ATLANTIC ZONE PROGRAMME

Report No. 77
Field Report 124

HYDROGEOLOGICAL RECONNAISSANCE OF THE RIVER TORTUGUERO CATCHMENT IN THE ATLANTIC ZONE OF COSTA RICA

T. de Jong

August 1993

CENTRO AGRONOMICO TROPICAL DE INVESTIGACION Y ENSEÑANZA - CATIE

AGRICULTURAL UNIVERSITY WAGENINGEN - AUW

MINISTERIO DE AGRICULTURA Y GANADERIA DE COSTA RICA - MAG

The Atlantic Zone Programme (CATIE-AUW-MAG) is the result of an agreement for technical cooperation between the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Agricultural University Wageningen (AUW). The Netherlands and the Ministerio de Agricultura y Ganadería (MAG) of Costa Rica. The Programme, that was started in April 1986, has a long-term objective multidisciplinary research aimed at rational use of the natural resources in the Atlantic Zone of Costa Rica with emphasis on the small landowner.

PREFACE

General description of the research programme on sustainable Landuse.

The research programme is based on the document "elaboration of the VF research programme in Costa Rica" prepared by the Working Group Costa Rica (WCR) in 1990. The document can be summarized as follows:
To develop a methodology to analyze ecologicaly sustainable and economically feasible land use, three hierarchical levels of analysis can be distinguished.

1. The Land Use System (LUS) analyses the relations between soil type and crops as well as technology and yield.
2. The Farm System (FS) analyses the decisions made at the farm household regarding the generation of income and on farm activities.
3. The Regional System (RS) analyses the agroecological and socio-economic boundary conditions and the incentives presented by development oriented activities.

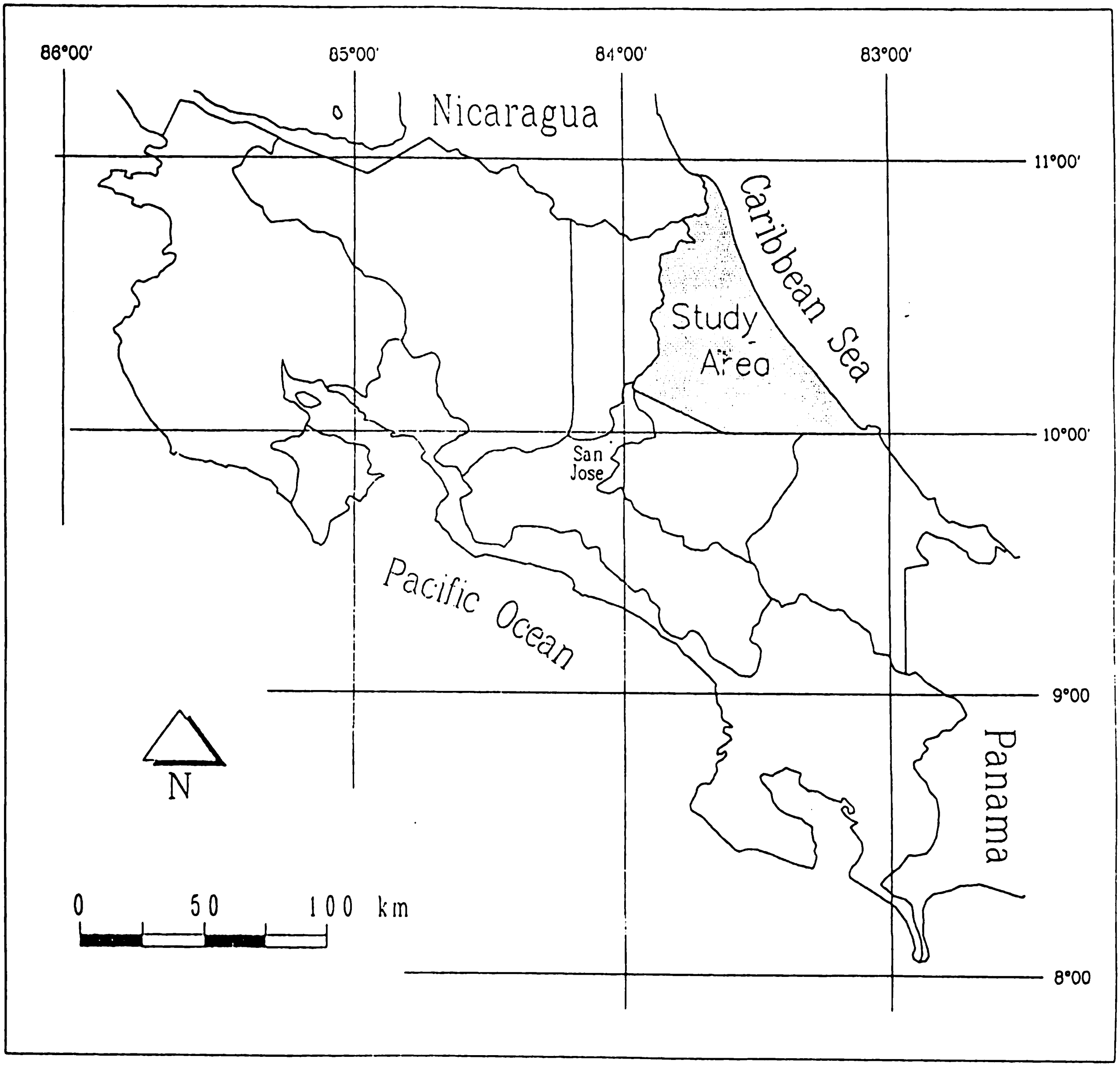
Ecological aspects of the analysis comprise comparison of the effects of different crops and production techniques on the soil as ecological resource. For this comparision the chemical and physical qualities of the soil are examined as well as the polution by agrochemicals. Evaluation of the groundwater condition is included in the ecological approach. Criterions for sustainability have a relative character. The question of what is in time a more sustainable land use will be answered on the three different levels for three major soil groups and nine important land use types.

Combinations of crops and soils

	Maiz	Yuca	Platano	Piña	Palmito	Pasto	Forestal I II III
Soil I	x	x	x		x	x	x
Soil II						x	x
Soil III	x			x	x	x	x

As landuse is realized in the socio-economic context of the farm or region, feasibility criterions at corresponding levels are to be taken in consideration. MGP models on farm scale and regional scale are developed to evaluate the different ecological criterions in economical terms or visa-versa.

Different scenarios will be tested in close cooperation with the counter parts.


86°00'
85°00'
84°00'
83°00'
11°00'
10°00'
9°00
8°00
Nicaragua
Caribbean Sea
Study Area
San Jose
Pacific Ocean
Panama
N
0
50
100 km

CONTENTS

LIST OF FIGURES

LIST OF MAPS

LIST OF APPENDIXES

LIST OF TABLES

ABSTRACT

This hydrogeological study, including quantitative and qualitative aspects, is in the first place a reconnaissance of the whole catchment of the river Tortuguero in the Northern Atlantic Zone of Costa Rica and secondly from an experimental area in the banana plantation Lomas de Sierpe in the catchment. We tried to find out if the catchment could be divided into subcatchments. This could lead to the distinction of regional and/or local systems of groundwater flow. The local system of groundwater flow was studied in an experimental area at the banana plantation Lomas de Sierpe, located at the alluvial plain, at the midstream part of the catchment, to find possible flow paths of polluted water.

The quantitative study consisted of discharge measurements of different rivers of the Tortuguero catchment, discharge measurements of two adjacent secondary canals of the experimental area at the banana plantation. Deep and shallow groundwater head at the experimental area were measured to find out if downward or upward seepage occurs.

The qualitative part of the study included the hydrochemistry of surface water samples, taken after a dry and wet period, to find out if streams in subcatchments are fed mainly by base flow or by surface runoff. This might lead to a subdivision of the catchment into secondary or even tertiairy catchments. Hydrochemistry of deep and shallow groundwater of the experimental area must give more insight if a downward or upward seepage situation occurs. The electric conductivity and surface water level of two different rivers of the Tortuguero catchment was measured to give insight in the discharge behaviour to find out if surface runoff or mainly base flow occurs.

The alluvial fan part of the Tortuguero catchment could be divided from the rest of the catchment. A local system of groundwater flow occurs with at the upper part of the fan a downward seepage situation while at the lower part an upward seepage situation occurs. This implies at the banana plantation, located at the lower part of the alluvial fan, leaching from the unsaturated zone of possible pollutants. It is likely that these pollutants follow a shallow flow path through the saturated zone. After a short residence time, these particles will feed the stream. In the Lomas de Sierpe area of the banana plantation a local system of groundwater flow occurs with a downward seepage situation. These flow conditions imply a possible risk of the groundwater resources. Some pollutants from the banana plantation might be transported to the deep aquifers and deteriorate the groundwater quality there. Furthermore, the sandsheets in the Holocene deposits form preferential, shallow flow pathes, which might transport (polluted) groundwater to the nearest stream. So, in the downstream part of the alluvial plain possible pollutants can follow a short flow path to the streams and a long flow path, with considerable residence times, through the deep aquifers.

1 INTRODUCTION

The Agricultural University Wageningen (AUW), Ministerio Agricultura Ganaderia (MAG) of Costa Rica and Centro Agrinomico Tropical de Investigacion y Enseñanza (CATIE) cooperate to develop the Atlantic Zone of Costa Rica. This agricultural development is to create a sustainable land use system to maintain the natural resources. Banana plantations (40000 ha) are the largest intensive agricultural land use system in the Atlantic Zone. Banana export is the first national income and shows its importancy. The monoculture of bananas creates an enormous pressure of pests and deseases and result to an intensive use of pesticides. The banana plantations pollute the environment by drainwater and brooks. No knowledge is present if pollution of deep groundwater occurs. To understand groundwater flow systems in a local area one must understand possible regional groundwater flow systems. A regional groundwater flow system could be expected from the alluvial fan against the Turrialba volcano (part of the Cordillera Central) to the alluvial plain and coastal plain near the Caribbean coast. Because of the lack of knowledge of regional and/or local groundwater flow systems it is sensible to try to determine expected flow systems. Therefore, a quantitative and qualitative reconnaissance of the river Tortuguero catchment was carried out. The rather small Tortuguero catchment is chosen because it stretch from the alluvial fan at the footslope of the Cordillera Central via the alluvial plain and coastal plain to the Caribbean sea. This catchment is representive for the northern Atlantic Zone and could give the possibility to find out if regional and/or local groundwater flow systems from the Cordillera Central to the Caribbean sea occurs.

The present study was carried out to get a deeper insight in some of the hydrogeological aspects of the northern Atlantic Zone of Costa Rica. The regional groundwater flow system was studied in the river Tortuguero catchment, while a local groundwater system was studied in a banana plantation in this catchment.

The goal is to give a description of distribution of rocks and the associated movement and storage of water in a part of the northern Atlantic Zone. This description must give information about possible flow routes of (polluted) water from, for example, banana plantations towards adjacent areas.

A description of the geological setting of Central America and Costa Rica is given in chapter 2, with some details of geomorphology and hydrology. Hydrological aspects and land use of the river Tortuguero catchment are discussed in chapter 3. The present climate is briefly discussed in chapter 4. In chapter 5 the materials and methods used in this study are described. The results and conclusions are given in chapter 6. Finally a hydrogeological system description of the river Tortuguero catchment is given in chapter 7.

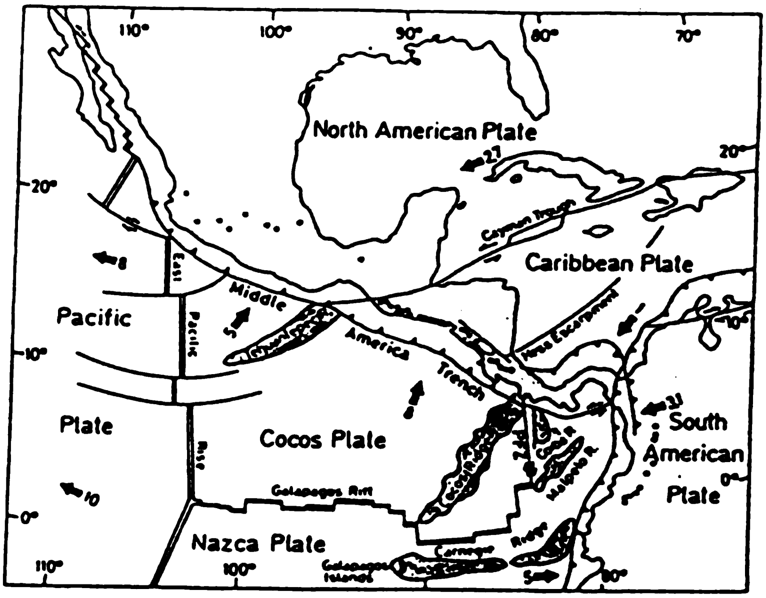


Figure 1 : Tectonic setting of Central America. Black arrows indicate drift directions; numbers represent absolute movement in cm • yr^{-1}, black dots are active volcanoes (Seyfried et al, 1991).

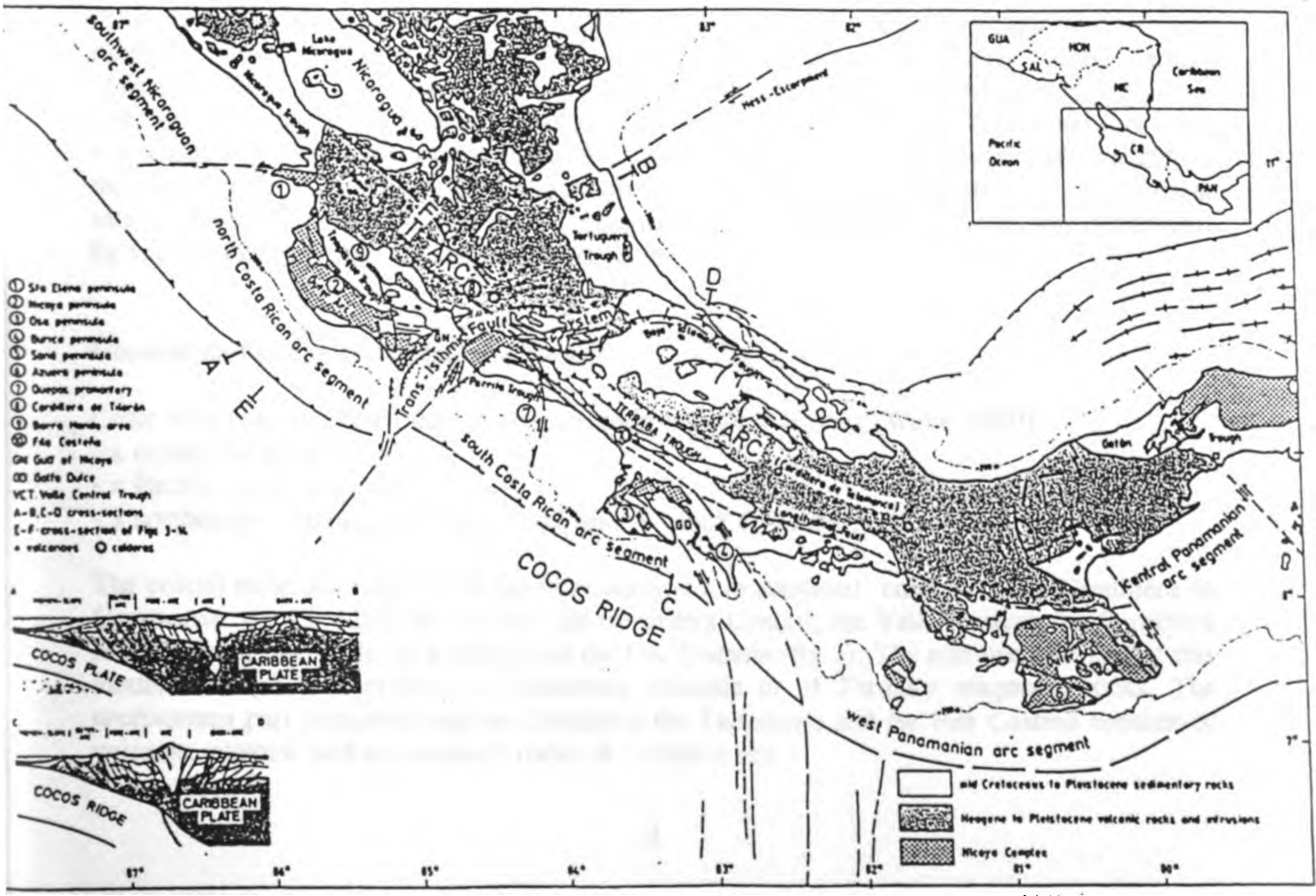


Figure 2 : Structural map of southern Central America, showing major tectonic elements; main tectonostratigraphic units and sedimentary basins (Seyfried et al, 1991).

2 GEOLOGICAL SETTING

Introduction

In this chapter first the geological setting of southern Central America is briefly discussed. Then an outline of different geomorphological units of the island-arc part on which Costa Rica is located, is given. Furthermore a description is presented of the geological and geomorphological characteristics of the back-arc area, the Limon Basin.

Geological setting of Central America

Central America is situated at the western margin of the Caribbean plate near the triple junction of the Cocos, Nazca and Caribbean plates (fig.1). Along the Middle American Trench, the Cocos plate is currently being subducted beneath the North American and Caribbean plates. The southern part of the Central American isthmus is the product of island-arc volcanism (Seyfried et al, 1991). An island-arc is a chain of stratovolcanoes formed by the melting of the crust material of the subducted plate beneath the overriding plate.
Southern Central America, which consists of Costa Rica and Panama, is fundamentally different in its geological development than northern Central America (Weyl, 1980). The oldest deposits in southern Central America are of Cretaceous age and consist of oceanic sediments and volcanic rocks. In different troughs this basement is overlain by deposits of chiefly marine Tertiair sediments. These sediments are only slightly deformed but are permeated by large quantities of volcanic and plutonic rocks which exhibit signs of a gradual transition from a basic oceanic volcanism to an intermediate and eventually saliac island-arc magmatism. Violent uplifting during the late Tertiary and Quaternary caused the isthmus to rise up and to form the present mountainous countries with their active volcanism (fig.2). The arcuate course was determined by various plate movements and transform faults.

Geomorphological units of Costa Rica

Costa Rica can be divided into three main morphological regions (Weyl, 1980):
- a central mountain range;
- a Pacific coastal region;
- a northeastern Atlantic-Caribbean Lowland (Cuenca de Limon);

The central mountain range, striking from northwest to southeast, consists of the Cordillera de Guanacaste, the Cordillera de Tilarán, the Cordillera Central, the Valle Central, the Cordillera de Talamanca, the Valle del General and the Fila Costena (fig.3). The northwestern part of this mountain range is composed of Quaternary volcanic or of Tertiairy magmatic rocks. The southeastern part compromising the Cordillera the Talamanca and the Fila Costena consists of volcanic, plutonic and sedimentary rocks of Tertiairy age.

igure 3 : Morphological map of Costa Rica (Weyl, 1980).

The Pacific coast of Costa Rica is extremely broken by peninsulas, bays and islands. This fore-arc area is formed by the uplift in the Late Mesozoic of the Caribbean plate, through the subducted Cocos plate. The land is uplifted to altitudes up to 1000 m. The uplifted plate is broken up in smaller parts like the Nicoya- and the Osa peninsula (fig.3).

The Atlantic-Caribbean Lowland, or the Limon Basin, is situated in the back-arc area. A back-arc basin is formed by crustal thinning behind the island-arc, initiated by tensional stress in the overriding plate due to a faster rate of sinking of the subducting Cocos plate than the forward motion of the overriding Caribbean plate. The uplifting of the island-arc, which started in the early Tertiary, has caused the formation of this sedimentation basin. During the Paleocene to Middle Eocene an ocean basin extended and the Rio Lari Formation of volcanoclastic sediments was sedimented with a thickness of about 2800 m (Weyl, 1980). There is less evidence of Middle to Upper Eocene deposits. The upper Eocene is distinguished in the approximately 800 m thick sandstone Tuis Formation with reef limestones intercalations. From the Oligocene to the Middle Miocene a succession of the Senosri Formation (850 m of limestone, sandstone and conglomerates), the Dácli Formation (1500 m of limestone, sandstone and conglomerates) and the Uscari Formation (1700 m of sandstone, clayey limestone and muddy deposits) was sedimented. From the Middle Miocene to Upper Miocene sandstones and siltstones were deposited up to 1700 m thick as the Gatún Formation, together with carbonate and lignitic lenses. The Suretka Formation (1700 m) consists of conglomerates and sandstones and lie as erosion products in which individual shallow water faunas appear only at the edges. From the Upper Miocene and during the Pliocene the Limón Formation has formed consisting of river and delta deposits interlock with lagoonal sediments and coral reefs which extend into the Pleistocene (fig.4).
Small basaltic volcanism occurred during the Pleistocene due to the crust tensions. Cerro del Tortuguero, Cerro Coronel and Lomas de Sierpe are examples of this feature, with an age of 1.2 million years. These volcanoes reach a heigth of about maximally 300 m above present sea level. The continuous subsidence of the basin and a rather stable sea level result in older deposits covered by younger ones. At some places the thickness of the Tertiary and Quaternary sediments is more than 10000 m. This indicates an average subsidence of about 0.25 mm yr^{-1} during these periods.
The main rivers of the Atlantic Zone, which is part of the Limon Basin, of Costa Rica are the Chirripo, Colorado and the San Juan which flow out in the Caribbean sea. The Tortuguero catchment is a primary river and is also part of the Atlantic Zone. The river flows out, via the canals and lagoons behind the beach ridges of the coastal plain, in the Caribbean sea.

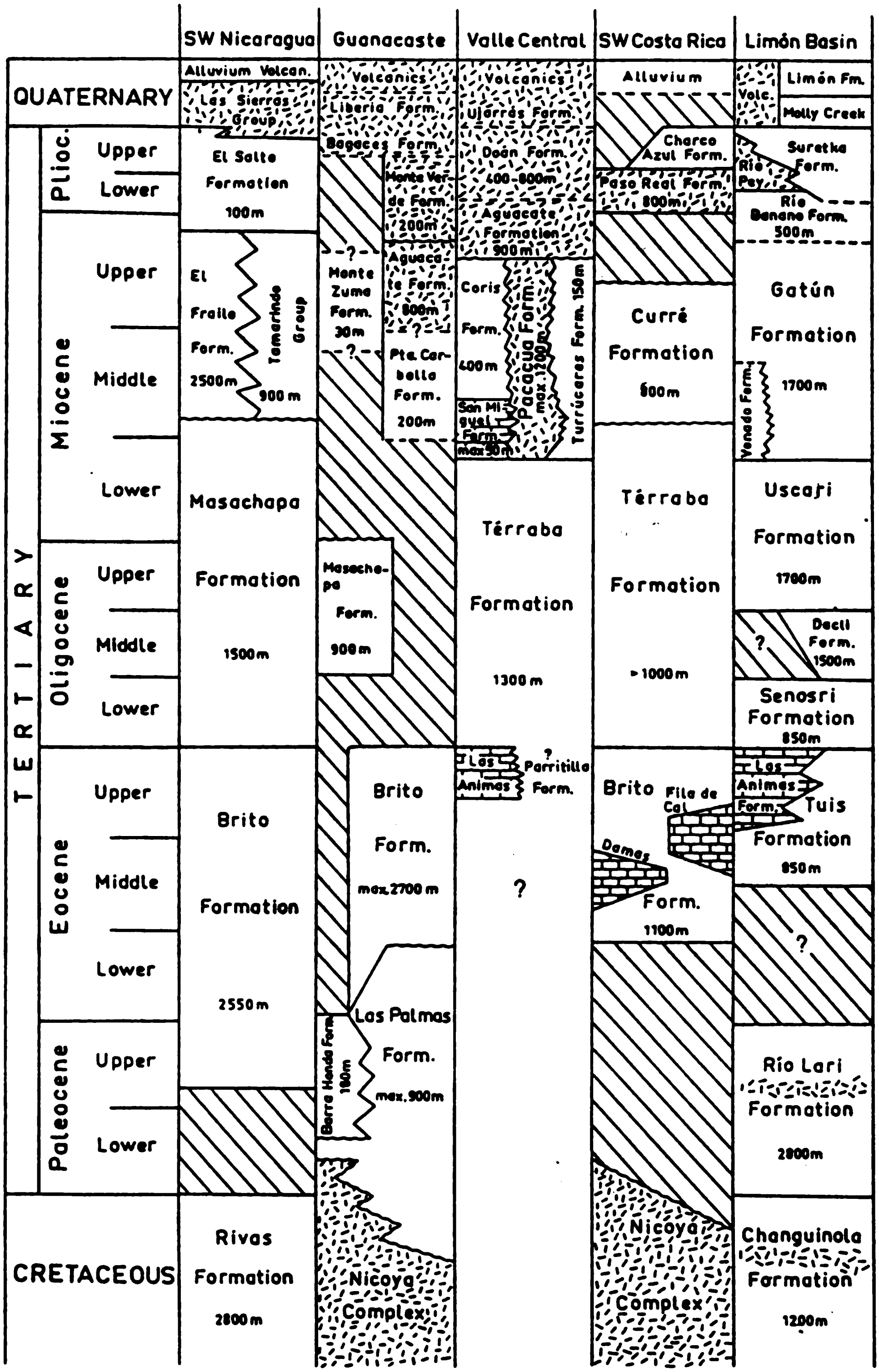


Figure 4: Stratigraphic correlation chart for the Cenozoic of Costa Rica (Weyl, 1980)

Three main superficial Holocene geomorphological units are distinguished in the Limon Basin (Nieuwenhuyse, pers. com., 1993):

- Alluvial fans

The alluvial fans cover an area of about 420 km^2. The largest alluvial fan, with an area of 300 km^2, is formed by the river Toro Amarillo and the river Sucio fan. Fans are situated in the footslope of the Cordillera Central. The upper part of the Toro Amarillo/Sucio fan is dissected as a result of the uplifting of the Cordillera Central and therefore inactive. The east side of the river Toro Amarillo fan also has become inactive, due to a lava flow from the Turrialba volcano which changed the stream direction of the river Toro Amarillo (Seeters, 1992).

- Alluvial plains

More seaward, the alluvial fans grade into alluvial plains which cover a total area of about 2400 km^2. The plains can be divided into active and inactive parts. The latter are never flooded. In this part of the plains river terraces can be found.

In the active plains, a levee-backswamp landscape occurs with on many places remnants of dissected Pleistocene terraces (red hills). Between the red hills infilling with Holocene sediments took place after the last glacial period. These sediments consist mainly of fine textured sediments. Coarse sandy deposits are also found in the form of sand sheets.

- Coastal plain

Wave action at the coast has thrown up sandy sediments to form beach ridges, with a total area of 690 km^2. With a transgressive sea in the Holocene, the succession of the beach ridges during the late Holocene was in upward and seaward direction. The higher sedimentation rate, which exeeded the rate of sea level rise caused this typical succession of beach ridges. Wetlands have formed behind them as a result of the very low hydraulic gradient of the distal part of the watersheds. In many of these marshes (topogenous) peat growth occurs as a result of persistent waterlogging and the low sediment supply (Driessen and Dudal, 1989).

3 RIVER TORTUGUERO CATCHMENT

Introduction

In this chapter the hydrological aspects and land use of the Tortuguero catchment are discussed. The hydrological aspects are dealt with the different subcatchments of the river Tortuguero with their area. The land use is discussed for the different geomorphological parts of the catchment. Finally, the hydrology of the banana plantation Lomas de Sierpe and the experimental area at the plantation are discussed briefly.

River Tortuguero catchment

Hydrological aspects

The river Tortuguero catchment is located in the Atlantic Zone of Costa Rica which is part of the Limon Basin. The actual spring of the river Tortuguero is on an inactive part of the Toro Amarillo alluvial fan near Guapiles. This part of the coarse textured fan is drained by a great number of brooks with a parallel pattern (map 1).
The catchment is narrow and the brooks flow in a northerly direction on the Toro Amarillo alluvial fan. Near Cariari, on the alluvial plain, the flow direction changes to an easterly direction. In this part of the catchment a low hydraulic gradient and drainage density occurs, with a meandering pattern. The low hydraulic gradient results in little swamps. Finally, the river Tortuguero enters the marshes north of the basaltic hills "Lomas de Sierpe". Here the meandering river Tortuguero changes in a more anastomosing flow type. This flow type maintains until finally the canals along the coast are reached.

The area of the river Tortuguero catchment is about 240 km^2. The main tributaries, i.e. river Guapiles and river Mata de Limon cover 45 km^2 and 46 km^2. The estimated mean discharge of the rivers in the mountains is between 150-200 $l\ s^{-1}ha^{-1}$, while in the alluvial area this is 80-100 $l\ s^{-1}ha^{-1}$, (Vahrson et al, 1990).
Formerly, the river Tortuguero was a major branch of the river Toro Amarillo (Van Seeters, 1992). Remnants of riverbed cobbles and boulders are now observed in the pastures along the road from Guapiles to La Rita.

Land use

On the alluvial fan plots of natural forest can still been seen along the brooks. Between the brooks mainly pastures are present, where cattle is kept for meat production. Dairy cattle is hardly found in this region. In this part of the catchment arable land is not found, due to large quantities of cobbles and boulders, which make tillage operations impossible.

In the midstream part of the catchment fine-textured deposits are found. The land use here is mainly banana plantation, but swampy grass lands with many trees and patches of forest are also found. Beef cattle is also kept here. In this area a rapid increase of banana plantations is expected to occur in the near future.
In the coastal swamps no agricultural land use occurs. This part of the catchment with the hills of Lomas de Sierpe belongs to the national park of Tortuguero and will not be reclaimed.
On the beach ridges along the coast people live in the village Tortuguero. No agricultural land use is found here and only tourism and fishery play an important role. In the coastal swamps and on the beach ridges mainly forest is present.

Banana plantation "Lomas de Sierpe"

The about 500 ha large banana plantation is situated at the alluvial plain of the river Tortuguero catchment on the Holocene deposits westerly of the basaltic hills "Lomas de Sierpe" with latitude of 10°25' and longitude of 83°36'. The altitude is about 20-15 m above sea level. The Holocene deposits consist of clayey, silty and sandy fluvial sediments (map 2).
Canals and ditches were digged to improve drainage in order to cultivate the area for banana plantations. The quaternary ditches have a more or less dendritic structure and drain into the tertiary ditches. They are mainly for the surface runoff which only occurs during heavy rainstorms. The tertiary ditsches flow perpendicularly towards the secondary canals. The secondary canals divide the banana plantation in more or less equal parts with a width of 100 m. The secondary canals come out mostly in primary canals and sometimes in natural brooks. The primary canals always come out in the natural brooks.

The experimental area (LS1) is located at the border, in the Southwest, of the plantation. A machine-made bore hole, with a depth of about 65 m, was made. This bore hole was situated near a primary canal (appendix 1A).

The experimental area (LS2) is located in the Southwest of the plantation. The area is bordered on the east and west side by secondary canals, with a length of about 300 m and width of 100 m. The western secondary canal flows out in a primary canal which flows out in the river Mata de Limon. The eastern secondary canal flows directly out in the river Mata de Limon. The north side of the detail area is bordered by a primary canal and in the south a little swamp prevails at the border of the river Mata de Limon (appendix 1B).

4 CLIMATE OF THE ATLANTIC ZONE OF COSTA RICA

Introduction

To understand climate of a certain area, knowledge of the atmospheric circulations in that part of the world is needed. These circulations can follow an annual, seasonly or daily pattern. In this chapter a description of these circulations in the tropics is given. In more detail the weather in the Atlantic zone of Costa Rica and its influence of the landscape of them is discussed, in particular the precipitation and temperature.

Climate

A continuous energy flow occurs in the atmosphere from the equator to the poles. This process creates characteristic air belts with constant circulations during the whole year. One of these air belts is the Inter Tropical Conversion Zone (ITCZ) which occurs around the equator. This is a high pressure belt in which no hurricanes and storms occurs. Another airbelt with trade winds is bounded to the ITCZ and gives in the Atlantic Zone of Costa Rica the dominant northeasterly wind direction. The effect is that the clouds are driven up on the mountains and create a high humidity, particular on the windward side of the mountains. After the clouds loose their humidity, on the leeward side the climate is drier.
The timing of the drier and rainy seasons varies somewhat between the Caribbean and Pacific slopes because of seasonal fluctuations in the strength of the northeastern trade winds and interactions of them with the major mountain chains to produce rain shadows, vortices and eddies. On the Caribbean slope, where the river Tortuguero catchment is located, the rainy season usually begins by mid to late April and continue through mid December in some years. In other years the rainy season finishes later. August and September are rather unpredictable drier months. The wettest months are usually July and November. At unpredictable intervals between about September and February, major storms, the "Temporales del Atlantico", bring more or less continuous rain for several days. They occur during invasions of cold air from the northern temperate regions. The most consistently drier months are February and March, when long periods of sunny days occur, with some nocturnal or early-morning showers, alternate with occasional temporales.
A typical wet season day has a few hours of sunshine in the morning and becomes cloudy by late morning or early afternoon, with rain for most of the afternoon and often continuing into the night.
Costa Rica is situated at 10° North latitude. On account of the position of Costa Rica close to the equator, the sun shines two times a year perpendicular on the earth surface. The high solar radiation, with an average value of about 15 MJ $m^2 day^{-1}$, varies dependent on the latitude, hour of the day and the day of the year (Erenstein, 1988).
Potential evapotranspiration, calculated with the Penman formulas, varies from 3 mm day^{-1} in the wettest period till 4.2 mm day^{-1} in the driest period, but depends strongly on cloudiness (Erenstein, 1988).

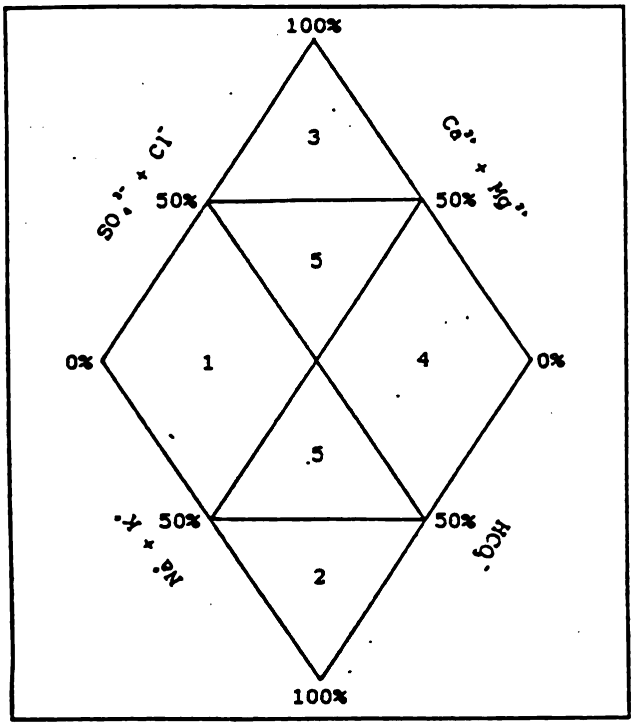
No summer or winter season exists, but according to the people the summer is during the months February, March and April, because these are the driest months and they have the highest temperatures.

Precipitation

The wettest areas in Costa Rica are the Caribbean slopes of the mountains, from the foothills into the upper elevations. In these areas even in the drier season long spells of rainy or misty weather are frequent. Near the coast in Tortuguero the mean annual precipitation is about 5320 mm. More land inward, the precipitation first decreases at La Mola in Cariari with a yearly precipitation of 3740 mm, but then it increases again at Los Diamantes in Guapiles, on the mountain footslopes, to 4550 mm rain and at La Montura, in the mountains, to 7060 mm precipitation per year (table 1 and appendix 2).
The "Temporales del Atlantico" give sometimes more than 100-200 mm day^{-1} with a duration of a few days. During the months February till April dry periods of one week to ten days and exceptions till sixteen days occur. Heavy downpours create the same circumstances as the Temporales but they have a more local nature and they appear in a shorter period. Then rain intensity can exceed 2 mm min^{-1}.

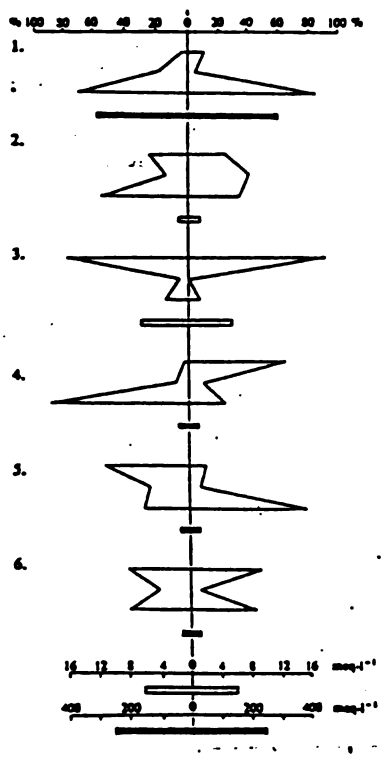
Temperature

Temperatures in Costa Rica vary with elevation instead of the time of year. The lowlands are always hot, the middle elevations cool and the high mountains cold. Daily variations in cloud cover and wind are also important. In the drier season night frost occurs above an elevation of 2500 m, it rarely occurs in the wet season.
The average annual temperature in the Atlantic Zone of Costa Rica is 26°C with a little variation through the year. Cloud cover is the most important factor for the seasonal and diurnal variation in temperature. On cloudy days the diurnal temperature differences are about 5°C or less, while this can be about 12°C on clear days.



1 = Secondary alkaline, $Ca(HCO_3)2$
2 = Primary alkaline, $Na/K(HCO_3)$
3 = Secondary saline, $CaSO_4/Cl_2$
4 = Primary saline, Na_2/K_2SO_4, Na/KCl
5 = no former ions dominate

Figure 5: Water classification according to Piper (Cultuurtechnisch Vademecum, 1988)



1 = Sodiumchloride-type, NaCl
2 = Infiltration-type
3 = Calciumbicarbonate-type, $Ca(HCO_3)2$.
4 = Sodiumcarbonate-type, $NaHCO_3$
5 = Calciumchloride-type, $CaCl_2$
6 = Mixed water-type

Figure 6: Water classification according to Stiff (Cultuurtechnisch Vademecum, 1988)

Table 4.1 : Mean monthly and annual precipitation of six meteorological stations (appendix 2)

Station	1	2	3	4	5	6
Jan.	457.5	215.8	253.4	302.6	434.5	493.2
Febr.	272.5	155.9	162.8	221.8	376.2	368.2
March	238.5	281.4	132.5	210.2	336.4	406.6
April	286.6	249.9	185.2	255.9	427.6	357.7
May	378.9	392.4	367.6	390.5	543.1	604.8
June	400.1	101.0	367.2	435.6	872.9	699.8
July	562.1	422.8	452.8	487.8	673.2	762.8
Aug.	507.2	478.9	446.2	477.4	869.6	797.8
Sept.	334.6	318.5	275.6	377.5	752.9	646.3
Oct.	509.9	446.2	357.8	455.7	721.4	719.3
Nov.	692.4	196.0	364.8	473.7	676.2	612.0
Dec.	676.6	492.3	374.5	461.2	408.8	594.2
Total	5316.6	3751.1	3740.4	4549.9	7092.8	7062.7

Station 1 : Tortuguero North, Tortuguero
Station 2 : Banana plantation Lomas de Sierpe, Lomas de Sierpe
Station 3 : La Mola, Cariari
Station 4 : Los Diamantes, Guapiles
Station 5 : Carillo, Carillo
Station 6 : La Montura, La Montura

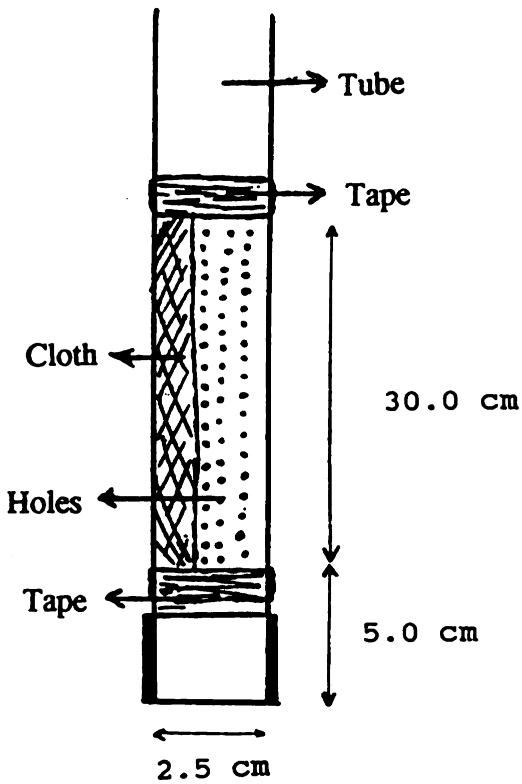


Figure 7: Detail of piezometer filter

5 MATERIALS AND METHODS

Introduction

In this chapter the materials and methods of the research are given. The hydrochemistry-, discharge- and groundwater head measurements are explained and a computer model FLOWNET is described which is used to visualize possible groundwater flow paths of regional and local systems.

Hydrochemistry

The hydrochemistry from ground and surface water was studied. Three samples were taken, after a dry period, of the rivers Sucio, Hondura and Chirripo because they drain a part of the Cordillera Central. The river Sucio also drain the slopes of the Irazu volcano. These sloping areas have volcanic ashes in the subsoil which are relevant as nutrient resource. This is an important phenomenon for other parts of the Atlantic Zone by influence of volcanoes.

Samples of surface water from the river Tortuguero were taken, both after a wet (28-01-1993) and dry (26-02-1993) period, in the up-, mid- or downstream parts of the catchment (map 1). These measurements were carried out to find out if the river Tortuguero or its tributaries are fed by base flow or mainly surface runoff. This might result into a subdivision of the primary catchment into secondary and tertiary catchments.

The rivers Guapiles and San Rafael, tributaries of the river Tortuguero (map 1), were also chosen for sampling because of the area and location of their catchment in the Tortuguero catchment. These two rivers have a rather large catchment, which stretches from the upstream part on the Toro Amarillo alluvial fan to the midstream part of the alluvial plains. Probably different surface watertypes can be found.
Samples of deep groundwater (30 to 60 m) and drainwater of the secondary canals, which border the experimental area at the banana plantation Lomas de Sierpe, were taken to find possible differences in watertype of deep and shallow groundwater. This could give more insight in a seepage or recharge situation. These samples were taken both after a dry and a rainy period.
Bottles (200 ml) were three times rinsed with sampling water before they were filled and cooled at 4°C. A total chemical analysis, of twelve samples which were taken after a dry period, was carried out in the Netherlands (Laboratory of the Department of Soil Science and Geology, Agricultural University Wageningen). This analysis is carried out on cations Fe^{3+}, Ca^{2+}, Mg^{2+}, Mn^{2+}, K^+, Na^+ and NH_4^+, on anions $H_2PO_4^-$, SO_4^{2-}, HCO_3^-, NO_3^- and Cl^- and on SiO_2.
Seventeen wet period surface water samples were analyzed in Costa Rica (Laboratory of 'Unidad de Suelos', Agricultural Ministry in San Jose) only on macro cations, i.e. Ca^{2+}, Mg^{2+}, K^+ and Na^+. There a total chemical analysis cannot be carried out. Every water sample is also analyzed on pH and Ec. The results of the water samples are interpreted according to Piper (fig.5) and to Stiff (fig.6).

Discharge

The discharges were measured of the rivers Los Diamantes in Guapiles and the Mata de Limon near the banana plantation Lomas de Sierpe, respectively in the upstream part and in the downstream part of the Tortuguero catchment. These measurements were done using the tracer method (Warmerdam, 1979). The measurements were repeated for different discharges.

A tracer method is based on the dilution of brooklet water, with for instance, salt or radioactive material. This method is useful when the water depth is shallow or there is much turbulence. The tracer method can be divided in two techniques of addition, namely:
- the continuous addition
- the momentaneous addition (integration method)

The continuous addition

A tracer, for instance sodiumchloride (NaCl) with a constant concentration (C_1), is added to the brooklet water at a location where a good mixing prevails.
The tracer is dissolved in a Mariotte bottle, which has a constant discharge (q) during the outflow period.
The brooklet water, with discharge Q, contains some salt with a concentration C_0. The water at the measuring point, downstream of the Mariotte bottle where complete mixing prevaile has a concentration C_2.
A mass balance can be written as follows:

$$Q\,C_0 + q\,C_1 = (Q + q)\,C_2 \qquad (1)$$

salt quantity at addition point	salt quantity at measure point

With equation 1 the discharge Q can be calculated as follows:

$$Q = q\,\frac{C_2 - C_1}{C_0 - C_2} \qquad (2)$$

The different concentrations (C_0, C_1 and C_2) and the discharge q must be measured. Mostly, the concentrations are less than 50 mg l^{-1} NaCl and in then the electric conductivity (Ec) is proportional to the concentration. In this case the Ec can be measured instead of the concentrations, which saves time. In equation 2 C_2 can be neglected relative to C_1 and C_0 relative to C_2. Equation 2 reduces to equation 3.

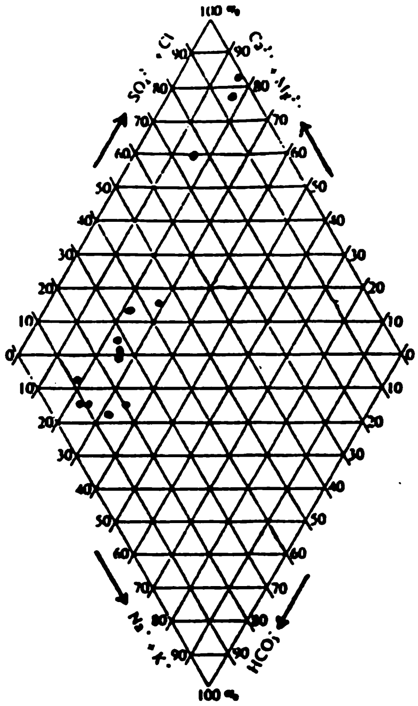


Figure 8: Piperdiagram of the dry period water samples

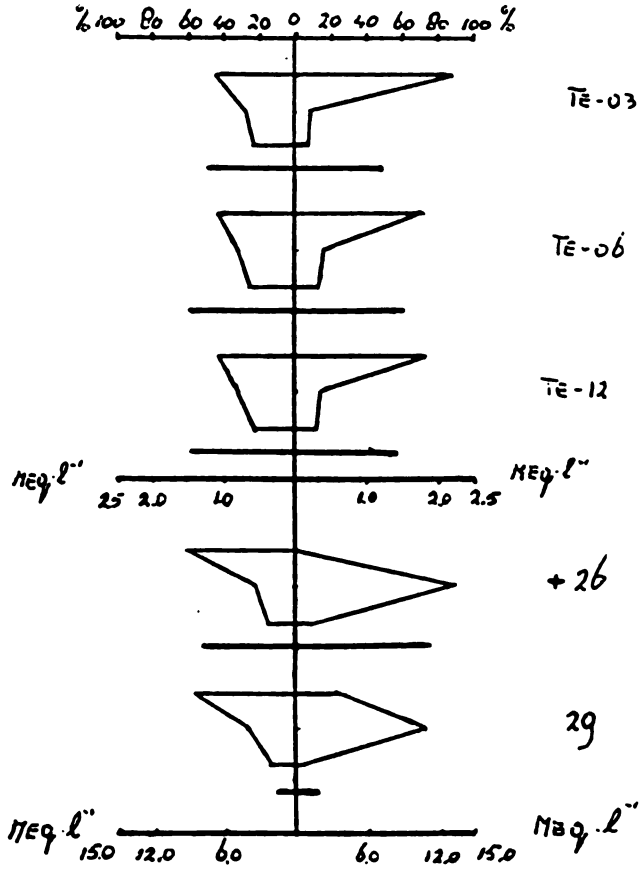


Figure 9: Stiffdiagram of samples Te-03, Te-06, Te-12, +26 and +29

In the brooklet a discharge (q) of a salt solution with a concentration C_1 and an electric conductivity Ec_1 is diluted by brooklet water with a discharge Q till a concentration C_2 and an electric conductivity Ec_2. Some meters downstream of the addition place, where a complete mixing occurs, the electric conductivity (Ec) is measured.

The discharge Q of the brooklet can be calculated as follow:

$$Q = q \frac{C_1}{C_2} = q R = q \frac{Ec_1}{Ec_2} \qquad (3)$$

where R is the dilution factor.

The momentaneous addition (integration method)

The salt solution is added during a very short period to the brooklet water. Assume that an amount salt is dissolved in V liter water which eventually has a concentration C_1. In the measure point an amount of salt passes during a period $t=t_0$ till $t=t_1$ which equals:

$$Q \int_{t_0}^{t_1} C_2(t)\, dt \qquad (4)$$

In equation (4) is Q the discharge of the brooklet, C_2 (t) is the salt concentration at the measure point. The concentration C_2 changes during the passage of the salt and at time t_n the total salt amount has passed the measure point. In equation form:

$$V C_1 = Q \int_{t_0}^{t_n} C_2(t)\, dt \qquad (5)$$

or:

$$Q = \frac{V C_1}{\int_{t_0}^{t_n} C_2(t)\, dt} \qquad (6)$$

Surface water level at a fixed point and electric conductivity of the river Los Diamantes were measured four to five times a week, during March-June 1993, to get more insight in the discharge response on precipitation. Actually the river Los Diamantes is not part of the Tortuguero catchment, but it is representative for the Toro Amarillo alluvial fan. However, it is assumed that the river Tortuguero and its tributaries in the upstream part, i.e. river Guapiles and river San Rafael, show a similar behaviour.

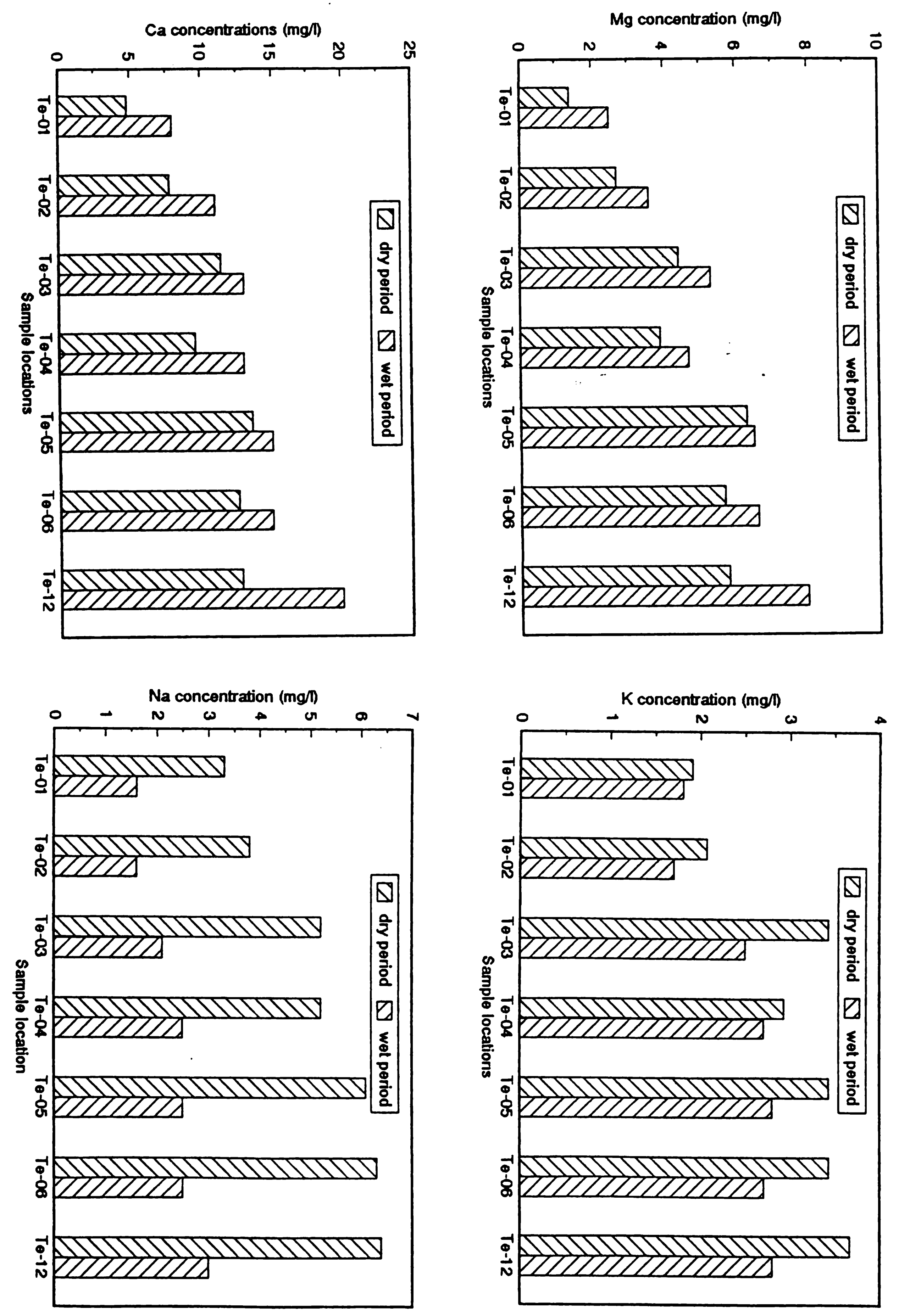


Figure 10: Bar diagram of the cation concentration (mg l^{-1}) of the dry and wet period surface water samples

Weirs were placed at the end of the two secondary canals of experimental area LS2 of the banana plantation (appendix 1B). These V-shape weirs were made of a steel plate. Discharge, on a particular time, was measured using a bucket in which the water was collected during a certain period of time. Moreover, each time the electric conductivity was measured. Each discharge measurement was done twice.

Groundwater heads

In two different experimental areas in the banana plantation Lomas de Sierpe groundwater heads were measured to study flow direction and velocity. The first area (LS1) is located at the border of the banana plantation near the airport (map 2 and appendix 1A). A deep tube was installed by the banana company to extract drinking water, with a filter depth of about 65 m. This provided the possibility to measure deep groundwater head relative to shallow groundwater head. The deep tube is situated near a primary drainage canal of the banana plantation. To find out whether upwards seepage or downward seepage exist, the shallow groundwater head must be known compared to the deep groundwater head. The shallow groundwater head, perpendicular to the primary canal, was measured with six bore holes located as transect TS1 (appendix 7). These bore holes vary in depth from 2.5 m to 3.5 m. The first bore hole is located at the same distance of the primary canal as the deep tube. The distance between the other bore holes was about 25 m (appendix 1A).
Above every bore hole a fixed point was prepared on a stake. Relative to this fixed point the shallow groundwater heads were measured. The fixed points of all bore holes were at the same level. This level was 126 cm beneath the top of the deep tube in which the deep groundwater head was measured. Levelling of the fixed points was done with a water hose. The groundwater heads were observed with a plunger fixed on a flexible steel rule.

The other area (LS2) contains three transects with piezometers (map 2 and appendix 1B). One in the downstream southern part (TS2) and one in the upstream northern part (TS3) of the experimental area (appendix 7). In each transect five tubes were installed perpendicular to the secondary canals. The distance between these tubes is about 20 m. The distance between the canal and the outermost tubes is about 10 m. The third transect (TS4) was perpendicular to the other two transects TS2 and TS3 located and has a north-south direction (appendix 7). The distance between these tubes varies from about 35 m to 70 m. The top of each tube was leveled relative to tube number 3 with a water hose. Each tube was sealed downwards and had a filter of about 30 cm length at the bottom which exists of small holes made with an electric drill. The filter screen was covered with a cloth and bounded with bandage at the top and bottom (fig.7). The groundwater head was measured in each tube relative to the top of the tube, and finally the groundwater heads were calculated relative to tube 3.

During the drilling of the bore holes and piezometers the different deposits were described in terms of depth, texture, color and comments. The depth of each bore hole or piezometer depends on the shallow groundwater depth, and vary from 2.5 m to 4.5 m below ground level.
Tube 13 was drilled to a filter depth of 7.5 m relative to tube 14 (3.7 m) to find possible

differences in the shallow groundwater heads in vertical direction. Differences are relevant for the determination of downward or upward seepage in the experimental area LS2.

Computer model FLOWNET

This computer model simulates two-dimensional steady-state saturated groundwater flow in a rectangular inhomogeneous anisotropic section of the subsoil (Van Elburg, 1989). The section is vertical, which means that depth and distance are the two spatial dimensions. Simulation of groundwater flow in a vertical transect is only relevant, if the transect is perpendicular to the groundwater contour lines. The pattern of flow lines and equipotential lines is obtained by using the finite-difference method. Therefore, a regular grid of rectangular cells has to be defined. The highest possible number of model cells is about 5000. Futhermore, FLOWNET calculates residence times, draws isochrones, and animates these patterns. The input data consist of hydraulic heads and to define the boundery conditions, hydraulic conductivity and effective porosity for each cell.

6 RESULTS AND CONCLUSIONS

Introduction

The chemical composition of groundwater and surface water is presented in this chapter. Furthermore the discharges of different parts of the Tortuguero catchment are given. Finally, the observed groundwater heads are dealt with. The results are seperately interpreted to explore possible presence of upward seepage or downward seepage and to indicate discharge behaviour of different catchment parts. A complete quantitative hydrological description of the Tortuguero catchment was beyond the scope of the study.

6.1 Hydrochemistry

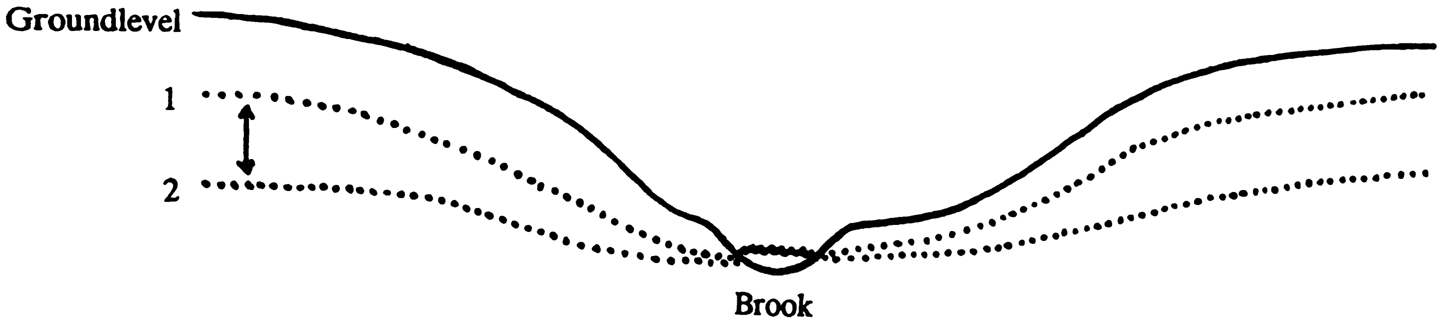
Results

First in table 6.1 the electric conductivity of precipitation near Guapiles is given.

Table 6.1 : Electric conductivity ($\mu S\ cm^{-1}$) and temperature ($^{\circ}C$) of daily precipitation (mm) near Guapiles

Date	Ec	temp.	precipitation	comment
19-3-1993	18	16.6	29.7	
20-3-1993	4	16.4	84.6	downpour
28-3-1993	11	17.2	86.1	
25-4-1993	12	16.8	50.9	
10-5-1993	17	17.5	56.2	
11-5-1993	12	17.5	26.0	
27-5-1993	7	17.2	15.9	
01-6-1993	3	17.0	23.8	downpour
07-6-1993	4	17.8	40.8	downpour
12-6-1993	4	18.2	79.5	downpour

The results of the water analysis were worked out according to Piper (fig.5) because of the absence of anion analysis of the wet sampling period and to make a comparison between dry and wet period water samples possible.
Water samples after a dry period from the river Sucio, Hondura and the up-, mid- and downstream samples of river Tortuguero were worked out according to Stiff (fig.6). Possible differences in ionic contents and concentrations of cations and anions can be shown.



1 : groundwater table during a wet period

2 : groundwater table during a dry period

↕ difference in storage capacity

Figure 11: Schematic sketch for the differences in groundwater storage capacity caused by different groundwater tables

The results of the laboratory analysis for the dry and wet period, sampling location and relative portion calculations of ions are given in appendix 3.
The calculated results for the dry period, are given in a Piperdiagram (fig.8). In table 6.2 water classification according to Piper for the dry and the wet period is given. After the wet period more locations were sampled then after the dry period. A comparison of similar sampling locations after the wet and dry period is made in table 6.2.

Table 6.2 : Water classification according to Piper, after a dry and a wet period, compared to similar sampling locations

Dry period	Wet period
Te-01 = Secondary alkaline	85684 = (Te-02) Secondary
Te-02 = Secondary alkaline	85685 = (Te-03) Secondary
Te-03 = Secondary alkaline	85686 = (Te-05) Secondary
Te-04 = Secondary alkaline	85687 = (Te-06) Secondary
Te-05 = Secondary alkaline	85688 = (Te-04) Secondary
Te-06 = Secondary alkaline	85689 = Secondary
Te-08 = Secondary alkaline	85690 = (Te-01) Secondary
Te-09 = Secondary alkaline	85691 = Secondary
Te-10 = Secondary alkaline	85692 = Secondary
Te-11 = Secondary alkaline	85693 = Secondary
Te-12 = Secondary alkaline	85694 = Secondary
	85695 = Secondary
+26 = Secondary saline	85696 = (Te-12) Secondary
+27 = Secondary saline	85697 = Secondary
+29 = Secondary saline	85698 = Secondary
	85699 = Secondary
	85700 = Secondary

Figure 9 shows Stiff diagrams of surface water samples of the upstream (Te-03), midstream (Te-06) and downstream (Te-12) part of the river Tortuguero, the river Sucio (+26) and river Hondura (+29).

Conclusions

The analyse results of water sample Te-07 are erroneous, probably due to oil contamination. They are not included in the conclusions.

The rain water Ec near Guapiles is during rain showers about 10-15 $\mu S\ cm^{-1}$. During downpours these values decreases to about 3-4 $\mu S\ cm^{-1}$, due to a lower dust content of the atmosphere then. This is important to understand the fluctuations of the Ec of surface water during downpours.

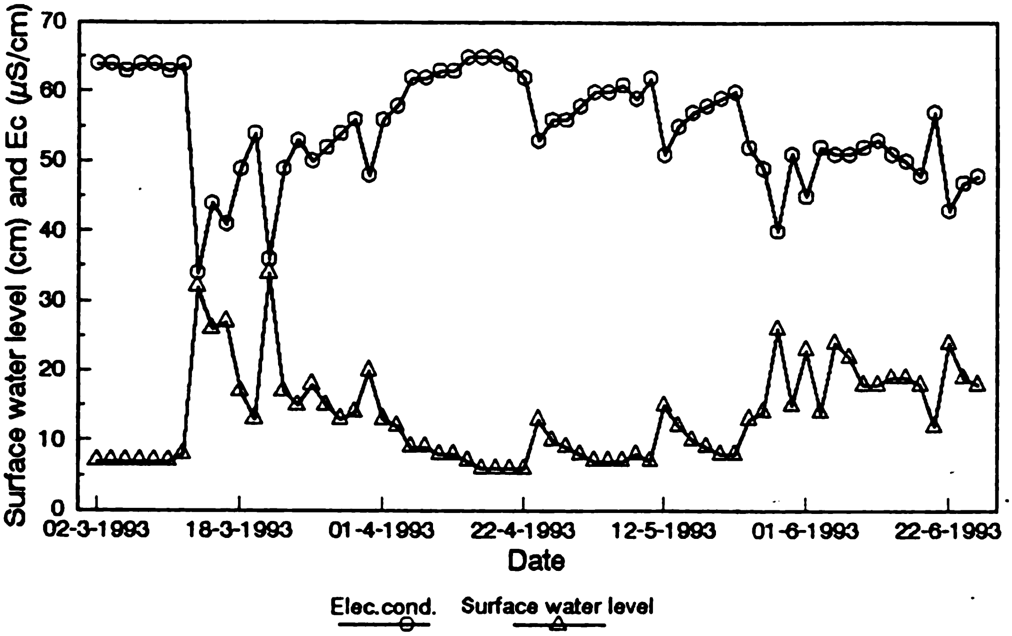


Figure 12: Electric conductivity and associated surface water level of river Los Diamantes from March to June 1993

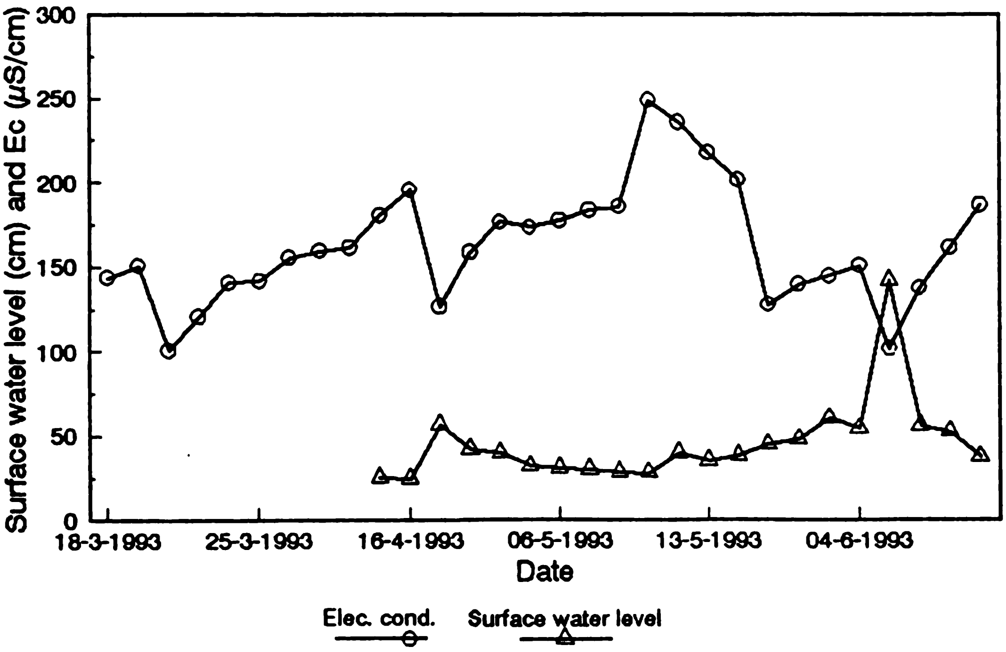


Figure 13: Electric conductivity and associated surface water level of river Mata de Limon from March to June 1993

With an Ec decrease of the surface water because of the precipitation, more insight could be get in the discharge increase caused by surface runoff. This is explained later when dealing with the discharge behaviour of the rivers Los Diamantes and Mata de Limon.

Surface water samples from the rivers Sucio (+26), Chirripo (+27) and Hondura (+29) are of a secondary saline watertype (fig.6 and fig.9). River Sucio, which contain a high SO_4^{2-} concentration (481 mg l^{-1}), drains the slope of the Irazu volcano and probably hydro termal water from the crater, which is green colored, flows into the river. The green color indicate a high concentration of especially $FeSO_4$ and also explains the enormous high concentrations of other ions. Another reason of the high SO_4^{2-} concentration of the river is probably due to rinsing of S from ashes.

The interpretation of cation concentrations, of the Tortuguero catchment, according to Piper shows no differences of watertype between a dry and wet period. This means that classification according to Piper is too rough. It is reasonable to assume that this also holds for the anions. There is no reason why the anion portion would change from an alkaline watertype, during or after a dry period, into a saline watertype during or after a wet period.
Ca^{2+} and Mg^{2+} concentrations of surface water during or after the wet period are slightly higher than these concentrations during or after the dry period for the Tortuguero catchment which means that leaching must occur during wet periods (fig.10). The opposite occurs for the K^+ and Na^+ cations with a higher concentration during or after dry periods. During a dry period a base flow with lower Ca^{2+} and Mg^{2+} and higher K^+ and Na^+ concentrations occurs. During the dry period a more intensive weathering must occur in the unsaturated zone, also the zone between 1 and 2 (fig.12). This chemical weathering result in a higher part of Ca^{2+} and Mg^{2+} than K^+ and Na^+. This must be due to rock composition. The zone between 1 and 2 of figure 12 is a result of groundwater head lowering due to a lack of precipitation while the base flow stays. The higher Ca^{2+} and Mg^{2+} concentration during wet periods (with higher groundwater heads) is due to leaching of Ca^{2+} and Mg^{2+} from the then saturated zone between 1 and 2 (fig.12) as a result of the steeper groundwater head gradiënts (Nota et al, 1987).

Samples Te-01 and Te-02 are taken upstream of Guapiles on the alluvial fan where no human influence occurs. These samples contain a total ion concentration after the wet period which is about twice the concentration after the dry period. The concentration of total ions along the river Tortuguero from the spring to the Caribbean Sea of the dry period surface water samples Te-03 (upstream), Te-06 (midstream) and Te-12 (downstream) shows a slight increase, while the wet period surface water samples 85685 (upstream), 85687 (midstream) and 85696 (downstream) shows a higher increase (appendix 3). A conclusion could be that during downpours surface runoff undoubtly occurs and brooklets and rivers are fed both by base- and surface flow. Ionic concentrations of surface water should be less during downpours relative to the situation when they are fed by base flow only. After rainstorms the water storage capacity of the soil is more filled which result in a higher groundwater head (fig.11). The steeper groundwater gradients results in a larger base flow content relative to periods before rainstorms and could mean that precipitation causes leaching of Ca^{2+} and Mg^{2+} ions with increasing cation concentrations from up- to downstream parts of the Tortuguero catchment due to differences of rock composition.

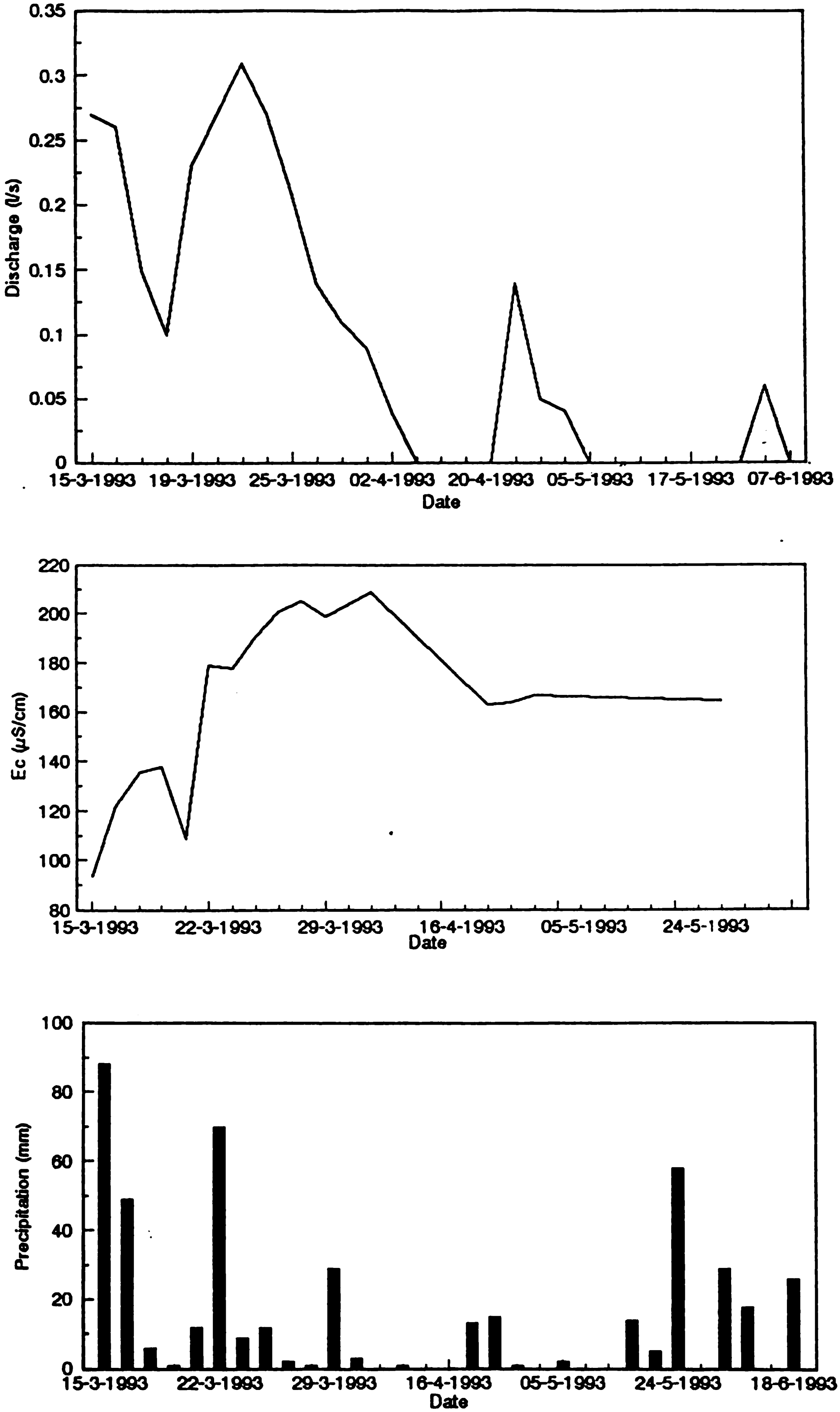


Figure 14: Discharge behaviour, compared with the Ec of drain water and precipitation, of the westerly situated secondary canal of experimental area LS2 of banana plantation Lomas de Sierpe

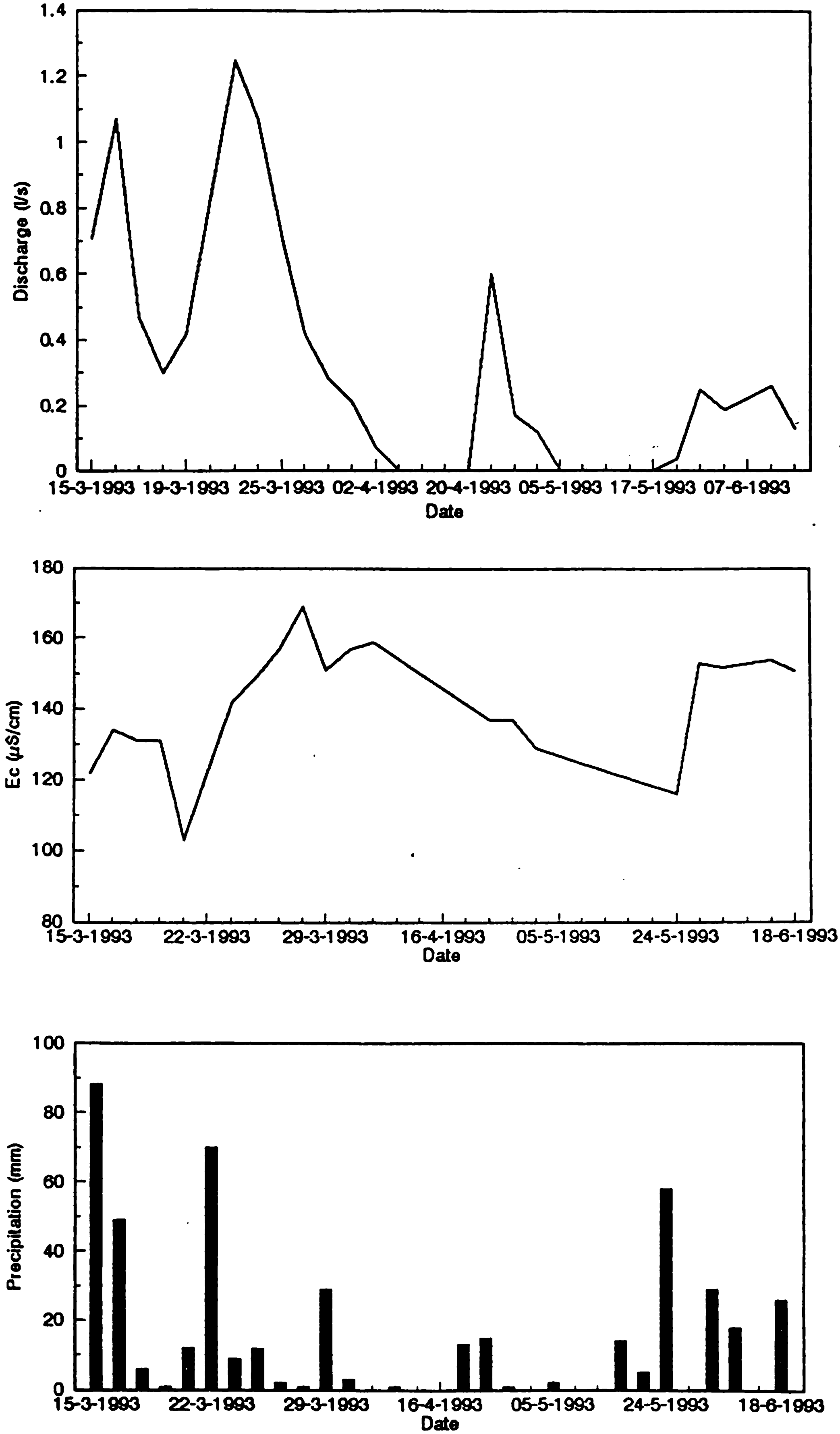


Figure 15: Discharge behaviour, compared with the Ec of drain water and precipitation, of the easterly situated secondary canal of experimental area LS2 of banana

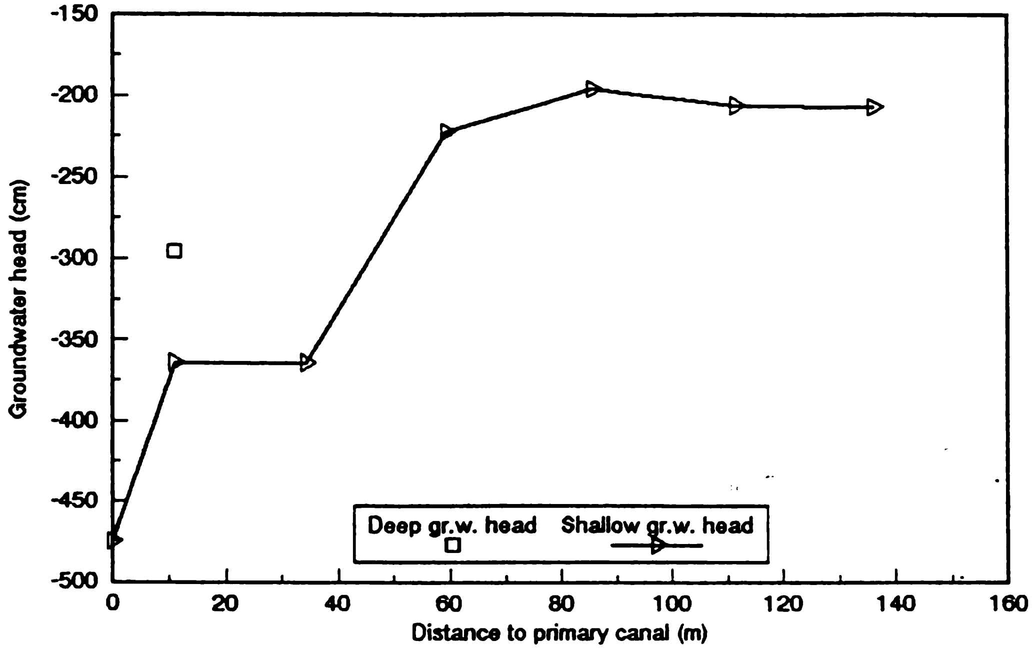


Figure 16: Deep and shallow groundwater heads after a wet period of experimental area LS1 of banana plantation Lomas de Sierpe.

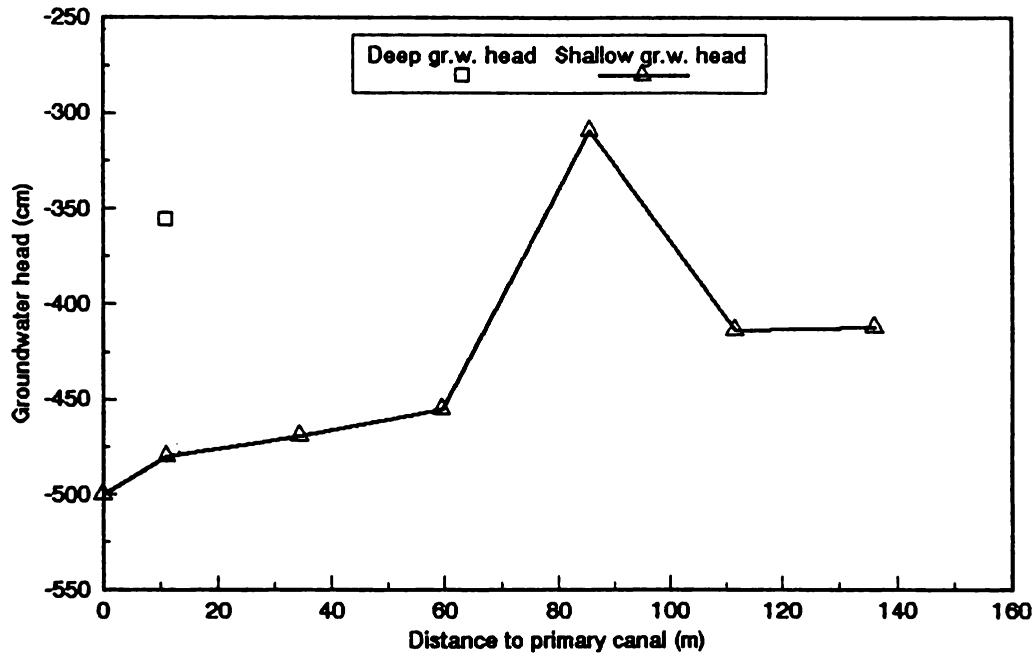


Figure 17: Deep and shallow groundwater heads after a dry period of experimental area LS1 of banana plantation Lomas de Sierpe.

A subdivision of the Tortuguero catchment into secondary and tertiairy catchments on the basis of hydrochemistry cannot be made. The upper part of the catchment, the alluvial fan, could be classified as different from the mid- and downstream parts of the Tortuguero catchment. Surface water concentrations of this part differ from the other parts, which probably could be due to sediment differences between the alluvial fan and alluvial plain.

Differences in ion concentration between Te-09 and Te-10, the secondary canals of the experimental area, are rather large while similarity was expected. Both canals drain the shallow groundwater system. Although watertype classification of these samples according to Piper is equal, differences are large. Differences could be caused by nitrogen and lime fertilization. Fertilization differs during time from part to part (i.e. area LS2) of the banana plantation. If this is the reason of the differences then sample Te-09 (no Nitrogen), with a higher content of Ca^{2+}, Mg^{2+} and HCO_3^-, could indicate lime manuring. Sample Te-08 (contains Nitrogen) could be a result of nitrogen fertilization. The higher amount of NO_3^- and NH_4^+ of samples Te-08 (1.4 mg N l^{-1}), Te-11 (2.5 mg N l^{-1}) (deep tubes) and Te-10 (2.9 mg N l^{-1}) compared to Te-09 (0 mg N l^{-1}) could indicate that Te-09 represent more or less groundwater which is less affected by human activities, with exeption of Ca^{2+}, Mg^{2+} and HCO_3^-. The higher nitrogen contents of water from deep wells suggests a downward seepage situation caused by nitrogen leaching. Samples from deep wells, Te-08 and Te-11, show no real similarity of cations and anions. This could be due to differences of depth, which is unknown.

6.2 Discharge

Results

In table 6.3 the results of the discharge measurements with the tracer method of different rivers of the Tortuguero catchment are given.
Electric conductivity and surface water level, relative to a fixed point, of the rivers Los Diamantes and Mata de Limon for the period March to June 1993 are shown in figures 12 and 13 respectively. The data are given in appendix 4. The discharge of the secondary canals adjacent to experimental area LS2 of the banana plantation Lomas de Sierpe from March to June 1993 is given for the westerly and easterly situated canal in figure 14 and 15, respectively. The discharge is compared with the Ec and precipitation to find out if these canals are fed by base flow or mainly surface runoff. Data is given in appendix 5.

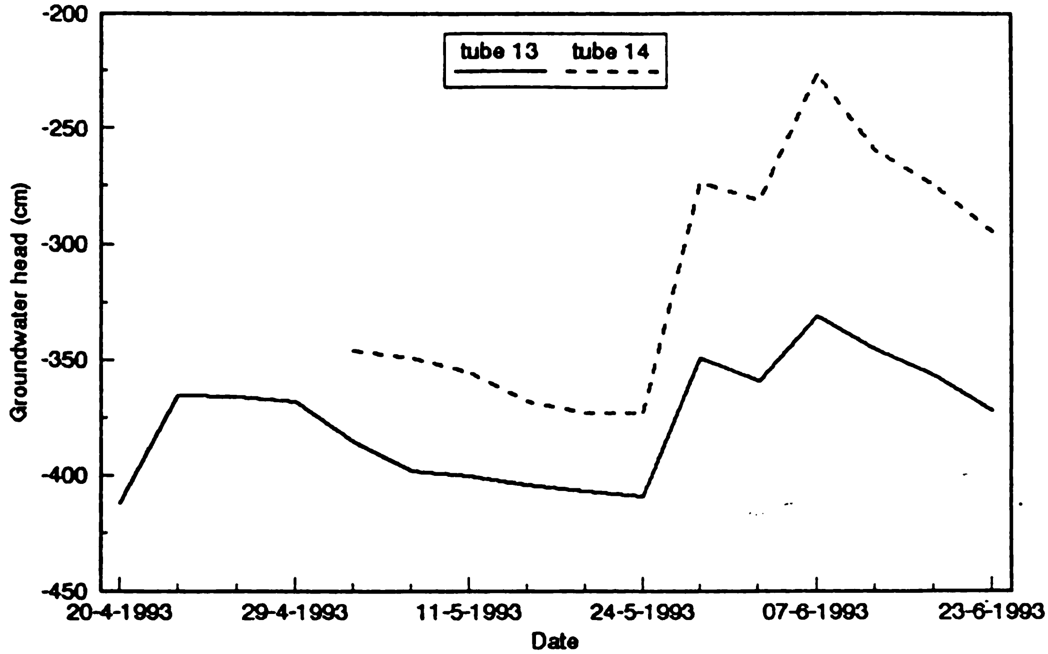


Figure 18: Groundwater heads of tube 13 and 14 of experimental area LS2 of banana plantation Lomas de Sierpe.

Table 6.3 : Results of discharge measurements in rivers Los Diamantes, Mata de Limon and Tortuguero (upstream part) using tracer method

Date	River	Location	Discharge ($m^3 s^{-1}$)
16-4-1993	Mata de Limon		0.067
			0.070
22-4-1993	Los Diamantes		0.222
18-6-1993	Tortuguero	up-stream	0.125
24-6-1993	Los Diamantes		0.476
			0.412

Conclusions

The discharges of the different rivers of the Tortuguero catchment (table 6.3) are given as an indication. No conclusions are given exept that this method of discharge measurement is not very exact. This is due to problems of salt dilution which result in large Ec fluctuations downstream of the addition point. The discharge is more an approach.

Discharge fluctuations of the river Los Diamantes are rather common, due to local rainstorms especially near the footslopes of the Cordillera Central. As mentioned in chapter 4 an increase of precipitation occurs with decreasing distance to the mountain range. An increase of precipitation results in lower Ec values due to dilution of base flow, with increasing surface water level (fig.12). The highest measured Ec of the river Los Diamantes is 65 $\mu S\ cm^{-1}$ (appendix 4), when the river is fed by base flow only and no rain occured for several days. Field observations on 16 March 1993 showed that during 45 minutes the Ec decreased from 63 $\mu S\ cm^{-1}$ to 31 $\mu S\ cm^{-1}$, while at the sampling location near Guapiles no rainfall occured. The average precipitation Ec during downpours is about 4 to 5 $\mu S\ cm^{-1}$ (table 6.3). This means that during these 45 minutes discharge roughly redoubled, caused by surface runoff.
River Mata de Limon has a higher Ec, probably due to pollution by villages and banana plantations. An other reason could be groundwater which has flown through other deposits. At 10 May 1993 an Ec occured of 186 $\mu S\ cm^{-1}$, while the other day it was 249 $\mu S\ cm^{-1}$ with almost the same surface water level (fig.13). The latter Ec is likely to be the result from herbicide or nematicide application to the banana plantations by airplanes. There is some correlation between Ec and surface water level but it is flattened and it might be that pollution by banana plantations plays a large role. Discharge fluctuations as for the river Los Diamantes are not measured as a result of the different precipitation regime and relief in the midstream part of the catchment and flattening of base flow over longer periods of time due to lower hydraulic conductivity of the finer textured sediments there.

Figure 14 and 15 show the relation between drainwater discharge, drainwater Ec of the secondary canals of the banana plantation and precipitation. The discharge of the western

secondary canal is 2 to 4 times less than the discharge of the eastern canal. The eastern canal is about 1 m deeper than the western canal in the downstream part of the experimental area (appendix 1B). This results in a discharge increase of the eastern canal as a result of differences in drainage basis compared with the groundwater head. The maximum groundwater convexity is not situated in the middle of the experimental area LS2 but more westwards towards the western canal.
During rainy periods the discharge increases while the Ec decreases. This is a result of mainly surface runoff during rainy periods. After these periods the discharge rapidly decrease instead of an increasing drainwater Ec. The discharge of the secondary canals then is fed by base flow only. A main conclusion is that the upstream part of secondary canals only drain surface runoff, during downpours, because the groundwater head there is lower than the canal bottom.

6.3 Groundwater heads

Results

Deep and shallow groundwater heads from the LS1 area after a wet and dry period are presented in figure 16 and 17, respectively. The groundwater heads are given in cm below the top of the deep tube. The distance between the bore holes is given in meters.
The groundwater heads from tubes 13 and 14, in experimental area LS2, are shown in figure 18. Tube 13 shows the deep (filter at 7.5 m) groundwater heads, tube 14 the shallow (filter at 3.7 m) heads. The groundwater heads are given in cm below the top of tube 3. The later installation of tube 14 resulted in less groundwater head data. For area LS2 a groundwater contour map for a wet (22-03-1993) and dry period (24-05-1993) is shown in figure 19 and 20, respectively. The dotted lines are drawn as groundwater contours from interpolated groundwater head values. The groundwater contours are given in cm below the top of tube 3. The solid lines show possible flow pathes of shallow groundwater.
Groundwater head data of the experimental areas LS1 and LS2 are given in appendix 6.

Information about the deposits noted during installation of the bore holes and piezometers is presented as transects in appendix 7.
Transect TS1 : experimental area LS1 of banana plantation Lomas de Sierpe
Transect TS2 : experimental area LS2 of banana plantation Lomas de Sierpe
tube 1 to tube 5
Transect TS3 : experimental area LS2 of banana plantation Lomas de Sierpe
tube 8 to tube 12
Transect TS4 : experimental area LS2 of banana plantation Lomas de Sierpe
tube 3 to tube 10

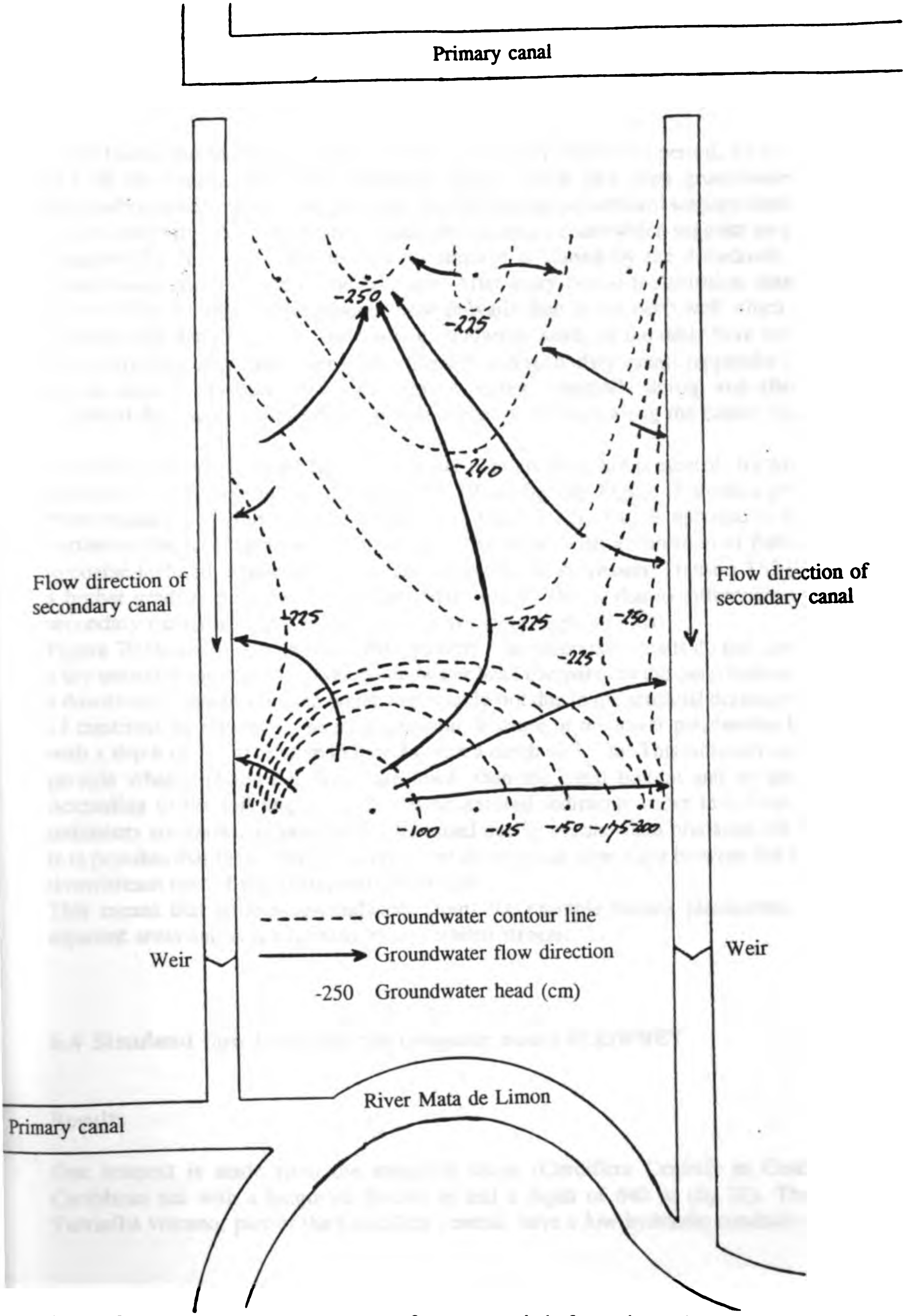


Figure 19: Groundwater contour map after a wet period of experimental area LS2 of banana plantation Lomas de Sierpe.

Conclusions

Data of deep and shallow groundwater heads especially after a wet period, for experimental area LS1 of the banana plantation Lomas de Sierpe, show that deep groundwater has a lower piezometric level than shallow groundwater. This implies downward seepage conditions. In about a 40 m wide strip along the primary canal the opposite occurs which suggests an upward seepage situation (fig.16). Probably this upward seepage is caused by the drawdown of the shallow groundwater head because of the drainage. After a dry period the situation changes, then only in bore hole 4 a higher groundwater head prevails than in the deep well which means upward seepage only there (fig.17). The lower groundwater heads of the other bore holes are possible due to draining of groundwater by the primary and secondary canals (appendix 1A). It is likely that in natural situation downward seepage occurs, especially during and after wet periods. Artificial drainage systems creates upward seepage in strips along the canals (fig.21).

For the experimental area LS2, groundwater contour maps are presented, for high (22-3-1993) and low (24-5-1993) groundwater heads (fig.19 and fig.20). Figure 19 shows a groundwater flow from transect TS2 (tube 1-5) to transect TS3 (tube 8-12). This is opposite to the slope of the bottom of the secondary canals. In transect TS4 (tube 3-10) a transition of fine-textured (TS2) to coarse-textured sediments (TS4) occurs and could be the reason. Transect TS2 (tube 1-5) show a higher gradient near the western secondary canal. This is due to differences in depth of the secondary canals wherefor no reasons are available (appendix 1B).
Figure 20 shows rougly the same flow pattern. The secondary canals do not drain water during a dry period because of the lower groundwater head compared to the canal bottom. This indicates a downward seepage situation which is probably not due to the artificial drainage system. Figure 13 confirms the downward seepage situation, because of the lower piezometric head of tube 13 with a depth of 7.5 m relative to tube 14 with a depth of 3.7 m. This situation occurs also in dry periods when groundwater heads are lower than the canal bottom and no discharge occurs. According to the soil map (map 2) coarse-textured sediments occur in a river pattern. These sediments are known as sandsheets, deposited during events when brooklets fill their own bed. It is possible that these sandsheets represent preferential flow ways between the brooklets in the downstream part of the Tortuguero catchment.
This means that polluted groundwater from, for example banana plantations, could flow to adjacent areas and is not drained by the nearest stream.

6.4 Simulated flow lines with the computer model FLOWNET

Results

One transect is made from the mountain range (Cordillera Central) in Costa Rica to the Caribbean sea with a length of 80.000 m and a depth of 640 m (fig.22). The rocks of the Turrialba volcano, part of the Cordillera Central, have a low hydraulic conductivity and acts as

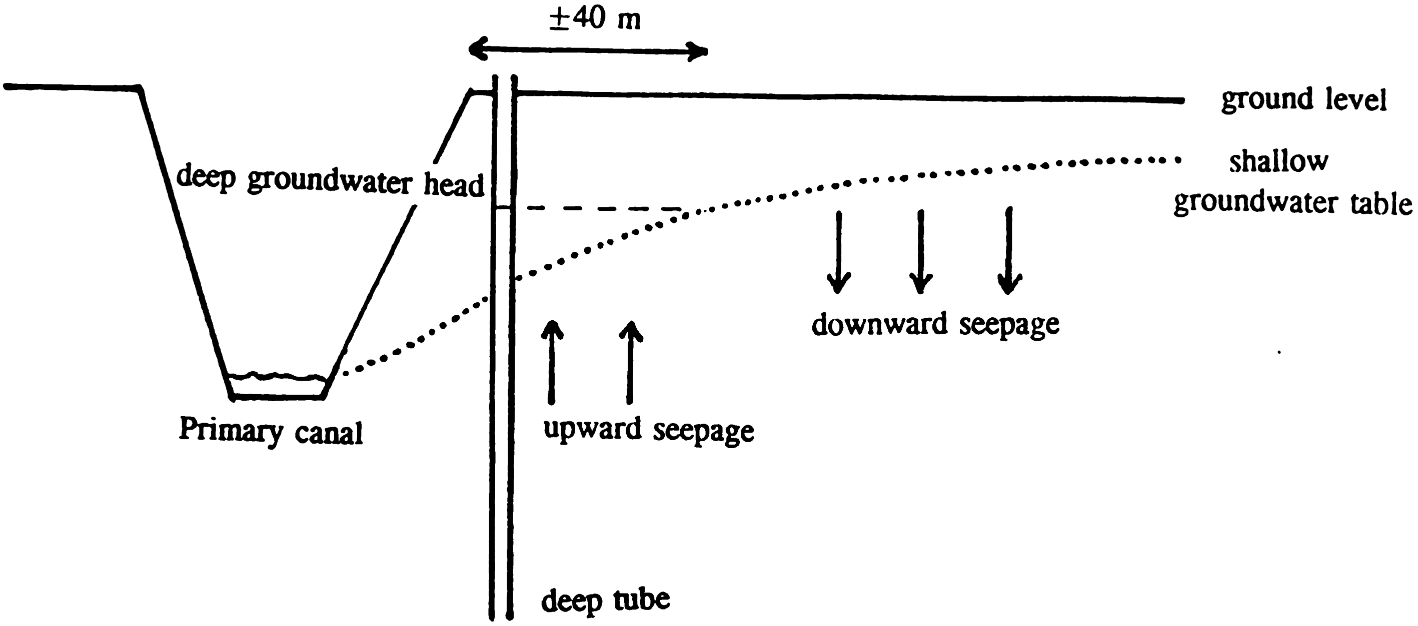


Figure 21: Schematic sketch of the downward- and upward seepage situation at experimental area LS1

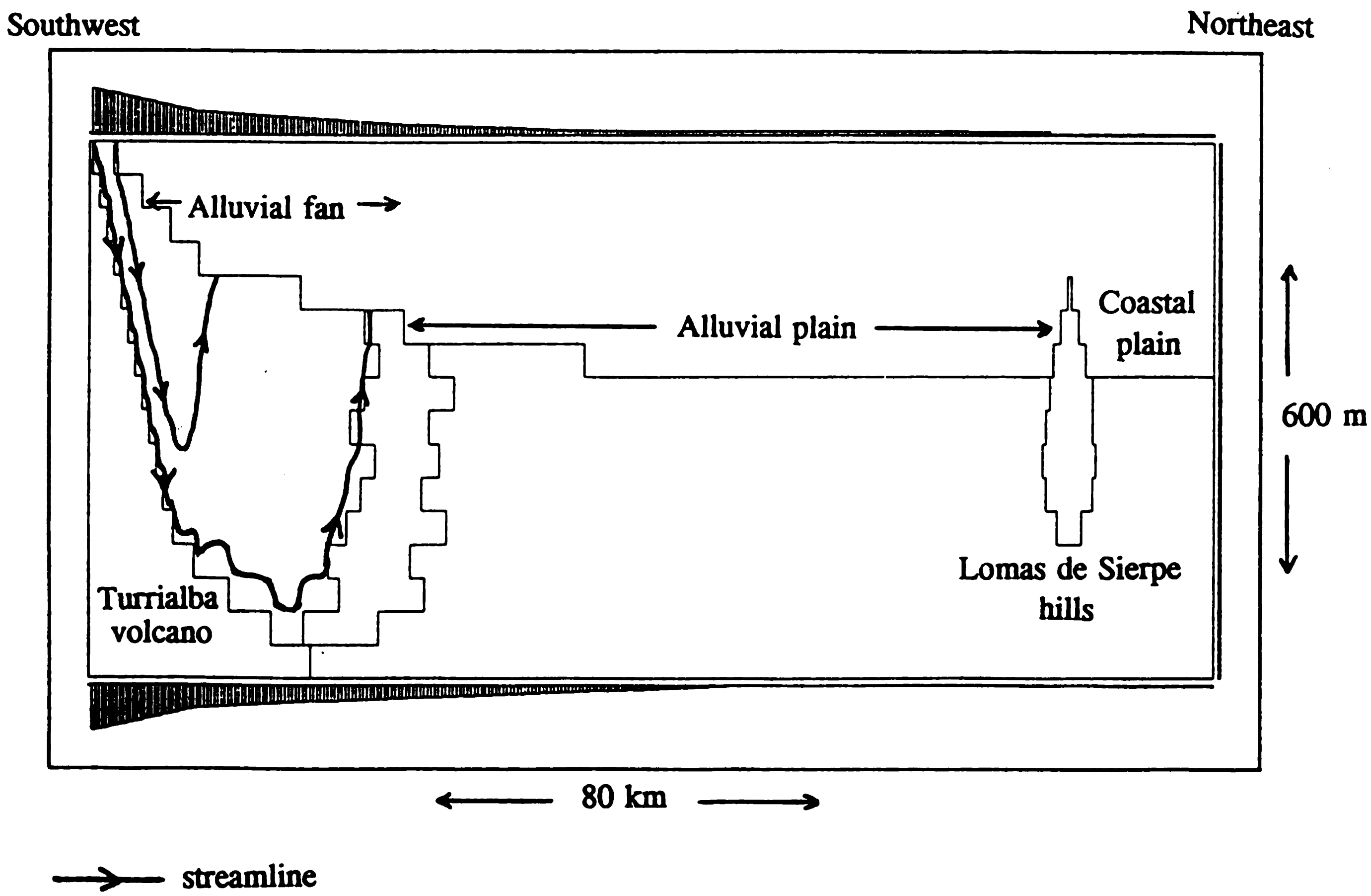


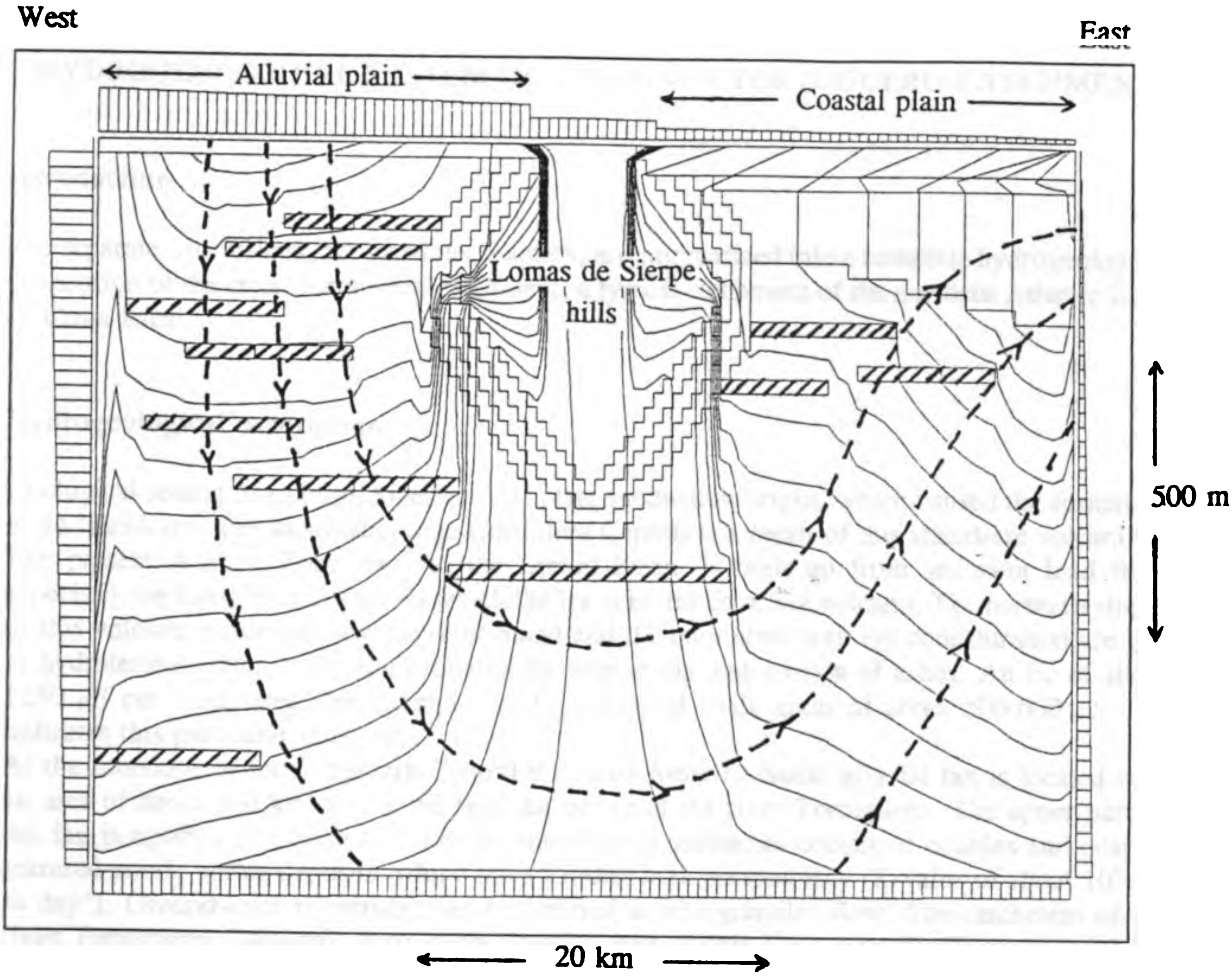
Figure 22: Simulated groundwater flow lines in a transect from the Cordillera Central to the Caribbean Sea of Costa Rica computed by the model FLOWNET

unpermeable. The alluvial fan is situated against the volcano with a rather high permability (10^2 m day^{-1}). A transition zone is defined between the alluvial fan and the deposits of the alluvial plain with a K-value of 10^{-1} m day^{-1} to 10^{-2} m day^{-1} (permeability of the alluvial plain). The basaltic hills Lomas de Sierpe are assumed to be unpermeable ($K=10^{-4}$ m day^{-1}). Finally, the coastal zone is expected to have the same hydraulic characteristics as the alluvial plain.
The hydraulic head (border condition) at the upper side of the transect are compared with the surface level gradiënt. The left side is defined as unpermeable with no hydraulic head. The right side is defined with an increasing hydraulic head with increasing depth, because an upward seepage situation is expected in the coastal plain. Finally, the hydraulic head at the bottom side shows a flattened gradiënt compared to the hydraulic head gradiënt at the upper side of the transect. At the left part, of the transect at the bottom side, a lower head occurs compared with the head at the right part of the upper side. At the right part, of the transect at the bottom side, the opposite occurs with a larger head at the bottom side compared to the head at the left part of the upper side, because of the expected upward seepage situation.

The second transect is made of the Lomas de Sierpe area where the experimental areas LS1 and LS2 are situated (fig.23). A transition is made from the alluvial plain deposits ($K=10^{-2}$ m day^{-1}) to the Lomas de Sierpe hills ($K=10^{-8}$ m day^{-1}) and from these hills to the coastal plain deposits ($K=10^{-2}$ m day^{-1}). The coastal plain consist of a peat layer ($K=10^{-4}$ m day^{-1}) and underneath a sandy deposit ($K=10$ m day^{-1}). Stratification of a few different coarse textured deposits are drawn. Information about these deposits is descended from drainage ingeneers of different banana plantations in the Lomas de Sierpe area.
The hydraulic head at the upper side of the transect is compared to the surface level gradiënt. The left side shows a decreasing head with increasing depth. This is defined according the conclusions about the deep and shallow groundwater head measurements in the LS1 experimental area at the banana plantation Lomas de Sierpe. The right side of the transect is defined with an increasing hydraulic head with increasing depth, because of the expected upward seepage situation there. The hydraulic head at the bottom side shows a flattened hydraulic gradiënt compared to the hydraulic head gradiënt at the upper side of the transect.

Conclusions

The results of the computer modelling are given as two different transects. In figure 22 the transection from the Cordillera Central to the Caribbean Sea is given. In the upper part of the alluvial fan a downward seepage situation occurs, while at the lower part of the alluvial fan an upward seepage situation occurs. This figure shows the local groundwater flow system of the alluvial fan.
Figure 23 shows the transect of the Lomas de Sierpe area where the experimental areas LS1 and LS2 are situated with the hills Lomas de Sierpe and the coastal area. The area of the banana plantation Lomas de Sierpe and adjacent areas shows a downward seepage system while the opposite occurs in the coastal plain. Streamlines are drawn in the basaltic rock of the Lomas de Sierpe hills, which is not acceptable because of the unpermeable character. A local system of groundwater flow occurs in the Lomas de Sierpe area.



- - -> - - streamline

——— equipotential line

////// Coarse textured sediments

Figure 23: Simulated groundwater flow lines in a transection from the alluvial plain to the coastal plain computed by the model FLOWNET

7 HYDROGEOLOGICAL SYSTEM OF THE RIVER TORTUGUERO CATCHMENT

Introduction

The separate conclusions, see previous chapters, are summarized into a complete hydrogeological description of the river Tortuguero catchment, a typical catchment of the northern Atlantic Zone of Costa Rica.

Hydrogeological description

Geological setting of Central America is of plate subduction origin, which caused the formation of an island-arc. The mountain range Cordillera Central is a result of this island-arc volcanism. The present Atlantic Zone, part of the Limon Basin, is built up from sediment load from especially the Cordillera Central in which the Irazu is still an active volcano. The northern slopes of this volcano are drained by the river Sucio and the enormous high ion concentration are due to hydrotermal crater water and probably by weathering and erosion of ashes. An Ec of about 1250 μS cm^{-1} compared, for example, to Ec values of chalk areas of about 500-600 μS cm^{-1} indicates this particular character.
At the footslope of the Cordillera Central the Toro Amarillo/Sucio alluvial fan is located with an area of about 300 km^2 where we find the spring of the river Tortuguero. The upper part of the fan is uplifted and dissected. The unconsolidated sediments consist of coubles and coarse-textured poorly sorted deposits, which have a rather high permeability (K-value of about 10^2-10^3 m day^{-1}). Groundwater movement can be typified as intergranular flow. The catchment of the river Tortuguero (240 km^2) starts at the inactive part of this Toro Amarillo/Sucio alluvial fan where a parallel drainage pattern of rather small brooklets occurs. Drainage density in this part of the catchment is high compared to the downstream parts. This drainage pattern is a function of subsurface permeability, climate, topographic slope and groundwater depth. Rain water and base flow, which is a result of infiltration on the fan, yields rather low Ec values of surface water. The highest measured Ec was 65 μS cm^{-1} (appendix 4), which suggests dilution with rain and a rather short residence time of base flow. Local downpours create enormous surface runoff, which could result in redoubling of discharges which fades away after a few hours (fig.12) and a decrease of the Ec to about 35 μS cm^{-1}. During dry periods, brooklets proceed carrying water, thus a rather large groundwater storage should exist. The size of the aquifer could be calculated, if the thickness of the fan was known.

First, regional groundwater flow system was expected to occur from the Toro Amarillo/Sucio alluvial fan at about 250 m above sea level to the alluvial plain at about 20 m height, which form the downstream part of the Tortuguero catchment and where the banana plantation Lomas de Sierpe is located. The alluvial fan is expected to be a recharge area, where downward seepage could occur. The high rainfall on the fan will partly flow as groundwater to the numerous brooklets after a short residence time, whereas the remaining part flows to the alluvial plains and/or the coastal plains as deep groundwater where upward seepage could appear from this deep

groundwater. However, this large system could not be identified by the simulation with FLOWNET. This condition can only prevail if permeable deposits occurs in the subsoil, with a rather great horizontal extend and which have an outcrop in the coastal area.
Considering the tectonic uplift of the Cordillera Central and the upper part of the alluvial fan adjacent to the Limon Basin, which has a maximum subsidence of 0.25 mm yr^{-1} in its centre, the required permeable sediments in the subsoil of the alluvial plain would not occur with an upward gradient and an outcrop. As a consequence of the uplifting, the upper part of the alluvial fan is expected to be rather thin. The lower part of the fan could have a interfinger structure with finer textured sediments. This could suggest a transition from a high to lower transmissivity. Therefore, it seems that at the alluvial fan a local system of groundwater flow occurs, which was confirmed by groundwater simulation (fig.22). The upper part of the fan acts as a recharge area with downward seepage while in the lower part upward seepage appears. The alluvial fan could be characterised as an unconfined aquifer. At the lower parts of the alluvial fan are banana plantations situated. With an upward seepage of groundwater in this area, pollution could only be distributed by brooks. Deep groundwater in this part will not be polluted.
This part of the alluvial fan is also used for drinking water winning. Surface water of brooks is catched, by weirs, and distributed by tubes to villages as Guapiles. No danger of water pollution occurs if banana plantations are located downstream of the water winning locations.

In the downstream part of the river Tortuguero, the river Mata de Limon has a less fluctuating Ec and surface water level response as compared to the respons of the river Los Diamantes (fig.13) which is situated in the upstream part of the Tortuguero catchment. In the downstream part a rather low drainage density occurs (map 1). In the banana plantation Lomas de Sierpe deep groundwater head (± 65m), especially during and after wet periods, has a lower piezometric level than shallow groundwater (fig.16 and fig.17). This results probably in leaching of nitrogen from shallow to deep groundwater. Shallow groundwater in the sandsheet deposits shows a decreasing head with increasing depth. Both observations indicate downward seepage in probably two directions. First, geomorphological units as the Pleistocene terrace remnants and between them the Holocene infill (sandsheets) could be the reason for the downward seepage of the shallow groundwater. Sandsheets have a rather high K-value (10^1-10^2 m day^{-1}) compared to the surrounding, deep weathered clayey Pleistocene remnants. It is reasonable that the sandsheets drain parts between the terrace remnants according to their sedimentation gradient. These sandsheets could be characterized as burried drainage systems (preferential flow paths). The groundwater in these sandsheets must somewhere flow out in a brooklet.
Downward seepage from shallow to deep groundwater could also indicate a local system of groundwater flow. Because of the rather high number of pumping locations near the banana plantation Lomas de Sierpe the downward seepage could be induced by human influence due to excessive pumping. The groundwater capacity of the layered coarse textured deposits could be to small for consumption, which result in a lower head compared with shallow groundwater head. The above mentioned process in the Lomas de Sierpe area means that a local systems of groundwater flow occur. Pollution with nutrients and pesticides might occur to adjacent areas by surface water (brooks), by shallow groundwater (sandsheets) and by deep groundwater.

REFERENCES

Cultuurtechnische Vereniging, werkgroep herziening cultuurtechnisch vademecum, (1988) Cultuurtechnisch Vademecum, Utrecht

Driessen, P.M. and Dudal, R., (1989) Lecture notes on the major soils of the world, Wageningen

Elburg, van H., Engelen, G.B. and Hemker C.J. (1989) FLOWNET version 5.1 User's manual

Erenstein, O., (1988) Los cultivos de Maiz y Yuca en el distrito de Rio Jiménez, Zona Atlantica de Costa Rica. Un estudio con enfasis en clima, operatividad y rendimiento, Guapiles

Nota, D.J.G., Bakker, A.M.G., Weerd, B. van der and Halma G., (1987) A hydrogeological study in the basin of Gulp Creek, a recoinnaissance in a small catchment area, Wageningen

Seeters, R.J.M. van, (1992) A study on geomophology, mineralogy and geochemistry of the Toro Amarillo-Tortuguero and the Chirripo-Matina river system in the Atlantic Zone of Costa Rica, Wageningen

Seyfried, H., Astorga, A., Amann, H., Calvo, C., Kolb, W. Schmidt, H. and Winsemann, J., (1991) Anatomy of an evolving island arc: tectonic and eustatic control in the south Central America fore-arc area, Utrecht

Vahrson, W.G., Arauz, B.I., Chacon, B.R., Hernandez, R.G. and Mora, C.S., (1990) Amenaza de inundaciones en Costa Rica, America Central.

Warmerdam, P.M.M., (1979) Handleiding voor debietmetingen in open leidingen en neerslagwaarnemingen

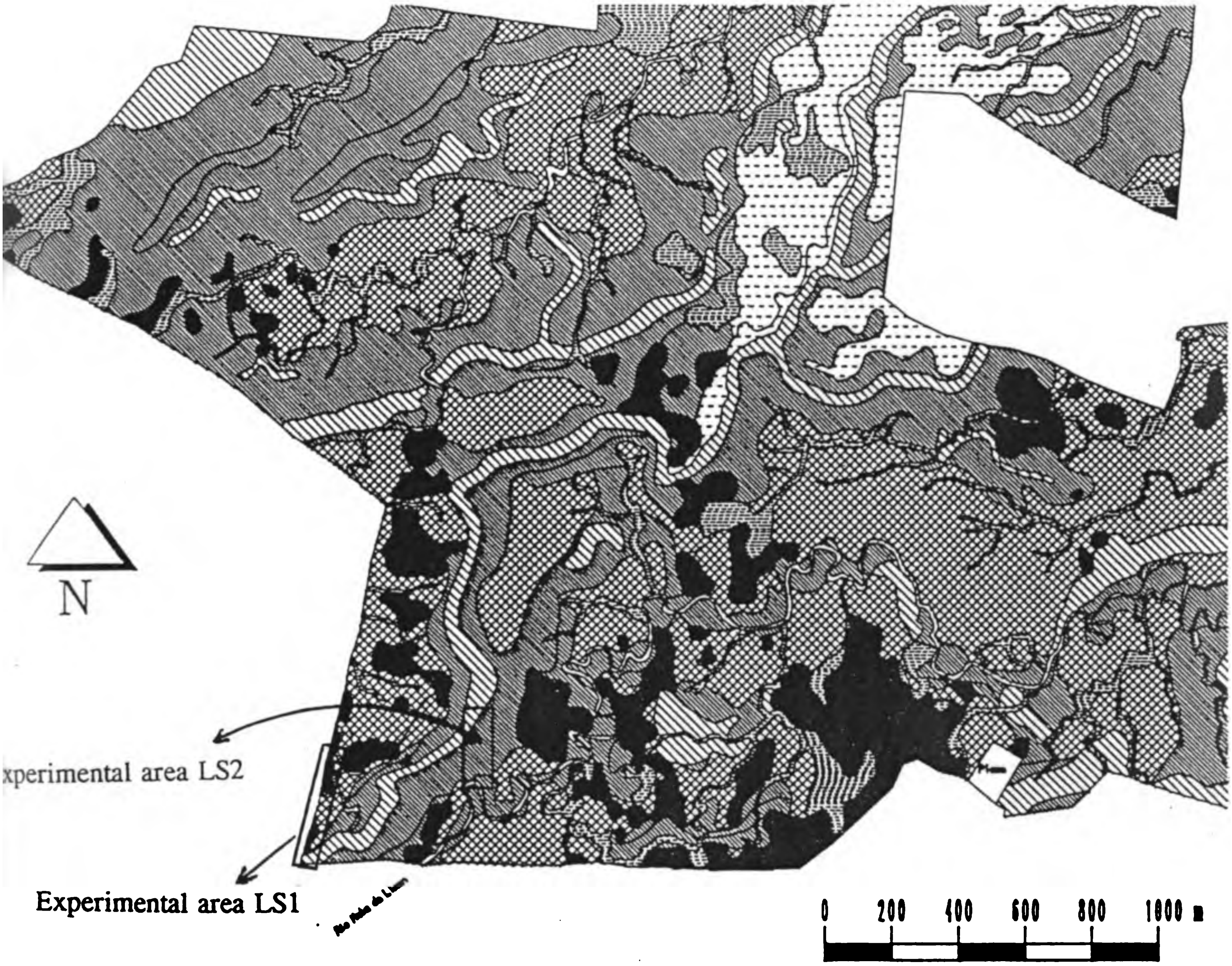
Weyl, R., (1980) Geology of Central America, Wageningen

MAP 1

Tortuguero catchment, with the main secondary catchments, their water divides and sampling locations

MAP 2

Soil map of a part of the banana plantation Lomas de Sierpe



LEGEND

Sandy textured soils

Loamy textured soils

Clayey textured soils

Bad drained loamy soils with some structure limitations

Bad drained clayey to loamy soils with severe structure limitations

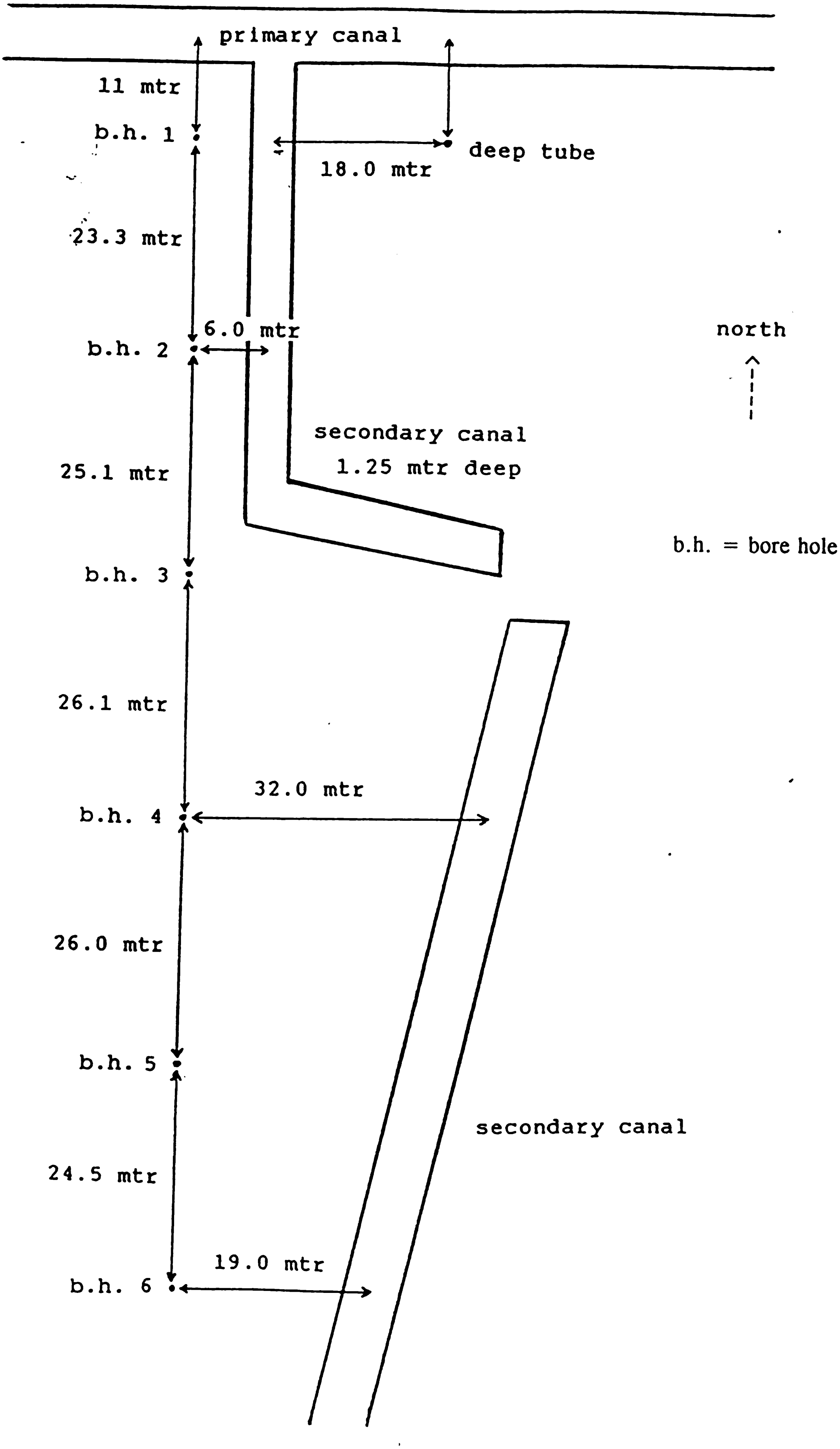
Well drained clayey soils with severe fertility limitations (red hills)

Sandy soils

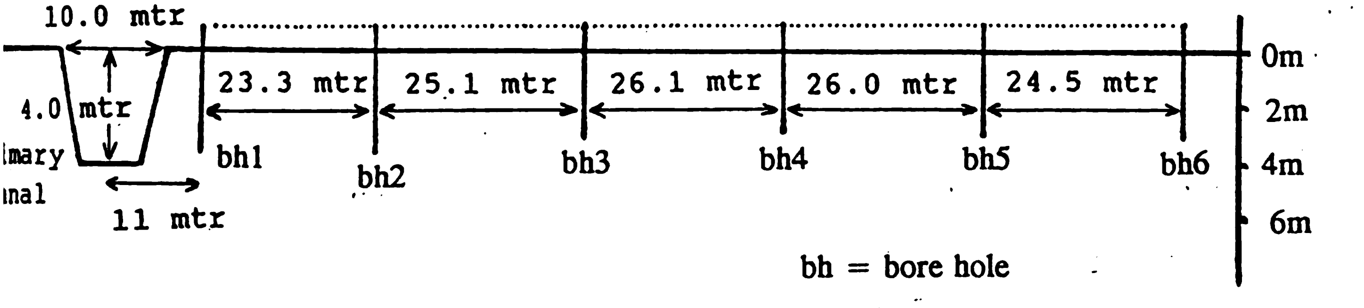
APPENDIX 1A

Experimental area LS1 of banana plantation Lomas de Sierpe. Groundplan and two cross sections with bore hole location and relative distances

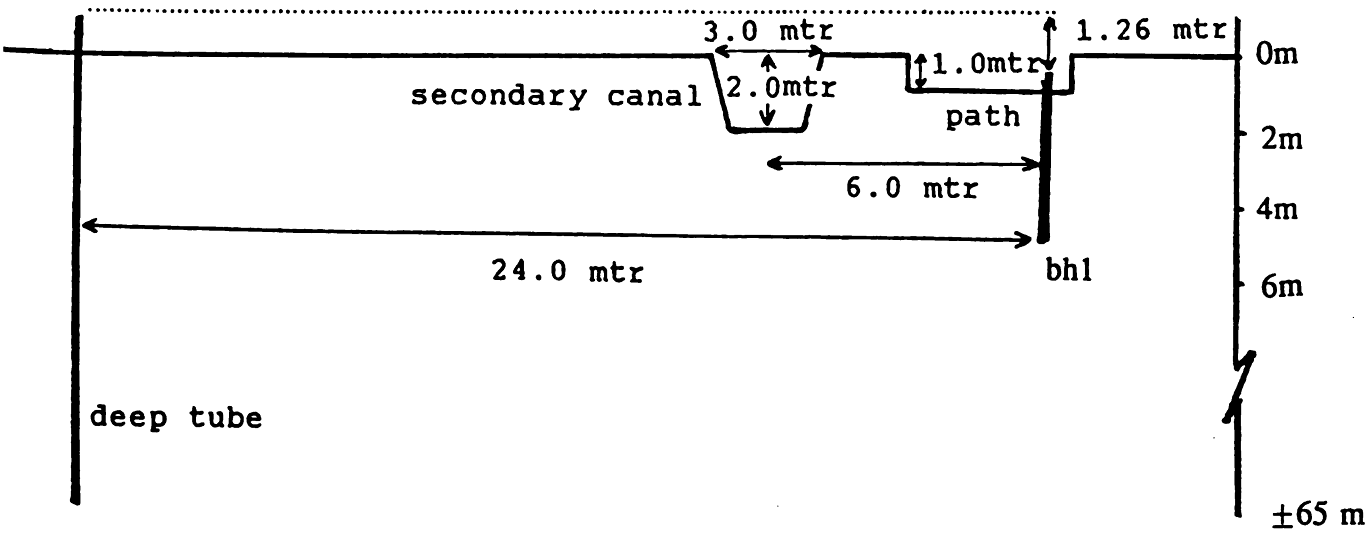
Experimental area LS1 of banana plantation Lomas de Sierpe : groundplan



Cross section (north-south) TS1 of experimental area LS1 ----> north



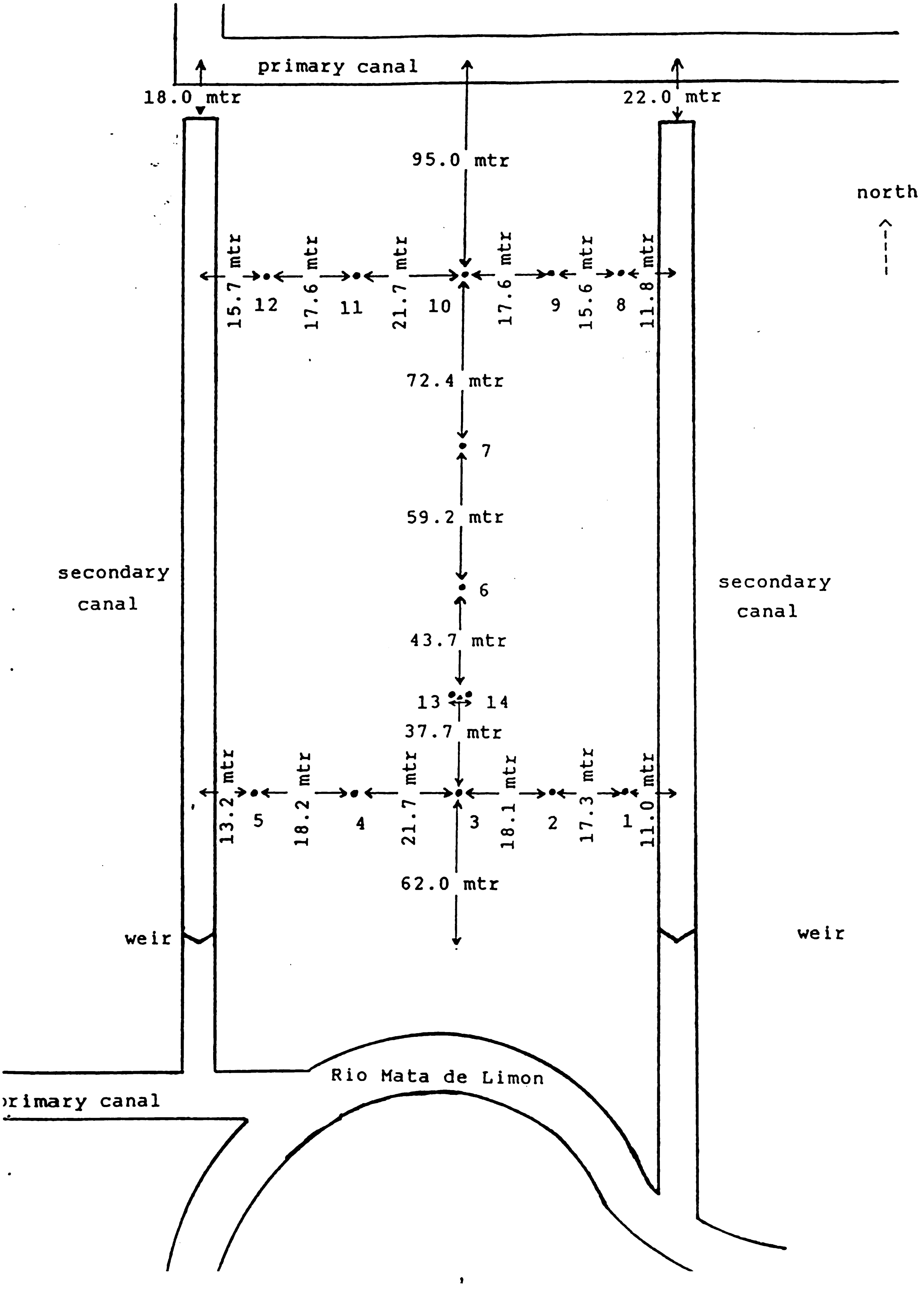
Cross section (west-east) TS1 of experimental area LS1 ----> east



APPENDIX 1B

Experimental area LS2 of banana plantation Lomas de Sierpe. Groundplan and two cross sections with tube location and relative distances

Experimental area LS2 of banana plantation Lomas de Sierpe : groundplan



River Los Diamantes

Ec.	: electric conductivity ($\mu S\ cm^{-1}$)
Temp.	: river water temperature ($^{\circ}C$)
S.L.W.	: surface water level at a fixed point in the river (cm)
----	: no data is available

date	Ec	temp.	s.w.l.
02-3-1993	64	15.0	7
05-3-1993	64	15.6	7
08-3-1993	63	16.0	7
09-3-1993	64	----	7
10-3-1993	64	----	7
11-3-1993	63	----	7
12-3-1993	64	16.7	8
15-3-1993	34	15.6	32
16-3-1993	44	16.2	26
17-3-1993	41	16.4	27
18-3-1993	49	15.8	17
19-3-1993	54	15.8	13
20-3-1993	36	16.6	34
22-3-1993	49	16.0	17
23-3-1993	53	16.1	15
24-3-1993	50	16.5	18
25-3-1993	52	16.2	15
26-3-1993	54	16.8	13
29-3-1993	56	16.5	14
30-3-1993	48	16.4	20
01-4-1993	56	16.9	13
02-4-1993	58	16.4	12
13-4-1993	62	16.4	9
14-4-1993	62	16.4	9
15-4-1993	63	16.5	8
16-4-1993	63	16.4	8
18-4-1993	65	16.4	7
19-4-1993	65	16.5	6
20-4-1993	65	16.4	6
21-4-1993	64	16.4	6
22-4-1993	62	16.5	6

date	Ec	temp.	s.w.l.
26-4-1993	53	16.7	13
27-4-1993	56	16.2	10
28-4-1993	56	16.6	9
29-4-1993	58	16.4	8
05-5-1993	60	16.8	7
06-5-1993	60	16.9	7
07-5-1993	61	16.4	7
10-5-1993	59	16.8	8
11-5-1993	62	16.6	7
12-5-1993	51	17.0	15
13-5-1993	55	16.5	12
14-5-1993	57	16.8	10
17-5-1993	58	16.9	9
18-5-1993	59	17.0	8
19-5-1993	60	16.7	8
21-5-1993	52	17.0	13
24-5-1993	49	17.0	14
25-5-1993	40	16.7	26
31-5-1993	51	16.9	15
01-6-1993	45	17.0	23
04-6-1993	52	17.0	14
07-6-1993	51	16.6	24
08-6-1993	51	16.2	22
14-6-1993	52	16.8	18
15-6-1993	53	17.0	18
16-6-1993	51	16.9	19
17-6-1993	50	16.8	19
18-6-1993	48	16.8	18
21-6-1993	57	16.7	12
22-6-1993	43	17.3	24
23-6-1993	47	16.7	19
24-6-1993	48	17.4	18

River Mata de Limon

Ec.	: electric conductivity ($\mu S\ cm^{-1}$)
Temp.	: river water temperature ($^{\circ}C$)
S.L.W.	: surface water level at a fixed point in the river (cm)
----	: no data is available

date	Ec	temp.	s.w.l.
18-3-1993	144	18.5	----
19-3-1993	151	18.0	----
22-3-1993	101	19.5	----
23-3-1993	121	18.1	----
24-3-1993	141	18.6	----
25-3-1993	142	18.4	----
26-3-1993	156	19.1	----
29-3-1993	160	18.7	----
30-3-1993	162	18.8	----
15-4-1993	181	20.4	25.6
16-4-1993	196	20.4	25.0
26-4-1993	127	18.8	56.9
28-4-1993	159	19.5	42.2
29-4-1993	177	19.4	40.0
05-5-1993	174	19.9	32.2
06-5-1993	---	----	30.9
07-5-1993	---	----	30.3
10-5-1993	186	19.6	28.8
11-5-1993	249	19.5	28.1
12-5-1993	---	----	40.0
13-5-1993	---	----	35.6
14-5-1993	202	19.7	38.5
17-5-1993	128	19.7	45.0
24-5-1993	140	19.2	48.0
31-5-1993	145	19.2	60.3
04-6-1993	151	19.1	54.1
07-6-1993	102	19.2	142.3
15-6-1993	138	19.8	56.3
18-6-1993	162	19.1	52.5
23-6-1993	187	19.0	37.5

APPENDIX 5

Discharge data of two secondary canals of the experimental area LS2 of banana plantation Lomas de Sierpe

Canal 1 : situated at the west side of the experimental area LS2
Discharge : discharge during measurement ($l\ s^{-1}$)
Ec. : electric conductivity ($\mu S\ cm^{-1}$)
Temp. : drain water temperature ($^{\circ}C$)
---- : no data is available

CANAL 1

Date	Discharge	Ec	temp.	comment
15-3-1993	0.27	94	17.6	
16-3-1993	0.26	122	18.5	
17-3-1993	0.15	136	19.8	
18-3-1993	0.10	138	20.9	
19-3-1993	0.23	109	17.8	
22-3-1993	---	179	20.4	weir washed away
23-3-1993	0.31	178	18.7	
24-3-1993	0.27	191	20.3	
25-3-1993	0.21	201	19.6	
26-3-1993	0.14	205	20.4	
29-3-1993	0.11	199	20.4	
30-3-1993	0.09	204	20.1	
02-4-1993	0.04	209	18.6	
13-4-1993	0.00	---	---	
15-4-1993	0.00	---	---	
16-4-1993	0.00	---	---	
20-4-1993	0.00	---	---	
26-4-1993	0.14	163	20.5	
28-4-1993	0.05	164	22.7	
29-4-1993	0.04	167	20.6	
05-5-1993	0.00	---	---	
10-5-1993	0.00	---	---	
11-5-1993	0.00	---	---	
14-5-1993	0.00	---	---	
17-5-1993	0.00	---	---	
24-5-1993	0.00	---	---	
31-5-1993	0.00	---	---	
04-6-1993	0.06	165	20.3	
07-6-1993	0.00	---	---	weir washed away

Canal 2 : situated at the east side of the experimental area LS2
Discharge : discharge during measurement (l s^{-1})
Ec. : electric conductivity (μS cm^{-1})
Temp. : drain water temperature ($^{\circ}$C)
---- : no data is available

CANAL 2

Date	Discharge	Ec	temp.	comment
15-3-1993	0.71	122	17.7	
16-3-1993	1.07	134	18.7	
17-3-1993	0.47	131	19.4	
18-3-1993	0.30	131	19.4	
19-3-1993	0.42	103	17.9	
22-3-1993	---	---	---	weir inundated
23-3-1993	1.25	142	18.6	
24-3-1993	1.07	149	19.9	
25-3-1993	0.71	157	19.2	
26-3-1993	0.42	169	20.3	
29-3-1993	0.28	151	20.1	
30-3-1993	0.21	157	19.8	
02-4-1993	0.07	159	18.6	
13-4-1993	0.00	---	---	
15-4-1993	0.00	---	---	
16-4-1993	0.00	---	---	
20-4-1993	0.00	---	---	
26-4-1993	0.60	137	20.3	
28-4-1993	0.17	137	22.2	
29-4-1993	0.12	129	20.9	
05-5-1993	0.00	---	---	
10-5-1993	0.00	---	---	
11-5-1993	0.00	---	---	
14-5-1993	0.00	---	---	
17-5-1993	0.00	---	---	
24-5-1993	0.04	116	20.6	
31-5-1993	0.25	153	19.6	
04-6-1993	0.19	152	19.6	
07-6-1993	---	---	---	weir inundated
15-6-1993	0.26	154	19.8	
18-6-1993	0.13	151	19.9	
23-6-1993	0.03	161	19.8	

APPENDIX 6

Groundwater head data from bore holes and tubes in the experimental areas LS1 and LS2 of banana plantation Lomas de Sierpe

Banana plantation Lomas de Sierpe, experimental area LS1
Calculated groundwater heads (cm) relative to deep tube

dt : deep tube for deep groundwater head (cm)
bh : bore hole for shallow groundwater head (cm relative to deep tube)
--- : no data is available

Date	dt	bh 1	bh 2	bh 3	bh 4	bh 5	bh 6
16-3-1993	-305	-414	-362	-213	---	-189	---
17-3-1993	-303	-430	-385	-247	-220	-220	-220
18-3-1993	-307	---	-400	-320	-235	-245	-240
19-3-1993	-309	-419	-407	-292	-209	-228	-228
22-3-1993	-293	-341	---	-225	-192	-200	-204
23-3-1993	-295	-364	-364	-222	-196	-206	-207
24-3-1993	-295	---	-378	-226	-206	-215	-217
25-3-1993	-297	-438	-390	-263	-230	-236	-237
26-3-1993	-302	-443	-411	-331	-252	-275	-267
29-3-1993	-308	-449	-415	-319	-237	-254	-269
30-3-1993	-309	-448	-416	-343	-246	-297	-275
02-4-1993	-315	---	-434	-399	-271	-358	-402
13-4-1993	-333	-126	-503	-450	-126	-415	-126
15-4-1993	-340	-508	-483	-446	-324	-438	-420
20-4-1993	-348	-524	-488	-470	-335	-427	-427
26-4-1993	-318	-468	-402	-260	-218	-226	-235
28-4-1993	-322	-470	-428	-386	-256	-326	-279
29-4-1993	-322	-480	-437	-405	-283	-337	-325
05-5-1993	-332	-480	-453	-435	-300	-290	-285
10-5-1993	-338	-493	-470	-442	-328	-405	-411
11-5-1993	-342	-495	-471	-454	-332	-410	-414
14-5-1993	-342	-505	-481	-463	-331	-417	-435
17-5-1993	-355	-480	-467	-455	-307	-413	-412

Banana plantation Lomas de Sierpe, experimental area LS2
Calculated groundwater heads (cm) relative to tube 3

tube: piezometer for shallow groundwater
----: no data is available

Date	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	Tube 6	Tube 7
15-3-1993	-238	-205	-231	-194	-218	-329	-332
16-3-1993	-201	-146	-139	-128	-158	-326	-334
17-3-1993	-215	-169	-156	-127	-149	-322	-331
18-3-1993	-225	-179	-169	-136	-149	-319	-323
19-3-1993	-232	-169	-169	-140	-150	-317	-322
22-3-1993	-184	-142	-122	-86	-97	-234	-240
23-3-1993	-190	-157	-136	-105	-119	-230	-236
24-3-1993	-200	-156	-137	-106	-124	-234	-244
25-3-1993	-212	-167	-149	-120	-132	-240	-249
26-3-1993	-226	-181	-169	-138	-144	-248	-257
29-3-1993	-237	-189	-182	-150	-155	-266	-273
30-3-1993	-246	-197	-190	-160	-163	-274	-281
02-4-1993	-268	-213	-206	-176	-176	-297	-295
13-4-1993	-317	-294	-282	-233	-227	-335	-331
15-4-1993	-326	-306	-291	-242	-237	-342	-334
16-4-1993	-330	-312	-292	-245	-241	-343	-336
20-4-1993	-332	-329	-291	-263	-249	-351	-341
26-4-1993	-229	-179	-159	-126	-132	-316	-313
28-4-1993	-249	-197	-187	-156	-149	-310	-306
29-4-1993	-258	-203	-220	-164	-158	-309	-306
05-5-1993	-290	-251	-255	-196	-188	-325	-321
10-5-1993	-320	-295	-282	-234	-218	-338	-334
11-5-1993	-323	-301	-286	-239	-224	-341	-338
14-5-1993	-332	-320	-291	-250	-238	-348	-345
17-5-1993	-331	-329	-291	-255	-246	-353	-348
24-5-1993	-311	-289	-288	-223	-234	-358	-347
31-5-1993	-247	-194	-209	-158	-155	-287	-285
04-6-1993	-248	-196	-213	-163	-166	-296	-297
07-6-1993	-169	-94	-101	-65	-88	-290	-292
15-6-1993	-244	-194	-207	-158	-159	-278	-278
18-6-1993	-261	-204	-218	-170	-171	-192	-291
23-6-1993	-275	-221	-234	-185	-185	-308	-307

Banana plantation Lomas de Sierpe, experimental area LS2
Calculated groundwater heads (cm) relative to tube 3

tube: piezometer for shallow groundwater
----: no data is available

Date	Tube 8	Tube 9	Tube 10	Tube 11	Tube 12	Tube 13	Tube 14
15-3-1993	-337	-319	-334	-341	-330	---	---
16-3-1993	-331	-326	-323	-340	-327	---	---
17-3-1993	-326	-329	-319	-334	-324	---	---
18-3-1993	-323	-323	-302	-331	-319	---	---
19-3-1993	-329	-318	-300	-329	-319	---	---
22-3-1993	-233	-238	-221	-250	-241	---	---
23-3-1993	-241	-241	-223	-253	-244	---	---
24-3-1993	-250	-247	-230	-261	-251	---	---
25-3-1993	-255	-254	-236	-266	-257	---	---
26-3-1993	-265	-264	-244	-275	-266	---	---
29-3-1993	-278	-248	-259	-287	-279	---	---
30-3-1993	-287	-286	-267	-296	-286	---	---
02-4-1993	-300	-299	-280	-316	-298	---	---
13-4-1993	-332	-329	-309	-348	-332	---	---
15-4-1993	-338	-334	-316	-354	-336	---	---
16-4-1993	-340	-336	-316	-355	-338	---	---
20-4-1993	-348	-335	-327	-356	-347	-413	---
26-4-1993	-305	-308	-290	-325	-307	-366	---
28-4-1993	-303	-305	-285	-321	-304	-367	---
29-4-1993	-305	-305	-286	-322	-304	-369	---
05-5-1993	-321	-321	-301	-337	-320	-386	-346
10-5-1993	-333	-337	-313	-349	---	-399	-349
11-5-1993	-336	-336	-315	-350	-350	-401	-355
14-5-1993	-345	-338	-323	-360	-360	-405	-368
17-5-1993	-348	-337	-330	-361	-367	-408	-373
24-5-1993	-357	-338	-339	-351	-373	-410	-373
31-5-1993	-289	-305	-270	-306	-306	-350	-273
04-6-1993	-299	-277	-279	-315	-314	-360	-281
07-6-1993	-284	-272	-271	-309	-306	-332	-226
15-6-1993	-281	-262	-263	-296	-298	-346	-259
18-6-1993	-292	-273	-274	-308	-310	-357	-274
23-6-1993	-308	-287	-290	-324	-323	-373	-294

APPENDIX 7

Transects with information about deposits.

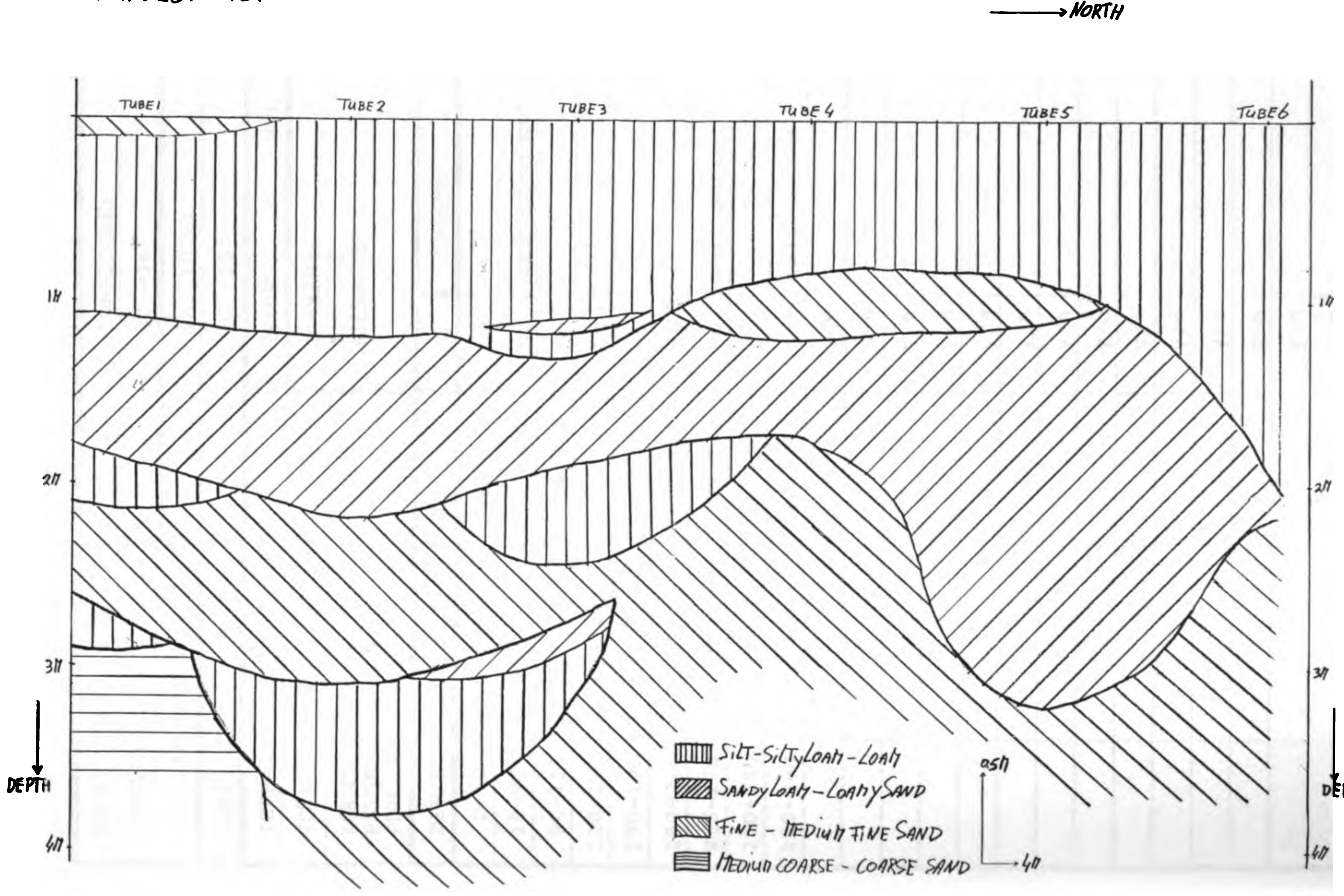
TS1 : Transect of bore holes 1 to 6 of experimental area LS1 of banana plantation Lomas de Sierpe

TS2 : Transect of tubes 1 to 5 of experimental area LS2 of banana plantation Lomas de Sierpe

TS3 : Transect of tubes 8 to 12 of experimental area LS2 of banana plantation Lomas de Sierpe

TS4 : Transect of tubes 3 to 10 of experimental area LS2 of banana plantation Lomas de Sierpe

TRANSECT TS1



DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 05-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: AIRFIELD PIEZOMETER 1
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-10	m. fine sand	7½YR 3/4	no	
10-90	loam	10YR 6/2	no	oxidation mottles
90-110	loamy-silt	10YR 3/1	no	
110-170	sandy-loam	10YR 4/1	no	
170-190	loamy-sand	10YR 3/1	no	
190-215	silty-loam	10YR 4/2	no	
215-280	m. fine sand	10YR 2/1	no	well sorted
280-290	silty-loam	2½Y 2/0	no	
290-360	m. c. sand	7½Y 2/0	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 330 cm

DRILLED BY: T. DE JONG DORPSSTRAAT 88 6871 AN RENKUM	LONGITUDE: 83°-36'
DATE: 05-03-1993	LATITUDE: 10°-25'
TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: AIRFIELD PIEZOMETER 2
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-75	silty-loam	10YR 5/2	no	oxidation mottles
75-100	silty-loam	10YR 4/6	no	
100-120	silt	10YR 4/2	no	oxidation mottles
120-220	loamy-sand	2½Y 4/2	no	
220-240	m. fine sand	2½Y 4/2	no	well sorted
240-260	m. fine sand	2½Y 2/0	no	well sorted
260-310	fine sand	2½Y 3/0	no	well sorted
310-350	silt	2½Y 3/0	no	
350-390	fine sand	2½Y 3/0	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 260 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36′
6871 AN RENKUM	LATITUDE:
DATE: 05-03-1993	10°-25′

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: AIRFIELD PIEZOMETER 3
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-65	silty-loam	10YR 5/8	no	reduction mottles
65-110	silty-loam	7½Y 4/2	no	oxidation mottles
110-115	sandy-loam	7½Y 4/2	no	oxidation mottles
115-135	loam	10YR 4/6	no	
135-190	loamy-sand	2½Y 3/0	no	
190-245	silt	2½Y 4/0	no	green mottles,o.m.
245-275	fine sand	2½Y 3/0	no	well sorted
275-290	loamy-sand	2½Y 4/0	no	
290-320	silt	2½Y 5/0	no	
320-360	fine sand	2½Y 3/0	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 220 cm

DRILLED BY: T. DE JONG DORPSSTRAAT 88 6871 AN RENKUM	LONGITUDE: 83°-36′ LATITUDE:
DATE: 05-03-1993	10°-25′
TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO AGRICULTURE : YES PASTURE : NO FORESTRY : NO	COMMENT: AIRFIELD PIEZOMETER 5

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-40	silty-loam	10YR 4/4	no	Mn+Fe ox. mottles
40-80	loam	10YR 4/4	no	ox.+red. mottles
80-90	silt	10YR 5/4	no	oxidation mottles
90-110	fine sand	7½YR 4/4	no	well sorted
110-150	sandy-loam	10YR 5/2	no	Mn+Fe concretions
150-160	sandy-loam	7½YR 5/8	no	
160-290	sandy-loam	10YR 4/2	no	green mottles
290-320	sandy-loam	10YR 4/2	no	green mottles
320-340	fine sand	10YR 4/2	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
EC:		pH:	GROUNDWATERDEPTH: 200 cm	

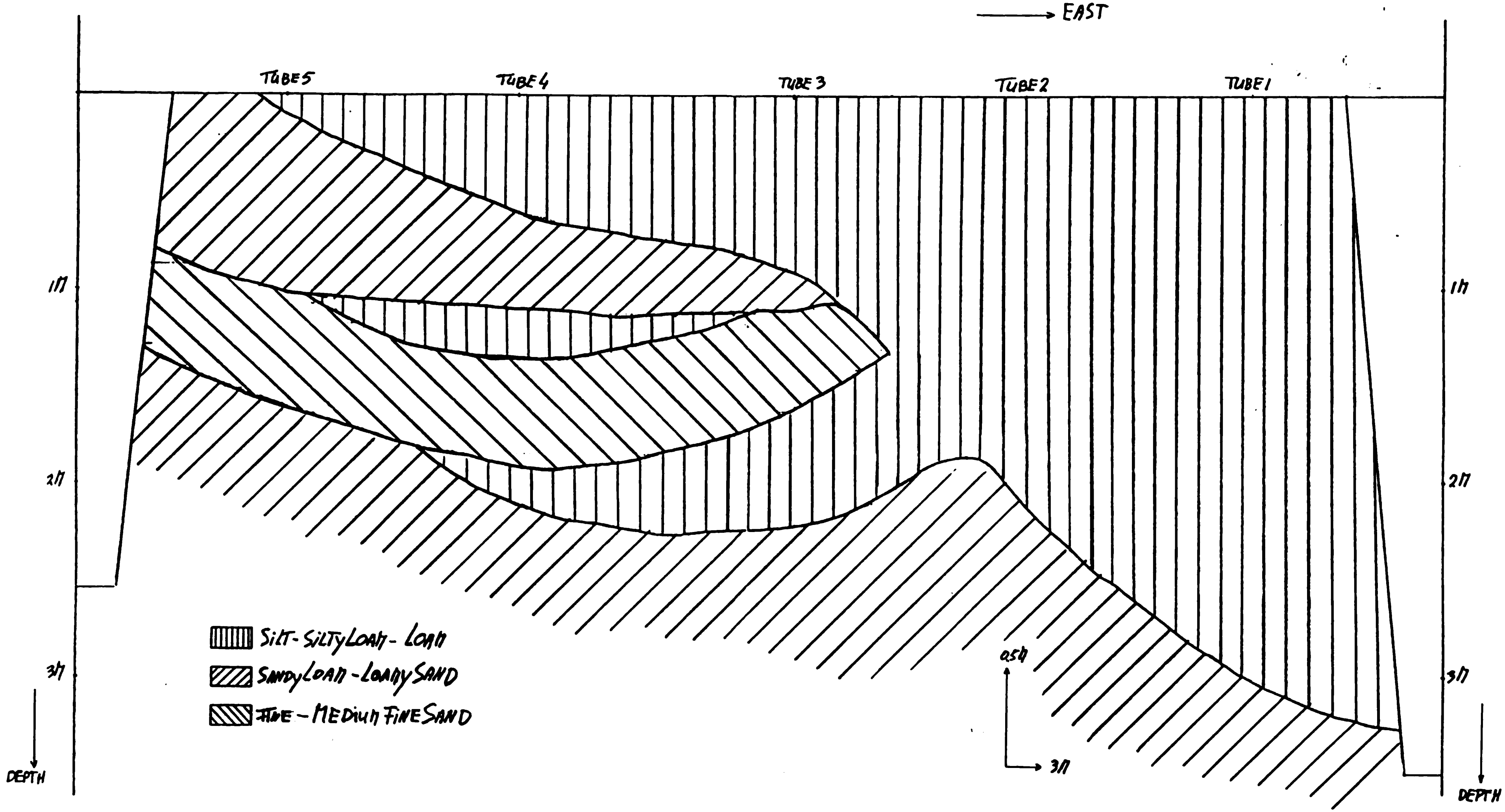
DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36′
6871 AN RENKUM	LATITUDE:
DATE: 05-03-1993	10°-25′

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: AIRFIELD PIEZOMETER 6
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

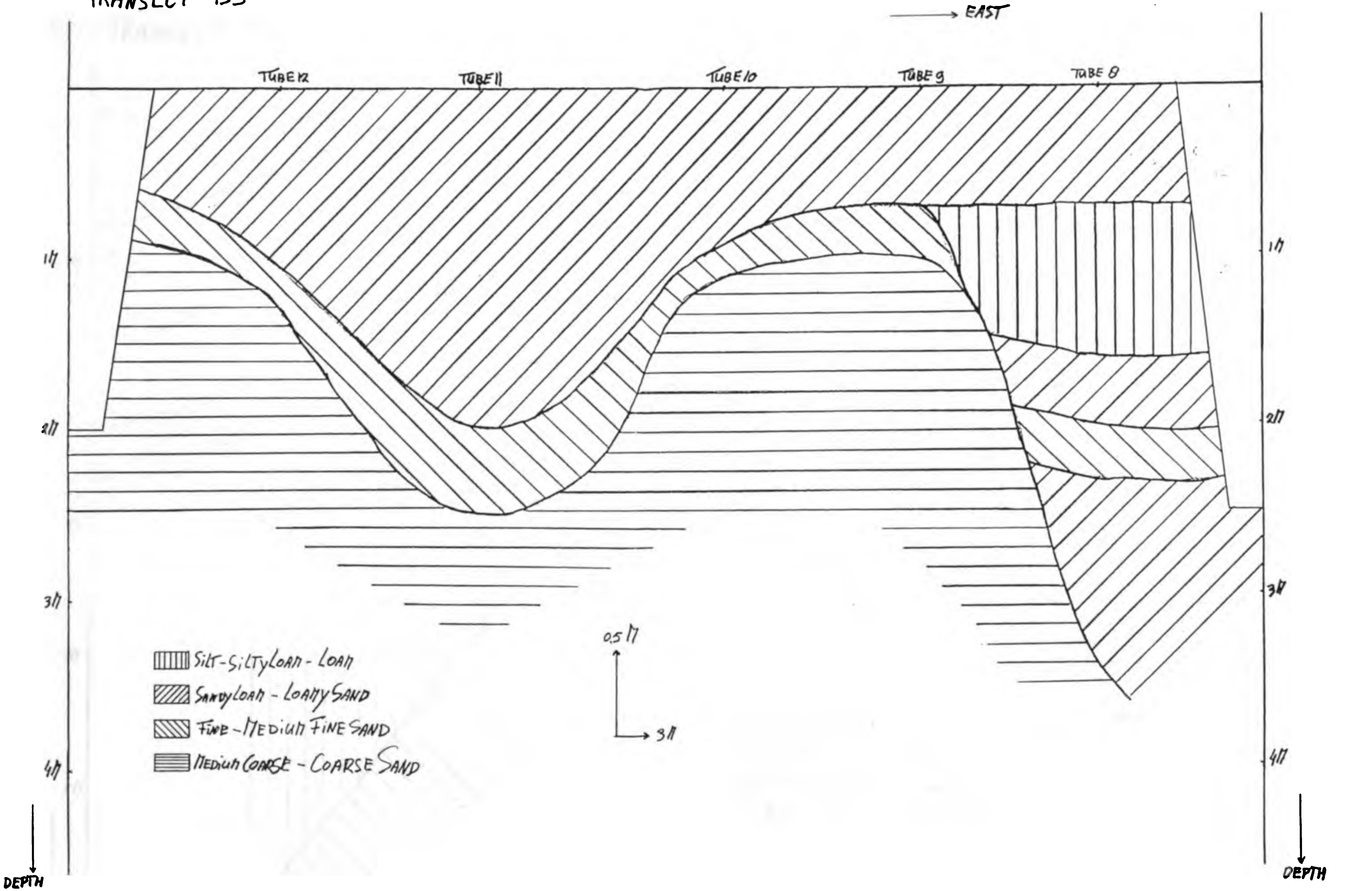
DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-30	silty-loam	10YR 4/4	no	Mn+Fe ox. mottles
30-100	silty-loam	10YR 5/2	no	Fe concretions
100-190	silt	10YR 4/1	no	organic matter
190-220	loamy sand	10YR 4/1	no	
220-280	m.fine sand	10YR 4/1	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 150 cm

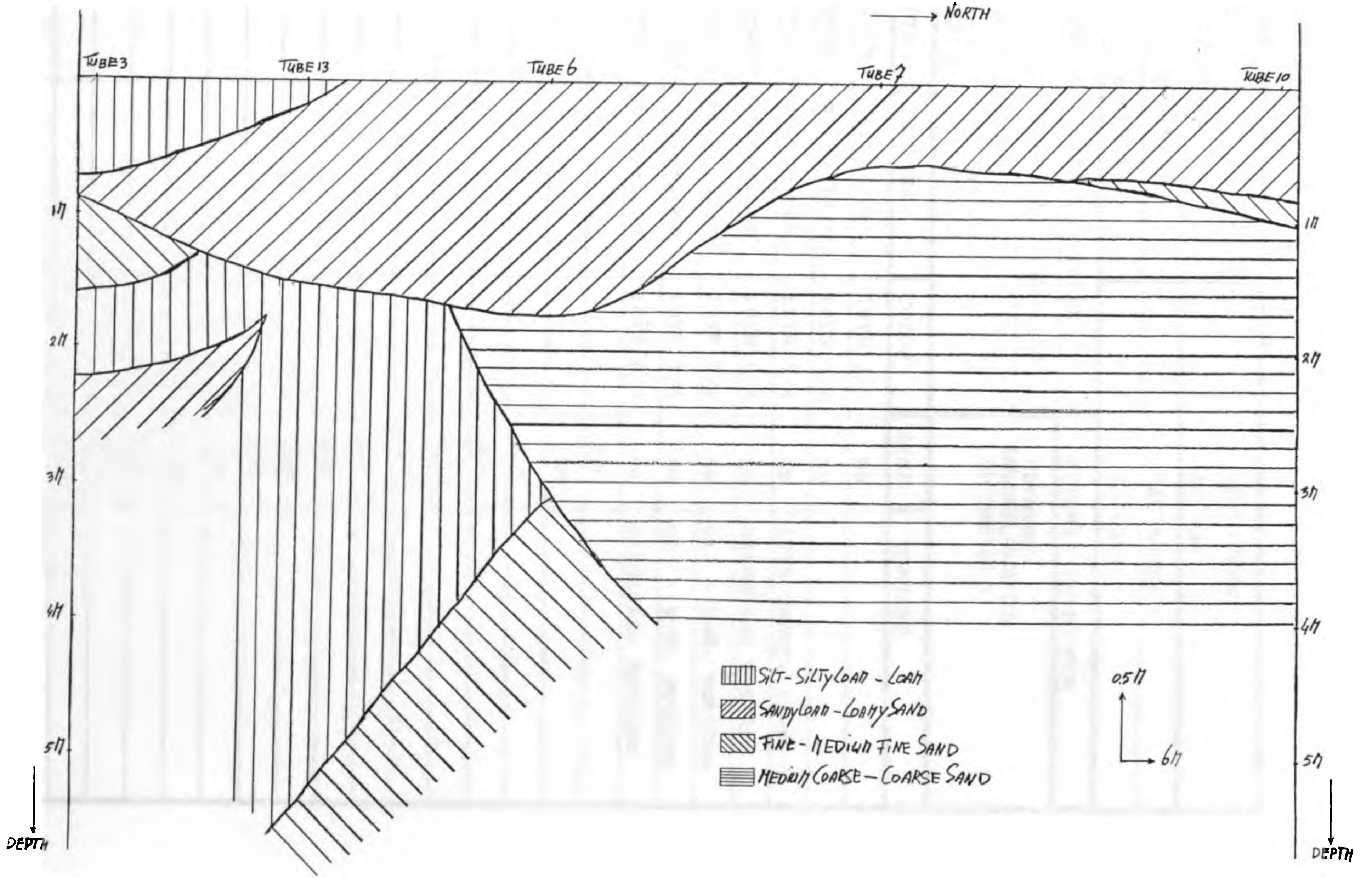
TRANSECT TS2



TRANSECT TS3



TRANSECT TS4



DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15-20 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 1
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-15	silty-loam	10YR 3/2	no	
15-75	silty-loam	10YR 3/4	no	
75-190	silty-loam	10YR 5/4	no	iron concr. (140)
190-200	silty-loam	10YR 5/4	no	oxidation mottles
200-290	silty-loam	10YR 5/2	no	ox. + red. mottles
290-300	silty-loam	10YR 5/6	no	ox. + red. mottles
300-320	sandy-loam	10YR 6/3	no	oxidation mottles
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 250 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 2
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-10	silty-loam	10YR 3/2	no	
10-55	silty-loam	10YR 3/4	no	
55-110	silty-loam	10YR 3/4	no	ox. + red. mottles
110-140	silty-loam	10YR 5/8	no	
140-185	loam	10YR 5/4	no	ox. + red. mottles
185-205	sandy-loam	10YR 5/4	no	ox. + red. mottles
205-230	sandy-loam	10YR 5/2	no	
230-300	sandy-loam	10YR 5/1	no	compact layer
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 210 cm

DRILLED BY: T. DE JONG DORPSSTRAAT 88 6871 AN RENKUM	LONGITUDE: 83°-36'
DATE: 02-03-1993	LATITUDE: 10°-25'
TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO AGRICULTURE : YES PASTURE : NO FORESTRY : NO	COMMENT: BANANAPLANTATION PIEZOMETER 3

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-15	silty-loam	10YR 3/2	no	
15-50	silty-loam	10YR 3/4	no	
50-70	silty-loam	10YR 3/4	no	ox. + red. mottles
70-90	sandy-loam	10YR 5/8	no	
90-110	fine sand	10YR 3/6	no	well sorted
110-160	m. fine sand	10YR 3/4	no	medium sorted
160-180	loam	10YR 5/4	no	ox. mottles
180-200	silty-loam	10YR 4/1	no	unripened
200-220	loam	10YR 5/2	no	ox.mottles
220-250	sandy-loam	10YR 5/1	no	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 200 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'
TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 4
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-10	silty-loam	10YR 3/2	no	
10-60	silty-loam	10YR 3/4	no	
60-95	sandy-loam	10YR 3/4	no	
95-110	sandy-loam	10YR 3/4	no	ox. + red. mottles
110-135	silty-loam	10YR 5/4	no	oxidation mottles
135-190	fine sand	10YR 5/4	no	well sorted + ox.m
190-210	loam	10YR 5/2	no	oxidation mottles
210-230	sandy-loam	10YR 5/2	no	oxidation mottles
230-260	sandy-loam	10YR 5/1	no	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 200 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 5
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-10	loam	10YR 3/2	no	
10-50	sandy-loam	10YR 3/4	no	
50-60	sandy-loam	10YR 3/4	no	oxidation mottles
60-100	loamy-sand	10YR 3/4	no	
100-160	m. fine sand	10YR 5/2	no	medium sort.+ox. m
160-250	sandy-loam	10YR 5/1	no	oxidation mottles
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 220 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 6
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-10	sandy-loam	10YR 3/2	no	
10-140	sandy-loam	10YR 4/4	no	
140-170	sandy-loam	10YR 4/4	no	ox. + red. mottles
170-200	m. c. sand	10YR 4/3	no	well sorted
200-310	m. c. sand	10YR 4/3	no	medium sorted
310-350	m.fine sand	10YR 4/2	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
EC:		pH:	GROUNDWATERDEPTH: 310 cm	

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 8
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-15	sandy-loam	10YR 2/2	no	
15-70	sandy-loam	10YR 3/4	no	oxidation mottles
70-160	silty-loam	10YR 3/4	no	
160-185	sandy-loam	10YR 3/4	no	
185-200	loamy-sand	10YR 3/4	no	
200-230	m. fine sand	10YR 4/6	no	well sorted
230-260	loamy-sand	10YR 4/4	no	
260-280	sandy-loam	10YR 4/4	no	oxidation mottles
280-300	loamy-sand	10YR 4/4	no	oxidation mottles
300-340	sandy-loam	10YR 4/3	no	
340-360	coarse-sand	10YR 4/2	no	bad sorted, gravel
360-410	coarse-sand	10YR 4/1	no	bad sorted, gravel
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 390 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 11
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-25	sandy-loam	10YR 3/3	no	
25-55	sandy-loam	10YR 3/4	no	
55-110	sandy-loam	10YR 4/4	no	
110-185	loamy-sand	10YR 4/4	no	ox.+red.mottles 175
185-200	loamy-sand	10YR 5/6	no	oxidation mottles
200-250	m. fine sand	10YR 5/4	no	well sorted
250-300	m. c. sand	10YR 4/2	no	bad sorted
300-320	coarse sand	10YR 4/2	no	ox. mott. bad sort.
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
EC:		pH:	GROUNDWATERDEPTH: 350 cm	

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36'
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25'

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 12
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-15	sandy-loam	10YR 3/3	no	
15-105	sandy-loam	10YR 3/4	no	
105-130	m. fine sand	10YR 5/6	no	well sorted
130-205	m. c. sand	10YR 4/2	no	bad sorted
205-350	coarse sand	10YR 4/2	no	bad sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 320 cm

DRILLED BY: T. DE JONG	LONGITUDE:
DORPSSTRAAT 88	83°-36′
6871 AN RENKUM	LATITUDE:
DATE: 02-03-1993	10°-25′

TERRAIN: LOMAS DE SIERPE	HEIGHT: 15 MTR
TOP: NO SLOPE: NO DALE: NO	COMMENT: BANANAPLANTATION PIEZOMETER 13
AGRICULTURE : YES PASTURE : NO FORESTRY : NO	

DEPTH	*TEXTURE*	*COLOR*	*LIME*	*COMMENT*
0-15	silty-loam	10YR 3/3	no	
15-45	sandy-loam	10YR 3/4	no	
45-55	loamy-sand	10YR 3/4	no	
55-110	sandy-loam	10YR 4/4	no	Fe ox.+red. mottles
110-130	sandy-loam	10YR 5/1	no	Fe ox. mottles
130-150	loamy-sand	10YR 5/1	no	Fe ox. mottles
150-200	silt-loam	10YR 5/1	no	Fe ox. mottles
200-230	silt	10YR 5/1	no	Fe ox. mottles
230-240	silt	10YR 4/1	no	Fe concretions
240-530	silt	10YR 4/1	no	
530-790	fine sand	10YR 4/1	no	well sorted
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	
			y/n	

EC:		pH:	GROUNDWATERDEPTH: 270 cm