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Hydrological behaviour of banana crops on a tropical soil: Estimation of the properties of an andosol and identification of the water processes at local scale

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Abstract

The intensification of banana cropping in the French West Indies linked with high levels of fertilizer and pesticide application and heavy rainfalls is responsible for serious water pollution. This phenomenon is worsened by the fact that the banana canopy concentrates rainwater at the banana tree foot. So inputs are likely to be displaced by surface runoff and drainage. The National Institute for the Agronomic Research (INRA) and the International Cooperation centre in Agronomic Research for the Development (CIRAD) are associated in a survey which aims to understand and predict the impact of agricultural practices on the hydrological behaviour of the banana plantation in Guadeloupe.

First, the hydrodynamic soil properties of the volcanic soil have been studied using three different methods: the Beerkan method, the laboratory ones (Wind's evaporation and constant-head permeameter) and the Decagon tension disc infiltrometer. The objective to validate the Beerkan method as a reference was not reached due to result disparities. Nevertheless, the analyses highlighted the low infiltration capacity of the crust and vegetated areas (10 – 30 mm/h) which are not affected by water inputs and the high infiltration capacity of the area down slope the banana tree stem (430 - 690 mm/h).

Secondly, the water processes inside a banana plantation at a single tree scale were studied. Results show that the hydrological behaviour of the experimental plot during rain events depends on the rainfall intensity and amount, and the initial soil hydraulic conditions. At the beginning of a rain event, most of the soil water is stored near the soil surface and then drains to the deepest soil horizon. The stemflow infiltrates quickly in the interception area located down slope the banana tree stem or evacuates by runoff down to an area where infiltration can occur. Runoff initiations occur at banana tree foot and the runoff coefficient is moderate to high depending on the rain event.

Acknowledgements

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List of Symbols and Abbreviations

Symbols	Units	Meaning
asl		above sea level
CIRAD		International Cooperation centre in Agronomic Research for the Development (centre de Coopération Internationale en Recherche Agronomique pour le Développement)
CSE Sol		Research on the Soil inside the department of Climate, Soil and Environment at the INRA of Avignon (France)
INRA		National Institute for the Agronomic Research (Institut National de la Recherche Agronomique)
LAI		Leaf Area Index
SSC		Soil Surface Characteristic
α	(m^{-1})	Soil characteristic constant
ε	(-)	Porosity
η	(-)	Shape parameter for the hydraulic conductivity function
θ	($m^3.m^{-3}$)	Volumetric water content
$\overline{\theta}$	($m^3.m^{-3}$)	Mean water content
θ_r	($m^3.m^{-3}$)	Residual soil water content
θ_s	($m^3.m^{-3}$)	Saturated soil water content
κ	(-)	Intermediate parameter of the Haverkamp's equation
ρ_b	($kg.m^{-3}$)	Dry bulk density
ρ_s	($kg.m^{-3}$)	Solid density $\approx$ 2.68 $kg.m^{-3}$
ΔS_c	(mm)	Calculated variation of water stock (Pr – R – D)
ΔS_m	(mm)	Variation of water stock measured with the tensiometers
d	(m)	Particle diameter
d_g	(m)	Normalization parameter for the particle diameter
dz	(m)	Variation of depth
h	(m)	Water pressure head ($\leq$0)
h_g	(m)	Scale parameter for the water pressure ($\leq$0)
m	(-)	Shape parameter of the water retention curve
i	($mm.h^{-1}$)	Water intensity
i_r	($mm.h^{-1}$)	Rainfall intensity
n	(-)	Shape parameter of the water retention curve
s	(-)	Intermediate parameter to find κ
t_0	(d)	Beginning of a rain event
t_{end}	(d)	End of a rain event
w_s	(-)	Soil moisture at saturation
w_0	(-)	Initial soil moisture
z	(mm)	Depth
D	(mm)	Drainage
F(d)	(-)	Cumulative frequency distribution of the particle size
H	(mm)	Water depth
K	($m.s^{-1}$)	Hydraulic conductivity
K_s	($m.s^{-1}$)	Hydraulic conductivity at saturation

Symbols	Units	Meaning
M	(-)	Shape parameter linked with the particle size distribution curve
M_s	(kg)	Initial mass of soil
M_w	(kg)	Mass of water
N	(-)	Shape parameter linked with the particle size distribution curve
P	(mm)	Pressure of water
P_{MN}	(-)	Parameter of the particle size distribution curve
P_{mn}	(-)	Parameter of the water retention curve
Pr	(mm)	Precipitation
R	(mm)	Runoff
T	(°C)	Temperature in Celsius degree
U	(mV)	Tension recorded by the data logger for each device
$V_{stemflow}$	(L)	Volume of stemflow in Litter
V_t	(m^3)	Volume of soil
Z_{lysi}		Depth where the lysimeters are settled (600mm)

A, B, Pente, P0, Y0, a_4, a_3, a_2, a_1 and b are parameters of calibration of each device on the experimental plot.

1 Introduction

1.1 Study location: Guadeloupe

Guadeloupe is a French overseas department situated in the Caribbean area. Mainland Guadeloupe comprises two islands divided by a narrow channel as shown in Figure 1-1. (Ministère de l'Outre-Mer 2005). The larger, western Basse-Terre is covered with a very dense forest. It is a volcanic region dominated by the volcano of La Soufrière. The smaller, eastern Grande-Terre is low limestone formation and the low altitude plate is favourable for agriculture.

Figure 1-1 : Map of Guadeloupe showing locality
Source: Ministère de l'écologie et du développement durable (2005) and Radio club India (2002)

The climate is subtropical tempered by trade winds and the humidity is moderately high. There are two extreme seasons per year: a dry one during February-March and the rainy season between July and October (Théault and Denhez 2005). Natural phenomena on a large scale (cyclones, for example), or on local scale (often violent and stormy rainfall), cause sometimes terrible bad weather, sources of catastrophic floods or strong winds. The cyclonic season extends normally from June to October (Metéofrance 2003). A spatial variability of rainfall occurs due to the direction East-West of trade winds, called *alizés,* and the presence of the volcano (Bonan and Prim 2001). "The average annual rainfall decreases from 4000 mm at 400 m above sea level (asl) (22 °C) to 2500 mm at 30 m asl (26 °C)" (Ndayiragije and Delvaux 2004). At the top of the volcano, it can be greater than 8000 mm. So, Basse-Terre receives important precipitation contrary to Grande-Terre where the rain is less and consequently, the hydrological network is poor. The water resource in Guadeloupe is also unequally distributed spatially: most of the water resource is located in Basse-Terre which possesses more than 50 perennial watercourses and important aquifers (Bonan and Prim 2001).

1.2 Background of information about banana crop

Banana is a *Musa* species of the family of Musaceae. It is a tree-like herb with a rhizome whose terminal bud produces the inflorescence and then dies. A series of bunches is produced from a single plant. The sequence can be repeated so the plant is considered to be a perennial. The stages of development of banana plants include sucker appearance, growth, flowering and harvest as shown in Figure 1-2. The minimum amount of water needed for good growth is 2000-2500 mm/year and good soil drainage is required (Samson 1980).

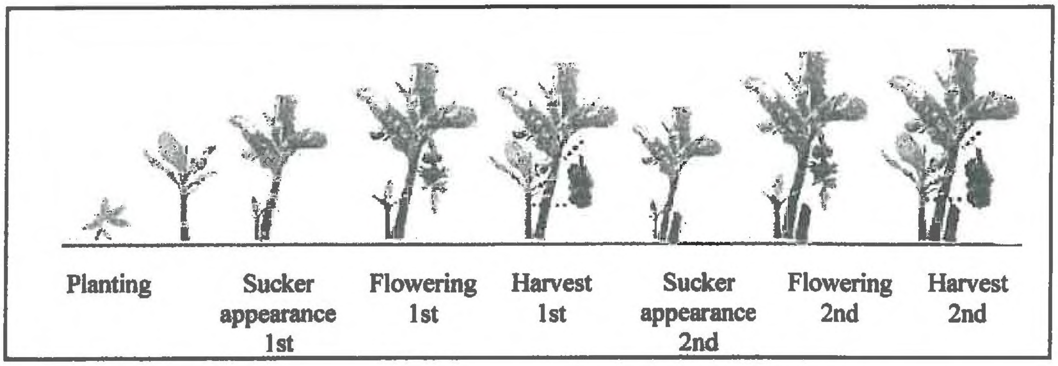


Figure 1-2 : Development stages of banana plant function.
Source: Tixier *et al.* (2004)

In Guadeloupe, the banana is the primary export product: more than 70% of the production is exported so it has an important role in the island economy. The area devoted to banana plantations is 10% of the agricultural land in the island (Ministère de l'Outre-Mer 2005). The crop mainly grows on Basse-Terre without crop rotation. It is commonly heavily mechanized monoculture with replanting every 3 or 4 years. Cattan *et al.* (2005) defined the traditional mechanized technical sequence which begins after the harvest of banana. Before planting, the soil is submitted to a cross ploughing, then harrowing and furrowing down the line of the slope. Then, the next generation of banana tree is from in vitro plantlets or the sucker depending of the quality of the latter. Every two months, chemical weeding is applied on the soil surface. After harvesting, plant residues are cut and spread on the soil to prevent soil erosion (Cattan *et al.* 2005). The banana sector has been affected by a series of cyclones (1989 to 1996), and has therefore not managed to fulfil its quotas. Moreover, it is confronted with a dramatic fall of the prices induced by a competition on the world market. So, the situation constrains some farmers to stop their activities. The existence of the West-Indian banana is compromised in the long term (Agrisalon.com 2003). In addition to the crisis, banana plantations are subjected to strong parasite pressure. Nematodes (*Radolphus Similis*) parasitize the root causing considerable loss of production and increased use of pesticides (Perret and Dorel 1999). The latter induces environmental impacts in terms of soil and water pollution (Ganry 2004).

1.3 Description of banana growing soils in Guadeloupe

Banana plantations usually grow on young volcanic ash soil called andosol which physical properties satisfy the plant requirements (Dorel *et al.* 2000). Andosols are defined by the single property of having volcanic ash parent material so they are present on the area surrounding the volcano of La Soufrière. Under tropical wet climate, they are often sloping and subject to intensive precipitation. They have a high infiltration rate greater than 50 mm/h and up to 300 mm/h due to their high porosity, so they are able to absorb most of the rainfall (Dorel *et al.* 2000). Moreover, they have a high structural stability due to their fine non-crystalline material and organic matter. They are resistant to water erosion. So, andosols should not be affected by runoff and erosion problems but "they may suffer erosion and deterioration of the cultivation layer if poorly managed." (Perret and Dorel 1999).

Andosols in Guadeloupe show two main horizons (Cattan *et al.* 2005; Perret and Dorel 1999):

- Horizon A (0 – 30 cm): it is a dark granular structure due to root mat and soil fauna, enhanced by the accumulation of organic matter (5 to 20% OM)
- Horizon B (30 – 60 cm): It is a reddish brown or yellowish brown horizon which feels loamy due to low density and high allophanic (component made of hydrated and amorphous silicate of aluminium) and water content. It still contains important amount of organic matter (1 to 5% OM). In the field, as shown in Figure 1-3, it appears massive, without aggregates but rich in micro-porosity.

Figure 1-3 : Geological profile of the soil in the plot called "Espérance-Haut"
Source: Malaval 2002 cited by Martin 2004

"Neither of the two horizons exhibits cracks at any time because the soil never dries out sufficiently due to the regularity of rainfall" (Cattan *et al.* 2005).

1.4 Environmental problems linked with banana plantations

1.4.1 Agricultural practices

The physical structure of andosols is largely determined to agricultural practices. Heavy machineries can cause soil deterioration and change the soil surface hydraulic properties. Cattan *et al.* (2005) show that the runoff is generally moderate on andosols and can cause significant surface water contamination due to the flow intensity and to the solubility of the pesticides applied on the soil surface.

1.4.2 Fertilizers and pesticides

Bonan and Prim (2001) report the existence of pollution in the banana plantation soils and in the surrounding aquatic environments by organo-chlorinated pesticides. In addition very strong contaminations of the river sediments were observed in the South of Basse-Terre. Banana plantations are subject to high parasite pressure and require large amounts of inputs: fertilizers and pesticides, which are applied at the banana tree foot on the soil surface. So, these products are likely to be displaced by the water flow (drainage and runoff), especially due to the stemflow. This is a source of aquifer and surface water pollution.

In Guadeloupe, the main water resources are localised in Basse-Terre. It is where the andosols are and therefore, where the banana trees are grown. So, good agricultural practices are urgently required to decrease pollution of water resources.

1.4.3 Changing the cropping system

Another problem is linked with the banana crisis in Guadeloupe. Some farmers are constrained to cease growing banana because it is becoming less and less profitable for them. They think about diversifying their activities by growing vegetables instead of banana. But, to maintain the yield, farmers have frequently applied fertilizers and pesticides which tend to deteriorate the soil quality (Perret and Dorel 1999). Some of these chemicals have a low degradation rate and remain in the soil. So, by changing the cropping system, there is a risk of non adaptability of the new crop with the soil quality and/or a possibility of massive leaching of chemical components to water bodies.

It is therefore necessary to understand the hydrological behaviour of the banana crop-soil system to propose alternative agricultural management for minimising the environmental impacts identified above.

1.5 Hydrological behaviour of banana crop-soil system

The water pathways inside banana plantations are not well known. INRA and the CIRAD are undertaking a survey which aims to define the present and alternative agricultural practices (ECCO PNRH, 2004). This research relies on experimentation and modelling, in order to understand and predict the impact of agricultural practices on the hydrological behaviour of the banana plantation in Guadeloupe.

Past studies have demonstrated rainfall redistribution occurs under banana canopy. Two phenomena were highlighted:

- Banana tree leaves are quite large, so have a high capacity to intercept rainfall and favour the concentration of rainwater in the central part of the plant as a result of stemflow. Consequently, the intensity of water falling along the banana stem and arriving at it foot can be ten to thirty times the rainfall intensity (Cattan *et al.* 2003). It can generate surface runoff and increase the amount of water which infiltrates the soil. The stemflow depends on the rainfall intensity, the Leaf Area Index (LAI), the angle and size of the leaves and the whole development of the plant, according to Van Elewijck (1989). The LAI is an index describing the development stage of a plant according the size of its leaves.
- The banana canopy acts like an umbrella. At the extremity of the leaves, rainwater falls and the drop intensity is greater than the rainfall. When the drops reach the soil, they create puddles from which the runoff can start when the drop intensity is greater than the infiltration capacity of the soil.

Both phenomena induce the heterogeneity of the water flow arriving at the soil surface (Figure 1-4). They also induce a spatial variability in the hydrodynamic properties at soil surface which influence the quantities of water which are going to runoff and infiltrate through the soil. Martin (2004) has identified four different soil surface characteristics (SSC) under a banana plantation according to their relation with the water flow:

- SSC 1: **"unsolicited area"** - the area upstream the pseudo-stem where solids have been deposited after being transported by overland flow. The pseudo-stem presents an obstacle to the runoff.
- SSC 2: **"water way"** - the area in inter row, eroded by the surface runoff.
- SSC 3: **"crust and moss"** - an area not affected by the water flow where a crust is formed and vegetation used to grow.
- SSC 4: **"banana foot"** - downstream of the pseudo-stem where the soil is quite often removed by the stemflow.

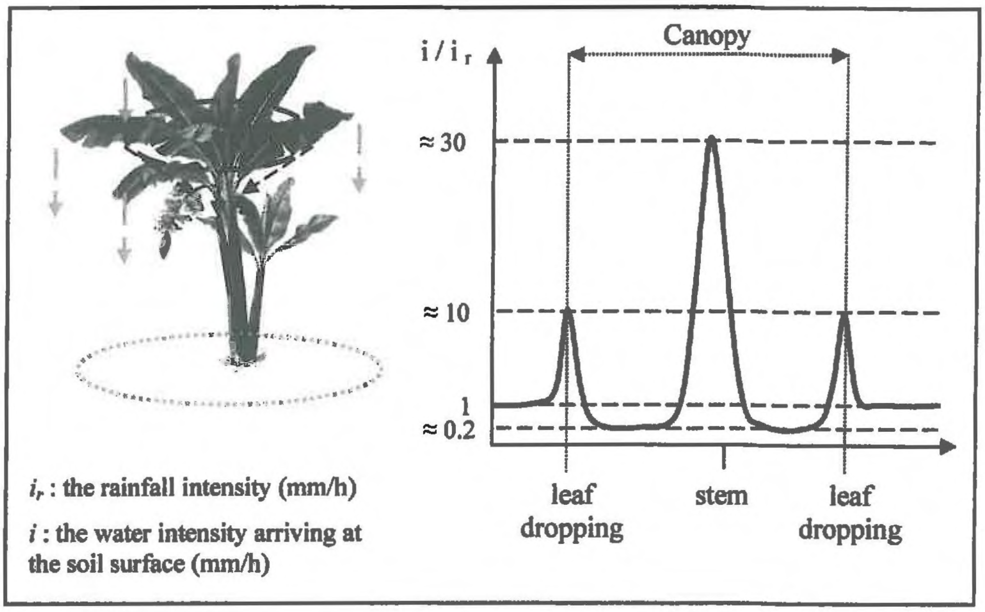


Figure 1-4 : Heterogeneity of the rainfall intensity arriving at the soil surface of a banana plantation

Moreover, Sansoulet *et al.* (2004) showed that the water pathways through soil depend on the development stage of banana trees. It is measured using the LAI which is maximal at the flowering development stage of the banana tree, six months after the plantation. According to the amount of stemflow and due to the redistribution of the runoff consequence of the different soil surface characteristics, hypotheses have been done:

- at the beginning of growth, all the stemflow infiltrates through soil at banana tree foot (see Figure 1-5 number 1); and
- when the leaves grow, the stemflow increases and water flow begins to run off and then infiltrates (see Figure 1-5 number 2).

Similar temporal variations in the SSC occur with each rainfall event. In fact, at the beginning of the rainfall, the water infiltrates at banana tree foot. At the end, because of water saturation, the rainfall is redistributed by the soil surface to infiltrate down the banana stem or run off. Another assumption considers the existence of lateral drainage through the soil: the water infiltrate at banana tree foot and then subsurface flows following the plot slope occur (see Figure 1-5 number 3).

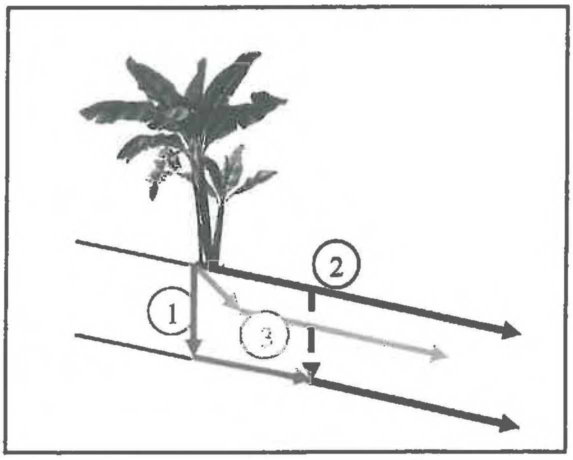


Figure 1-5 : Hypotheses concerning the water pathways at the soil surface and subsurface

In 2004, Martin undertook experiments and studied the hydrological behaviour of banana plantation at a single tree scale. A new hypothesis takes into account a plough layer (low permeability layer) appearing at 25 – 30 cm deep due to machinery works.

1.6 Objectives

The INRA and CIRAD work on the consequences of the hydrological functioning of banana crop on andosol associated with the input of fertilizers and pesticides. They already demonstrated that:

- a low percentage of rainfall is transformed into surface runoff;
- the rainfall redistribution has a high impact on the drainage flow; and,
- the genesis of runoff down the banana tree foot creates a redistribution of inputs and soil particles.

Data collected by Martin (2004) as part of the overall study needs to be analysed and interpreted to help understand the behaviour of the crop and to find solution to the environmental impacts cited previously.

This MSc project aims to determine the role of the soil surface on the genesis and spreading of runoff using a method to evaluate soil hydrodynamic properties and to understand the hydrological behaviour of the soil-banana crop system by quantifying the water volumes which infiltrate, run off and are stored.

The objectives are to:

- validate the Beerkan method as a reference method to measure the soil hydrodynamic parameters;
- describe the experimental plot using values of hydraulic conductivity at saturation;
- describe the water processes at rainfall event scale (variation of water storage, drainage and runoff coefficients);
- establish relationship between the soil hydrodynamic properties and the water flows; and
- confirm the assumptions of Sansoulet *et al.* (2004) by characterising lateral drainage through andosol and runoff volumes, but also by the analysis of the soil water potential during a rainfall event.

2 Methodology

In this part, the experimental methodology used by Martin (2004) for data collection is included to give an understanding of the whole research programme. It concerns mainly the experimental protocols and the description of the studied plot. The following theories and methodologies for calculations have been used in the MSc project.

First, the hydrodynamic properties of andosols in Guadeloupe have been studied. The aim was to validate the method developed by Haverkamp *et al.* (1998), called the Beerkan method, by comparing it with other methods. The heterogeneity of soil surface properties has been analysed by studying the infiltration rate of different soil surface characteristics.

Secondly, the water flow pattern was studied at a single tree scale by analysing the inputs (rainfall and stemflow) and outputs (drainage and runoff) of water and to estimate the variation of water storage in the soil. The data used were from the experimentation carried out by Martin (2004), so results depend strongly on the quality of the data set.

2.1 Site survey description

Experimentations were made at the Neufchâteau experimental station (16°04'38'' North, 61°36'04'' West, 250 m asl), on the windward side of Basse-Terre, as shown in Figure 1-1. The field experiment was conducted at "Espérance-Haut" with a 6000 m^2 surface area and an average slope of 12% (Cattan *et al.* 2005). A small part of this field (8.8m^2) called "the plot", has been used to conduct an experiment at the banana tree scale and is described in the section 2.3.1.

2.2 Estimation of the soil hydrodynamic properties

INRA and CIRAD aim to solve the Richard's equation to model the water flow through soil. For that the water retention curve and the hydraulic conductivity curve as well as other soil hydrodynamic properties are needed. There are various methods of calculating them (Appendix 5.1).

Experimental methods exist to find the static and dynamic soil properties but they are valid at local scale and are laborious to undertake. Empirical methods using the hydrodynamic soil properties are easier to carry out. The following three were used to analyse the existing raw data and the results compared with each other:

- The Beerkan method;
- The disk infiltrometer of Decagon type;
- The Wind's evaporation method.

The objective was to try to validate the Beerkan method as a reference method to estimate the hydrodynamic properties of a soil and to find the key components of the Richard's equation used when modelling water movement through soil.

2.2.1 The Beerkan method

The method called "*Beerkan*" method developed by Haverkamp is an indirect method for the determination of the soil hydrodynamic properties *in situ* (Haverkamp *et al.* 1998). It is an infiltration method at zero pressure head. The hypothesis is that every infiltration curve can be modelled to an adimensional one. According to Braud *et al.* (2004), this method "provides the most efficient and cost-effective way to estimate soil scaling factors and soil hydrodynamic properties at a large number of sampling point".

Findeling (2001) describes the infiltration rate in a soil using:

- The soil texture: *determination of the shape parameters of the water retention curve n and m, and the shape parameter of the hydraulic conductivity curve* η;
- The dry bulk density ρ_b and the initial and final (saturation) soil moisture θ_0 and θ_s: *determination of the soil porosity* ε, θ_0 *and* θ_s; and
- The cumulative infiltration $I(t)$ of water through soil under constant pressure head: *determination of the structural parameters: the hydraulic conductivity at saturation* K_s, *the scale parameter for the water pressure* h_g *and the initial hydraulic conductivity* K_0.

θ_s and h_g are constant for a type of soil.

So, six parameters are needed to estimate both of the curves. There are divided in two categories: the textural or shape parameters: n, m and η and the structural or scale parameters: K_s, h_g and θ_s. Explanations of their calculation are given in Appendix 5.2.

Experimental protocol : This procedure is a summary of the one proposed by Braud *et al.* (2004). To obtain the cumulative infiltration, known volumes of water are poured into a metallic cylinder (5 to 15 cm diameter) localised at soil surface as shown in Figure 2-1.

Figure 2-1 : Demonstration of the Beerkan method.
Source: Haverkamp and Angulo-Jaramillo (2004)

Samples to estimate soil initial properties are taken before and after the experiment. Each volume of water is poured after the total infiltration of the previous one. At every addition of water the time is noted. The experiment is stopped when the time between two additions is constant: the permanent regime is reached.
The method is destructive, so has to be undertaken outside the experimental plot to preserve the soil for other experiments. The field work occurred the 12th of May 2004 and was done for different soil surface characteristics defined in section 1.5.

Theory: The theory is explained by Braud *et al.* (2004). Data were analysed in one-dimension infiltration and in three dimensions. The experimental curve *I(t)* is modelled by using a theoretical time $t(K_s, \alpha_I)$ defined by the equation (1) of Green and Ampt.

$$t\,(K_s,\alpha_I) = \frac{\Delta I_1}{K_s - K_0} - \frac{\alpha_I}{K_s - K_0}\ln\left(1 + \frac{\Delta I_1}{\alpha_I}\right) \qquad (1)$$

where $$\Delta I_1 = I_3 + [K_0 + \delta(K_s,\alpha_I)]\,t \qquad (2)$$

α_I is a factor taking into account the adimensional (modelled) and experimental infiltrations. K_s and α_I are variable which have to be optimized to fit the experimental time. The parameter δ includes the effect of the water movement in three dimensions.

So, δ equals to zero for the analysis of infiltration in one dimension. I_3 is the measured cumulative infiltration which occurs naturally in three dimensions. The algorithm in Figure 2-2 has been used for the calculations.

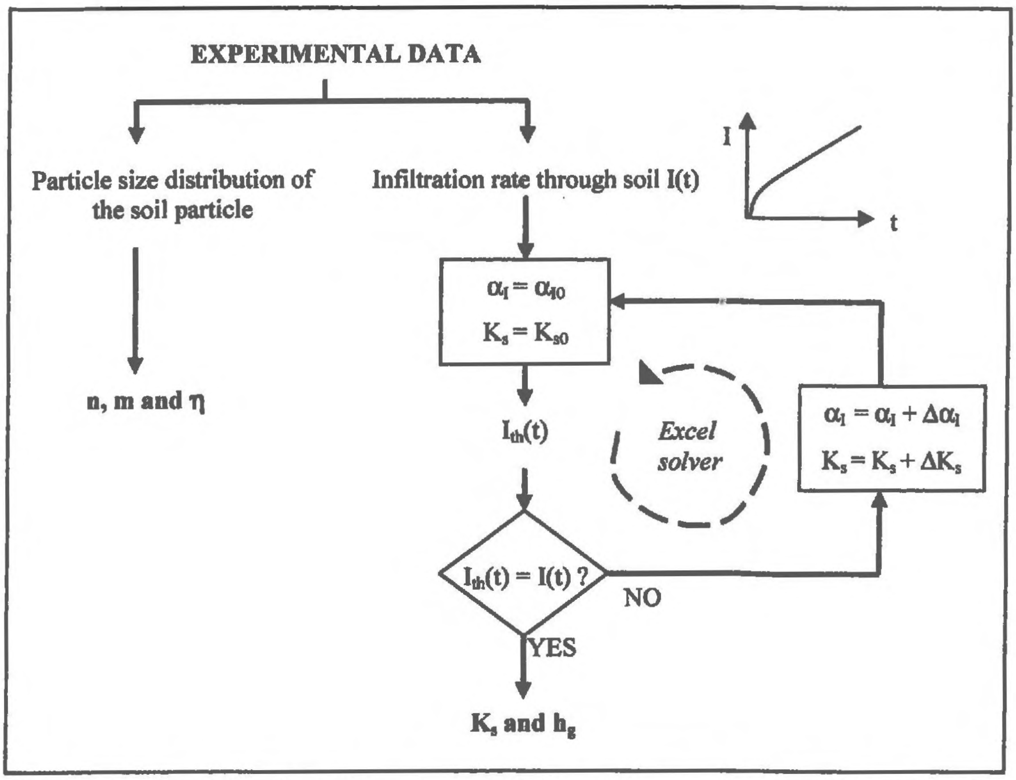


Figure 2-2 : Algorithm describing the calculations when analysing the Beerkan data

Two or three samples of data were collected by Martin (2004) at the soil surface for each SSC and at 30 cm deep.

2.2.2 The tension disc infiltrometer of Decagon type

Coquet *et al.* (2000) described the tension disc infiltrometer method as "a useful tool for the measurement of the soil hydraulic conductivity near saturation". The water potentials vary between -25 cm and 0 cm. This method does not allow the description of the water retention curve. The principle consists in measuring the infiltration rate of water in soil through a porous membrane. The Decagon's device has been used as a simplified tension disc infiltrometer.

Experimental protocol: The infiltrometer (Figure 2-3) is filled with water by immersion. Then, it is put on the soil surface which has been cleared of plants and covered, if necessary, by a thin layer of sand. Once the infiltrometer is placed, water begins to leave the water reservoir and infiltrate into the soil at a rate determined by the hydraulic properties of the soil and by the suction imposed by the infiltrometer through the suction control tube. As the water level drops, the water volume in the device at specific time intervals is recorded. Different experiments are carried out using a different diameter for the suction control tube.

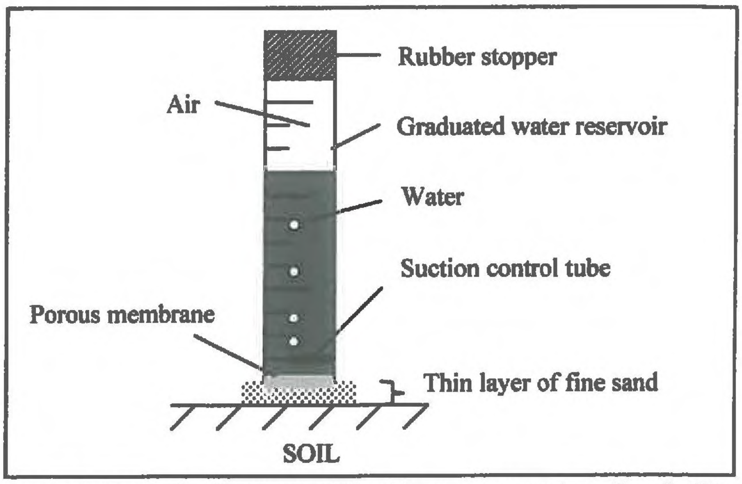


Figure 2-3 : Schematic diagram of the Decagon tension disc infiltrometer

Theory: Data can be analyzed in various ways in transient state or steady state regime. The data were analysed using the theory of axisymmetric infiltration in pseudo-permanent regime of Reynolds and Elricks (1991). The multipotential method (Coquet *et al.* 2000) uses the solution of Wooding (equation (3)).

$$q_{\infty}(h) = K(h)\left[1 + \frac{4}{\pi r \alpha}\right] \qquad (3)$$

$q_{\infty}(h)$ is the infiltration rate (infiltration per unit of time). K_s and α are the two unknowns. The hypotheses are:

- the soil is a semi-infinite (limited only by its surface), homogeneous and isotropic media;
- the soil is initially dry;
- the relation of Gardner

Reynolds and Elricks rewrote the equation (3) into the following one.

$$\ln(q_\infty(h)) = \ln\left(K(h)\left[1+\frac{4}{\pi r}\right]\right)+\alpha h \qquad (4)$$

This is a linear equation with α, the slope and ln(K(h)[1 + 4/(πr)]) the y-intercept as explained the Figure 2-4. It has been demonstrated that α is not constant. So, three experimentations have been undertaken at three different suctions: -6, -2 and -0.5 cm. The line between the potential -2 cm and -0.5 cm has been used to estimate the hydraulic conductivity near saturation.

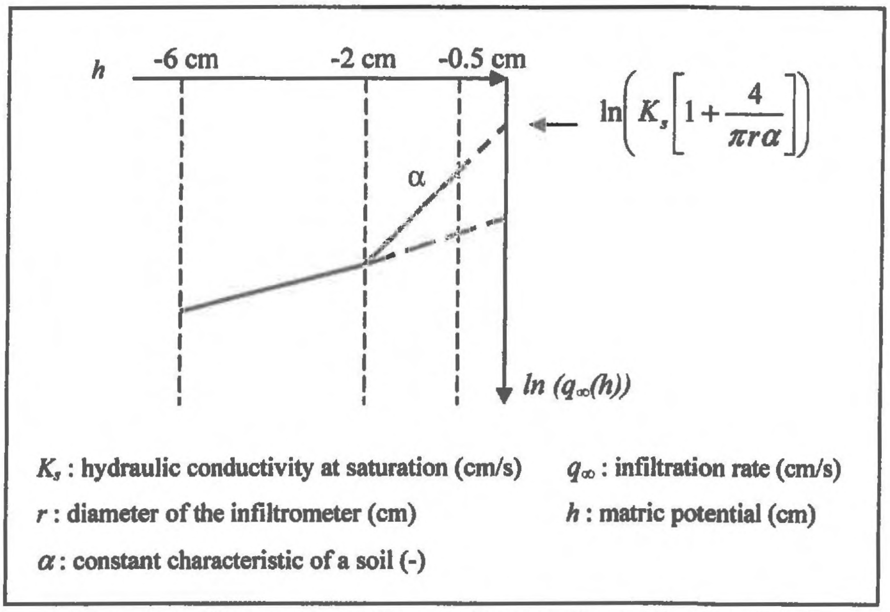


Figure 2-4 : Explanation of the method of Reynolds and Elricks

The method has been undertaken inside and outside the experimental plot for the different soil surface characteristics to verify that the soil hydraulic properties are the same in both areas as the other methods cannot measure them on-site as they are destructive.

2.2.3 The Wind's evaporation method

The Wind's method is a reference method which allows the simultaneous determination of hydraulic conductivity curve in an unsaturated media (*h* between -50 and -700 cm) and the water retention curve (*h* between 0 and -800 cm) in laboratory. The hydraulic conductivity curve near the saturation has been estimated using a constant-head permeameter. This method gives directly the curves *h(θ)* using the model of Van Genutchen (Appendix 5.1) and *K(θ)* using the Darcy's law.

Experimental protocol: Undisturbed sample of soil are taken from field and then wetted up to the saturation. By evaporation, the soil is dried. During this step, the soil tension at different levels is measured using tensiometers and the sample is weighed, as shown in Figure 2-5. The experiment finishes when air penetrates in one of the tensiometers. At the end, the soil sample is weighed, dried in the oven and weighed again to determine the water content at each specific time.

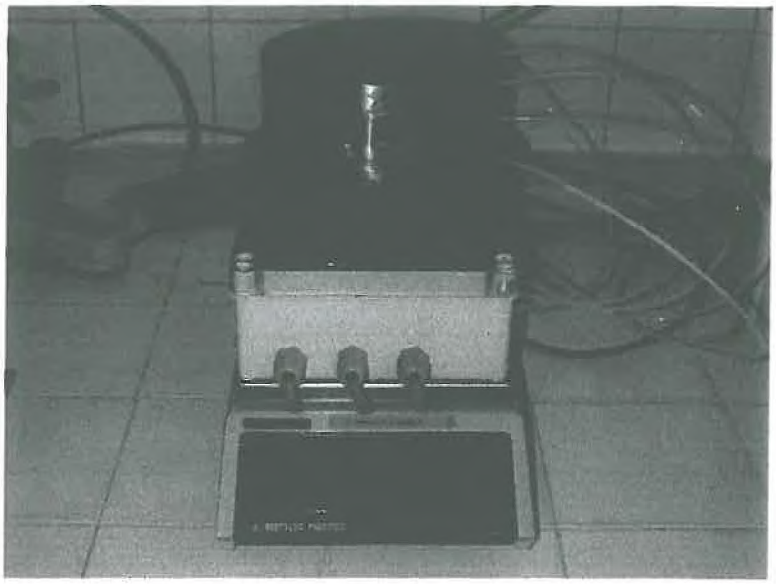


Figure 2-5 : Picture of the Wind's method experimentation
Source: laboratory of Climate Soil and Environment – INRA Avignon 2005

It is assumed that the soil sample hydraulic properties are homogeneous and the water flow in the soil is one-dimensional.

Data were analysed by INRA using a modified method from the normalized method ISO 11275 (2004). The results were compared to the Beerkan results. Experiments have been undertaken near the experimental plot as it is necessary to take samples of soil. Two series of data exist one from November 2000 undertaken by INRA at Montpellier when the field was in fallow and another one in February 2004 undertaken by INRA at Avignon just after the harvest.

2.3 Water balance at banana tree scale

2.3.1 Description of the experimental plot

This part aims to describe the experimentation undertaken by Martin (2004) in order to understand the origin of the data. Inside the field "Espérance-Haut" a small plot has been used to study the water flows at single tree scale (Figure 2-6).

The plot has been isolated to control the entering and leaving water flows. Devices like rain gauge, lysimeters and tensiometers were installed to follow the time course of precipitation, drained water volumes and soil water contents during a rain event. Also, a runoff vat and a stemflow receptacle measured the surface water and stemflow quantities. A data logger recorded the measurements of each device simultaneously. A more specific description of the plot is given in Appendix 5.3.

The experiment began on the 25th of June 2004 and finished around the 25th of September 2004. The banana trees were at the flowering development stage with an LAI of 2-3.

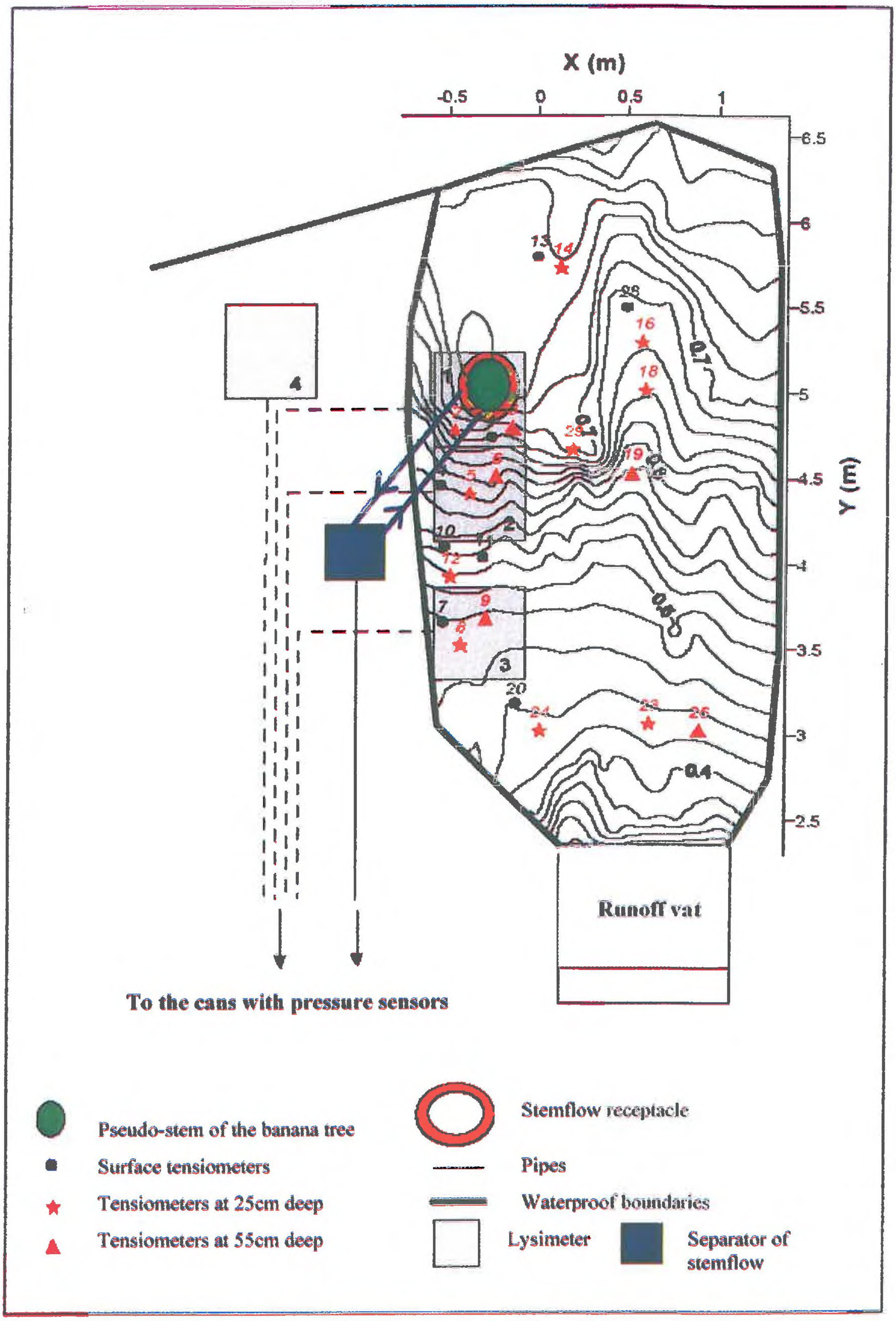


Figure 2-6 : Plot layout for banana hydrology experiment in Guadeloupe
Source: adapted from Martin (2004)

2.3.2 Estimation of the water balance inside the plot

2.3.2.1 Water pathways inside the banana plantations

To analyse the raw data an estimation of the water balance (Figure 2-7) inside the experimental plot has been done at rainfall event scale according to the hypothesis given in the introduction.

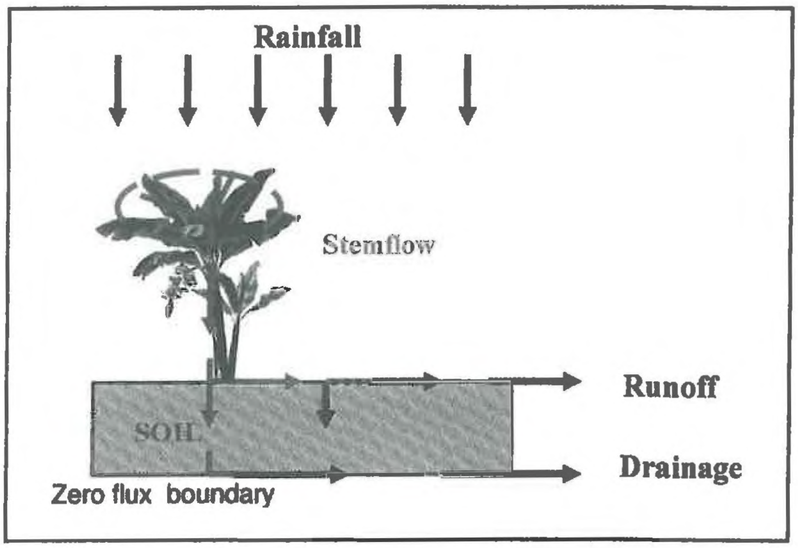


Figure 2-7 : Scheme of the water balance at the plot scale

Evaporation and evapotranspiration are negligible during rainfall events due to the high moisture of the air in Guadeloupe. Throughout the year, the relative humidity varies between 75 and 85% (Théault and Denhez 2005). As the amount of water retained by the banana leaves is difficult to estimate, it has not been taken into account in the water balance.

At the end of the rain events, the variation of water storage ΔS in soil can be written as following:

$$\Delta S = \text{Inputs} - \text{Outputs} \tag{5}$$

$$\Delta S = \text{Rainfall} - \text{Runoff} - \text{Drainage} \tag{6}$$

The stemflow does not appear directly inside the water balance equation as it is a part of the precipitation. Nevertheless, as it concentrates large amount of water at banana tree centre then at its foot, it is an important factor to study to see how it influences the drainage and runoff.

2.3.2.2 Data calibration

The data logger of Campbell type provides the recorded measurements of each device for each time step in form of a database. Software called "R" was used to sort out and analyse the data.

For the transducers, two calibrations were necessary to transform the tension recorded by the data logger into a water depth expressed in mm (volume/surface area). The last relation is different for each device: lysimeter cans, runoff vat and stemflow receptacle. The relations of calibration for the rain gauge, the stemflow receptacle, the lysimeter cans, the tensiometers and runoff vat are described in Appendix 5.4.

To estimate the water balance inside the plot, it is essential to evaluate the quantity of water which is drained through the soil. As the experimental plot is not totally covered with lysimeter, it has been divided into different parts according to the banana canopy cover (Figure 2-8). The drained quantities of water (in mm) of the subplots 1, 2, 4 and 5 are respectively associated to the lysimeters 1, 2, 3 and 4. For the subplot 3, without lysimeter, the mean measurement of the lysimeters 2 and 3 has been used. So, the drainage is a mean value, contrary to the runoff which is directly given by the runoff vat. The precipitation at the plot scale is also an extrapolation of the water depth recorded by the rain gauge.

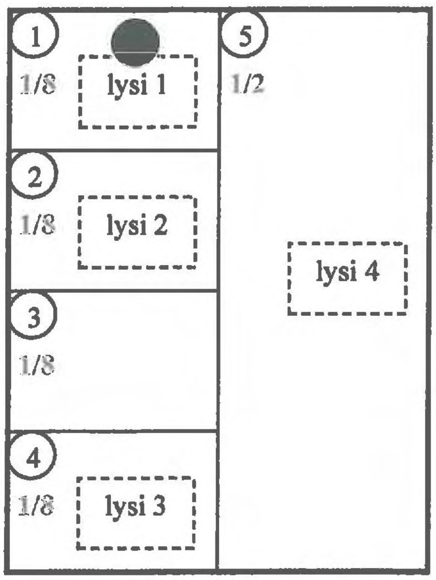


Figure 2-8 : Division of the plot in subplot to estimate the drained water volume
The green disc represents the banana tree

2.3.2.3 Estimation of the variation of water storage

After the data calibration step described in Appendix 5.4, the tensiometer data are expressed in matric potential *h* (m). To estimate the variation of water storage in the soil, the soil water content is needed. The water retention curve *h(θ)* given by Van Genutchen (Appendix 5.1) has been used (equation (7)).

$$\theta = \left[1 + \left(\frac{h}{h_g}\right)^n\right]^{-m} \cdot (\theta_s - \theta_r) + \theta_r \qquad (7)$$

The variation of water storage ΔS (mm) can be estimated using the variation of soil water content during a rain event (equation(8)).

$$\Delta S(t_0, t_{end}) = \int_0^{Z_{lysi}} [\theta(z, t_{end}) - \theta(z, t_0)]\, dz \qquad (8)$$

Z_{lysi} is the lysimeter depth (600 mm), *dz* is the variation of depth (mm) and t_0 and t_{end} are respectively the beginning and the end of the rain events (d). According to the position of the tensiometers inside the plot, a weight has been allocated at each of them to know the mean soil water content $\overline{\theta}$ of the plot taking into account the depth at which the tensiometers are established (Table 2-1). This procedure is similar to the one used to evaluate the drained water depth (Figure 2-8). The tensiometer locations inside the plot are shown in Figure 2-6.

Table 2-1 : Weight allocated to each tensiometer to estimate the water storage variation

Subplot (see Figure 2-9)	1	2	3	4	5	
Tensiometer number at 6 cm deep	1	4	mean of (10 and 11)	7	mean of (28, 13 and 20)	total
Weight allocated	1/8	1/8	1/8	1/8	1/2	1
Tensiometer number at 25 cm deep	2	5	12	8	mean of (14, 16, 18, 23, 24 and 29)	total
Weight allocated	1/8	1/8	1/8	1/8	1/2	1
Tensiometer number at 55 cm deep	3	6	mean of (6 and 9)	9	mean of (19 and 26)	total
Weight allocated	1/8	1/8	1/8	1/8	1/2	1

The variation of depth *dz* has been estimated by calculating the space between each tensiometer as shown in Figure 2-9.

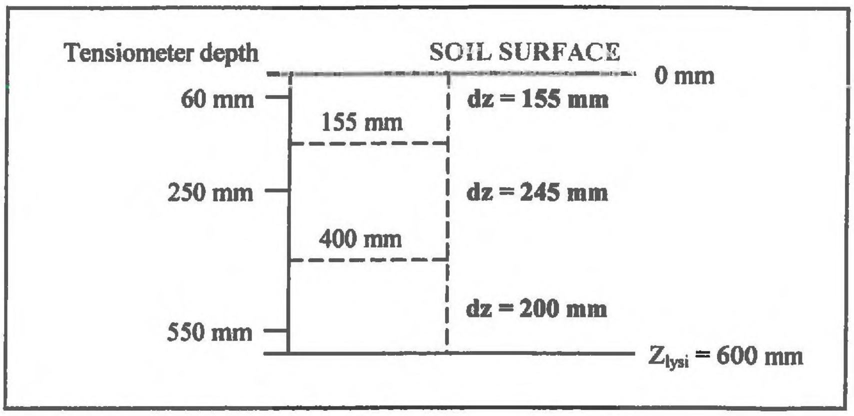


Figure 2-9 : Calculation of the difference of depth between the tensiometers

Finally, equation (8) becomes:

$$\begin{aligned}\Delta S = &\left[\bar{\theta}(60,t_{end}) - \bar{\theta}(60,t_0)\right]\times 155 \\ &+\left[\bar{\theta}(250,t_{end}) - \bar{\theta}(250,t_0)\right]\times 245 \\ &+\left[\bar{\theta}(550,t_{end}) - \bar{\theta}(550,t_0)\right]\times 200\end{aligned} \quad (9)$$

The variation of water storage during an event can be estimated by the calculation using the tensiometers explained above (ΔS_m) or by deduction from the rainfall, runoff and drainage ΔS_c (equation (6)). The ΔS_c has been compared to the ΔS_m to see if the approximations done to calculate the ΔS_m are correct in order to be sure of the results given by the tensiometers.

2.4 Spatial analysis of the water pathways in the plot

For each selected event, data from the tensiometers and the lysimeters has been analysed in order to see how the water is drained, where it is stored in the experimental plot and where the runoff begins.

For the drainage, it consists on plotting the evolution of the drainage measured by the four lysimeters. The objective is to check which lysimeter collect the more or the less drained water in order to confirm the hypotheses about the water movement through soil.

For the tensiometers, it consists on looking at the different tensiometer measurements according to its depth and its location inside the plot during the rain events. Hypotheses about surface and subsurface water movements are expected.

3 Results and Discussion

3.1 Hydrodynamic properties of the soil

3.1.1 Soil textural parameters

The textural parameters were deduced from the particle size analysis of three samples of soil. Two of these samples were collected at 10 - 17 cm deep and the last one at 3 - 10 cm deep. An average was made on the three samples to represent the surface soil grading curve (Figure 3-1). The soil contained 9% clay, 47% silt and 44% sand. The andosol studied is a loam or sandy loam (Soil Survey Manual 1993). However, Dorel *et al.* (2000) showed that it is actually a clay soil (with 62% of clay and 32% of silt) which is consistent with andosol properties. The results are not in agreement, the laboratory may have done a mistake when analysis the soil. The distribution of particles size should have been achieved by dispersion using a sodic resin to avoid problems linked with the presence of micro aggregates of clay particles in andosol which are very stable and can have the same size that a sand particle. In the absence of any other analyses, the data have been used.

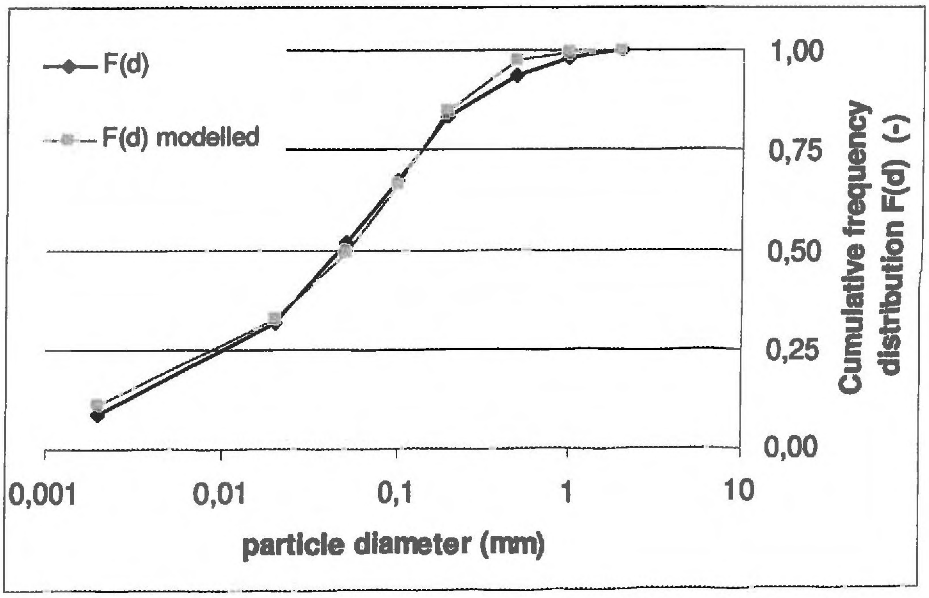


Figure 3-1 : Experimental and modelled particle size distribution curve of surface soil

The modelled curve was adjusted and the values of the different parameters given in Table 3-1 were used to find the parameters of the water retention curve *n*, *m* and η. These results are intermediate ones, so no values of them have been found in the literature.

The soil structural parameters θ_0 and θ_s were directly from Martin (2004) for each infiltration measurements undertaken.

Table 3-1 : Parameters found with the particle size distribution curve

	At soil surface	At 30 cm deep
ε	0.7168	0.7739
dg	0.0002	
M	0.1865	
N	2.4584	
m	0.1645	0.1552
n	1.1969	1.1837
η	13.1593	13.2724

3.1.2 Dynamic parameter: K(θ)

3.1.2.1 The Beerkan samples analysed in one and three dimensions

The infiltration rate of water through andosol has been analysed in one and three dimensions. Braud *et al.* (2004) explained that "generally, the infiltration is three dimensional due to lateral dispersion of water during the experiment with the cylinder." The 1D analysis does not take into account the horizontal soil capillarity effect but only the vertical gravimetric and capillary components of the infiltration, so it overestimates the value of K_s. The 3D analysis considers both (Figure 3-2).

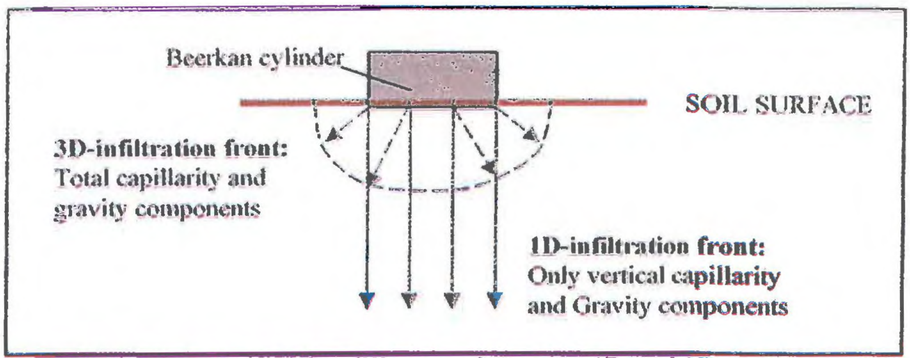


Figure 3-2 : Explanation of the difference between 1D and 3D analyses of data

Figure 3-3 confirms that in most of the cases the 1D hydraulic conductivity is higher than the 3D one. Problems of convergence and optimization of the parameters occurred during the analysis in three dimensions. It appeared that in some case the algorithm (Figure 2-2) did not work, especially when the difference between θ_0 and θ_s was small. So the 1D-analysis results of the Beerkan method, even if they are overestimated, have been used thereafter.

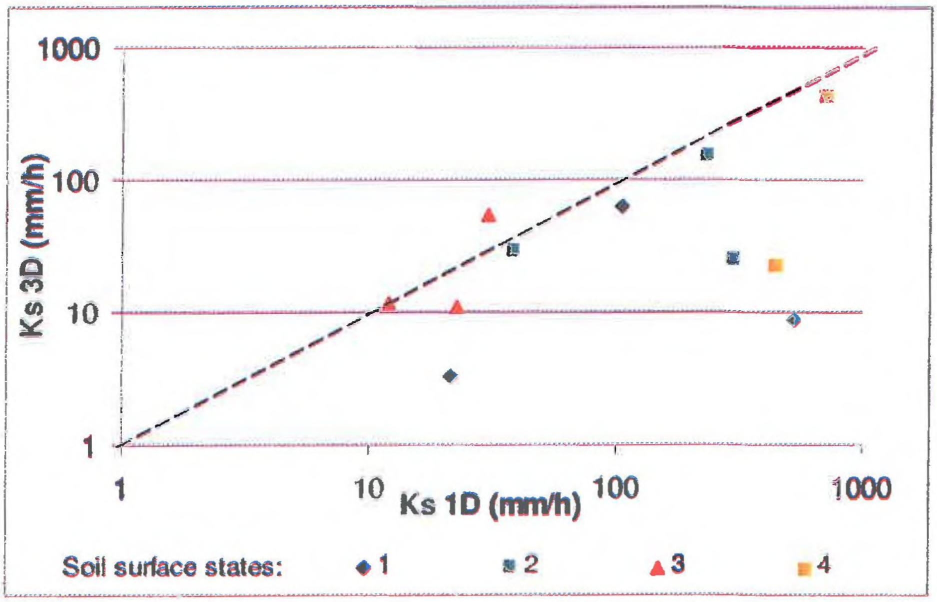


Figure 3-3 : Comparison between 1D and 3D hydraulic conductivities at saturation

3.1.2.2 Comments on the variation of hydraulic conductivity at the soil surface

The overall hydraulic conductivities are high compare to usual soil (Figure 3-4). This is due to andosol properties highlighted in introduction. Only, two or three measurements have been taken on site by surface states, more samples are needed to describe soil surface hydraulic characteristics with accuracy. The overall mean K_s value (221 mm/h) presents a high variance (239 mm/h) but is coherent with the literature values found for this kind of soil in Guadeloupe (from 26 to 350 mm/h) which also present a high variability but are incomplete in term of variance and sample sizes (Perret and Dorel (1999); Dorel *et al.* (2000); Clermont-Dauphin *et al.* (2004) and Cattan *et al.* (2005)). The high variability of K_s inside the SSCs may reflex an inadequate definition of them and a high variability of K_s at the soil surface. The data from the SSC 1 and SSC 2 are dispersed so no generalisation can be done for the hydraulic conductivity of these SSCs. Nevertheless, the hydraulic conductivity in crusty and vegetated surface (SSC 3) is lower than the others (10 - 30 mm/h). The soil surface is less permeable. Near the banana tree stem (SSC 4), the hydraulic conductivity tends to be very high (430 - 690 mm/h).

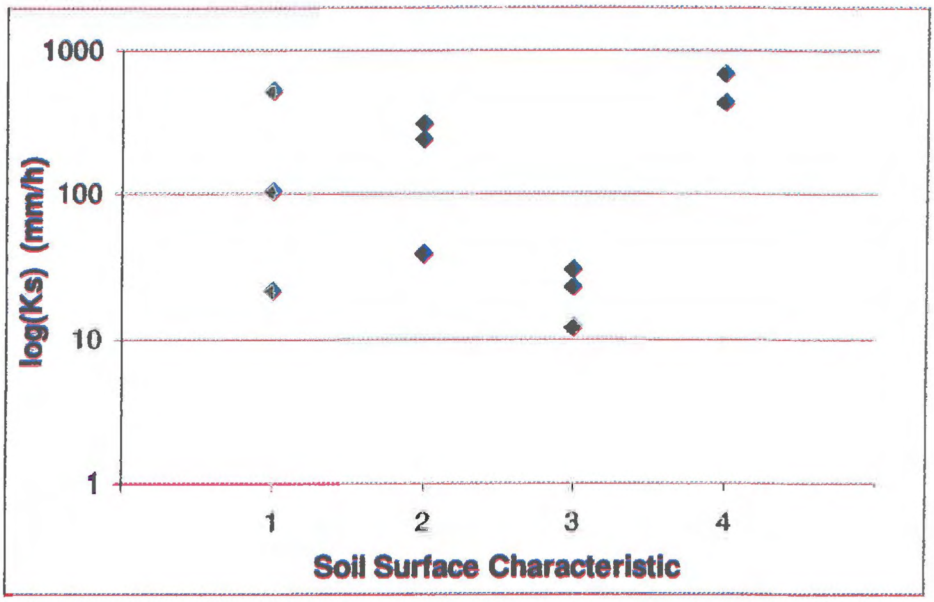


Figure 3-4 : Characterisation of the hydraulic conductivity of the soil surface using the Beerkan method in one-dimension.

1 - Accumulation area, 2 - Water pathway, 3 - Crust & mosses, 4 - Banana pseudo-stem,

3.1.2.3 Comparison between the Decagon tension disc infiltrometer and the Beerkan methods

The idea was to be able to describe the hydraulic conductivity at saturation anywhere in the plot by using a non destructive method. The tension disc infiltrometer method is a non destructive method which operates at a very small scale (approximately 2 cm). This method enables easy and quick measurements of replicates but is highly dependant on local variability of soil properties and does not give direct access to the hydraulic conductivity at saturation. It cannot be considered as a reference. The Beerkan method is a destructive method that provides K_s and was used as the reference method. We tried to find a relationship between both methods.

The tension disc infiltrometer K_s given in the Table 3-2 was calculated from the linear equation between the potential at -2 cm and -0.5 cm extrapolated at 0 cm of suction. The raw data are available in Appendix 5.5. This extrapolation is a lower bound approximation due to the non-linearity of K near saturation as shown in Appendix 5.1. This value was, however, used in order to compare the two methods.

Table 3-2 : Hydraulic conductivities estimated with the Beerkan and tension disc infiltrometer for two soil water potentials.

Soil Surface Characteristic		Infiltrometer implemented outside the plot		Infiltrometer implemented inside the plot		Beerkan
		K (-2 cm)	Ks	K (-2 cm)	Ks	Ks
1 Accumulation area	*mean (mm/h)*	121	**398**	-	-	**218**
	σ/mean (%)	66	73	-	-	124
	sample number	4	4	-	-	3
2 Water pathway	*mean (mm/h)*	10	**22**	179	**2138**	**194**
	σ/mean (%)	74	75	67	106	71
	sample number	8	8	6	6	3
3 Crust & mosses	*mean (mm/h)*	4	**9**	58	**1447**	**26**
	σ/mean (%)	54	64	35	50	21
	sample number	6	6	5	5	3
4 Banana stem	*mean (mm/h)*	17	**40**	77	**1428**	**564**
	σ/mean (%)	59	65	70	132	52
	sample number	4	4	3	3	2
Total	*mean (mm/h)*	30	**90**	103	**1559**	**221**
	σ/mean (%)	181	206	93	105	109
	sample number	22	22	16	16	11

Some samples did not give physically realistic results, for example the hydraulic conductivity was higher at - 2 cm of matric potential than at -0.5 cm. So, they have not been used for the interpretation of the results. This suggests some problems with the experimental methods. Some technical problems occurred with Decagon devices: the porous membrane sometimes presented some leakages and the tension control tube were not always well stuck to the water reservoir, so some air leakage occurred which might have altered the suction applied.

For each SSC and each method outside and inside the plot, the results are very different. Obviously, a problem occurred during the experimentation undertaken inside the plot, the measured values are incoherent with the literature values mentioned previously. So no generalisation about the value of the hydraulic conductivity at a particular SSC can be made.

Measurement carried out outside the plot show that SSC 3 was clearly the one which had the lowest hydraulic conductivity as commented in the previous section. This type of surface develops crusts and mosses which substantially reduced its permeability.

3.1.2.4 Comparison between the laboratory and Beerkan methods

The K_s obtained with the constant-head permeameter are consistent between each other as shown in Table 3-3. The hydraulic conductivities at saturation in depth are higher than the one at the soil surface:

Ks (50-57 cm deep) > Ks (30-37 cm deep) > Ks (10-17 cm deep) > Ks (3-10 cm deep)

Table 3-3 : K_s values found with the Wind and Beerkan methods

<table>
<tr><th></th><th colspan="2">depth (cm)</th><th colspan="3">Ks (mm/h)</th><th>Mean (mm/h)</th><th>σ (mm/h)</th><th>Sample size</th></tr>
<tr><td rowspan="3">WIND (2004)</td><td colspan="2">3-10</td><td>16</td><td>13</td><td></td><td>15</td><td>2</td><td>2</td></tr>
<tr><td colspan="2">10-17</td><td>49</td><td></td><td></td><td>49</td><td>-</td><td>1</td></tr>
<tr><td colspan="2">50-57</td><td>727</td><td>2862</td><td>1680</td><td>1756</td><td>1070</td><td>3</td></tr>
<tr><td rowspan="5">BEERKAN</td><td rowspan="4">Surface</td><td>SSC1</td><td>22</td><td>528</td><td>106</td><td rowspan="4">221</td><td rowspan="4">239</td><td rowspan="4">11</td></tr>
<tr><td>SSC2</td><td>39</td><td>237</td><td>305</td></tr>
<tr><td>SSC3</td><td>30</td><td>23</td><td>12</td></tr>
<tr><td>SSC4</td><td>689</td><td>438</td><td></td></tr>
<tr><td colspan="2">30-37</td><td>211</td><td>162</td><td>225</td><td>199</td><td>33</td><td>3</td></tr>
</table>

The K_s at soil surface from the Beerkan experiment and at 3-10 cm deep from the Wind one are expected to be quite similar as the samples were taken at a close depth, but the K_s at 3-10 cm deep wers lower than those one of Beerkan at the soil surface. The soil surface was taken off in the Wind's samples to have a homogeneous soil surface. During this operation the soil surface pores may have been altered (sealing) which can explain lower water conductivity.

The values obtained at 50-57 cm deep (1.7-2.9 m/h) are very high and do not seem reliable. Other experiments need to be undertaken to confirm or reject these value as they are not consistent with the one found by Cattan *et al.* (2005) for the horizon B (32 mm/h).

Cattan *et al.* (2005) used a controlled-suction disc infiltrometer and found a mean K_s of 135 mm/h for the horizon A (0 – 30 cm) and 32 mm/h for the horizon B (30 – 60 cm) for an untilled soil. On a traditional management of the field, the mean K_s for the horizon A was 265 mm/h. The possible explanation of low K_s for the soil horizon B is the hypothetical presence of a ploughing layer at about 30 cm deep where the samples were undertaken in Cattan *et al.* experiment. The Beerkan samples were taken below 30 cm.

It is difficult to decide which of both methods give the more realistic values since the experiments undertaken and their results are quite different.

The laboratory method can be considered the most reliable as it is commonly used for a large range of soil (ISO 2004), however, it can present some artefacts due to preferential flow between the cylinder and the soil. The Beerkan method has the advantage of being an in situ method.

To conclude, only the qualitative trends of each method have to be retained, but the absolute values of K_s cannot be used with confidence.

3.1.3 Static parameters: *h(θ)*

The results from the Wind's experimentation undertaken in 2000 and 2004 were compared to the Beerkan ones. Table 3-4 sums up the needed parameters to describe the water retention curve. The soil horizons A and B are differentiated.

Table 3-4 : Summary of the parameters of the water retention curve

Soil	Methods	sample size		θ_r*	θ_s*	$1/h_g$*	n*
Horizon A (0 – 30 cm deep)	WIND (2004)	3	mean	0,30	0,73	9,143	1,165
			σ	*0,15*	*0,02*	*8,514*	*0,082*
	WIND (2000)	5	mean	0,20	0,69	36,576	1,158
			σ	*0,16*	*0,08*	*34,894*	*0,076*
	BEERKAN	11	mean	-	0,68	14,691	1,197
			σ	-	*0,00*	*10,321*	*0,000*
Horizon B (30 – 60 cm deep)	WIND (2004)	3	mean	0,30	0,75	29,279	1,098
			σ	*0,18*	*0,01*	*19,787*	*0,049*
	WIND (2000)	8	mean	0,37	0,70	7,743	1,196
			σ	*0,14*	*0,03*	*6,769*	*0,105*
	BEERKAN	2	mean	-	0,73	3,967	1,184
			σ	-	*0,00*	*1,470*	*0,000*
Horizons A + B (0 – 60 cm deep)	WIND (2004)	6	mean	0,30	0,74	19,211	1,131
			σ	*0,15*	*0,02*	*17,529*	*0,071*
	WIND (2000)	13	mean	0,31	0,70	18,832	1,182
			σ	*0,17*	*0,05*	*25,412*	*0,094*
	BEERKAN	13	mean	-	0,68	14,691	1,197
			σ	-	*0,02*	*10,236*	*0,005*

* θ_r : residual soil water content ($m^3.m^{-3}$), θ_s : soil water content at saturation ($m^3.m^{-3}$), h_g.: scale parameter for the water pressure (m) and n : shape parameter for the water retention curve

The Beerkan result for horizon A is the mean of each parameter for the 11 samples taken at the soil surface whatever the soil surface characteristic. For horizon B, it is the mean result of the experiments undertaken at 30 cm deep. The number of samples is too low to carry out a complete relevant statistical analysis. Nevertheless, some general trends can be highlighted.

Although the data are highly variable, there were no big differences between the Wind's results of 2000 and 2004. A Student's T-test was carried out on $1/h_g$ and *n* to compare at 5% probability level for horizon A, horizon B and the whole profile (A+B). The test revealed that only the means on $1/h_g$ of horizon B cannot be assumed equal.

The Beerkan results are close to those from the laboratory. However, the variances of the values are high so do not allow a strong relationship between both methods to be defined.

3.1.4 Partial conclusion

The results from the three methods gave highly variable and quite different values for the soil hydraulic properties. Nevertheless, these analyses highlighted the low K_s of the crust and vegetated areas (10-30 mm/h) which are not affected by water input and the high infiltration capacity of the area down slope from the banana tree stem (430-690 mm/h) compared to the mean experimental value (221 mm/h) and literature value (26-350 mm/h).

The Beerkan method could not be correlated satisfactorily to the non destructive Decagon tension disc infiltrometer method. The discrepancies between both methods were due to technical malfunction of Decagon devices and different operating scales.

The comparison between Beerkan results and the laboratory WIND's results showed a general agreement in spite of large uncertainties.

The use of those three methods may be questionable in the case of andosol as the concepts of saturated and residual water contents are poorly defined for andosols in which water is one of the components of soil solid structure. For instance, the Beerkan method proved to be useful to determine the hydrodynamic parameters in a soil cultivated with beans subjected to dry period in Brazil (Souza *et al.* 2003). This method may, however, be suitable for certain types of soil and not adapted to andosol. Further experiments are required to address this point.

3.2 Water balance at banana tree scale

To evaluate the water stored in the soil, the relation $h(\theta)$ derived from the laboratory method because it is a direct physically-based method and so assume more reliable. Between both sets of data, the one from 2004 was kept because the beginning of the experiments on the plot began the same year.

3.2.1 Description of the rain events

In July and August 2004, the amounts of precipitation were 368 mm and 300 mm respectively. These values are far above the average monthly precipitations which are 193 mm for July and 206 mm for August at Pointe-à-Pitre (see Figure 1-1) (Students of the World 2001). So, the water processes may be emphasized in terms of water volumes.

Most of the rain events analysed was chosen by Martin (2004). Parameters have been set up to ensure the independence of each event in order to visualise the amount of runoff and drainage without the interference of another event. (Appendix 5.6)
Five events have been chosen according to their main characteristics (Table 3-5). Figure 3-5 presents the evolution of each water outputs during the selected events. The range of cumulative rainfall was large (5.58 - 80.82 mm) and the duration of each event was comprised between 23 min and 20 h.

Events 1 and 2 are quite similar in terms of amount of precipitation (respectively 5.58 mm and 6.66 mm) but their runoff coefficients and drained amount of water are very different.
Due to the high mean rainfall intensity (14 mm/h) the rain during event 1 did not have time to infiltrate into the soil and 35% of the precipitation ran off. In Guadeloupe very high rainfall intensity is around 30 mm/h (Rossignol 1990). This is a maximum recorded over a period of one minute; the intensity calculated here is a mean on the event. This event lasted 23 min. Nevertheless, some water was drained through the soil (18%). The rest of water was stored in the soil (47%). Event 2 lasted 3 h 41, and the mean rainfall intensity was less important (2 mm/h). Only 8% of the precipitation ran off and 5% drained. Consequently, the water storage had increased greatly after the event: 88% of the precipitation was stored which represents 5.8 mm.

Table 3-5 : Main characteristics of the five selected rainfall events

Event	Start	Duration (h : min)	Pr (mm)	R (mm)	D (mm)	ΔS_c (mm)	mean intensity (mm/h)	R/Pr	D/ Pr	ΔS/ Pr	θ_0 at 6cm deep	θ_f at 6cm deep	θ_0 at 25cm deep	θ_f at 25cm deep	θ_0 at 55cm deep	θ_f at 55cm deep
1	3/7/04 2:38	0:23	5.58	1.95	1.02	2.61	14.35	0.35	0.18	0.47	0.639	0.642	0.648	0.652	0.661	0.666
2	11/7/04 1:12	3:41	6.66	0.52	0.28	5.87	1.80	0.08	0.04	0.88	0.578	0.624	0.599	0.613	0.649	0.662
3	11/7/04 6:00	2:51	21.60	7.01	9.07	5.52	7.54	0.32	0.42	0.26	0.624	0.628	0.613	0.639	0.662	0.665
4	15/7/04 3:36	20:48	80.82	17.15	51.86	11.81	3.88	0.21	0.64	0.15	0.634	0.644	0.631	0.652	0.666	0.691
5	27/8/04 21:36	4:02	51.12	21.55	14.88	14.70	12.63	0.42	0.29	0.29	0.629	0.621	0.629	0.637	0.647	0.667

Pr : Precipitation, R : Runoff, D : Drainage, ΔS_c : Calculated variation in water storage, θ_0 and θ_f : Mean initial and final soil water contents.

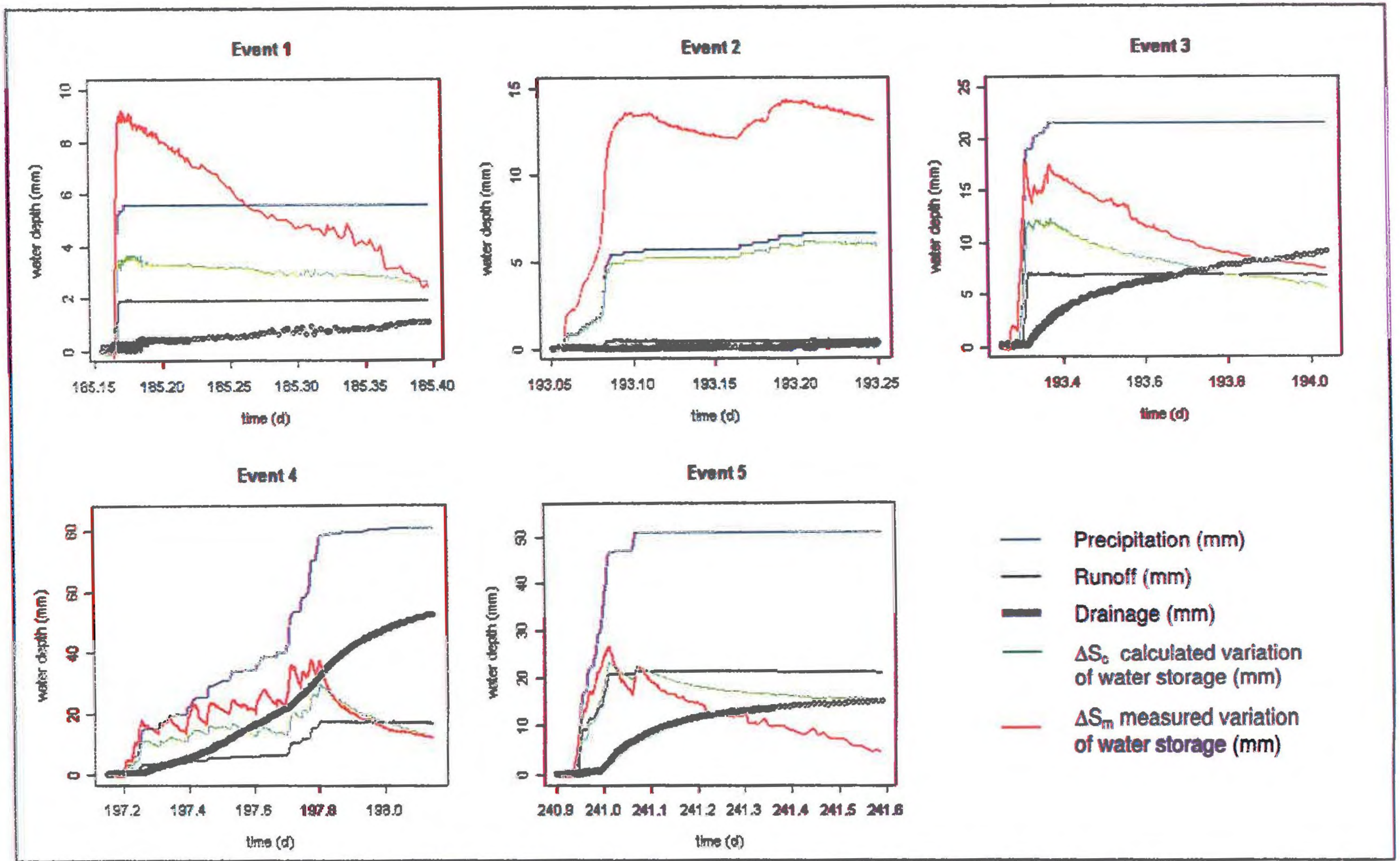


Figure 3-5 : Evolution of the runoff, drainage and water storage during the rain events

The mean rainfall intensity of events 1 and 5 are similar (14 and 13 mm/h respectively). and seems to be linked with the amount of rainfall evacuated by runoff (35 and 42% respectively). Cattan *et al.* (2005) demonstrated that despite the high infiltration capacity of the soil, moderate runoff may occur in banana plantation on andosol (mean runoff coefficient of 5-11% but less than 34%). Precipitations were quite high during July and August which can explain higher runoff coefficient found.
The initial soil water content before event 2 was less than before event 1 (Table 3-5). Thus, the water storage increased more during event 2 than during event 1. The soil was able to store more water during event 2 because it was initially drier.

During event 4, 64% of the precipitation drained through the soil. This is a consequence of the low rainfall intensity (mean of 4 mm/h) during the 20 h of rainfall and the high initial soil water content. The water had time to infiltrate; therefore the runoff water quantity is small. Also, the rainwater could not be stored in large quantities as the soil water content was initially high. Consequently, the drained water quantity was very large. At the end of the event, the soil water content recorded is the highest of all the selected events.
So, the hydrological behaviour of the plot during a rain event depends on the rainfall intensity and amounts, and the initial hydraulic conditions of the soil.

3.2.2 Variation of soil water storage

3.2.2.1 Comparison between the two calculations of the soil water storage

The variation of water storage during an event can be estimated by the tensiometers (ΔS_m) or calculated with the water budget from the rainfall, runoff and drainage terms (ΔS_c). The comparison of both methods allows to check if the data recorded were consistent with each other. ΔS_c may have been overestimated as the evaporation, the evapotranspiration and the amount of water absorbed by the plant were not taken into account. ΔS_m is estimated using an empirical equation and the data recorded by each tensiometer. So, uncertainties exist in both methods.
As it appears in Figure 3-5, the two methods present well marked differences for the events 1 and 2. The measured variation of ΔS_m was very high, and even higher than the

precipitation for the event 1 and 2. It is not possible as the unique input of water is from the rainfall, so the method overestimates ΔS_m. Nevertheless, the shapes of both ΔS_m and ΔS_c are similar. It is important to find out why both methods differ to ensure the consistency and the quality of the experimental data.

By analysing each parameters entering in the calculation of ΔS_m, it has been found that the shape parameter *n* of the water retention curve has been overestimated (Appendix 5.7). As mentioned above, the particle size analysis of the soil is not reliable, a value of 1.1 for *n* should have corresponded to a soil composed mainly by clay particles and ΔS_m should have been closed to ΔS_c.

Nevertheless, the two methods reveal that the sets of data are consistent with each other.

3.2.3 Stemflow influence on surface runoff and drainage

Some rain events were recorded when all the stemflow was intercepted but technical problems occurred so the data could not be analysed. Event 5 is the only event selected for which stemflow data existed. The Figure 3-6 shows how much water was concentrated by the banana canopy during the event 5. For this event, the stemflow was up to 37 times the precipitation in term of water depth. This is comparable to the approximation of Cattan *et al.* (2003) who found 10 to 30 times the incident rainfall. This point confirmed that the rain is redistributed by banana tree canopy and dramatically concentrated at the tree stem.

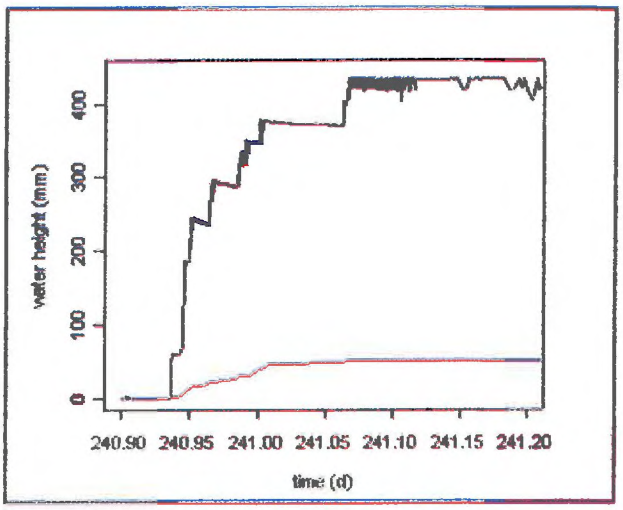


Figure 3-6 : Comparison between the stemflow (black line) and rainfall (blue line) amount of water during the event 5

3.2.4 Partial conclusion

The analysis of the experimental measurements showed that the data recorded on the plot were reliable. Also, this analysis confirmed the statement of Cattan *et al.* (2005) that the hydrological behaviour of the plot during rain events depends on the rainfall intensity and amount, and the previous hydraulic conditions of the soil. At the beginning of each event, the major part of the soil water storage was stored near the soil surface and then drained to the deepest soil horizon from which it may reach the aquifer as suggested by Sansoulet et al. (2003) (number 1 Figure 1-5). At the event scale, the water storage occurred mainly in the deepest soil horizon. The runoff was confirmed to be moderate on the plot. Under the banana tree canopy, the rainfall reached the soil after being highly concentrated which pointed out the importance of the stemflow. These results are in good agreement with those of literature in terms of stemflow and hydrological behaviour of the soil.

3.3 Spatial analysis of the water flows in the plot

3.3.1 Contribution of each lysimeters to the drained water volumes

Events 1 and 2 were the smallest in terms of water depths, consequently the corresponding drained water amounts were very small (respectively 1.0 and 0.3 mm) as shown in Table 3-6. These events were not used to describe the contribution of each lysimeter to the drainage.

Figure 3-7 and Table 3-6 show that lysimeter 2, immediately down slope lysimeter 1, is collected more water than lysimeter 1 located just below the banana stem. Moreover, lysimeter 2 received little direct rainwater as it was protected by the banana canopy, but collected more water than the rainfall amount. That means that even though a small proportion of the water collected was coming directly from precipitation, the main quantity was from stemflow. This point highlighted the influence of stemflow on drainage and suggested that a redirection of stemflow occurred down the banana tree foot in direction of lysimeter 2. This redirection occurred from the soil surface runoff flow (vertical infiltration) or in form of subsurface flow (lateral horizontal flow) as suggested by Martin (2004) and Sansoulet *et al.* (2003) (number 3 Figure 1-5).

Table 3-6 : Cumulative amounts of water (mm) collected in each lysimeters at the end of each event

Event	Lysimeter 1	Lysimeter 2	Lysimeter 3	Lysimeter 4	Mean drainage	Precipitation
1	2.88	3.52	0.00	0.00	1.02	5.58
2	1.03	0.00	0.00	0.30	0.28	6.66
3	21.94	29.11	0.18	1.67	9.07	21.60
4	75.31	121.31	14.31	34.03	51.86	80.82
5	39.95	51.41	0.00	0.49	14.88	51.12

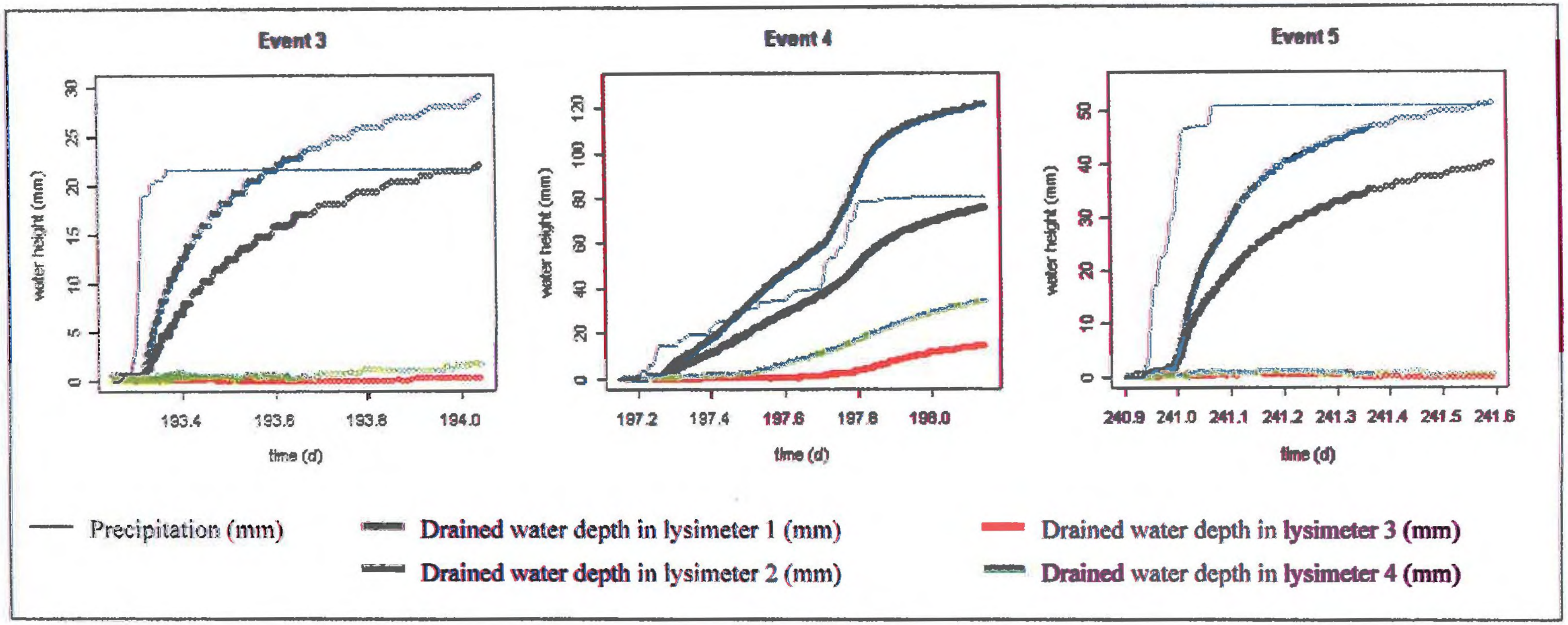


Figure 3-7 : Evolution of the drained water depths

For events 3 and 5, the contribution of lysimeters 3 and 4 appeared very small compared to the other events. During event 4, the greatest event in term of rainfall quantity, the contributions of lysimeters 3 and 4 were more substantial. Lysimeter 4 located between two rows contributed more than lysimeter 3 located outside the area covered by the canopy. This phenomenon can be related to the larger amount of water present above lysimeter 4, in the water pathway where rain water was concentrated.

It would help understanding the water regime of the banana tree plantation to observe when drainage started in the lysimeters. Unfortunately, the measurement occurred in cans which were linked with pipes to the lysimeters. So there was an unknown lag time between actual drainage onset and beginning of measurements, which hindered such a study.

3.3.2 Time course of soil water content inside the plot

As there were implemented at different locations and different depths inside the plot, a comparative analysis of the data recorded by the tensiometers should highlight some preferential water ways. The time course of each tensiometer according to its depth and for each rainfall event is summarized in Appendix 5.8. The main characteristics analysed are the initial soil water content or soil matric potential, the hydrodynamic soil properties (SSC), location of the tensiometers inside the plot (under or outside the canopy and close or far from the banana tree stem) and the rainfall event (rainfall amount and intensity, runoff coefficient, etc). The following section aims to describe the hydrological behaviour of the plot to be able to model it in the future.

Without taking into account the banana tree and the spatial rainfall redistribution, the initial matric potential is assumed to increase with depth (Figure 3-8). During the rain event, an increase of soil water content is expected due to the input of water. The tensiometers located above lysimeter 3 and inside the subplot 5 (in inter row, see Figure 2-8) reacted in this way. The stemflow had already been drained or evacuated by run off before reaching them.

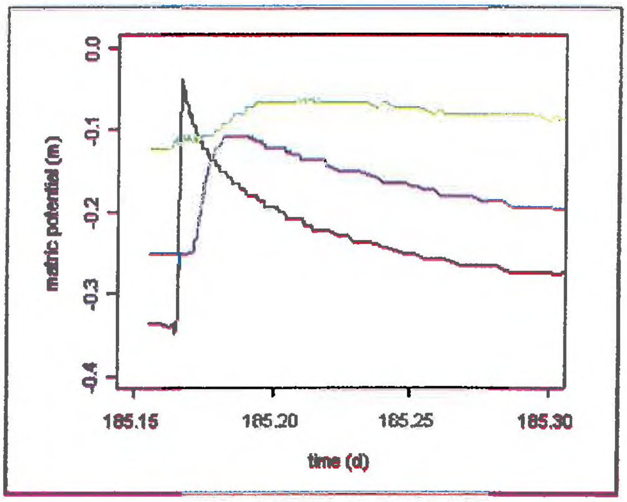


Figure 3-8 : Typical variation of the soil matric potential at 6 (black line), 25 (blue line) and 55 cm deep (green line) during a rainfall event

By analysing each soil water content according to the depths of the tensiometers, it appeared that the upper soil layer (at 6 cm deep mainly but also at 25 cm deep) made the greatest contribution to the soil water storage at the beginning of the event as shown in Figure 3-8). Moreover, there was a delay between the variation of matric potential recorded by the tensiometers located at 6, 25 and 55 cm deep. This traced the natural water flow through the soil from the soil surface to the deepest horizon.

At depth (25 and 55 cm deep), the variations of soil matric potentials were low to non-existent for the less important event (events 1, 2 and 3), whereas large amounts of water were stored after events 4 and 5. The results confirmed that the water was preferentially stored in the deepest horizon of soil where it is less easily extracted by the plant and less subject to evaporation.

Tensiometers 18, 19 and 28 (see Figure 2-6) presented potentials a bit higher than tensiometers 7, 8 and 9 (above lysimeter 3) during rainfall events: they were located in the inter row which is an inter row which concentrated water runoff flow down to the lowest point of the plot. This hypothesis was sounded with the amount of water collected in lysimeter 4 which was greater than the amount collected in the lysimeter 3.

The tensiometers located above lysimeter 1 received the most water. The large amount of stemflow explained that the three tensiometers were the firsts to react with the

beginning of the rain. The maximum soil water contents recorded by these tensiometers reached the saturation level. So, the area located just down slope of the banana tree stem was an area of runoff initiation despite the high infiltration capacity of the soil. Also, runoff was generated above lysimeter 2. This runoff initiation was already reported by Cattan *et al.* (2005). The tensiometers located above lysimeter 2 showed very similar patterns as the tensiometers located above the lysimeter 1 with a slighter increase of matric potentials and a small delay to reach the maximum soil matric potentials.
At 55 cm deep, tensiometers 3 and 6 corresponding to the subplots encompassing lysimeters 1 and 2 were most of the time the only ones to receive water during rain events. Tensiometers 9, 19 and 26 implemented at the same depth had a slighter or no reaction to the input of rain which reinforced the hypothesis that the stemflow impact was limited to subplots 1 and 2 (see Figure 2-8 for their location).
Moreover, some discontinuities were observed for tensiometers 4, 10 and 12 located above and down slope from lysimeter 2. They received less water than the nearest tensiometers (tensiometers 5 and 11). They were located outside the area affected by stemflow. Surface tensiometers 7, 13 and 20 had a similar behaviour. Therefore, the stemflow was absorbed by the soil before reaching them, in the area located above the right side of lysimeters 1 and 2 (where tensiometers 1, 3, 5, 6 and 11 were implemented).
This analysis of soil matric potentials emphasized the impact of stemflow, runoff generation areas and runoff pathways localisation in the water regime of the plot.

The main difficulty when analysing the tensiometer data was to put together the results. This comes from the fact that tensiometers were installed at different depths and scattered in the plot. Moreover, the experimental plot was designed as a first experiment to study the evolution of the hydrological behaviour. It was not conceived to highlight runoff generation, subsurface flow and to conclude whether they were linked with the stemflow or the soil hydrodynamic properties. A specific instrumentation is required for this purpose.

3.3.3 Partial conclusion

The stemflow was infiltrated quickly in the interception area located down slope the banana tree stem (about 1m long by 0.5 m wide) or evacuated by runoff down to an area where infiltration could occur. The fact that the stemflow can feed the runoff pathways remains a hypothesis which needs to be confirmed. It is in this interception area where the rain water was drained to the deeper soil horizon. The presence of a lateral subsurface water flow and the redistribution of surface runoff suggested by the results of in this study and by those of Martin (2004) needs to be described with more accuracy which the tensiometer study could not achieve. Runoff initiations occurred mainly at banana tree foot as also demonstrated by Cattan *et al.* (2005). The fact that the drainage is more important below the water pathways than below other areas not affected by stemflow is a hypothesis which needs to be confirmed.

An integrated study of the plot may be improved by installing tensiometers regularly throughout the plot at different depths, for example on a grid. This depends on the resource allocated for such a survey and can disturb the processes inside the plot. Moreover a description of the SSC where each tensiometer is located should be useful in order to study the link between the SSC and possible surface pathways.

To conclude, the objective of this section was to describe as precisely as possible the water pathways at a single banana tree scale to understand better and eventually model the water regime of a banana tree plantation. This objective was partially reached but new questions arose. On September – November 2005, a second experimentation will be carried out on the same plot. It will be specifically designed to tackle these new questions and aims at precising, confirming or rejecting the corresponding hypothesis formulated in this manuscript and by Martin (2004).

4 Conclusions and Recommendations

This MSc project aimed at determining the role of heterogeneous soil properties on the genesis and the transfer of runoff using different methods to evaluate soil hydraulic properties. The final objective of the project was to describe and understand the hydrological behaviour of the soil-banana tree system by quantifying the water amounts stored in the soil or lost by drainage and runoff.

The use of three different methods (Beerkan, Decagon and Wind) provided different results but permitted to point out a general trend of soil hydraulic properties: low K_s of the crust and vegetated areas (10-30 mm/h) which mainly contributed to runoff, and high K_s, typical of andosols, of the areas down slope the banana tree stem (430-690 mm/h). The Beerkan method proved efficient even though it could not be validated. The results disparities and the lack of link with other methods were the main causes. Also, the three methods showed their limits in the case of an andosol in which water is a structural component of the soil. Nevertheless, measurements showed that the water fluxes inside the banana plantation were highly linked to the spatial rainfall redistribution by banana tree canopy which, in turn, induced a great spatial variability of the hydraulic soil surface properties.

In terms of water regime, the analysis of the experimental measurements showed that the data recorded on the plot were reliable. Measurements confirmed the moderate percentage of runoff on the plot (8% for a small event – 42% for a large and intense event). The water processes depended mainly on the rainfall amount and intensity, and the initial moisture conditions of the soil. Under banana tree canopy several phenomena successively occurred: (i) the stemflow infiltrated totally at banana tree foot (high K_s) in the few square meter down slope the tree, till soil saturation was reached, (ii) then runoff initiated and runoff flow infiltrated where the soil water conditions were favourable and/or join main pathways and was evacuated from the plot. Drainage was maximal in lysimeters 1 and 2 as confirmed by the sharp patterns of the tensiometers above those lysimeters. The fact that the stemflow can represent a significant fraction of surface runoff has not been clearly demonstrated in this study. Outside the banana canopy, the rain water flowed from the soil surface to the deepest horizon of the soil where it was stored preferentially. Drainage seemed to be larger below the water pathways than below other areas not affected by stemflow. Moreover, the hypothesis of the presence of a ploughing layer or lateral flow between both soil horizons noticed by Perret and Dorel (1999) and Martin (2004) has not been confirmed. Finally, the presence of a lateral subsurface water flow and/or the redistribution of surface runoff suggested by the results of this study and by those of Martin (2004) needs to be described with more accuracy which the tensiometer study could not achieve.

To conclude, the objective of the study was partially reached but new questions arose. On September – November 2005, a second experimentation will be carried out on the same plot. It will be specifically designed to tackle these new questions and aims at confirming or rejecting the corresponding hypothesis formulated in this manuscript and by Martin (2004). It will be based on a better implementation of the tensiometers. Also, runoff genesis and transfer is expected to be visualised on video camera. A period of data collection without stemflow should be renewed to be able to confirm its impact.

As mentioned in the introduction, erosion and water pollution occur in the banana plantation, so a weighing of the particles collected in the runoff vat and an analysis of water quality in the runoff vat and the drainage cans should highlight the impact of hydraulic fluxes on surface and deep water pollution. Finally, Sansoulet *et al.* (2003) demonstrated that water pathways depended on the development stage of the banana tree. So another perspective is to analyse water dynamics over the whole cropping cycle to get a global knowledge of the processes.

5 Appendices

5.1 Theory of water conduction through soil

Richards (1931) developed the following equation derived from the continuity equation and the generalized Darcy's law, which describes the isothermic and one-dimensional conduction of water in a homogeneous and non saturated porous media.

$$\underbrace{C(\theta)}_{\text{From the water retention curve}}\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left[\underbrace{K(\theta)}_{\text{Hydraulic conductivity curve}}\cdot\left(\underbrace{\frac{dh}{dz}}_{\text{Capillarity term}}\underbrace{-1}_{\text{Gravity term}}\right)\right]$$

where $C(\theta)=\dfrac{\partial \theta}{\partial h}$

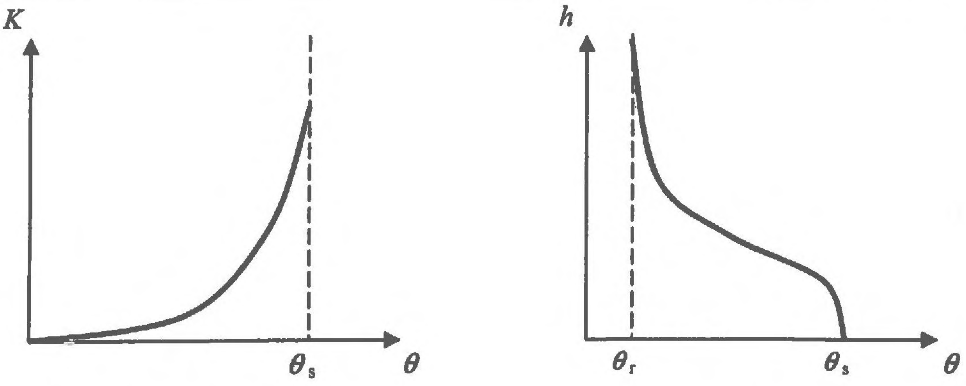
To solve this equation, the water retention curve *h(θ)* and the hydraulic conductivity curve *K(θ)* have to be established. These curves are related to the soil water content therefore depend on the soil properties, are specific to a given area and change with the time.

The solution of the Richard's equation is also subject to given initial and boundary conditions.

Soil static and dynamic properties

The water retention curve *h(θ)* varies with the soil type but it is a *static* parameter for a given soil. It depends on the soil properties such as soil texture and the hysteresis associated with the phenomenon of saturation/drying of the soil. The decrease of the matric suction of a soil is linked with the increase of soil water content (see the following Figure).

The hydraulic conductivity *K(θ)* or *K(h)* is a measure of water velocity in a soil under the influence of the total potential head (sum of the pressure and gravitational potential heads). It is a *dynamic* soil parameter. When the soil becomes dry, the hydraulic conductivity decreases (see the following Figure).



K : hydraulic conductivity (mm/h)
θ: soil water content (-)
*θ*r: residual soil water content (-)
h : matric suction (m)
*θ*s: soil water content at saturation (-)

An example of hydraulic conductivity and water retention curves

Numerous models exist to define the curves, the most used are:

- the Van Genutchen's equation (1980) for the water release curve, *θ(h)* or *h(θ)* :

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \quad \text{or} \quad h(\theta)=h_g\left[\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-1/m}-1\right]^{1/n}$$

θ_r is the residual water content (≈ 0), h_g a scale parameter (m) and *m* and *n* curve shape parameters.

- the Brook and Corey's equation (1964) for the hydraulic conductivity curve *K(θ)* :

$$\frac{K}{K_s}=\left(\frac{\theta}{\theta_s}\right)^{\eta}$$

where K_s is the hydraulic conductivity at saturation, and η a curve shape parameter.

- the Gardner's equation (1958, cited by Coquet *et al.* 2000) for the hydraulic conductivity curve *K(θ)* :

$$K(h) = K_s \exp(\alpha h)$$

where α is a characteristic constant of soil.

5.2 Estimation of the textural and structural soil parameters

Soil textural properties

The soil texture has to be studied to determine the shape parameters *m* and *n* which are linked mathematically and η. The soil texture is related to physical and chemical soil properties and the distribution of soil particles. These parameters are relatively constant for a given soil and are related to particle shape and size.

Three samples of soil were taken from the field and the soil particle size analysis was undertaken by the Laboratory of soil analyses of Arras (France). Haverkamp *et al.* (1998) showed using the theory of geometric similitude that a relation exists between the pore distribution in a soil and the cumulative frequency distribution of the soil particle size. The data obtained from the soil texture provide the cumulative frequency distribution *F(d)* as a function of particle diameter *d* to which the following equation of Haverkamp *et al.* (1998) is fitted:

$$F(d)=\left[1+\left(\frac{d_g}{d}\right)^N\right]^{-M} \qquad \text{where} \qquad M=1-\frac{2}{N}$$

F(d) is the cumulative frequency distribution of the soil particle size, *d* particle diameter (m), d_g a scale parameter for the particle diameter (m) and *M* et *N* shape parameters.

The normalized parameter for the particle diameter d_g and the shape parameter *N* have been optimized by the least squares methods using the Microsoft Excel Solver. Then, the shape parameters for the water release curve *m* and *n* can be estimated using the theory of similitude explained by Haverkamp *et al.* (2004) and summarised in the following equations.

$$p_{MN}=\frac{MN}{1+M} \qquad \text{from the grading curve}$$

$$p_{mn}=\frac{mn}{1+m} \qquad \text{for the water retention curve}$$

$$p_{MN}=(1+K)p_{mn} \qquad \text{where} \qquad K=\frac{2s-1}{2s(1-s)}$$

s is the solution of the last equation. ε is the soil porosity. It is a structural parameter and the method to measure it is explained in the following section.

$$(1-\varepsilon)^s + \varepsilon^{2s} = 1$$

Then the shape parameter η can be estimated:

$$\eta = \frac{2}{mn} + 2$$

Soil structural parameters

Soil structure is characteristic of the arrangement of soil particles and can be described by the soil porosity ε, the dry bulk density ρ_b and the soil water content θ. K_s and h_g depend on the soil structure. Contrary to soil texture, the soil structure is changing with time and space due to agricultural practices, growth of vegetation and animal activities in the soil, for examples.

To find m (and n), the soil porosity is needed and to estimate θ_0 and θ_s, the soil moisture, w needs to be measured. These parameters were estimated by Martin (2004).

θ_0, θ_s and w were estimated by taking a sample of a known volume of soil and by weighting it at different water content: initial, at saturation and after drying it in the oven. The porosity can be obtained using the following equations.

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s}$$

where $\rho_b = \frac{M_s}{V_t}$ and $\rho_s = \frac{M_s}{V_s} \approx 2.68 kg / m^3$

M_s are the initial mass of soil sample and V_t the volume of soil taken. The soil moisture is measured initially w_0 and at saturation w_s to obtain θ_0 and θ_s.

$$\theta = w \cdot \rho_b \qquad \text{where} \quad w = \frac{M_w}{M_s}$$

M_w, the mass of water in a sample of soil, is the difference between the initial mass of the soil M_s and the one after drying the sample in the oven.

5.3 Description of the experimental plot

Around the banana tree, a boundary was built using metallic plate to prevent water from entering or leaving the plot. At 90 - 100 cm deep, the soil is supposed to be impermeable due to the presence of a volcanic base. So the plot is hydraulically isolated and considered as an entity as shown in Figure 2-6.

The following description is mainly from Martin (2004). All the devices are linked with a data logger which records the measurement of each device settled in the plot:

- One tipping bucket rain gauge located near the banana pseudo-stem on a 5 m high mast to collect water above the banana tree canopy. All the experimental devices were automatically controlled to start recording data the beginning of each rainfall event. At the first tip of the rain gauge bucket the data logger began to record from each device according the procedure explained in the following table.

Time steps for the record of measurements by the data logger

Time step between two data records	10 s	30 s	5 min	15 min
Duration	During the **rainfall event** *(up to 10min after the tip of the rain gauge)*	During **1h** after the event	During **6h**	Up to the next event

- Four wick lysimeters, with one outside the plot, at 60 cm deep aimed to collect the drained water. Lysimeter 3 was not affected by the banana tree canopy in contrast to the lysimeters 1 and 2. The lysimeter 4 was situated between two rows of banana trees, on the water way. Lysimeter water contents were collected through small pipes which were linked with four cans. Each can was equipped with a pressure transducer which measured a tension (mV) equivalent to the water height in the can. A thermometer was located near each transducer as the temperature has an influence on the measurement.
- One runoff vat to collect the surface water was located at the lowest point of the plot. The system to measure the water height inside the vat was the same as the one used for the lysimeters.
- 25 tensiometers at three different depths (6, 25 and 55 cm) measured the water potential of the soil. The water potential is the sum of the gravitational potential, matric

potential (sum of the capillarity and electrostatic forces) and the osmotic potential (negligible). Two measurements of temperature had been done for the 25 tensiometers.

- One circular receptacle halfway up the banana tree stem to estimate the stemflow. At the beginning of the experimentation, the stemflow was not intercepted. From the 30th of July, all the stemflow was collected but then from the 5th of August, only around 10% of the stemflow was intercepted for measurement and the remained 90% was released at banana tree foot to be able to estimate the surface runoff and drainage flow.

5.4 Calibration of the data recorded on the experimental plot

For the cans and tensiometers, the tension recorded *U* (mV) has to be translated into water pressure *P* (mm). The water pressure is proportional to the tension *U* recorded by the data logger.

$$P = \alpha U + \beta$$

α and β are two variables depending on the temperature *T* (°C).

$$\alpha(T) = a_1 + a_2 T$$

$$\beta(T) = b + a_3 T + a_4 T^2$$

So the final equation is as follows:

$$P = a_4 T^2 + a_3 T + a_2 U.T + a_1 U + b$$

a_4, a_3, a_2, a_1 and b are calibrated coefficients. For the lysimeters and the runoff vat, the coefficient a_4 is null.

Analysis of Precipitation

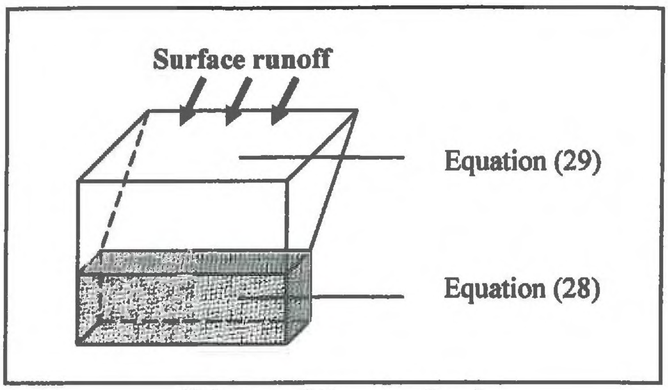
Concerning the rainfall data, the data logger has recorded the number of times the bucket tipped. So, the data have to be multiplied by the height of water corresponding to a bucket (0.18 mm) and to be summed to give rainfall in mm.

Analysis of Runoff

For the runoff vat, the following equations translate the pressure *P* (mm) into water height *H* (mm).

- if $(P - P_0) \leq 0.2$ $\quad H = Pente\,(P - P_0)$
- else $\quad H = \alpha (P - P_0)^2 + \beta (P - P_0) + Y_0$

The coefficients *Pente*, P_0, α, β and Y_0 are given by the calibration of vat done by Martin (2004). The following figure explains the use of the previous equations.



Scheme of the runoff vat

Analysis of Drainage

For the drainage, the equation translates the pressure *P* (mm) in the 4 cans into a water height *H* (mm).

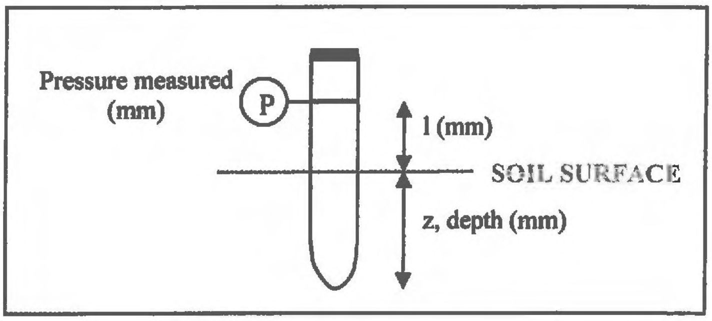
$$H = Pente\ (P - P_0)$$

The coefficients *Pente* and P_0, are given by the respective calibration of the 4 cans.

Analysis of the soil water potential

The tensiometer data are expressed in pressure of water *P* in mm. The pressure is related to the position of the tensiometer as shown in the following figure. To have the matric potential *h* (mm) at 6, 25 and 55 cm deep, the following change is necessary:

$$h = P + l + z$$



Scheme of a tensiometer

Analysis of stemflow

The following relation translates the pressure *P* recorded in the stemflow can into a volume of water *V* (L).

$$V = \text{Pente}\ (P - P_0)$$

To be able to compare it with the precipitation for example, it is necessary to transform it in height of water *H* (mm).

$$H = \frac{V}{\pi r^2} \cdot 10^6$$

where *r* is the diameter of the banana tree stem estimated at 25 cm.

5.5 Comparison between the Beerkan and tension disc infiltrometer methods

Hydraulic conductivities (mm/h) estimated with the Beerkan and tension disc infiltrometer for two soil water potentials

Soil Surface Characteristic	Infiltrometer implemented outside the plot		Infiltrometer implemented inside the plot		Beerkan
	K (-2cm)	Ks	K (-2cm)	Ks	Ks
1 Accumulation area	228	809			22
	77	327			528
	49	127			
	128	329			106
mean	*121*	*398*			*218*
σ	*79*	*290*			*271*
2 Water pathway	17	37	114	426	39
	8	19			237
	21	43	99	5889	
	1	1	359	4016	
	4	10	304	1118	
	3	5	89	555	
	10	19	108	824	305
	16	41			
mean	*10*	*22*	*179*	*2138*	*194*
σ	*7*	*17*	*120*	*2272*	*138*
3 Crust & mosses	2	5	79	922	30
	5	10	80	2033	23
	7	19	40	449	12
	3	7	40	2087	
	2	4	52	1743	
	3	7			
mean	*4*	*9*	*58*	*1447*	*26*
σ	*2*	*5*	*20*	*727*	*5*
4 Banana stem	13	25	93	656	689
	30	75	17	47	
	17	46	122	3580	
	7	16			438
mean	*17*	*40*	*77*	*1428*	*564*
σ	*10*	*26*	*54*	*1889*	*314*

5.6 Parameters to select rain events

To ensure the independence of each event, parameters of the choice of events are:

- A significant amount of rainfall were recorded in a short time (twenty minutes to a day);
- The rainfall height during the three hours before the event is less than 2 mm; and
- The rainfall height after the event is less than 10 mm with no event recording more than 3 mm of rainfall.

The last constraint is to be able to visualise the amount of drainage without the interference of another event.

5.7 Sensitivity analysis of the parameters used to estimate the measured variation of water storage

Two possible hypotheses concerning the overestimation of ΔS_m have been found:

- The soil thickness *dz* allocated to each tensiometer (see Figure 2-10) is not adequate, especially at 6 and 25 cm deep; or
- One or more of Wind's parameters to describe the water retention curve (θ_s, θ_r, h_g and n) have not been well estimated.

Both of these assumptions were tested varying one by one each parameter and comparing the corresponding ΔS_m to the reference ΔS_m estimated for unchanged parameters. A smaller representative thickness of soil has been allocated at the tensiometers implemented at 6 and 25 cm deep (respectively 10 cm and 20 cm, so 30 cm were allocated to the deeper tensiometers). Variations of the Wind's parameter have been chosen using the sensitivity range found in Table 3-4 for the horizon A.

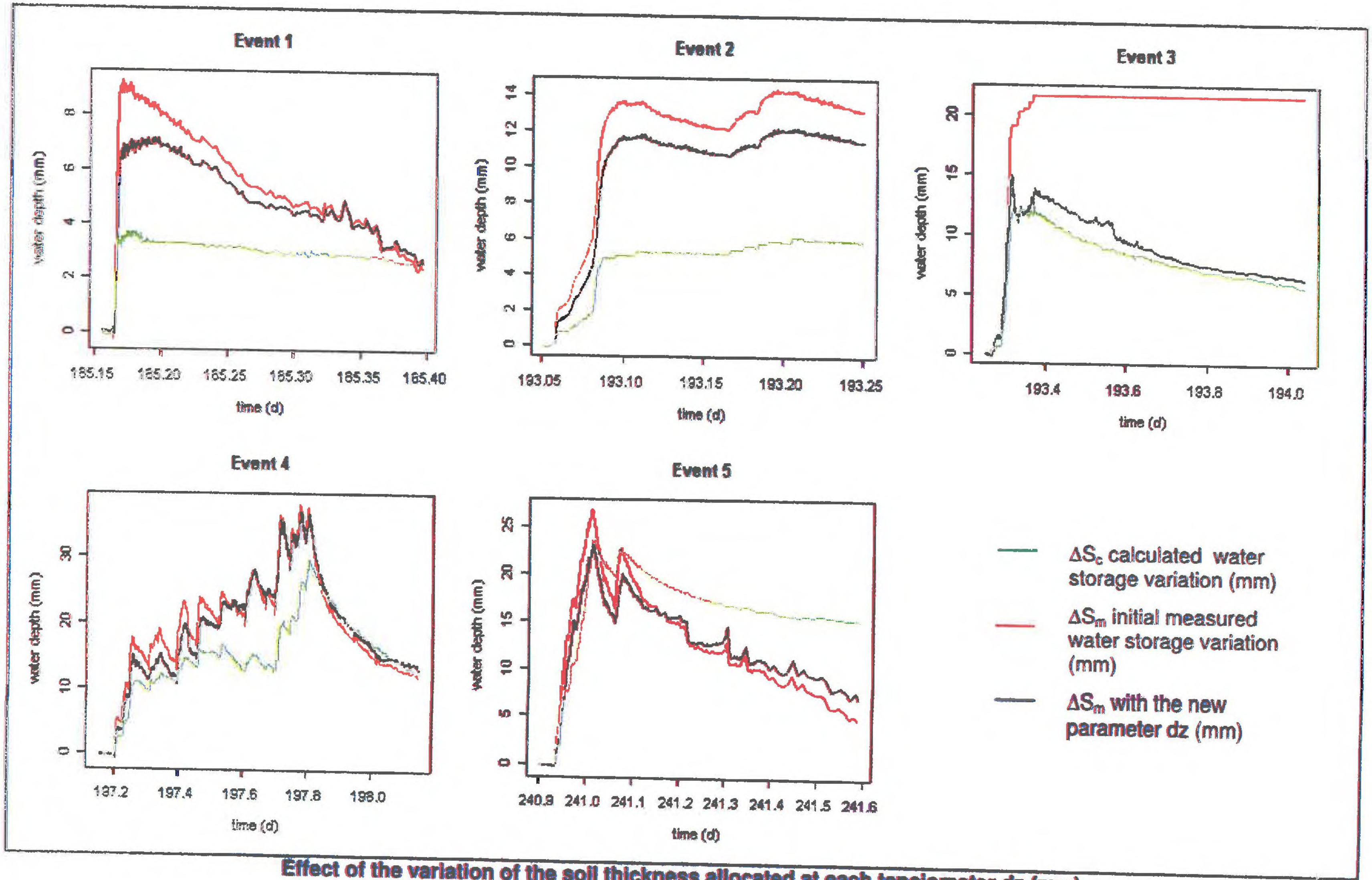
- a variation of more and less 10% was applied to θ_s;
- a variation of more and less 20% was applied to θ_r;
- h_g was multiplied and divided by 2; and
- values of 1.05, 1.1 and 1.3 were tested for n.

These variations were tested for each event (see the following graphs). The thickness of soil allocated to each tensiometer implemented near the soil surface should be decreased (see the following Table).

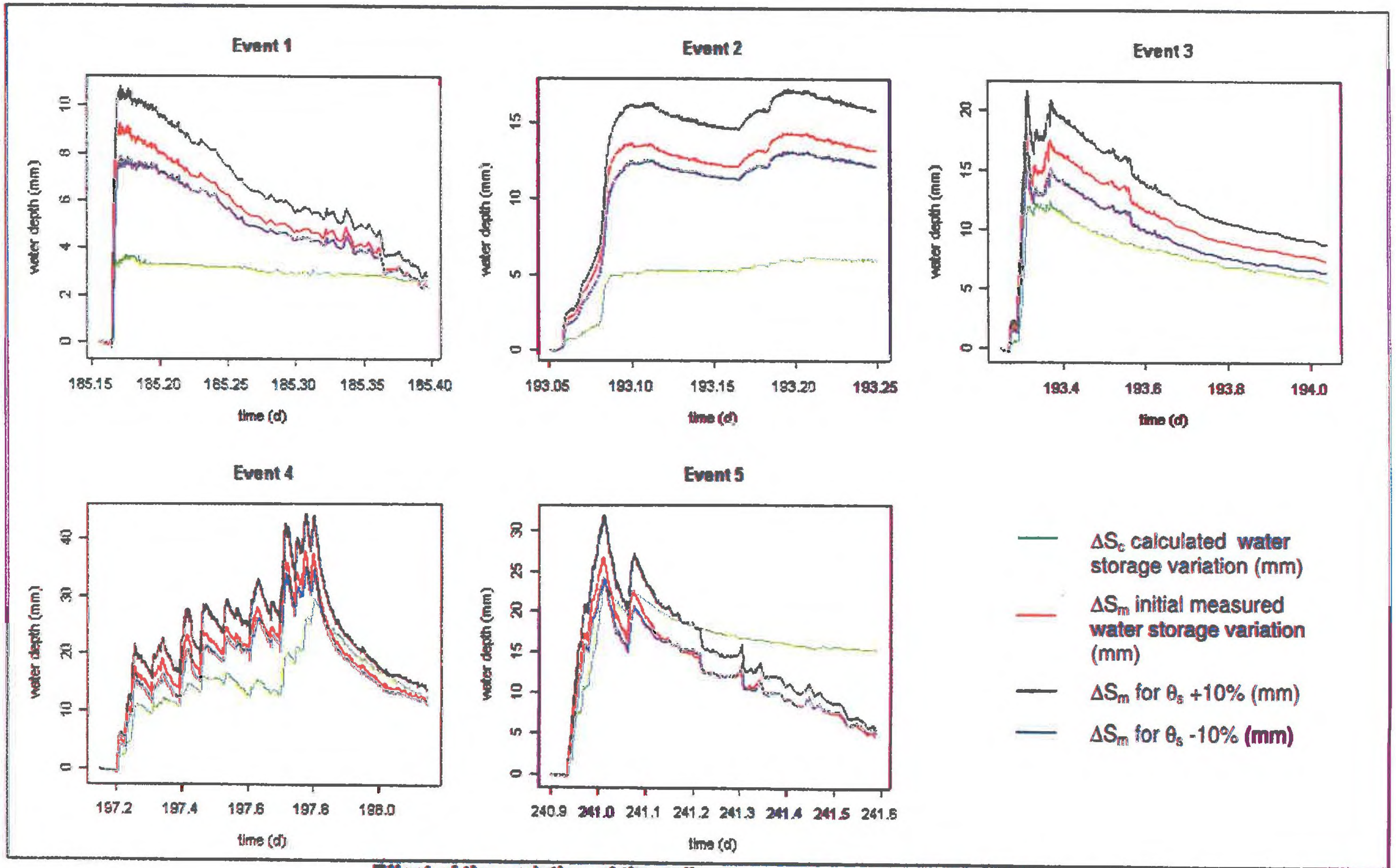
Maximum and average difference of soil water storage (ΔSm ; mm) over five rainfall events when varying each parameter

	dz*	θ_s*		θ_r*		h_g*		n*	
		+10%	-10%	+20%	-20%	x 2	/ 2	1.3	1.05
Maximum difference	-2.88	2.93	-2.93	-2.42	2.42	-3.56	2.43	10.33	-11.32
Average difference	-1.71	1.91	-1.91	-1.58	1.58	-1.85	0.88	6.55	-7.34

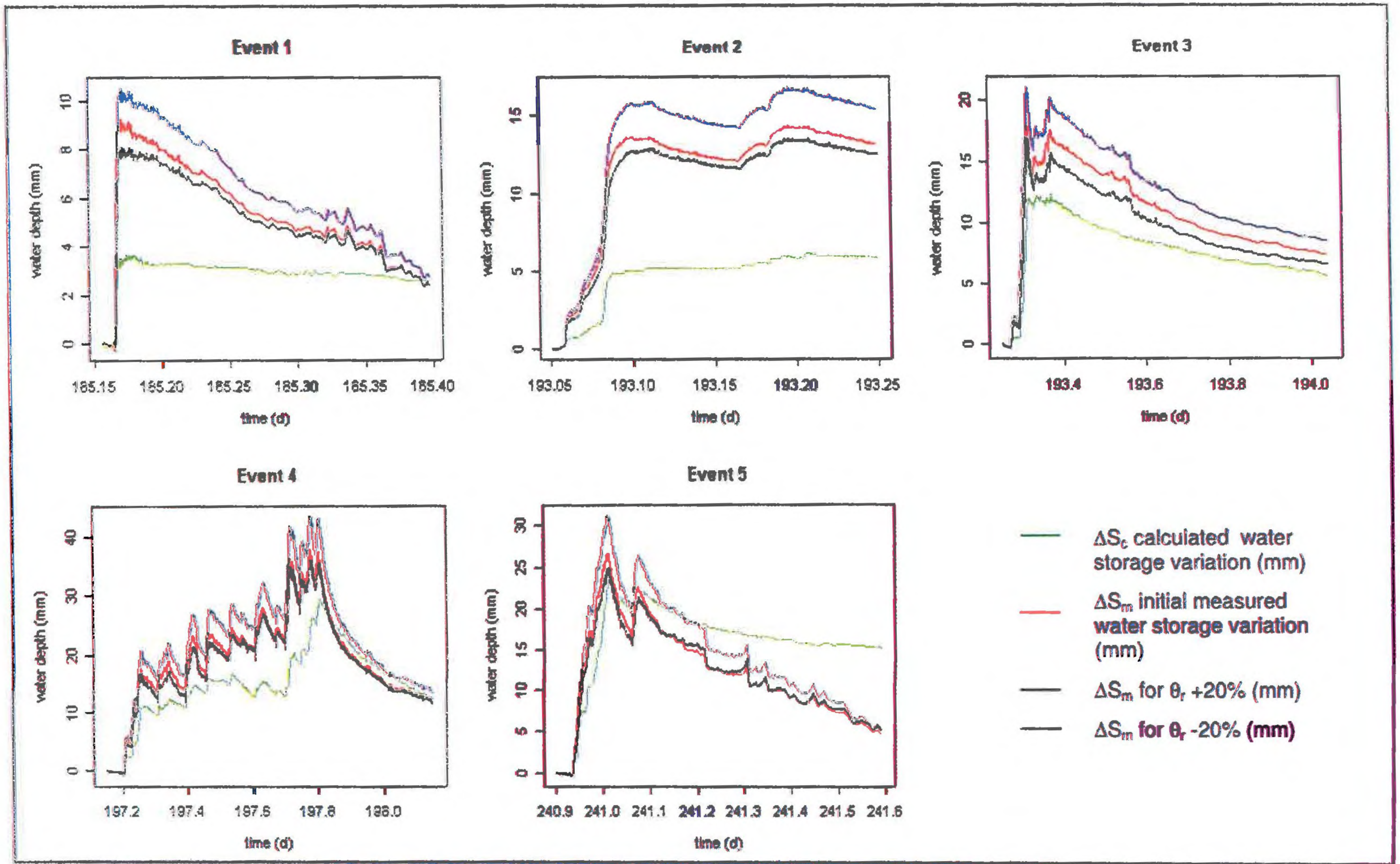
*dz : soil thickness allocated to each tensiometer (mm), θ_r : residual soil water content ($m^3.m^{-3}$), θ_s : soil water content at saturation ($m^3.m^{-3}$), h_g : scale parameter for the water pressure (m) and n : shape parameter for the water retention curve



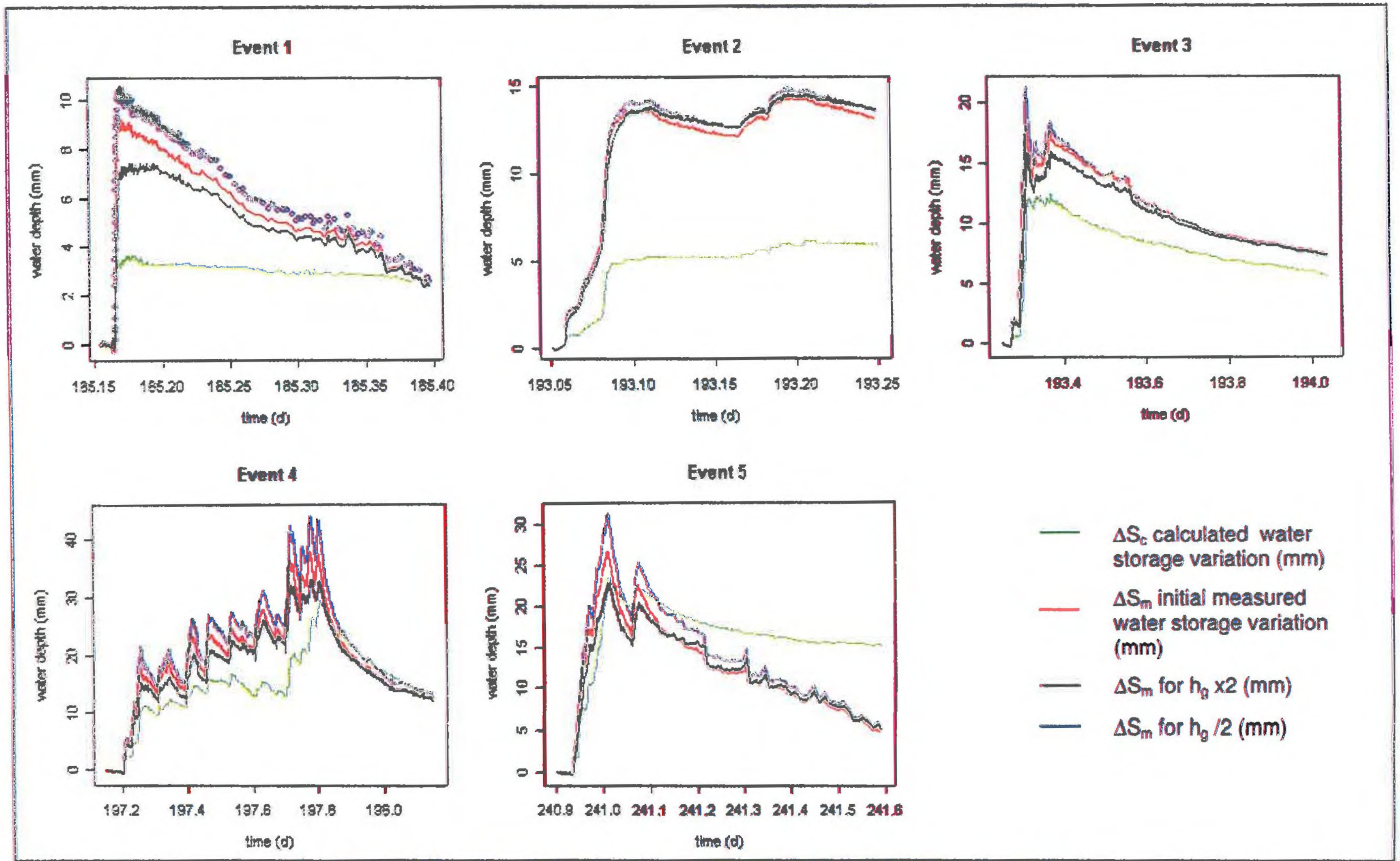
Effect of the variation of the soil thickness allocated at each tensiometer dz (mm)



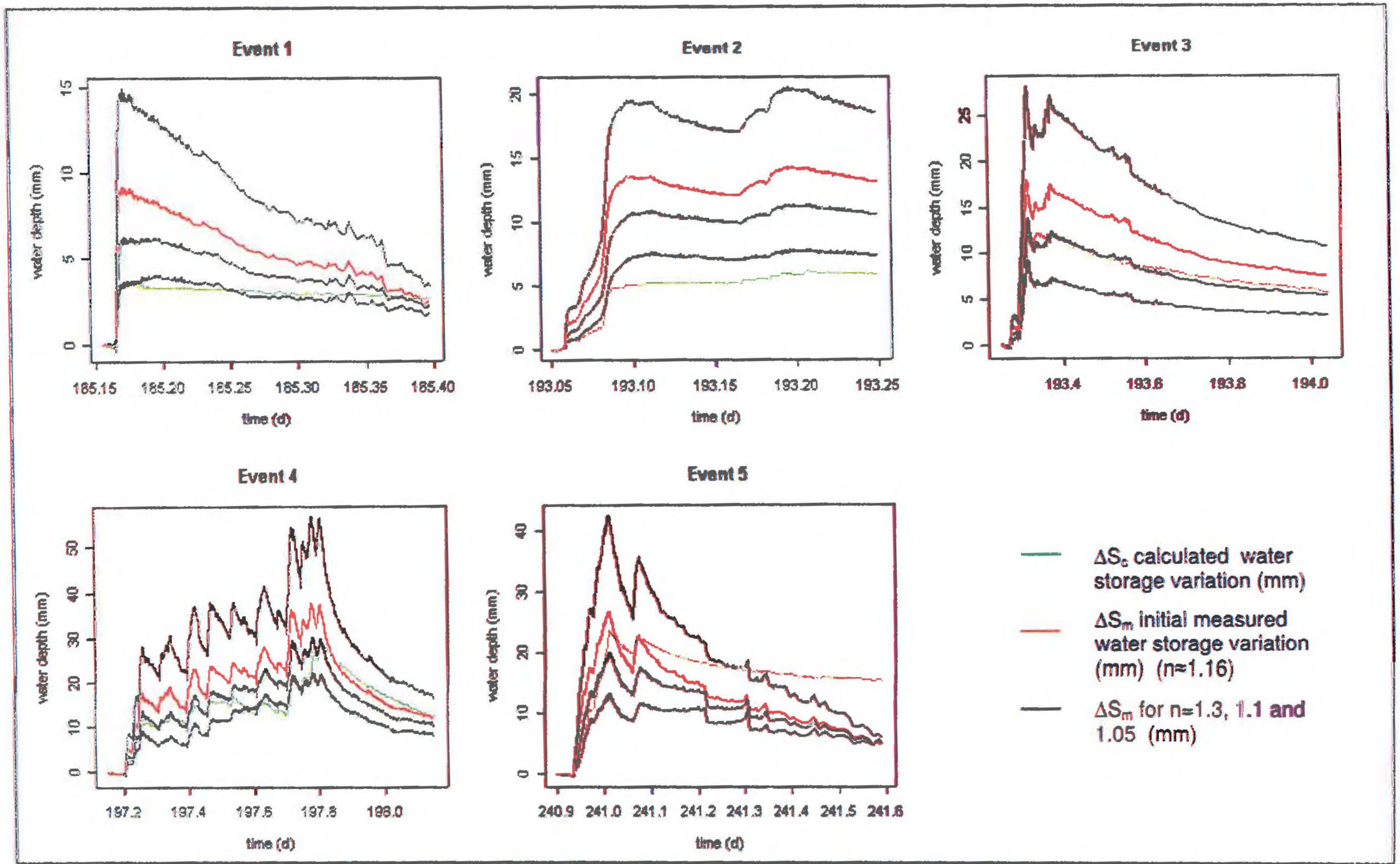
Effect of the variation of the soil water content at saturation θ_s (-)



Effect of the variation of the residual water content θ_r (-)



Effect of the variation of the scale parameter for the water pressure h_g (m)



Effect of the variation of the shape parameter for the water retention curve *n*

5.8 Spatial analysis of the soil matric potentials inside the plot of each event

Summary of the main characteristic of each tensiometer (Ts) during the five rain events. h_i, h_f and h_{max} are the initial, final and maximum soil matric potentials

t_m is the time to reach h_{max}. In green are the Ts implemented at 6 cm deep, in black at 25 cm deep and in red at 55 cm deep.

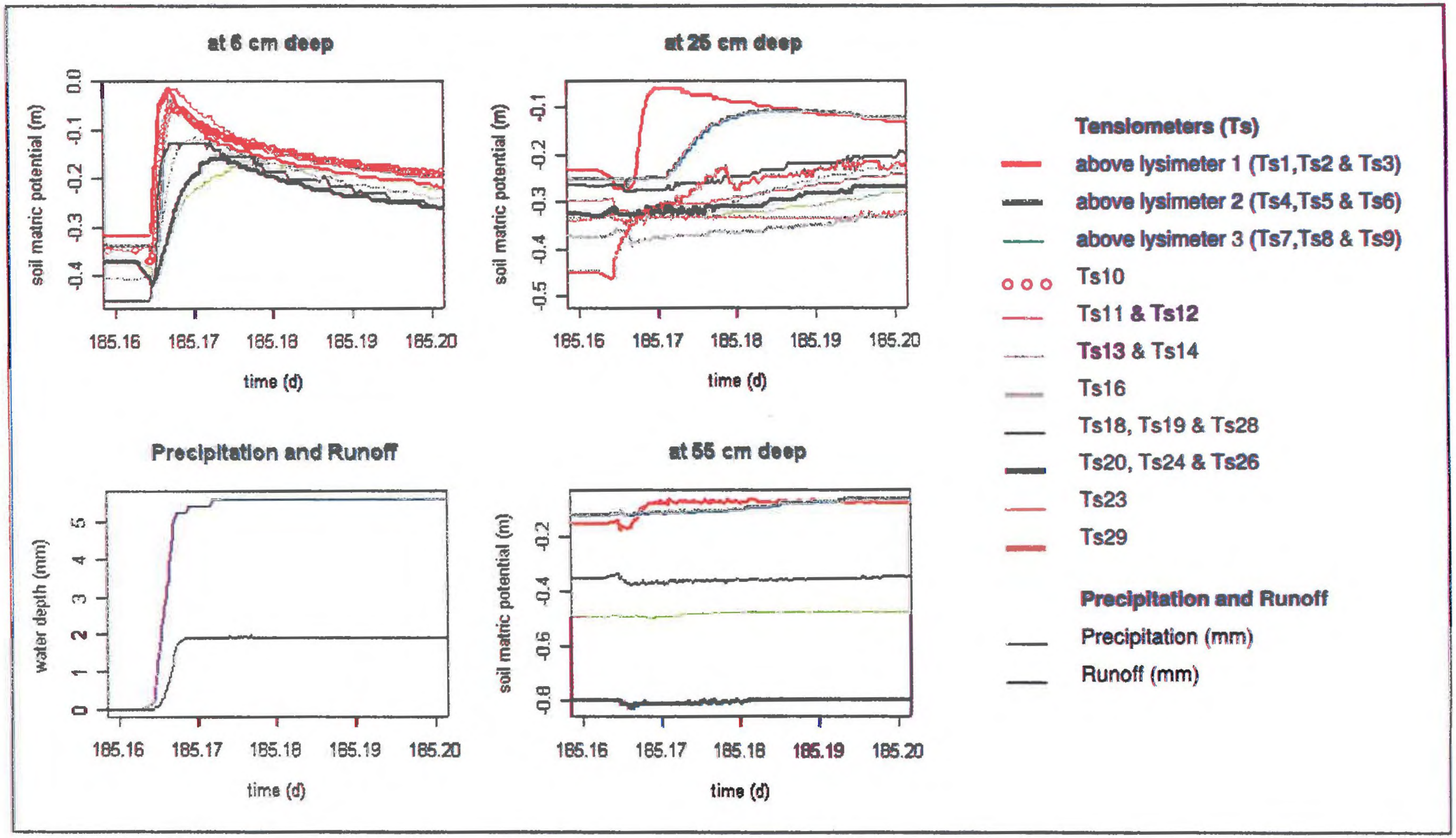
Event 1	Ts01	Ts02	Ts03	Ts04	Ts05	Ts06	Ts07	Ts08	Ts09	Ts10	Ts11	Ts12	Ts13	Ts14	Ts28	Ts16	Ts18	Ts19	Ts20	Ts29	Ts22	Ts23	Ts24	Ts25	Ts26
h_i (m)	-0.31	-0.23	-0.15	-0.34	-0.25	-0.12	-0.37	-0.32	-0.49	-0.34	-0.34	-0.29	-0.40	-0.33	-0.45	-0.37	-0.26	-0.36	-0.37	-0.45	-0.43	-0.33	-0.33	-2.22	-0.81
h_f (m)	-0.31	-0.24	-0.13	-0.32	-0.24	-0.11	-0.35	-0.27	-0.41	-0.32	-0.33	-0.25	-0.38	-0.28	-0.42	-0.32	-0.23	-0.26	-0.34	-0.51	-0.41	-0.31	-0.29	-1.94	-0.73
h_{max} (m)	-0.02	-0.06	-0.07	-0.04	-0.11	-0.06	-0.17	-0.24	-0.41	-0.05	-0.02	-0.20	-0.11	-0.21	-0.13	-0.30	-0.18	-0.25	-0.16	-0.22	-0.11	-0.29	-0.24	-1.55	-0.73
t_m (hh:mm)	0:16	0:20	0:48	0:16	0:38	1:16	0:32	1:57	5:37	0:17	0:16	1:57	0:20	1:57	0:20	1:57	1:57	5:37	0:25	0:53	0:20	3:42	1:47	0:22	5:37

Event 2	Ts01	Ts02	Ts03	Ts04	Ts05	Ts06	Ts07	Ts08	Ts09	Ts10	Ts11	Ts12	Ts13	Ts14	Ts28	Ts16	Ts18	Ts19	Ts20	Ts29	Ts22	Ts23	Ts24	Ts25	Ts26
h_i (m)	-0.49	-1.03	-0.54	-2.32	-0.91	-0.47	-1.08	-0.90	-0.53	-2.19	-4.11	-0.88	-1.95	-0.87	-1.51	-0.74	-0.75	-0.45	-1.17	-1.19	-2.17	-0.76	-0.91	-2.49	-0.53
h_f (m)	-0.20	-0.20	-0.11	-1.52	-0.61	-0.14	-0.38	-0.85	-0.52	-1.42	-0.78	-0.87	-0.44	-0.83	-0.50	-0.65	-0.70	-0.46	-0.45	-1.04	-1.36	-0.67	-0.84	-2.03	-0.54
h_{max} (m)	0.00	-0.10	-0.07	-1.52	-0.61	-0.12	-0.31	-0.85	-0.52	-1.42	-0.64	-0.86	-0.39	-0.83	-0.17	-0.65	-0.70	-0.45	-0.32	-1.04	-1.36	-0.63	-0.84	-1.34	-0.51
t_m (hh:mm)	0:45	0:57	1:09	4:43	4:43	1:54	3:33	4:33	4:15	4:46	1:22	4:39	3:46	4:27	0:50	4:32	4:15	0:37	1:00	4:43	4:31	0:09	4:34	0:52	0:24

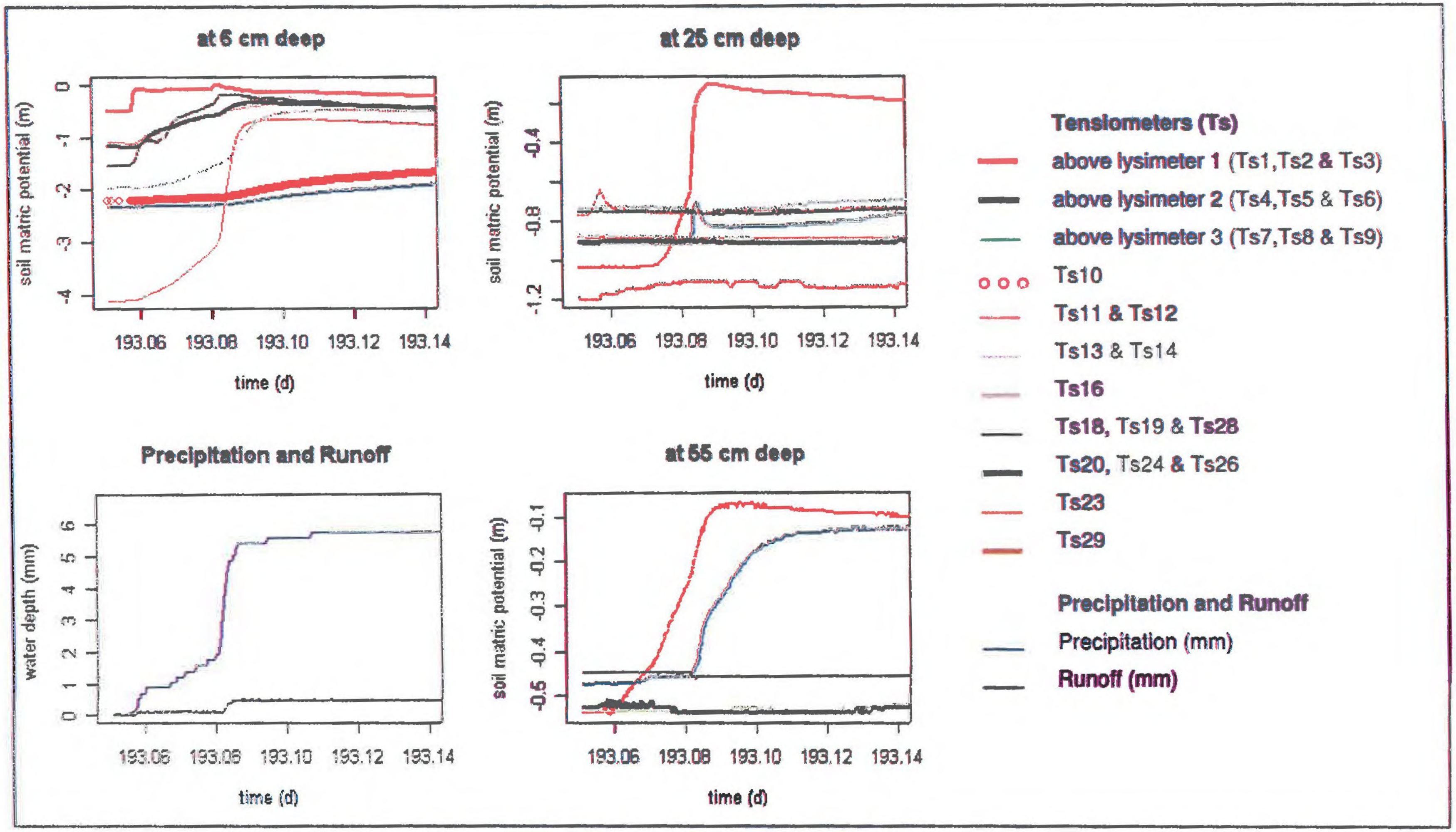
Event 3	Ts01	Ts02	Ts03	Ts04	Ts05	Ts06	Ts07	Ts08	Ts09	Ts10	Ts11	Ts12	Ts13	Ts14	Ts28	Ts16	Ts18	Ts19	Ts20	Ts29	Ts22	Ts23	Ts24	Ts25	Ts26
h_i (m)	-0.20	-0.20	-0.11	-1.52	-0.61	-0.14	-0.39	-0.85	-0.52	-1.42	-0.78	-0.87	-0.44	-0.83	-0.50	-0.65	-0.70	-0.46	-0.45	-1.04	-1.36	-0.67	-0.84	-2.02	-0.54
h_f (m)	-0.36	-0.34	-0.21	-0.45	-0.35	-0.18	-0.45	-0.37	-0.35	-0.46	-0.47	-0.36	-0.48	-0.34	-0.69	-0.35	-0.29	-0.31	-0.46	-0.69	-0.52	-0.39	-0.40	-2.77	-0.44
h_{max} (m)	0.00	0.01	-0.01	-0.08	-0.12	-0.01	-0.12	-0.22	-0.35	-0.06	-0.04	-0.27	-0.06	-0.20	-0.11	-0.31	-0.22	-0.31	-0.13	-0.42	-0.30	-0.29	-0.30	-1.50	-0.44
t_m (hh:mm)	1:29	1:27	1:26	1:34	1:38	1:27	1:37	3:59	18:45	1:32	1:30	5:41	1:31	3:30	1:38	3:59	4:16	18:45	1:37	4:46	2:58	6:36	4:00	1:37	17:00

Event 4	Ts01	Ts02	Ts03	Ts04	Ts05	Ts06	Ts07	Ts08	Ts09	Ts10	Ts11	Ts12	Ts13	Ts14	Ts28	Ts16	Ts18	Ts19	Ts20	Ts29	Ts22	Ts23	Ts24	Ts25	Ts26
h_i (m)	-0.23	-0.21	-0.12	-0.43	-0.29	-0.12	-0.42	-0.59	-0.46	-0.50	-0.36	-0.56	-0.46	-0.53	-0.51	-0.47	-0.45	-0.35	-0.47	-0.62	-0.40	-0.51	-0.61	-2.25	-0.50
h_f (m)	-0.23	-0.21	-0.11	-0.34	-0.27	-0.13	-0.35	-0.29	-0.20	-0.33	-0.35	-0.27	-0.38	-0.28	-0.35	-0.29	-0.22	-0.10	-0.36	-0.51	-0.64	-0.26	-0.30	-2.92	-0.14
h_{max} (m)	0.03	0.00	0.03	-0.02	0.00	0.00	-0.08	-0.07	-0.07	-0.02	-0.02	-0.05	-0.06	-0.07	-0.05	-0.15	-0.06	-0.03	-0.07	-0.16	-0.08	-0.09	-0.09	-1.70	-0.08
t_m (hh:mm)	2:20	2:29	13:26	13:23	13:30	13:32	15:04	15:15	15:45	14:58	2:20	13:41	13:29	15:09	15:42	6:35	14:31	14:46	13:30	13:41	13:23	14:07	15:05	1:21	14:46

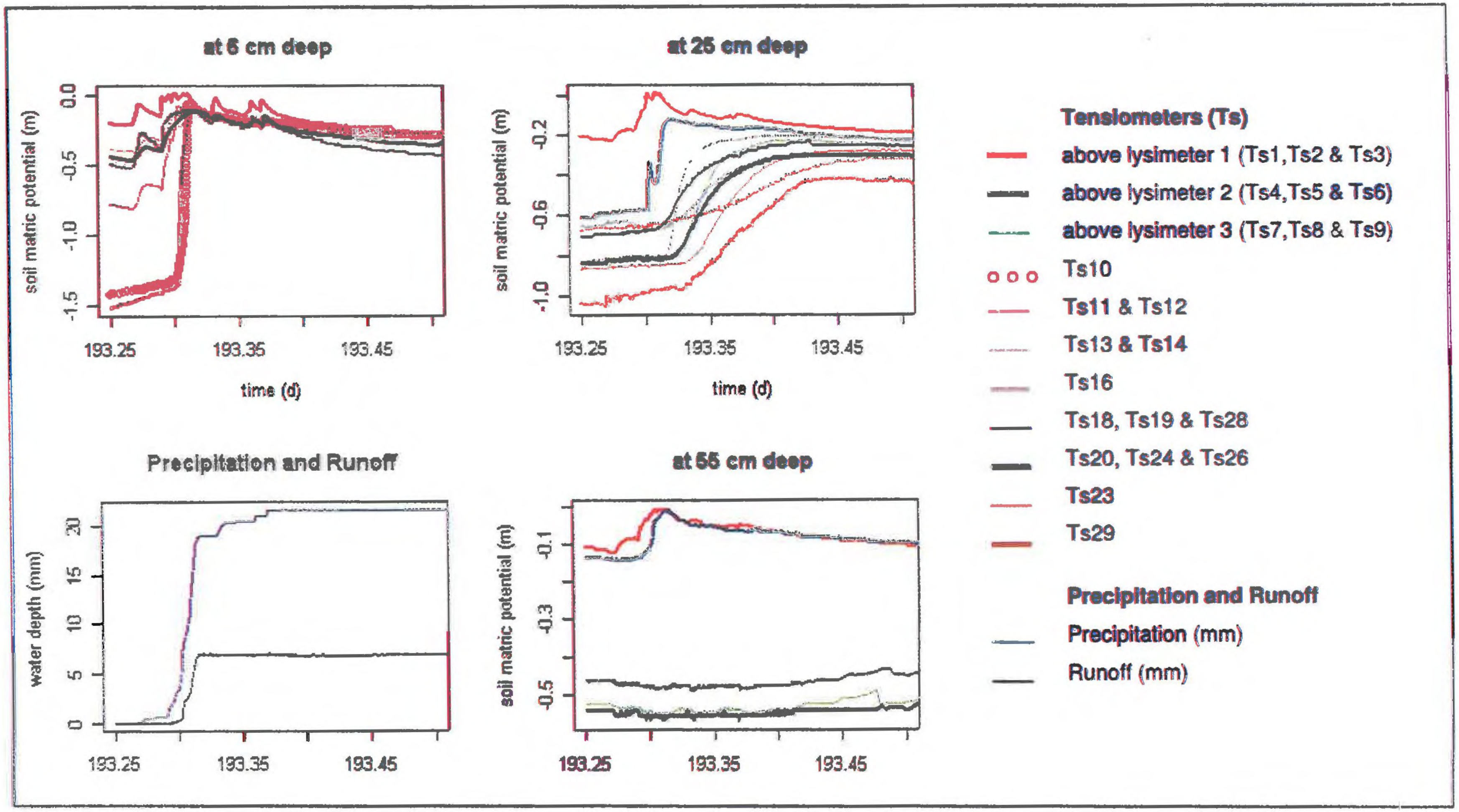
Event 5	Ts01	Ts02	Ts03	Ts04	Ts05	Ts06	Ts07	Ts08	Ts09	Ts10	Ts11	Ts12	Ts13	Ts14	Ts28	Ts16	Ts18	Ts19	Ts20	Ts29	Ts22	Ts23	Ts24	Ts25	Ts26
h_i (m)	-0.19	-0.37	-0.25	-0.51	-0.37	-0.19	-0.46	-0.42	-0.48	-0.37	-0.46	-0.37	-0.50	-0.44	-0.79	-0.51	-0.45	-0.67	-0.46	-0.90	-53.20	-0.88	-0.42	0.35	-1.32
h_f (m)	-0.43	-0.33	-0.19	-0.47	-0.33	-0.17	-0.46	-0.35	-0.29	-0.43	-0.51	-0.31	-0.56	-0.34	-1.09	-0.34	-0.28	-0.18	-0.48	-2.10	-0.74	-0.41	-0.35	-0.35	-0.75
h_{max} (m)	0.03	-0.05	-0.03	-0.07	-0.04	-0.01	-0.10	-0.10	-0.04	-0.02	-0.04	-0.05	-0.08	-0.08	-0.23	-0.18	-0.10	-0.15	-0.12	-0.22	-0.07	-0.27	-0.07	1.19	-0.73
t_m (hh:mm)	1:06	1:15	2:44	1:16	2:30	2:36	2:42	2:45	7:12	1:37	1:14	2:38	2:36	2:43	2:33	4:31	2:59	13:08	2:24	2:51	2:33	5:08	2:36	1:15	15:53



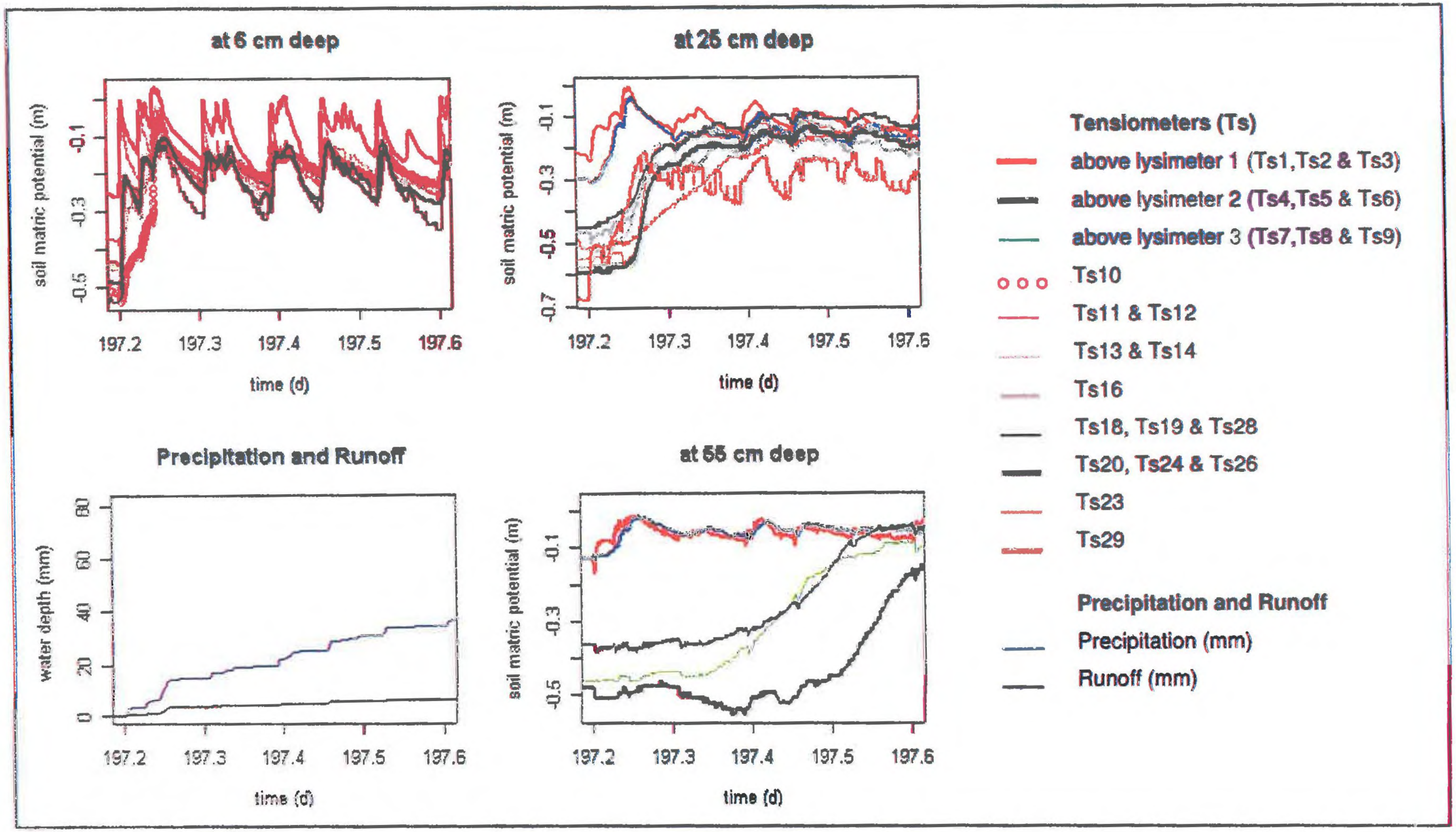
Evolution of each tensiometer according its depth during Event 1



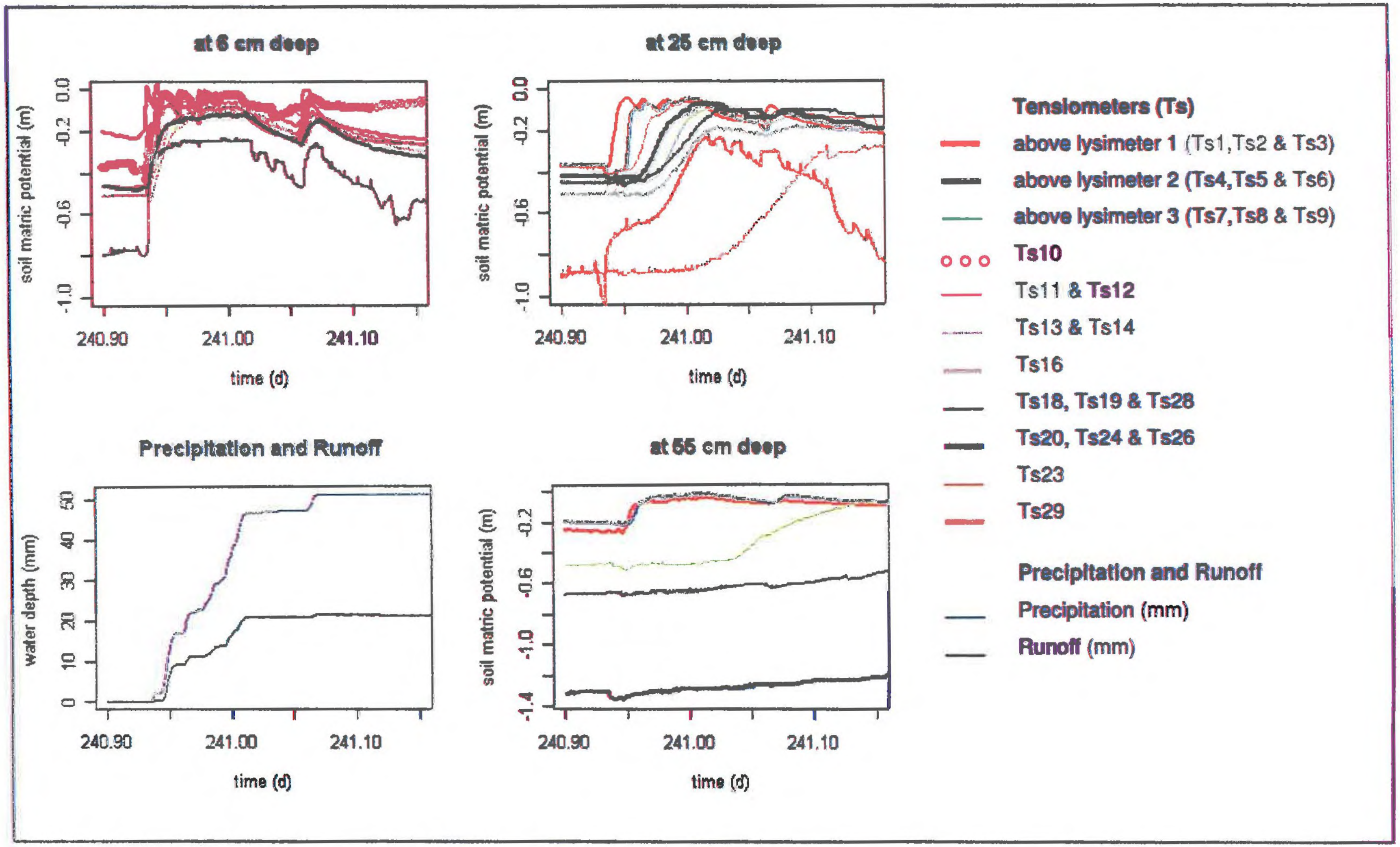
Evolution of each tensiometer according its depth during Event 2



Evolution of each tensiometer according its depth during Event 3



Evolution of each tensiometer according its depth during Event 4



Evolution of each tensiometer according its depth during Event 5

References

Agrisalon.com (2003) Les exportations de bananes antillaises en baisse. Actualité Cultures spécialisées. http://www.agrisalon.com/06-actu/article-10585.php (accessed 22 June 2005)

Bonan, H and Prim, J L (2001) *Rapport sur la présence de pesticides dans les eaux de consommation humaine en Guadeloupe.* Rapport n°2001-070. Ministère de l'Aménagement du Territoire et de l'Environnement, Ministère de l'Emploi et de la Solidarité. Paris.

Braud, I, De Condappa, D, Soria, J, Haverkamp, R, Angulo-Jaramillo, R, Galle, S and Vauclin, M (2004) Use of scaled forms of the infiltration equation for the estimation of unsaturated soil hydraulic properties (Beerkan method). *European Journal of Soil Science*, 13 October 2004 doi: 10.1111/j.1365_2389.2004.00660.x.

Brook, R H and Corey, C T (1964) *Hydraulic Properties of Porous Media.* Hydrological Paper 3, Colorado State University, Fort Collins, CO.

Cattan, P, Cabbidoche, Y M, Lacas, J G and Voltz, M (2005) Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical andosol. *Soil & Tillage Research*, article in press.

Cattan, P, Bussière, F and Nouvellon, A (2003) Rainfall partitioning in banana plantations increased the runoff risk on andisols. Journal of Hydrology, article in press.

Clermont-Dauphin, C, Cabidoche, J M and Meynard, JM (2004) Effects of intensive monocropping of bananas on properties of volcanic soils in the uplands of the French West Indies. *Soil Use and Management*, 20, 105-113.

Coquet, Y, Boucher, A, Labat, C, Vachier, P and Roger-Estrade, J (2000) Caractérisation hydrodynamique des sols à l'aide de l'infiltromètre à disques. Aspects théoriques et pratiques. *Etude et gestion des sols*,7,7-24.

Dorel, M, Roger-Estrade, J, Manichon, H and Delvaux B (2000) Porosity and soil water properties of Carribean volcanic ash soil. *Soil Use and Management,* 16, 133-140.

ECCO PNRH, ECosphere COntinentale et Programme National de Recherche en Hydrologie (2004) Etude et Modélisation à l'échelle locale des transferts 3D de l'eau de pluie concentrée par le bananier à la surface d'un andosol. *Dossier scientifique.*

Findeling, A (2001) *Etude et modélisation de certains effets du semis direct avec paillis de résidus sur les bilans hydrique, thermique et azoté d'une culture de maïs pluvial au Mexique.* Thèse. Ecole nationale du génie rural des eaux et forêts, Centre de Montpellier.

Ganry, J (2004) Plant biology and pathology. Diversité spécifique des peuplements végétaux à l'échelle du basin versant et contrôle des parasites des cultures : l'exemple de la culture bananière aux Antilles françaises. *CR. Biologies* 327, 621-627.

Haverkamp, R and Angulo-Jaramillo, R (2004) Adimensionnaliser les équations de l'infiltration. Laboratoire d'étude des Transferts en Hydrologie et Environnement. http://www.lthe.hmg.inpg.fr/Equations_infiltration.htm (accessed 1 July 2005)

Haverkamp, R, Leiji, F J, Fuentes, C, Zin and I and Ross P J (2004) Soil water retention. 1. Development of a shape index. *Soil Science Society of America Journal*, article in press.

Haverkamp, R, Zammit, C, Bouraoui, F, Rajkai, K and Arrue J L (1998) *Survey of soil field data and description of particle size, soil water retention and hydraulic conductivity functions.* GRIZZLY, Grenoble catalogue of soils, Laboratoire d'étude de Transfert en Hydrologie et Environnement. Université Joseph Fourier, Grenoble 1.

International Organization for Standardization (2004) ISO 11275:2004, Soil quality. Determination of unsaturated hydraulic conductivity and water retention characteristic. Wind's evaporation method.

Martin, J (2004) *Observation et quantification des principaux processus gouvernant le fonctionnement hydrologique du système sol-bananier sur andosol de Guadeloupe, à l'échelle locale de la placette.* Rapport de stage du DESS Hydrogéologie et Environment. Université d'Avignon et des pays du Vaucluse.

Météo France (2003) Le Climat d'Outre-Mer, Antilles, Guadeloupe. http://www.meteofrance.com/FR/climat/fiche_guad.jsp (accessed 23 June 2005)

Ministère de l'Outre-Mer (2005) La Guadeloupe. http://www.outremer.gouv.fr/outremer/front?id=outremer/decouvrir_outre_mer/guadeloupe (accessed 20 June 2005)

Ministère de l'Ecologie et du développement durable (2005) Le volcanisme. http://www.prim.net/citoyen/definition_risque_majeur/dossier_risq_volcanique/lerisquevolcanique.htm# (accessed 28 June 2005)

Ndayiragije, S and Delvaux, B (2004) Selective sorption of potassium in weathering sequence of volcanic ash soils from Guadeloupe, French West Indies. *Catena* 56, 185-198.

Perret, S and Dorel, M (1999) Relationship between land use, fertility and Andisol behaviour: examples from volcanic islands. *Soil Use and Management* 15, 144-149.

Radio club India (2002) Guadeloupe. Map. World wide section. http://www.radioclubindia.com/worldwide/map/d_m/guadeloupe.html (accessed 28 June 2005)

Reynolds, W D and Elricks, D E (1991) Determination of hydraulic conductivity using a tension infiltrometer. Divison S-1 Soil physics. *Soil Science Society of America journal*, 55, 633-639.

Richard, L A (1931) Cappillary conduction of liquids through porous media. *Physics*,1: 318-333.

Rossignol, D (1990) *Les Régimes Pluviographiques de la Guadeloupe*. Institute for Research and Development, Montpellier, France, p. 13.

Samson, J A (1980) *Tropical fruits*. Tropical agriculture series. Longman Group Limited, London.

Sansoulet, J, Cabidoche, Y M, Cattan, P, Clermont-Dauphin, C and Desfontaines, L (2004) Solute transfert in an andosol after application of KNO3 under banana crop : from the aggregate to the field experiment. Rala Report n°214, Volcanic Soil. Resources in Europe, Cost Action 622 Final Meeting, Iceland.

Soil Survey Division Staff. 1993. *Soil survey manual*. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Souza, E S, Angulo-Jaramillo, R, Antonino, A C D, Netto, A M, Soria, J M and Haverkamp, R (2003) Spatial and seasonal variability of the hydrodynamic parameters of a fluvent soil in the northeast of Brazil. *European Geophysical Society*, Vol. 5, 12499, 2003

Students of the World (2001) Basic information, Guadeloupe. http://www.studentsoftheworld.info/country_information.php?Pays=GDL (accessed the 3 August 2005)

Théault, T and Denhez, F (2005) *Guadeloupe Geoguide*. Guide Gallimard.

Tixier, P, Malezieux, E and Dorel, M (2004) A cohort population model for long term simulation of banana crop harvest. *Ecological Modelling*,180, 407-417.

Van Elewijck, L (1989) Stemflow on maize : a stemflow equation and the influence of rainfall intensity on stemflow amount. *Soil technology*, 2, 41-48.

Van Genutchen, M T (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society American Journal*, 44, 892-898.