 m. from Río Palacios. All measurements are averages of replicated observations in the same augerhole. Suffixes A, B or C indicate replicate observations from a new augerhole at the same site. A * indicates that, the replicate observation is done in the same augerhole but with the bottom of the augerhole at greater depth.

The observation sites (indicated in the table by numbers) are plotted on the map of the research area (appendix 1). The table shows that the variability in K-sat values measured with the augerhole method is quite large in this area, sometimes even at very short distances. This variability stems from extensive root channels of former swamp vegetation in the subsoil. The roots have decayed and channels (often about 2 cm in diameter) remain. If an augerhole intersects with such a channel, the water in the channel is emptied in it. In some parts no holes could be made without meeting a root channel.

The question now is how to interpret these conductivities. On the one hand we measure the rate at which the water flows from the channel into the augerhole rather than the conductivity of the soil (matrix). On the other hand; this is the field situation and such channels cannot be ignored because they certainly influence overall conductivity. The contribution of the root channels to hydraulic conductivity, depends on how far the channels extend, if they form a closed system or if they have outlets in a drain or river, how much water they can store, etc. When enough replications per site are measured, the obtained values are certainly valuable. In this particular situation additional measurements of the K-sat of the top-layer (0-30 cm) are indispensable.

By and large we can say that the augerhole method is suitable for this type of soil with a high water-table. About four measurements per day, including replications, could be done by two people. On 14 locations along the transect the augerhole method was applied, thus obtaining a view of the variability of the terrain on K-sat. In this particular case measurement of the hydraulic conductivity of the top-layer by another method was indispensable for two reasons: 1) the subsoils (root channels) had different properties compared with the top-layer, and 2) for modelling the physical properties of the upper layers are most important. But here the two methods (augerhole and column) yield complementary results.

2.2 COLUMN METHOD

2.2.1 Introduction

This field test has been done earlier, albeit with the use of a crust, and was discussed comprehensively in a number of papers (Bouma, et al., 1983, Klute, 1986, Spaans, et al., 1989). Therefore only a brief discussion is presented here.
A column of undisturbed soil with a height and diameter of approximately 35 cm is carved out. Its surface is smoothend and cleaned to obtain an undisturbed exposed infiltration surface. A steel ring with a diameter of 30 cm is placed on top of the soil column and carefully pressed down a few centimetres. The entire column is coated with cement, in order to obtain one-dimensional vertical water flow. After the cement has hardened a steady infiltration rate is measured at pressure head h = 0. Infiltration is measured with a burette and a mariotte device. For more details, the reader is referred to the mentioned publications.

The column method was performed on two layers for each profile; 0-30 cm and 15-45 cm, the same layers that were used for the one-step-analyses. This was done in order to obtain physical characterization of both topsoil and subsoil. No crust was used and therefore only K-sat values were measured. In profile #1, one measurement at -6 cm succeeded. No tensiometers were used; unit gradient was assumed.

2.2.2 Results and discussion

The obtained values will probably overestimate K-sat, as water could freely move through the macro-pores. However, the poorly drained soils are often completely saturated and therefore, for the present situation, the K-sat value can be considered representative. When considering artificial drainage, K-(sat) values measured with the crust test are desirable, as in the (artificially) drained soil the macro-pores will conduct no water.
In the following table the results are presented of both the column measurements and the augerhole measurements performed on the same site.

profile no	K -sat (m/d)	
	column	augerhole
1	A1 8.87	-
	A2 4.42	
2	A1 2.63	0.95-10.01
	A2 4.68	
3	A2 0.53	0.13

Table 3: K-sat values of two methods performed on the same site.

The augerhole method was not was not applied to profile #1, as the ground water table was too low.
The two methods are conceptually different, one measuring vertical and the other horizontal hydraulic conductivity, and their values can therefore not be directly related. However, the K-sat values of the two methods are expected to be in the same order of magnitude. Table 3 reveals that the K-sat values measured with the column method are quite high, except for

profile 3. If the crust method would have been applied, the values would probably have been lower. The variability of the values obtained with the augerhole method was explained in paragraph 2.1.2. At the site of profile #2 several augerholes (only ½ to 1 m apart) were measured, yielding different values. The variability in the subsoil, with extensive root–channels, explains the variable results obtained with the augerhole method. The reliability of the values obtained with the column method is expected to be higher. Therefore, and because the column method values concern the hydraulic conductivity of the topsoil, the column method values were used in crop growth simulation with the PS123N-model.

3. ESTIMATING VAN GENUCHTEN PARAMETERS

3.1 INTRODUCTION

As models for simulation of water- and/or solute transport in soil and for simulation of crop growth become better, good quality physical soil data become ever more crucial. Algorithms are needed to describe the K(h) and Θ(h) relations as accurately as possible. Such algorithms should be applicable to a wide range of soils. Measurements for estimating K(h) and Θ(h) relations must be as simple and accurate as possible. One method for estimating K(h) and Θ(h) relations (a so-called inverse approach in the form of a parameter optimization technique) is the one-step-outflow method.

3.2 ONE-STEP-OUTFLOW METHOD

3.2.1 Theory

The one-step-outflow method estimates Θ(h) and K(h) from measurements of cumulative outflow over time from an initially saturated soil upon changes in gas pressure in a pressure desorption cell. By inverse modelling of transient flow events, such as the one-step outflow measurements, in combination with statistical optimization, parameter values for the closed form equations as proposed by van Genuchten (1980) can be obtained (Booltink, 1991). The unknown parameters in hydraulic functions are estimated by minimizing deviations between observed and model-predicted output.

Numerical simulation of vertical flow in soil can be done by combining Darcy's law and the mass conservation law as in Richards' equation:

$$\frac{\delta\theta}{\delta t}=\delta[K(h)(\delta h/\delta x-1)]/\delta x \tag{3}$$

The system (of soil and porous plate) has the following initial and boundary conditions:

$h = h_0(x)$	$t = 0$	$0 \leq x \leq L$
$\delta h/\delta x = 1$	$t > 0$	$x = 0$
$h = h_L - h_a$	$t > 0$	$x = L$

Where x = 0 represents the top of the soil core, L the height of the sample plus the ceramic plate, h_L the initial water potential below the ceramic plate and h_a represents the pneumatic pressure applied.

Once all functional relations are known, simulation of water flow can commence. The hydraulic functions were described by van Genuchten and Mualem; unknown parameters in their functional relations are found by optimizations (Van Dam, Booltink, Weitz). Retention and outflow functions are fitted on measured outflow- and retention data in the program SFIT and corresponding conductivity functions are estimated. The Θ(h)function based on Mualems concept contains four independent parameters (Θ_r, Θ_s, α, n), which have to be estimated from observed soil-water retention data.

The formula for $\Theta(h)$ (the soil moisture retention at pressure h):

$$\theta(h)=\theta r+\frac{(\theta s-\theta r)}{(1+(\alpha*h)^{n})^{m}} \tag{4}$$

and:

$$m=(1-\frac{1}{n}) \tag{5}$$

The relative saturation (Se):

$$Se=[1+|\alpha h|^{n}]^{-m} \tag{6}$$

and K(h) (the hydraulic conductivity at pressure h):

$$K(S_{e})=K_{s}S_{e}^{\gamma}[1-(1-S_{e}^{1/m})^{m}]^{2} \tag{7}$$

or expressed in terms of soil water pressure head:

$$K(h)=K(sat)*\frac{[((1+(\alpha*h)^{n})^{m})-(\alpha*h)^{(n-1)}]^{2}}{(1+(\alpha*h)^{n})^{(m*(\gamma+2))}} \tag{8}$$

In which:

Θ_s = saturated volumetric water content [$cm^3.cm^{-3}$]
Θ_r = residual volumetric water content [$cm^3.cm^{-3}$]
$\Theta(h)$ = actual volumetric water content [$cm^3.cm^{-3}$]
α = empirical parameter (approximately 1/air entry value) [$1.cm^{-1}$]
n = fitting parameter [-]
m = fitting parameter [-]
γ = fitting parameter [-]
K_s = saturated hydraulic conductivity [$cm.hour^{-1}$]
k(h) = actual conductivity [$cm.hour^{-1}$]
S_e = relative saturation [-]
h = pressure head [cm]

As an input value in SFIT for the residual water content (Θ_r), the amount of water retained by a soil sample after applying a pressure of 15 atmospheres (≈pF 4.2) was used. α, n and m are empirical parameters that determine the shape of the curve. Parameter γ, called pore-connectivity parameter by van Genuchten (1991), is a strictly empirical parameter, estimated at 0.5 by Mualem (1976, in: Kool and Parker, 1987) from a regression between observed and predicted K(Θ) for 45 different soils. The slope of the K(h)-curve in the high suction section is influenced by γ (Booltink, pers.comm.). Parameter n is thought to be inversely related to the width of the pore size distribution and has a value between 1.1 and 3.5 (van Genuchten, 1980, van Genuchten and Nielsen, 1985; quoted in: Kool et al, 1985). The value of n influences the shape of the retention curve; the rate at which the S-shaped retention curve turns towards the ordinate for large negative values of h, reflecting the steepness of the curve

(Wösten & van Genuchten, 1988). Parameter α is the inverse value of the air entry pressure and has a value between 0.5 and 5.0 m^{-1}. For α the lowest value reported is 0.15 m^{-1} for a heavy clay soil, whereas for n the upper limit is about 10 for materials with narrow pores. Coarse soils are thought to have high values for α and n, whereas fine soils have lower values (Kool et al, 1985).

One problem in parameter estimation is "non-uniqueness". This occurs when several parameter sets give roughly the same outcome. This can be caused by parameters being correlated; a change in one parameter will then be accompanied by a change in the associated parameter. But even if parameters are independent, the available experimental data may lead to an objective function that lacks sensitivity to one or more parameters, again with the result that these parameters have large estimation variances. Instability occurs when the estimated parameters are excessively sensitive to changes in data. Relatively small errors can then lead to significant errors in estimated parameter values (Kool et al, 1986).

3.2.2 Material and Methods

Outflow was induced by applying a positive pressure to the top of saturated soil samples that were placed in pressure cells. The experimental set-up is shown in fig. 1 and fig. 2, appendix 7. Ten undisturbed soil samples, in 300 cm^3 cores with 7.25 cm diameter and height, were placed in pressure cells (see fig. 2, app. 7) on ceramic plates with an air entry value of approximately 100 KPa. Greased rubber rings are placed between the (top and the bottom of the) core and the pressure cell. It proved to be difficult to prevent air entry past these rubber rings. A tiny scratch on the sample core or a grain of sand in the grease on the ring can already cause leaking. Carefully selected cores for sampling, new rubber rings and a bit of good luck proved important in making the samples airtight. Sampling in the field and preparation of the sample must be done with great accuracy. During sampling the cores may not be hammered into the ground but must be pushed. The pore system of a soil with andic properties is very delicate. Tapping or hammering the ring will make the pore system collapse (A. Weitz, pers. comm.). When the samples are taken excess soil is removed with a knife and minor roots are removed with small scissors. A smooth surface of the soil sample is essential, small holes are filled up with "Blokzijl"-sand. Thus one obtains a good contact between the ceramic plate and the soil sample. The samples are saturated from below by keeping the outflow level above the top of the sample and by regularly adding water via the outflow tube. It has to be checked that water is not trapped in the tubes or in the pressure cell. After saturation the samples are placed on their holders with the outflow level exactly at the top of the sample. When there is equilibrium, all samples are saturated and no extra water is retained in the tube above the sample. Measurements start by applying a pneumatic pressure to the sample, inducing unsaturated flow in the soil sample, while the ceramic plate remains saturated. Cumulative outflow of water is recorded in burettes as a function of time. During measurements the level of outflow, at the overflow device, is placed halfway the core.

First, two points in the low-pressure range of the retention curve are measured, applying pressures of 2.5 kPa and 4.0 kPa until equilibrium is reached and outflow stops. Next, a one-step pressure head of approximately 60 kPa is applied and maintained for about five days. Higher pressures are not applied as this would cause problems with dissolving and releasing air in soil water (Booltink et al, 1991). Outflow over time is measured in the burette, initially after short intervals (one to several minutes) increasing to time-steps of about four hours. The outflow experiment is stopped after 5 days by removing the samples from the pressure cells. Immediately thereafter the samples are weighed and dried at 105 °C for 24 hours. Bulk density and saturated water content can be calculated. After oven-drying, the samples are inspected visually on features that could influence outflow, f.i. cracks, and pieces of wood. This proved to be important; some of the deviating curves could be explained by these features, afterwards.

3.3 SFIT

3.3.1 The programme and inputs used

SFIT is a programme that estimates values for Van Genuchten parameters on the basis of an iterative fitting procedure in which measured and observed outflow- and retention data are compared, using parametrized soil hydraulic functions (van Genuchten). Before running the FORTRAN-program an input file has to be prepared. Initial program parameter values have to be defined, notably the number of elements that are used for numerical solution, the number of observations (outflow and water-retention), the maximum number of iterations plus the number of repetitions and the model parameters Θ_r, pore volume (ccm/ccm) and the saturated hydraulic conductivity (cm/h). In addition, data on the initial and boundary conditions and on the observed values have to be specified.

Eight model parameters can be optimized. In the present set-up, hysteresis is not considered (no distinction is made between adsorption or desorption), 6 parameters remain to be optimized, viz. α, n, Θ_r, Θ_s, K_s and γ. Measured values were taken as initial values for K_s, Θ_s, Θ_r (pF4.2) measured values were taken. K_s (in most cases) and Θ_s were not optimized as they were determined independently. Θ_r is considered to be without much physical meaning (van Genuchten, 1991) and is arbitrarily defined (in this study) as the volumetric fraction of soil water retained at pF 4.2. Initial values for α and n were borrowed from the so called "Staring-reeks". 0.5 was taken as an initial value for γ as this value appeared satisfactory for many soils (Mualem 1976, in: van Genuchten et al, 1991). Boundaries for n and α were kept within realistic ranges; $1.001 \leq n \leq 3$ and $0.001 \leq \alpha \leq 0.5$. Since gamma γ is strictly a fitting parameter no limitations need to be considered ($0 \leq \gamma \leq 100$), (Booltink, 1991).
Input values for initial conditions (initial moisture and/or pressure status of the sample) and boundary conditions are obtained from the experiment. Observed cumulative outflow over time and four $\Theta(h)$ measurements were used for parameter optimization. The optimization procedure is repeated 3 times by putting a minus sign before the number 20 (max. no. of iterations) in the input file. The initial values are optimized in the first run and the second and third time randomly chosen values are used (Booltink, 1991). The iterative optimization procedure is continued until the relative change in each parameter is <1% (Kool et al, 1985,I).

As input for Θ_s, the values used were those calculated with the one-step procedure, because they stem from the same sample (variation between such small samples can be large). The one-step Θ_s-values are likely to be somewhat too high, as the zero-pressure head is situated at the top of the sample in this procedure and not at the bottom like as in traditional pF-measurements. With the zero-pressure head situated at the top of the sample, the larger pores, that actually have no capillarity in the soil, are saturated. This effect is seen in the following table, in which the differences between the Θ_s-values measured on separate samples and the Θ_s-values measured in the one-step procedure are shown.

Tab 4: Average Θ_s-values found with the one-step procedure and measured separately.

profile/layer	1A1	1A2	2A1	2A2	3A2
measured Θs:	0.63	0.60	0.75	0.67	0.74
one-step Θs:	0.78	0.68	0.75	0.73	0.70

* measured=determined on separate samples taken with either 100 or 300 cc cores.

Note that the separately measured Θ_s-values are lower than the one-step values with the exception of 2A1 (equal values) and for 3A2 (1-step is higher than measured).

3.3.2 Results and discussion

Quality check of output

The generated parameter values can be checked in several ways. In addition to visual control of the K(h)-, Θ(h)- and outflow curves (shape of the curves, degree to which the lines fit the observed data points), the program offers two statistical procedures to check the quality of the optimization. One is the weighted sum of squared differences (SSQ) between measured and optimized values, which should be as small as possible. The SSQ is a summation; for comparison with other samples, the value should be divided by the number of measurements. Another check is the generated squared correlation coefficient, R^2, which is independent from the number of observations and should be close to one. R^2 expresses the regression between observed and predicted outflow- and retention data. The program outputs a correlation matrix, the standard error and a 95% confidence interval for each parameter as well as an AIC-value (Akaike Information Criterion; should be as low as possible).

General

The first runs concerned all samples and included optimization of K(s). Equal weights (1) were assumed for retention- and pF-observations. The results were unsatisfactory; in ten out of fourteen cases, the curves could not be fitted well through observed retention points; in most cases the conductivity curve-fit was poor as well. Per sample, many more data are available for outflow observations than for pF-points. The non-linear minimization routine used in SFIT is based on the Levenberg-Marquardt method but has the number of observations (not only the value itself) included in the calculations. Therefore outflow observations influence the outcome more than pF-observations (Booltink, pers.comm). In this first SFIT run, the outflow curves were well fit, in contrast to the pF- and K-curve. Four samples gave, more or less, satisfactory results for all curves in the first SFIT-run; two samples from the second layer (15-30 cm) of profile #1 (1A2) and two samples from the second layer of profile #2 (2A2). These samples showed the anticipated outflow pattern, except for one sample 2A2, of which the outflow does not reach a plateau. The quality of the fits of all other samples was poor. It was decided therefore to make a second run with the same data, but without K-optimization (taking the measured value as fixed input) and to give the measured pF-values more weight than the measured outflow points. The four outflow points first measured were given a relative weight of 0.5, the other outflow points were given a weight of 1 and the retention points were given a weight of 3. Fittings of both K- and pF-curves improved as a result, but in some cases quality of outflow-fit decreased.

See appendix 8 for the obtained K(h)-, Θ(h)- and outflow curves. Sample 2A2-20 has a more than acceptable outflow pattern. The first half of the pF-curve is well fitted. The second part of the curve is much higher than the observation points, because the fitting procedure is based on measurements up to 600 mb (≈pF2.7) and curves in the higher pressure range are therefore largely based on extrapolation. The reliability of the K(h)- and of the pF-curves in the range ≥ 600 mb is low.

Outflow curves

Van Dam (1990) discerns three parts in the outflow curve:
in the first part the flow rate is determined by the resistance to flow in the ceramic plate; outflow is proportional to time. In the second part the flow decreases with desaturation; outflow is linearly related to $\sqrt{t}$. In the last part flow resistance increases as initial concentration in the top decreases. Outflow is plotted against the square root of time.
Samples from both layers in profile #1 (1A1/1A2) and two samples from 2A2 (profile 2, 15-30 cm) give well fitted curves with the anticipated outflow pattern. The runs for the top-layer of profile 2 (2A1) and for the second layer of profile #3 (3A2) all give an almost linear result and in some cases total outflow is low. It seems as if flow resistance caused by some kind of barrier levelled the flow pattern. For the patterns of profile 2 a soil morphological explanation can be given: between 5-10 cm (i.e. in the 2A1-samples) a very thin accumulation layer of rust was found. Thin plates were seen. It was observed that, even though the top-layer was high in organic matter and well rooted (grass), the subsoil had a higher conductivity than the top-layer. The thin iron pan will have obstructed the outflow in both the column measurements and the one-step measurements. All samples of profile #3 had some deviations caused by small pieces of wood (roots) in the sample, it is not clear if or to what extent this has influenced the outflow pattern. It is suspected that the samples with low conductivity have a tendency to give a more linear outflow pattern. Two additional samples were analyzed in the one-step procedure; two samples from the reduced, slowly permeable silty layer (≥2m), to get an idea about the hydraulic properties of this layer. Neither K-sat, nor pF 3.5 or 4.2, were available; they were estimated using values from other samples with comparable texture. The outflow pattern of this silty layer is regular, but tending to linearity.

Retention curves

The Θ-values at pF 3.5 are remarkably high. The difference in volumetric water content between pF3.5 and pF4.2, according to these data, is 10 to 15%. In some cases (see the combined water retention curves of layer 2A1) the difference is even 25%, which seems unrealistic. One is tempted to doubt the accuracy of the measurements. It is striking though that all samples with the largest differences originate from the same layer (prof 2, 0-30cm; thin iron pan). All samples for pF3.5 and pF4.2 were left on the ceramic pressure plates for four days, which is perhaps too short. It is possible therefore that some of the samples had not yet reached equilibrium conditions. However, if it is assumed that both pF3.5 and pF4.2 measurements were realized over a period of four days, this does not explain the large difference in Θ between the two 'high' pF points.
The Θ_s-values are high (≥0.68) and so are the Θ-values for pF 1.4 and for pF 1.6. The pF-curve is very 'wet' in the section from 10-50/75 mbar; some curves are practically horizontal in that pressure range. The samples supplied to the laboratory were 'field-moist'. The instructions were, and we can only assume that they were followed, not to dry, sieve or do

any other treatment than saturate and desaturate them on the pressure plates.

Values for estimated 'available' water capacity are given in table 5. The amount of water stored in the soil between pF2 and pF 4.2. gives a rough impression of water availability in these soils and makes comparison possible. The boundary value for wilting point (set at pF 4.2) is theoretical, as the pressure head value for wilting point is dependent on the plant species. However, PSI_{leaf} for maize is estimated at 17000 cm, which is close to pF 4.2 (Reinds, cited in Driessen and Konijn, 1992).

Table 5: Estimated amount of water (vol%) stored between pF2 and pF 4.2.

Sample no.	Bulk dens. g/cm3	SM0 vol%	FC vol%	WP vol%	AWC vol%= mm/dm	AWC*RD cm H2O
1A1-16	0.78 g/cm3	68	52	20	32	54.4
1A1-17	0.78 g/cm3	69	55	20	35	59.5
1A1-13	0.78 g/cm3	69	57	20	37	62.9
1A2-6	0.90 g/cm3	68	57	18	39	66.3
1A2-8	0.90 g/cm3	69	57	18	39	66.3
2A1-7	0.56 g/cm3	76	62	25	37	62.9
2A1-9	0.56 g/cm3	74	50	25	25	42.5
2A1-14	0.56 g/cm3	74	61	24	37	62.9
2A2-19	0.64 g/cm3	73	59	18	41	69.7
2A2-15	0.64 g/cm3	74	58	19	39	66.3
2A2-20	0.64 g/cm3	72	61	19	42	71.4
3A2-4	0.76 g/cm3	68	52	18	34	57.8
3A2-5	0.76 g/cm3	69	50	18	32	54.4
3A2-10	0.76 g/cm3	66	57	19	38	64.6

FC=Field capacity;defined here as pF 2.
WP=Wilting point;defined here as pF 4.2.
AWC='Available'watercapacity.
SM0= θ_s ;Total pore fraction.
RD= Maximum rooting depth maize,
assumed to be 170 cm (Driessen & Konijn, 1992).

The volumetric fraction of soil moisture at pF4.2 ranges between 0.18 and 0.25, which is rather high for (clay)loamy soils. This tallies with the 'andic properties' of the soil.

Conductivity curve

Most conductivity curves show rapidly descending K(h) as pressure increases. Often K(h) is already infinitely small ($\leq 10^{-4}$) at 100 cm ($\approx$100 mbar) pressure. PS123N-model had difficulties calculating the K-unsat figures (became too small for calculation) obtained through the van Genuchten relations and a lower boundary for the K(h)-value was defined in the program. Another problem with the K(h)-curves, is that the curves are almost all under the measured K-sat (and occasional K-unsat) points. For the K-sat points this is partly due to the fact that the x-scale is logarithmic and therefore starts at 1 (and the K-sat values were measured at h=0). Between 45 cm and 600 cm pressure the K(h)-curve is probably most reliable.

Conclusions & Discussion

The model bases its estimations on measurements in the low suction range (up to 600 mb, $\approx$pF 2.7); estimated characteristics for K(h) and Θ(h) for pressures over 600 mb are obtained by extrapolation. The validity of the hydraulic relations for the higher suction range is questionable. Measurements were done up to a maximum pressure of 600 cm from a minimum pressure of 25 cm. Although the results seem to be comparable, the optical judgement is misleading, as the graphs are presented with double logarithmic scales. Small differences between curves can obscure 10, 100 or 1000 times higher values. For these soils, under a wet climate, the low pressure range is useful, as these soils are in the wet part of the curve during most of the year.

Many outflow curves were well fitted, but often the pF-curves and K-curves were misfitted. Especially for the higher pressure range the curve was fitted often way above the measured points. By giving the measured pF-points a higher weight the pF-curves were improved but fitting of the outflow curves became (slightly) worse. The pF-curves, however, improved considerably. The K-curve could be improved by fixing the input value for K-sat. Comparing the first (no weights) with the second SFIT-run (added weights to pF-points) shows that the van Genuchten parameters do not change much when weights are changed (see f.i. van Genuchten parameter data from two runs of sample 2A2-20; appendix 8). Parameters α and n do not differ much in value between the two runs; Θ-res is the same in both runs; negligibly small. Of course gamma differs greatly between the two runs, but that is not much of a problem, as gamma is a fitting parameter and has no physical meaning. It seems therefore that, if necessary (in case of poor quality graphs), adding the lowest possible weights to the pF-observation points (especially the two in the high suction range) can draw the curve down to the measured points in the high suction (=extrapolation) range, without significant consequences for the van Genuchten values.

The fact that the results of the one-step estimation procedure are not always satisfactory, suggests that the van Genuchten/Mualem relations might not be entirely appropriate for use on highly aggregated porous andosols or soils with andic properties. In volcanic soils, water is held in small pores rather than on charged surfaces (this is also an explanation for the tixotropy of Andosols; van Breemen et al, 1992). A serious problem with volcanic soils, is that sampling is difficult because the pore system is vulnerable. It is questionable whether the pore system of volcanic soils can withstand the large pressures that are applied on samples in the one-step procedure. It might well be that pores collapse already under these pressures, although this would probably be visible from the outflow pattern. In many cases a 'reasonable' outflow curve was obtained. Another problem might be the change of bulk density and moisture content as pressure is applied. Some samples shrunk during the one-step analyses, probably due to the high pressure applied on them and the lowered moisture content. A space between the sample and the ring could be seen. It is unknown in when shrinking starts, but this is quite important, as the outflow characteristics from that moment on could change drastically. Additional research is needed to study the adequacy of the one-step outflow method on volcanic soils.

The values for α varied greatly between fits. The range over all samples is also quite large; viz. from 0.0001 to 0.30. The value for n was less variable; values from 1.05 to 1.45 were found. Note that n is an exponential parameter in the model and a slight change in n, results in a large difference in K(h) and Θ(h). The value of Θ-res is also quite variable between three fits of a sample. γ is extremely variable, but this was expected as γ is a fitting parameter. Note further that the dimensions of the individual parameters can only be evaluated in relation to other parameters of the same fit, as they are not independent.

4. QUANTIFIED LAND EVALUATION WITH THE PS123N-MODEL

4.1 INTRODUCTION

The purpose of gathering physical soil data was not only to study the causes of the poorly drained conditions, but also to study possibilities for drainage and to run scenarios for land use alternatives, partly based on these physical soil data. In calculating production potentials of alternative land use scenarios (f.i. maize after drainage of this soil), the significance of the physical data can be studied in terms of effect on plant production. In this way the adequacy and relevance of physical data can be studied. For this purpose a model for crop growth simulation, the PS123N-model, was used. The physical relations were adapted to the van Genuchten formulas. For more information on the PS123N-model reference is made to Driessen & Konijn (1992).

Production situation 1 (PS-1) represents a rigidly, simplified land-use system. A PS-1 model quantifies the crop performance, within the physiological possibilities of the crop, as a function of land qualities on which the farmer cannot exert influence: availability of solar radiation and temperature. All other land qualities are considered to be unconstraining. In production situation 2 (PS-2) the water-limited production potential is calculated. The land quality 'moisture availability' is quantified and matched against the consumptive water needs. The result of this matching is incorporated in the PS-1 calculation procedure. In PS-2 calculations other land qualities or land characteristics than intercepted radiation, temperature and the availability of water (such as the availability of nutrients, weed competition, pest and diseases, harvest losses and other possibly limiting factors that are relevant to practical farming) are assumed not to constrain crop performance. The PS123N-model has an option for calculation of a third production situation that includes a study of nutrient limitations (PS-3).

PS2-calculation can be valuable for planning and decision making when considering alternative crops on a particular land unit or when considering agricultural possibilities in a virgin or abandoned area. In this way the physical suitability of an area for cultivation of a crop can be evaluated, optimum planting or sowing dates identified, water management decisions supported, etc. (Driessen & Konijn, 1992). In sustainability studies PS2/3 analyses can determine the best possible land use or the impact of erosion on water limited crop production.

However, biophysical production studies for an agricultural area can only be the first and never the only step. Socio-econonomic factors are just as important, as in practice often the prices, nearness to a market or labour availability determine the feasibility or sustainability of a land use scenario.

4.2 DATA NEEDS

The PS123N-program requires various input data; viz. data on the crop, the soil and the climate.

4.2.1 Climate file

The original climate files, obtained from the 'Instituto Meteorológico Nacional', contained the following daily data: irradiation (MJ m^{-2} d^{-1}, T-minimum (°C), T-maximum (°C), vapour pressure (mbar) measured at three different times, mean wind speed (km/h), precipitation (mm d^{-1}), sunshine hours (h). An existing conversion program ('Convmtod' and 'Convclim'in Quick basic language) was adapted to calculate from these data the data needed as input for the PS123N-model and to write it in a file in the correct format. The data needed as input for the PS123N-model are: Tmax, Tmin (°C), prec (cm/d), RHA (0-1), E0 (cm/d), SUNH (h/d), ET0 (cm/d). For calculating RHA, the three vapour pressures were averaged, see formulas 9 and 10. E0 and ET0 were calculated with the original Penmann formula (1948), using the aforementioned adapted 'convclim'-program.

$$RHA = VAP/SVAP \qquad (9)$$

(10)

$$SVAP = 6.11 * \exp(17.4*T_{24}/(239+T_{24}))$$ (Driessen, 1992).

Irradiation data were not used. Sunshine hours (SUNH) are believed to be more useful, as irradiation data are often measured at one moment in the day and therefore have a limited representability. Cloudiness and day length during the growing season greatly influence the rate of total assimilation, and thus the rate of production. For that reason higher productions for rice or maize can be obtained in the summer, with clear and long days, in the South of Europe than in many equatorial areas, like f.i. in Indonesia (pers. comm., P.M. Driessen). Consequently it seems better to use sun hours, to estimate overall daily irradiation (at given latitude and longitude), than single irradiation data. Climatic data were available for several stations in the Atlantic Zone, but were mostly incomplete. The daily data from Hacienda "El Carmen" (1973-1991) and from "Puerto Limon" (1970-1990) were best in the set, both in data per annum and in the amount of years. Rather extensive data coverage was available for weather station "La Mola", albeit only for three years (1980-1982). For "El Carmen", wind data (incomplete) were available for 1989-1991 only, these data were extrapolated to a generic set for a whole year and used for all years. The wind speed data for Puerto Limon were available for 1979-1990. For the period of 1970-1978 averaged wind speed data from later years were used. Many years of climate data had data gaps for some days or some weeks. For missing data average values (calculated from previous and later days) were substituted.

4.2.2 Soil file

The soil file for PS123N-analyses contains the following input data per sample:

SM0 : total pore space (cm^3/cm^3)
GAM : fitting parameter gamma ($1.cm^{-1}$)
PSI_{max} : Boundary suction value (cm)
K0 : saturated hydraulic conductivity ($cm.d^{-1}$)
ALFA : empirical parameter alfa (app. 1/air entry)
AK : high suction parameter ($cm^{-2.4}.d^{-1}$)
S0 : reference sorptivity (cm^3/cm^3)
Ktr : transmission rate ($cm.d^{-1}$)
n : fitting parameter (-)

Tabulated values were taken for PSI_{max}, AK, S0 and Ktr. These values were hardly used, only in the subroutine for calculation of capillary rise (PSI_{max}, AK) and for infiltration capacity (S0, Ktr). GAM, SM0, ALFA, n were obtained from the one-step outflow results. K0 was measured in the column test. Other values needed for determining K(h) and Θ(h) in the van Genuchten/Mualem formulas (f.i. Se) are calculated in the PS123N-program (for formulas see chap. 3).

4.2.3 Crop file

The crop file contains data for 6 crops, viz. 5 annuals and one perennial:

1) cassava (cv. Faroka, Indonesia)
2) cotton (cv. from P.R. of China)
3) maize (cv. Aris, Greece)
   (cv. from P.R. of China)
   (cv. Arjuna, Indonesia)
4) sorghum (generic data set)
5) vegetables (green pepper)
6) wheat (cv. from P.R. of China)

Crop data needed for PS123N-analyses per species/variety are: photosynthetic mechanism (C3/C4), maximum specific leaf area (SLA_{max} in m2.kg^{-1}), minimum specific leaf area (SLA_{min} in m2.kg^{-1}), extinction coefficient for visible light (ke), treshold temperature for development (T0 in °C), heat requirement for full development of plant T_{sum} in °C/d), heat requirement for full leaf development (T_{leaf}).

The crop selected for this study, was the maize variety Arjuna from Indonesia. This variety was chosen, because the growing conditions in Indonesia resemble most those of Costa Rica (compared to the other maize varieties).

4.3 PRODUCTION SITUATION-2 ANALYSES

The PS123N-model assumes that the rooted soil is homogeneous; (no separate layers are distinguished). The theory behind this is that plants take up water from layers with the lowest potential, which is not necessarily the layer with highest water content, so that the potential becomes the same throughout rooted part of the profile (P.M. Driessen, pers. comm.). Regional variability is another problem; how representative is one point observation. A representative average value, which should be based on many point observations, within the ranges of grouped texture classes, is more valuable.

PS2-analyses were performed with the following data as input:
Meteorological station: Hacienda EL Carmen/Puerto Limon/La Mola.
Selected crop: maize, var. Arjuna (Republic of Indonesia).
Production situation: 1/2/3.
Selected soil: profile #1/profile #3.
Julian day of sowing/planting: variable.
$PSI\text{-}_{init}$ (matric suction at planting/germination): 333 cm.
SSC (equivalent surface storage capacity): 5 cm.
ASSC (actual surface storage capacity): 0 cm.
Water table depth(fixed/variable): 200/300 cm fixed.
Sowing density: 25 kg/ha.

Mortality: 15%.
Applied irrigation: 0 cm.

4.3.1 Selection of profiles for modelling

The results of outflow measurements on profile #2 were not satisfactory. For the toplayer there was a clear morphological reason (thin iron pan influencing outflow). Samples from the topsoil of profile #1 and the subsoil of profile #3 were used for simulation. Note that profiles #1 and #3 represent two extremes in the research area; profile #1 is a dry (for the area), medium to coarse soil near the river and with a relatively high saturated hydraulic conductivity and is moderately well drained, whereas profile #3 is situated halfway between the two rivers, has clay loamy textures and is very poorly drained and has a relatively low hydraulic conductivity. Profile #1 could represent the profile after these soils are artificially drained. Profile #3 is not saturated with water throughout the year, at least not the topsoil. For profile descriptions, see appendix 10. There are parts along the transect that are saturated year round (Gley sols).

4.3.2 Running PS123N

For three sites the optimum sowing date and the maximum yield potential were calculated for each year and for two ground water depths. As a reference, PS1 was calculated for the optimum PS2 sowing date. Running the PS123N-model with the obtained 'van Genuchten'-parameter set for the selected profiles initially gave some problems. The K(h)-values became infinitely small and calculations stopped, because 'division by zero'-errors occurred. Therefore an extra condition was built in, namely that $K(h) \geq 10^{-6}$ cm/day; K(h) thus will never be smaller than this value.

4.3.3 Results

Profile #1

The highest PS2-yields calculated per year for profile #1 (with the ground-water fixed at 3 metres), were high, but quite variable over the years. As shown in figure 1, PS2-yields may be between 5 and 11 tons,

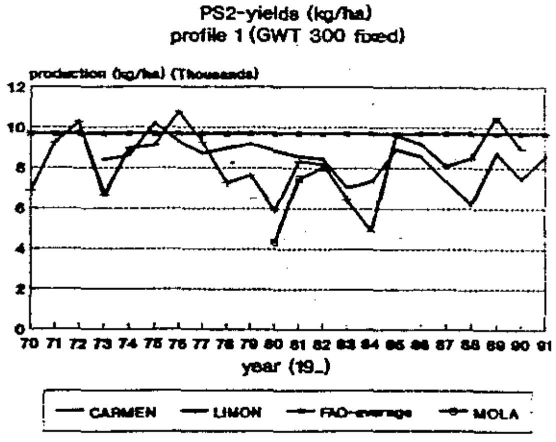

Figure 5

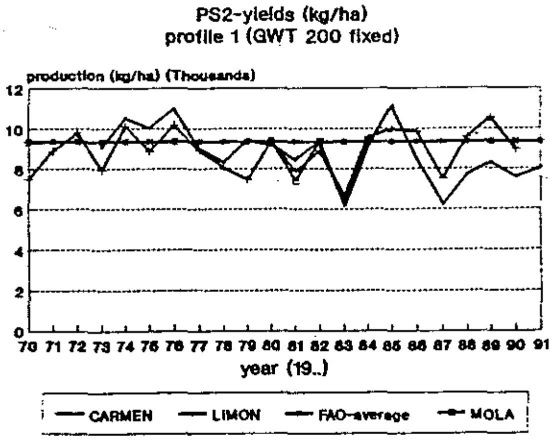

Figure 6

The average is about 8 tons/ha for GWT 3 metres and about 9 tons/ha for GWT 2 metres. The maximum PS2-production potential is more steady for El Carmen than for Limon.
The highest PS2-yields for the same situation but with the GWT fixed at 2 metres, yield the same results but the pattern over the years is more steady and the difference between the stations is less marked. See figures in appendix 12.
Comparing PS1- with PS2-yields, see fig. 1 to 8 in app. 13, reveals that PS2-yields are mostly lower that PS1-yields (about 1 ton). However, at GWT 2 metres, the difference is quite constant; PS2-yield and PS1-yield have the same pattern. With GWT fixed at 3 metres, however, the PS1/PS2-ratio is variable. This is probably because the drainage is optimal in wetter years (PS1=PS2), but in relatively drier years some moisture stress may occur. For GWT fixed at 2 metres this effect is mitigated; moisture stress probably does not occur but periods of moisture excess might occur (therefore PS1 ≠ PS2). Highest PS2-yields calculated with the data from La Mola (1980-1983), are considerably less than PS1 in 1980 (about 50%), slightly less in 1981 (about 1 ton) and almost equal to PS1 in 1982.

Profile #3

For profile #3 PS2-yields are on average slightly above PS2-yields calculated for profile #1 and less variable. Yields vary between 7 to 11.5 tons/ha for GWT fixed at 2 and 3 metres resp. However, in this case calculations with climate data from El Carmen yield more variable results than from Puerto Limon (which was the reverse for profile #1). For Hacienda El Carmen, PS1 = PS2 for both GWT's. With data of Puerto Limon PS1 = PS2, if GWT=2 metres. With GWT fixed at 3 metres, PS2 is only (slightly) less than PS1 in the 1980, 1984 and 1985. Which means that yearly, highest PS2-yields are always optimal and no stress occurs because of excess or lack of moisture. Calculations with the climate data of La Mola gave PS1 = PS2, for both GWT's and all three years.

For comparison, the model was runned with (tabulated) parameter values based on texture. For this the PS123N-model with the original physical relations ("Rijtema") was run with the 'Rijtema-loam'. PS2-productions calculated with the 'Rijtema-loam' and with the 'van Genuchten' data were in the same order of magnitude, however, PS2-productions calculated with "Rijtema-loam" were often slightly less than the production calculated with the measured data set. For profile #3 at Hacienda El Carmen 1980, using the optimum sowing date found with runs using 'van Genuchten'-data, the production potential calculated for the 'Rijtema-loam' was 1.5 ton less than the production calculated with the measured data-set and about 1 ton less at GWT 200 fixed.

FAO-data

Optimum sowing data and maximum PS2-yields were calculated for El Carmen and for Puerto Limon using average monthly data obtained from a FAO-database (multiple year averages). For that purpose the monthly data were interpolated to daily data with a conversion programme in Quick Basic ('Convmtod' and 'Convclim', P.M. Driessen, 1992). Interpolation of monthly to daily rainfall data yields unrealistic figures; an exactly evenly distributed rainfall over all days in the month. The exercise was done to see if such data would still yield representative 'average' yield figures.
The line in the graphs (fig 5, 6, and fig. 1 to 4, app. 12) representing the PS2-yield calculated with the average FAO-data, is an average of the PS2-yields of 'El Carmen' and of 'Puerto

Limon' (values calculated for these two stations deviated only by a few hundred kg's per ha.). With GWT at 2 metres for both profiles, the FAO-yield is just about the average of the yields calculated for the three stations. In the case of GWT fixed at 3 metres (both profiles), however, the PS2-yields, based on the average FAO-data, seem to overestimate the PS2-yields (see fig 5,6).

Optimum sowing date

The optimum sowing dates for both profile #1 and profile #3, with GWT fixed at 3 metres, was in January/February (the end of December or at the beginning of March is some years). With GWT fixed at 2 metres, the optimum sowing date was slightly more variable, but on average also in January/February. This is not far from the current practise, as farmers in the Atlantic Zone sow maize in December/January (Nieuwehuyse, 1988). The optimum sowing date can, however, not be predicted to the day. The problem is, that sowing 15-20 days before or after the optimum sowing date, may change the calculated production potential by several tons/ha. Studying the optimum sowing date per year in relation to the rainfall distribution of that year could yield some more information about the relation between optimum sowing date and rainfall pattern. Note that the optimum sowing date for each year was selected on the basis of highest PS2-production figure generated for each year. This means that high production might also be obtained on other days of the year (which was often the case around julian day 100, deviating only 100 kilos from the highest PS2-production earlier in the year).

4.3.4 Discussion

We can conclude from these calculations, that every single year, a reasonable yield is biophysically possible. However, disasters could still occur and in practise a sowing date is chosen, based on the experience of the farmer. In most cases some yield will be obtained, in some (but few) cases the crop drowns or wilts. The Atlantic Zone has a wet climate, with more than 200 mm of rainfall almost every month. As a consequence maize can be grown almost throughout the year, but production might be low. High rainfall and relative humidity are conducive to fungal diseases and weeds.
In this study the model-runs with interpolated monthly FAO-data yielded reasonable results. In most cases the calculated 'average' was of the same order of magnitude as the yields calculated with daily data, and within the range of the prediction error (estimated at about 20%). However, the interpolated data give no insight in yield variations. For humid climates with evenly distributed rainfall, monthly data can be useful when appropriate data are lacking, to obtain indicative production figures. However, in other (drier) climates, the usefulness of interpolated monthly data for simulation studies is doubtful.

Substantial information can be deduced from the PS2-runs. Limitation of production because of moisture stress does occasionally lead to yield reduction (GWT 300 fixed), but never to catastrophes, because of the amount and even distribution of rainfall. However, yield reductions are mostly caused by lack of oxygen in the root zone because of prolonged water stagnation. Growing maize on these soils will therefore be principally a matter of managing the excess of water in the root zone (at the PS2-level; at lower PS-levels other limiting factors can and will also play a role). PS2-yields are quite comparable between the two profiles. With GWT fixed at 3 metres, the yield pattern over the years is more variable than in the case of the GWT fixed at 2 metres.

Drainage will be difficult and costly. Using the drain-spacing formula of Hooghoudt (Agr. Comp., 1989), the drain spacing was calculated 23 metres for drains with dimensions of 1.6 m depth and 1.5 m width, keeping the GWT at 1 m.

It seems realistic to aggregate the soils within the poorly drained unit, as far as the physical parameters are concerned. For regional quantitative analyses of land use scenarios, calculated yield potentials for profile #1 and 3 are comparable. Note that these calculations are based only on two point values may not be representative for the whole unit. Aggregation to a representative average parameter set for the whole poorly drained soil unit, should be based on many point observations, and ranges of texture classes. Several authors have related soil water retention and hydraulic conductivity parameters to textural groups (f.i. FAO 1979a; in Landon, p. 76, 1992). Driessen (1992a) gives an overview of hydraulic parameters related to soil structure and texture. In a study that is currently running (GETE, 1993) van Genuchten parameters estimated for standard texture classes with several procedures (Rawls, Carsel & Parrish and Rijtema) were used to calculate production possibilities with the PS123N-model. The parameters used (α, K0, Θ_0) were obtained from literature and based on regression analyses of many soils. Interesting, but preliminary, conclusions from this study are that many texture classes yield similar potential (crop)production. Calculated 'clouds' of production figures, suggest that many of the texture classes could be lumped together, and only four texture classes remain, with the same parameter values. This finding has consequences for quantitative studies of sustainable land use in the Atlantic Zone. Aggregation of soil types within each of the three great units on the bases of observed (ranges of) soil structure and related to textural groups facilitates regional analyses. The aggregation could partly be based on, and checked by, crop growth simulation runs using the presently available physical soil data. The calculated yield and production potentials should then be validated in field experiments.

5:ABSTRACT

For modelling three broad categories of soil have been distinguished in the Atlantic Zone of Costa Rica; (1) fertile and (2) unfertile, well drained soils and (3) fertile, poorly drained soils. For this study descriptions and physical characterisations were made of the poorly drained soil group. The adequacy for use of the physical soil data in quantified land evaluation was evaluated. For physical characterization use was made of the one-step-outflow method and the growth of maize (var. Arjuna) was simulated with the PS123N-model.

The study area is located in the Atlantic-Caribbean lowland of Costa Rica, in the north of Limon province. This lowland is part of a large tectonic unit formed by subduction of the Cocos plate under the Caribbean plate. Most soils in the Atlantic zone are andosols or soils with 'andic' properties. The Atlantic Zone has a tropical rainy climate (A) and has no distinct dry season (f); the driest months have more than 60 mm of precipitation.

Due to the high pressure on the land elsewhere forest was cleared at a fast rate. The current land use on poorly drained soils in the Atlantic Zone is predominantly extensive cattle farming, mainly for meat production.

In the the study area, it is not clear how the ground-water is discharged. In many parts of the study area the hydraulic conductivity above the impermeable layer (0 to appr. 2m) is quite high; the flat topography and the considerable distance between the drains are thought to be causing this soil to be poorly drained. Although not many gullies could be found, a probable explanation is that part of the water is discharged through small gullies parallel to the river. Drainage will probably be difficult and costly.

Saturated hydraulic conductivities were measured, using both the column method and the augerhole method. The K-sat values measured were relatively high (around 4 m/day). Due to variability in the subsoil, the augerhole method yielded differing results. For crop growth simulation, the K-sat values obtained with the column method were used, as they are representative for the top layers.

In the one-step-outflow method, estimated characteristics for K(h) and Θ(h) for pressures over 600 mb are obtained by extrapolation. The validity of the hydraulic relations for the higher suction range is questionable. For these soils, under a wet climate, the low pressure range is useful, as these soils are in the wet part of the curve during most of the year.

The fact that the results of the one-step estimation procedure are not always satisfactory, suggests that the van Genuchten/Mualem relations might not be entirely appropriate for use on highly aggregated porous andosols or soils with andic properties. Additional research is needed to study the adequacy of the one-step outflow method on volcanic soils.

It seems realistic to aggregate the soils within the poorly drained unit, as far as the physical parameters are concerned. Aggregation to a representative average parameter set for the whole poorly drained soil unit, should be based on many point observations, and ranges of texture classes. Aggregation of soil types within each of the three great units on the bases of observed (ranges of) soil structure and related to textural groups facilitates regional analyses. The aggregation could partly be based on, and checked by, crop growth simulation runs using the presently available physical soil data. The calculated yield and production potentials should then be validated in field experiments.

From calculted waterlimited production potentials (PS2) for maize (var. Arjuna) with the PS123N-model it is concluded that every single year, reasonable yields are biophysically possible. The Atlantic Zone has a wet climate, with more than 200 mm of rainfall almost every month. As a consequence maize can be grown almost throughout the year, but production might be low. High rainfall and relative humidity are conducive to fungal diseases

and weeds. PS2-yields, calculated for two profiles with two groundwater tables (fixed at 2 and 3 metres), varied between 6 and 11 tons/ha (storage organ); with an average of about 8 tons. In this study model-runs with interpolated, monthly FAO-data yielded reasonable results. Yield reductions are mostly caused by lack of oxygen in the root zone because of prolonged water stagnation. Growing maize on these soils will therefore be principally a matter of managing the excess of water in the root zone (at the PS2-level; at lower PS-levels other limiting factors can and will also play a role). The optimum sowing date in the crop growth simulation was in January/Februari. This is not far from the current practise, as farmers in the Atlantic Zone sow maize in December/January (Nieuwehuyse, 1988). The optimum sowing date can, however, not be predicted to the day. Studying the optimum sowing date per year in relation to the rainfall distribution of that year could yield some more information about the relation between optimum sowing date and rainfall pattern.

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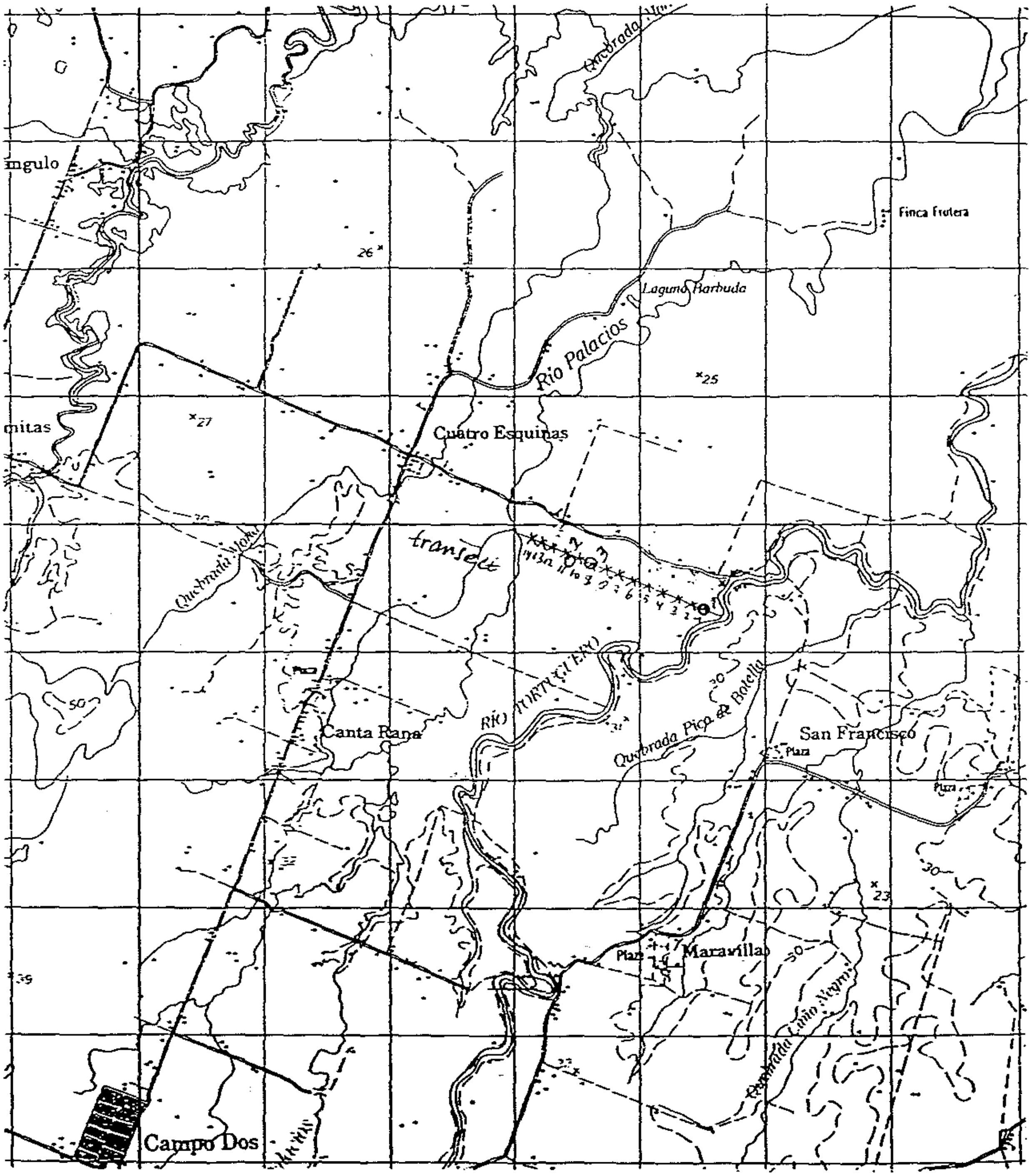
APPENDICES

1. Location of study area.
2. Map of Costa Rica.
3. Soil types.
4. Climate characteristics.
5. Topography and location of piezometers.
6. Theoretical waterprofiles.
7. Experimental set-up of the One-step outflow.
8. One-step curves and van Genuchten parameters.
9. Bulk density values and organic matter contents.
10. Soil profile descriptions.
11. Augerhole descriptions.
12. Calculated PS2-productions.
13. PS1/PS2-productions.

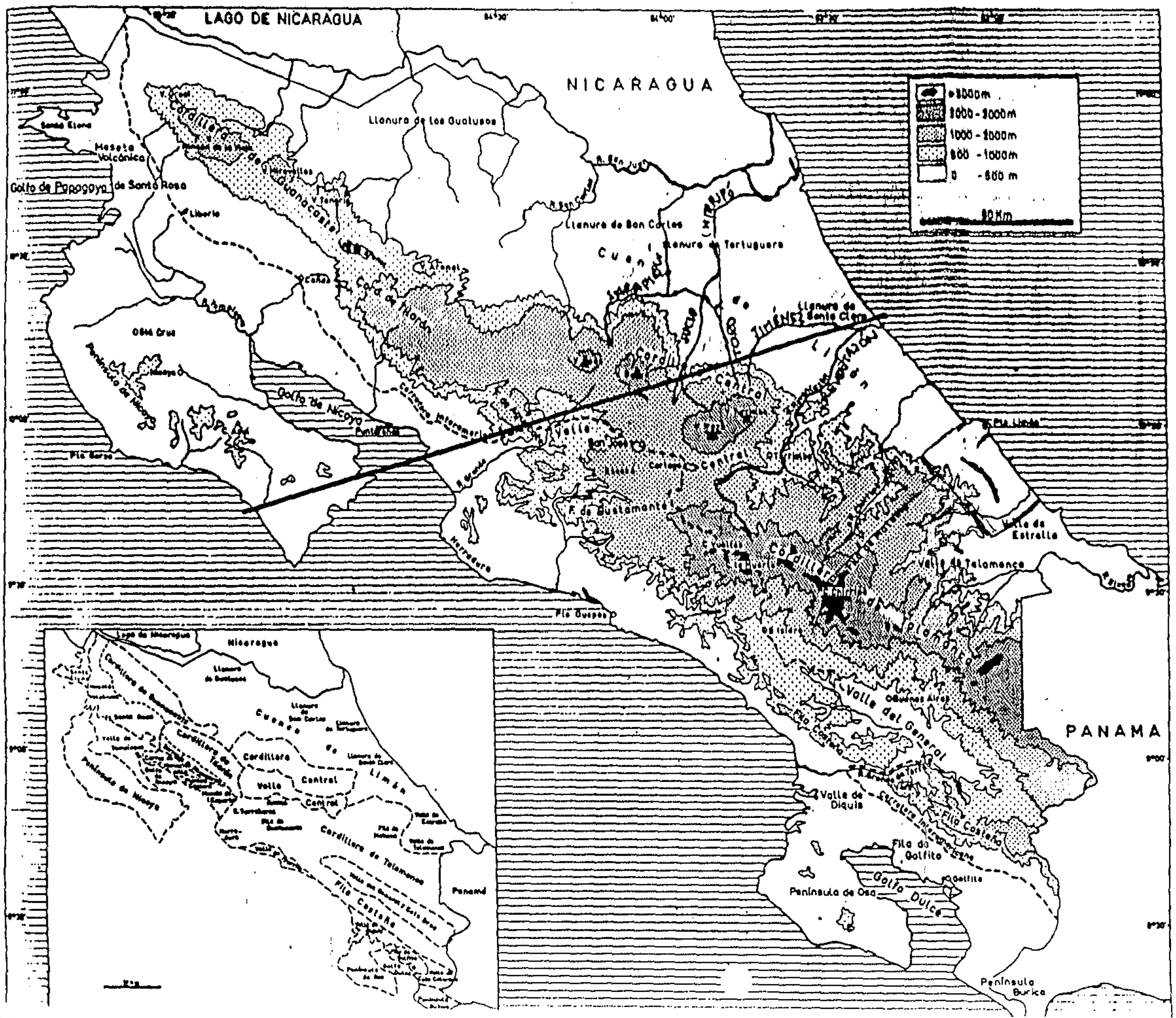
APPENDIX 1

Appendix 1: Study area and location of auger holes and profile pits.



Location of augerhole observations (no. 1-14) along the transect between Río Palacios and Río Tortuguero. The dottes with number (1-3), indicate the location of the soil profile pit.(Abstract from "Hoja 3447 II, Agua Fria; Lambert-coordinate of the lower left corner: Latitude 2.65 and longitude 5.69).

APPENDIX 2



Appendix 2: Map of Costa Rica.

APPENDIX 3

Appendix 3: Soil types.

fase de desarrollo								
8		LA CABANA	PRECIPICIO		SILENCIO			
7	RIO PACUARE	SURETKA COCORI CIMARRONES	NEGUEV	LA RAMBLA				
6	GUAYACAN	LOMAS DE SIERPE	HUETAR MILANO	LA ALDEA				
5	SAN VALENTIN	LAGUNILLAS IROQUOIS	JIMENEZ ALEGRIA	MERCEDES				
4	SAN ISIDRO BONILLA A. LA ROCA GUAYABO	ST. TERESITA BARRANCA LAS DELICIAS	CHIRRIPO CORINTO RIO CHRISTINA	CARTAGENA	LIGIA			
3		IRAZU RIO ROCA (VARIANTE)	RIO MOLINO SUERRES HORQUETAS	LOS DIAMANTES RIO FRIO TORTUGUERO	SANTA CLARA DESTIERRO	MATAS DE COSTA RICA	COOPE MALANGE	
2	RIO ROGA	RIO ROGA	DOS NOVILLOS (VARIANTE)	MONTELIMAR DOS NOVILLOS LA LUCHA	BOSQUE SARDINA PARISMINA	ZENT PERLA		
1				FLORES GAVILAN BARRA SAN RAFAEL		FLORES SAN RAFAEL	AGUA FRIA LIQUIDO BARRO	CANO BRAVO CANO NEGRO CANO MORENO
MATERIAL PARENTAL	CENIZA/ LAVA	LAVA/ CENIZA	FLUVIO-LAHAR	ALUVIAL VOLCANICO	ALUVIAL FINO Y VOLC	ALUVIAL NO VOLCANICO (GRUESO	ALUVIAL MUY FINO	PANTANOS CON TURBA
PRECIPITACION ANUAL	> 6000 MM	<------------ 3000 MM -- 6000 MM ----------->						
DRENAJE	BUENO-IMPERFECTO	BUENO	BUENO-IMPERFECTO	BUENO Y MALO	BUENO Y IMPERFECTO	BUENO Y MALO	POBRE A PANTANOSE	PANTANOSE

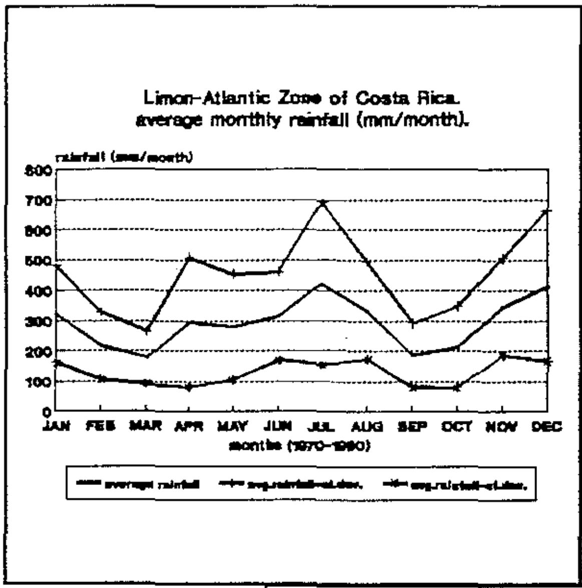
Set-up of the distinguighed soiltypes and their relation with development stage and physical environment. (WIELEMAKER & KROONENBERG, 1992).

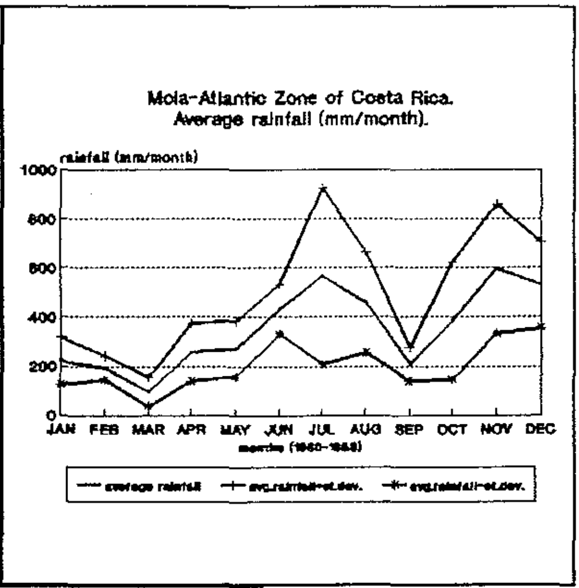
APPENDIX 4

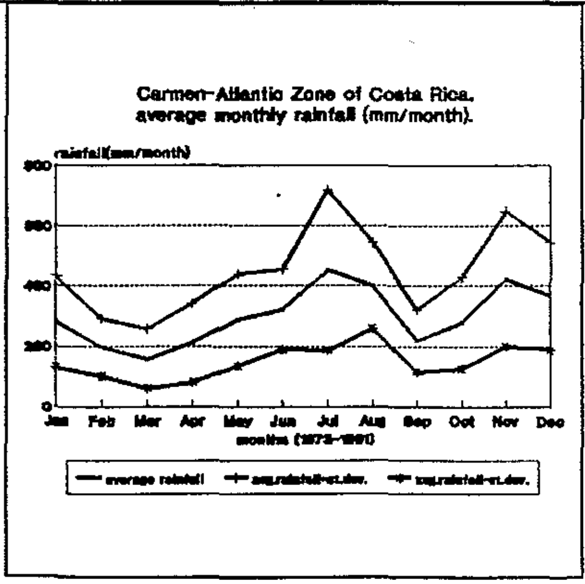
Appendix 4: Climate characteristics.

Tabel 1. Climate characteristics Puerto Limon/Hacienda 'El Carmen'.

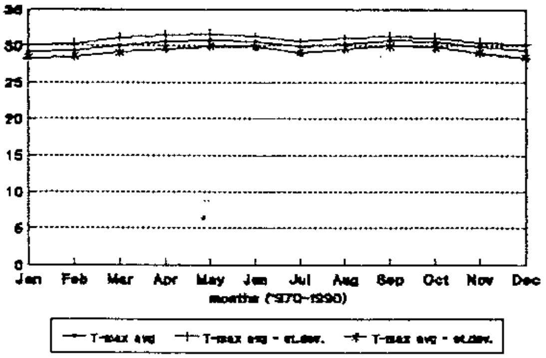
limon	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T-MAX(˚c)	29.7	30.0	30.4	30.7	31.2	30.8	30.0	30.4	30.9	30.9	29.9	29.7
T-MIN (˚c)	20.2	20.2	20.7	21.5	22.1	22.2	22.2	21.9	22.1	21.8	21.4	20.6
RHA (%)	88	87	88	87	89	89	90	90	88	88	90	89
windsp.(km/d)	121	121	130	130	112	112	112	112	112	112	121	130
ET0(mm/d)	3.2	3.5	3.8	3.9	3.7	3.5	3.3	3.6	3.7	3.6	3.1	3.0
PREC(mm/m)	319	217	205	278	283	289	441	306	140	207	399	453
sol.rad.(MJ/ m-2/d)	15.1	16.5	17.7	18.2	17.4	16.1	15.2	16.7	17.0	16.7	14.7	14.2
SUNH (h/d)	5.2	5.4	5.5	5.6	5.4	4.7	4.0	4.8	5.1	5.3	4.7	4.8
Carmen	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T-MAX(˚c)	29.3	29.2	29.9	30.0	31.0	30.9	30.2	30.4	31.2	30.7	29.5	28.7
T-MIN (˚c)	20.4	20.5	20.6	21.5	22.5	22.4	22.2	22.4	22.1	21.9	21.7	20.7
RHA (%)	86	86	87	87	86	88	89	88	87	89	89	90
windsp.(km/d)	95	104	104	104	95	95	86	95	95	95	95	95
ET0(mm/d)	3.1	3.4	3.7	3.7	3.7	3.4	3.3	3.4	3.6	3.4	2.9	2.8
PREC(mm/m)	271	215	137	228	248	334	335	388	251	253	461	419
sol.rad.(MJ/ m-2/d)	15.4	16.5	17.9	17.8	17.5	15.5	15.2	15.8	16.8	15.9	13.9	13.9
SUNH (h/d)	5.4	5.4	5.6	5.4	5.4	4.3	4.0	4.2	4.9	4.8	4.2	4.6







Limon-Atlantic Zone of Costa Rica
Monthly average T-max and st.dev.



Limon-Atlantic Zone of Costa Rica
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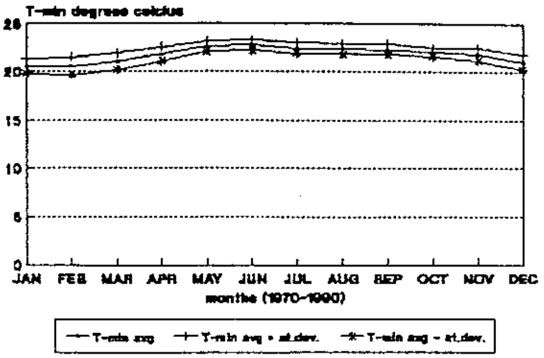
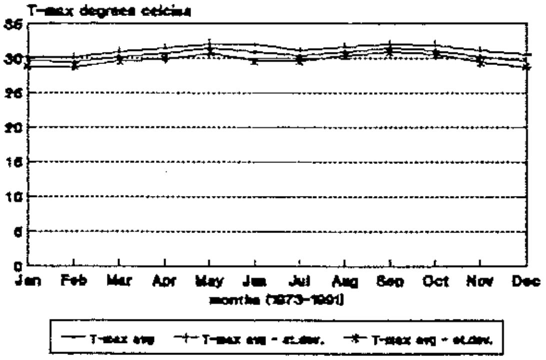
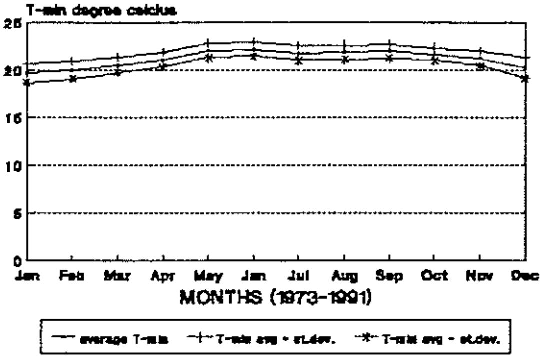


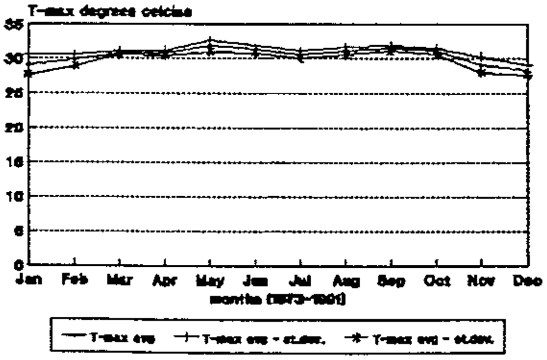
CARMEN-Atlantic Zone of Costa Rica
Monthly averages T-max and st.dev.



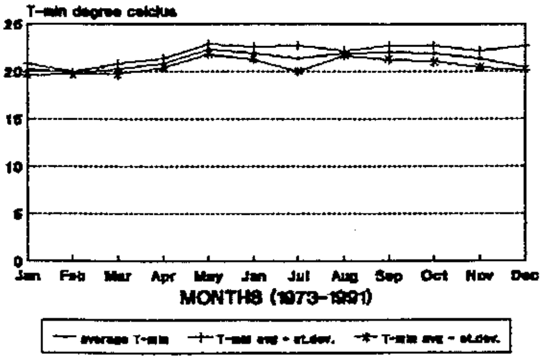
CARMEN-Atlantic Zone of Costa Rica
Monthly averages T-min and st.dev.



MOLA-Atlantic Zone of Costa Rica.
Monthly averages T-max and st.dev.

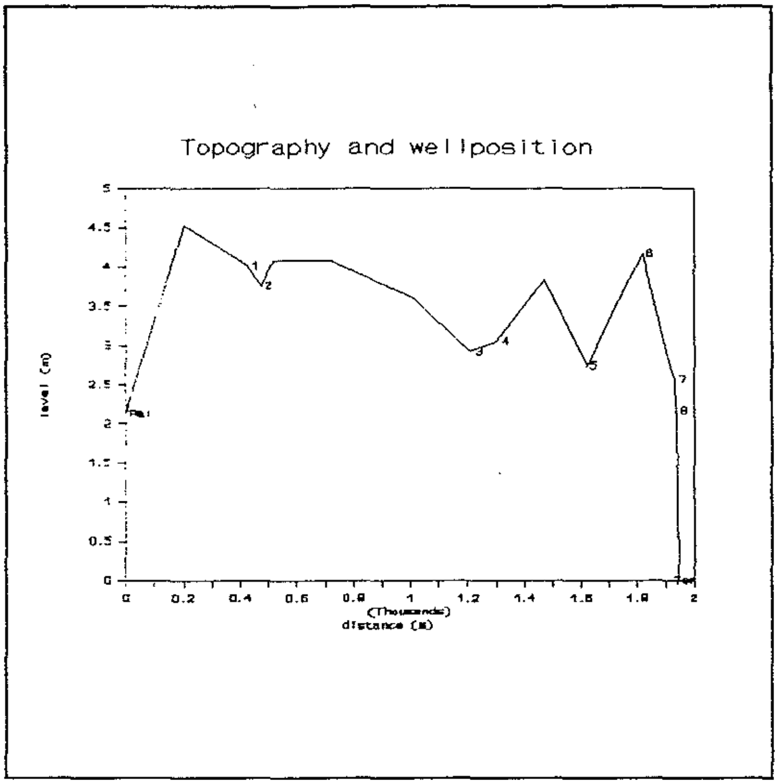


MOLA-Atlantic Zone of Costa Rica
Monthly averages T-min and st.dev.



APPENDIX 5

Appendix 5: Topography and location of piezometers.



	distance x (m)	elevation (m)
Río Palacios	0	2.12
	200	4.52
piezo #1	430	4.01
piezo #2	476	3.75
	515	4.09
	715	4.08
	1015	3.61
piezo #3	1202	2.92
piezo #4	1295	3.05
	1474	3.84
piezo #5	1620	2.74
	1690	3.26
piezo #6	1819	4.16
	1908	2.84
piezo #7	1935	2.57
piezo #8	1940	2.16
Río Tortuguero	1945	0

Source: Maebe, 1992.

APPENDIX 6

Appendix 6: Theoretical waterprofiles.

Figure 1: Theoretical water profiles calculated for a 3 mm/day natural recharge with hydraulic conductivity equal to 5m/day and the impervious layer 1m, 5m or 10m below the bed of the Tortuguero River and a fixed potential of 1.9 m at 1300 m. Source: Maebe, 1992.

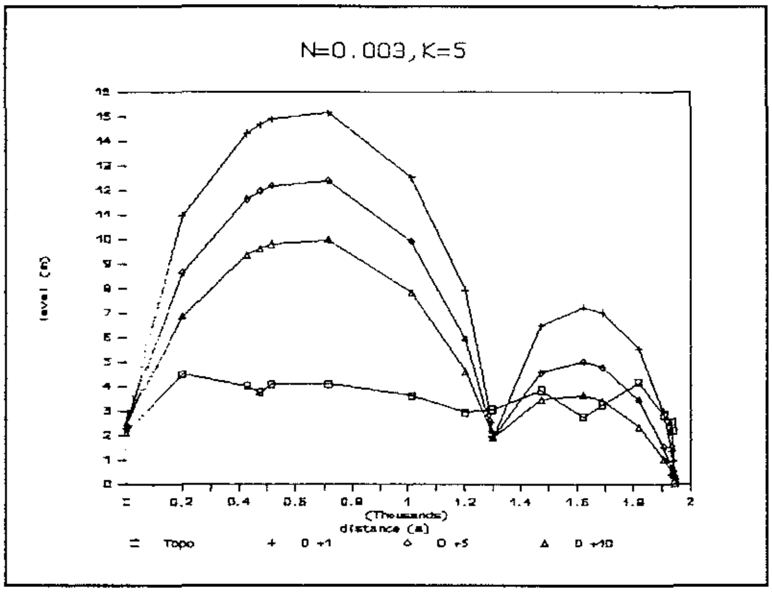
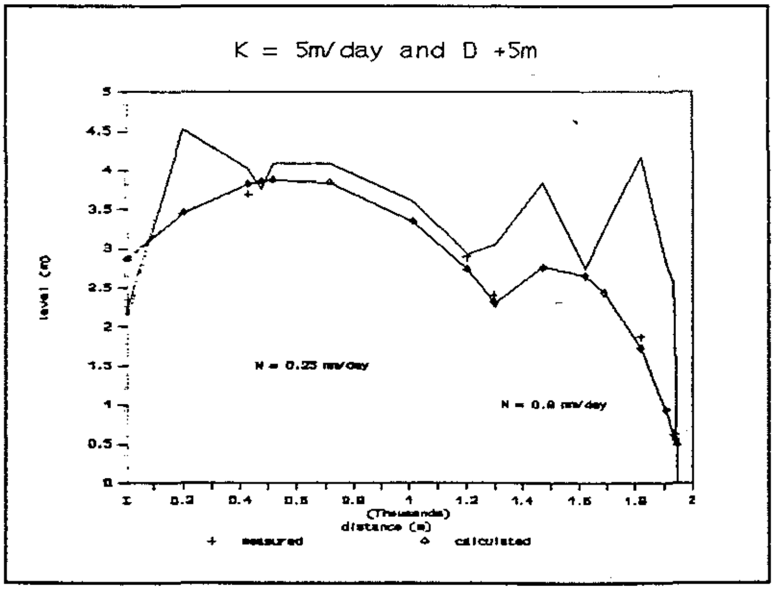


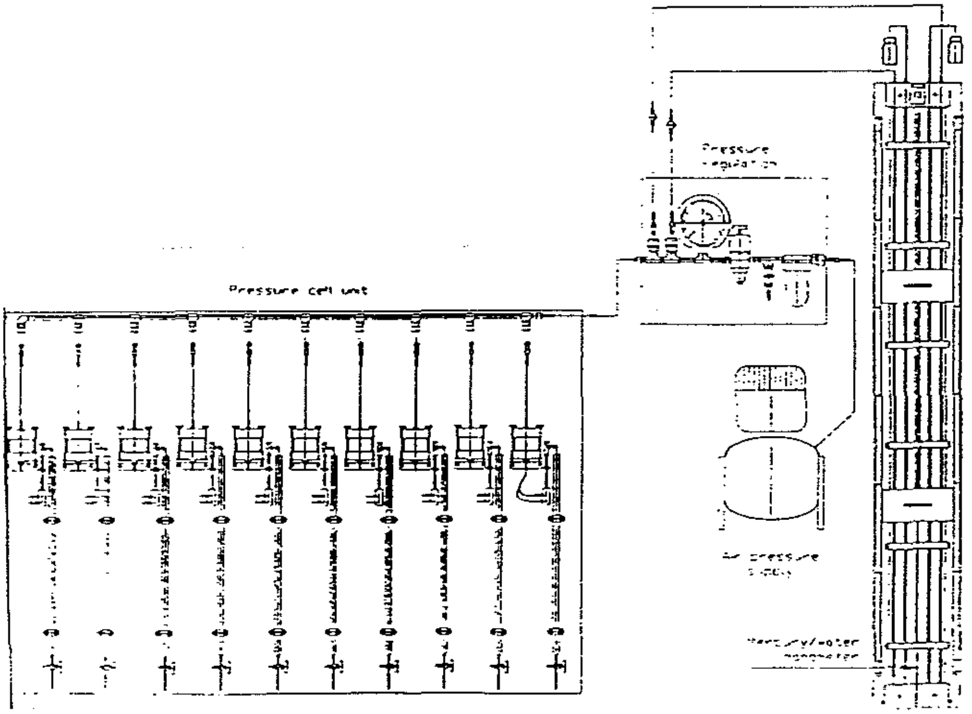
Figure 2: Theoretical water profile fitted through water levels observed on 04/07/92 (day 103); the impervious layer is 5m below the bed of the Tortuguero and K is set to 5 m/day; a fixed potential equal to 2.4 m is set at 1300m. The natural recharge N was found to be 0.25 mm/day to fit with the observed levels on the left side and found to be equal to .8 mm/day to fit with the observed levels on the right side. Source: Maebe: 1992.



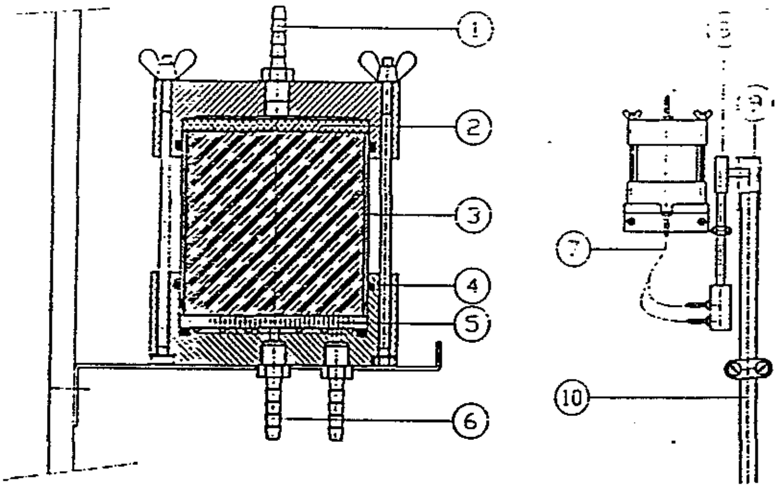
APPENDIX 7

Appendix 7: Experimental set-up of the One-step outlfow.

1. *Schematic overview of the One-step outflow (TFDL, The Netherlands).*



2. *Detail of pressure cel (TFDL, The Netherlands).*

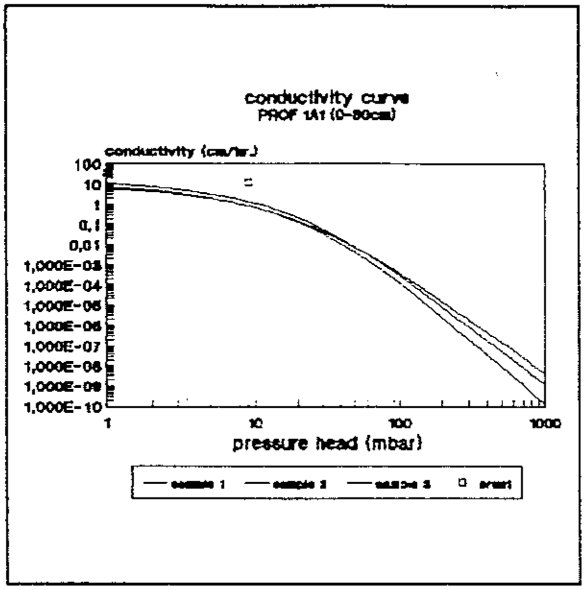


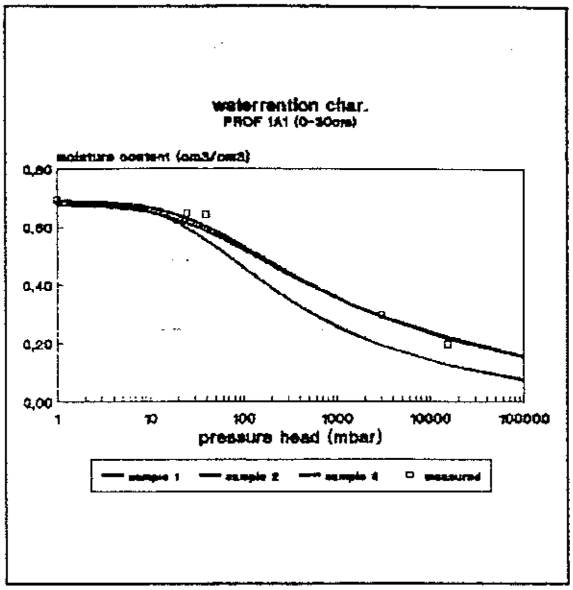
1. Air pressure supply
2. Synthetic filter
3. Sample ring
4. Rubber O-ring
5. Ceramic filter
6. Water discharge air exclusion
7. Polyethylene tubing
8. Flow over
9. Cap to prevent evaporation
10. Buret

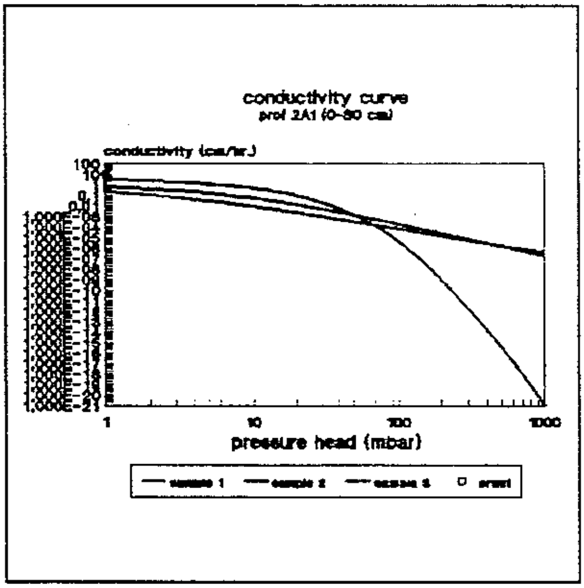
APPENDIX 8

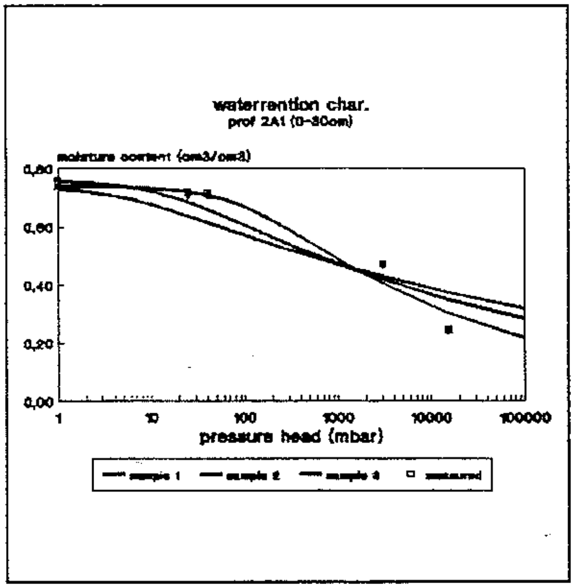
Appendix 8: One-step curves.

Conductivity and water retention curves:

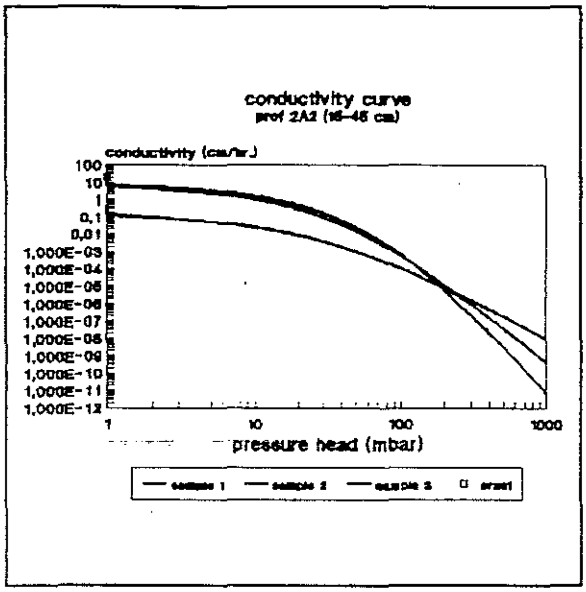


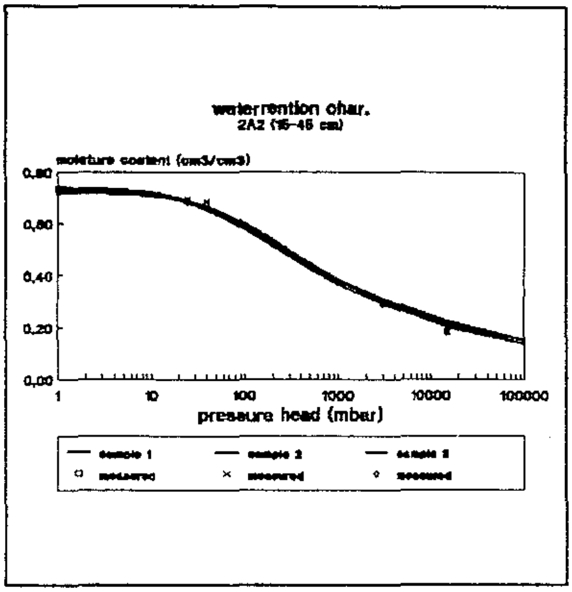


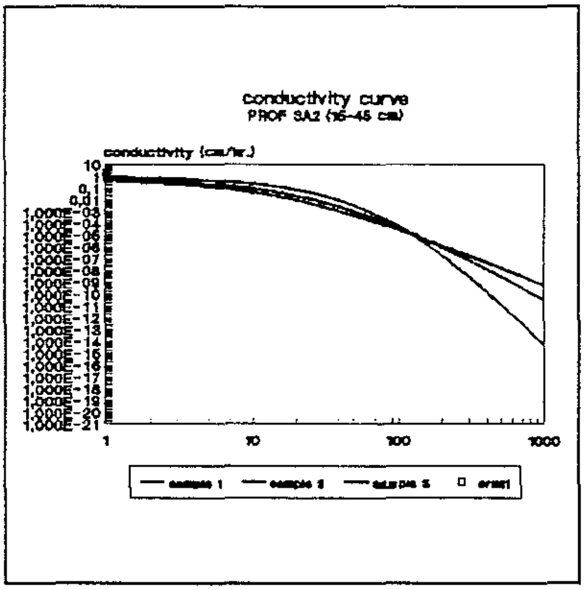


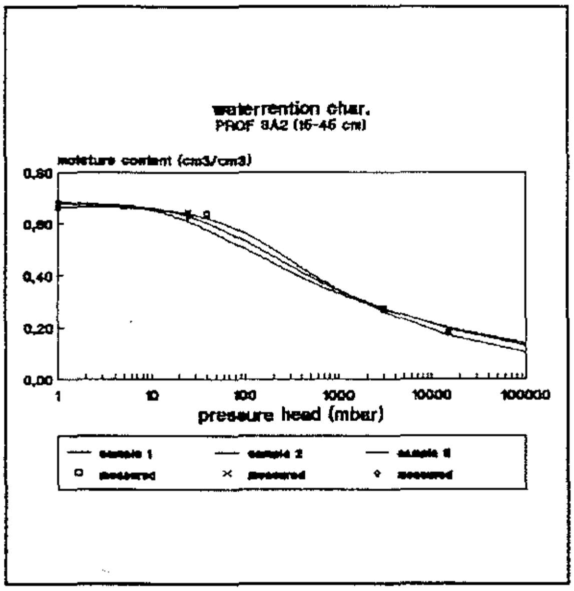


Conductivity and water retention curves:



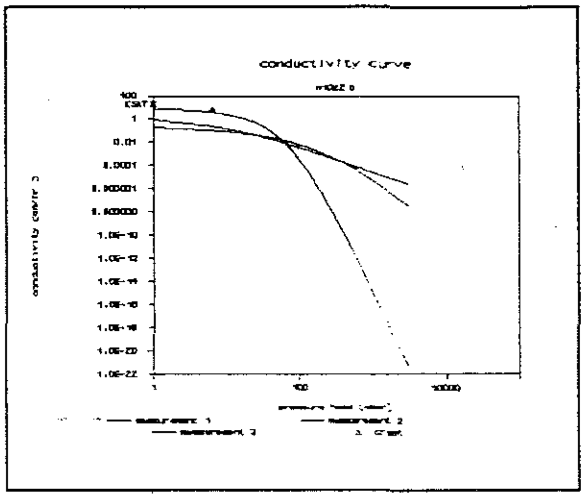




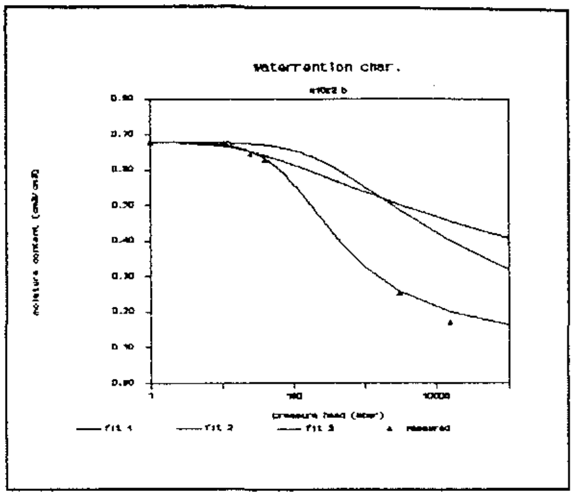


Conductivity and water retention curves:

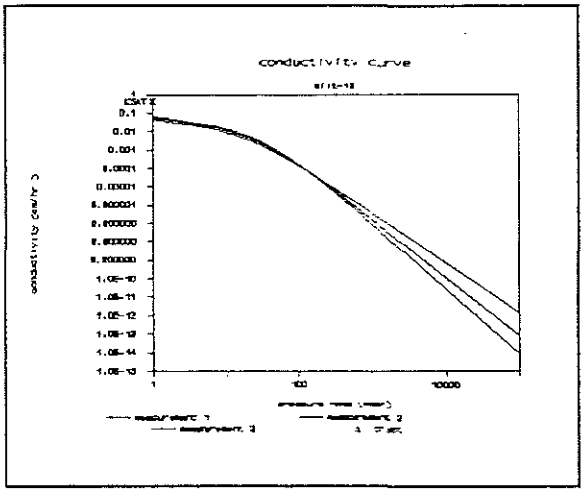
prof. 1-A2 (15-45 cm)



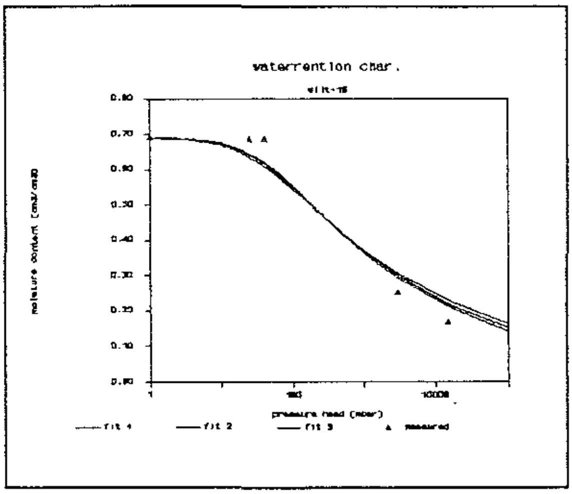
prof. 1-A2 (15-45 cm)



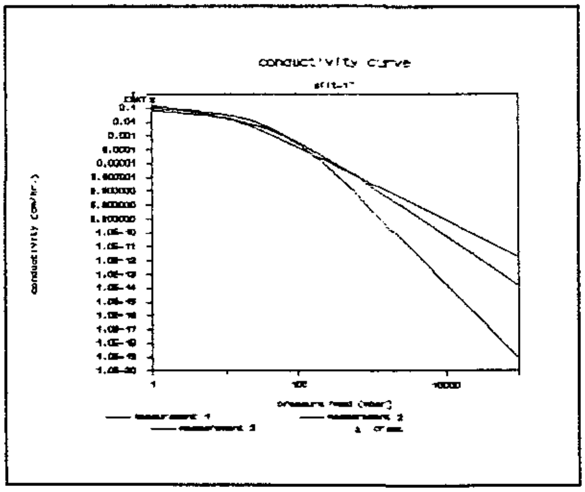
silty layer



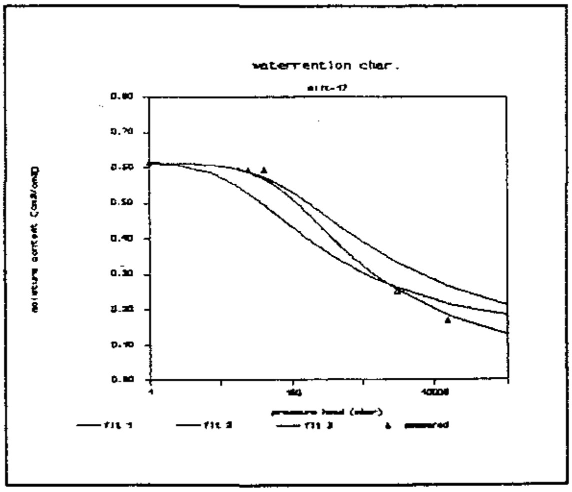
silty layer



silty layer

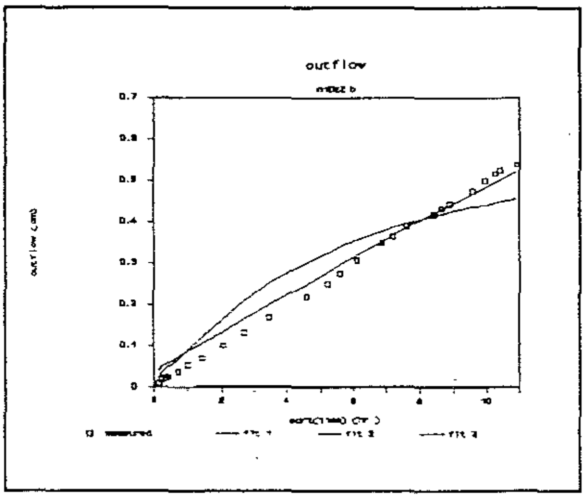


silty layer



Outflow curves:

prof. 3-A2 (15-45 cm)



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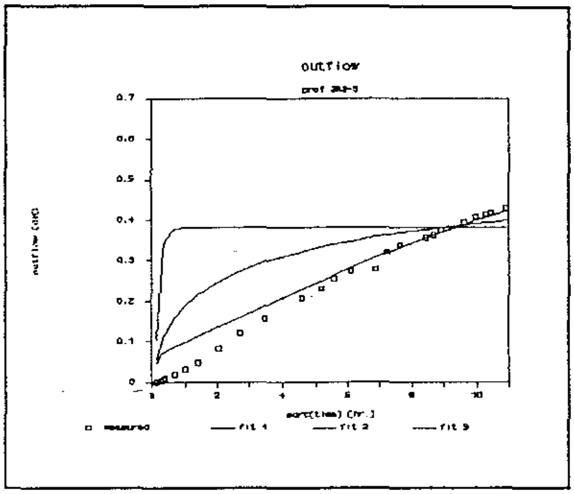
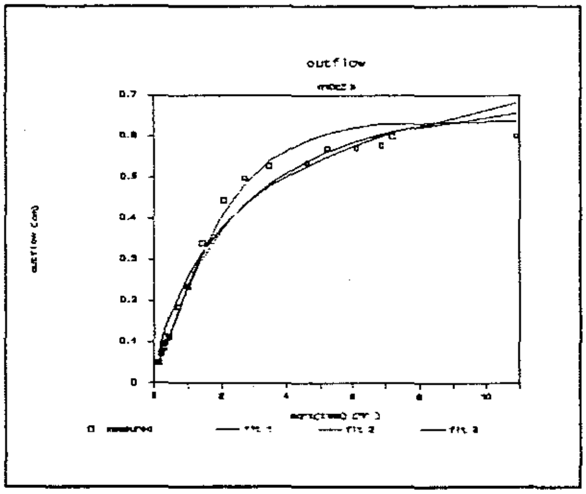
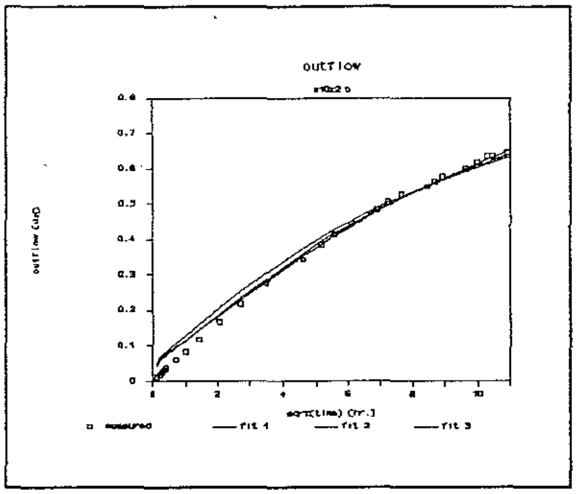


prof. 1-A2 (15-45 cm)



prof. 2-A1 (0-15 cm)



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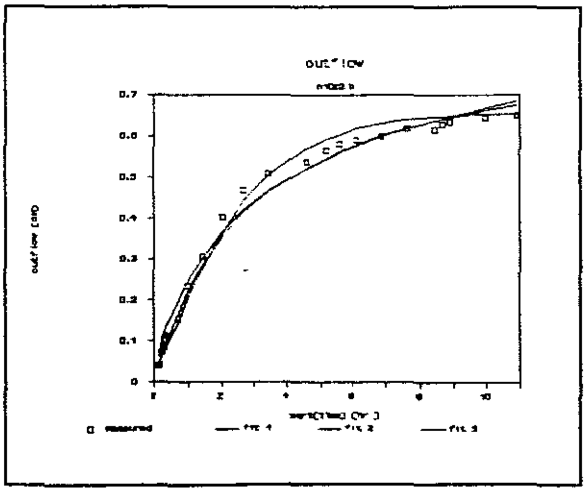

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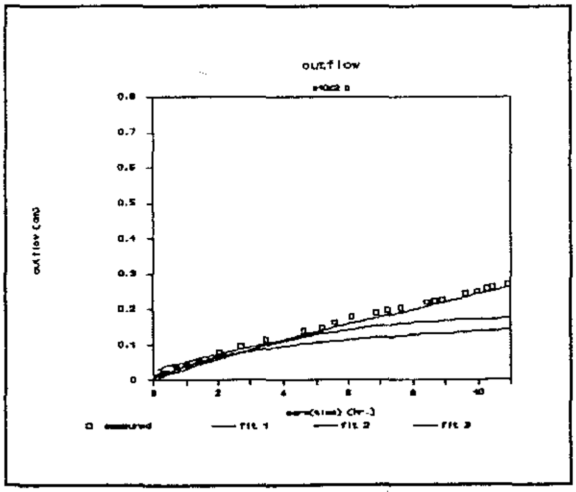
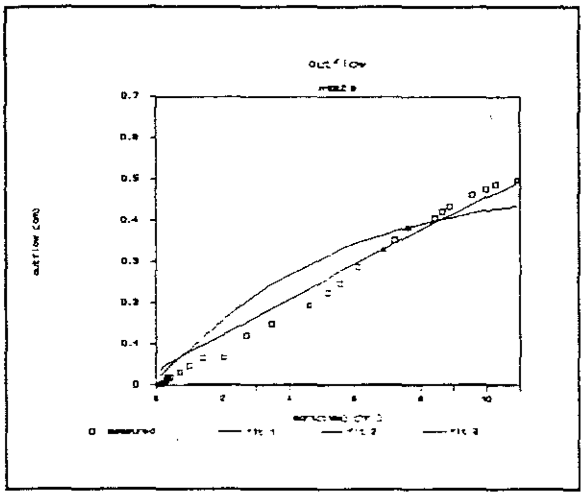
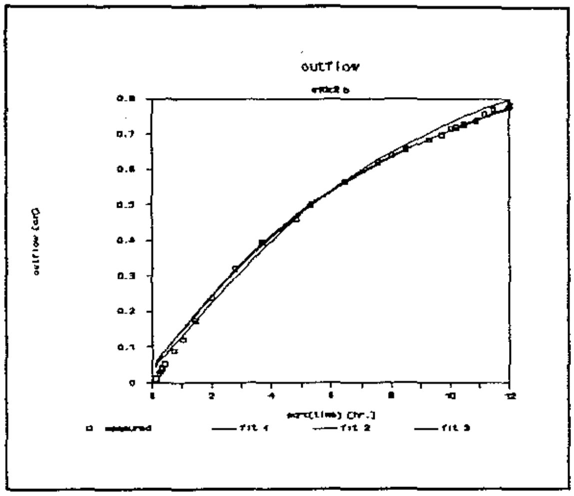


Outflow curves:

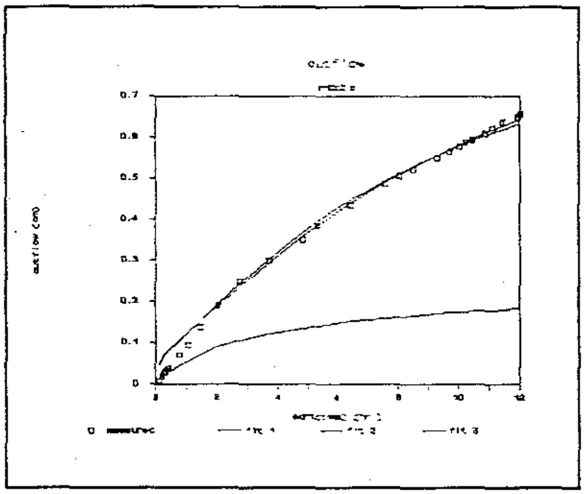
prof. 3-A2 (15-45 cm)



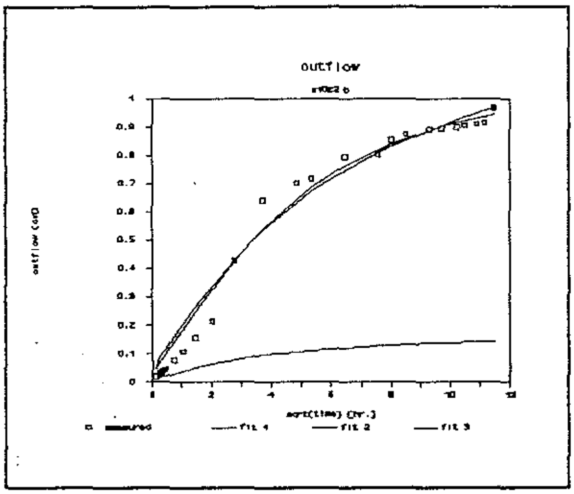
prof. 1-A1 (0-15 cm)



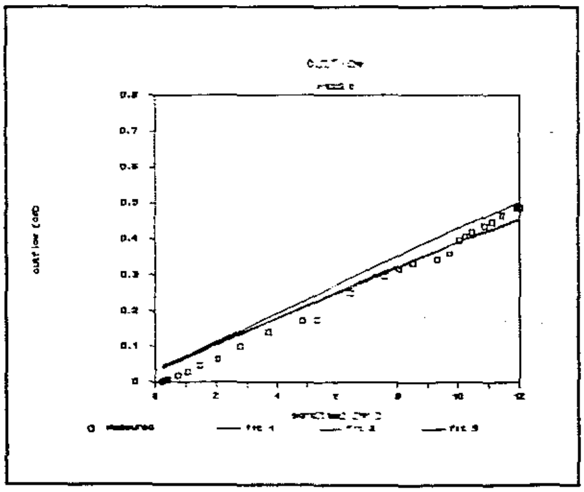
prof. 1-A1 (0-15 cm)



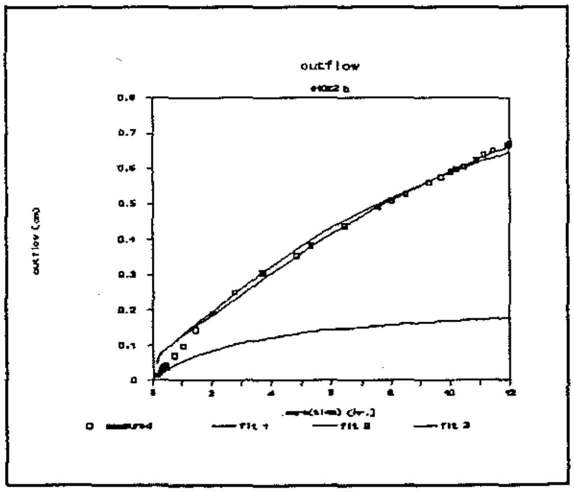
prof. 1-A1 (0-15 cm)



prof. 2-A1 (0-15 cm)

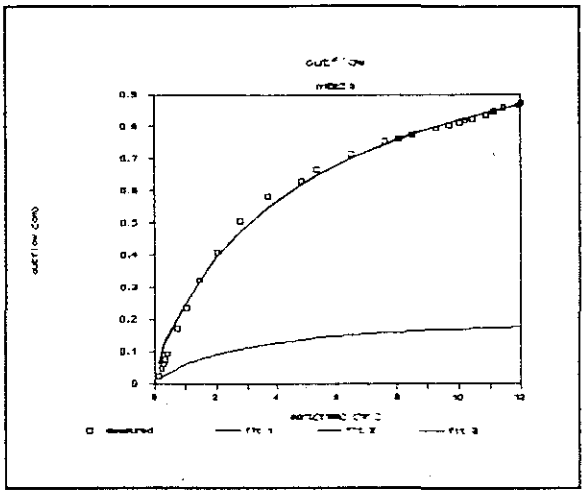


prof. 2-A2 (15-45 cm)

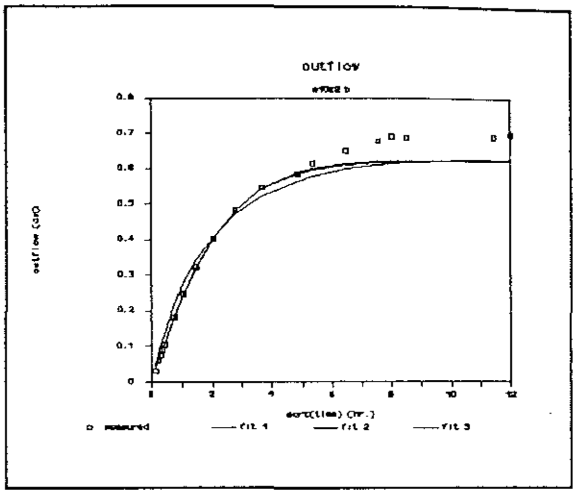


Outflow curves:

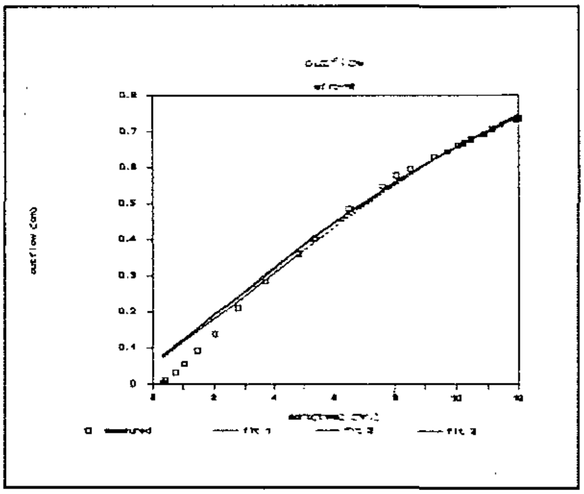
prof. 2-A2(15-45 cm)



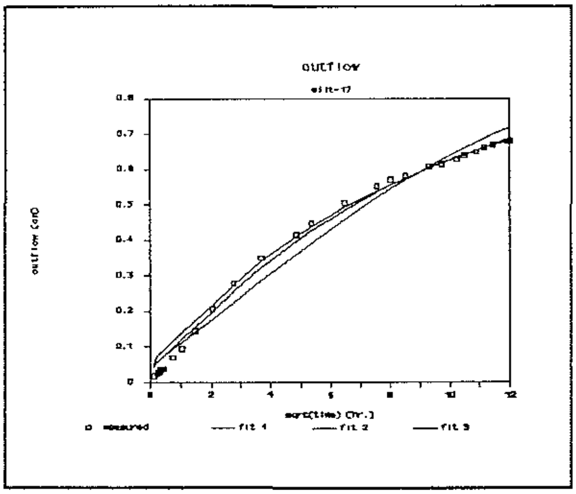
prof. 2-A2(15-45 cm).



silty layer

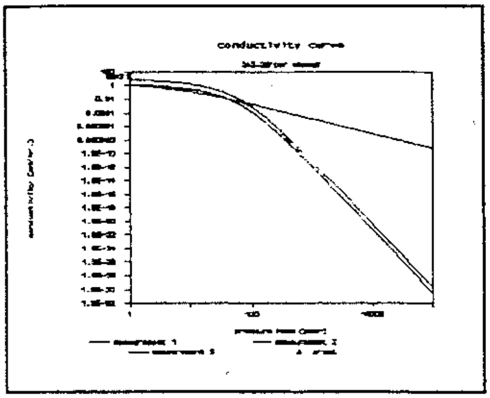


silty layer

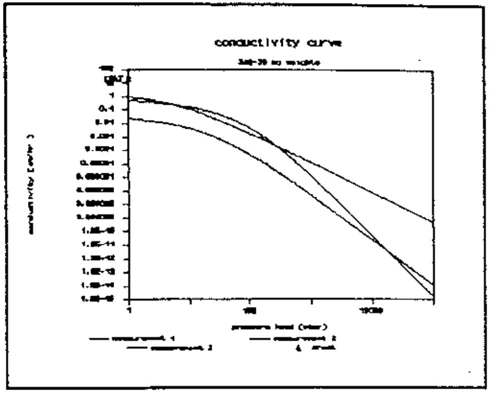


Comparison of two runs on the same sample: with/without added weights.
Sample 2A2-20 (15-45 cm).

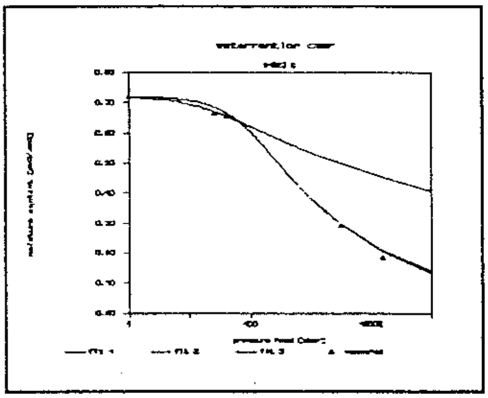
Conductivity curve (weigths added)



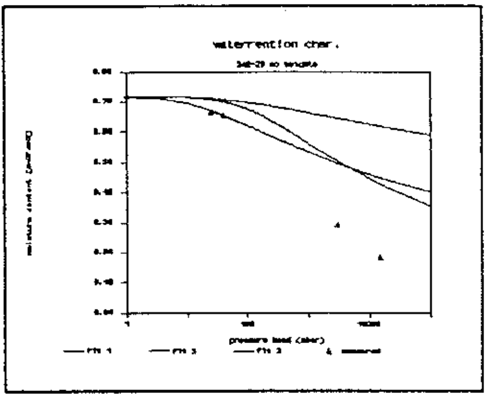
Conductivity curve (no weights added)



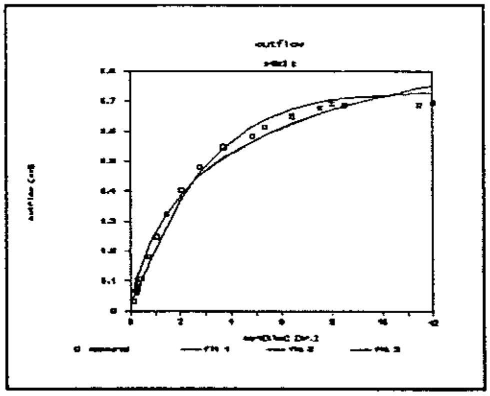
Waterretention curve (weights added)



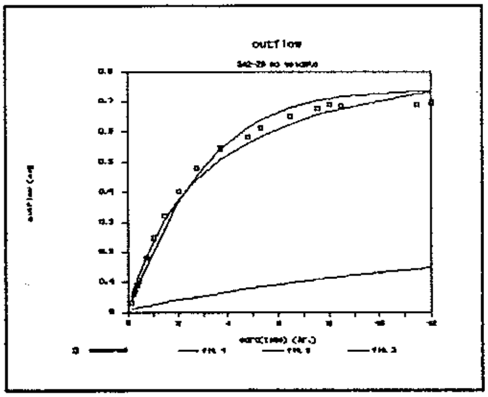
Waterretention curve (no weights added)



Outflow curve (weights added)



Outflow curve (no weights added)



Van Genuchten parameters for run with/without weights sample 2A2-20:

Sample 2A2-20:	sample 2A2-20: (no weights)	(weights added)
Alpha	0.00915	0.01493
n	1.12691	1.23489
Theta-res	0.08867	0.01012
K-sat	2.52674	19.5
Gamma	17.58154	29.10987
R^2	0.9185	0.989

> The difference in K-sat is explained by the fact that in the run without weights, K-sat was fitted, whereas in the run with weights, the value of K-sat was fixed.

Van Genuchten parameters/SFIT-analyses of a fertile, poorly drained soil

Prof. 1-A1 (0-15 cm).

Sample:	1	2	3
Alpha	0.0421	0.03823	0.0345
n	1.17542	1.17585	1.18448
Theta-res	0.001	0.001	0.01
K-sat	36.948	35.948	35.95
Gamma	11.83058	16.41792	21.83136
R2	0.9828	0.9908	0.9919

Prof. 1-A2 (15-45cm).

Sample:	1	2
Alpha	0.01296	0.01349
n	1.40014	1.26732
Theta-res	0.13267	0.0173
K-sat	11.11094	16.03257
Gamma	26.20425	30.97268
R2	0.9694	0.9873

Prof. 2-A1 (0-15 cm).

Sample:	1	2	3
Alpha	0.00971	0.19945	0.6988
n	1.17746	1.08814	1.11123
Theta-res	0.001	0.02012	0.00111
K-sat	10.958	10.958	11.24848
Gamma	100	1.48675	8.3915
R2	0.9904	0.9638	0.9827

Prof. 2-A2 (15-45cm).

Sample:	1	2	3
Alpha	0.01493	0.02281	0.02484
n	1.23489	1.22019	1.20308
Theta-res	0.01012	0.00275	0.001
K-sat	29.10987	20.54021	0.468
Gamma	19.5	19.64519	9.78925
R2	0.989	0.9936	0.9907

Prof. 3-A2 (0-15 cm).

Sample:	1	2	3
Alpha	0.02434	0.04205	0.01179
n	1.21378	1.19952	1.26267
Theta-res	0.001	0.01155	0.001
K-sat	2.21	2.21	2.21
Gamma	19.95096	12.73543	37.13464
R2	0.9889	0.9906	0.9791

Prof. silt layer (> 2m).

Sample:	1	2
Alpha	0.01436	0.02629
n	1.26802	1.19262
Theta-res	0.0487	0.001
K-sat	0.22982	0.2
Gamma	10.82037	4.07595
R2	0.9896	0.9783

The values of all samples represent the best out of three fits.

APPENDIX 9

Appendix 9: Bulk density measurements.

Table 1: Bulk density (g/cm^3) values.

replications:	1	2	3	4	A	B
prof.: 1-A1	0.78	0.77	0.75	-	0.82	0.80
prof.: 1-A2	0.85	0.87	-	-	0.91	0.98
prof.: 2-A1	0.52	0.57	0.57	0.59	0.49	-
prof.: 2-A2	0.64	0.61	0.65	0.65	0.66	-
prof.: 3-A2	0.71	0.86	0.90	-	0.56	-
silty layer	0.94	0.92	-	-	-	-

Values in column 1 to 4 result from measurements done after the one-step measurements (300 cc cores). In column A and B, bulk density values are presented that were measured on samples from the same layers, but independently sampled for this purpose (100/300 cc cores). A1 = 0-30 cm, A2 = 15-45 cm).

Table 2: Organic matter content (%) of top soils.

prof.: 1-A1	3.00
prof.: 2-A1	1.72
prof.: 3-A1	1.72

APPENDIX 10

Appendix 10: Soil profile descriptions.

Profile number: 1.
Classification:
PZA: Suelo Bosque(M31-111)?
FAO (1988):
USDA Soil Taxonomy: Andic Aquic Eutropepts.
Date of observations: june 16th 1992.
Author: Stephan Mantel.
Location: 120 m north-west of Rio Tortuguero and app. 50 m south of all weather road to Cuatro Esquinas.
Photograph no.: 24952/R-177/L-212 (1:35.00); 17-3-'81.
Approximately N:-
E:-
Altitude: -
Geological formation: fluvial deposits.
Geomorfological unit: Atlantic-Carribbean lowland (back-arc basin).
Land form: old river plain.
Surrounding landform:
Microtopography: flat to almost flat.
Slope: < 1%.
Vegetation/landuse: pasture (extensive cattle farming).

GENERAL INFORMATION ON SOIL AND SITE:

Parent material: alluvial sediment.
Drainage: Moderately well drained (class 3).
Moisture conditions in profile:
Depth of groundwater (cm): < 100 cm.
Soil Fauna: worms, ants.
Presence of surface stones and rock outcrops: no (<1%).
Presence of salt and alkali: not visible.
Erosion: not visible.
Sedimentation: no.

BRIEF DESCRIPTION OF PROFILE

The profile was described at short distance from Río Tortuguero. This profile was not especially representative for the study area, but was described to get a better impression of variability. The textures are coarser than average in the area; loamy to sandy (downwards in the profile).

SOIL PROFILE DESCRIPTION:

Horizon 1: A1.
Depth: 0-9/11 cm.
Moist color: Dark yellowish brown (10 YR 4/3).
Redoximorphic features:
-ox. : 7.5 YR 4/4 common, coarse, prominent, sharp boundary.
-red.: 10 YR 4/2 many, coarse, prominent, sharp boundary.
Texture: Clay Loam.
Gravel and stones - abundance: -
- form: -
Structure: weak, very coarse, angular blocky
Consistence: slightly sticky (wet), slightly plastic, friable (moist).

Pores: open, tubular and continuous pores of variable sizes (inped/exped).
Roots: abundant fine and very fine.
nature of boundary - width:
- topography:

Horizon 2: A2.
Depth:9/11-25/78.
Moist color: Yellowish brown (10 YR 5/4).
Redoximorphic features:
-ox. : 10 YR 4/4 few, fine, faint, clear boundary.
-red.: 10 YR 3/3 few, medium, prominent, sharp boundary.
Texture: Sandy Clay Loam.
Gravel and stones - abundance: -
- form: -
Structure: weak, very coarse angular blocky.
Consistence: slightly sticky (wet), slightly plastic, friable (moist).
Pores: open, tubular and continuous pores of variable sizes.
Roots: frequent, very fine and fine roots.
nature of boundary - width:
- topography:

Horizon 3: A2/C.
Depth: 25/78-37/43.
Moist color: 10 YR 4/4.
Redoximorphic features:
-ox. : 7.5 YR 5/8; common, medium, prominent.
-red.: 10 YR 6/1; common, medium, prominent.
Texture: sandy loam.
Gravel and stones - abundance: -
- form: -
Structure: weak, very coarse, angular blocky
Consistence: slightly sticky (wet), slightly plastic, friable (moist).
Pores: common, fine, continuous, inped, vertical, open tubular.
Roots: frequent, fine and very fine.
nature of boundary - width:
- topography:

Horizon 4: C.
Depth: 37/43-120 cm.
Moist color: 10 YR 4/3 and 10 YR 2/2.
Redoximorphic features:
-ox. : 7.5 YR 3/4; common, medium, faint, clear boundary.
-red.: 10 YR 5/3; few, fine, faint, diffuse boundary.
Texture: loamy sand to sand (210 to 300 µm).
Gravel and stones - abundance: -
- form: -
Structure: structureless.
Consistence: non-sticky, nonplastic (wet), loose when moist.
Pores: few, fine, continuous, inped, vertical, open tubular.
Roots: few, very fine and frequent fine.
nature of boundary - width:
- topography:

Profile number: 2.
Classification:
PZA: Suelo Bosque?
FAO (1988):
USDA Soil Taxonomy: Andic Aquic Eutropepts.
Date of observations: june 20th 1992.
Author: Stephan Mantel.
Location: 1100 m north-west of Rio Tortuguero and app. 100 m south of all weather road to Cuatro Esquinas. Close to augerhole observation no. 13.
Photograph no.: 24952/R-177/L-212 (1:35.00); 17-3-'81.
Approximately N:
E:
Altitude: -
Geological formation: fluvial deposits.
Geomorfological unit: Atlantic-Carribean lowland (back-arc basin).
Land form: old river plain.
Surrounding landform: -
Microtopography: flat to almost flat.
Slope: < 1%
Vegetation/landuse: pasture (extensive cattle farming).

GENERAL INFORMATION ON SOIL AND SITE:

Parent material: alluvial sediment.
Drainage: very poorly drained.
Moisture conditions in profile:
Depth of groundwater (cm): 40 cm.
Soil Fauna: worms, ants.
Presence of surface stones and rock outcrops: no (<1%).
Presence of salt and alkali: not visible.
Erosion: not visible.

BRIEF DESCRIPTION OF PROFILE:

The profile has a dark (high organic matter content) surface layer of ± 15 cm, underlain by a greyish brown loamy layer. Downward in the profile the grey becomes dominant over brown. Deeper in the profile layers with strong redoximorphic features predominate. Observations through augering showed black sand of volcanic origen between 1.50 and 2.60 metres. At 2.60 metres a completely reduced silty layer was found. Under this 20 cm thick layer again black volcanic sand is found, with redoximporphic features, becoming stronger downwards (oximorphic features esp.). At 4 metres the reduced unsaturated silty layer is found again.

SOIL HORIZON DESCRIPTIONS

Horizon 1: A1gh.
Depth:0-10/13 cm.
Moist color: 10 YR 3/2.
Redoximorphic features:
-ox. : 5 YR 4/4, many, medium, prominent, sharp boundary.
-red.: matrix color.
Texture: Loam.
Gravel and stones - abundance: -
- form: -
Structure: moderate, fine angular blocky.

Consistence: slightly sticky (wet), slightly plastic, friable (moist).
Pores: common to many, fine, continious, inped/exped, vertical and horizontal orientation, open, dentritic tubular.
Roots: abundant, very fine and fine.
nature of boundary - width: abrupt.
- topography: wavy.
observation:

Horizon 2: A/B.
Depth: 10/13-37/43 cm.
Moist color: 10 YR 4/3.
Redoximorphic features:
-ox. :5 YR 4/4; common, medium, prominent, clear boundary.
-red.:10 YR 3/2; common, medium, distinct, diffuse boundary.
Texture: Sandy Loam.
Gravel and stones - abundance: -
- form: -
Structure: moderate, fine (sub) angular blocky.
Consistence: slightly sticky (wet), slightly plastic, friable (moist).
Pores: common, fine, continious, vertical and horizontal, tubular, open and dentritic in- and expeds.
Roots: frequent, very fine and fine.
nature of boundary - width: gradual.
- topography: smooth.
observation:

Horizon 3: B.
Depth: 37/43-73 cm.
Moist color: 10 YR 4/2.
Redoximorphic features:
-ox. : 10 YR 4/4; oxidized spots in reduced matrix.
-red.: -.
Texture: Sand Loam.
Gravel and stones - abundance: -
- form: -
Structure: weak, fine, angular blocky.
Consistence: slightly sticky (wet), slightly plastic, friable (moist).
Pores: common, fine, continious, vertical, tubular, open and dentritic in- and expeds.
Roots: frequent, very fine and fine.
nature of boundary - width:
- topography:
observation:

Horizon 4: B/C.
Depth: 73-128/134.
Moist color: 10 YR 4/1 - 10 YR 4/4.
Redoximorphic features:
-ox. : 10 YR 3/4; oxidized spots in reduced matrix.
-red.: Downwards gley becomes more dominant and mottles become concretions.
Texture: Loam.
Gravel and stones - abundance:-
- form: -
Structure: weak, medium angular blocky.
Consistence:slightly sticky and not plastic when wet, friable when moist.
Pores: few, fine, continuous, vertical, tubular, dentritic, open inpeds.
Roots: frequent, very fine and fine.

nature of boundary - width:
- topography:
observation:

Horizon 5: C.
Depth: 128/134-150 cm.
Moist color: 10 YR 3/1.
Redoximorphic features:
-ox. : 10 YR 3/3; many, coarse, prominent, clear to diffuse boundary.
-red.: -.
Texture: Loamy Sand to Sand.
Gravel and stones - abundance: -
- form: -
Structure: structureless.
Consistence: non-sticky, non-plastic when wet, loose when moist.
Pores: no clear pores could be distinguished.
Roots: -.
nature of boundary - width: -
- topography:
observation:

Remarks: profile is very different on the right and on the left side-walls of the pit. On the right side large balls of cemented silty material were found in the first 30 cm. On the right side on 1 m depth a 30 cm thick greyish black silt layer is found, while on the left side-wall of the pit a sandlayer is found. In the upper part of the profile many grassroots are found, while throughout the profile tree roots and holes of rotted tree roots are found; at 24 cm and 51 cm a rootchannel of ϕ 3 cm was found. A remarkable feature of this profile was a thin iron pan, with a color of 5 YR 2.5/2 to 5 YR 3/3, between 5 and 10 cm. Samples for the one-step-outflow measurements taken from this layer showed, when examined after the measurements, the same thin iron pan. Oxidizes rootchannels were also found.

Profile number: 3.
Classification:
PZA: Suelo Bosque?
FAO (1988):
USDA Soil Taxonomy: Andic Aquic Eutropepts.
Date of observations:
Author: Stephan Mantel.
Location: 820 m north-west of Rio Tortuguero and app. 20 m south of all weather road to Cuatro Esquinas.
Photograph no.: 24952/R-177/L-212 (1:35.00); 17-3-'81.
Approximately N:
E:
Altitude:
Geological formation: fluvial deposits.
Geomorfological unit: Attlantic-Carribean lowland (back-arc basin).
Land form: old river plain.
Surrounding landform:-
Microtopography: flat to almost flat.
Slope: < 1%
Vegetation/landuse: pasture.

GENERAL INFORMATION ON SOIL AND SITE:

Parent material: alluvial sediment.
Drainage: very poorly drained.
Moisture conditions in profile:
Depth of groundwater (cm): ± 30 cm.
Soil Fauna: worms, ants.
Presence of surface stones and rock outcrops: no (<1%).
Presence of salt and alkali: not visible.
Erosion: not visible.
Sedimentation:-

BRIEF DESCRIPTION OF PROFILE:
The profile has a dark brown (10 YR 4/1) toplayer of ± 15 cm, consisting almost exlusively of grassroots. This is underlain by a reduced clayey layer with many mottles. Underlain by a transition very mottled layer to a bleached layer with a sharp boundary. Then a thick layer of completely reduced silty material is found. Under this silty layer, that is interrupted by a very thin peat layer, a thick peat layer of app. 2 m. thick.

SOIL HORIZON DESCRIPTIONS

Horizon 1: A1.
Depth: 0-10/15 cm.
Moist color: 10 YR 4/1.
Redoximorphic features:
-ox.:7.YR 3/4, common, fine, distinct, clear boundary.
-red.: -.
Texture: Clay Loam.
Gravel and stones - abundance: -
- form: -
Structure: moderate, medium subangular blocky.
Consistence: friable when moist.
Pores: many, very fine to fine, continious, inped, vertical and horizontal orientation, open tubular.
Roots: abundant, very fine and fine.

Nature of boundary: - width:
- topography:
observation:

Horizon 2: A2.
Depth: 10/15-33/35 cm.
Moist color: 5 YR 3/1.
Redoximorphic features:
-ox. : 10 YR 3/3; common, medium, prominent.
-red.: -.
Texture: Clay Loam.
Gravel and stones - abundance: -
- form: -
Structure: moderate, medium angular blocky.
Consistence: firm (moist).
Pores: few, fine, continious, vertical, tubular and open inpeds.
Roots: frequent, very fine and fine.
nature of boundary - width: -
- topography: -
observation:

Horizon 3: A2/C.
Depth: 33/35-50/56 cm.
Moist color: 5 Y 3/1.
Redoximorphic features:
-ox. : 10 YR 3/4; common, medium, prominent.
7.5 YR 3/4; many, coarse, prominent.
-red.: green spots (no chart color matched); common, coarse, prominent.
Texture: Clay Loam.
Gravel and stones - abundance: -.
- form: -.
Structure: moderate, medium angular blocky.
Consistence: slightly sticky, slightly plastic when wet.
Pores: few, fine, inped tubulars.
Roots: common.
nature of boundary - width:-
- topography:-
observation:

Horizon 4: C1.
Depth: 50/56-60/62 cm.
Moist color: 5 Y 6/1.
Redoximorphic features:
-ox. : 10 YR 4/6; common, medium, prominent.
-red.: 2.5 Y 4/0, common, many, prominent.
Texture: Clay Loam to Clay.
Conretions - abundance: (hardened mottles), few
- form: small.
Structure:
Consistence: slightly sticky, plastic when wet.
Pores: few, very fine, inped tubulars.
Roots: few.
nature of boundary - width:-

- topography:-

observation: Black mottles are found (Manganese?); 2.5 Y 2/0.

Horizon 5: C2.
Depth: 60/62-170 cm.
Moist color: 2.5 Y 4/0.
Texture: Silty Clay Loam.
Conretions - abundance: (hardened mottles), few
- form: small.
Structure: weak, coarse, angular blocky.
Consistence: sticky, plastic.
Pores: few, very fine, inped tubulars.
Roots: few.
nature of boundary - width:-
- topography:-

Horizon 6: C3.
Depth: > 170 cm.
Moist color: 10 YR 2/2.
Texture: Silty Clay Loam.
Conretions - abundance: (hardened mottles), few
- form: small.
Structure: weak, coarse, angular blocky.
Consistence: sticky, plastic.
Pores: few, very fine, inped tubulars.
Roots: few.
nature of boundary - width:-
- topography:-

Profile number: 4.
Classification:
PZA: Suelo Bosque ?
FAO (1988):
USDA Soil Taxonomy: Andic Aquic Eutropepts.
Date of observations: june 16th 1992.
Author: Stephan Mantel.
Location: approximately 200 m. east of Rio Tortuguero.
Photograph no.: 24952/R-177/L-212 (1:35.00); 17-3-'81.
Approximately N:-
E:-
Altitude:
Geological formation: fluvial deposits.
Geomorfological unit: Atlantic-Carribean lowland (back-arc basin).
Land form: old river plain.
Surrounding landform:-
Microtopography: flat to almost flat.
Slope: < 1%.
Vegetation/landuse: recently drained and cleared from forest and planted to banana.

GENERAL INFORMATION ON SOIL AND SITE:

Parent material: alluvial sediment (Holocene).
Drainage: deep channels (main channels are ± 3 m deep) recently excavated.
Moisture conditions in profile:
Depth of groundwater (cm): > 3 m.
Soil Fauna: ants and worms.
Presence of surface stones and rock outcrops: no.
Presence of salt and alkali: not visible.
Erosion: not visible.
Sedimentation:

BRIEF DESCRIPTION OF PROFILE

The profile description was performed on one of the sides of a recently excavated main drainage ditch in area for banana planting. Walking along the deep main channels, of about 3 metres deep it could clearly be seen that this soil type is reasonably isotropic. Roots are found to a depth of about 250 m. (but very few at that depth). Rotted roots of (former) swamp vegetation are found up to the silty layer down in the profile. Walking through the channels it was seen that laterally flowing water (draining into the ditches) flows over the slowly permeable silty layer. As evidence for this also iron dreg was flowing out of the side of the ditches just above the slowly permeable silty layer (see photo 1, page 6).

SOIL HORIZON DESCRIPTIONS

Horizon 1: A1.
Depth: 0-17/20 cm.
Moist color: 10 YR 4/4.
Redoximorphic features:
-ox. : -
-red.: -
Texture: Sandy Loam.
Gravel and stones - abundance: -
- form:-
Structure: moderate, medium (sub) angular blocky.
Consistence: friable.

Pores: common, fine, inped/tubular.
Roots: fine and medium roots.

Horizon 2: A2
Depth: 17/20-51/57 cm.
Moist color: 10 YR 4/4.
Redoximorphic features:
-ox. : few, fine, distinct, 7.5 YR 4/6.
-red.: -
Texture: Loamy Sand.
Gravel and stones - abundance:-
- form:-
Structure: weak, coarse angular blocky.
Consistence: loose/friable.
Pores: common, fine, inped/tubular.
Roots: fine to medium roots.

Horizon 3: A3.
Depth:51/57-89 cm.
Moist color: 10 YR 4/4.
Redoximorphic features:
-ox. : common, fine, distinct, 7.5 YR 5/6.
-red.: common, fine, prominent, 10 YR 5/2.
Texture: Sandy Loam.
Gravel and stones - abundance: -
- form: -
Structure: medium, course, angular blocky.
Consistence: friable.
Pores: common, fine/medium, inped/tubular.
Roots: fine to medium roots.

Horizon 4: A4.
Depth: 89-96/97 cm.
Moist color: 10 YR 5/4.
Redoximorphic features:
-ox. : common, coarse, prominent 10 YR 4/6.
-red.: -
Texture: Silty loam.
Gravel and stones - abundance:-
- form:-
Structure: moderate, medium angular blocky.
Consistence: firm.
Pores: common, fine/medium, inped, tubular.
Roots: -

Horizon 5: A/B.
Depth: 96/97-121/124 cm.
Moist color: 10 YR 4/4.
Redoximorphic features:
-ox. : common, medium, prominent; 10 YR 4/4.
-red.: few, fine, prominent; 10 YR 5/3.
Texture: Sandy Loam.
Gravel and stones - abundance:-

- form:-

Structure: weak, coarse, angular blocky.
Consistence: slightly firm.
Pores: common, fine, medium, inped, tubular and few coarse, inped, tubular.
Roots: -

Horizon 6: C1.
Depth: 121/124-165 cm.
Moist color: 10 YR 4/2.
Redoximorphic features:
-ox. : common, medium, prominent; 7.5 YR 3/4.
-red.: -.
Texture: Loamy Sand.
Gravel and stones - abundance: -.
- form: -.
Structure: structureless.
Consistence: loose.
Pores: few, fine, inped/tubular.
Roots: -

Horizon 7: C2.
Depth: 165-223/227 cm.
Moist color: 10 YR 5/2.
Redoximorphic features:
-ox. : common, medium, prominent; 7.5 YR 4/6.
-red.: -.
Texture: Sandy Clay Loam.
Gravel and stones - abundance: -
- form: -
Structure: weak, coarse angular blocky.
Consistence: slightly firm.
Pores: few, fine, inped/tubular.
Roots: -

Horizon 8: C3.
Depth: 223/227-264 cm.
Moist color: 10 YR 4/1.
Redoximorphic features:
-ox. : common, coarse, prominent; 7.5 YR 3/4.
-red.: -.
Texture: Loamy Sand.
Gravel and stones - abundance: -.
- form: -.
Structure: weak, medium, angular blocky.
Consistence: friable (moist).
Pores: few, medium, inped/tubular.
Roots: -

Horizon 9: C4.
Depth: 264-284 cm.
Moist color: 10 YR 3/1.
Redoximorphic features:
-ox. : few, coarse, prominent; 7.5 YR 4/4.
-red.: -.

Texture: Loamy Sand.
Gravel and stones - abundance: -
- form: -
Structure: Structureless.
Consistence: firm, slightly sticky, slightly plastic.
Pores: few, coarse, inped/tubular.
Roots: -

Horizon 10: C5.
Depth: 284-310 cm.
Moist color: 7.5 YR 4/0.
Redoximorphic features:
-ox. : -.
-red.: -.
Texture: Sandy Loam.
Gravel and stones - abundance: -
- form: -
Structure: Structureless.
Consistence: firm, slightly sticky, slightly plastic.
Pores: few, coarse, inped/tubular.
Roots: -

Horizon 11: C6.
Depth: 310- cm.
Moist color: 10 YR 3/1.
Redoximorphic features:
-ox. : -.
-red.: -.
Texture: Silty Clay.
Gravel and stones - abundance: -
- form: -
Structure: Structureless.
Consistence: very firm, slightly sticky, plastic.
Pores: few, fine, inped/tubular.
Roots: -

APPENDIX 11

ID.

Location: nearby river (app. 20 m.).
Position: app. 2 m. above river water level.
GWT: > 200 cm.
Microtopography:almost flat.
Observation no.: 1.
Max. slope: < 2 %.
Parent material: alluvial sediment.
Vegetation/landuse: pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 4/4	c/f/prom/10 YR 4/6	10 YR 4/1	C	3
2	15-30	10 YR 4/4	f/f/dist/10 YR 4/6	-	C	3
3	30-45	10 YR 4/4	f/m/dist/7.5 YR 4/4	10 YR 4/2	C	3
4	45-60	10 YR 4/4	f/f/dis/ 10 YR 4/6	-	LS	2
5	60-75	10 YR 4/4	f/f/dis/ 10 YR 4/6	10 YR 5/2	SCL	2
6	75-90	10 YR 4/3	f/f/fai/ -	-	SL	2
7	90-105	10 YR 4/3	c/f/prom/10 YR 3/6	10 YR 4/3	SCL	2
8	105-120	10 YR 4/4	f/f/dis/ 10 YR 4/6	10 YR 4/2	CL	2
9	120-135	10 YR 4/4	c/m/prom/7.5 YR 4/4	10 YR 5/2	LS	2
10	135-150	10 YR 4/4	m/c/fai/ 10 YR 4/4	-	SL	2
11	150-165	10 YR 4/2	f/f/dis/ 10 YR 4/6	-	SL	2
12	165-180	10 YR 4/3	c/m/dis/ 10 YR 5/6	-	SL	2
13	180-195	10 YR 4/4	f/f/fai/ 10 YR 4/6	-	LS	2
14	195-210	10 YR 4/2	c/c/dis/ 10 YR 4/3	-	SL	2
15	210-225	10 YR 4/3	c/m/dis/ 10 YR 3/4	-	SL	2
16	>210	10 YR 4/3	f/f/fai/ -	-	LS	2

Remarks: -In the upper part of the profile, oxidized rootchannels are found.
-No groundwater was found in 0-208 cm.

ID

Location: app. 120 m. from river.
Position:
GWT: 165 cm.
Microtopography:almost flat.
Observation no.: 2.
Landform: alluvial plane.
Max. slope: < 2 %.
Parent material: alluvial sediment.
Vegetation/landuse:pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 4/4	c/f/prom/10 YR 4/6		SCL	3
2	15-30	10 YR 4/4	c/f/dis/ 7.5 YR 3/4	some (faint)	CL	3
3	30-45	10 YR 4/4	c/m/dis/ 7.5 YR 4/4	10 YR 4/2	CL	3
4	45-60	-	f/f/dis/-some (faint)		SL	2
5	60-75	10 YR 3/6	f/f/dis/10 YR 3/6	some (faint)	SL	2
6	75-90	10 YR 4/6	f/f/fai/10 YR 4/6	-	SL	3
7	90-105	10 YR 4/4	c/f/prom/10 YR 3/6	10 YR 4/2	SCL	3
8	105-120	10 YR 4/3	f/f/dis/10 YR4/4	10 YR 5/1	SCL	2
9	120-135	10 YR 3/3	f/f/fai/10 YR 3/6	some faint	LS	2
10	135-150	10 YR 4/1	m/c/prom/10 YR 3/6	-	LS	2
11	150-165	10 YR 3/1	m/c/prom/7.5 YR 4/6	-	SCL/SC	3
12	165-180	10 YR 3/3	c/f/dis/10 YR 3/4	-	LS	2 BVS
13	180-195	10 YR 3/1	-	-	LS	2

Completely reduced zone.

Remarks: -Groundwater table at 165 cm.
- BVS=Black Volcanic sand.

Location: app. 220 m. from river.
Position:
GWT: 100 cm.
Microtopography: almost flat and swampy.
Observation no.: 3.
Max. slope: < 2 %.
Parent material: alluvial sediment.
Vegetation/landuse: pasture with cattle.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 4/2	m/f/prom/7.5 YR 4/4	-	C-CL	3
2	15-30	10 YR 4/4	c/f/dist/10 YR 3/4	10 YR 5/2	C-Cl	3
3	30-45	10 YR 5/2	c/m/prom/10 YR 3/4	-	C-CL	3
4	45-60	10 YR 5/1	c/c/prom/10 YR 3/4	-	C	3
5	60-75	7.5YR 4/1	c/m/prom/7.5YR 4/4	-	C	3
6	75-90	10 YR 4/1	m/c/prom/10 YR 4/6	-	C	3
7	90-105	10 YR 4/3	m/c/prom/7.5YR 4/6	-	C	3
8	105-120	10 YR 3/3	f/f/faint/10YR 3/4	10 YR 3/2	LS	1 BVS
9	120-135	10 YR 3/1	no mottles	faint	LS	1 BVS

Remarks: -BVS=black volcanic sand.

Location: app. 320 m. from river.
Position:
GWT: 40 cm.
Microtopography: almost flat and swampy.
Observation no.: 4.
Max. slope: < 2 %.
Parent material: alluvial sediment.
Vegetation/landuse: pasture with cattle.
Author: Stephan Mantel.
Date: 28-5-1992.

	depth (cm)	colour (field)	Redoximorphic features: rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 3/2	f/f/faint/10 YR 3/4	10 YR 4/2	CL	2
2	15-50	10 YR 3/1	m/c/prom/7.5 YR 3/4	-	CL	2
3	50-70	10 YR 4/1	m/m/dist/10 YR 5/6	-	CL	2
4	70-100	10 YR 4/1	c/m/prom/7.5YR 3/4	-	CL	2
5	100-120	10 YR 4/2	m/c/prom/10 YR 3/6	-	CL	3
6	120-135	10 YR 5/1	c/m/prom/10 YR 3/6	-	L	3
7	135-155	10 YR 4/1*	m/c/prom/**	-	L	3
8	155-170	10 YR 3/1	f/m/prom/10 YR 4/3	-	L	3

Remarks:
- * strong bright mottling; no clear separation.
- ** mottles inside 10 YR 2/2.
  mottles outside 10 YR 4/6.

Location: app. 420 m. from river.
Position:
Microtopography: almost flat and swampy.
Observation no.: 5
Max. slope: < 2 %.
Parent material: alluvial sediment.
Vegetation/landuse: pasture with cattle.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rustmottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 3/2	m/c/prom/7.5 YR 4/6	-	C	3
2	15-45	10 YR 3/1	c/m/prom/10 YR 4/6	yes	C	3
3	45-60	10 YR 5/1	m/c/dist/10 YR 4/6	yes	C	3
4	60-75	10 YR 4/2	c/m/prom/10 YR 3/6	yes	C	pl *
5	75-80	10 YR 4/1	c/c/prom/10 YR 3/6	yes	C	pl *
6	80-95	10 YR 5/1	m/m/prom/7.5YR 4/6	yes	C	pl *
7	95-110	10 YR 6/1	m/c/prom/7.5YR 4/6	yes	C	pl *
8	110-125	10 YR 5/1	m/f/prom/7.5YR 4/6	yes	C	pl *
9	125-140	10 YR 5/1	m/c/prom/10 YR 4/6	yes	C	pl *
10	140-155	10 YR 2/1	no mottling	yes	C	n.st/n.pl **BVS.
11	155>170	10 YR 2/1	reduced	yes	SL	n.st/n.pl **BVS.

remarks: - * pl = plastic.
- ** n.st/n.pl = non-sticky/non plastic.
- BVS = Black and Volcanic Sand.

Location: top of neguev hill, app. 520 m. from Rio Tortuguero.
Position:
Microtopography:
Observation no.: 6.
Max. slope: 15 %.
Parent material: alluvial sediment.
Vegetation/landuse: pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	7.5YR 3/4	f/f/dist/2.5YR 4/6	-	C	3
2	15-25	7.5YR 3/4	no mottles	-	C	3
3	25-35	7.5YR 3/4	f/f/prom/2.5 YR 4	-	C	3
4	35-60	7.5YR 3/4	no mottles	-	C	3
5	60-70	7.5YR 3/4	f/f/dist/2.5 YR 4/8	-	C	3
6	70-85	7.5YR 3/4	f/m/prom/2.5 YR 4/6	-	C	3
7	85-95	7.5YR 3/4	no mottles	-	C	3

remarks:
- grass roots are found throughout whole profile.
- throughout whole profile very few gley spots.
- a deep homogeneous profile with a heavy texture.

Location: behind neguev hill, app. 620 m. from Rio Tortuguero.
Position: 620 m. from rio tortugero.
Microtopography: swampy and flat.
Observation no.: 7.
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

	depth (cm)	colour (field)	Redoximorphic features: rust mottling ab/s/ct/col	gley spots	text	cons
1	0-30	10YR4-3/1	m/c/prom/10 YR 3/6	-	CL	3
2	30-45	10 YR 3/1	m/c/prom/10 YR 3/6	-	CL	pl/sl.st*
3	45-60	10 YR 3/1	m/c/prom/10 YR 3/6	-	CL	2
4	60-75	10 YR 4/1	c/m/prom/10 YR 3/6	-	CL	sl.st/pl *
5	75->150	10 YR 3/1	c/c/prom/10 YR 4/6	-	SCL	ns/sl.pl *

remarks: - wet and GWT at 30/40 cm.
- gley spots throughout whole profile.
-* pl = plastic.
* sl.st = slightly sticky.
* n.st = non-sticky.
* sl.pl = slightly plastic.

Location: rest of nequev hill, app. 720 m. from Rio Tortuguero.
Position: 620 m. from rio tortuguero.
Microtopography: plateau of 30 cm high.
Observation no.: 8
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture and trees.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-20	10 YR 4/4	c/f/prom/7.5 YR 4/4	7.5 YR 4	CL	3
2	20-100	10 YR 4/6	no mottles	-	CL	3
3	100-140	10 YR 5/2	m/m/prom/10 YR 4/6	-	CL	3
4	140-160	10 YR 5/2	m/m/prom/5 YR 4/6	-	CL	3
5	160-180	10 YR 5/2	c/m/prom/7.5 YR 4/6	-	C	4
6	180-200	10 YR 5/2	c/m/prom/10 YR 3/6 *	-	C	4
7	200-220	10 YR 5/2	m/m/prom/10 YR 3/6	-	C	4

remarks: * iron concretions.

Location: ± 820 m from Rio Tortuguero.
Position: app. 1 m above surrounding swampy area.
Microtopography: swampy, micro relief.
Observation no.: 9
Max. slope: < 1%
Parent material: alluvial sediment.
Vegetation/landuse: pasture and trees.
Author: Stephan Mantel.
Date: 28-5-1992.

	depth (cm)	colour (field)	Redoximorphic features: rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10YR4-3/1	c/m/prom/7.5 YR 4/6	-	CL	3 #
2	15-30	10 YR 3/1	f/f/dist/10 YR 4/4	-	CL	3 #
3	30-45	10 YR 4/1	f/f/dist/10 YR 3/6	-	C	st.pl *
4	45-60	5 Y 4/1	c/f/dist/10 YR 5/6	-	C	st.pl *
5	60->90	10 YR 3/1	c/f/dist/10 YR 5/6	-	CL	st.pl*#

remarks:
* st.pl = sticky plastic
# presence of organic material
- GWT at 30 cm

Location: nearby latrine; ± 920 m from Rio Tortuguero..
Position:
Microtopography: swampy and flat.
Observation no.: 10
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture and trees.
Author: Stephan Mantel.
Date: 28-5-1992.

			Redoximorphic features:			
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 4/2	m/f/prom/10 YR 3/6	-	C	3
2	15-30	10 YR 4/3	m/f/dist/10 YR 4/3	-	C	3 #
3	30-45	10 YR 4/4	no mottles	10 YR 4/2	CL	st.pl *
4	45-60	10 YR 4/3	c/m/dist/10 YR 4/6	-	CL	n.pl
5	60-75	10 YR 3/1	c/c/prom/7.5 YR 3/4	-	LS	2
6	75-90	10 YR 4/4	c/c/dist/10 YR 3/4	10 YR 4/1	LS	2
7	90-105	10 YR 4/4	no mottles	-	LS	2
8	135-150	10 YR 5/2	m/c/prom/7.5 YR 3/4	-	SCL	1
9	150-180	10 YR 5/2	m/c/prom/5 YR 3/4	-	CL	3 $
10	> 195	10 YR 3/2	m/m/prom/10 YR 5/8	-	L	2 @

remarks:
- groundwaterlevel at 60 cm under soilsurface.
- $ spots of 5 cm or more and concretions of ± ϕ ½cm.
oxidised rootholes.
* some gley spots.
@ yellow spots.

Location: app. 1 km from Rio Tortuguero.
Position:
Microtopography: humid and swampy.
Observation no.: 11
Max. slope: < 1 %.
Parent material: alluvial sediment.
Vegetation/landuse: inundated pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-45	10 YR 4/1	c/f/dist/10 YR 3/6	-	SiCL	3 #
2	45-60	10 YR 4/1	m/m/prom/10 YR 3/4 *	-	SiCl	2
3	60-75	10 YR 5/2	c/m/prom/10 YR 3/6	-	SiCl	3 @
4	75-90	10 YR 5/2	c/m/prom/7.5 YR 3/4	-	SiCl	3 @
5	90-105	10 YR 5/2	c/c/prom/7.5 YR 3/4 **	-	SiCl	3
6	105-150	10 YR 3/2	m/c/prom/10 YR 4/6 **	-	SL	2 @
7	150-200	10 YR 3/2	f/f/dist/10 YR 2/2	-	LS	1

remarks:
- * concretions of app. 2 mm.
- ** concretions of app. 0.5 cm.
- # reduced.
- @ green spots.

Location: 200 m from latrine, app. 1100 m from Rio Tortuguero.
Position:nearby blue house.
Microtopography: humid, swampy and flat.
Observation no.: 12.
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-20	10 YR 3/2	f/f/dist/10 YR 5/2	-	SiCL	2 #
2	20-30	10 YR 4/3	f/f/dist/7.5 YR 3/4	-	SiCL	2 @
3	30-45	10 YR 4/3	c/f/dist/7.5 YR 4/6	10 YR 4/2	SiCL	2
4	45-60	10 YR 3/3	f/f/faint/10 YR 3/4	-	SiCL	sl.st /sl.pl *
5	60-75	10 YR 3/2	f/f/faint/10 YR 3/3	-	SiCL	sl.st /sl.pl *
6	75-90	10 YR 3/2	no mottling	-	SL	sl.st /sl.pl *
7	90-120	10 YR 3/2	c/c/prom/10 YR 4/6	-	LS	n.st /n.pl ** $
8	120-135	10 YR 3/2	c/m/dist/10 YR 3/4	10 YR 4/1	LS	n.st /n.pl ** $
9	135-165	10 YR 3/2	f/m/dist/10 YR 4/4	10 YR 4/1	LS	n.st /n.pl ** $
10	165-210	10 YR 3/2	c/m/prom/7.5 YR 3/4	10 YR 4/1	LS	n.st /n.pl ** $

remarks:
- GWT at 40 cm.
- rooting untill 40 cm under soilsurface.
- typical swamp vegetation, mainly "ARONSKELKEN".
- * sl.st/st.pl = slightly sticky/slightly plastic.
- ** n.st/n.pl = non-sticky/nonplastic.

abundant roots.
@ mottling around the rootsholes.
$ volcanic.

Location: app. 1200 m from Rio Tortuguero.
Position:
Observation no.: 13
Microtopography: flat and swampy.
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-20	10 YR 3/2	-	10 YR 3/2	-	- #
2	20-30	5 Y 5/1	c/m/prom/7.5 YR 3/4	-	C	v.st/pl$
3	30-60	5 Y 5/1	c/m/prom/10 YR 4/6	-	C	v.st/pl*@
5	60-75	10 YR 5/1	c/f/dist/10 YR 4/4	-	C	v.st/pl*@@
6	75-105	10 YR 4/1	m/c/prom/7.5 YR 3/4	-	C	sl.st/ n.pl**
7	105-135	10 YR 3/2	m/m/prom/ 7.5 YR 3/4 app. 80 % mottles	-	LS	n.st/ n.pl ***
8	135-155	10 YR 3/1	c/f/dist/10 YR 3/4	-	SL-S	n.st/ n.pl ***
9	155>165	10 YR 3/1	no mottles	- with green spots	SL	sl.st/ sl.pl ****

remarks:
- @ dark green concretions
- @@ light green spots
- * v.st/pl = very sticky/plastic
- ** sl.st/n.pl = slightly sticky/nonplastic
- *** n.st/n.pl = non-sticky/nonplastic
- **** sl.st/sl.pl = slightly sticky/slightly plastic
- # black, more roots than soil
- $ grey coloured clay with small roots

Location: app. 1300 m from Rio Tortuguero.
Position:
Observation no.: 14.
Microtopography: flat and swampy.
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture with cattle
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-10	10 YR 3/2	no mottles	-	C	-
2	10-40	10 YR 3/1	no mottles	5 Y 3/2	C	3
3	40-60	10 YR 5/1	m/m/prom/10 YR 4/6	-	C	3
4	60-70	2.5 Y 5/0	c/m/prom/10 YR 4/6	-	C	3
5	70-90	10 YR 4/1	m/c/prom/10 YR 3/4	10 YR 5/1	SL	n.st/n.pl*
6	90-105	10 YR 4/1	m/c/prom/7.5 YR 3/4	-	SCL	sl.st/ sl.pl**
7	105-120	10 YR 3/2	c/f/prom/7.5 YR 3/4	-	LS	n.st/n.pl *
8	120-135	10 YR 4/1	c/f/prom/7.5 YR 4/6	-	LS	n.st/n.pl *
9	135-150	7.5YR 2/0	no mottles	-	LS	n.st/n.pl *
10	> 150	7.5YR 3/0	no mottles	-	SiC	sl.st/ sl.pl **

remarks:
- GWT at 40 cm.
- * n.st/n.pl = non-sticky/nonplastic.
-** sl.st/sl.pl = slightly sticky/slightly plastic.

Location: app. 1400 m from the Rio Tortuguero.
Position: next to badly drained field.
Observation no.: 15.
Microtopography: flat and micro-relief.
Max. slope:
Parent material: alluvial sediment.
Vegetation/landuse: pasture
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	7.5YR 3/2	c/f/prom/5 YR 3/4	-	CL	2 #
2	15-30	10 YR 4/3	c/f/prom/7.5 YR 3/4	10 YR 5/4	SiCL	2
3	30-45	10 YR 4/6	no mottles	10 YR 6/1	SiCL	3
4	45-60	10 YR 4/6	c/f/dist/7.5 YR 4/6	10 YR 6/2	SiCL	3
5	60-75	10 YR 4/6	m/m/prom/7.5 YR 4/6	10 YR 5/2	SiCL	3
6	75-90	10 YR 4/4	c/m/prom/5 YR 4/6	-	SCL	3 @
7	90-165	10 YR 3/1	f/f/dist/7.5 YR 3/4	-	LS-S	n.st/n.pl
8	165-180	7.5YR 3/0	f/m/prom/7.5 YR 3/4	-	SiL	sl.st/pl**

remarks:
- GWT at 75 cm.
- * n.st/n.pl = non-sticky/nonplastic
- ** sl.st/pl = slightly sticky/plastic
- # oxidised rootholes
- @ volcanic

Location: app. 1500 m from Rio Tortuguero.
Position:
Observation no.: 16
Microtopography: swampy, level area.
Max. slope: < 1%.
Parent material: alluvial sediment.
Vegetation/landuse: pasture.
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 2/2	no mottles	10 YR 4/2	CL	2
2	15-30	10 YR 2/2	c/f/dist/10 YR 4/6	10 YR 4/2	CL	2
3	30-60	10 YR 5/2	c/m/dist/10 YR 4/6	-	C	3
4	60-75	10 YR 5/1	m/m/prom/10 YR 3/4	-	SCL	sl.st/sl.pl
5	75-105	10 YR 4/1	m/m/prom/7.5 YR 3/2	-	LS	n.st/n.pl*
6	105-135	10 YR 3/1	c/c/prom/7.5 YR 3/4	-	LS	n.st/n.pl
7	> 135	7.5YR 2/6	no mottles	-	LS	n.st/n.pl

remarks:
- bad soil drainage.
- GWT at 30 cm.
- concentration of roots at the soilsurface.
- * n.st/n.pl = not sticky/not plastic.

Location: app. 1600 m from Rio Tortuguero.
Position:
Observation no.: 17.
Microtopography: dry, level area.
Max. slope: < 1%.
Parent material: alluvial sediment.
Vegetation/landuse:
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 3/2	m/m/prom/7.5 YR 3/4	10 YR 5/2	SL	1 #
2	15-30	10 YR 4/4	f/f/dist/10 YR 3/4	10 YR 4/1	L	2
3	30-45	10 YR 4/4	f/f/dist/10 YR 3/4	10 YR 5/2	L	2
4	45-75	10 YR 4/4	f/f/dist/10 YR 4/6	10 YR 5/1	LS	2
5	75-90	10 YR 4/4	f/m/prom/7.5YR 3/4	10 YR 5/1	SL	0 @
6	90-120	10 YR 4/3	f/f/dist/10 YR 4/6	10 YR 5/2	LS-L	0 $
7	120-135	10 YR 5/3	c/c/prom/10 YR 3/6	-	LS	0
8	135-150	10 YR 5/3	c/m/prom/7.5YR 3/4	10 YR 5/2	SCL	2
9	150-200	10 Y 5/3	m/c/prom/7.5YR 3/4	-	LS	0 **

remarks:
- in the first 5 cm abundant roots.
- # oxidized rootsholes.
- * gley spot around roots.
- ** very big mottles.
- @ some mottle concretions.
- $ few and faint gley.

Location: app. 1700 m from Rio Tortuguero.
Position:
Observation no.: 18
Microtopography:
Max. slope: < 1%.
Parent material: alluvial sediment.
Vegetation/landuse:
Author: Stephan Mantel.
Date: 28-5-1992.

Redoximorphic features:

	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons	
1	0-30	10 YR 4/4	no mottles	-	L	2	
2	30-45	10 YR 4/3	no mottles	-	SL	2	
3	45-60	10 YR 3/3	no mottles	-	SL	2	
4	60-90	10 YR 4/3	f/f/faint/10 YR 4/4	-	LS	2	
5	90-105	10 YR 4/4	f/f/faint/10 YR 4/6	10 YR 5/3	LS	2	
6	105-120	10 YR 4/4	no mottles	10 YR 5/3	LS	2	$
7	120-135	10 YR 4/4	f/f/faint/10 YR 4/6	10 YR 5/3	LS	2	#
8	135-150	10 YR 4/4	no mottles	-	LS	2	
9	150-165	10 YR 4/4	f/f/faint/10 YR 4/6	-	SL	2	
10	165-180	10 YR 4/3	c/m/prom/7.5 YR 4/4	-	SCL	2	
11	180-195	10 YR 4/3	m/c/prom/10 YR 4/6	10 YR 6/2	SCL	2	
12	195-210	10 YR 4/3	c/m/prom/10 YR 3/4	-	SCL	2	

remarks:
- roots at app. 60 cm under soilsurface.
- GWT at app. 90 cm.
- # few gley spots.
- $ few gley spots

Location: ± 1800 m from Rio Tortuguero and 15 m from Rio Palacios.
Position: ± 2 m above river (water) level.
Observation no.: 19.
Microtopography: riverplain.
Max. slope: < 2%.
Parent material: alluvial sediment
Vegetation/landuse: pasture and cattle.
Author: Stephan Mantel.
Date: 28-5-1992.

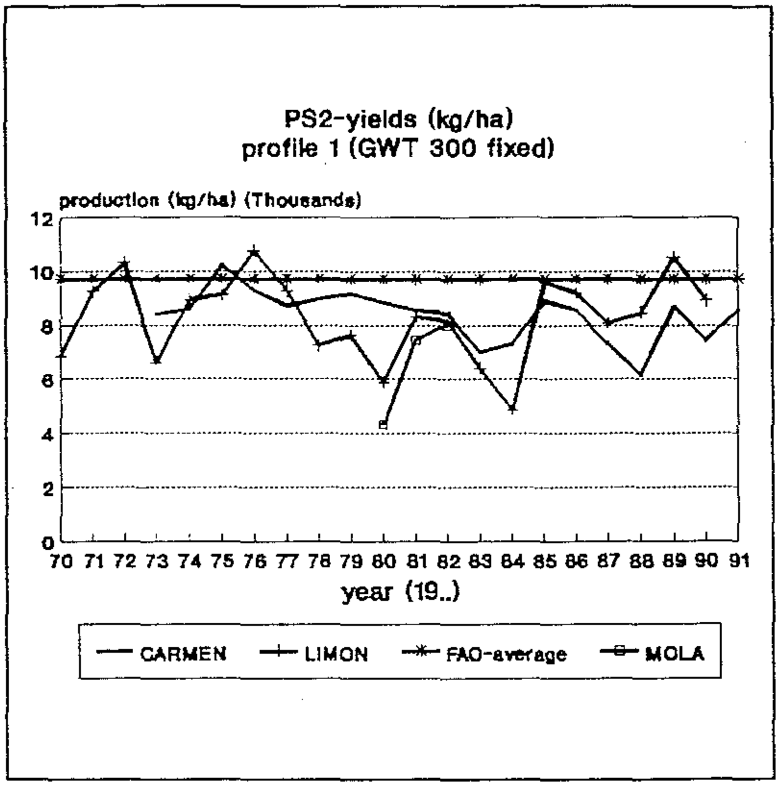
Redoximorphic features:

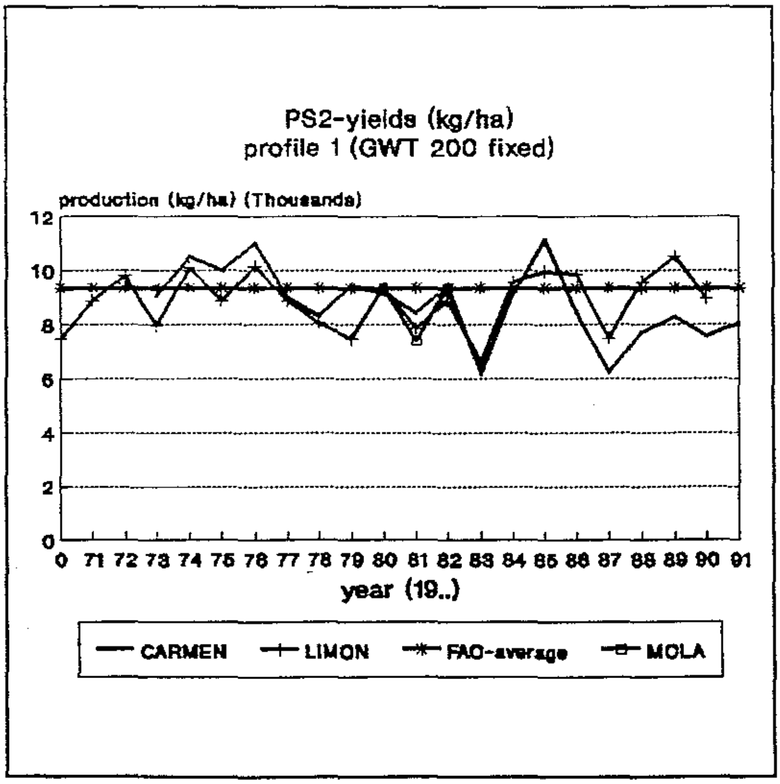
	depth (cm)	colour (field)	rust mottling ab/s/ct/col	gley spots	text	cons
1	0-15	10 YR 3/3	m/m/prom/7.5 YR 3/4	-	L	2
2	15-30	10 YR 4/4	no mottles	-	L	2
3	30-45	10 YR 4/4	c/f/prom/5 YR 3/4	-	L	2
4	45-60	10 YR 4/6	m/f/prom/7.5 YR 4/6	10 YR 6/2	CL	2
5	60-75	10 YR 4/4	c/f/prom/7.5 YR 4/4	10 YR 5/3	CL	2
6	75-90	10 YR 4/4	m/m/prom/7.5 Y 4/4	10 YR 5/3	CL	2
7	90-105	10 YR 5/3	m/c/prom/5 YR 4/6	-	CL	2
8	105-120	10 YR 5/2	m/m/prom/5 YR 4/6	-	SCL	2
9	120-135	10 YR 6/2	m/c/prom/7.5 YR 3/4	-	SCL	2
10	135-150	10 YR 5/2	m/c/prom/7.5 YR 3/4	-	SCL	sl.st/ n.pl *
11	150-165	10 YR 5/2	c/c/prom/7.5 YR 4/6	-	SCL	sl.st/ sl.pl **
12	165-180	10 YR 4/1	m/m/prom/7.5 YR 4/0	-	SCL	sl.st/ sl.pl ** @
13	180-195	10 YR 4/2	c/f/prom/7.5 YR 3/4	-	SiL	sl.st/ sl.pl **
14	195-210	10 YR 4/2	c/f/prom/7.5 YR 3/4	-	LS	n.st/ n.pl ***

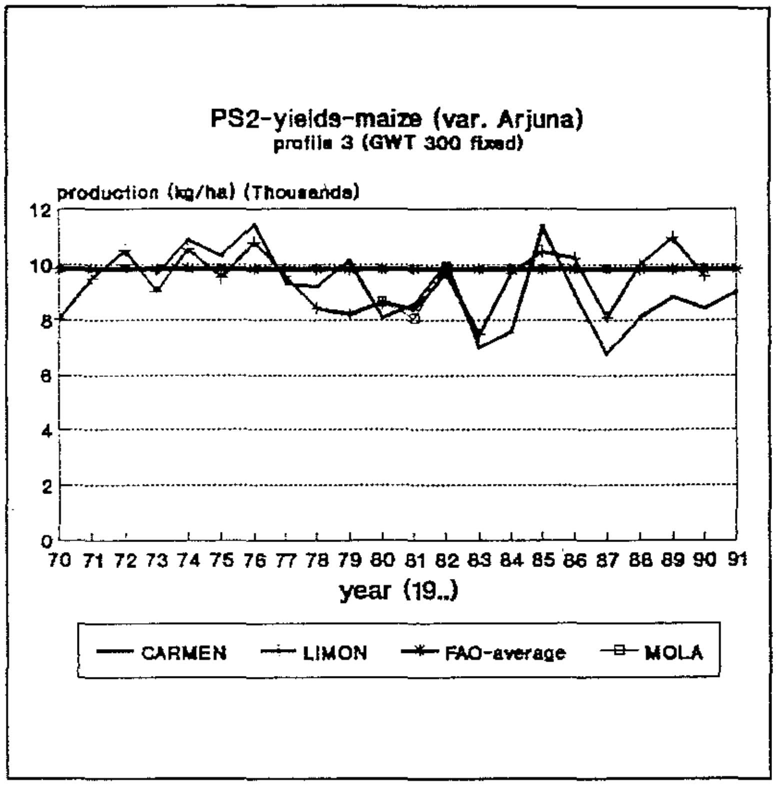
remarks: -groundwater at 1.80-2.00 m.
- @ concretions.

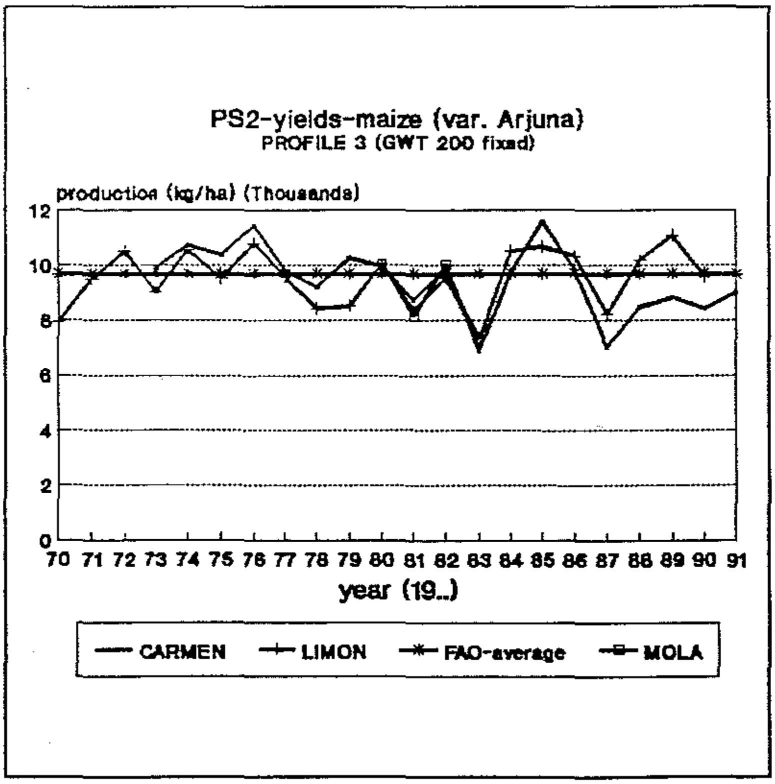
APPENDIX 12

Appendix 12: Calculated PS2-productions.






PS2-yields-maize (var. Arjuna)
profile 3 (GWT 300 fixed)


PS2-yields-maize (var. Arjuna)
PROFILE 3 (GWT 200 fixed)

PS123-yields Hacienda "El Carmen".
PSI-init: 333 cm.
SSC: 5 cm.
ASSC: 0 cm.
Sowing dens.: 25 kg/ha.
Mortality: 0.15
sample 1A1-17

year	julian day	PS1-yield	highest PS2-yield	GWT
FAO	30	9877	9877	300 FIX
1973	330	9698	8411	300 FIX
1974	360	10374	8605	300 FIX
1975	360	10453	10216	300 FIX
1976	15	11406	9281	300 FIX
1977	25	8720	8720	300 FIX
1978	45	8976	8976	300 FIX
1979	30	9577	9179	300 FIX
1980	45	9947	7400	300 FIX
1981	15	8754	8553	300 FIX
1982	60	8549	8435	300 FIX
1983	45	7012	7012	300 FIX
1984	360	7588	7319	300 FIX
1985	65	10483	8911	300 FIX
1986	15	8796	8558	300 FIX
1987	330	7643	7333	300 FIX
1988	15	6902	6178	300 FIX
1989	45	8833	8705	300 FIX
1990	45	8498	7439	300 FIX
1991	30	8826	8557	300 FIX
FAO	35	9841	9181	200 FIX
1973	350	9845	9070	200 FIX
1974	25	10902	10536	200 FIX
1975	25	10360	10025	200 FIX
1976	15	11406	11009	200 FIX
1977	65	9462	8991	200 FIX
1978	85	8828	8324	200 FIX
1979	360	10138	9435	200 FIX
1980	45	9947	9184	200 FIX
1981	10	8746	8451	200 FIX
1982	25	10031	9381	200 FIX
1983	10	6711	6179	200 FIX
1984	55	9601	9130	200 FIX
1985	25	11782	11142	200 FIX
1986	10	8937	8458	200 FIX
1987	360	6755	6233	200 FIX
1988	75	8329	7727	200 FIX
1989	35	8813	8306	200 FIX
1990	25	8341	7589	200 FIX
1991	25	8548	8048	200 FIX

PS123-yields Hacienda "El Carmen".
PSI-init: 333 cm.
SSC: 5 cm.
ASSC: 0 cm.
Sowing dens.: 25 kg/ha.
Mortality: 0.15
sample 3A2-4

year	julian day	PS1-yield	highest PS2-yield	GWT
FAO	30	9877	9877	300 FIX
1973	345	9698	9698	300 FIX
1974	25	10902	10902	300 FIX
1975	355	10334	10334	300 FIX
1976	25	11442	11442	300 FIX
1977	55	9300	9300	300 FIX
1978	55	9216	9216	300 FIX
1979	360	10138	10138	300 FIX
1980	360	8948	8093	300 FIX
1981	360	8575	8575	300 FIX
1982	25	10033	10033	300 FIX
1983	45	7012	7012	300 FIX
1984	360	7588	7588	300 FIX
1985	15	11435	11379	300 FIX
1986	10	8937	8937	300 FIX
1987	25	6779	6779	300 FIX
1988	85	8107	8107	300 FIX
1989	45	8833	8833	300 FIX
1990	45	8398	8398	300 FIX
1991	35	9030	9030	300 FIX
FAO	35	9841	9841	200 FIX
1973	360	9925	9925	200 FIX
1974	35	10748	10748	200 FIX
1975	1	10379	10379	200 FIX
1976	25	11442	11442	200 FIX
1977	75	9829	9829	200 FIX
1978	55	9216	9216	200 FIX
1979	1	10260	10260	200 FIX
1980	45	9947	9555	200 FIX
1981	10	8746	8746	200 FIX
1982	10	9899	9899	200 FIX
1983	35	6884	6884	200 FIX
1984	60	9786	9786	200 FIX
1985	10	11580	11580	200 FIX
1986	10	9837	9837	200 FIX
1987	1	7013	7013	200 FIX
1988	60	8485	8485	200 FIX
1989	45	8833	8833	200 FIX
1990	45	8398	8398	200 FIX
1991	35	9030	9030	200 FIX

PS123-yields "Puerto Limon".
PSI-init: 333 cm.
SSC: 5 cm.
ASSC: 0 cm.
Sowing dens.: 25 kg/ha.
Mortality: 0.15
sample 1A1-17

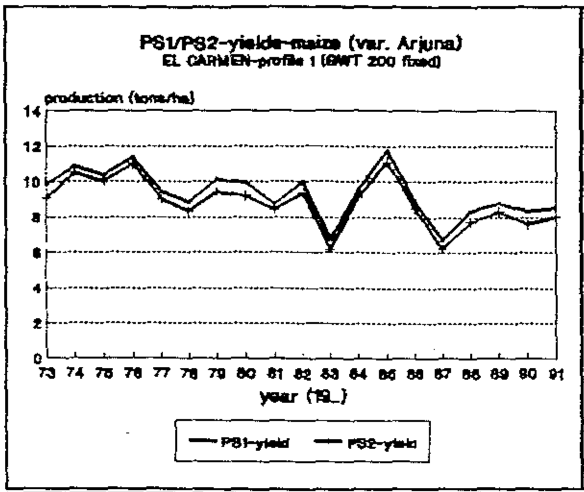
year	julian day	PS1-yield	highest PS2-yield	GWT
FAO	50	9543	9543	300 FIX
1970	25	7376	6857	300 FIX
1971	65	9489	9254	300 FIX
1972	45	10307	10307	300 FIX
1973	1	7666	6620	300 FIX
1974	1	9916	8957	300 FIX
1975	45	9524	9119	300 FIX
1976	25	10815	10775	300 FIX
1977	65	9565	9261	300 FIX
1978	25	8185	7255	300 FIX
1979	25	7625	7625	300 FIX
1980	15	9734	5895	300 FIX
1981	1	8470	8320	300 FIX
1982	15	9480	8153	300 FIX
1983	15	6598	6417	300 FIX
1984	35	6918	4888	300 FIX
1985	25	9937	9606	300 FIX
1986	350	10094	9196	300 FIX
1987	45	8083	8083	300 FIX
1988	25	8698	8469	300 FIX
1989	45	10809	10513	300 FIX
1990	45	9558	8928	300 FIX
FAO	45	9538	9538	200 FIX
1970	35	7490	7490	200 FIX
1971	65	9489	8882	200 FIX
1972	25	10.454	9819	200 FIX
1973	45	10307	7940	200 FIX
1974	15	10917	10126	200 FIX
1975	35	9592	8881	200 FIX
1976	15	10586	10173	200 FIX
1977	65	9565	8886	200 FIX
1978	350	8453	8050	200 FIX
1979	15	8199	7465	200 FIX
1980	25	9760	9381	200 FIX
1981	15	8479	7870	200 FIX
1982	15	9480	8888	200 FIX
1983	85	7455	6608	200 FIX
1984	35	10328	9588	200 FIX
1985	65	10383	9981	200 FIX
1986	10	10193	9857	200 FIX
1987	360	7989	7489	200 FIX
1988	75	10145	9596	200 FIX
1989	35	11166	10547	200 FIX
1990	15	9146	8970	200 FIX

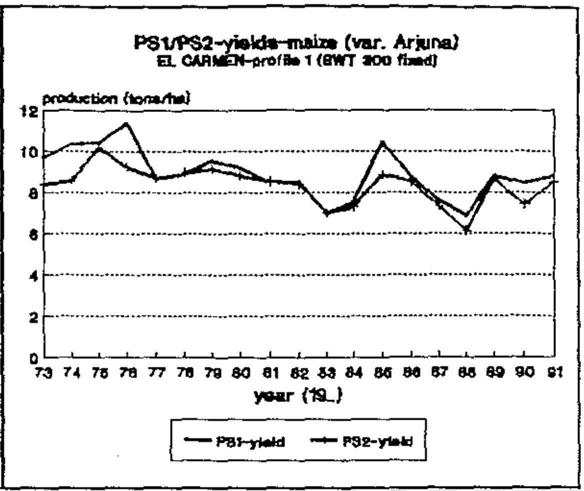
PS123-yields "Puerto Limon".
PSI-init: 333 cm.
SSC: 5 cm.
ASSC: 0 cm.
Sowing dens.: 25 kg/ha.
Mortality: 0.15
sample 3A2-4

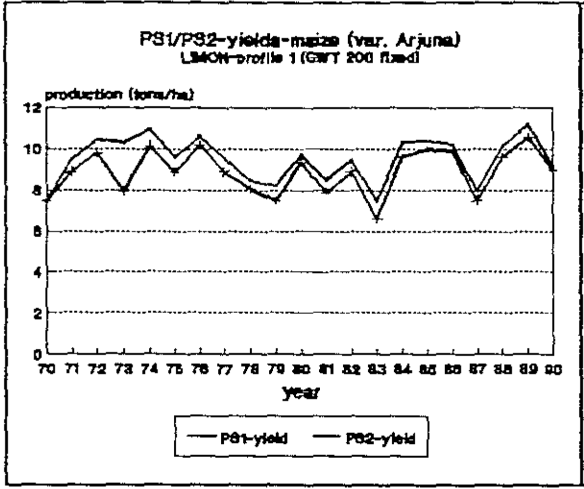
year	julian day	PS1-yield	highest PS2-yield	GWT
FAO	45	9806	9806	300 FIX
1970	45	8026	8026	300 FIX
1971	65	9489	9489	300 FIX
1972	35	10535	10535	300 FIX
1973	45	9019	9019	300 FIX
1974	45	10567	10567	300 FIX
1975	45	9524	9524	300 FIX
1976	25	10815	10815	300 FIX
1977	65	9565	9565	300 FIX
1978	360	8429	8429	300 FIX
1979	15	8199	8199	300 FIX
1980	65	9099	8636	300 FIX
1981	360	8370	8370	300 FIX
1982	25	9693	9693	300 FIX
1983	100	7462	7462	300 FIX
1984	45	10532	9699	300 FIX
1985	45	10683	10487	300 FIX
1986	365	10247	10247	300 FIX
1987	15	8101	8101	300 FIX
1988	45	10007	10007	300 FIX
1989	25	10998	10998	300 FIX
1990	30	9583	9583	300 FIX
FAO	50	9543	9543	200 FIX
1970	60	7939	7939	200 FIX
1971	65	9489	9489	200 FIX
1972	35	10535	10535	200 FIX
1973	45	9019	9019	200 FIX
1974	45	10567	10567	200 FIX
1975	45	9524	9524	200 FIX
1976	25	10815	10815	200 FIX
1977	65	9565	9565	200 FIX
1978	358	8435	8435	200 FIX
1979	230	8516	8516	200 FIX
1980	45	10036	10036	200 FIX
1981	360	8370	8370	200 FIX
1982	30	9542	9542	200 FIX
1983	230	7344	7344	200 FIX
1984	45	10532	10532	200 FIX
1985	45	10683	10683	200 FIX
1986	360	10337	10337	200 FIX
1987	10	8208	8208	200 FIX
1988	60	10176	10176	200 FIX
1989	30	11104	11104	200 FIX
1990	30	9583	9583	200 FIX

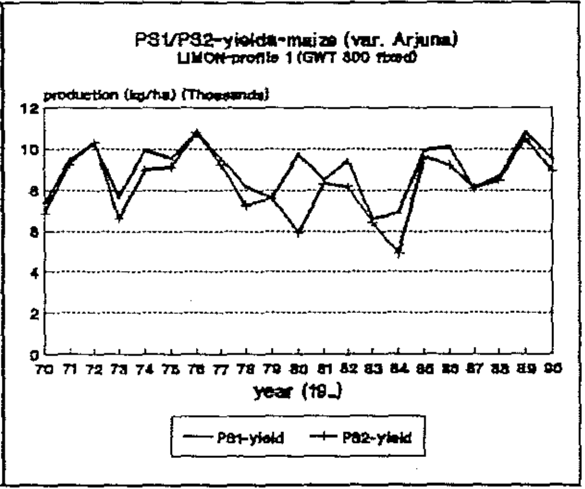
```
PS123-yields       "La Mola".
PSI-init:          333 cm.
SSC:               5 cm.
ASSC:              0 cm.
Sowing dens.:      25 kg/ha.
Mortality:         0.15
sample 1A1-17
year      julian            highest     GWT
          day      PS1-yieldPS2-yield

1980      360      8660      4350      300 FIX
1981      15       8041      7453      300 FIX
1982      65       8243      8016      300 FIX

1980      25       9862      9360      200 FIX
1981      15       8041      7408      200 FIX
1982      25       10017     9371      200 FIX

PS123-yields       "La Mola".
PSI-init:          333 cm.
SSC:               5 cm.
ASSC:              0 cm.
Sowing dens.:      25 kg/ha.
Mortality:         0.15
sample 3A2-4
year      julian            highest     GWT
          day      PS1-yieldPS2-yield

1980      360      8660      8660      300 FIX
1981      25       8045      8045      300 FIX
1982      15       9919      9919      300 FIX

1980      45       10036     10036     200 FIX
1981      10       8155      8155      200 FIX
1982      20       10035     10035     200 FIX
```

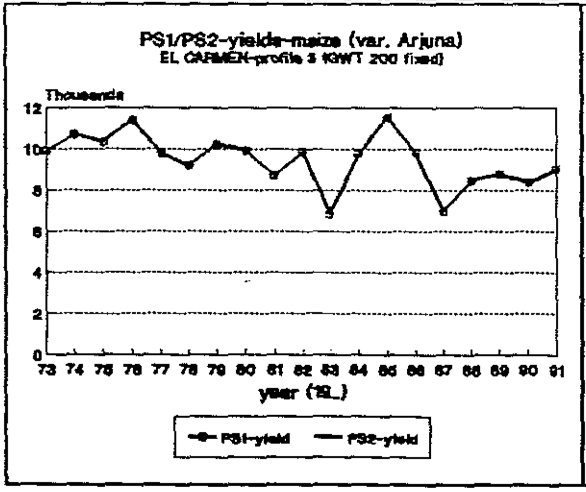
Appendix 13: PS1/PS2-productions.

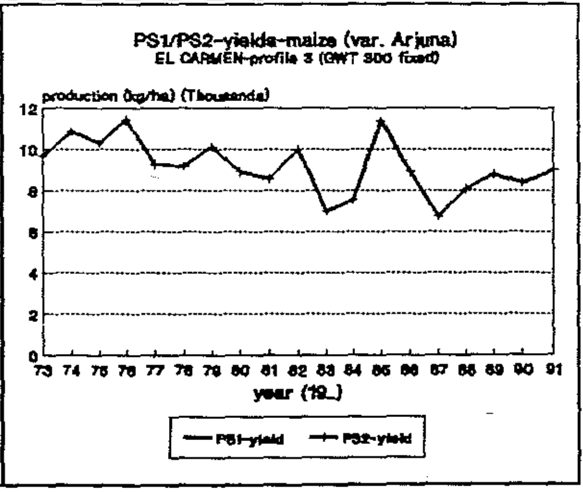


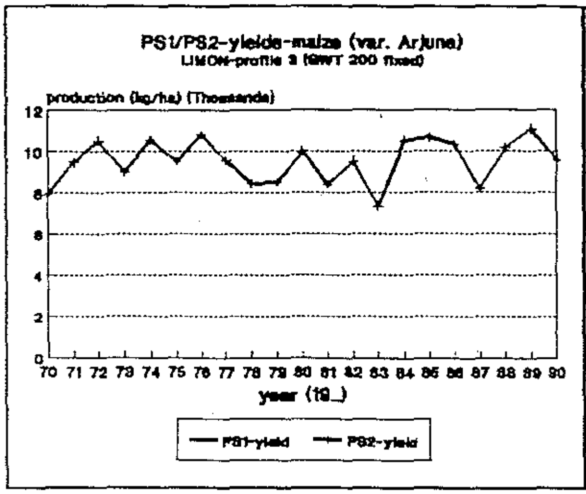


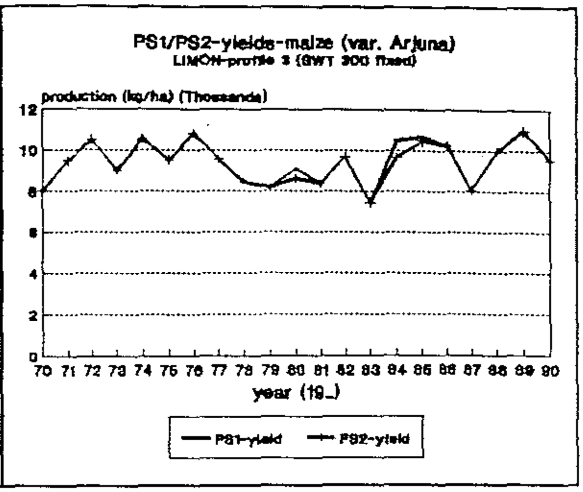









PS1/PS2-yields-maize (var. Arjuna)
LIMON-profile 3 (GWT 200 fixed)
production (kg/ha) (Thousands)
12
10
8
6
4
2
0
70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
year (19_)
PS1-yield
PS2-yield


PS1/PS2-yields-maize (var. Arjuna)
LIMON-profile 3 (GWT 300 fixed)
production (kg/ha) (Thousands)
12
10
8
6
4
2
0
70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
year (19_)
PS1-yield
PS2-yield