ROLOGY AND DRAINAGE OPTIONS
TLANTIC ZONE OF COSTA RICA

Robert Sevenhuysen
Pascal Maebe

CATIE

Serie Técnica
Informe Técnico No. 247

HYDROLOGY AND DRAINAGE OPTIONS

ATLANTIC ZONE OF COSTA RICA

Robert Sevenhuysen
Pascal Maebe

Centro Agronómico Tropical de Investigación y Enseñanza

CATIE

1995

Turrialba Costa Rica

El CATIE es una institución de carácter cientifico y educacional, cuyo propósito fundamental es la investigación y la enseñanza de posgrado en el campo de las ciencias agropecuarias y de los recursos naturales renovables aplicados al trópico americano.

631.62097286

S497 Sevenhuysen, Robert
Hydrology and drainage options Atlantic zone of Costa Rica / Robert Sevenhuysen, Pascal Maebe. — Turrialba, C.R. : CATIE, 1995.
66 p. ; 21 cm. — (Serie técnica. Informe técnico / CATIE ; no. 247)

ISBN 9977-57-197-x

1. Hidrología - Costa Rica - Zona Atlántica
2. Drenaje - Costa Rica - Zona Atlántica
I. Título II. Serie

Esta es una publicación del Programa Zona Atlantica, un convenio de cooperación técnica entre el Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), la Universidad Agrícola Wageningen (UAW) de Holanda y el Ministerio de Agricultura y Ganaderia (MAG) de Costa Rica, financiado por la UAW.

CATIE

MAG
Costa Rica

Agricultural University
Wageningen

Table of contents

Chapter 1: Introduction 11

1.1. Report objective and content 11

Chapter 2: Drainage conditions in the Atlantic Zone 13

2.1. Location and general characteristics of the study area. 13
2.2. The natural drainage network 15
2.3. Hydrology and natural drainage. 18

Chapter 3: Methodology 22

3.1. Soil water movement. 22
3.2. Groundwater flow. 22
3.3. Combined soilwater movement and groundwater flow 23
3.4. Surface runoff and excess rainfall 24

Chapter 4: Analysis of observations. 29

4.1. Introduction 29
4.2. Surface runoff from eroded hills (pleistocene soils) 29
4.3. Physical soil data 31
4.4. Phreatic aquifer data. 34
  4.4.1. Parameters 34
  4.4.2. Observations and interpretation for well drained and poorly drained soils 39
4.5. Discussion and conclusions 49

Chapter 5: Simulation of water table fluctuations 50

5.1. Introduction 50
5.2. Drainage scenarios. 50
5.3. Simulated water table fluctuations 51
5.4. Drain factor 55
5.5. Water balance 56
5.6. Discussion and conclusions 58

Chapter 6: Crop growth simulation 59

6.1. Introduction 59
6.2. Description 59
6.3. Results 61
  6.3.1. Banana 61

6.3.2. Maize. 67
6.4. Discussion and conclusions 71

Chapter 7: Drainage and transport of agrochemicals 72

7.1. Introduction 72
7.2. Water qualities. 72
7.3. Nutrient and pesticide losses on banana plantations. 73
7.4. Residence time in groundwater 75
7.5. Discussion and conclusions 75

Chapter 8: Conclusions and recommendations. 77

8.1. Conclusions 77
8.2. Crop production 77
8.3. Recommendations 78

References 79

Appendix 1 82

Preface

This study was made within the framework of the Altantic Zone Programme, a cooperation between the Agricultural University of Wageningen (The Netherlands), the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and the Ministerio de Agricultura y Ganadería (MAG).

The report is prepared on the basis of data that are presented in a number of field reports prepared by students of the Agricultural University of Wageningen working in the Atlantic Zone of Costa Rica. Additional field observations were conducted to complement this reports and to allow for an integration.

Information on surface runoff and erosion was collected within the framework of an agreement between FAO, MAG and the University of Wageningen.

Pascal Maebe was contracted as an independent hydrologist to carry out computer modeling and drafting of a large part of the text.

Don Jansen, the University's field team staff agronomist cooperated in modeling crop growth (chapter 5).

Robert Sevenhuysen, field team coordinator and agrohydrologist, was responsable for the initiation and guidance of most of the field work as well as for preparing materials and editing of this report.

We acknowledge the comments of the field team, members of the Wageningen University and the support of the editorial board of CATIE.

Robert Sevenhuysen - Pascal Maebe.

Chapter 1

Introduction.

The general aim of the Atlantic Zone Programme is to develop a methodology for sustainable land use planning, taking into account ecological as well as economic aspects. Sustainability criteria that have been developed include nutrient depletion, biocide use and economic feasibility of agricultural production at field and farm levels. Farm types are developed on the basis of soil types and farm size to allow agregation from farm to (sub)regional level.

During the study period from 1991 until 1994, a large number of field investigations were conducted, of which activities related to drainage formed a relatively small, but supporting part.

Drainage problems in large parts of the Atlantic Zone of Costa Rica are related to the humid tropical climate in this area and to the relatively flat topography and limited elevation above sea level.

In general, drainage conditions are determined by (sub)regional conditions and have a clear effect on land use at the farm level. Measures to improve drainage conditions are mostly aimed at yield improvement but have effect also on nutrient and biocide leaching.

1.1. Report objective and content.

Based on field observations and measurements, together with literature information, an effort is made to analyze the present drainage condition and suggest possible measures to improve drainage in perspective with crop production and nutrient and agrochemical leaching.

The analysis of the drainage condition and of the measures that can be taken to improve crop production can present basic information on which future drainage projects can be developed. However, as the study aims at a general understanding in the Atlantic Zone, for every new project additional field observations remain required.

Engineers and Agronomists involved in land reclamation, as well as students in the subject can benefit from the materials presented.

As many agrochemicals are transported to a larger or smaller extend by drainage water, aspects of leaching are also included. Environmental studies can make use of the procedures and data presented in this report. Crop production and leaching of agrochemials are also important components in the broader evaluation of the sustainability of a land use system. The scope of this report was to contribute to this evaluation. However to arrive at solid conclusions more information on the behaviour of the large diversity of agrochemicals is required; only indications can be presented in this study.

The structure of the report is as follows:

The report begins with a description of the present drainage condition of the Atlantic Zone north of Siquirres. A rough water balance is presented for each physiographic sub-area (chapter 2).

In Chapter 3 the basic methodology to analize the different components of the drainage process: soil water movement, saturated ground water flow and surface run off are presented and briefly discussed.

Observations and analysis are presented for each sub area in chapter 4. This chapter presents the input data for further mathematical modeling in chapter 5.

Options for drainage measures are presented for selected locations in chapter 5. Extrapolations in time are made using simulation programmes.

Drainage measures analyzed in chapter 5 are used to estimate groundwater table fluctuations in selected profiles. Crop growth simulation models are used to estimate the effect of these measures on crop photosynthesis and production (chapter 6).

The limited number of water quality data that are available are discussed in relation to drainage measures and nutrient and biocide leaching (chapter 7).

In appendix 1 some guidelines for the design of practical drainage networks will be presented, including a rough estimate of costs based on present networks.

Quantitative information presented in chapters 4 and 7 of this report are based on observations and measurements conducted in pilot areas by field team members. Field reports in which the original data are presented are available at the Atlantic Zone Programme. Analytical procedures used in chapters 3, 4, 5 and 6, refer to agrohydrological, soil physical and theoretical crop production methodologies.

Chapter 2

Drainage conditions in the Atlantic Zone.

2.1. Location and general characteristics of the study area.

According to Weyl (1980) Costa Rica can be divided into three principal morphological regions:

1) The central mountain range stretching from Panama to the Nicaraguan border;
2) The Pacific Coastal region in the west;
3) The subsiding northeastern Atlantic - Caribbean lowlands or Limón Basin.

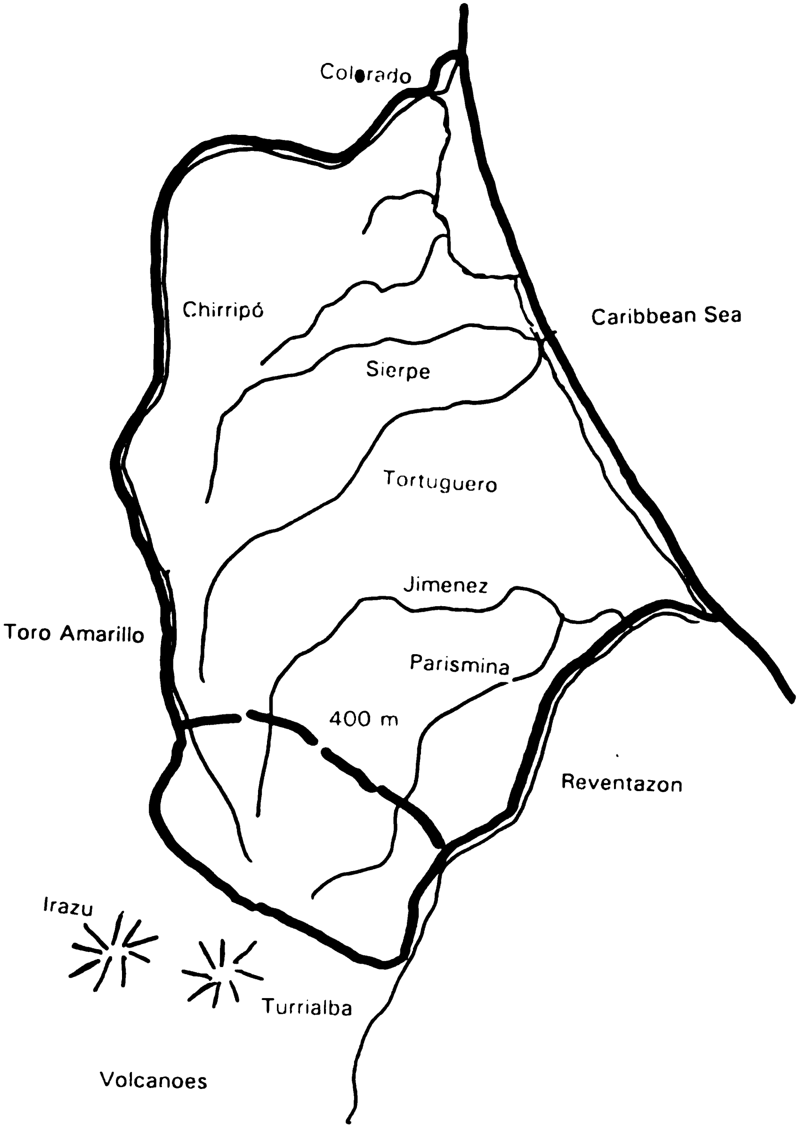
The study site is located in the Limón Basin and has an area of about 400.000 ha. Approximate limits of the study area are formed by the Caribbean Sea in the northeast; the Reventazón River in the south; the 400m contour in the southwest up to the Chirripó River and, the Chirripó and Colorado Rivers in the northwest (see figure 2.1).

The mountain range in which major rivers begin is formed by Quarternary volcanoes. These volcanoes have been active occasionally during recent history. Fresh volcanic material is exposed on the upper slopes and transported by water into the basin.

At present about 75% of the soils in the Limón Basin are of Holocene age and 25% of Pleistocene age. Three main geo-morphological sub-units can be distinguished in the Holocene deposits. Alluvial fans are formed by rivers at the transition point between the central mountain range and lowlands and are composed mainly of gravel and sand. Alluvial plains below the fans can be divided in active parts which are occasionally flooded and non-active parts where old river terraces are found. Sediments in the alluvial plains consist, in general, of fine textured materials, while old river beds are often filled with sand transported by flash floods. Soils in the alluvial plains are very heterogeneous. The coastal plain is a landscape formed by beach ridges and coastal swamps. Tidal movements in the Caribbean sea are limited to about 50cm resulting in very limited salt intrusion. A clear mangrove belt in the tidal area is absent. In the coastal swamps peat formation occurs in a fresh water environment.

Within the alluvial plain deposits, two other formations can be distinguished: eroded Pleistocene terrace remains and a few small early Pleistocene basaltic volcanoes. These volcanoes have elevations of less than 300m above sea level and are steeply dissected. The old eroded Pleistocene landscape appears at the surface, scattered over about one quarter of the study area. Except for these sub-units, topography is rather flat with a continuous decreasing slope from the foothills to the coast. Alluvial fans start at an elevation of some 400m and extend with an average slope

Figure 2.1: Study area.



of 3% up to about the 150m level. The alluvial plain, with an average slope of 0.5% ends at about the 10m level, from where coastal marshes start at some 5 to 10km from the coast.

The humid tropical climate of the study area is characterized by an average rainfall of 4000 mm per year and an average temperature of 26°C. The "dry" months February, March and September, still have averages of 200 mm each. In the wet months, July and November, the rainfall exceeds 400 mm. Mean daily sunshine amounts to 5.5 hours and 4 hours in the dry and wet months. Evaporation ranges between 3 and 5 mm per day.

A water deficit for crops seldom occurs. Shallow rooted crops suffer from drought only during exceptional dry spells of more than 14 days. Crop growth is more often limited by excess water in the root zone than by drought.

2.2. The natural drainage network.

In the study area two major and a few smaller river systems carry water towards the Caribbean Sea. The catchment areas of the two major river systems, Toro Amarillo - Chirripó and Jiménez -Parismina reach high up into the Irazú and Turrialba volcanoes. Many small tributaries and brooks originate in the foot hills and alluvial fan and flow into these major rivers.

Smaller rivers like Tortuguero and Sierpe originate in the alluvial fans and plains and also collect water from a large number of tributaries in the alluvial plain. Discharge of small rivers in the coastal plain is blocked by beach ridges with only a few openings to the sea. Major rivers, however, discharge directly into the Caribbean Sea.

The tributary network of major and minor rivers is strongly related to topography and to geomorphologic units into which they flow.

In the alluvial fan and in the upper part of the alluvial plain, with slopes between 5 and 1%, tributaries flow perpendicular to the contour lines with an average density of three streams in every km of contour (as measured on the 50.000 scale map). Small tributaries or brooks unite about every two to three km forming larger ones but new small streams originate often.

In the middle part of the alluvial plain, with slopes between 1 and 0.5%, the tributary network density is about 1 per km of contour line. No significant new tributaries originate in this section but existing ones do unite, making the network density much less than in the higher parts. Stream flow in this part is also no longer perpendicular to the contour lines, but follows a meandering or anastomosing pattern.

In the lower part of the alluvial plain, only a relatively small number of streams remain that enter and pass through the swamps of the coastal plain with slopes below 0.5%. Swamps in this area contain mostly eutrophic peat and clays, but some oligotrophic peat formations are also found, indicating permanent stagnant water conditions.

In the eroded Pleistocene terrace, the sequence of hills and valleys is erratic as is the natural drainage network. Only a few medium sized streams like the Río Jiménez, originating from above the alluvial fan, cut through this hilly landscape to unite with other streams in the middle and lower part of the Holocene alluvial plain. Streams in the pronounced valleys are small but mostly permanent. Some valley bottoms are filled with eutrophic peat or small lakes. The natural drainage network in this formation has about the same density as the network of the upper parts of the Holocene alluvial plain.

Figure 2.2 gives a schematic presentation of the typical natural drainage network of the study area.

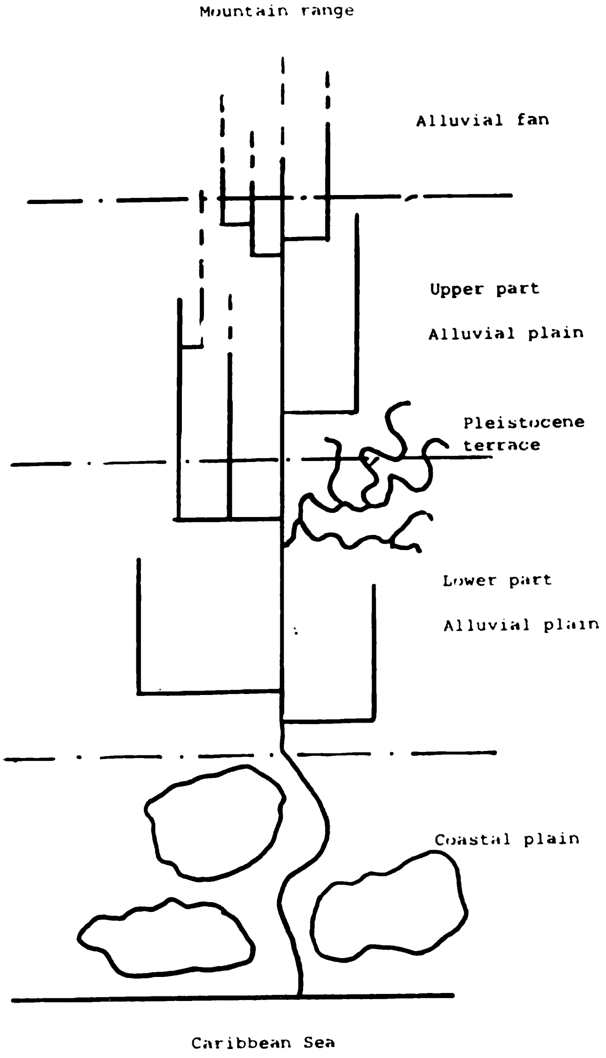


Figure 2.2: Schematic presentation of the natural drainage network of the study area.

2.3. Hydrology and natural drainage.

Natural drainage, or water outflow, is an important component of the hydrological cycle in an area. Other components are rainfall, water inflow, evaporation and water storage.

For every moment in time, the hydrological situation in the study area can by described by means of a water balance:

P + Qin = Ev + Qout ± S (or P - Ev = Qout - Qin ± S)

In which:

P : precipitation or rainfall;
Ev : evaporation from soil, water and vegetation;
Qin : inflow by the rivers and groundwater from higher areas;
Qout : all outflow by major and small rivers and groundwater flow into the sea;
S : change in water storage on and under the surface of the study area;
P -Ev: rainfall surplus.

For the period of one year or a full hydrologic cycle, the change in water storage, S, can often be assumed equal to zero (0). If this is not the case, the study area becomes (gradually) flooded or dryer. For shorter periods, S is not equal to zero: in low areas flooding occurs after heavy rainfall in the uplands. Also the groundwater table during rainy months is higher than in dry months.

A rough estimation of the inflow from upstreams (Qin) into the study area is based on observations of discharge and rainfall in the Toro Amarillo catchment (data from ICE: Instituto Costarricense de Electricidad).

The water balance of the upper part of the Toro Amarillo catchment can be estimated at:

Precipitation	5050 mm/year
Evapotranspiration	1000 mm/year
Total outflow	4050 mm/year

Using these data for total upstream catchments (Río Toro Amarillo, Jiménez and Parismina), estimated at 60.000ha, inflow into the study area would amount to 2,43 x

10^9 m^3/year. A hydrogeological study indicated that part of this volume will enter the study area by means of groundwater seepage into the alluvial fan (de Jong, 1993). On the basis of transport time (see chapter 7), it is estimated that this amount will be less than 5%. The majority of the outflow will be carried by major rivers through the study area toward the sea.

Similarly, the contribution of the study area to total outflow can be estimated at:

Precipitation	4000 mm/year
Evapotranspiration	1250 mm/year
Outflow study area	2750 mm/year

With a total area of about 400.000ha, the outflow amounts to 11.0 x 10^9 m^3/year. Total outflow from the upstream area and the study area is thus estimated at: 13.4 x 10^9 m^3/year. The natural drainage network, described in 2.2 , acts as the main collector system of this outflow. The rainfall surplus (rainfall -evapotranspiration) reaches the collector system by means of direct surface runoff and groundwater flow. Distribution between these two flows is governed by the infiltration capacity of the top soil layer and rainfall intensities. Infiltration capacity depends on soil type and water content in the soil profile. A saturated soil profile cannot absorb any rainfall and surface runoff will occur. Water storage capacity of the soil profile depends on the groundwater table and porosity . The position of the groundwater table is influenced by groundwater flow to the (natural) drainage network. In chapters 3 & 4, the relations between soil properties, groundwater flow and surface runoff are explained and used to analyze field observations made in typical locations of the study area.

Hydrological conditions in a section between two (natural) drains can also be expressed by means of a water balance:

$$P - E = Qsurf + Qground \pm S \quad (mm)$$

P - E represents the rainfall surplus, Qsurf, the surface runoff and Qground, the groundwater flow towards the drains. S represents water storage in the soil profile in the section.

To illustrate the division of surface and groundwater drainage components in different subunits of the study area, estimated water balances are presented (see chapters 4 & 5 for explanation).

A. Alluvial fan and upper part of alluvial plain:

Rainfall	4325 mm	100%
Evaporation	1132 mm	26%
Qsurf	1137 mm	31%
Qground	1858 mm	43%

B. Lower part of alluvial plain:

Rainfall	3714 mm	100%
Evaporation	1278 mm	35%
Qsurf	2162 mm	58%
Qground	274 mm	7%

The extensive drainage network in situation B induces a considerable higher surface runoff as compared to situation A (58 and 31%). Differences in groundwater flow are even more dramatic, 7% compared to 43%.

In the eroded pleistocene landscape the situation compares with situation A regarding drainage density. Natural drains, however, are much deeper, which results in greater storage capacity in the profile. Surface runoff occurs only when rainfall intensity exceeds infiltration capacity in non-saturated conditions.

The water balance on a yearly basis can be estimated at:

Rainfall	4325 mm	100%
Evaporation	1132 mm	26%
Qsurf	217 mm	5%
Qground	2979 mm	69%

In marshy and swamp areas, typical for the coastal plain, the groundwater table is almost permanently at the surface level and storage capacity is negligable. In the water balance for this area, the groundwater component is, apart from the beach ridges, very small. Since this area, under present conditions, is not suitable for agriculture, no measurements regarding quantification of drainage components are taken.

Based on a soil survey conducted by the project, distribution of the areas for which the typical water balances count can be estimated at:

	% of area	Qsurf %	Qground %
Well drained Holocene	41	31	43
Poorly drained Holocene	28	58	7
Eroded pleistocene	15	5	69
Marches and swamps	16	(60)	(4)

() assumption.

These water balances presented for sub-areas should only be taken as indicative and rough estimations (see chapter 4 & 5 for more details). Irregular distribution of soil physical characteristics are inherent to the alluvial soils present in the study area. By measuring hydrological characteristics in cross sections of 100 to 1000m of length, some spatial variations are compensated for.

The water balances presented also neglect losses to the deep groundwater system and the possible contribution by seepage. Seepage might occur, especially in the alluvial fan. Due to large transport distances, losses and seepage related to deep groundwater flow are generally in a much smaller order of magnitude than components of shallow groundwater (see also chapter 7).

Chapter 3

Methodology

3.1. Soil water movement.

To describe mathematically the movement of moisture in the soil, Darcy's law of ground water flow is combined with the continuity equation to obtain the well-known Richard's equation:

$$\frac{\partial\theta}{\partial t}=\frac{\partial\left[K(\psi)\cdot\left(\frac{\partial\psi}{\partial z}-1\right)\right]}{\partial z} \qquad (3.1)$$

with t : time
z : vertical coordinate
ψ : suction head
θ : water content
$K(\psi)$: vertical hydraulic conductivity as a function of suction head

This partial differential equation can be solved using finite difference techniques to simulate soil water contents at different depths as a function of time. Using equation (3.1), one assumes only vertical flow in the soil profile. This flow can be unsaturated or saturated. An important limitation of Richard's equation is that it assumes horizontally homogeneous soils, that is, soils which do not have strong structure or preferential flow paths such as cracks or worm holes.

The most important input parameters for such a model are:

- top boundary condition (rainfall and evapotranspiration);
- bottom boundary condition (groundwater table position, free draining or a flux boundary);
- vertical hydraulic conductivity as a function of suction head (conductivity curve);
- suction head as a function of water content (retention curve).

3.2. Groundwater flow.

Groundwater flow refers to saturated flow below the water table. In this study, it is assumed that there is only horizontal flow (so-called Dupuit-Forchheimer assumption) in one dimension. Again, Darcy's law and the equation of continuity are combined to describe this flow, obtaining the following differential equation (known as the Boussinesq equation):

$$\mu\frac{\partial H}{\partial t}=\frac{\partial\,[K_h H\frac{\partial H}{\partial x}]}{\partial x}+N \qquad (3.2)$$

with t : time
X : horizontal coordinate
H : water table height with respect to an impermeable base
K_h : saturated horizontal hydraulic conductivity
μ : drainable pore space
N : groundwater recharge per unit length

Using a finite difference technique, this equation can be solved to simulate the groundwater table position as a function of time. The important limitation of this model is that it only models horizontal flow in one dimension. This will introduce considerable errors when depth of the impermeable base is very small or when drain spacing is short. In the case of short drain spacings, acceptable results can be obtained with equation (3.2), if the real depth to the impermeable substratum is replaced by a smaller depth (Hooghoudt's equivalent depth) to compensate for the higher resistance due to radial flow near the drains. Another situation where simulation based on equation (3.2) is not suitable arises when the drains are not at all parallel and when different drains are draining water in different directions. This situation causes a two dimensional flow that might still be horizontal.

The most important input parameters for this model are:
- boundary condition (water level in a river or drain);
- drainable pore space;
- saturated horizontal hydraulic conductivity;
- depth to the impermeable substratum;
- distance between two drains or rivers;
- groundwater recharge per unit length.

3.3. Combined soil water movement and groundwater flow.

The ideal situation would be to use a model that computes saturated and unsaturated flow at the same time in two, or even three dimensions. However, many restrictions favor the use of more simplified models as described in sections 3.1 and 3.2. First of all, these models are easier to program and less time consuming when simulating long time series. Moreover, often the ultimate objectives or available data do not justify the use of complex models.

In this study, the models described in section 3.1 and 3.2 are used separately. An important advantage of using a combined model would have been that there was probably no need to calculate excess rainfall separately (see section 3.4).

3.4. Surface runoff and excess rainfall.

Excess rainfall[1] is rainfall which does not infiltrate into the soil and will cause surface runoff (overland flow). Two types of overland flow can be distinguished. *Hortonian overland flow* occurs when rain intensity exceeds soil infiltration capacity, while *saturation overland flow* is produced when rain falls onto saturated soil (Chow, 1988). In Hortonian overland flow, soil is saturated from above by infiltration, while in saturation overland flow it is saturated from below by sub-surface flow. Saturation overland flow occurs most often at the bottom of hill slopes and near stream banks. As in the Atlantic Zone, soil infiltration capacity exceeds observed rainfall intensities for all except the most extreme rainfalls, Hortonian overland flow will rarely occur and most of the surface runoff will be caused by saturation overland flow. This implies that effects of shallow water tables on surface runoff have to be taken into account.

A useful method to estimate excess rainfall is the hydrograph analysis of discharge data for small rivers (or drains). Preferably, these data should be recorded hourly. The volume of excess rainfall is obtained by separating groundwater runoff from the observed hydrograph yielding a direct runoff hydrograph. The area under this direct runoff hydrograph can then be translated into excess rainfall. This excess rainfall is not a constant, but will depend on rainfall characteristics and antecedent soil moisture conditions. Consequently, several hydrographs recorded under different conditions must be available. Analysed watersheds should be small and homogeneous, to assure that excess rainfall shows little spatial variability within the watershed.

For drainage basins where no sufficient discharge data exist, infiltration models or the curve number method may be used to estimate the amount of excess rainfall.

Infiltration model.

To estimate excess rainfall with an infiltration model some information about rainfall intensities is indispensable. Data from the National Meteorological Institute available for the station 'El Carmen', located north of Siquirres, were analysed. For two

---

[1] The expression "excess rainfall" is used in hydrology to indicate rainfall that does not infiltrate; the term "rainfall surplus" is used in agronomy to indicate the difference between rainfall and evapotranspiration of the crop system.

years (1987-1988), maximum rainfall intensities were determined for a 5 and 15 minute period (table 3.1).

Table 3.1: Number of days (during two years) that the highest rainfall intensity (f) occurring in five and fifteen minutes exceeded a specified value.

Station: El Carmen
Period: 1987-1988
Number of days with rain: 467 days

5 minutes		15 minutes	
f(mm/h)	days	f(mm/h)	days
30≤f<60	84	20≤f<40	75
60≤f<120	52	40≤f<60	38
120≤f<180	4	60≤f<80	8
f ≥ 180	0	f > 80	9

The infiltration model LEACHM (Wagenet & Hutson, 1989) was used to simulate soil water movement as described in section 3.1. When using free draining or a groundwater table as a bottom boundary, the model assumes that the underlying groundwater system can discharge any amount of percolated water (in other words, there is no restriction on the flux calculated at the bottom boundary of the soil profile). When the soil profile becomes saturated, the infiltration capacity computed with the model will equal the saturated hydraulic conductivity of the soil. As the saturated hydraulic conductivities for most of the investigated soils were high (mostly between 2 and 20 cm/hr), almost all the rain, even with high intensity, would infiltrate into the soil, under the previous described bottom boundary condition. However, the local groundwater systems in the study area often have restricted storage capacity (except under the pleistocene eroded soils) and this may reduce infiltration capacity significantly. Observation of discharges after heavy rains confirms that there is a significantly quick response in river runoff, indicating that an important amount of rainfall was not infiltrating into the soil (de Jong, 1993). Unfortunately, the LEACHM model does not have the option of a flux boundary as bottom boundary, the flux being calculated with a groundwater flow equation or model.

Curve number method.

This method, developed by the US Soil Conservation Service, was originally designed for conditions prevailing in the United States, and was later tested in other regions. The rainfall-runoff relation developed is an empirical one which, nevertheless, has a conceptual basis. The relationship allows for the determination of direct runoff response from rainfall depth depending on maximum possible retention.

Daily excess rainfall (or direct runoff) is related to the amount of daily rainfall:

$$Q=\frac{(R-cS)^2}{R+(1-c)S} \tag{3.3}$$

with Q = total volume of direct runoff (mm)
R = total volume of rainfall (mm)
S = potential maximum retention (mm)
c = coefficient relating initial abstraction of rainfall (I_a)
with S: $I_a = c\,S$

The initial abstraction I_a consists mainly of interception, infiltration and surface storage, all of which occur before runoff begins. Originally, calibration of rainfall and runoff data from experimental small drainage basins in the United States yielded c=0.2. Later research revealed that for most drainage basins the c-value should be taken closer to 0.1 (Schmidt & Schulze, 1987).

The potential maximum retention S depends on drainage basin characteristics and antecedent moisture conditions. Instead of using the parameter S, the curve number (CN) is used as the independent variable:

$$CN=\frac{25400}{254+S} \tag{3.4}$$

The value of CN depends on.

- land use or cover (fallow, pasture, forest, row crops, ...);
- treatment practice (straight row, contoured or terraced);
- hydrologic condition (primarily determined by the density of vegetation);
- soil condition (determined by infiltration rate and permeability rate of the soil);
  highest infiltration rate: hydrologic soil group A

lowest infiltration rate: hydrologic soil group D
- antecedent moisture condition.

The U.S. Soil Conservation Service composed a table (Boonstra, 1987; Schmidt & Schulze, 1987) with CN-values for different combinations of basin characteristics and for average moisture conditions (CN-II). The following algebraic expressions can be used to adjust the CN-value from the average to wet (CN-III) and dry (CN-I) antecedent moisture conditions:

$$\text{CN-I} = \text{CN-II}/(2.334 - 0.01334\ \text{CN-II}) \tag{3.5}$$

$$\text{CN-III} = \text{CN-II}/(0.4036 + 0.0059\ \text{CN-II}) \tag{3.6}$$

According to Schmidt & Schulze (1987) a wet condition corresponds to a soil at field capacity, a dry condition to a soil at wilting point and a normal condition to a soil where half of the 'available moisture' is exhausted.

Since the wet condition prevails in the Atlantic Zone of Costa Rica, it was decided to calibrate soil moisture conditions with the CN-value for wet conditions (CN-III). A CN-II value is chosen for the given basin characteristics. This value is then converted into the corresponding CN-value for wet conditions using equation (3.6). The corresponding maximum potential retention S-III for wet conditions is calculated with equation (3.4).

Soil water balance.

The curve number method is combined with the groundwater flow model (section 3.2) and a simplified soil water balance to enable the calculation of changes in the maximum potential retention, S, with respect to the S-III value. The value of S can increase due to evapotranspiration of soil water at the top and drainage of soil water at the bottom of the profile, while water infiltrating at the top of the profile will decrease the value of S. The lowest value allowed for S is S-III.

The S-III value is calibrated under soil moisture conditions in the Atlantic zone by means of the infiltration model LEACHM and using soil physical data as described in section 4.3. Starting with a completely saturated soil one meter deep and assuming a fixed water table depth of 1.5m as bottom boundary condition, the amount of water drained from the soil at different time intervals was calculated. The assumption was made that the soil is at 'wet condition', and consequently, the maximum potential retention equal to S-III, after one day of drainage. The amount of water drained during the second day, the third day and so on, will be called the additional amount of water drained and will increase the maximum potential retention, S.

During dry periods and when the groundwater table is lower than one meter, the maximum potential retention S-III of the soil increases due to the additional amount of water drained from the soil and the amount of soil water evapotranspirated. The final value of the maximum potential retention will depend on the number of days the dry period lasted. This S-value is used (equation 3.3) to calculate excess rainfall for a given amount of rainfall. When the groundwater table is less than one meter deep, it is assumed that due to capillary rise, the soil will be constantly wet (no additional water drainage from the soil). In this case, the maximum potential retention S-III is only increased with the amount of soil water evapotranspirated during the dry period.

When the groundwater table is between 10 cm and 50 cm deep, the same procedure is followed but with a CN-II value corresponding to a hydrologic soil group one unit lower, and if the groundwater table is less than 10 cm deep, with a CN-II value corresponding to a hydrologic soil group two units lower. CN values of lower hydrologic soil groups are used to compensate for the reduced permeability rate due to the high water table position. In the last two cases, the CN-II values are again adjusted to CN-III values first, and then converted to the corresponding S-III values.

Chapter 4

Analysis of observations.

4.1. Introduction.

The basic concepts of surface runoff, soil water movement and groundwater flow, explained in chapter 3, are used to analyse the results of field observations, conducted in four different pilot areas. The drainage conditions of these pilot areas are considered to be representative for substantial parts of the different hydrologic units as described in chapter 2. Nevertheless, high variations in soil profiles can be expected within each unit (e.g. occurence of sedimented lahar flows at less than 3m depth).

The soil profile in the northern part of Los Diamantes banana plantation consists of sandy loam, with layers of loamy sand, sand and stones, up to a depth of 2.5m. The groundwater table is usually found between 1 and 2 m below the surface. This profile is assumed to represent the alluvial well drained soils.

Two locations, Quatro Esquinas and Lomas de Sierpe, represent poorly drained alluvial soils. In Quatro Esquinas, the soil profile consists of loamy and sandy loamy layers up to 2.2m, followed by an impermeable layer of variable thickness. Some old river beds filled with sand are found. The groundwater table is present within 1m. At Lomas de Sierpe, no impermeable layers are found, but the texture of the soil layers often includes more clay. At these locations, piezometer observations were combined with measurements of soil physical characteristics.

A different approach was used for the eroded Pleistocene landscape. Together with the soil conservation programme of FAO and MAG, 20x7m erosion plots were installed in the Neguev settlement on slopes between 10 and 30 %. Rainfall, runoff and soil losses were measured. Deep profiles of medium and heavy textured soils are found, while the groundwater table is always below 5 m.

4.2. Surface runoff from eroded hills (pleistocene soils).

Non-fertile, well drained soils are located on dissected terrace remains and have deep groundwater tables. As soil erosion might be an important cause of nutrient losses, 20x7m plots were installed on these soils to measure surface runoff and soil erosion (carried out in cooperation with the soil conservation program of FAO/MAG). Plots were installed under palm hearts, pineapples and grassland. Due to problems with the automatic measurement equipment, only rainfall-runoff data are available for the plot under palm hearts. This plot has a slope of ±20%. The infiltration capacity of this soil can be estimated from physical soil data (aHpe soiltype in Weitz, 1992). The lowest infiltration rates (at saturation) are between 10 and 15 cm/hr. Under these conditions, i.e. high infiltration capacity and deep groundwater table, little surface runoff is to be expected. A total rainfall of 403 mm, observed from the beginning of November until the beginning of January, caused 3.6 mm surface runoff, which is less than 1%. A similar ratio exists between daily rainfall and daily surface runoff (see figure 4.1).

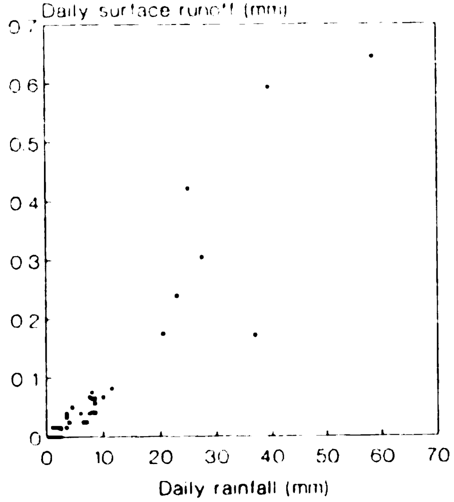


Figure 4.1: Daily surface runoff as a function of rainfall, measured on non-fertile soils under palm heart.

Manual measurements indicate that surface runoff on the soil under pasture is greater than under palm heart (approximately 6 times).

From June until September, approximately 123 kg soil per ha was lost under palm heart. These provisional data are comparable with results obtained from erosion plots installed close to Puriscal (Vahrson & Cervantes, 1991): runoff under coffee ± 1%, runoff under grassland ± 2.5%, soil losses under coffee (without shadow) 168 kg/ha, under grassland 340 kg/ha. Results can also be compared with observations near Turrialba (Tineo, 1993): runoff lower than 1%.

A curve number can be estimated for the soiltype under palm heart, based on observed surface runoffs. As daily rainfall amounts up to 58.5 mm are causing very little surface runoff, the CN-II value will be less than 50 and probably very small.

For grassland, the CN-value might be slightly higher. To specify this value more precisely, observations during higher daily rainfall periods are needed. As these soils have high infiltration capacities and are located on hills with deep groundwater tables, both Hortonian overland flow and saturated overland flow will rarely occur.

4.3. Physical soil data.

Models for simulation of water transport in soil need data about the conductivity curve and the retention curve (see section 3.1). The one-step-outflow method combined with the column method was used in the Atlantic Zone Program to establish functions describing these two curves. Functions as proposed by van Genuchten (1980) were used. For more information on this method, the reader is referred to Booltink et al, 1991 (a&b).

The equation used for the retention curve is:

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + (\alpha * \psi)^n)^m} \tag{4.1}$$

The equation used for the conductivity curve is:

$$K(\psi) = K_s * \frac{[((1 + (\alpha * \psi)^n)^m) - (\alpha * \psi)^{(n-1)}]^2}{(1 + (\alpha * \psi)^n)^{(m \cdot (\gamma + 2))}} \tag{4.2}$$

and: $m = (1 - \frac{1}{n})$

with θ_s : saturated volumetric water content [$\text{cm}^3.\text{cm}^{-3}$]
θ_r : residual volumetric water content [$\text{cm}^3.\text{cm}^{-3}$]
$\theta(\psi)$: actual volumetric water content [$\text{cm}^3.\text{cm}^{-3}$]
K_s : saturated hydraulic conductivity [cm.hr^{-1}]
$K(\psi)$: actual conductivity [cm.hr^{-1}]
ψ : suction head [cm]
α, γ, n : fitting parameters

Van Genuchten parameters were determined for the three major soil types. Data obtained for the fertile/well drained soils can be found in Weitz(1992) and Leummens(1993), data for the non-fertile/well drained soils in Weitz (1992), and data for the poorly drained soils in Mantel (1993). For the well drained soils, data are available for different soil use types, while for the poorly drained soils, only data for soils under pasture are available. One parameter set for each of the three major soil groups is shown in table 4.1. The corresponding conductivity and retention functions are presented in figure 4.2 and 4.3. These graphs do not reflect the difference between the three major soil groups, as could be wrongly interpreted, because variations within each of these three soil groups were greater than differences observed in the graphs. Land use type and reclamation history appeared to have more effect on soil physical characteristics than soil type did.

Saturated vertical hydraulic conductivity was relatively high at most of the sites. Most of the observed K_s-values were between 2 and 20 cm/hr (≈0.5 and 5 m/day). As a consequence, most of the time the final infiltration rate is greater than 20 mm/hr, unless a very shallow water table limits infiltration.

It should be noted that the van Genuchten parameters, as they were calculated up to now, turned out to be not very suitable to describe the conductivity and retention curve for soiltypes encountered in the Atlantic Zone (Leummens, 1993). This could be due to the volcanic origin of the soils. One of the consequences is that equation (4.2) underestimates hydraulic conductivity in the wet range (at least for suction heads between 0 and 10 cm).

Table 4.1: Van Genuchten parameters (see equation 4.1 and 4.2).

(1): fertile/well drained soil under bananas (Weitz, 1992: sample eHpe A)
(2): non-fertile/well drained soil under palm heart (Weitz, 1992: sample aHpe A)
(3): fertile/poorly drained soil under pasture (Mantel, 1993: sample 2-A2)

	θ_s	θ_r	K_s	α	n	γ
(1)	0.68	0.334	12.8	0.0451	1.5446	1.570
(2)	0.65	0.002	12.6	0.0127	1.1654	25.052
(3)	0.73	0.010	19.5	0.0149	1.2349	29.110

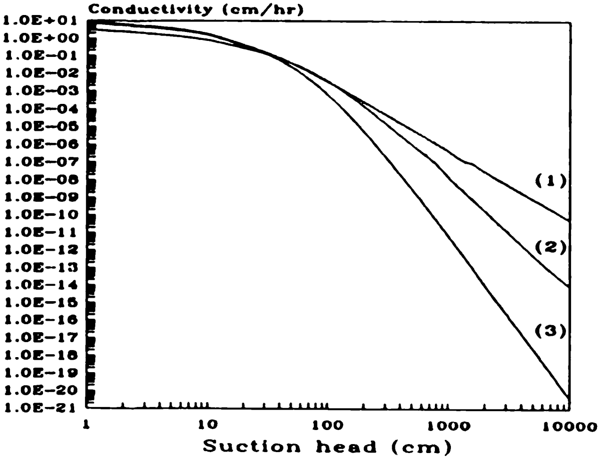


Figure 4.2: Conductivity curves (see data in table 4.1).

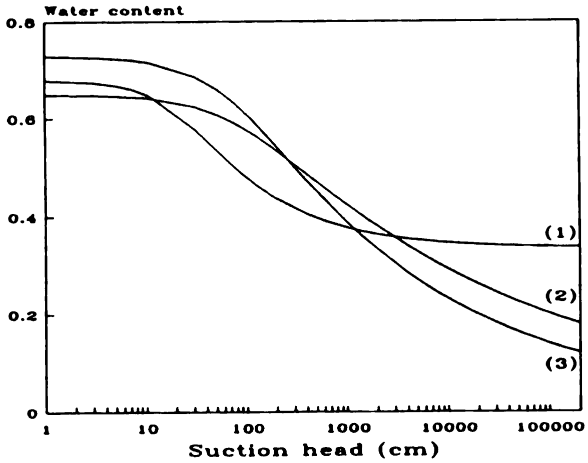


Figure 4.3: Retention curves (see data in table 4.1).

(1) - fertile/well drained soil
(2) - non-fertile/well drained soil
(3) - fertile/poorly drained soil

4.4. Phreatic aquifer data.

4.4.1 Parameters.

A numerical solution of equation (3.2) will be used to fit parameters to observations and to forecast effects of drainage on the groundwater table position. Each of the parameters needed will be briefly discussed.

Drain spacing (L).
This is the distance between two parallel drains or rivers. As the model used is only one-dimensional, the effect of non-parallel smaller drains located between these two drains can not be simulated. The boundary conditions for equation (3.2) are fixed water table heights at x=0 and at x=L (water level in drain 1 and drain 2).

Aquifer depth (D).

The water table height (H) in equation (3.2) is relative to an impermeable layer. When studying the effects of drains, it is convenient to split the water table height into an aquifer depth (D) and a water table head (h): H = h + D. The aquifer depth is the part of the aquifer below the drain level up to an impermeable layer, while the water table head is the part of the aquifer above the drain level. As mentioned in section 3.2, the depth D is replaced with a smaller equivalent depth (d) to correct for radial flow between the two drains. The following analytical expression can be used to calculate the equivalent depth (Smedema and Rycroft, 1983):

$$d=\frac{D}{\frac{8D}{\pi L}\ln\frac{D}{u}+1} \qquad (for\ D<\tfrac{1}{4}L) \tag{4.3.a}$$

and

$$d=\frac{\pi L}{8\ln\frac{L}{u}} \qquad (for\ D>\tfrac{1}{4}L) \tag{4.3.b}$$

with D : real aquifer depth (m)
L : drain spacing (m)
u : wetted perimeter of the drain (m)

Equation (4.3.b) shows that when the impermeable layer is very deep, the equivalent depth only depends on drain spacing (L) and wetted perimeter (u). This means that from a specific depth, the impermeable layer no longer influences the general flow pattern toward the drains (see figure 4.4).

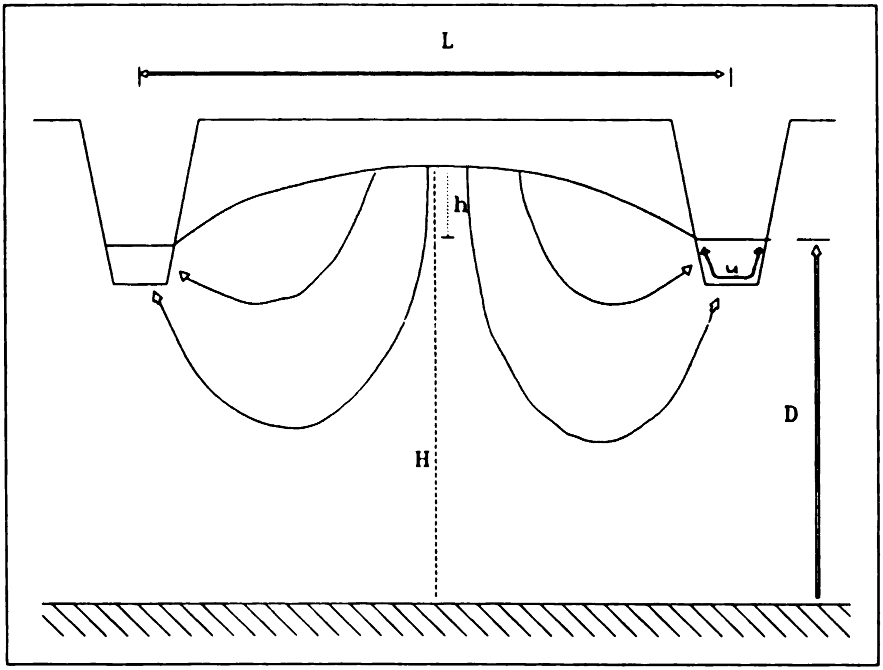


Figure 4.4: Flow pattern toward drains illustrating the case where the impermeable layer does not influence the flow pattern and the equivalent depth may be calculated with equation (4.3.b).

Saturated horizontal hydraulic conductivity (K_h).

Horizontal saturated hydraulic conductivity can be determined by the augerhole method, which is a useful method in the case of a shallow water table. Due to the variability of the soil, this hydraulic conductivity can vary between the two drains. As the numerical solution used assumes a constant K_h between the two drains, an average of the different measured K_h values is used.

Transmissivity (T).

The product of saturated hydraulic conductivity and total aquifer thickness, K_h*H, is called the transmissivity of the aquifer. Equation (3.2) shows that the transmissivity and the slope of the water table determine the flow toward the drains. This implies that aquifers with the same transmissivity have similar drainage possibilities. For phreatic aquifers, the transmissivity is not a constant because of the variability of the water table. If the flow above the drain level is small compared to the flow below the drain level (i.e. $h << d$), the transmissivity can be approximated by $K_h * d$.

Drainable pore space (μ).

The pore space which drains/fills with a fall/rise of the water table is called the drainable pore space. The μ-value is expressed as a percentage and is the ratio between pore water drained or added (Δ w) and the resulting change in water table head (Δ h):

$$\frac{\Delta w}{\Delta h}\cdot 100 = \mu(\%) \tag{4.4}$$

Indicative values according to Smedema and Rycroft, 1983 are:

- dense clay	$\mu = 1 - 2$ %
- well structured loams, clay loams and clays	$\mu = 4 - 8$ %
- fine sand	$\mu = 15\text{-}20$ %
- coarse sand	$\mu = 25\text{-}35$ %

When the retention function is available, the μ-value can be estimated by calculating the equilibrium soil moisture profile for two different water table positions. The area between the two soil moisture profiles equals the drainable pore space (figure 4.5).

The μ-value is not a constant, but varies slightly with the starting water table depth and the magnitude of change of water table head. Also the water table often changes before the soil moisture profile reaches an equilibrium. Moreover, the μ-value varies also from point to point due to the lack of homogeneity of the soil between the drains. In this study, a groundwater flow model was used to calibrate the μ-value by fitting simulated water table heads with observed heads between two drains.

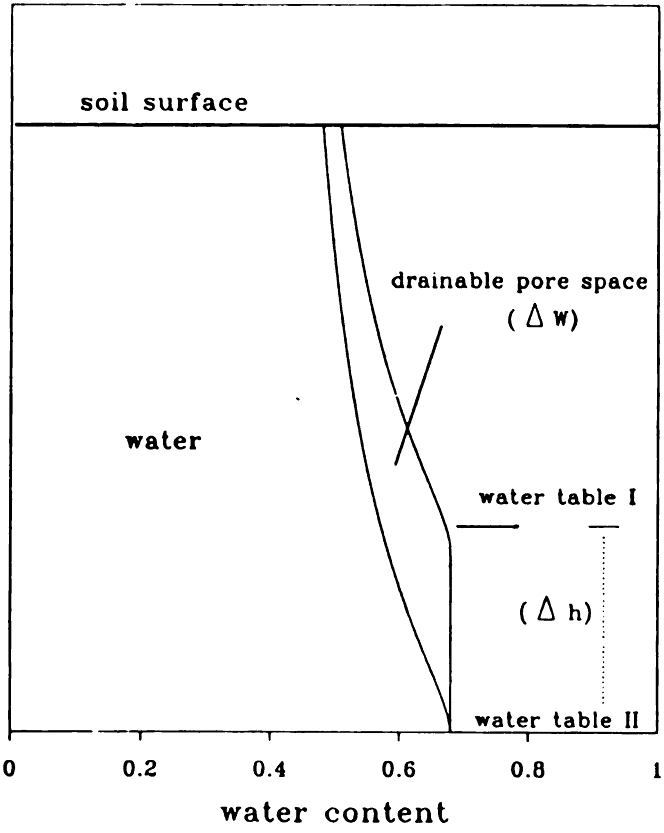


Figure 4.5: Concept of drainable pore space.

Groundwater recharge (N).

Water that infiltrates into the soil profile in excess of the storage capacity will recharge the groundwater. The amount of water infiltrated into the soil is calculated by abstracting excess rainfall (CN-method) from rainfall. When the soil water reservoir is at field capacity all infiltrated water percolates to the groundwater system. If, however, the soil water reservoir is below field capacity, part of the infiltrated water is used to bring the soil water content up to field capacity. Evapotranspiration is taken from the soil water unless the water table is very shallow. In this case, part of the evapotranspiration comes from the groundwater system and is considered as a negative groundwater recharge.

4.4.2. Observations and interpretation for well drained and poorly drained soils.

A. The following measurements were done in the locations mentioned in section 4.1:

Los Diamantes (LD):

1) observation of water levels in 3 piezometers between two drains (drain spacing: 100m) during 32 days (Aalbers, 1993);
2) augerhole method in each piezometer (Aalbers, 1993);
3) crust method and one-step-outflow method at one location (Weitz, 1992);

Quatro Esquinas (QE):

1) observation of water levels in 7 piezometers between two rivers (distance: 2000m) during 4 months (Maebe, 1992);
2) augerhole method along the transsect, at an interval of ± 150m (Mantel, 1993);
3) crust method and one-step-outflow method at 3 locations (Mantel, 1993);

Lomas de Sierpe (LS):

1) observation of water levels between two drains at 3 sites during 17 days (Aalbers, 1993):
   site 1 (LS1): 3 piezometers, drain spacing = 100m,
   site 2 (LS2): 3 piezometers, drain spacing = 58m,
   site 3 (LS3): 3 piezometers, drain spacing = 128m;
2) augerhole method in each piezometer of site 2 and 3, no observations at site 1 (Aalbers, 1993);

B. Input data used to fit aquifer parameters to observed water levels:

Los Diamantes:

- daily rainfall observed at Los Diamantes;
- daily evapotranspiration: was set equal to 3.1 mm/day in accordance with average daily potential evapotranspiration for Los Diamantes as calculated by Castro (1985);
- CN-II=62 (CN-II=71 for water tables between 10 and 50cm deep and CN-II=78 for water tables less than 10cm deep);
- initial abstraction coefficient c = 0.1;
- maximum potential retention S was calibrated to soil moisture conditions using data set 1 of table 4.1;

- drain spacing, drain depth and K_h: see table 4.2.

Quatro Esquinas:

- daily rainfall observed at banana plantation Banagro;
- daily evapotranspiration: was set equal to 3.5 mm/day in accordance with average daily potential evapotranspiration for Siquirres as calculated by Castro (1985);
- CN-II=68 (CN-II=79 for water tables between 10 and 50cm deep and CN-II=86 for water tables less than 10cm deep);
- initial abstraction coefficient c = 0.15;
- maximum potential retention S was calibrated to soil moisture conditions using data set 3 of table 4.1;
- drain spacing, drain depth and K_h: see table 4.2;
- aquifer depth d = 2m.

Lomas de Sierpe:

- daily rainfall observed at banana plantation Lomas de Sierpe;
- daily evapotranspiration: was set equal to 3.5 mm/day (see Quatro Esquinas);
- CN-II=62 (CN-II=71 for water tables between 10 and 50cm deep and CN-II=78 for water tables less than 10cm deep);
- initial abstraction coefficient c = 0.1;
- maximum potential retention S was calibrated to soil moisture conditions using data set 3 of table 4.1;
- drain spacing, drain depth and K_h: see table 4.2.

C. Discussion:

A constant daily evapotranspiration was used because fluctuations are generally not significant for the calculation of groundwater flow. The potential evapotranspiration was used because it is assumed that, due to the humid climate, actual evapotranspiration is often close to the potential.

The curve number selection was based on row crops as land use, except for Quatro Esquinas where pasture with poor hydrologic conditions was chosen, and on hydrologic soil group A . This soil group stands for soils having a final infiltration rate ≥ 25 mm/h and a permeability rate > 7.6 mm/h (Schmidt & Schulze, 1987). A higher initial abstraction coefficient was chosen for Quatro Esquinas to compensate for higher depression storages. The selection of an appropriate CN-value is very difficult when runoff data are not available; thus the presented CN-values should be considered as a first approximation.

Saturated horizontal hydraulic conductivity was based on augerhole observations except at site 1 of Lomas de Sierpe, where the K_h value was chosen arbitrarily.

There was no clear presence of an impermeable layer at Lomas de Sierpe or at Los Diamantes. For this reason, the aquifer depth was determined by model calibration. Normally, the aquifer depth obtained with calibration should be at most equal to the equivalent depth calculated with formula (4.3.b). A slightly greater value was allowed if this improved calibration: first, because of the uncertainty in the choice of the wetted perimeter value in equation (4.3.b) and second, if hydraulic conductivity was underestimated, an increase in the value of the aquifer depth would compensate this. For Quatro Esquinas, the aquifer depth was set equal to 2m since field observations revealed the presence of a less permeable layer at a depth of approximately 2m at most of the observed points in the cross section. This less permeable layer is not continuous over the whole cross section because at some points it is interrupted by old river beds filled up with coarse sand.

Drain spacing and drain depth are measured values except at Quatro Esquinas where the natural drain distance was set arbitrarily at 400m and drain depth at 1.5m. These values were chosen to take into account groundwater flow toward gullies. It should be noted that under these conditions, the amount of groundwater flow is relatively small and that fluctuations in the water table are caused mainly by evapotranspiration. This also implies that better simulations could probably be obtained by using an evapo-transpiration model.

D. Calibration and results:

The observed water table heads were fitted with simulated water table heads to calibrate aquifer data (drainable pore space, μ, and aquifer depth, d). This is done by repeating the simulations with different values for μ and d, until an acceptable agreement is obtained between simulated and observed water tables. At Quatro Esquinas, only the value of μ was calibrated with the model.

Phreatic aquifer data, obtained from field observations and model calibrations are shown in table 4.2. Simulated water table heads are compared with observed heads in figures 4.6 to 4.10.

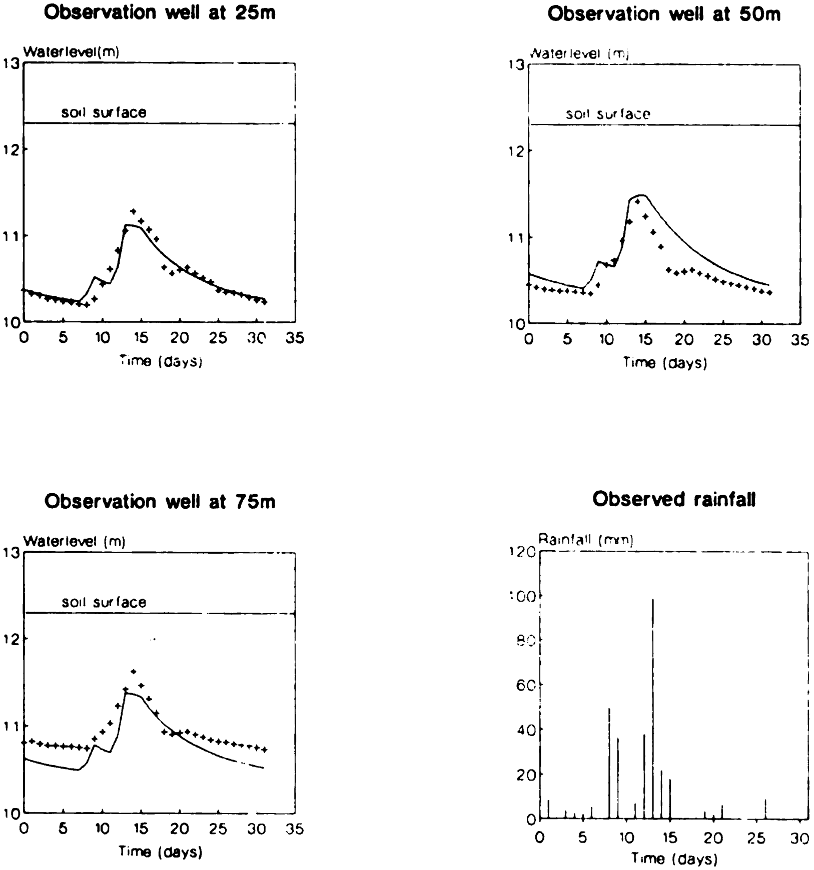
The advantage of model calibration to determine aquifer data is that the heterogeneity of hydraulic conductivity and aquifer depth between the two drains can be combined in one transmissivity value. Therefore, transmissivity values in table 4.2 are more important than the K_h values or equivalent depth values alone. The small equivalent depth (1.3m) obtained for site 2 of Lomas de Sierpe could be an indication that K_h was over-estimated, as there was no clear evidence of an impermeable layer within the first four meters.

At Quatro Esquinas, the simulated water levels were compared with water levels observed in the wet part of the cross section (at least 250m away from the main rivers). To simulate water levels close to the main rivers (the well drained part of the cross section), other aquifer data must be used.

Table 4.2: Phreatic aquifer data obtained for three sites at Lomas de Sierpe (LS), one site at Quatro Esquinas (QE) and one site at Los Diamantes (LD).

L: drain spacing (m);
W: drain depth (m);
d: equivalent aquifer depth (m);
K_h: saturated horizontal hydraulic conductivity (m/day);
T: transmissivity, $=K_h*d$ (m^2/day)
μ: drainable pore space (%)

	LS1	LS2	LS3	LD	QE
L	100	58	128	100	400
W	2.3	2.0	1.0	2.3	1.5
d	5.0	1.3	8.0	10	2.0
K_h	2.0	1.25	2.4	1.65	3.0
T	10	1.63	19.2	16.5	6
μ	5	1	4	13	5


Observation well at 25m

Observation well at 50m

Observation well at 75m

Observed rainfall

Figure 4.6: Simulated water levels (——), observed water levels (+) and rainfall at Los Diamantes. Water level heights are relative to the "equivalent" impermeable layer and the well location is relative to one drain.

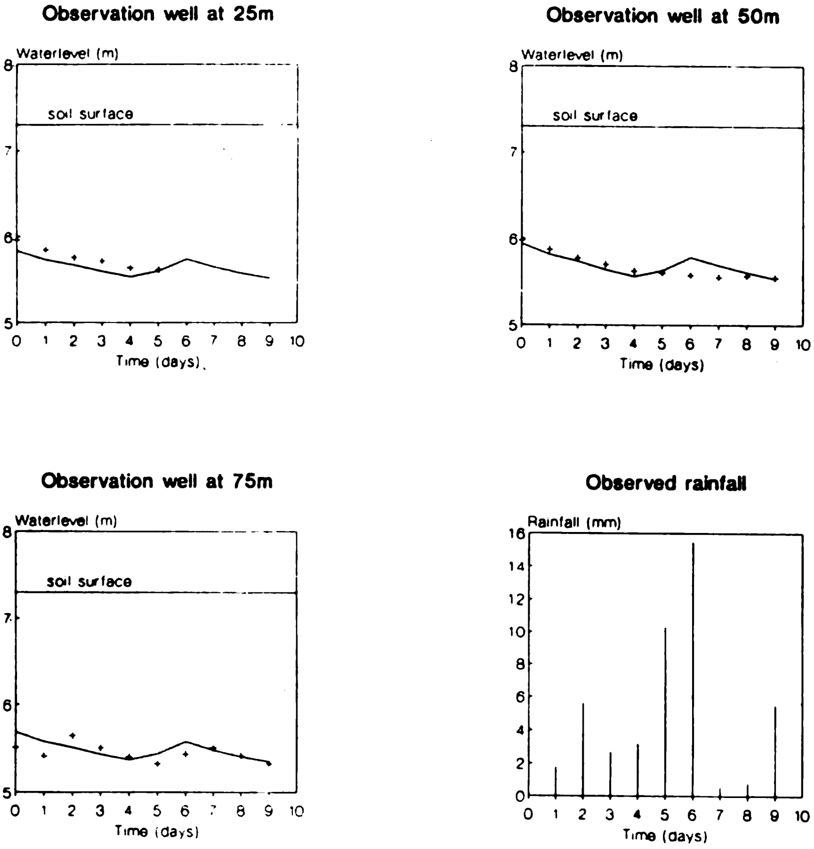


Figure 4.7: Simulated water levels (——), observed water levels (+) and rainfall at Lomas de Sierpe (site 1). Water level heights are relative to the "equivalent" impermeable layer and the well location is relative to one drain.

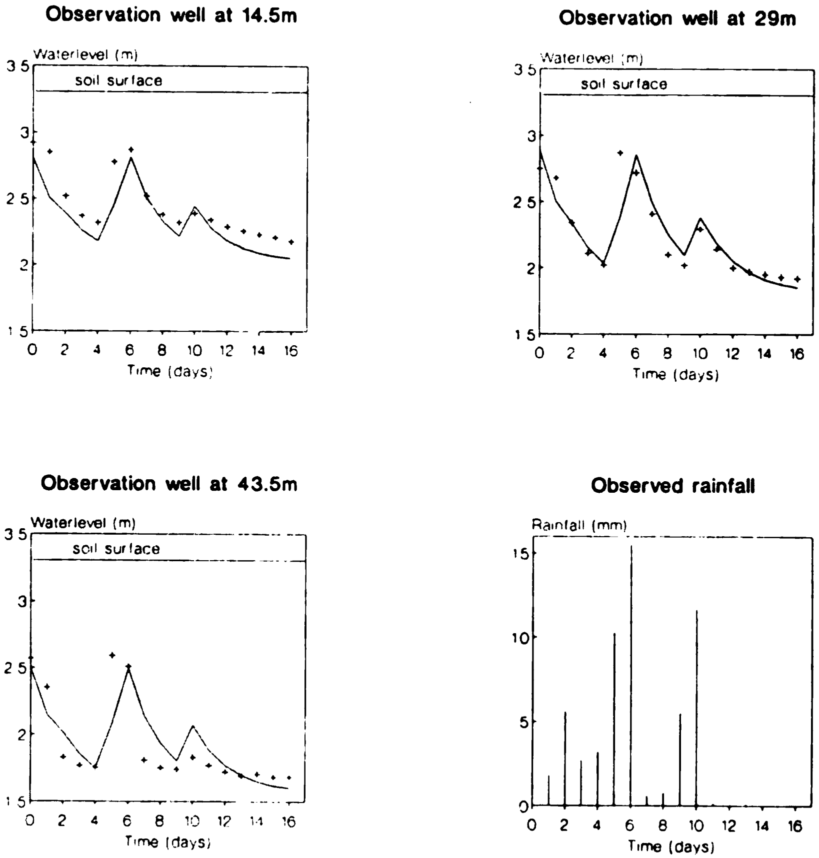


Figure 4.8: Simulated water levels (——), observed water levels (+) and rainfall at Lomas de Sierpe (site 2). Water level heights are relative to the "equivalent" impermeable layer and the well location is relative to one drain.

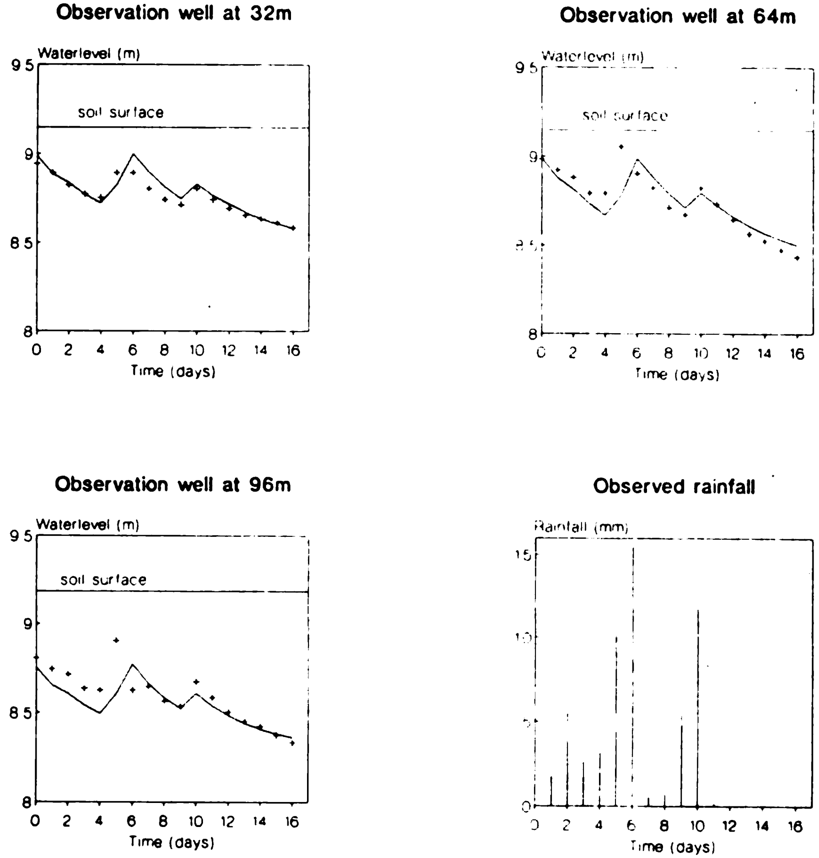


Figure 4.9: Simulated water levels (——), observed water levels (+) and rainfall at Lomas de Sierpe (site 3). Water level heights are relative to the "equivalent" impermeable layer and the well location is relative to one drain.

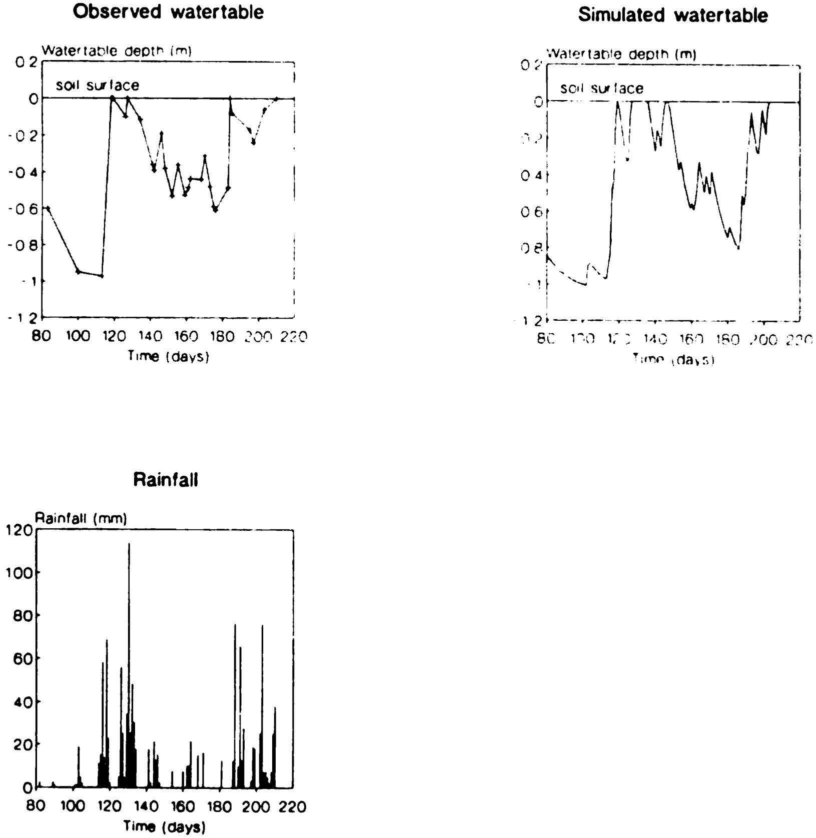


Figure 4.10: Simulated water levels (——) and observed water levels (+) at Quatro Esquinas. Observed water levels correspond to the levels observed in well #5 of Maebe, 1992. Rainfall was observed at Cobal's Banagro banana plantation. Water levels are relative to the soil surface.

4.5. Discussion and conclusions.

Soil physical data and phreatic aquifer data were collected at different sites to evaluate drainage possibilities in the Atlantic zone. Values for vertical hydraulic conductivity indicate soils with high infiltration rates. Transmissivity values of the phreatic aquifers are reasonably high in most cases. The most important reason why some soils in the Atlantic zone are poorly or insufficiently drained is because of the relatively great distance between natural drains. High infiltration rates and transmissivities also indicate that drainage improvement with groundwater drainage systems (deep ditches or pipe drains) is feasible.

In some cases the transmissivity value of the phreatic aquifer is relatively low, very often caused by a shallow impermeable layer. This was clearly the case at Quatro Esquinas. In this case, relatively short drain spacings (<50m) will be necessary to obtain a good groundwater drainage system.

The phreatic aquifer data (i.e. transmissivity and drainable pore space) presented in table 4.2 can be used as indicative values. These data are used in chapter 5 to simulate fluctuations of the water table over extended periods. This simulation will be repeated for different drainage scenarios, to eventually determine the effects of drainage. Data obtained for site 1 of Lomas de Sierpe will not be used since hydraulic conductivity was not determined in the field, but obtained from model calibration.

Chapter 5

Simulation of water table fluctuations.

5.1. Introduction.

The groundwater flow model, combined with the curve number method and a simplified soil water balance (chapter 3), enables the simulation of the water table over an extended period on the basis of available rainfall and evapotranspiration data. Water table hydrographs can be developed for, say, a 10 year period, using historical weather data for a range of different drainage design scenarios. These results may then be used in a crop growth simulation model to investigate the effects of improved drainage on crop production. Phreatic aquifer data from table 4.2 are used for the simulation of different scenarios. Simulation results obtained with the aquifer data for Los Diamantes are assumed to represent most of the well drained soils. Simulation results for site 2 of Lomas de Sierpe can be used for poorly drained soils with low transmissivity (T = 1-4 m^2/day, clayey soils or soils with an impermeable layer at a depth of less than four meters), while results for site 3 of Lomas de Sierpe can be used for poorly drained soils with reasonably high transmissivity (T = 10-20 m^2/day, loamy soils or soils with an impermeable layer at a depth of more than four meters).

5.2. Drainage scenarios.

Initially, all simulations with artificial drains were done with a drain depth of 1.5m. This value is probably more appropriate for drains with a spacing of 50m. Nevertheless, this value is also used for drains with a spacing of 100m, since it is possible to examine the `true´influence of drain spacing on drain efficiency only when using the same drain depth. Some simulations with different drain depths were also done.

The equivalent aquifer depth, d, was adapted for each situation to drain spacing with equation (4.3). An average wetted perimeter of 1.3m was used for ditch systems. Note that this implies a water depth of about 30 cm below the assumed drainage depth.

Well drained soils. Water table hydrographs were simulated for a 10 year period with the phreatic aquifer data for Los Diamantes (LD) and with rainfall data from the Los Diamantes meteorological station. Evapotranspiration and curve number value were chosen as described in section 4.4.2. Three different scenarios were simulated:

- natural condition with an average river distance of 300m and an

average river depth of 2.5m;
- drained condition with a drain spacing of 100m and a drain depth of 1.5m;
- drained condition with a drain spacing of 50m and a drain depth of 1.5m;

Poorly drained soils. Simulations are done for a 10 year period with rainfall data for the La Mola meteorological station. Again, evapotranspiration and curve number value are chosen as in section 4.4.2. Phreatic aquifer data for site 2 and site 3 of Lomas de Sierpe (LS2 and LS3) were used to simulate drained conditions. The different scenarios simulated were:
- drained condition with a drain spacing of 100m and a drain depth of 1.5m;
- drained condition with a drain spacing of 50m and a drain depth of 1.5m;
- drained condition with a drain spacing of 25m and a drain depth of 1.5m (only for LS2);
- drained condition with a drain spacing of 100m and a drain depth of 2m (only for LS2);
- drained condition with a drain spacing of 50m and a drain depth of 2m (only for LS2);
- drained condition with a drain spacing of 30m and a drain depth of 2m (only for LS2);

Phreatic aquifer data for Quatro Esquinas (QE) were used to simulate the natural condition: gully distance of 400m and a depth of 1.5m.

5.3. Simulated water table fluctuations.

As an example, figure 5.1 shows rainfall for 1983 and corresponding water table fluctuations for well drained soils of Los Diamantes with drains at 100m and at 1.5m depth. Note the typical difference in rainfall distribution in the first and second half of the year.

The water table fluctuations for all the different scenarios are summarized in frequency tables (table 5.1 to 5.4). The groundwater level on a specific day is not a constant between the two drains, but has a parabolic curvature (see also figure 4.4). Therefore, the average water level (WTa) and the mid-spacing water level (WTm) are used in the frequency tables.

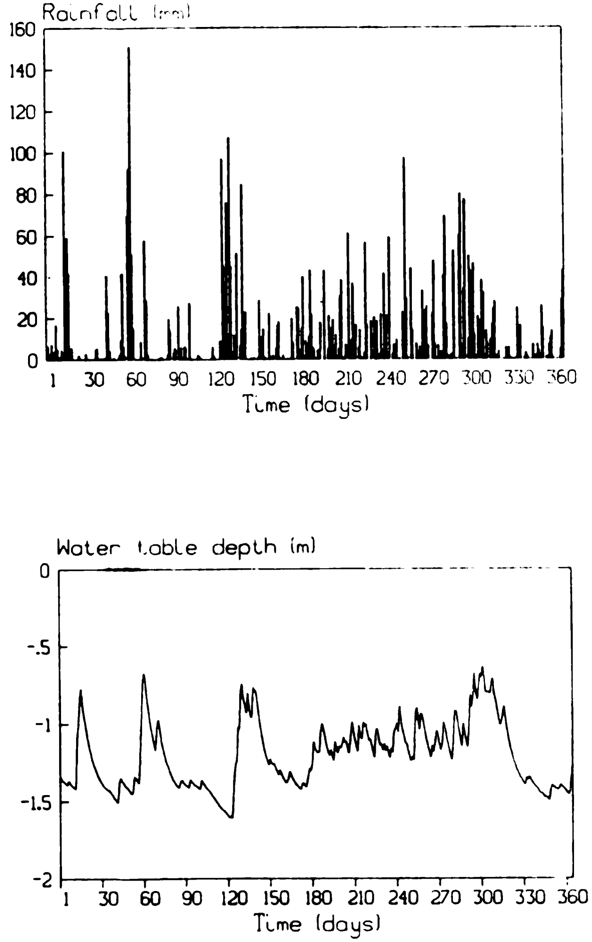


Figure 5.1: Rainfall and simulated water table fluctuations at Los Diamantes in 1983 for a drained condition with drain spacing of 100m and drain depth of 1.5m.

Table 5.1: *Well drained soils, Los Diamantes (LD).* Average number of days per year with average water table (WTa) or with mid-spacing water table (WTm) at or within depth indicated from the soil surface.

Natural condition: river distance = 300m
river depth = 2.5m
Artificial drain depth = 1.5m.
df: drain factor (day^{-1})

Water table depth	natural df = 0.002		drains 100m df = 0.018		drains 50m df = 0.042	
	WTa	WTm	WTa	WTm	WTa	WTm
0.0m	6	229	0	1	0	0
< 0.2m	42	253	0	3	0	0
< 0.4m	102	278	0	10	0	0
< 0.6m	179	303	3	29	0	0

Table 5.2: *Poorly drained soils, Lomas de Sierpe, site 2 (LS2).* Average number of days per year with average water table (WTa) or with mid-spacing water table (WTm) at or within depth indicated from the soil surface. The natural condition refers to the simulation results for Quatro Esquinas (QE), with a gully distance = 400m and a gully depth = 1.5m.

Artificial drain depth = 1.5m.
df: drain factor (day^{-1})

Water table depth	natural df= 0.0004		drains 100m df = 0.002		drains 50m df = 0.009		drains 25m df = 0.036	
	WTa	WTm	WTa	WTm	WTa	WTm	WTa	WTm
0.0m	101	255	56	110	5	28	0	0
< 0.2m	184	289	80	127	14	42	0	0
< 0.4m	238	326	106	149	26	56	0	2
< 0.6m	286	354	129	174	43	74	0	6

Table 5.3: *Poorly drained soils, Lomas de Sierpe, site 2 (LS2).* Average number of days per year with average water table (WTa) or with mid-spacing water table (WTm) at or within depth indicated from the soil surface.

Artificial drain depth = 2.0m.
df: drain factor (day^{-1})

Water table depth	drains 100m df = 0.002		drains 50m df = 0.0065		drains 30m df = 0.018	
	WTa	WTm	WTa	WTm	WTa	WTm
0.0m	44	99	2	21	0	0
< 0.2m	63	113	8	29	0	1
< 0.4m	84	132	13	40	0	3
< 0.6m	103	153	24	52	0	6

Table 5.4: *Poorly drained soils, Lomas de Sierpe, site 3 (LS3).* Average number of days per year with average water table (WTa) or with mid-spacing water table (WTm) at or within depth indicated from the soil surface.

Artificial drain depth = 1.5m or 2.0m
df: drain factor (day^{-1})

Water table depth	drains 100m depth= 1.5m df = 0.017		drains 100m depth= 2.0m df = 0.017		drains 50m depth= 1.5m df = 0.043	
	WTa	WTm	WTa	WTm	WTa	WTm
0.0m	0	7	0	2	0	0
< 0.2m	1	13	0	4	0	0
< 0.4m	6	25	0	7	0	1
< 0.6m	15	43	5	12	0	3

5.4. Drain factor.

To indicate the overall drainage condition, a drain factor, df, was introduced:

$$df = \frac{10K_h d}{L^2} \tag{5.1}$$

with K_h : saturated horizontal hydraulic conductivity (m/day)
d : equivalent aquifer depth (m)
L : drain spacing (m)

The physical meaning of this drain factor can be explained as follows:

a) Under steady state conditions, and when drainage flow above the drainage base may be neglected, the drain discharge (q) is linearly related to the mid-spacing water table head (h), (so-called simple Hooghoudt formula):

$$q = \frac{8K_h d}{L^2} \cdot h \tag{5.2}$$

with q: drain discharge per unit length of drain spacing (m/day)
h: mid-spacing water table head relative to the drain base (m)

b) Under non-steady state conditions and when the flow to the drains is essentially horizontal and when there is no recharge (nor evapotranspiration of groundwater), the falling water table can be described with the Glover-Dumm formula:

$$\frac{h_t}{h_o} = 1.16e^{-\alpha t} \tag{5.3}$$

where

$$\alpha = \frac{10K_h d}{\mu L^2} \tag{5.4}$$

with t : time (days)
h_o : initial mid-spacing water table head (m)
h_t : mid-spacing water table head at t=t (m)
a : reaction factor (days^{-1})
μ : drainable pore space ($m^3.m^{-3}$)

Drain systems with a similar drain factor, df, will thus have a similar drain efficiency. Some difference in efficiency is possible due to differences in drainable pore space and drain depth as these parameters are not included in the drain factor.

According to the frequency tables of the previous section, it can be concluded that sufficient drainage efficiency (the water table remains below 0.6m almost throughout the whole year) is obtained when the drain factor (df) is approximately 0.04 day^{-1} and the drain depth is 1.5m. This efficiency is slightly better for well drained soils (Los Diamantes), due to a higher drainable pore space. For Los Diamantes and site 3 of Lomas de Sierpe, this efficiency is achieved when using a drain spacing of 50m, while for site 2 of Lomas de Sierpe a spacing of 25m is needed. For a deeper drain depth, a lower drain factor is needed to obtain the same efficiency. For example, if drain depth is 2.0m, a drain factor of approximately 0.02 day^{-1} will be sufficient.

In Appendix I, drainage recommendations are given for the Atlantic Zone based on this drain factor.

5.5. Water balance.

An additional consequence of artificial drainage is the change of the water balance. As the water table lowers, more water will infiltrate, resulting in higher groundwater runoff. Higher infiltration can lead to increased leaching of nutrients from the soil. Moreover, the residence time of (bio-)chemical components in the groundwater reservoir will be smaller as the average distance between canals is shorter. Water balances for the different drainage scenarios are presented in tables 5.5 and 5.6. The different components of the water balance are presented as percentages of average yearly precipitation. Evapotranspiration was not simulated in the model but set at 3.1 mm/day for Los Diamantes and 3.5 mm/day for Lomas de Sierpe.

Some remarks should be made for the natural conditions. The water balance for Quatro Esquinas, with 58 % surface runoff, was obtained for the wet part of the cross section. A significant part of this surface runoff will not cause a quick response in the river system, but will fill up depression storages of the micro relief, which will carry the water slowly toward the river system. In the dry part of the cross section (representing at most 15 % of the whole cross section), the water balance is probably comparable with the water balance obtained for the drained conditions of site 2 of Lomas de Sierpe. The natural condition for Los Diamantes represents relatively wet sections of the well drained soils as the average water table is at a depth less than 0.6m during half of the year. For sections with better natural drainage, results of the drained conditions could be used as an approximation.

Table 5.5: *Well drained soils, Los Diamantes.* Water balance under different drainage conditions. Average annual rainfall = 4329 mm. Surface runoff ($Q_{surf.}$), groundwater runoff ($Q_{grw.}$) and potential evapotranspiration (E.T.) are presented as a percentage of rainfall (R).

(1): natural condition
(2): drains at 100m and drain depth = 1.5m
(3): drains at 50m and drain depth = 1.5m

	(1)	(2)	(3)
Q_{surf}	31 %	19 %	19 %
$Q_{grw.}$	43 %	55 %	55 %
E.T.	26 %	26 %	26 %
R.	100 %	100 %	100 %

Table 5.6: *Poorly drained soils, Lomas de Sierpe (LS).* Water balance under different drainage conditions. Average annual rainfall = 3736 mm. Surface runoff ($Q_{surf.}$), groundwater runoff ($Q_{grw.}$) and potential evapotranspiration (E.T.) are presented as a percentage of rainfall (R).

(1): natural condition at Quatro Esquinas
(2): drains at 100m and drain depth = 1.5m (LS, site 2)
(3): drains at 50m and drain depth = 1.5m (LS, site 2)
(4): drains at 25m and drain depth = 1.5m (LS, site 2)
(5): drains at 100m and drain depth = 1.5m (LS, site 3)
(6): drains at 50m and drain depth = 1.5m (LS, site 3)

	(1)	(2)	(3)	(4)	(5)	(6)
$Q_{surf.}$	58 %	37 %	22 %	16 %	17 %	15 %
Q_{grw}	8 %	29 %	44 %	50 %	49 %	51 %
E.T.	34 %	34 %	34 %	34 %	34 %	34 %
R.	100 %	100 %	100 %	100 %	100 %	100 %

5.6. Discussion and conclusions.

The presence of drains results in a drastic shift in the water balance components, surface runoff and groundwater flow (tables 5.5 and 5.6). In the calculation procedure it is assumed that surface runoff takes place in one day. In well drained soils with slopes between 1 and 5% and a well developed natural drainage system, this can indeed be observed. In the poorly drained soils, superficial drainage is less efficient due to the micro-relief, and an additional surface drainage network will be required. In many banana plantations on well drained soils, one can observe that excavated soil from the major drainage ditches is obstructing the natural surface drainage system, and a shallow ditch system is installed to restore surface runoff.

In principle, a shallow drainage network for surface runoff is more economical than a deep network for groundwater control. However, the abundant rainfall and high infiltration rate of the soil, together with deep rooting crops, make a groundwater drainage system indispensable. See also chapter 6.

Crop growth simulation.

6.1. Introduction.

Which drainage efficiency is needed to achieve optimum crop yield depends on different factors:

a) *Crop dependence:* Some crops can tolerate the water table inthe root zone more easily than others.

b) *Soil dependence:* The effect of the water table depth on the available moisture in the soil profile depends on the soil type. In general, optimum yield occurs at higher water tables for light soils (e.g. sandy loam) than for heavy soils (e.g. clay). Moreover, effects of over-drainage (moisture shortage in the soil profile) when lowering the water table excessively are more likely to occur in light soils than in heavy soils.

c) Other factors such as climatology (e.g. distribution of rainfall in time, when dry or very wet periods occur etc.), farm practices (e.g. planting date) and the relationship between water table depth and soil workability may be taken into account when establishing the desired drainage efficiency.

Crop growth simulation models based on the MACROS crop growth model (Penning de Vries et al, 1989) and the SAWAH model for soil water balance (Ten Berge et al, 1992) were used to evaluate drainage efficiency. Growth or photosynthesis rate of two crops, maize and banana, was simulated under the different drainage conditions, and different soil types, as described in chapter 5. With the results of these simulations, a relation between water table position and crop production was established.

6.2. Description.

The processes affecting crop growth were calculated on a daily basis in the deterministic crop growth simulation models used. This includes calculation of potential evapotranspiration (based on the Penman formula), of soil water movement, of water uptake by the roots (and sensitivity to water stress), of transpiration by the plant, of photosynthesis and of conversion of photosynthesis into dry matter (or yield).

Daily data such as precipitation, temperature, wind speed, radiation or sunlight hours and vapour pressure are necessary for the simulation of climatological effects on crop growth. The simulation of soil water movement requires some soil data (i.e. van Genuchten parameters, water table levels). Crop data (root depth, leaf area formation, photosynthesis parameters, effects of temperature on plant and leaf development, sowing density, sowing date, etc...) are needed in the simulation of different processes interfering in crop growth. For a more detailed description of the input data, the reader is refered to Penning de Vries et al (1989) and Ten Berge et al (1992).

Simulations were done under the assumption that besides climatology, the soil moisture status was the only constraining factor. Other possible limiting or reducing factors (such as availability of nutrients, weed competition, diseases,...) are assumed not to constrain crop performance.

Water stress reduces transpiration and can be quantified by the ratio of actual transpiration and potential transpiration. For many crop types, optimum soil water content approximates field capacity. Water stress occurs when the soil water content approaches wilting point, and oxygen stress occurs when the soil water content increases nearing saturation. For maize, it is assumed that from field capacity to saturation, actual photosynthesis relative to potential decreases linearly from 1 to 0.6. In other words, at saturation only 60% of potential photosynthesis is achieved. Bananas are assumed to be affected more strongly by excess soil water, and actual photosynthesis in saturated soil water conditions is set at 30% of potential. It should be noted that the followed approach is less accurate when soil remains saturated over longer periods. Water stress remains at 1 for water contents between field capacity and critical water content on the dry side (somewhere between field capacity, θ_{fc}, and wilting point, θ_{wp}). The exact value of this critical water content depends on crop type and evaporative demand, where amounts average 0.86 x $(\theta_{fc}-\theta_{wp}) + \theta_{wp}$. Below this critical water content, water stress decreases linearly to 0 (no transpiration) at wilting point. Due to the prevailing humid climate in the Atlantic zone, water stress caused by excess moisture is much more important than water stress caused by moisture shortage. Water stress affects photosynthesis. How this affects crop yield will depend on the plant's development stage. For bananas, a high linear correlation was found between calculated photosynthesis and actual banana production in the Atlantic Zone (de Bruin, 1991). For maize, sufficient data were available to simulate the growth of the plant completely (including grain yield), while for banana, only the effects of water stress on photosynthesis were simulated, due to a lack of data.

A root depth of one meter, constant in time, was assumed for bananas. Moreover, a constant leaf area index of 4.5 $m^2.m^{-2}$ was assumed (following de Bruin,1991). For maize, root depth begins with ten centimeters at germination increasing to one meter with a maximum growing rate of 6 cm per day. The time between sowing date and harvest date is approximately 110 days, and is determined by temperature and day length. Simulations are done for twelve different sowing dates (intervals of 30 days, starting on January 10). The sowing density amounts to 20 kg seeds per ha.

Crop simulations were done for Los Diamantes with the climato-logical data from the Los Diamantes meteorological station. Physical soil data used was the data set obtained for eutric Hapludand, perennial crop (eHpe) by Weitz (1992). For Lomas de Sierpe and Quatro Esquinas, climatological data from the La Mola meteorological station was used. For profile 3 of Lomas de Sierpe (LS3) and Quatro Esquinas, the physical soil data set obtained for profile 2-A2 by Mantel (1993) was used, while for profile 2 of Lomas de Sierpe (LS2), the physical soil data set obtained for profile 3-A2 by Mantel (1993) was used. This selection was made in such a way that soil physical data representing relatively better drained soils (loamy) were used with the relatively better drained profile LS3 and data representing very poorly drained soils (clayey) were used with the poorly drained profile LS2.

Instead of daily rainfall, the rainfall minus excess rainfall, as estimated with the curve number method (section 3.4) was used, since this was assumed to give a better estimate. Simulated water table levels, as presented in chapter 5, were used as lower boundary conditions. As water table levels depend on the location between the drains, simulations for bananas were done at one half and at one sixth of the drain distance (at 50 and 100m). For maize, the simulations were done with an average water table level and only for a drain spacing of 50m.

Of course, crop growth simulation models also have their limitations (simplification of the real processes, lack of data, etc.). For this reason, simulation results should be compared with observed field data whenever possible.

6.3. Results.

6.3.1. Banana.

There is a clear relationship between reduction in photosynthesis for bananas and water table depth. The reduction in photo-synthesis, ps, compares potential photosynthesis (which would occur if there were no water stress) with actual photosynthesis and is defined as:

$$ps = \frac{\text{pot. photosynthesis - act. photosynthesis}}{\text{pot. photosynthesis}} \text{ X } 100 \ (\%)$$

Reduction in photosynthesis for periods of 10 days is related to mid-spacing water table levels for Los Diamantes and Lomas de Sierpe, site 2, with drains at 50m distance (see figures 6.1 to 6.4.). The reduction in photosynthesis is mostly caused by excess moisture due to high water tables. A linear regression-analysis was done for the complete time series (1980-1989) and for all the different drainage scenarios. The average water table level (m) over 10 days, expressed as a negative value with respect to the soil surface, was considered as the independent X-variable, and the reduction (%) in photosynthesis over 10 days as the dependent Y-variable. The best fitting linear equations and the corresponding correlation-coefficients, r^2, were calculated (see table 6.1). These relations are useful since they can be used in the future to estimate photosynthesis reduction from water table data without using crop growth simulation models. Of course, these relations are only valid for the region and the soil type for which they were assessed.

Linear equations obtained for the different drainage scenarios are relatively similar. Small variations are due to differences in soil type and in water table levels occurring in the different scenarios. This last phenomenon is due to the fact that a slightly curved line (or a composition of 2 or more straight lines) would give a better fitting. The curve fitting is relatively poor for the results of site 2 of Lomas de Sierpe (LS2). High and quick oscillations in the water table, due to the small drainable pore space (μ= 1%), could be a possible explanation. Also, physical soil data used for LS2 represent clayey soils with relatively low saturated vertical hydraulic conductivity (K_s=2.2cm/hr), and this could easily cause some extra water stress, independent from the water table level.

The optimum water table level (i.e. the water table level which causes no water stress and consequently no reduction in photosynthesis) can be estimated from the linear equations by finding the X-intercept. Values lying between -1.6m and -2.1m were obtained. This is quite logical as, under equilibrium conditions, a water table at a depth of 2m will cause a suction head of 100cm in the soil at 1m. This implies that the water content in the upper first meter of the soil profile will be below field capacity. For Los Diamantes, an extra simulation was done with a fixed water table at 2m. The reduction in photosynthesis for this simulation was, as could be expected, zero. No simulations were done with deeper water tables, but it can be expected that in this case some reduction in photosynthesis will occur due to moisture shortage in the dry period.

Average reductions in photosynthesis over the entire simulation period show a significant improvement due to drainage at Los Diamantes and at Lomas de Sierpe, site 3 (see table 6.1). Average water table levels (taken over the simulation period) could be used to estimate the reduction and consequently, drainage efficiency.

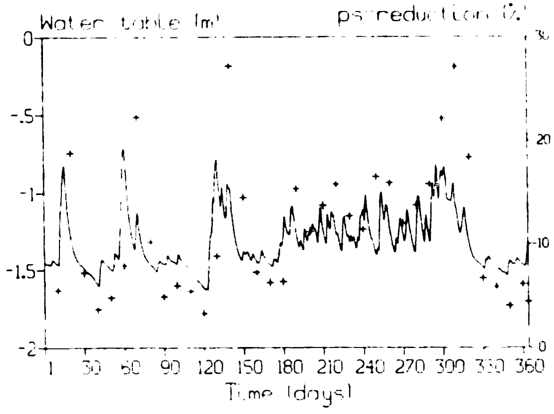


Figure 6.1: Mid-spacing water table (———) at Los Diamantes compared with the reduction in photosynthesis for periods of 10 days, ps (+) for bananas. Year: 1983, drains at 50m and drain depth = 1.5m.

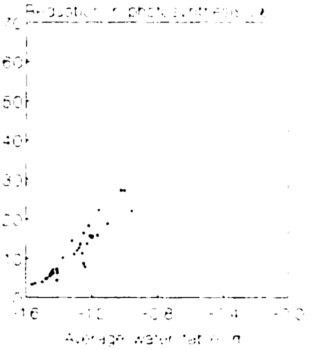


Figure 6.2: Relation between reduction in photosynthesis for periods of 10 days and the average water table level. Based on the time series presented in figure 6.1. (Los Diamantes).

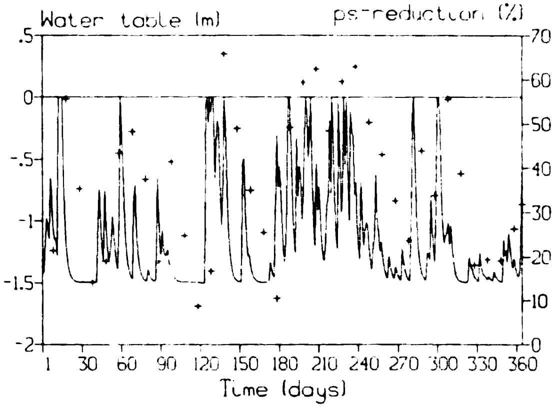


Figure 6.3: Mid-spacing water table (———) at Lomas de Sierpe, site 2, compared with the reduction in photosynthesis for periods of 10 days, ps (+) for bananas. Year: 1983, drains at 50m and drain depth = 1.5m

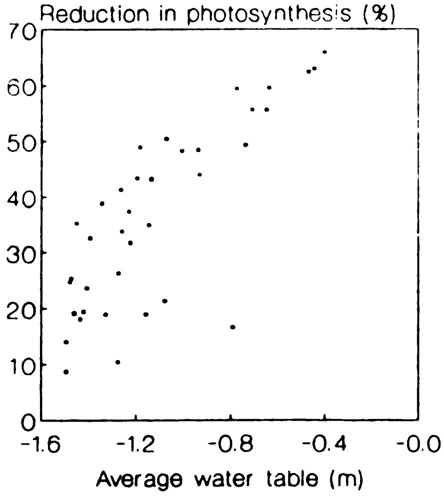


Figure 6.4: Relation between reduction in photosynthesis for periods of 10 days and average water table level. Based on the time series presented in figure 6.3. (Lomas de Sierpe, site 2).

Table 6.1: Average reduction in photosynthesis for bananas (RED) and average water table depth (GWT) for the period 1980-1989; best fitted line between the reduction in photosynthesis and average water table depth over ten days (EQ), and the corresponding correlation-coefficient, r^2 (COR) for different drainage scenarios.

SIT	CON	POS	RED	GWT	EQ	COR
Well drained soils:						
LD	nat	avg	40 %	-0.72m	Y=74+46X	0.96
LD	100	L/2	23 %	-1.07m	Y=74+47X	0.91
LD	100	L/6	13 %	-1.26m	Y=64+39X	0.90
LD	50	L/2	11 %	-1.33m	Y=60+36X	0.83
LD	50	L/6	8 %	-1.41m	Y=48+28X	0.83
Poorly drained soils:						
QE	nat	avg	59 %	-0.30m	Y=70+36X	0.89
LS2	100	L/2	51 %	-0.62m	Y=72+34X	0.75
LS2	100	L/6	45 %	-0.85m	Y=77+38X	0.72
LS2	50	L/2	40 %	-1.03m	Y=80+38X	0.66
LS2	50	L/6	36 %	-1.19m	Y=95+48X	0.63
LS3	100	L/2	26 %	-1.13m	Y=76+44X	0.86
LS3	100	L/6	21 %	-1.27m	Y=84+49X	0.86
LS3	50	L/2	18 %	-1.34m	Y=90+53X	0.82
LS3	50	L/6	16 %	-1.40m	Y=109+66X	0.83

SIT: Site (LD: Los Diamantes, QE: Quatro Esquinas, LS2: Lomas de Sierpe - site 2, LS3: Lomas de Sierpe - site 3)

CON: nat: natural condition;
100 : drains with spacing of 100m and depth of 1.5m;
50 : drains with spacing of 50m and depth of 1.5m;

POS: avg : crop growth simulated with average daily water table level between the two drains;
L/2 : crop growth simulated with the daily water table level half between the two drains;
L/6 : crop growth simulated with the daily water table level at L/6m from the drain (L= drain spacing);

EQ:best fitted linear equation with
Y : reduction in photosynthesis over 10 days (%);
X : average water table depth over 10 days (m, negative with respect to the soil surface);

6.3.2. Maize.

The reduction in photosynthesis cannot be translated directly into a reduction in crop yield, as this will depend on the crop's development stage. This also implies that the assessment of relationships between water table levels and reduction in crop yield is not so obvious and crop growth simulation models must be used for every new situation. Maximum possible (potential) grain yields were simulated for Los Diamantes and Lomas de Sierpe for the case where no stress occurs, i.e. optimal water and nutrient availability and absence of pests and diseases. Average grain yields with limited water were simulated for the natural condition and for the condition with drains at 50m and a drain depth of 1.5m (see tables 6.2 and 6.3). The coefficient of variation (CV), defined as the ratio between standard deviation and mean, is an indication of the variability over the simulation period 1980-1989. The highest crop yield is obtained when sowing took place at the beginning of February, and the lowest crop yield when sowing was at the beginning of October. This is clearly related to effects of the rainy season. Increase in grain yield due to drainage depends on the sowing date. For Los Diamantes, the implementation of drains at 50m and a depth of 1.5m, improves the production of grain yield by 9% (of potential yield) when sowing in February, while the improvement amounts to 44% when sowing takes place in October. This illustrates clearly that, when investigating the feasibility of drain systems, present and possible future farm practices must be considered. For poorly drained soils, the gain in grain yield produced by the implementation of drains at 50m and a depth of 1.5m, is 37% when sowing takes place in February and 47% when this is done in October. It should be mentioned that these data were obtained by comparing the very wet site of Quatro Esquinas with the relatively well drainable site 3 of Lomas de Sierpe. This implies that the gain in yield will often be lower (because natural drainage is already better or drainage capacity of the soil is lower and shorter drain spacings are necessary). The reduction in variability (CV) of expected yields under artificial drainage conditions is an additional positive aspect of drainage. Potential grain yields indicate that a denser drain system than proposed until now, could possibly still improve production, especially at Lomas de Sierpe. More simulations are necessary to verify if these denser drain systems would still be feasible or not, because it can be expected that at this level, high additional costs will only produce small additional gains in yield. It should be noted that climatological conditions at La Mola (meteorological station used for Lomas de Sierpe and Quatro Esquinas) allow higher potential productions than climatological conditions at Los Diamantes.

Table 6.2: *Well drained soils.* Average grain yield for maize in function of sowing date, obtained from data for Los Diamantes for the period 1980-1989.

POT: Potential Grain yield (kg/ha) under optimal water availability condition (no water stress occurring).
NAT: Grain yield (as % of potential grain yield) for natural condition (river distance=300m, river depth= 2.5m).
D50: Grain yield (as % of potential grain yield) for drained condition (drain spacing=50m, drain depth= 1.5m).
CV: Coefficient of variation.

sowing date*	POT	CV	NAT	CV	D50	CV
10	8561	14%	79%	30%	92%	18%
40	8619	12%	83%	26%	92%	16%
70	8129	10%	79%	22%	90%	12%
100	7473	11%	66%	25%	90%	13%
130	7373	10%	54%	19%	90%	11%
160	7700	8%	43%	27%	87%	10%
190	7839	9%	39%	27%	87%	11%
220	7120	12%	39%	21%	88%	14%
250	6615	16%	42%	27%	87%	18%
280	6399	17%	39%	34%	83%	22%
310	6843	17%	47%	41%	87%	24%
340	7693	16%	62%	37%	89%	22%
average	7530		57%		89%	

* julian date

Table 6.3: *Poorly drained soils.* Average grain yield for maize in function of sowing date, obtained from data for Lomas de Sierpe for the period 1980-1989.

POT: Potential Grain yield (kg/ha) under optimal water availability condition (no water stress occurring).
NAT: Grain yield (as % of potential grain yield) for natural condition (Quatro Esquinas: gully distance= 400m, gully depth = 1.5m).
D50: Grain yield (as % of potential grain yield) for drained condition (Lomas de Sierpe, site 3: drain spacing=50m, drain depth= 1.5m).
CV: Coefficient of variation.

sowing date*	POT	CV	NAT	CV	D50	CV
10	8821	6%	46%	25%	87%	10%
40	8873	6%	51%	25%	88%	10%
70	8439	3%	51%	23%	86%	6%
100	7914	4%	44%	24%	82%	6%
130	7876	4%	35%	13%	80%	8%
160	8098	5%	30%	21%	78%	8%
190	8118	5%	29%	19%	80%	8%
220	7599	4%	31%	21%	81%	7%
250	7108	4%	33%	23%	80%	5%
280	6907	4%	30%	34%	77%	10%
310	7333	4%	30%	41%	79%	5%
340	8014	5%	35%	37%	83%	10%
average	7925		38%		82%	

* julian date

6.4. Discussion and conclusions.

Crop growth simulation indicates that installation of drain systems can significantly reduce the effect of soil water on crop growth, for both bananas and for maize. The corresponding gain in yield will be higher in poorly drained soils than in well drained soils. Relatively good drainage is achieved for Los Diamantes with drain spacing of 50m and depth of 1.5m. A slightly smaller drain spacing or greater drain depth will be efficient for site 3 of Lomas de Sierpe, while for site 2 of Lomas de Sierpe, a significant impairment of crop growth is still occurring with this drain system. Here, a drain spacing of 25m is needed. The ideal drain system would be one in which the water table remains between 1.5m and 2m during the whole year. The proposed drain systems allow production yields between 80% and 90% of the potential production.

Data of crop yields for maize (see tables 6.2 and 6.3) can be used to make a cost analysis (comparing gain in crop yield with the cost of the drain system) to investigate the feasibility of the implementation of a drain system. Similar data for bananas are not available, but simulated reductions in photosynthesis (see table 6.1) can be used to make a rough estimate. Simulated average water table levels could be used to estimate reductions in photosynthesis. Observed water table levels can be used to estimate actual photosynthesis reduction.

Simulated crop yields should be compared with observed crop yields before doing cost analysis. This is necessary, not only because of limitations of the models used, but also due to factors such as fertilization and farming practices, which were not taken into account. Crop yield data given in this chapter should be used first as relative indicative values.

Chapter 7

Drainage and transport of agrochemicals.

7.1. Introduction.

High rainfall and high temperatures, together with the high permeability of the soils in the study area, have an effect on the leaching of agrochemicals such as fertilizers and biocides. To obtain insight into the quantities involved with the drainage process of surface runoff and groundwater flow, a number of water samples were collected and analyzed for major elements. At Los Diamantes, a more detailed survey included a comparison of applied fertilizer and nematicides with respective amounts lost by the drainage system.

The installation of drainage networks such as those present in banana plantations, results in a substantial shift in the drainage process and in the transportation time of leached agrochemicals. Surface drainage occurs rapidly while groundwater flow is much slower. On the basis of results presented in chapter 5, an estimate of the residence time of soluble agrochemicals in the groundwater is made.

7.2. Water qualities.

Water samples of surface- and groundwater were taken under different soil types. Although measured values depend to some extent on the moment of sampling in relation to rainfall occurrence, data are presented indicating the order of magnitude of concentrations (table 7.1). The concentrations (in ppm) show clearly the effect of fertilizer in well drained and eroded soils (banana, palm heart and pineapple).

To obtain more insight into the distribution of water qualities in the natural drainage system, the Tortuguero River was sampled during wet and dry periods (de Jong, 1993). This river originates in the alluvial fan and flows through the alluvial plain into the Carribean Sea and is considered a typical natural drain of the study area. Results are presented in figure 7.1. There is a marked increase in concentrations in the first part of the catchment which can be explained by the location of banana plantations in the upper part of the alluvial plain from which higher quantities of nutrients are leached.

Table 7.1: Indicative water qualities (ppm) in the study area.
Reference: (1) Rosales et al, 1992
(2) This report
(3) de Jong, 1993

		K	Ca	Mg	NO3	ref
Well drained soils:						
Surface water:	pasture	3.5	8.9	3.1	0.2	(1)
	banana	4.5	14.0	6.2	5.2	(1)
Groundwater:	pasture	3.0	9.5	3.5	0.2	(2)
	banana	4.7	9.7	3.1	3.4	(1)
Poorly drained soils:						
Surface water:	pasture	3.0	14.0	6.0	-	(3)
Groundwater:	pasture	4.5	10.1	1.9	0.7	(2)
Eroded soils:						
Surface water:	palm heart	9.6	8.5	1.4	9.5	(2)
	pine apple	7.5	14.9	0.8	11.0	(2)
	pasture	2.4	4.0	0.9	-	(2)
Groundwater:		1.3	1.2	1.1	-	(2)

7.3. Nutrient and pesticide losses on banana plantations.

Investigations on losses of nutrients and nematicides under drained condition were done on the Los Diamantes banana plantation (Rosales et al, 1992). From this study, the following conclusions were made:

- a high correlation exists between amount of nutrients lost and discharge in the drain canal;
- probably, between 20 and 30 % of the N and K fertilizer is lost by leaching with the infiltrated water;
- losses of nematicides were very low;
- concentrations of the measured parameters of the drainage water were at an acceptable level for domestic use.

The observation that the concentration of nutrients is almost constant at high and low discharges can be explained when residence time and groundwater flow are considered.

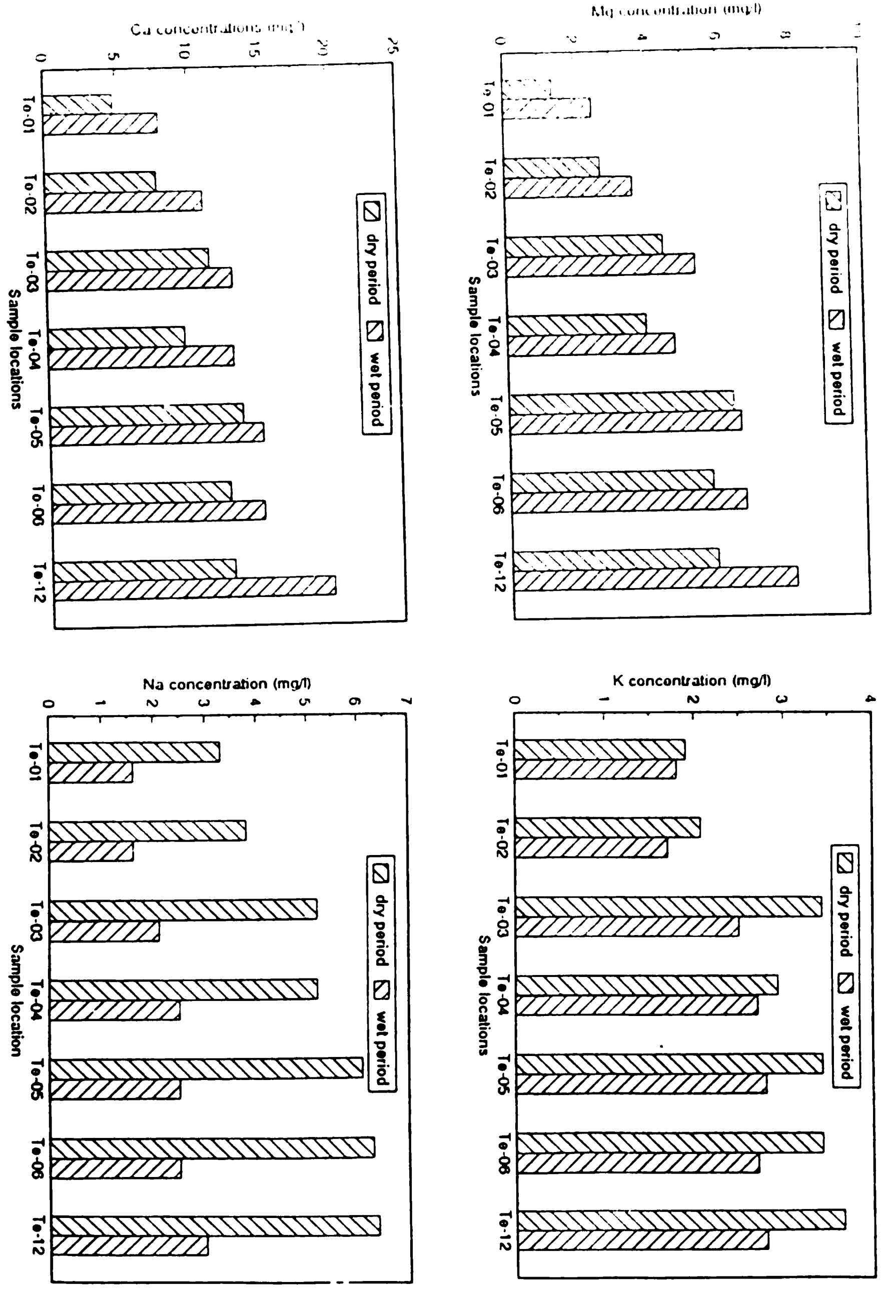


Figure 7.1: Bar diagram of the cation concentration (mg l^{-1}) of the dry and wet period surface water samples (Tortuguero river).

Te-01: near origin

Te-12: before coastal plain

7.4. Residence time in groundwater.

Nutrients and pesticides leached from the soil profile are slowly carried with the groundwater toward the drain and river system. The time needed will depend on the phreatic aquifer characteristics and drain distance. A finite difference model based on equation (3.2), but assuming steady state condition (i.e. the term on the left side of equation (3.2) equals zero) was used to estimate the time of residence (travel time). This also implies that groundwater recharge is considered constant in time. The average groundwater runoff values from tables 5.5 and 5.6 were used as input for the groundwater recharge. The time of residence obtained in this way is an average over a whole year. Results are presented in table 7.2. Porosity was set equal to 0.5. Residence times for other porosities can be easily calculated by dividing the time given in table 7.2 by 0.5 and then multiplying this number with the new porosity.

Greater travel times can be beneficial as they allow decomposable substances to decompose further. This is of course only the case for substances that decompose under anaerobic conditions of the phreatic aquifer system. At the same time, the groundwater buffers the leaching of agrochemicals that are applied evenly over the surface: leached chemicals applied at 1/6 or 1/3 the distance from the drain reach the collector ditch at very different moments (see table 7.2).

Also fixation of pollutants to soil particles plays an important role as the soil volume through which leaching occurs is large.

It should be noted that these residence times consider only the groundwater component. A significant amount of agrochemicals can reach the drain or river system very quickly (few hours or days) with surface runoff.

7.5. Discussion and conclusions.

As mentioned before, the presented interpretation regarding the leaching of agrochemicals is based on a limited number of observations. More systematic sampling surveys can certainly improve conclusions. It appears that installing a groundwater drainage system by means of an open ditch network will reduce the surface drainage component considerably.

Contamination by groundwater flow is buffered due to the great differences in residence time. Leached agrochemicals which are initially spread evenly on the surface, will reach the drainage network with time intervals of many days: leached components from half way between drains reach the ditches some 100 to 200 days after the leached components from ten meters from the drains. Contaminants in surface water reach the drain and river system very quickly.

Table 7.2: Expected average time of residence (travel time) for different drainage scenarios. Travel time is calculated for a stream line starting at L/3m and at L/6m from a drain (with L: drain spacing). A drain depth = 1.5m is used for all situations except for the natural condition of Los Diamantes (river depth= 2.5m). The natural condition QE^1 represents drainage to gullies (gully depth= 1.5m) while QE^2 represents drainage to the river system (river depth= 2.5m).

LD: Los Diamantes
LS2: Lomas de Sierpe, site 2
LS3: Lomas de Sierpe, site 3
QE: Quatro Esquinas

site	condition	drain spacing	time (days)	
			at L/3	at L/6
LD	natural	300m	1465	512
LD	drained	100m	688	261
LD	drained	50m	415	139
QE^1	natural	400m	1867	579
QE^2	natural	1000m	3780	1020
LS2	drained	100m	377	124
LS2	drained	50m	207	64
LS2	drained	25m	139	51
LS3	drained	100m	578	219
LS3	drained	50m	371	124

Chapter 8

Conclusions and recommendations.

8.1. Conclusions.

The possibility of improving drainage of fertile soils in the Atlantic Zone was investigated. Physical soil data (hydraulic conductivity and retention curve) and phreatic aquifer data (transmissivity and drainable pore space) were collected at different sites. Daily water table levels and the effect on crop growth were simulated at these sites for different drainage scenarios.

Well drained soils at Los Diamantes often consist of loamy to sandy soils above sandy substrata with relatively high transmissivity (≈15m^2/day or more). These soils are characterized by a relatively dense natural drainage network. When natural drainage is not sufficient like for deep rooted crops (bananas) in the lower part of this drainage unit, improvement can be obtained by constructing drains with a spacing of 50m and a depth of 1.5m or drains with a spacing of 100m and a depth of 2m (which ever is most convenient in the production system).

Poorly drained soils at Lomas de Sierpe and Quatro Esquinas are characterized by a relatively broad and flat natural drainage network. Two units can be distinguished. One unit has good drainage possibilities and consists mainly of loamy or sandy loamy soils above sandy or loamy substrata having relatively high transmissivities (≈10m^2/day or more). Similar drain systems as proposed for the well drained soils, preferably with a slightly smaller drain spacing or greater drain depth, will significantly improve growing conditions for all crops on these soils. The other unit consists mainly of clayey soils, or soils with a shallow impermeable layer as in Quatro Esquinas. A drain spacing of 25m with a depth of 1.5m or a drain spacing of 30m with a depth of 2m is necessary to achieve good drainage for all crops in these soils. More detailed information about drainage possibilities is given in Appendix 1.

Deep groundwater tables and high infiltration rates in the unfertile Pleistocene soils cause little surface runoff and only limited erosion hazard.

8.2. Crop production.

Crop growth simulation models for photosynthesis of bananas and yields of maize were applied to evaluate production potentials for alluvial soils with different drainage characteristics. Results for bananas show, that under natural conditions, photosynthesis is reduced by about 40% and 60%, on the average, in well drained soils and poorly drained soils, respectively. A drainage network with a spacing of 50m and effective depth of 1.5m results in a reduction of some 10% in well drained soils and between 17% and 38% for poorly drained soils (all values compared with potential levels without limitations in drainage and nutrient conditions). To reach photosynthesis levels in poorly drained soils with 10% reduction from the potential, drain spacing should be reduced to 25m.

For maize, the potential production level is about 7500 kg/ha (without limitations). In natural conditions on well- and poorly drained soils, calculated yields are at 57% and 38% of the potential level. A drainage system with 50m spacing and effective depth of 1.5m can improve yields on well drained soils up to 89% and on poorly drained soils up to 82% of the potential values.

All this information, as presented in chapter 6, refers to calculated values. No field experiments were conducted since they would require high costs. The numbers should, therefore, be used as indications only.

8.3. Recommendations.

Due to the heterogeneousness of the aluvial deposits, it is difficult to asses transmissivity of the phreatic aquifer system between the drains. For this reason, transmissivity and drainable pore space must be fitted by model calibration. For this study, daily observations of water table levels were available for periods of 1 to 3 months only. Of course, an initial estimate of transmissivity must be based on observed hydraulic conductivities and aquifer depths. Observations of water table levels over longer periods, including different rain storms and different average water table levels, are necessary to improve model calibration.

Excess rainfall, causing surface runoff, was estimated by the curve number method. Observation of runoff in drainage canals (preferably hourly observations) can be used to improve selection of the curve number and, consequently, the estimate of excess rainfall.

Validity of physical soil data should be checked by comparing simulated soil moisture movement with observations of soil moisture in the field, and other functions to describe the conductivity and retention curve should be tested. Results of crop growth simulations should be compared with field observations under drained situations.

Further study of the leaching process of agrochemicals, and the subsequent transport by groundwater flow would require labled elements and an enlarged monitoring system under different soils, land use systems and drainage conditions.

References

AALBERS H.D.W., 1993. Drainage research in the Atlantic zone of Costa Rica. Agricultural University of Wageningen/CATIE/MAG. Atlantic Zone Programme, Internal report. 16pp.

BERGE H.F.M. ten, JANSEN D.M., RAPPOLDT K. and STOL W., 1992. The soil water balance module SAWAH: description and users guide. Simulation reports. ABO-TT No.22. ABO/TPE, Wageningen, the Netherlands, 78pp.

BRUIN S. de, 1991. Simulation of potential banana photosynthesis in the Atlantic Zone of Costa Rica. Turrialba 41(3): 299-305.

BOOLTINK H.W.G., BOUMA J. and GIMENEZ D., 1991(a). Suction crust infiltrometer for measuring hydraulic conductivity of unsaturated soil near saturation. Soil Science Society of America Journal, volume 55, No.2, March-April 1991.

BOOLTINK H.W.G., KOSMAS C., SPAANS E. and PETERS P.D., 1991(b). Application of the One-Step Outflow method for determining hydraulic properties of soils. Soil and groundwater research report II: Nitrate in soils, 116-127. Commission of the European Communities, Luxembourg.

BOONSTRA J., 1987. Estimation of peak runoff rates. In: 26th International Course on land drainage, International Institute for Land Reclamation and Improvement/ILRI, Wageningen, The Netherlands.

CASTRO LEON V., 1985. Estudio climático de Costa Rica para la zonificaci6n agropecuaria y forestal. Vol. 1. Manual de uso (Convenio Sepsa-Mideplan).

CHOW V.T., MAIDMENT D.R. and MAYS L.W., 1988. Applied hydrology. McGraw-Hill series in Water Resources and Environmental Engineering, Singapore. 572pp.

GENUCHTEN M.Th. van, 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44: 892-898.

JONG T. de, 1993. Hydrogeological reconnaissance of the river Tortuguero catchment in the Atlantic Zone of Costa Rica. Agricultural University of Wageningen. Department of Water Resources. Group Hydrology.

LEUMMENS H.J.L., 1993. The variation of soil physical properties in fertile well-drained soils under banana. Msc-Thesis of the Department of Soil Science and Geology, Wageningen Agricultural University, The Netherlands. 44pp.

MAEBE P., 1992. Drainage observations in poorly drained soils in the Atlantic zone. Agricultural University of Wageningen/CATIE/MAG. Atlantic Zone Programme, report No. 39, field report No. 85. 5pp.

MANTEL S., 1993. Soil physical properties of a fertile poorly drained soil and their adequacy for use in quantified land evaluation. Msc-Thesis of the Programme Soil and Water, Wageningen Agricultural University, The Netherlands. 33pp.

PENNING de VRIES E.W.T., JANSEN D.M., ten BERGE H.F.M. and BAKEMA A., 1989. Simulation of ecophysiological processes of growth in several annual crops. Simulation Monographs 29, Pudoc, Wageningen, 271pp.

ROSALES A., MAEBE P. and SEVENHUYSEN R., 1992. Determination of losses of nutrients and nematicides on a banana plantation in the Atlantic zone. Agricultural University of Wageningen/CATIE/MAG. Atlantic Zone Programme, report No. 33, field report No. 80. 12pp.

SCHMIDT E.J. AND SCHULZE R.E., 1987. Flood volume and peak discharge from small catchments in Southern Africa, based on the SCS technique. Department of Agricultural Engineering, University of Natal, South Africa. Agricultural catchments research unit, report No. 24. Water Research Commission, WRC Project No.155, TT31/87.

SMEDEMA L.K. AND RYCROFT D.W., 1983. Land Drainage: planning and design of agricultural drainage systems. Batsford Academic and Educational Ltd, London.

TINEO BERMUDEZ A.L., 1993. Erosión hídrica, lixiviación y balance de N, P, K, Ca, y Mg, en una rotación frijol-maíz con prácticas agronómicas de conservación de suelos, en tierras de ladera, Turrialba, Costa Rica. CATIE, Turrialba, Costa Rica.

VAHRSON W.G. and CERVANTES C.U., 1991. Tasas de escorrentía superficial y erosión laminar en Puriscal, Costa Rica. Escuela de Ciencias Geográficas, Universidad Nacional, Costa Rica. Internal paper. 19pp.

WAGENET & HUTSON, 1989. LEACHM, Leaching Estimation And Chemistry Model. A process-based model of water and solut movement, transformations, plant uptake and chemical reactions in the unsaturated zone. New York State College of Agriculture and Life Sciences, Cornell University, Ithaca.

WEITZ A.M., 1992. Soil physical characterization of two soil types under four different land use forms in the Atlantic zone of Costa Rica. Agricultural University of Wageningen/CATIE/MAG. Atlantic Zone Programme, report No. 40, field report No. 86. 9pp.

WEYL, 1980. Geology of Central America, Wageningen.

Appendix 1

Drainage criteria in the Atlantic zone.

1. Introduction.

The main objective of agricultural land drainage is to remove excess water in order to improve the profitability of farming the land. Excess water may occur on the land surface (surface ponding, combined with waterlogging of the topsoil) or deeper down in the soil profile (waterlogging of the rootzone due to high water tables). Waterlogging of the soil causes impairment of crop growth and farm operations. Benefits from drainage of agricultural land may accrue from improved crop growth conditions or from improved soil workability conditions. Measures taken to improve drainage conditions of an area ultimately depend upon expected benefits compared with the costs of drainage improvements (installation and maintenance of a drain system). Possible adaptations in farming should be considered.

2. Drainage systems.

Groundwater drainage systems consist of a network of deeply installed field drains. They may either be pipes or deep open ditches. If a suitable drain spacing is selected, low watertable depths are maintained and the overlying soil profile will drain to field capacity. Groundwater drainage is applicable in soils where excess water is able to infiltrate and percolate through the rootzone at reasonable rates and where the rootzone is underlain by strata of reasonable transmissivity. A number of factors enter into the choice between pipe drains and ditch systems:

- ditch systems can also collect surface runoff (important in the humid tropics);
- installation cost of ditch systems is lower;
- up to 10% of the land can be lost when installing ditch systems, while in the case of pipe drainage, no land is lost;
- ditches will hinder farm operations (this disadvantage becomes less important when ditches are widely spaced, when the land is used for perennial crops or when farm operations are mostly done manually);
- ditches require frequent maintenance;
- generally pipe drains are better installed (under good grade) while ditches often have adverse bed grades;
- clogging of pipes by iron compounds may favour the use of ditches, while caving in of ditches may favour the use of pipe drains.

In soils with poor infiltration or percolation characteristics or with poorly permeable substrata, shallow drainage systems (consisting of shallow ditches) must be used to drain the water ponded on the surface by lateral overland flow.

3. Drain spacing.

Optimum drain spacing, L, depends on the transmissivity, T, of the phreatic aquifer system. Transmissivity, T (m^2/day), is defined as:

$$T = K \cdot d \tag{1}$$

with K: saturated hydraulic conductivity of the aquifer (m/day);
d: equivalent thickness of the aquifer (m).

A drain factor, df, may be defined as follows:

$$df = \frac{10 K \cdot d}{L^2} \tag{2}$$

with L: drain spacing (m).

From results of chapters 5 and 6, it can be concluded that an efficient drainage system, with crop yields possibly between 80 and 90% of the potential yield, is obtained if the drain factor is approximately 0.04 day^{-1}, the drain depth is 1.5m or 0.02 day^{-1}, and drain depth is 2m. Using these values, the following formulas for calculating drain spacing can be proposed:

if drain depth = 1.5m: $$L = \sqrt{250T} \tag{3}$$

if drain depth = 2.0m: $$L = \sqrt{500T} \tag{4}$$

About 30cm must be added to the drain depth to compensate for water depth in the drain. Drain spacing values, based on equations 3 and 4 are presented in table 1.

Table 1. Drain spacing (L) as a function of transmissivity (T) and drain depth (W).

T (m^2/day)	W (m)	L (m)
15	1.5	61
5	1.5	35
15	2.0	87
5	2.0	50

These values are of course only valid for conditions prevailing in the Atlantic Zone.

The drain factor, as defined in equation 2, does not include drainable pore space (μ). Consequently, some difference in drainage efficiency may be expected due to difference in drainable pore space. For smaller μ-values, larger drain factors resulting in shorter drain spacing must be used. From the results of chapter 5, it can be concluded that these differences are relatively small. This can be explained by the fact that if drainable pore space is smaller, the water table will rise higher but will also fall quicker.

For each different site, phreatic aquifer data should be determined and effective drain spacing selected. Some indicative values found for some sites in the Atlantic zone are given. For well drained soils of Los Diamantes, it was found that a drain spacing of 50m with a depth of 1.5m produces efficient drainage. In these soils, a wider drain spacing could often be sufficient, especially when natural drainage is better. In poorly drained soils of Lomas de Sierpe, two drain spacings for a depth of 1.5m were proposed: 50m for substrata with reasonable transmissivity and 25m for those with low transmissivity. Deeper drain depth or shorter drain distance might still give some significant improvement in these poorly drained soils.

Relations between water table depth and reduction in photosynthesis, given in chapter 6 can be used to estimate the "efficiency" of present drainage based on observed water table levels.

4. Phreatic aquifer data.

Hydraulic conductivity can be determined in the field by the augerhole method or the piezometer method. Aquifer depth is the distance between the drain level and the impermeable layer. This depth must be converted into an equivalent depth to compensate for radial flow resistance (see section 4.4). This will yield satisfactory results if the aquifer system is homogeneous between the drains. In the case of very heterogeneous soils, it will be difficult to determine the 'overall' transmissivity of the aquifer system. In this case, observation of water table heads between drains and observation of drain discharges allow the determination of the 'overall' transmissivity with equations like (5.2) or (5.3) or with a groundwater model based on equation (3.2). The exact determination of drainable pore space is less important as the influence of this parameter on drainage efficiency is relatively small.

5. Field layout of the drain system.

Drain spacings and drain depths proposed in this report are applicable to the tertiary canals of a general layout. Tertiary canals will discharge into secondary, and these will discharge into primary canals. To establish good gradients for the discharge, secondary and primary canals must be deeper. Secondary and primary canals are not only collecting water of tertiary canals, but they will also cause some additional drainage improvement. Main drains should, wherever possible, follow the depressions and downslope sides of the field. Wherever feasible, use should be made of the existing natural drains (some minor canalization or re-alignment may be necessary). This alignment based on topograhy will assure a good gradient and good discharge functioning. On the other hand, a regular layout may be advantageous for efficient farming. For this reason, only main drains should be aligned on the basis of topography and lower order canals should preferably have a regular layout. Shallow ditches can be installed in between the tertiary canals to drain part of the surface runoff. Excavated soils from ditches will impede surface drainage. Preferably, these ground spills should be leveled. If this is not done, a network of ditches with a depth of 30 to 50 cm is required to avoid stagnant water on the land surface.

The water level at the final outlet point, often a natural river, must be low enough to assure a low water level in the canals. If not, river water will enter the drain system and greatly hinder drainage. This problem is likely to occur in flat low lands close to the coast. If water at the outlet point is not constantly at a high level (e.g. only during high tide or during storms), sluices might be used to prevent river water entering the drain system. When sluices must be avoided, areas lower than about 25m above sea level should not be considered for simple drainage networks with free outlets to natural drains.

6. Drainage costs.

For the purpose of comparing drainage costs for different drainage units a rough estimation of the required soil excavation can be based on the recommended drain spacing and depth.

A typical tertiary drain with an effective depth of 1.5m requires 3.6m^3/m of excavation.

For secondary drains or collector drains this is estimated at 5m^3/m and for primary drains 7.5m^3/m.

Costs for excavation and levelling (or surface drainage networks) are based on current 1993 data obtained from banana plantations.

A. *Well drained soils;* high producing sensitive crops; drain spacing 50m, effective depth 1.5m.
Distance between natural drains suitable for drain outlet: 400m.
Layout: 7 tertiary parallel drains of 200m length; 3.6 m^3/m.
1 collector drain of 350m length; 5 m^3/m.
Total excavated volume: 6750m3
Average cost per m^3: 100 ¢
Excavation cost: 675,000 ¢
Land leveling and/or surface drainage network: 125,000 ¢
Total cost for drainage network: 800,000 ¢
Total area drained: 8 ha (400 x 200m), cost per ha: ± 100,000 ¢

B. *Poorly drained soils;* high producing sensitive crops; drain spacing 25m, effective depth 1.5m.
Distance between natural drains suitable for drain outlet: 1600m.
Layout: 1 primary collector drain of 1500m length; 7.5 m^3/m.
8 secondary collectors (x2) of 500m each; 5 m^3/m.
19 tertiary drains (x2) of 200 m length; 3.6 m^3/m.
Total excavated volume: 300,000m3
Average cost per m^3: 100 ¢
Excavation cost: 30,000,000 ¢
Land leveling and/or surface drainage network: 2,400,000 ¢
Total cost for drainage network: 32,400,000 ¢
Total area drained 160 ha(1600 x 1000m), cost per ha: ± 200,000 ¢

C *Poorly drained soils;* medium sensitive crops such as improved grass lands; same layout but half the number of tertiary drains.
Total excavated volume: 175,000m3

Average cost per m^3: 100 ¢
Excavation cost: 17,500,000 ¢
Land leveling and/or surface drainage network: 2,400,000 ¢
Total cost for drainage network: ± 20,000,000 ¢
Total area drained 160 ha, cost per ha: ± 125,000 ¢

7. Hydraulic design of drainage canals.

As this is not part of the objective of this report, only a short introduction will be given. For more details, reference is made to the relevant handbooks. The hydraulic design of drainage canals may be based for almost all cases on steady uniform flow using the Manning formula:

$$Q = K_m R^{\frac{2}{3}} I^{\frac{1}{2}} A \tag{5}$$

with Q : discharge rate (m^3/sec);
K_m : Manning roughness coefficient ($m^{1/3}$/sec);
R : hydraulic radius (m);
I : hydraulic gradient (m/m);
A : wet cross-section (m^2);

Given a design discharge (Q) to be carried by the canal and a hydraulic gradient (I) and some characteristics of the canal (K_m, cross-sectional shape), the dimensions of the canal can be calculated with the Manning formula. When determining the hydraulic design of the canals, various requirements must be met. Low water levels in the tertiary canals must guarantee the necessary field drainage base. The water level in the secondary and primary canals must permit an unimpeded outflow from tertiary canals. The design must provide adequate over-capacity for the canal to carry high discharges (with high return periods, e.g. 1 x 25 year) without running over the banks. It should be noted that in groundwater discharge systems, canals are often very deep to ensure the field drainage base level and keep flood risks low. Other requirements to be met are adequate hydraulic gradients, permissible flow velocities to reduce erosion and stability requirements of the slopes. Hydraulic design should also consider the foreseen maintenance of the canal as the roughness coefficient will depend on the degree of maintenance. Selection of the design discharge can be based on observed discharges, or rainfall-discharge relation-ships (taking into account groundwater discharge and/or surface runoff) can be used.

Formulas similar to the Manning formula can be used to calculate the required diameter of a pipe drain. It is obvious that in this case the design discharge must be based on groundwater discharges.

Based on field observations and measurements, together with literature information, an effort is made to analyse the present drainage condition.. Possible measures to improve the drainage are presented. The analysis of the drainage condition and of measures to improve crop production can present basic information for future drainage projects. Engineers and Agronomists, involved in land reclamation as well as students of the subject can benefit from the presented materials.

As many Agrochemicals are transported by drainage water aspects of leaching are also included. Environmental studies can make use of the procedures and data presented in this report. Crop production and leaching of inputs are also important components in the broader evaluation of sustainability of a land use system. The scope of this report is to contribute to this evaluation.