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# AN EXPERIMENTAL STUDY OF POLLUTANT TRANSPORT AND EROSION SUSCEPTIBILITY IN TUNISIA

## - A STUDY WITH RAINFALL SIMULATION AND DYE IN THE M'RICHET EL ANZE CATCHMENT

**Master of Science Thesis**
**Minor Field Study**
**Lund 1997**

**Ola Palmquist**
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KUNGL
TEKNISKA
HÖGSKOLAN

Royal Institute of Technology
CITEC

# Preface

This study has been carried out within the framework of the Minor Field Studies (MFS) Scholarship Programme, which is funded by the Swedish International Development Cooperation Agency, Sida.

The MFS Scholarship Programme offers Swedish university students an opportunity to carry out two months' field work in a Third World country on a basis of a Master's dissertation or a similar in-depth study. These studies are primarily conducted within areas that are important for development and in a country supported by the Swedish pro-gramme for international development assistance.

The main purpose of the MFS programme is to increase interest in developing countries and to enhance Swedish university students' knowledge and understanding of these countries and their problems. An MFS should provide the student with initial experience of conditions in such a country. A further purpose is to widen the Swedish personnel resources for recruitment into international cooperation.

The Centre for International Technical and Educational Cooperation, CITEC, at the Royal Institute of Technology, KTH, Stockholm, administers the MFS programme for all faculties of engineering and natural sciences in Sweden.

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## Abstract

The purpose of the study was to investigate the effects of heavy rain storms on the clayey soils in the watershed of M'Richet el Anze, Tunisia. The study included an investigation and visualization of the preferential flowpaths, different ways to determine the relationship between runoff and infiltration, an approximate measurement of erosion effects, and a discussion according to pollutant transport through the unsaturated zone to the groundwater. Six rainfall simulations were carried out. The rainfall water was colored with dye, Brilliant Blue (4 g/l). Afterwards, the plots were excavated in 2.5 cm thick vertical slices. Every slice was photographed. The photos were scanned, digitized, and plotted in three dimensions. Soil samples for determination of soil water contents were collected before rainfall, immediately after rainfall, and just before excavation. Sediment samples were collected to investigate erosion effects. Infiltration was measured and calculated using three different methods.

We found that preferential flow existed and that a great deal of the infiltrated water passed through root-channels, cracks, and macro-pores. At site 1 the infiltration had a maximum depth of 1.5 m, which implies that pollutants may reach directly to the groundwater after heavy rainfall. At the other two sites the maximum penetration was 73 cm (site 2) and 1.35 m (site 3).



**Key words:** rainfall simulator, dye tracer, preferential flow, graphic visualization


**Lund 1997**


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## Acknowledgments

We would like to thank Mr. Jacques Claude, Director of ORSTOM, Tunis, Mr. Najib Rejeb, Director of INRGREF, Tunis and Mr. Habib Farhat, Director of CES, Tunis without whose cooperation this study had been impossible to carry out.

We would like to give huge thanks to our supervisors Dr. Akissa Bahri, INRGREF, Tunis, Dr. Jean Albergel, ORSTOM, Tunis and Dr. Ronny Berndtsson, Department of Water Resources Engineering, Lund University.

We would also like to thank the staff of ORSTOM, especially Patrick Zante and Mohamed Ben Younes, and the staff of INRGREF.

For great help with the graphic processing we would like to thank Professor Leif Bjelm and Dr. Petter Pilesjö.

Finally, but not least, we would like to give big thanks to our friend Nathalie Rahaingomanana for taking care of us socially in Tunisia.

Lund in May 1997

**CONTENTS**

# 1. SUMMARY

This M.Sc. diploma work was carried out in Tunisia and Lund, Sweden. The study was a cooperation between CES (Direction de la Conservation des Eaux et des Sols, Ministère de l'Agriculture, Tunis), INRGREF (Institut National de Recherche du Génie Rural, des Eaux et Forêts, Tunis), ORSTOM, Tunis (Institut Francais de Recherche Scientifique pour le Développement en Coopération) and the Department of Water Resources Engineering, Lund University, Sweden. We received a Minor Field Study scholarship from SIDA (Swedish International Development Agency) for the study.

The purpose of the study was to investigate the effects of heavy rain storms on the clayey soils in the watershed of M'Richet el Anze, Tunisia. The study included an investigation and a visualization of preferential flowpaths, different ways to determine runoff and infiltration amounts, an approximate measurement of erosion effects and a discussion according to pollutant transport through the unsaturated zone to the groundwater table. The field work took place, during some hectic weeks in October-1996, in the watershed of M'Richet el Anze near Bargou, about 110 km south-west of Tunis.

Six rainfall simulations were carried out. The rainfall water was colored with a dye Brilliant Blue, 4 g/l. Afterwards, the plots were excavated in 2.5 cm thick vertical slices. Every slice was photographed. Soil samples for determination of soil water contents were gathered before rainfall, immediately after rainfall and just before excavation. Sediment samples were collected to investigate erosion effects. Infiltration rates were determined in different ways. First they were measured from rainfall simulations and second calculated from the soil samples. In Sweden the photos were scanned, digitized and plotted in three dimensions. The infiltration rates were calculated in a third way using stained volumes and porosities. The different ways to determine the infiltration rates did not correspond very well to each other.

We found that preferential flow existed and that a great deal of the infiltrated water passed through root-channels, cracks and macro-pores. On site 1 the infiltration had a maximum depth of 1.5 m, which implies that pollutants may reach the groundwater directly in combination with extreme rainfall. On the other two sites there were no such risk for the investigated rainfall amounts. On site two the maximum infiltration depth was 74 cm and on site 3 1.35m. The dominating soil in the catchment is Inceptisols, Vertic Xerochrepts, the same soil as at site 3. This soil shows good resistance against erosion but is easily infiltrated. Near the reservoir, where the groundwater table is highest there are other types of soils that are more difficult to infiltrate, but can contain separate deep cracks. In summary this means that the catchment is quite resistible against erosion and there is no pronounced risk for pollutants to reach the groundwater in the short term.

# 2. INTRODUCTION

## 2.1 Background and problem description

Tunisia, as well as many other countries in arid or semi-arid zones, will likely suffer from water shortage next century. Problem of water scarcity may increase because of growing population, rise in living standard, and more effective agriculture. To solve this problem the Tunisian government, as one first step, has decided to build 1000 small hill reservoirs. The reservoirs have different purposes. They will protect downstream infrastructures from floods and erosion, and locate fresh water in several points in the landscape, that otherwise will suffer from lack of water. The latter is to create better possibilities for agriculture and to rise the living standard for people. The reservoirs will also increase the recharge of groundwater, decrease the loss of fresh water to the sea and improve the environment by creation of oases, reforestation etc. At present about 400 dams have been built, M'Richet el Anze is one *(figure 1)*, and the intention is to evaluate the results so far. This investigation is performed by, among others, Natural Research Institute for Agricultural Engineering, Water and Forestry, Ministry of Agriculture, Tunisia (INRGREF), the French Institute of Scientific and Research for Development in Cooperation (ORSTOM) and the Department of Water Resources Engineering, Lund University (TVRL). Our study was carried out within this cooperation.

The theory about soil water flow and solute transport in unsaturated homogeneous soil is well known. What is less well known is the behavior in inhomogeneous unsaturated soil. The problem is that all natural soils are, more or less, inhomogeneous. The soils at M'Richet el Anze are no exception. Because of high contents of soil particles of small size (45-63% clay), the transport through the soil matrix is small and slow. Therefore, it was expected that some of the water and solutes would pass through macro-pores, root-channels, and cracks. The effects of these phenomena can not be predicted well by traditional equations. Other properties of conceivable importance, especially in semi-arid climates such as in Tunisia, are swelling soil and the hysteresis effect. They are seldom taken into account because of problems to treat them mathematically correct. The temperature of the water and its salt content can also affect the results *(Gullberg, Persson, 1993)*.

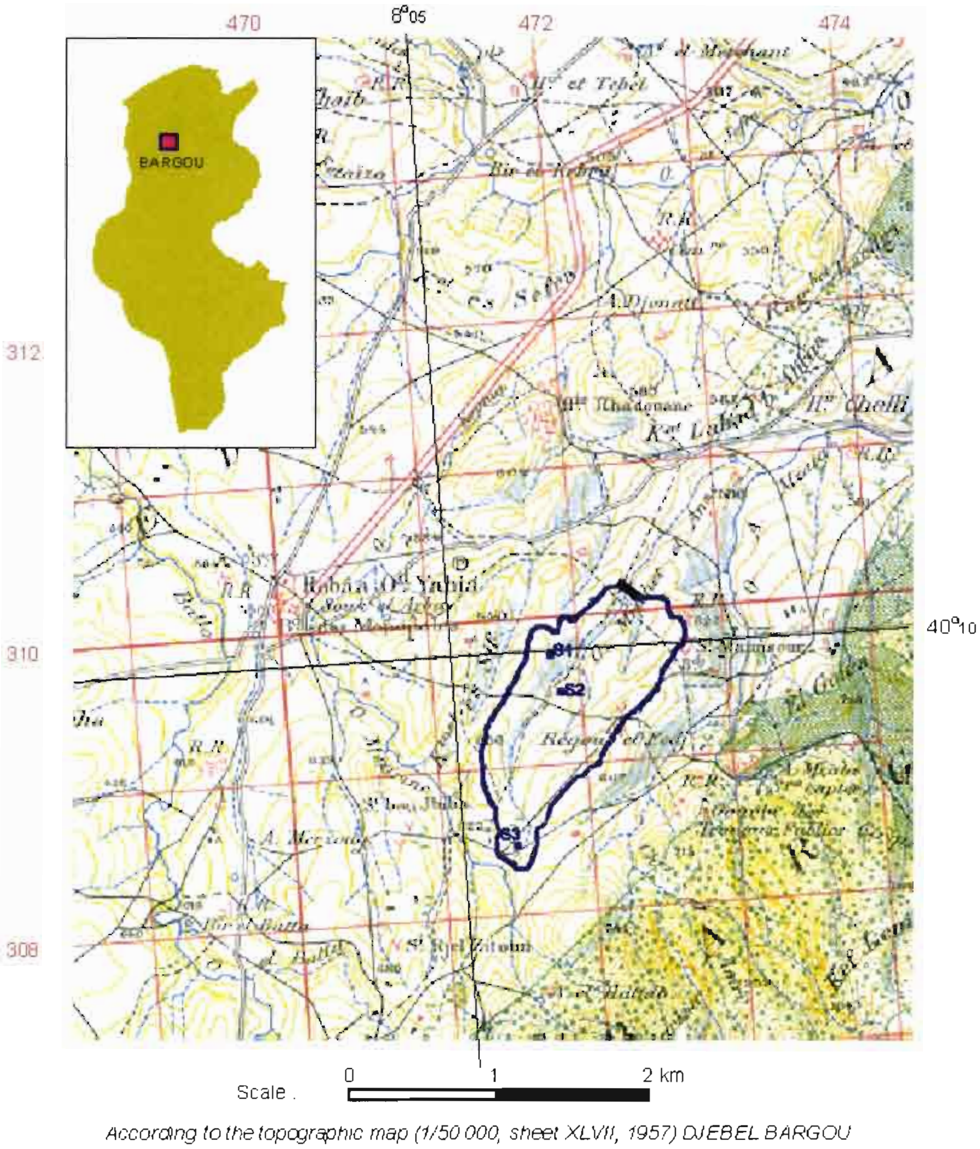



*Figure 1. Location of the watershed of M'Richet el Anze. S1, S2 and S3 are the different experimental sites.*

## 2.2 Objectives

The quality of water in the reservoirs, as well as the groundwater is one important issue to consider. Therefore it is of importance to have a good knowledge about how water, solutes, and nutrients are transported from the surface of the soil to the groundwater and to the lake. The flow pathways of water and solute are still poorly understood, especially in structured fine-textured soils like the ones at M'Richet el Anze. Therefore, studies of preferential flows in soils have become an important topic during the latest decades. One of the objectives of our study was to investigate the preferential flowpaths in the clay soils of M'Richet el Anze. To perform this a rainfall simulator and a dye, Brilliant Blue, were used.

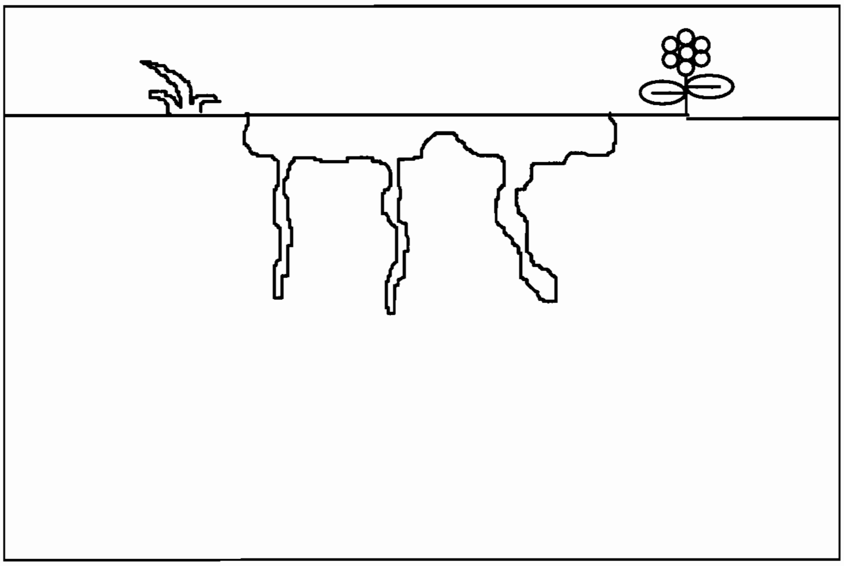


*Figure 2. Preferential flowpaths of an infiltrating solute.*

The other main objective was to investigate the erosional effects of heavy rainstorms. This is of interest because erosion destroys agricultural lands and silt up reservoirs.

**2.3 Literature review**

Preferential flowpaths probably exists in all kinds of soil, but are more common in soils with high contents of small particles (clay, silt). Preferential flows occurs when water is transported in root channels, macro-pores and cracks, with higher speed than water in the homogeneous soil, *(figure 2)*. This transport is often more or less vertical, but horizontal preferential flow exists as well. The latter occurs, for example, where two different soil layers are in contact.

Earlier studies in Tunisia have shown that preferential flow exists. *Gullberg and Persson, 1993,* used bromide to show that a significant part of the applied water moved downwards through preferential flowpaths. They spread water uniformly over their plot (6,2*3,5 m) and obtained a ponding of about 0.05 m during 1,5-2 hours. A neutron probe was used to measure the volumetric soil water content to evaluate the soil water movement.

Later on, *Yasuda et. al., 1996,* used another method for the same purpose. They colored water with a dye, Brilliant Blue, that stains the flowpaths in the soil. The colored water, 50 l, was spread instantaneously at a 1*1 plot, delimited by a steel frame. Afterwards they recorded the stained patterns by excavating the plot both vertical and horizontal. The patterns showed that preferential flow existed.

Since we decided to use a camera to record the flowpaths our choice of tracer was Brilliant Blue. The tracer should, mainly, meet three criteria.

1. The chemical should be easily visible in the soil.
2. It should be readily mobile.
3. It should not be toxic.

*Flury and Flühler, 1994,* state that this is valid for Brilliant Blue. In field experiments *Flury and Flühler, 1995,* also showed that Brilliant Blue was a suitable tracer.

We wanted to achieve results representative for natural conditions. Therefore our intention was to simulate a heavy rain storm. *Albergel, 1988,* used a design rainfall simulator successfully. Later, the simulator was developed to be run by a computer unit, (*Bernard, 1987),* to get more momentaneous changes in rainfall intensities. This simulator type was used in our field experiments.

Heavy rainstorms cause erosion damages. Large erosion will destroy agricultural lands and silt up reservoirs. *Snoussi, 1993,* did a detailed erosion investigation in the watershed of M'Richet el Anze. This is the watershed where our experiments later took place.

# 3. MATERIALS AND METHODS

## 3.1 Experimental conditions

### 3.1.1 Climate

The M'Richet el Anze watershed is situated in the semi-arid zone with typical Mediterranean climate, which means hot dry summers and mild, rainy winters.

- the yearly average temperature is 16.6°C
- the lowest average temperature in January is 2.6°C
- the highest average temperature in July is 35.3°C
- the dominating wind direction is north-west
- the average amount of rainfall is 455 mm/year and the distribution during the year is shown in *table 1*.

| month | Sept | Oct | Nov | Dec | Jan | Feb | Mars | Apr | May | June | July | Aug |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rain (mm) | 35.4 | 67.8 | 59.2 | 37.6 | 31.7 | 24.3 | 38.2 | 59.7 | 43.6 | 27.0 | 12.2 | 18.7 |

*Table 1. Average annual distribution of rainfall in Siliana, hydrological year.*

- the rainfall amount of the period September-95 to August-96 was 586.8 mm which corresponds to a 10-year return period. The distribution is shown in *table 2*.

| month | Sept | Oct | Nov | Dec | Jan | Feb | Mars | Apr | May | June | July | Aug |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rain (mm) | 147.9 | 15.9 | 42.9 | 28.7 | 45.2 | 99.8 | 32.2 | 34.0 | 64.8 | 18.8 | 7.5 | 49.1 |

*Table 2. The rainfall distribution for the latest hydrological year (1995-96).*

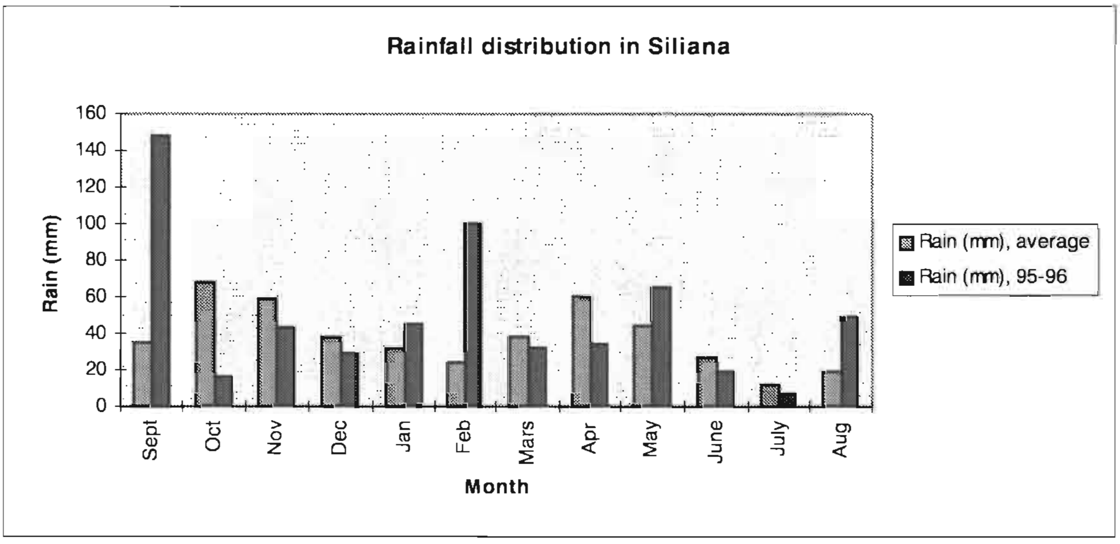



*Figure 3. The rainfall distribution in Siliana for an average hydrological year and the latest hydrological year (1995-96).*

- the average actual evaporation is 1383 mm/year

The experiments were carried out 961015-27. The conditions in the soils were dry and therefore it was likely that a number of cracks existed. These cracks can lead to deep infiltration.

| Week | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 |
|---|---|---|---|---|---|---|---|---|---|
| Rain (mm) | 22.5 | 6.5 | 4.0 | 4.5 | 59.0 | 3.0 | 0.0 | 1.0 | 0.0 |

*Table 3. Rainfall distribution week by week from two months before the experiments (960812-961013).*

### 3.1.2 Experimental site

The experiments were carried out in the catchment of M'Richet el Anze, Governorate of Siliana near Bargou about 110 km south-west of Tunis, Tunisia, see *figure 1.* Immediately east of M'Richet el Anze is the mountain Djebel Bargou situated, which is a northern part of the Atlas mountain range. The direction of Djebel Bargou is from south-west to north-east and its presence influences both the micro-climate as well as the geology.

The area of the watershed is about 158 ha, the maximum length 5.5 km and the altitude between 590 and 730 m a.m.s.l. The average slope is 12 %. The dam was built in 1992 and its lake had a volume of 42400 $m^3$ and a surface of 2.0 ha. Approximately one year later, the 3rd of June 1993, the sediment volume was measured to 370 $m^3$, that is not much compared with other similar reservoirs, (*Albergel et al., 1996*). The dam capacity had decreased to 42030 $m^3$.

*Figure 4. View of the catchment and lake.*

### 3.1.3 Pedology

The watershed is dominated by Inceptisols (*Soil Taxonomy, 1995*) which is evenly spread over the area. Near the reservoir, areas with Entisols exist and at the upper part of the watershed Rendolls are found. The east and west boarder of the watershed is made of bedrock. See *figure 6*. In *figure 5* simplified soil structures of the three different experimental sites are shown.

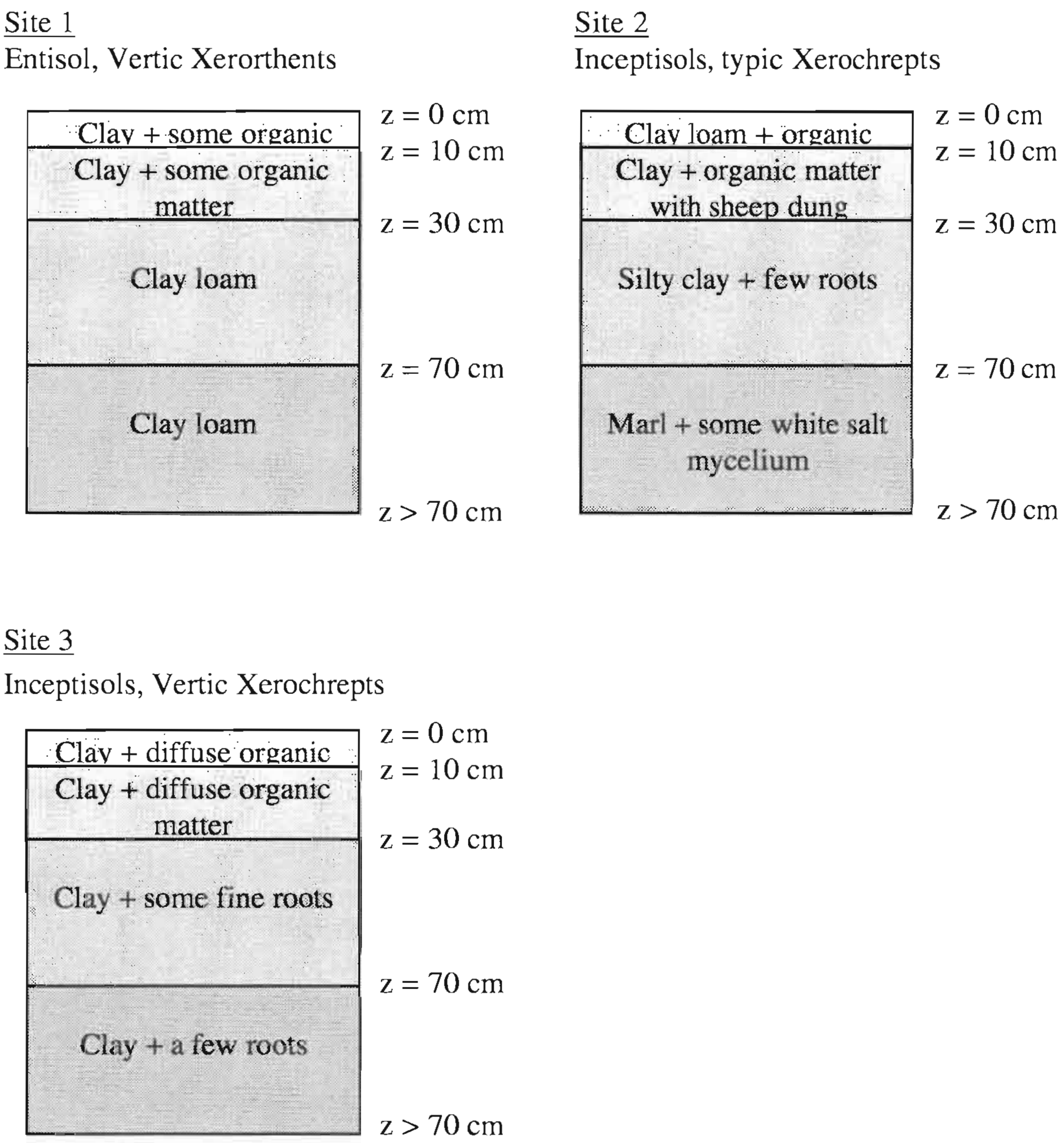



*Figure 5. Simplified soil structures for the three sites.*

| Depth (cm) | | Site1 | Site 2 | Site 3 |
|---|---|---|---|---|
| | Physiographic position and GPS-coordinates | Near the lake<br><br>36°05′26N<br>009°35′29E | In the middle of the watershed<br>36°05′12N<br>009°35′22E | Upstream in the watershed<br>36°04′43N<br>009°35′12E |
| | Slope (°) | 1.9 | 3.9 | 2.6 |
| | Classification acc. to Soil Taxonomy | Entisol, Vertic Xerorthents | Inceptisols, Typic Xerochrepts | Inceptisols Vertic Xerochrepts |
| | | | | |
| **0-10** | Humidity | Dry | Dry | Dry |
| | Color | Dark brown | Light brown | Dark brown |
| | Textural class | Clayey | Clay loam | Clay |
| | Structure | Blocky | Prismatic | Blocky |
| | Organic matter | Some | Many sheep dung | Diffuse |
| **10-30** | Humidity | Moist | Moist | Moist |
| | Color | Dark brown | Yellow-brown | Dark brown |
| | Textural class | Clay | Clay | Clay |
| | Structure | Blocky | Massive | Blocky |
| | Organic matter | Few | Sheep dung | Diffuse |
| **30-70** | Humidity | Moist | Moist | Moist |
| | Color | Light brown | Yellow-brown | Dark brown |
| | Textural class | Clay loam | Silty clay | Clay |
| | Structure | Massive | Massive | Blocky |
| | Organic matter | No | Few roots | Some fine roots |
| **>70** | Humidity | Moist-wet | | Moist |
| | Color | Yellow-brown | | Dark brown |
| | Textural class | Clay loam | | Clay |
| | Structure | Thick | Platy blocks | Blocky |
| | Organic matter | No | Salt mycelium | Few roots |

*Table 4. Soil classification and profile description of the experimental sites (Zante, 1996, personal communication).*

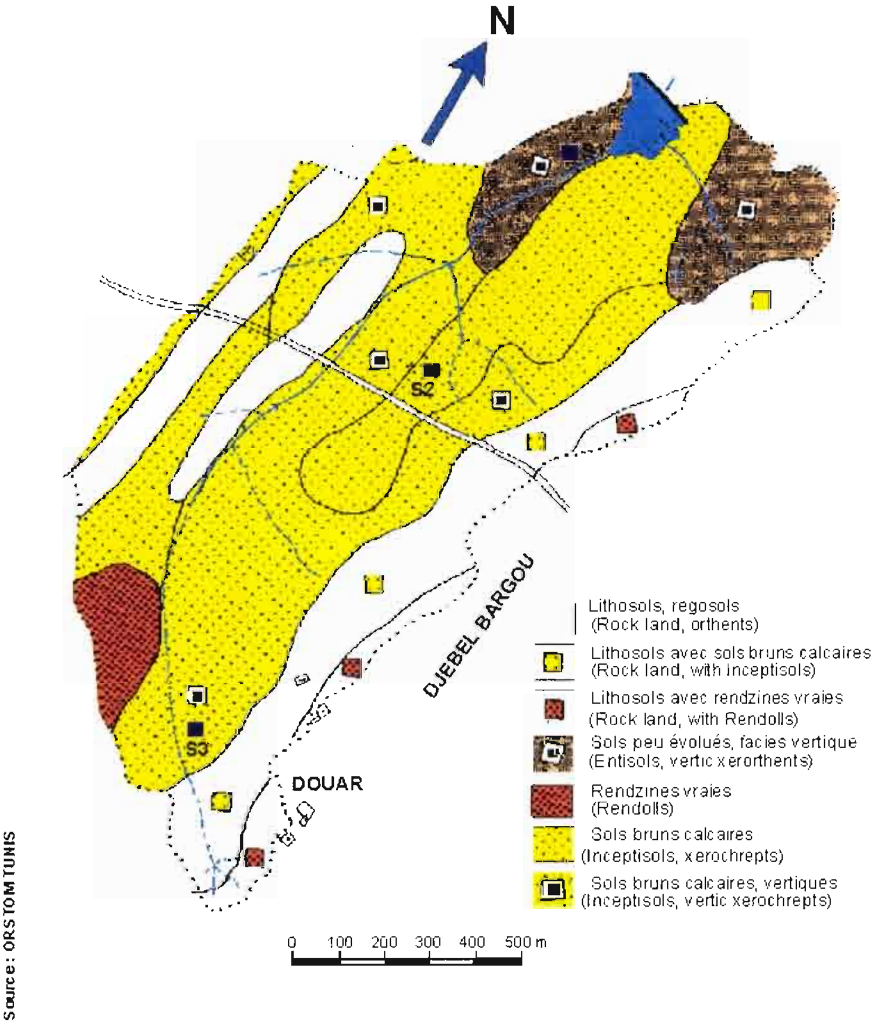



*Figure 6. Pedological map of the watershed. S1, S2 and S3 are the different experimental sites, (Snoussi, 1993).*

### 3.1.4 Geology

The watershed is situated at the west of the Djebel Bargou, which is a part of the North East Tunisian Atlas. On the west side of the Djebel, the slope of the bed rocks is 60 to 80° NW. Between the lines of the calcareous bed rocks (Cretace and Eocene) the outcrops are of clay, marl and calcareous marl (Cretace, Eocene, Oligocene). Quaternary deposits (colluvium, alluvium) are generally horizontal layers on geological rocks. They are of stone layers into clay and calcareous crust. They cover the low parts where they form an impermeable fan, particularly in the downstream parts of the valley (*Snoussi,1992*).

### 3.1.5 Land use

Almost all of the watershed is used for agriculture. The most common crops are wheat, fodder and legume, but also some fruit farming exists. When we did our experiments, 961015-27, all land, except the fruit farms, were tillaged or lay fallow, (see *figure 7*). Water from the reservoir is used as irrigation water for the fruit farms near the reservoir and as drinking water for cattle.

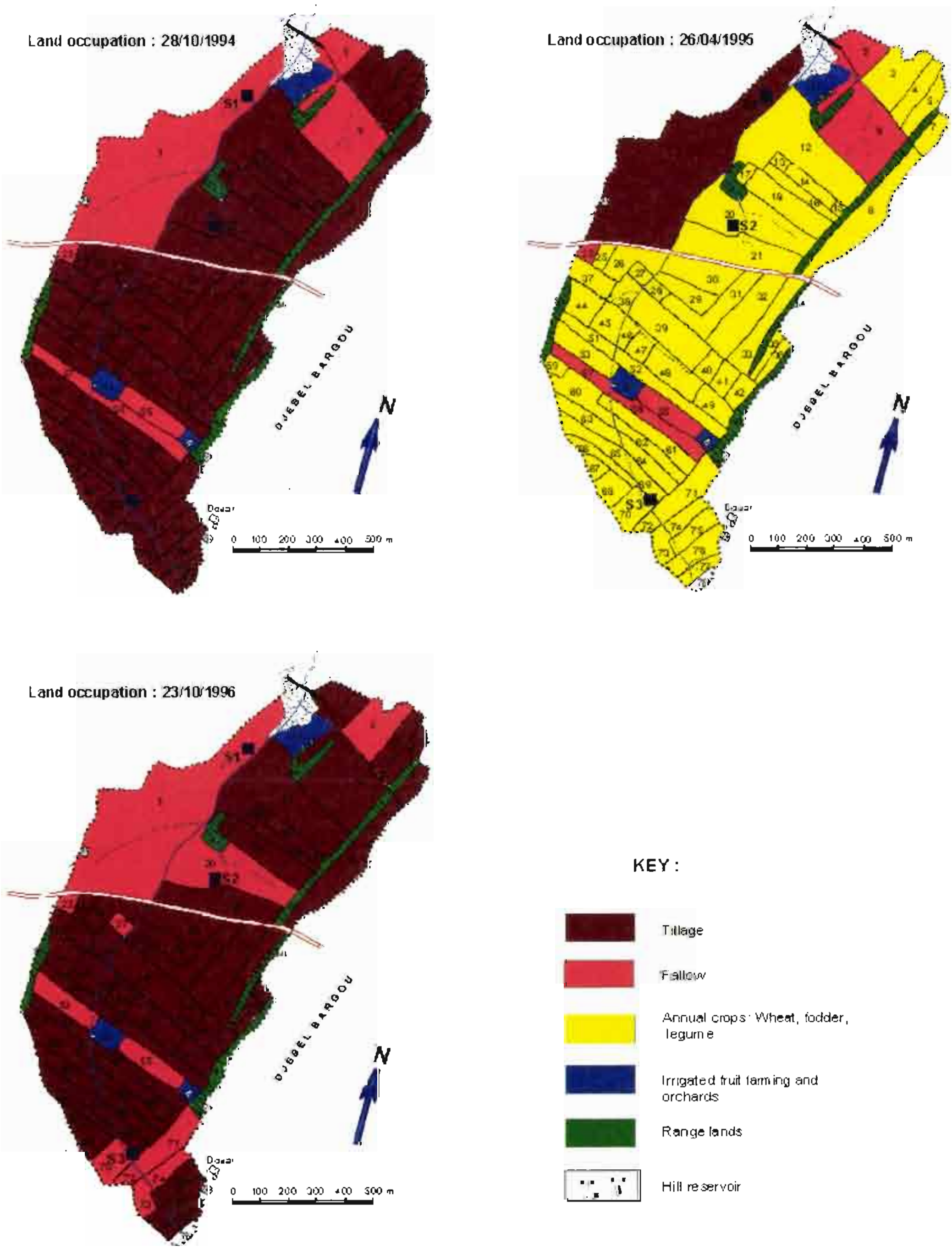



*Figure 7. Map of the land use in the catchment (after data collected by ORSTOM, Tunis).*

### 3.2 The experiments

To investigate preferential flowpaths and effects of heavy rain storms, we used a rainfall simulator and a dye. The dye colors the water blue and will later be adsorbed to the soil and stain the flowpaths in the soil, which among others consists of cracks and root channels, green-blue. To describe the conditions and the behavior of the watershed three different representative sites for the experiments were chosen. It was desirable to cover the differences in pedology and topography in the watershed. There are mainly three different types of soils (Entisols, Vertic Xerorthents; Inceptisols, Typic Xerochrepts; Inceptisols, Vertic Xerochrepts) *see figure 6*, therefore one site was selected in each type of soil. Also different distances from the lake were desirable because of various groundwater table depths at different sites, and therefore varying impact on the soil water contents. At each site two plots, 1*1 m, were chosen for the simulations. The two plots were placed close to each other to find out something about the areal variation in a small scale. To have the desired amount of water during the simulations without adjustment of the rainfall simulator, places with small slopes were chosen. A 1*1 m steel frame was placed at each of the chosen plots, to delimit the experimental area. In the lowest situated frame wall there were holes to discharge runoff water, to be measured. The vegetation at the plot was removed by hand and the surface was cultivated, to a depth of about 10 cm, using a pick. These activities took place to have the same type of surface at all plots.

*Figure 8. The soil was cultivated.*

*Figure 9. Frame and cultivated soil.*

The rainfall simulator was put in place with help of a weight from the nozzle at the top of the tower. The simulator was adjusted until the weight was in the middle of the steel frame and the top of the simulator was horizontal. This was done by moving the tower and adjusting the length of the simulator's four legs. To control that the top was horizontal a spirit level was used.

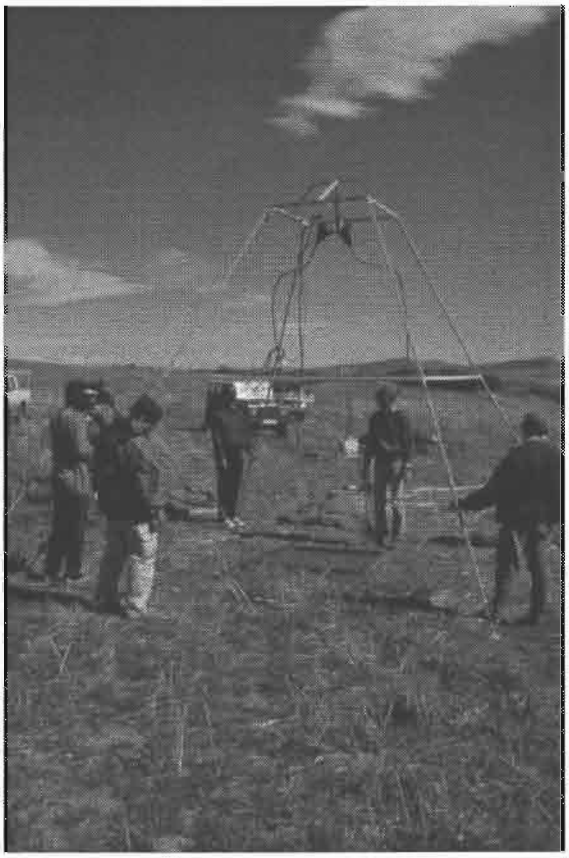


*Figure 10. Setting up the rainfall simulator.*

Before the experiment, the rainfall simulator was calibrated by putting a steel sheet over the frame to make all water run off. The runoff water was lead to a tank in which a float was placed, the float was connected to a pen. The pen indicated the amount of runoff water on a paper sheet detached to a turning metal cylinder, to have the amount as a function of the time, which means the intensity, (see *figure 12).* This observed intensity was compared to a pre-determined one and if necessary the intensity from the rainfall simulator was adjusted. This was done for all six different intensities for the designed rainfall.

*Figure 11. Calibration of the rainfall simulator.*

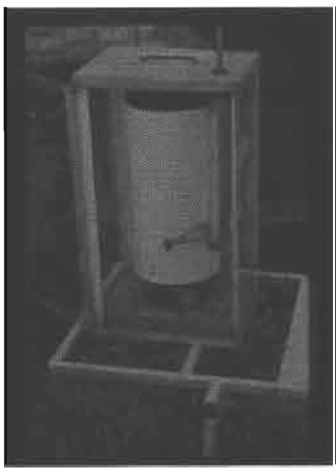


*Figure 12. Runoff amount measurement instrument.*

For the simulations, drinking water was brought from Bargou in a tank and later poured into two barrels. The calibrations were carried out with uncolored water. During the simulations, one person checked the clock and the runoff instrument to note time for ponding and time for runoff. Another person changed the rainfall intensity at the right time. After runoff started, a sample of water was taken in the middle of each intensity to measure the amount of sediment in the water. If the runoff tank was full it was emptied by a pump. After the experiment, the plot was covered by a plastic sheet to avoid evaporation. At least 24 hours after the simulations the plots were excavated vertically in 2.5 cm thick slices to make the stained flowpaths visible and the patterns were photographed.

### 3.2.1 Dye tracer

The food-grade dye pigment Brilliant Blue FCF was chosen as a tracer. It colors the water blue and the soil green-blue. The reasons for this choice were several. The tracer has low toxicity, good visibility in soil and weak adsorption to the soil, (*Flury et al., 1994*). This is a well known tracer used in several similar tests before, (*Yasuda et al., 1996; Flury et al., 1995*). Concentrations of the dye required for good visibility in soil are 3-5 kg/m$^3$. We used 4 kg/m$^3$. On each site, both simulations were done in a close sequence and before the experiments 500 l colored water was prepared, 250 l/rainfall. Mixing of dye and water was carried out in two barrels. Plastic bags, in which the dye was kept, were opened under the water surface. A small amount of water was let into the bags which was kneaded to facilitate the dissolving of dye into water. The dye is very volatile when not dissolved in water and will float to the water surface where it can be spread by the wind. To make the mixing faster and easier we recommend a use of few but big plastic bags. The bag should be big compared with the amount of dye in it to facilitate the mixing procedure and to avoid dye to float to the surface.

*Figure 13. Mixing of dye.*

### 3.2.2 The rainfall simulator and the simulated rainfall intensities

The simulator was designed by ORSTOM, (*Bernard, 1987),* and it consists of an approximately 4 m high tower, a nozzle and a motor, to turn the nozzle, which both were attached to the top of the tower (*figure 16).* The nozzle spreads water over the plot by forward and backward turning of the motor. The nozzle is designed to deliver drops, and a distribution of drops, as similar as possible to natural rainfall. The intensity was changed by changing the angle of which the nozzle was turning, (a small angle gives a high intensity and vice versa). The simulator was run by a computer unit. To the nozzle, water was led from two barrels with a pump. Not only the 1*1 m plot but also a bigger area was covered by the rainfall to be sure that the plot had exactly the same conditions in every point. When an area big enough had been covered with water the rest of the water of the nozzle turn was recycled to the barrels. The required amount of water was about 250 l/rainfall. The tower was covered with plastic sheets to avoid influence of wind to the simulation.

*Figure 14. The complete rainfall simulation equipment.*

*Figure 15. The nozzle.*

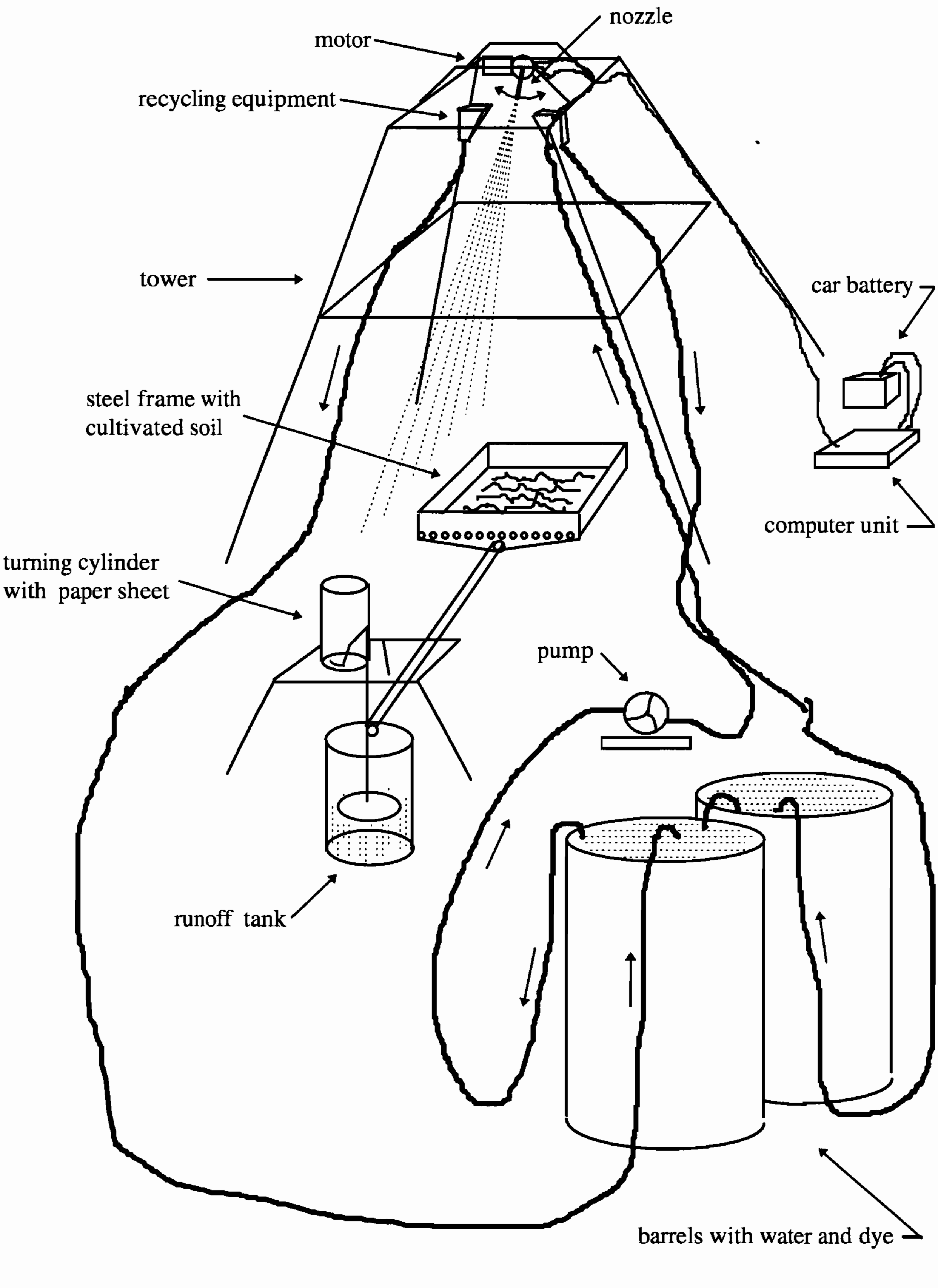



*Figure 16. Experimental arrangement.*

A simulated rainfall has to fulfill many different objectives. In our case, it was important that the simulation showed some kind of "extreme case" to know how deep solutes can move. Therefore the 20-year storm was determined suitable. It is a heavy rainfall but since it is supposed to occur every twenty years, it is still not unlikely. There are no strict rules to follow for a choice like this. To be able to use the results for a comparison with natural conditions, the simulated rainfall must be as similar as possible to a real rainfall. To obtain this we used statistics, (*Sakiss et al.,1991; Ghorbel, 1991),* and data collected by ORSTOM, Tunisia. From these data five rainfalls, from 1993-1996, in M'Richet el Anze, containing the largest depth were selected. Some of them had a large accumulated depth, but a very long duration and therefore low intensities. According to the statistics, we should have a rainfall with rather high intensities during the entire rainfall. Therefore we chose the heaviest rainfall in the ORSTOM data, 73 mm during 85 min (it is probably a convective rainfall, *Berndtsson, 1988*). In the statistics the 20-year storm had a constant intensity of 52 mm/h, that is 74 mm/85 min. The ORSTOM data contain accumulated rainfall for every five minutes, in the statistics, it is only possible to find duration and depth, which give no clue about the pattern in time. Therefore we used the ORSTOM data. The heaviest rainfall was from 940909 and had the pattern shown in *figure 17.*

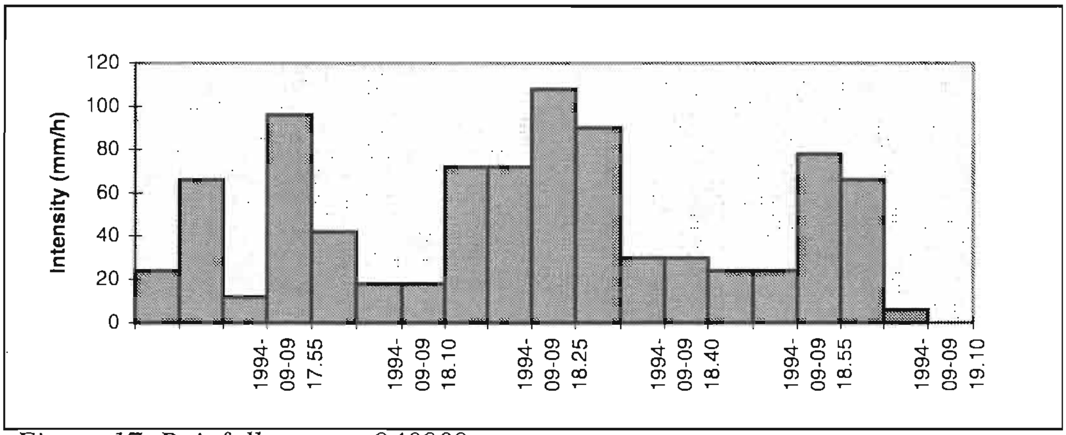


*Figure 17. Rainfall pattern 940909.*

This rainfall is difficult to simulate because of the short duration for each intensity and the big changes in time. Therefore a designed pattern, a so called single peak distribution was used instead. The lower intensities were gathered to a smaller amount of heavier intensities, this means the simulated rainfall has a shorter duration, but the same accumulated quantity of water as the real one. We also kept the highest intensity intact. The rainfall we used had the pattern shown in *figure 18.*

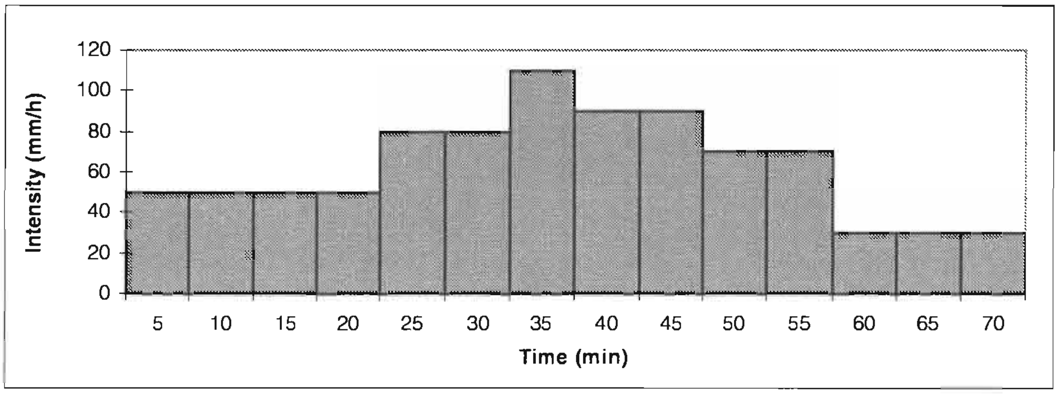


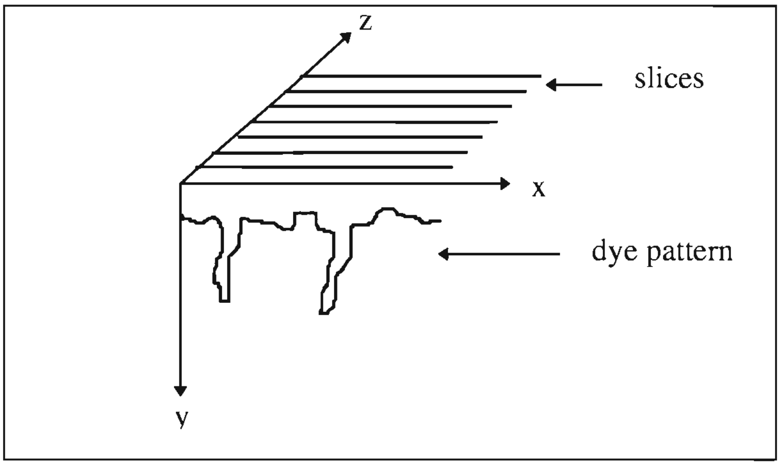

*Figure 18. The design rainfall used for the experiments.*

The rainfall has a duration of 70 min, a total depth of 73 mm and a highest intensity of 110 mm/h.

### 3.2.3 Excavation, photographs and graphic processing

After that each rainfall experiment was finished a trench was dug in connection with the plot. The trench was approximately 1 m deep and 2.5 m long. From this trench the plot was excavated. The excavation did not begin earlier than 24 h after the rainfall experiment. At this time all dye was assumed to have been adsorbed to the soil. Before the excavation began the iron frame was replaced by three steel bars to mark the positions of the plot. Two bars, which were fixed with nails, were placed in z-direction. The third bar lay above the other two in x-direction and was moved after every slice to show the positions for the next slice, see *figure 19 and 21*. The plots were excavated in vertical slices, each slice 2.5 cm thick, that means 40 slices per plot and 240 slices altogether. Each slice was created first using a spade to get rid of most of the soil and afterwards using a knife to smooth the surface and to remove loose particles. In spite of this treatment, the slices were not exactly vertical, something that had to be kept in mind. Then a note with the z-coordinate and a palette with four reference colors, white, red, yellow and blue were attached to the vertical surface. Eventually, four nails were placed on the surface at exactly the same places for each slice. The latter was carried out to make it possible to know how to place the photos in relative position to each other when visualizing the infiltration.

*Figure 19. Coordinate system for infiltration plots.*



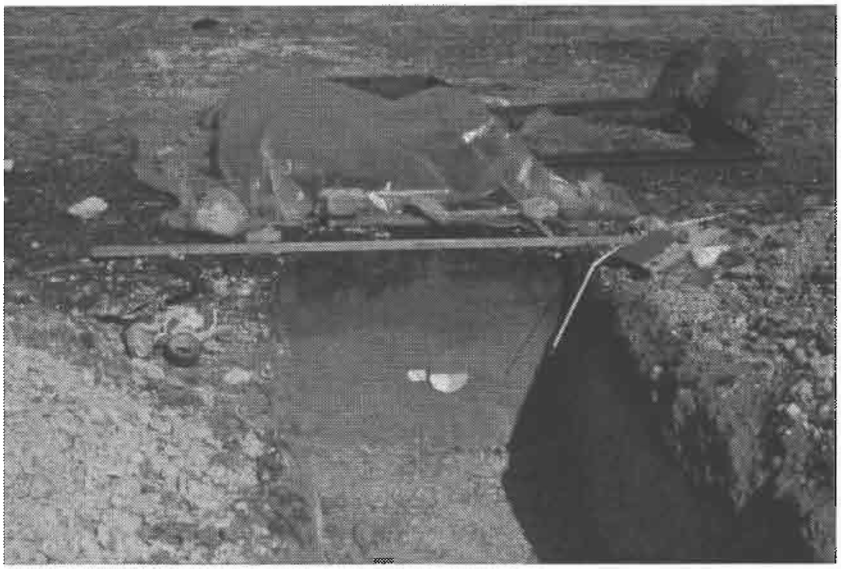


*Figure 20. Trench for excavating the infiltration plot.*

*Figure 21. Excavation of the plot, using a spade.*

Now the two-dimensional distribution of the green dye pattern could be recorded using a 35 mm camera (Nikon F801-S with a fixed 50 mm objective and Kodachrome 64 film). To avoid different light conditions a plastic sheet was held in a way that both camera and surface were protected from sunlight. This means that all photos were taken in shadow (using a Nikon SB23 flash). The distance from camera to surface was constantly 1.70 m. The slices had, all the time, a width of 1.00 m and a depth between 0.60 and 1.50 m depending on the rate of infiltration.

The aim of the graphic processing was to develop a method to put our photos, taken during the excavation of the plots, together and visualize the infiltration in three dimensions. This was carried out in four different steps:

1. scanning the photos
2. digitize the border between dye-stained and not dye-stained area
3. convert the coordinates to our own coordinate system
4. plotting the coordinates in three dimensions

When we selected the photos (two photos were taken at each slice) to be used in this process we discovered that one film was destroyed, about 75% of the photos were too dark to use. Because of this, there were no data for plot 2.

**1. Scanning process:**
The photos were scanned into a computer using a diapositive scanner and converted to *.TIF-files using two different softwares, Desk Scan and Adobe Photoshop.

**2. Digitization:**
In this step the *.TIF-files were imported to another software (Idrisi) that was used to convert screen-pictures to vector-pictures. This means that the mouse is used to click along the borders that separates stained (infiltrated) soil from not stained soil. The points, made by the mouse, were saved in a file as coordinates with values in both x- and y-direction.

**3. Convertion of coordinates:**
The Idrisi-software used in the former step has one major disadvantage. It is not possible to decide were to place the origin. The software always places the origin down in the left corner, but since we had four points with known coordinates in each photo, we wanted one of them (the one down to the left) to be the origin. To obtain this a computer program was written, in Pascal, that managed both to turn the picture so its top and bottom were parallel to the x-axis and moved the points to the right place related to the settled origin. This program also gathered all coordinates for one plot in one file, instead of one file per photo.

**4. 3-D plotting:**
The last step was to visualize the infiltration by plotting the coordinates in three dimensions. This was made in Surfer, using Kriging to extrapolate between different z-coordinates (photos). The results are shown in *figures 58-67*, where the ground level is at zero and the plotted volume represents the blue soil, but seen upside-down. Unfortunately these figures do not show the real conditions. In reality the maximum infiltration was deeper and the contours were more sharp at all plots. This is because the software can only manage to treat one y-value per x-value, but it is very common that two or more y-values exist for one x-value. For example, imagine the following situation:

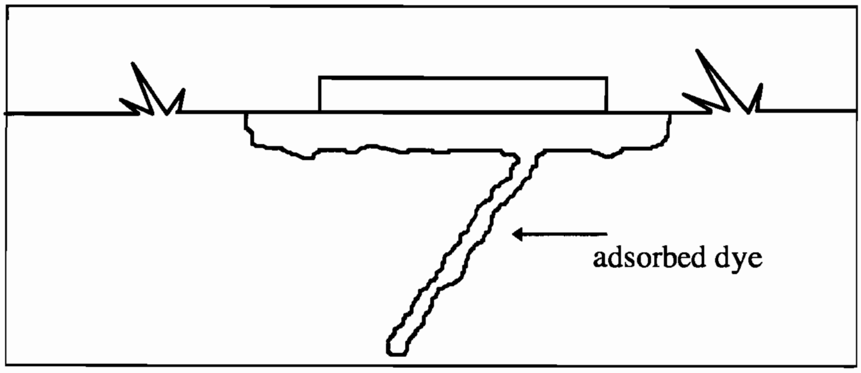
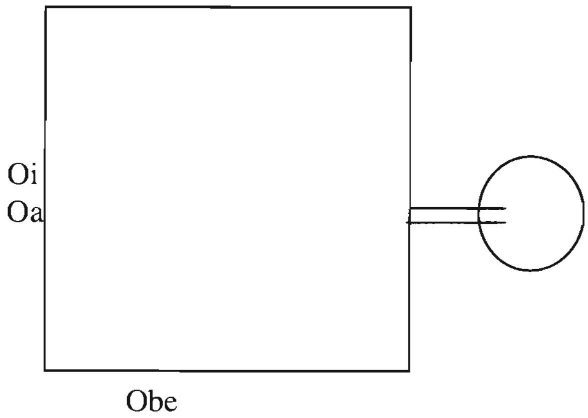



*Figure 22. A section of an oblique crack.*

In this example an average will be plotted, that will result in a figure more smooth than the real one. Probably there are softwares that can deal with similar problems, but we did not have access to them. This deficit can, in extreme cases as in plot 1 where we had an extremely deep crack in a very limited area, lead to big errors. The figure shows a deepest infiltration depth at about 1.1 m, but the real infiltration, measured in the field, was 1.49 m.

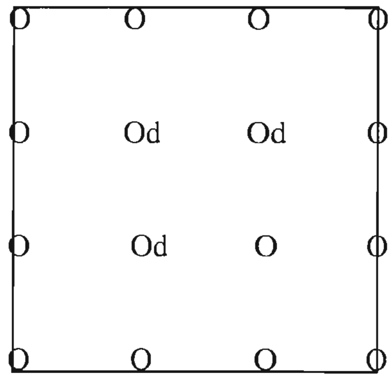
### 3.2.4 Soil samples

To understand what happens with the water after it has infiltrated, i.e. the movement of the humidity front, soil structure and texture are of importance. In connection with the experiments, samples were taken, using an auger, just before the simulation to have dry conditions, immediately after simulation and just before beginning of excavation to see how the humidity front moved. The samples were collected at seven levels: 0-10, 10-20, 20-30, 30-40, 40-60, 60-80 and 80-100 cm. To have a representative soil sample at each level, soil was taken from different parts within the limits of each sample. Each sample contained about 100-150 g soil or about 100 $cm^3$. The distance between the two plots at one site was approximately 7-8 m and the GPS-coordinates were measured in the middle between the two plots (*table 4*).




O = sample point
i = initial conditions, samples taken before the rainfall experiment.
a = after, samples taken right after the experiment was carried out.
Be = before excavation, samples taken in connection with the excavation.

*Figure 23. Plan of where the soil samples were collected.*




d = deep, samples taken at all seven depths, the other were taken at the depth 30-40 cm.

*Figure 24. Plan of where the samples for the statistical verification were collected.*

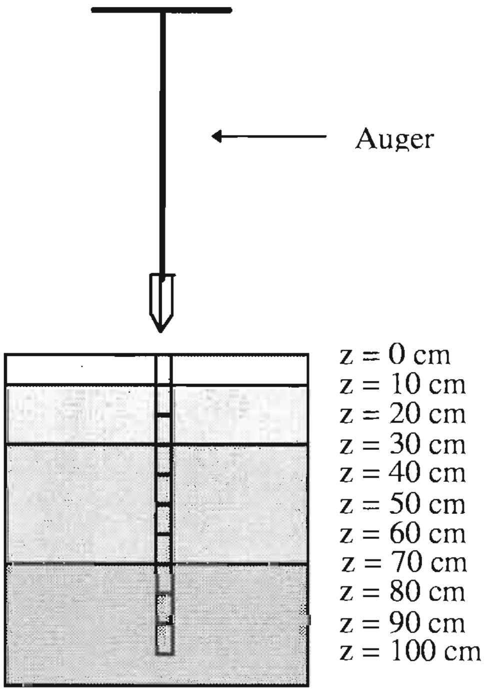



*Figure 25. Section of where the soil samples were collected.*

It was easy to push down and pull up the auger at site 1 and 3 but more difficult at site 2. This was caused by the heavier clay content at site 2.

*Figure 26. Collecting soil samples at site 2, using an auger.*

In laboratory, the samples were put on a scale to determine the weight of wet soil plus glass can. Afterwards the samples were put in an oven, 105°C for 24 hours, to dry. The samples were weighed again to have the dry weight of soil plus glass can. The weight of the glass cans was measured before the samples were taken. The mass of water in the samples were determined by subtracting the weight of dry soil plus glass can from the weight of wet soil plus glass can.

$$m_{water} = m_{wetsoil+glasscan} - m_{drysoil+glasscan}$$

To have the water quantity in percent of soil mass the mass of water was divided by the mass of dry soil and multiplied by 100.

$$Water(\%) = \frac{m_{water}}{m_{drysoil}} * 100$$

Later on more samples were taken to verify the results statistically. They were collected in a grid, 16 points in 1 $m^2$. In three of the points, forming a triangle in the middle of the square meter, see *figure 24,* soil from all seven depths were collected, from the other 13 only from one depth, 30-40 cm. The same procedure was repeated in all three sites in a representative place between the two plots, approximately 3-4 m from each plot, where the simulations had taken place. The new samples were treated in the same way in the laboratory as the first ones collected. More samples were collected in cylinders, 94 $cm^3$ with Ø5.6 cm, to determine bulk density. On the same depths (0-10, 10-30, 30-70 and >70 cm) soil samples were collected in plastic bags for further analyses in laboratory. These analyses were: particle size distribution (Robinson's pipette), true density (pycnometer), organic matter and structural stability (Henin's method).

# 4. RESULTS AND DISCUSSIONS

## 4.1 Rainfall and runoff

### 4.1.1 Rainfall- and runoff patterns

The runoff intensities were determined from the paper sheet, containing the accumulated runoff amount. A value of the runoff amount was read every 30 seconds and from this value the previous value was subtracted to have the change of runoff, i.e. the runoff rate. If the runoff was low and the readable value did not change every 30 seconds the calculated runoff rate was zero in the interval of unchanged runoff data. Because of this discontinuous way of determining runoff rate the runoff graph will be unsmooth. To make the graph more like the reality the graph was graphically smoothed without changing the total amount of runoff. The difference between an unsmoothed graph and a smoothed one is shown in *figure 27*. In *figures 28-33* rainfall and runoff patterns for the different plots are shown. At plot 3 and 4 the runoff is rather large and the changes in intensities follow the changes in rainfall intensities quite well. At plot 2, 5 and 6 the runoff amount is small. The big difference between plot 1 and 2 can be explained by trouble with the equipment during the simulation at plot 2. Soil particles were gathered in the holes in the steel frame and stopped the runoff water.

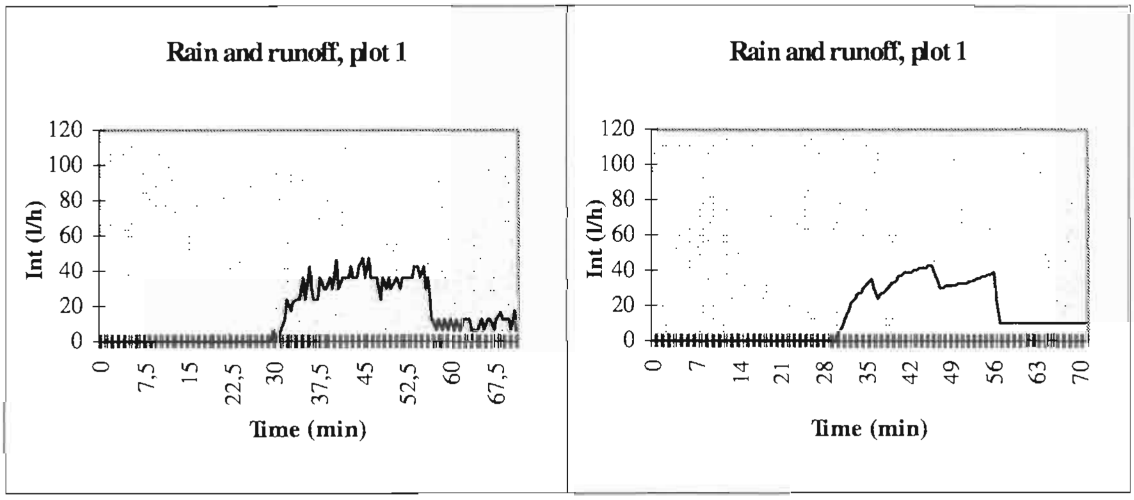
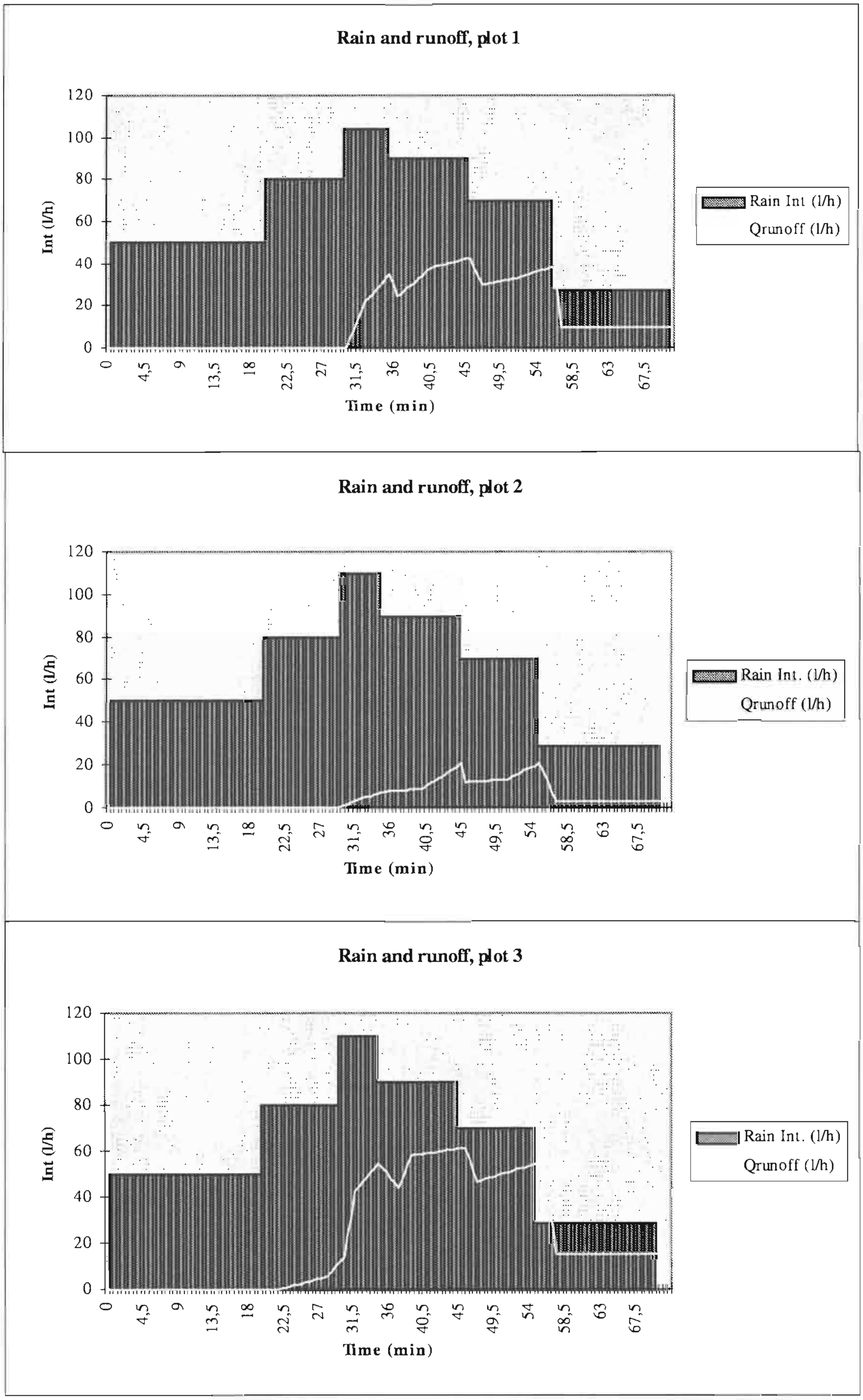
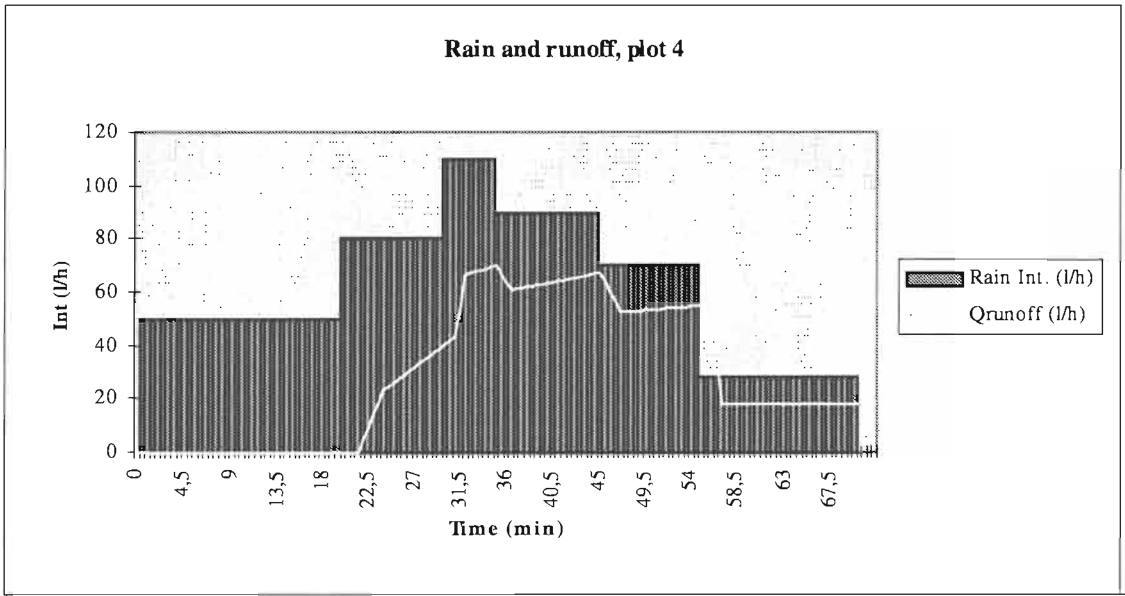
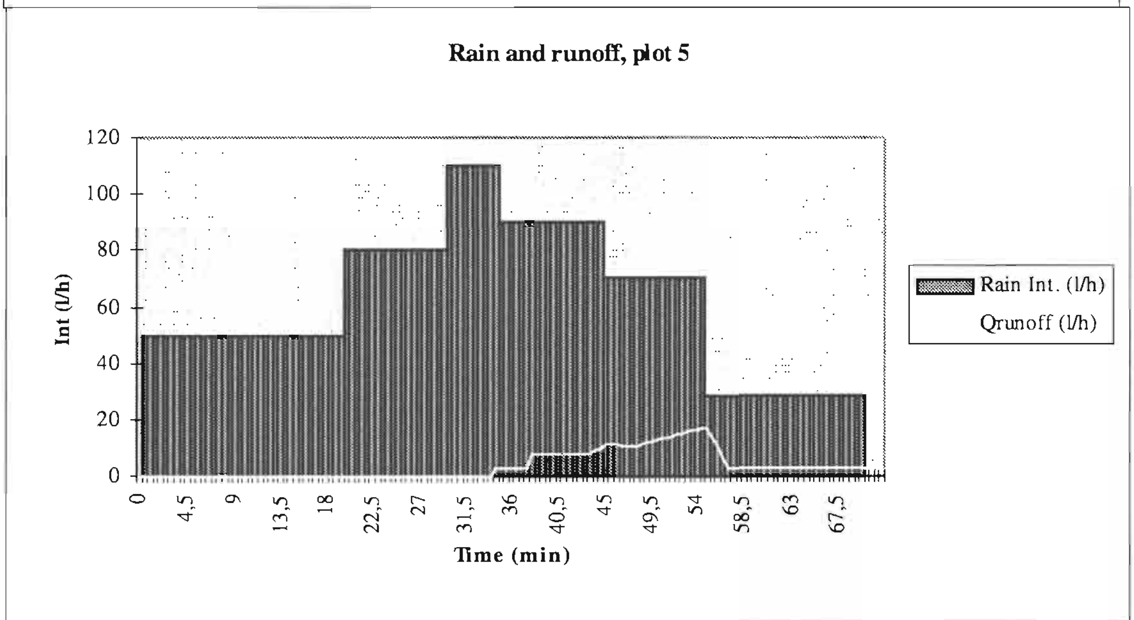


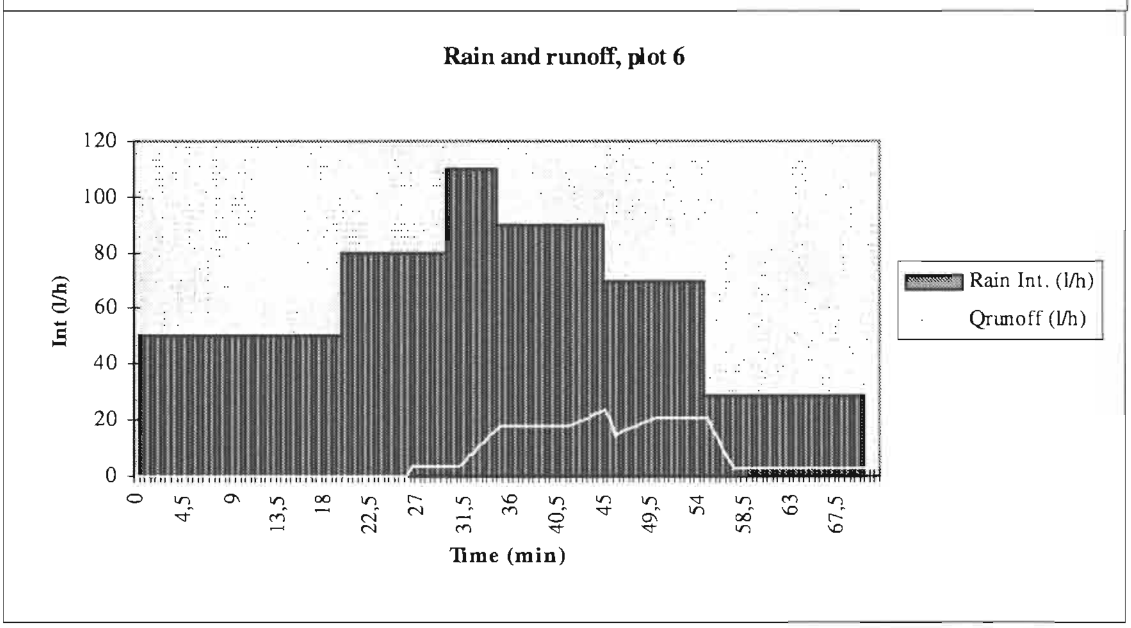

*Figure 27. Differences between unsmoothed and smoothed graphs.*




*Figures 28-30. Rainfall and runoff patterns for plot 1-3.*



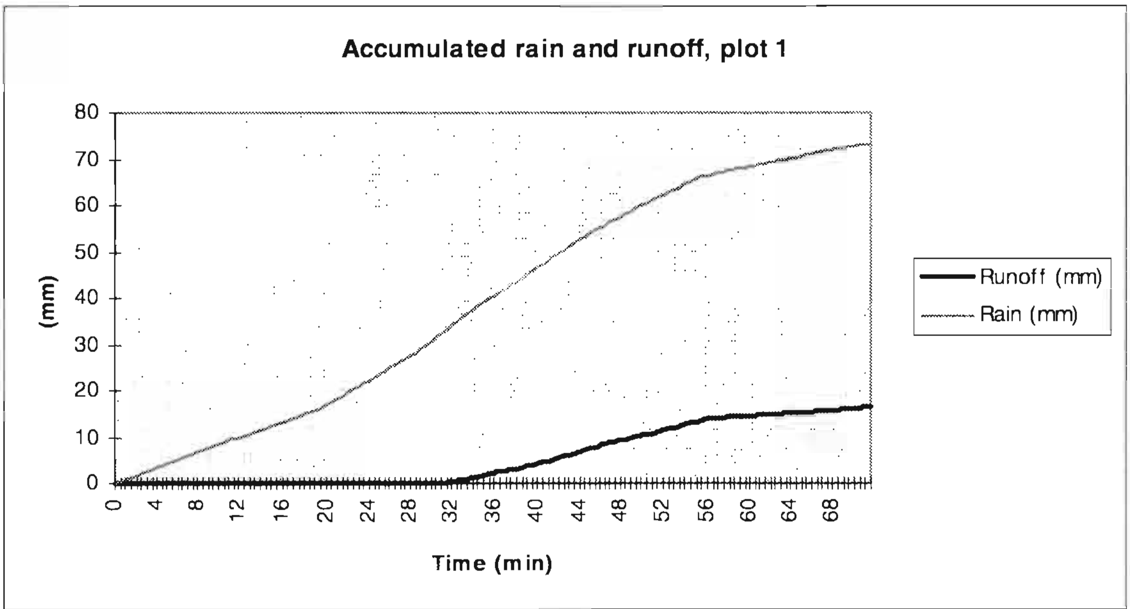



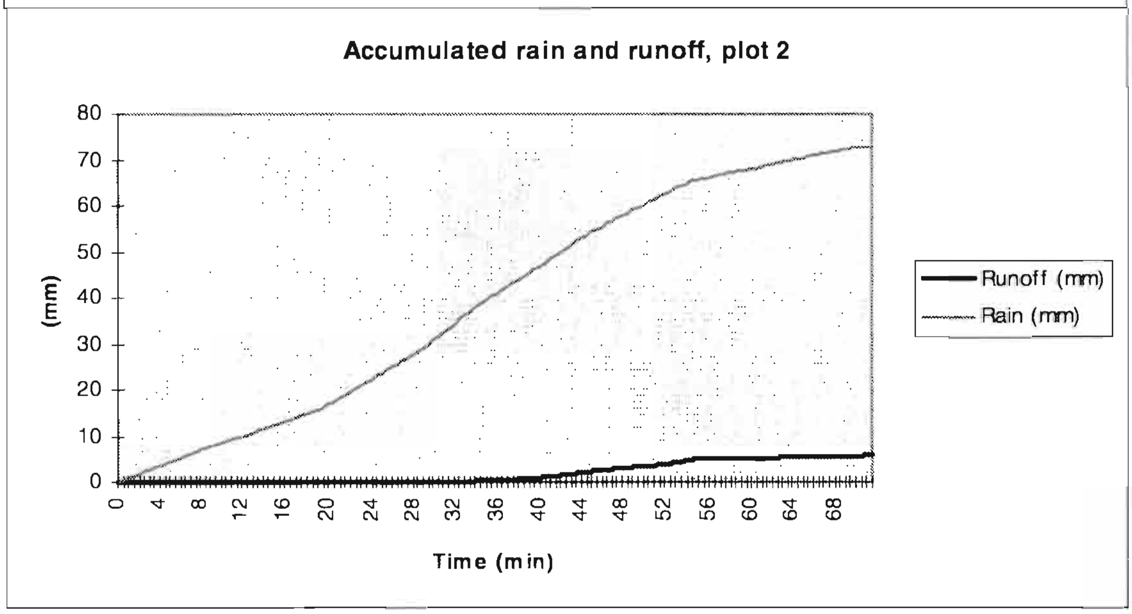




*Figures 31-33. Rainfall and runoff patterns for plot 4-6.*

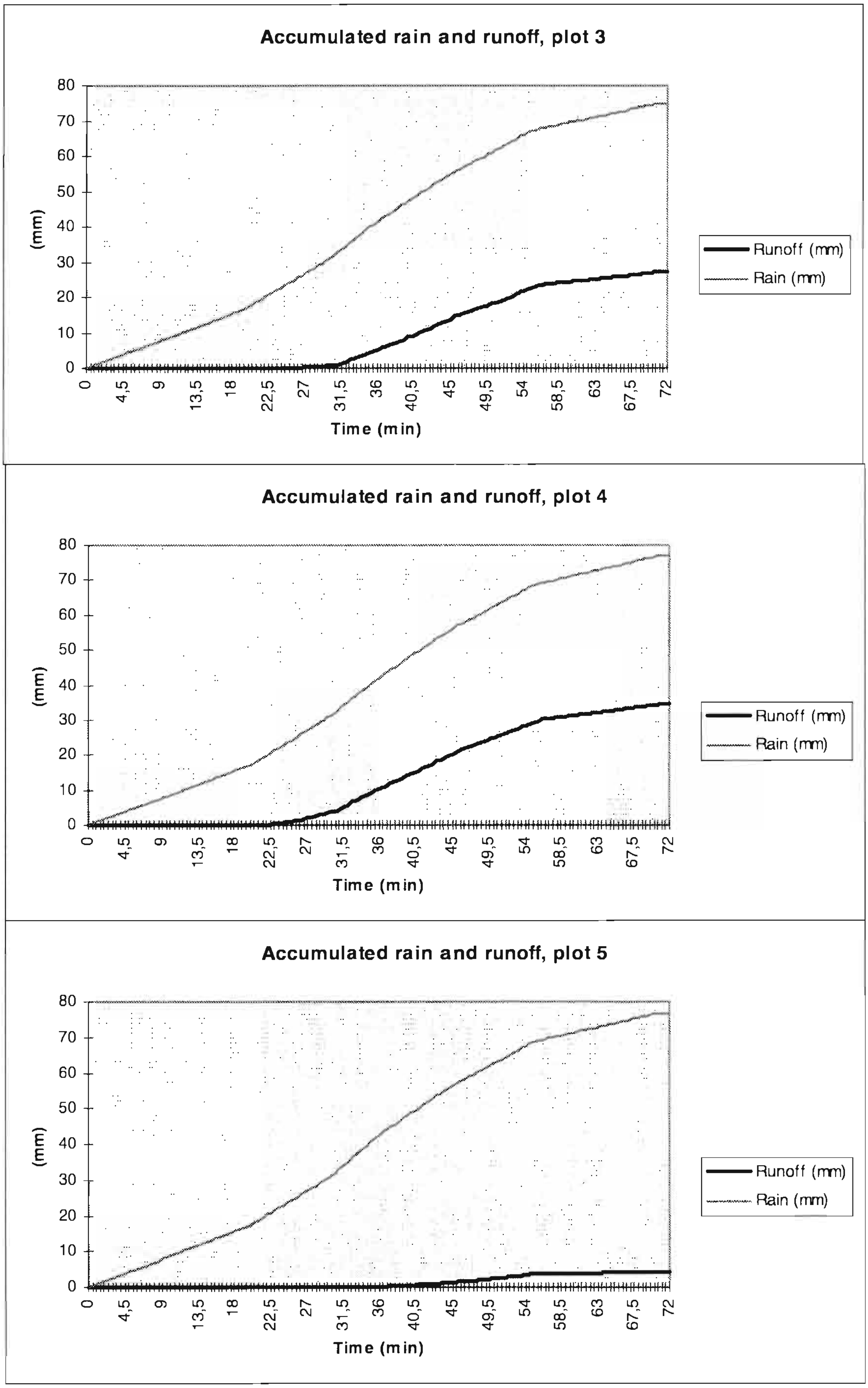
### 4.1.2 Accumulated rainfall and runoff

The values of rainfall and runoff were determined every 30 seconds and accumulated. The accumulated amount of rainfall is not exactly the same on all plots and the reason is that the simulator must be moved from plot to plot. Even if calibration is made for every plot it is not possible to have exactly the same rainfall, but the difference does not affect the results. *Figures 34-39* show the accumulated rainfall- and runoff amount. The tendency is similar to *figures 28-33*. Large runoff at plot 3 and 4, small at plot 2, 5 and 6. At plot 2, this is because of problems with the equipment.




*Figures 34-35. Accumulated rainfall and runoff for plot 1-2*




*Figures 36-38. Accumulated rainfall and runoff for plot 3-5.*

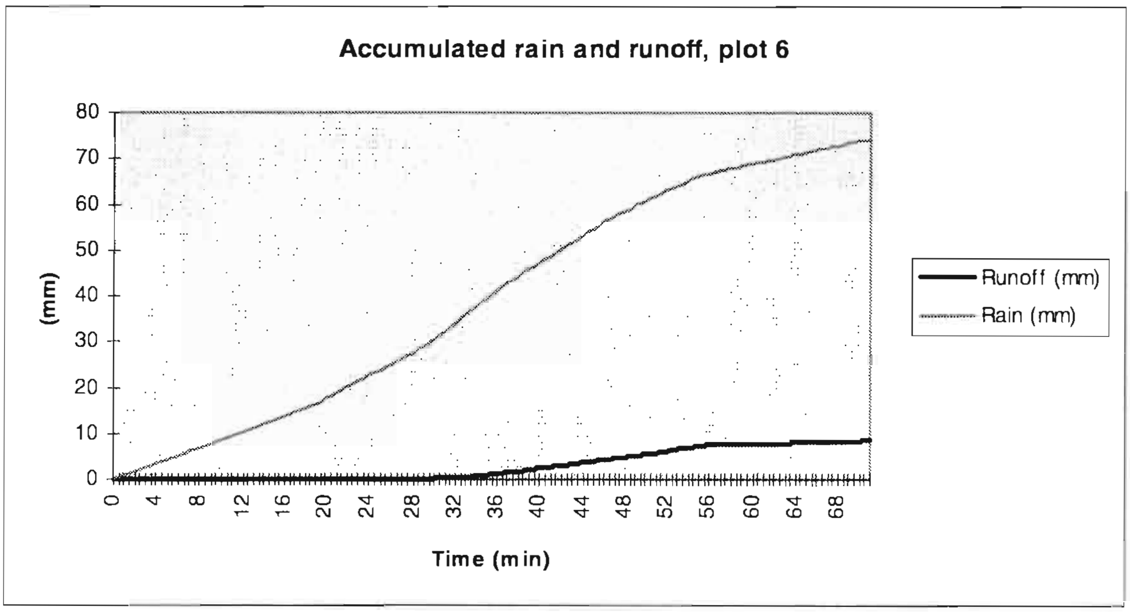



*Figure 39. Accumulated rainfall and runoff for plot 6.*

### 4.2 Sediment transport

From runoff samples taken at the middle of each intensity (when runoff occurred), the erosion was measured. The samples were collected from the runoff in small plastic bottles. The water samples were filtered through fine paper filters, 0.45 µm, whose mass were known by using scales. Filters with sediment were put in an oven to dry, 105°C for 24 hours. The sediment amount in each water sample was now determined by subtracting the filter mass from the mass of filter plus sediment, this gave the sediment mass [m] in each sample. This mass was divided with the sample's water volume [V] to have the concentration of sediment mass per volume [m/V]. Sediment transport intensity, mass per time unit [m/t], was calculated by multiplying sediment concentration with runoff intensity, volume per time unit [V/t]. The sediment transport intensity was plotted versus the time. By multiplying the values of the sediment transport intensity with the 30 seconds that it is valid for, the transported mass of sediment for each 30 seconds interval during the rainfall event could be calculated. To have the total transported mass during the rainfall event all masses were added together.

Since just one sample of sediment amount per rainfall intensity was taken and considered to be valid for the entire period of that intensity, these calculations will show a simplified model of the real event and this must be considered when analyzing the results.

To determine the totally transported sediment mass of the entire catchment, for a 20-year storm, the catchment was divided into three parts. Each part's qualities described by one experimental site where two rainfall simulations were carried out. The areas of the parts were determined from a map and multiplied with the average "total sediment transport" from the two rainfall simulations at the corresponding site. By adding these sediment masses from the three parts together the total transported sediment mass of the catchment was calculated. The volume of the transported sediment was determined by dividing the transported mass with the bulk density of the soil.

These calculations give the sediment amount that starts to move at a 20-year storm but not the amount that will reach the reservoir, some of the sediment will settle before it reaches the reservoir. On the other hand these calculations consider an average water transport length of

0.5 m. In the reality the water will be transported much longer and can bring more soil on its way to the reservoir. As a comparison it can be mentioned that the reservoir volume decreased 370 $m^3$ because of sediment transport from 1992-1993. In the calculations presented in *table 5*, we have not paid any attention to the results at plot 2, because of the earlier mentioned problems with the equipment. Also, the calculations were carried out for dry sediment. In reality the sediment will be, more or less, dissolved in runoff water. This means the transported volume of water-sediment solution will have a larger volume than the figures that "dry sediment" show.

| | Area ($m^2$) | Plot (nb) | Sediment transport ($g/m^2$) | Sediment transport (kg) | Bulk density ($kg/m^3$) | Sediment transport, dry sediment ($m^3$) | Average dry sediment transport ($m^3$) |
|---|---|---|---|---|---|---|---|
| Part 1 | 152 900 | 1 | 127.15 | 19441 | 1205.9 | 16.12 | |
| | | 2 | *20.25* | *3096* | 1205.9 | *2.57* | 16.12 |
| Part 2 | 225 100 | 3 | 161.17 | 36279 | 1325 | 27.38 | |
| | | 4 | 125.88 | 28336 | 1325 | 21.39 | 24.38 |
| Part 3 | 586 100 | 5 | 14.53 | 8516 | 1471.2 | 5.79 | |
| | | 6 | 50.03 | 29323 | 1471.2 | 19.93 | 12.86 |
| Sum | | | | | | | 53.36 |

*Table 5. Sediment transport in the catchment.*

*Figures 40-45* indicate that it will be large erosion at soil types represented by site 1 and 2, and small erosion damages at soil types represented by site 3 for the investigated rainfall amounts.

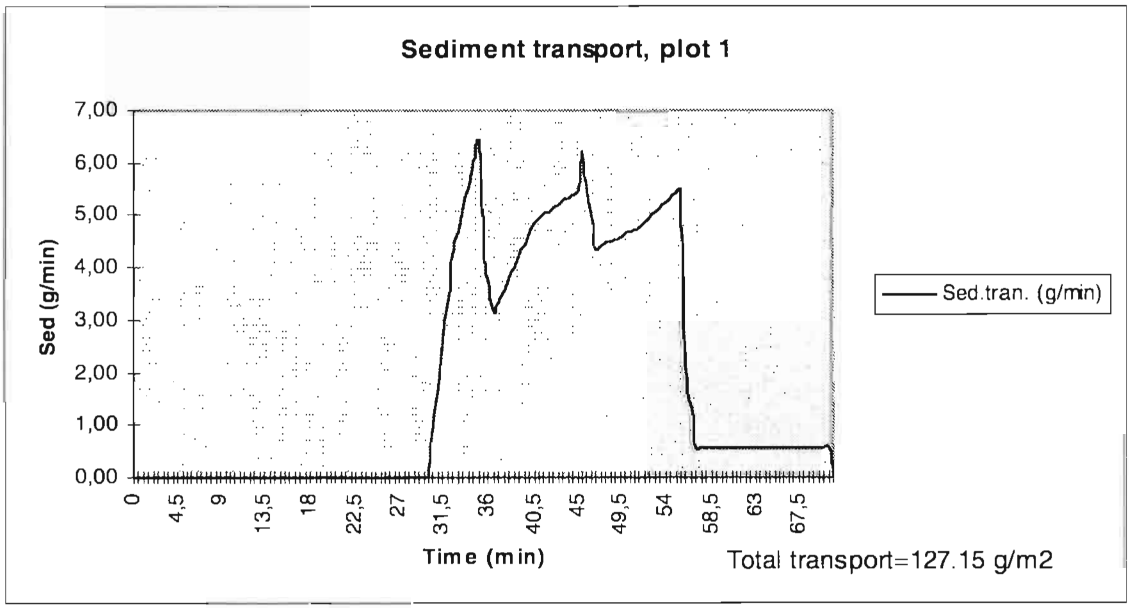
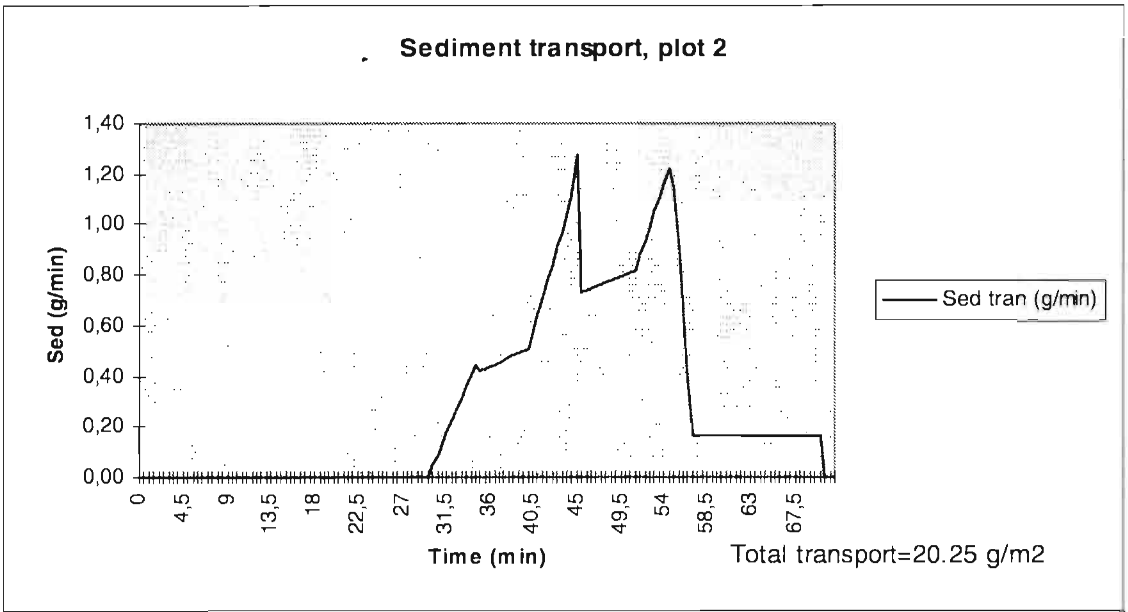
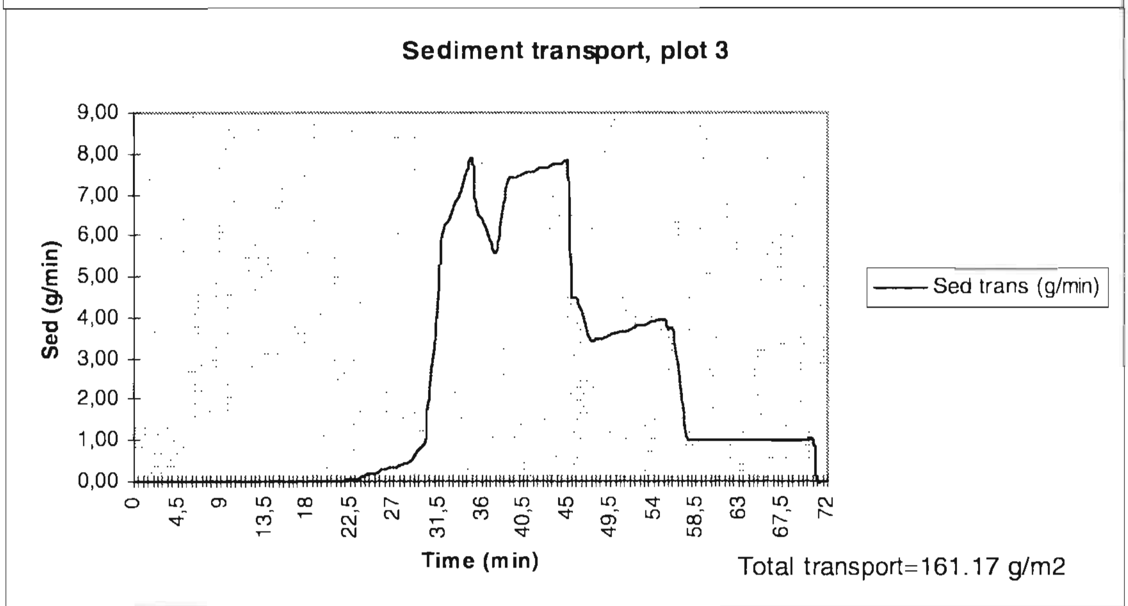
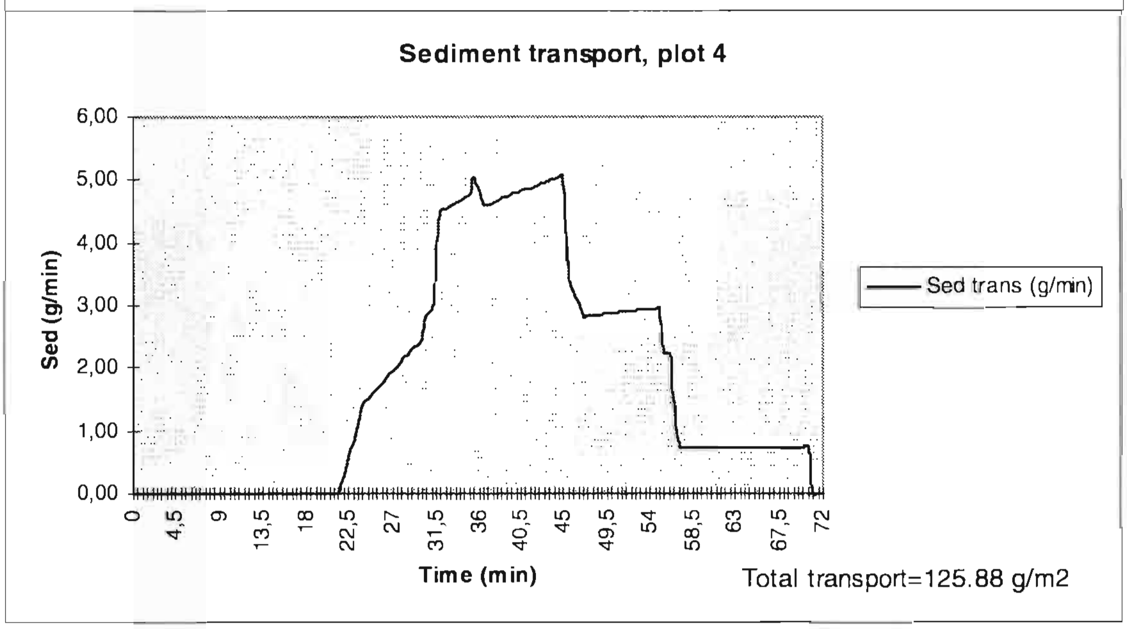


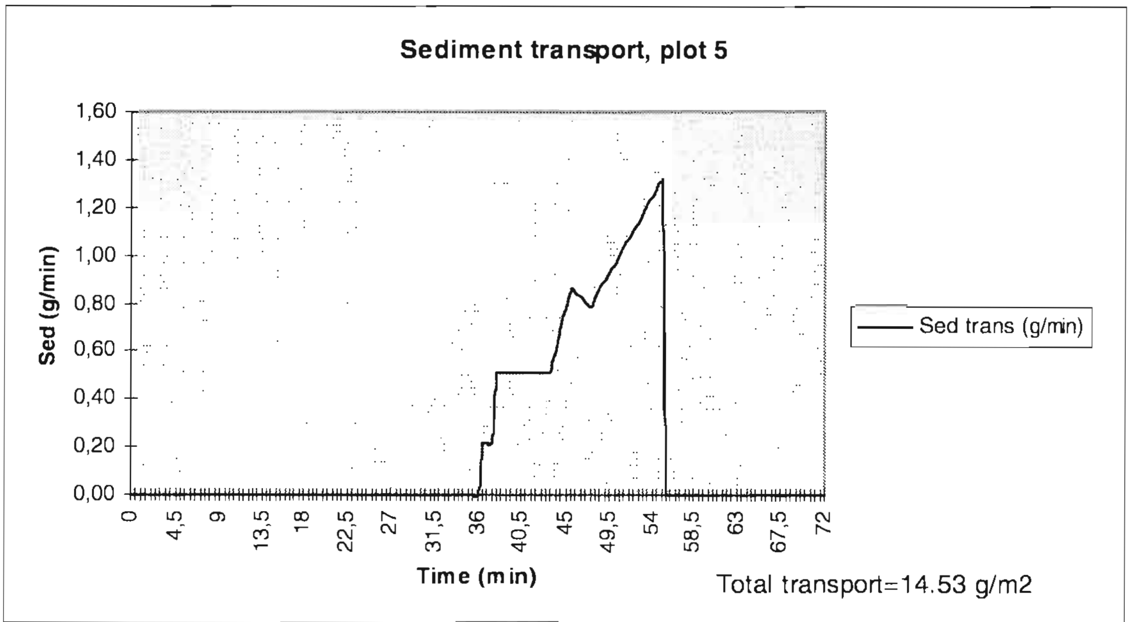

*Figure 40. Sediment transport at plot 1.*

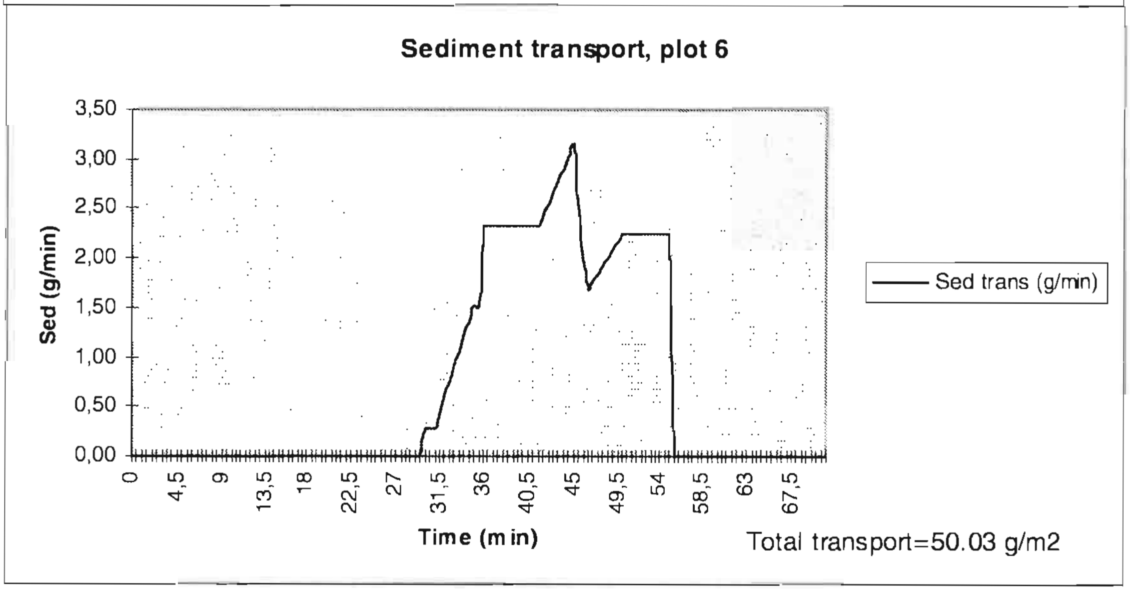



*Figures 41-43. Sediment transport at plot 2-4.*




*Figures 44-45. Sediment transport at plot 5-6.*

## 4.3 Infiltration rates measured from the rainfall simulations

Runoff intensities were plotted as functions of rainfall intensities, see *figures 46-51,* and from these graphs the infiltration rates were calculated. It is assumed that the soil is saturated when there is runoff. This is not really true because when the rainfall intensity increases the infiltration increases as well. This indicates that there is air in the soil that disappears when the pressure from the water above increases, the soil is only seemingly saturated. After a change in rainfall intensity to a higher value it will take some time until the soil is saturated again. This is the reason why some points in the diagrams are very low, these points are ignored in the calculations. A straight line is plotted in the diagrams and its equation is calculated from the formula:

Runoff Int = k * Rain Int + m

k = the slope of the curve
m = where the curve intersect the Runoff Int axis

The infiltration, $I_s$, is determined from the formula:

$I_s$ = Rain int - Runoff int(Rain int)

| Plot, nb | Infiltration, $I_s$ (mm/h) | $R^2$ |
|---|---|---|
| 1 | 0.54 * Rain Int -3.26 | 0.964 |
| 2 | 0.26 * Rain Int -4.64 | 0.991 |
| 3 | 0.79 * Rain Int -7.85 | 0.985 |
| 4 | 0.70 * Rain Int -1.85 | 0.969 |
| 5 | 0.34 * Rain Int -7.55 | 1.000 |
| 6 | 0.36 * Rain Int -6.62 | 0.934 |

*Table 6. $I_s$ at the different plots.*

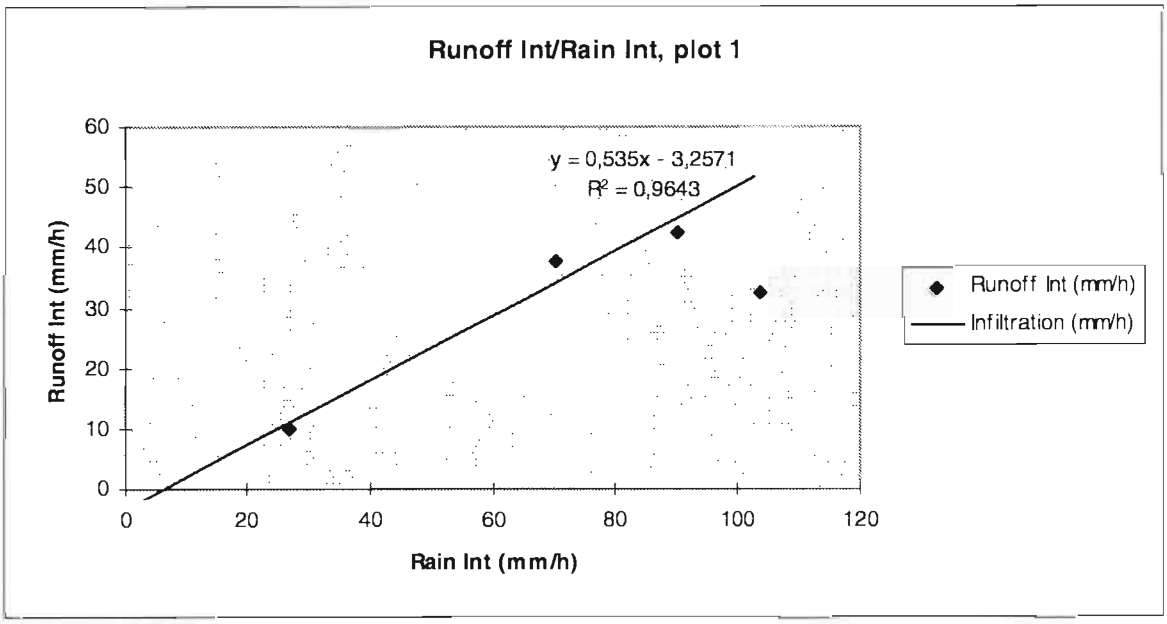
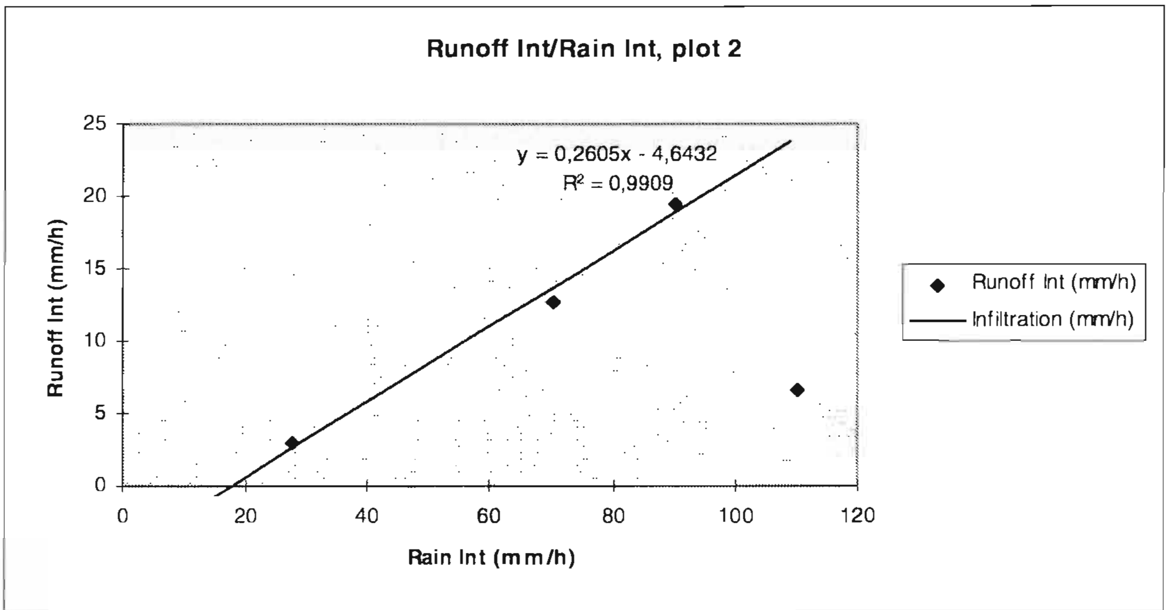
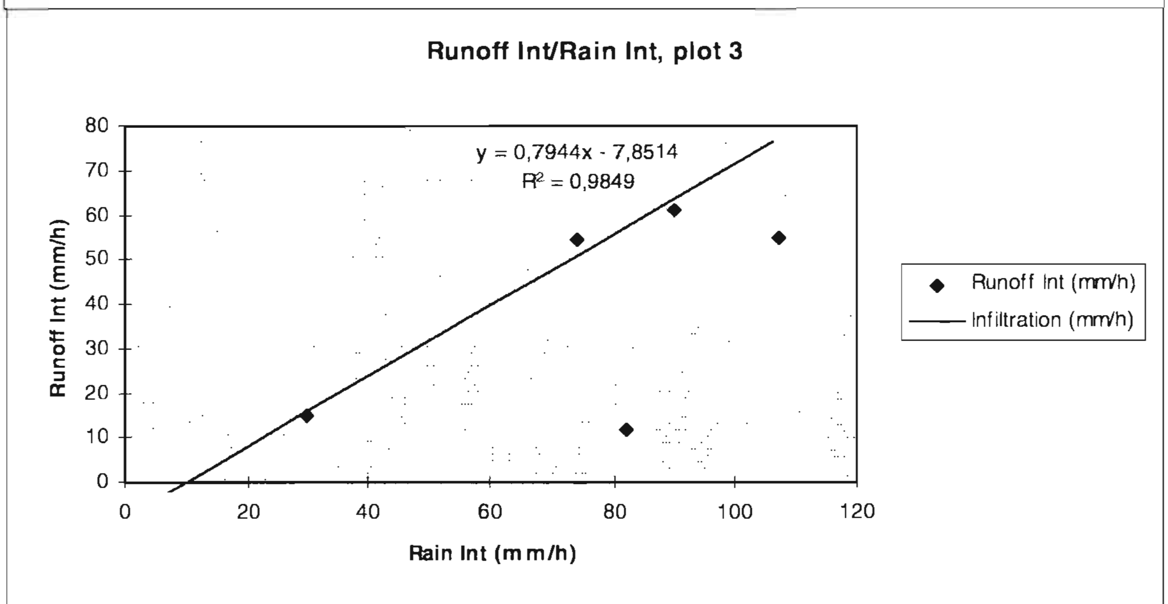
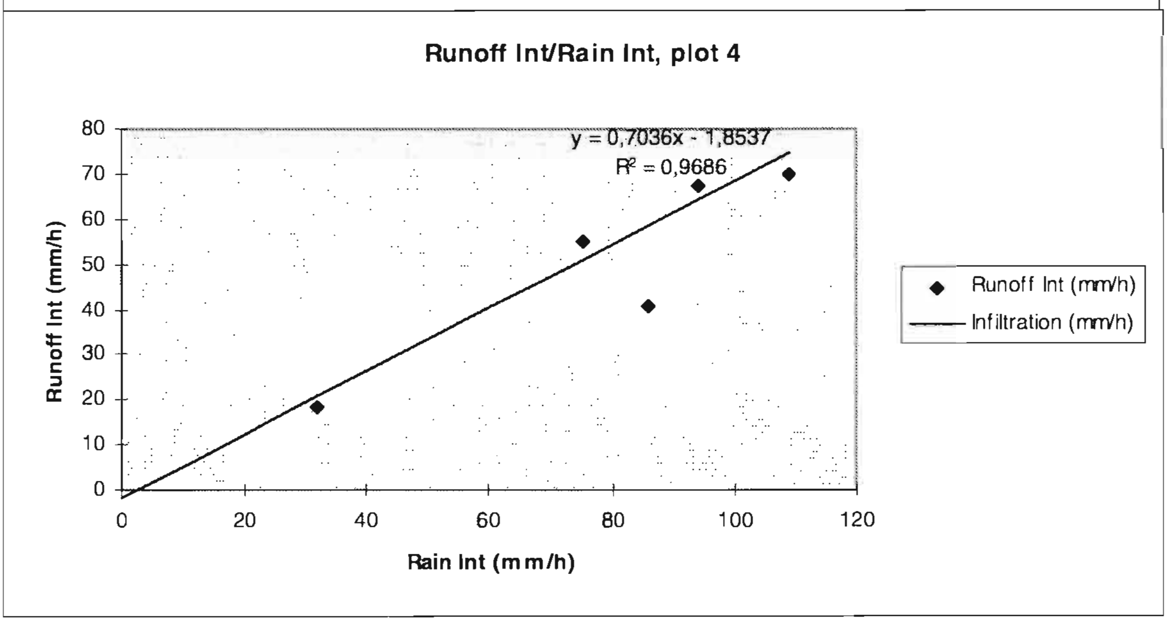


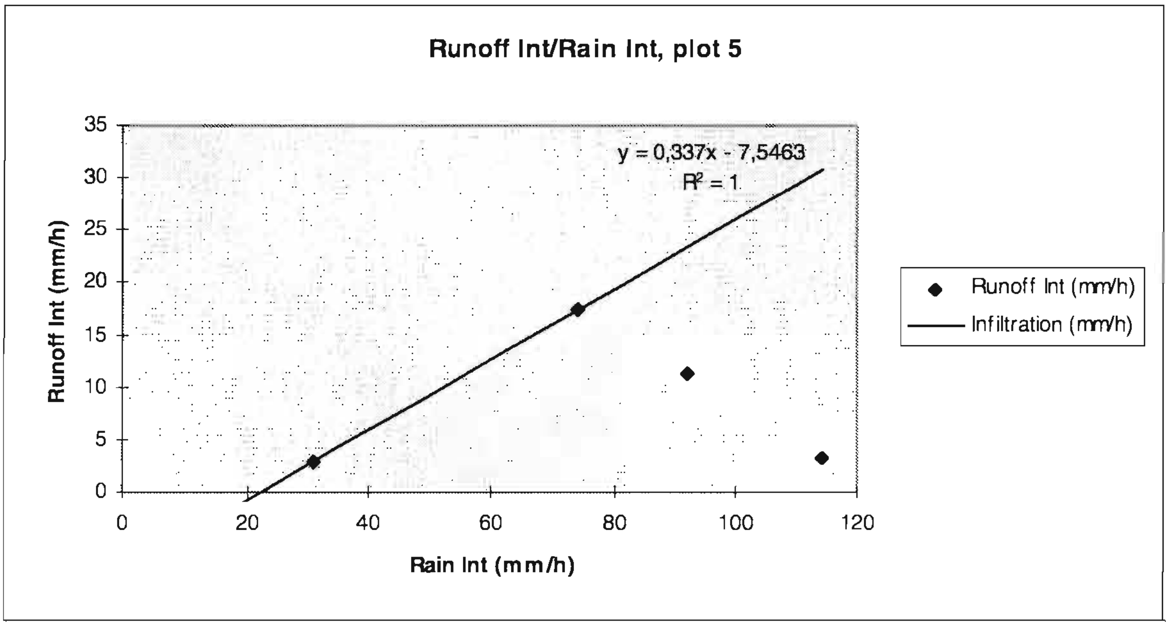

*Figure 46. The infiltration rate as a function of rainfall intensity at plot 1.*

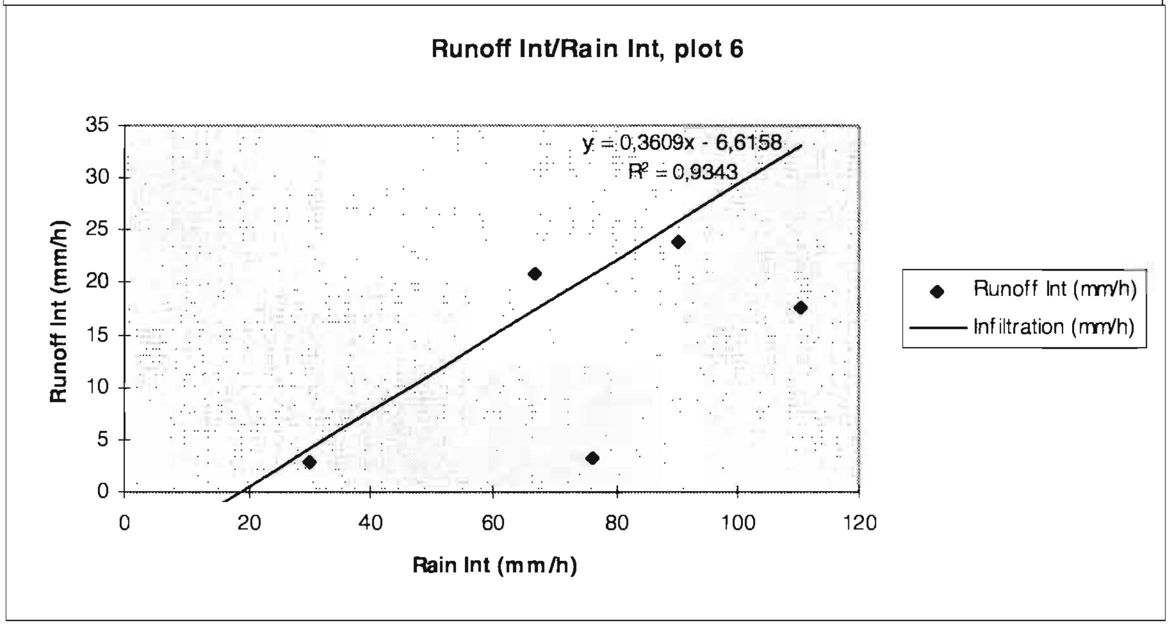



*Figures 47-49. The infiltration rates as functions of rainfall intensities at plot 2-4.*




*Figures 50-51. The infiltration rates as functions of rainfall intensities at plot 5-6.*

### 4.4 Infiltration rates determined from soil samples

The water contents calculated from soil samples taken before rainfall, immediately after rainfall and just before excavation were plotted versus the depth where the sample was taken. The infiltration rates from "before rain" and "immediately after rain" and from "before rain" and "just before excavation" were determined by calculating the areas between the graphs "initial conditions" and "after rain" and the "initial conditions" and "just before excavation". The areas were calculated by subtracting the water content value for "initial conditions" at one depth from the water content value for "after rain" or "just before excavation" at the same depth. The same operation was carried out for the depth below and the mean value of these was calculated. The mean value was multiplied with the value of the first depth subtracted from the second, the depth of which the mean value of the water content is valid for.

Mean value between for example "initial" and "after rain" =

$$= \frac{(\text{After rain}(5cm) - \text{Initial}(5cm)) + (\text{After rain}(15cm) - \text{Initial}(15cm))}{2}$$

Valid depth = depth (15cm) - depth (5cm)

Infiltration rate = $\Sigma$ ( mean value * valid depth )

This was carried out for all depths and then the areas were added together to have the total area. The same calculations were carried out to have the infiltration rate just before excavation but with the values from the samples taken just before excavation and the initial values.

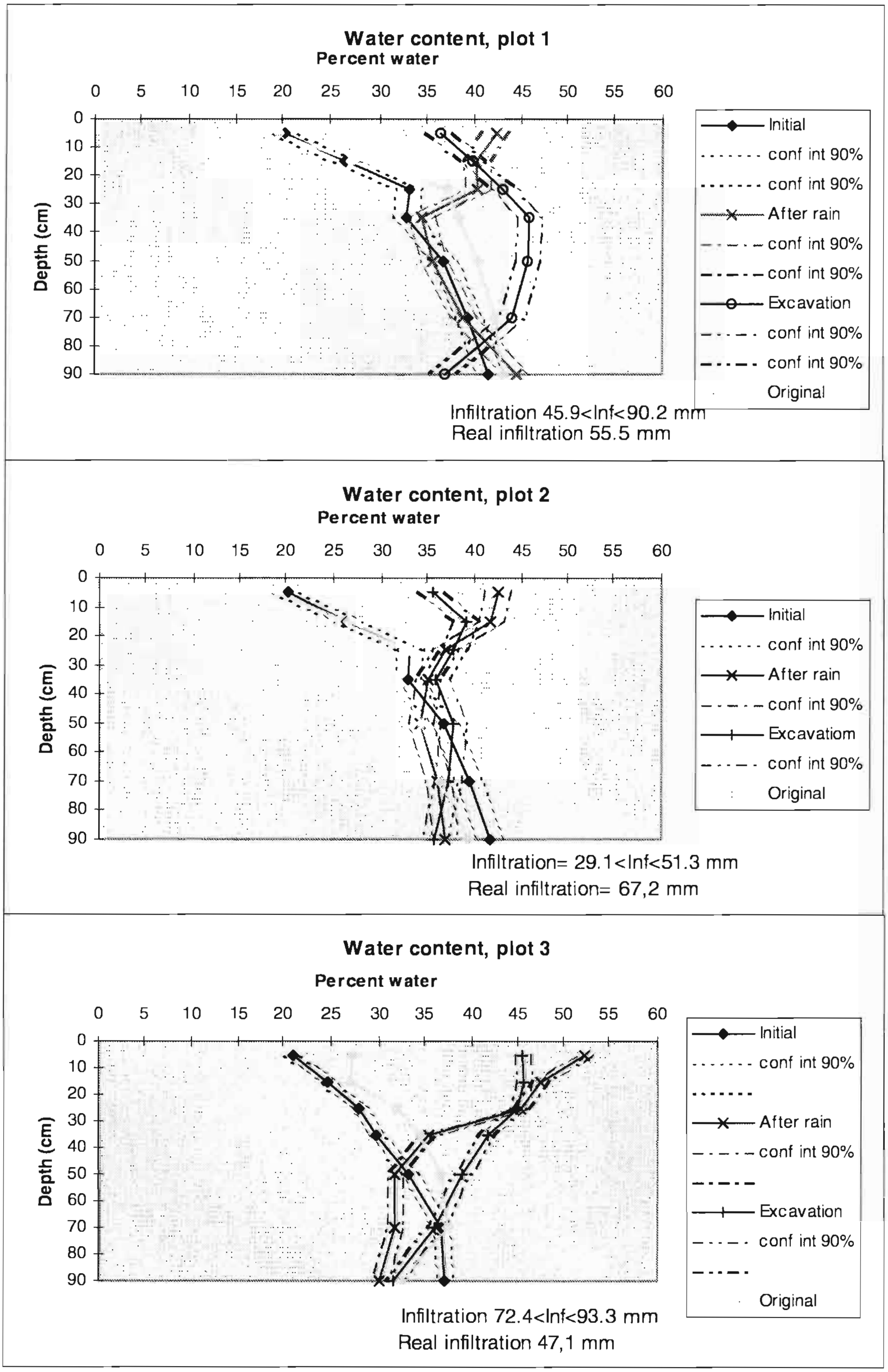
The infiltration rates calculated by this way did not correspond very well with the ones from the rainfall simulations ($Rain_{acc.}$-$Runoff_{acc.}$). The variation was large, the values were both higher and lower than the real results. Therefore more samples were taken later on to verify the results.

From the new samples the 90%-percentile was determined which led to a confidence interval in which the water contents values can vary. New infiltration rates were calculated, the biggest possible and the smallest possible referred to the confidence intervals of the water content values. For example the largest infiltration after rainfall was determined using the same formulas as before, but with the smallest "initial" values in the confidence interval and the biggest "after rain" values in the confidence interval.

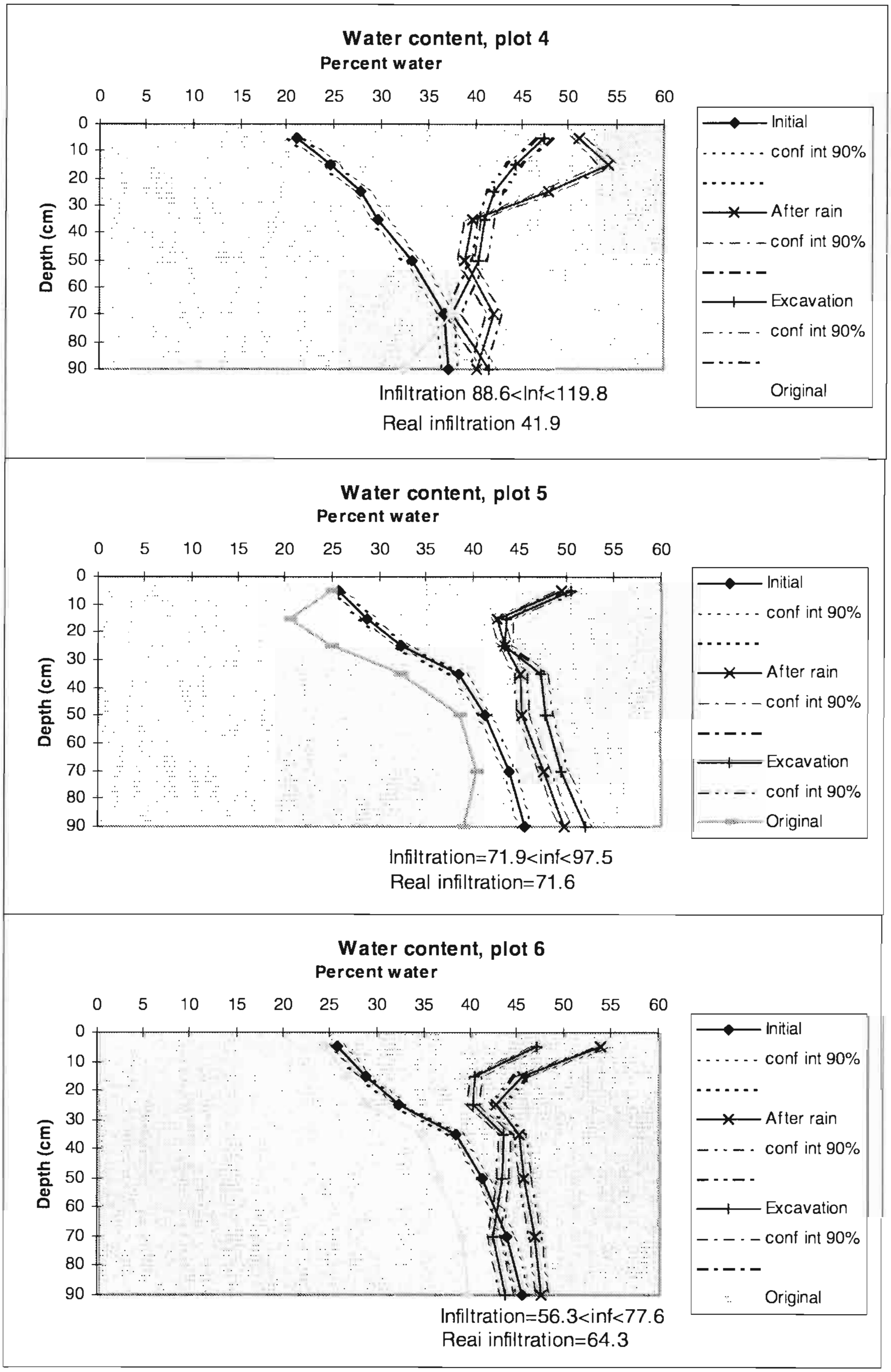
| Plot nb. | Infiltration measured from rain simulations, Vs (mm) | Infiltration calculated from soil samples, Vss (mm) | Vss/Vs |
|---|---|---|---|
| 1 | 55.5 | 45.9<Inf<90.2 | 0.83<Vss/Vs<1.63 |
| 2 | 67.2 | 29.1<Inf<51.3 | 0.43<Vss/Vs<0.76 |
| 3 | 47.1 | 72.4<Inf<93.3 | 1.54<Vss/Vs<1.98 |
| 4 | 41.9 | 88.6<Inf<119.8 | 2.11<Vss/Vs<2.86 |
| 5 | 71.7 | 71.9<Inf<97.5 | 1.00<Vss/Vs<1.36 |
| 6 | 64.3 | 56.3<Inf<77.6 | 0.88<Vss/Vs<1.21 |

*Table 7. A comparasion between different ways to calculate infiltration rates.*

At plot 1 and 2 (Entisol, Vertic Xerorthent) and at plot 5 and 6 (Inceptisols, Vertic Xerochrepts) where there were a lot of cracks, the results, Vss/Vs, correspond relatively good. But on plot 3 and 4 (Inceptisols, Typic Xerochrepts) where there were a few cracks, the results are too big .




*Figures 52-54. Water contents at plot 1-3.*




*Figures 55-57. Water contents at plot 4-6.*

To establish water content diagrams, see *figures 52-57,* several small soil samples were taken in the field. Samples were collected before rainfall simulation to have the initial conditions, just after the simulations to have wet conditions and before the excavation started to see how the humidity front has moved. Later on more samples were taken to have a better statistical significance in the results. From the latter samples the confidence interval (90%-percentile) that have been used in the calculations was determined. On each site 16 samples, symmetrically placed within 1 $m^2$, at one depth (30-40 cm) were collected, see *figure 24.* Statistical treatment for these samples lead to the used confidence interval. It is not correct to use this confidence interval on all depths because the interval is probably larger near the ground surface and smaller deeper down. However, shortage of time forced us to use this simplification. In three of the 16 holes a complete profile was taken, this means samples from seven different depths, see *figure 25.* Since there had been no rainfall after the simulations these results were considered as initial conditions. An average was determined from these three profiles and the two taken before simulation. This average is plotted as "Initial". The area between "Initial" and "After rain" or between "Initial" and "Excavation" is the infiltrated amount of water. Ideally, these two areas are the same. The limits of infiltration is determined as an average between the largest, and smallest, possible from the Initial -After rain- area and the Initial- Excavation- area. What is called "Real infiltration" is result from the rainfall simulations. The runoff was measured and, therefore, the infiltration can be determined as rainfall minus runoff. Although, only three of the six plots had an infiltration within the limits. There are different possibilities to explain this phenomena. As the photos show, see *figures 58-63,* the rate of infiltration is varying a lot within small distances. This means it is likely to hit a crack, containing much water, with one profile and a dry area, containing almost no water, within another. If one is unlucky, on one plot, the "After rain"-profile can be a crack and the "Excavation"- profile can be dry. This will lead to strange results. Of course also the "Initial"- profile can be either a crack or a dry one, but since it is an average from five different profiles, it is not so likely. Another possibility is that water has continued deeper than 1 m and has not been registered with our soil samples. This can be the case on plot 5 and 6 since the lines are not intersecting each other. The photos verify this theory too since there were a lot of blue color even deeper than one meter. Yet another possibility is that the dye has been adsorbed to the soil particles so that water may have moved further down even if there are no blue stains. This can be the explanation to poor results on plot 3 and 4. The conclusion is that this is not a very good way to determine infiltration in a clay soil, because of the big differences within small distances. If similar experiments are to be carried out again, we suggest to take more soil samples to have a better statistical value.

### 4.5 Other results from soil samples

Results from the laboratory analyses are presented in the tables below. The analyses are bulk density, true density, organic matter and particle size distribution.

| | Site 1 | | Site 2 | | Site 3 | |
|---|---|---|---|---|---|---|
| Depth (cm) | Bulk density ($kg/m^3$) | True density ($kg/m^3$) | Bulk density ($kg/m^3$) | True density ($kg/m^3$) | Bulk density ($kg/m^3$) | True density ($kg/m^3$) |
| 0-10 | 1205.9 | 2754.0 | 1325,0 | 2730.3 | 1471.2 | 2722.2 |
| 10-30 | 1393.8 | 2725.7 | 1510.2 | 2669.6 | 1424.8 | 2748.9 |
| 30-70 | 1359.4 | 2698.3 | 1523.1 | 2742.2 | 1563.6 | 2745.4 |
| >70 | 1359.4 | 2698.3 | 1523.1 | 2742.2 | 1584.6 | 2674.9 |

*Table 8. Bulk densities and true densities (pycnometer) at the different sites.*

| Site (nb) | Depth (cm) | C total (%) | N total (%) | Organic matter (%) | C/N |
|---|---|---|---|---|---|
| 1 | 0-10 | 1.51 | 0.159 | 2.6 | 9.5 |
| | 10-30 | 1.32 | 0.168 | 2.28 | 7.9 |
| | 30-70 | 0.58 | 0.069 | 1.01 | 8.5 |
| 2 | 0-10 | 2.06 | 0.236 | 3.55 | 8.7 |
| | 10-30 | 1.11 | 0.152 | 1.91 | 7.3 |
| | 30-70 | 0.68 | 0.107 | 1.17 | 6.3 |
| | >70 | 0.52 | 0.052 | 0.9 | 10.1 |
| 3 | 0-10 | 1.57 | 0.172 | 2.7 | 9.1 |
| | 10-30 | 1.23 | 0.148 | 2.12 | 8.3 |
| | 30-70 | 1.11 | 0.126 | 1.41 | 8.8 |
| | >70 | 1.22 | 0.123 | 2.17 | 10.3 |

*Table 9. Content of organic matter*

| Site nb | Depth (cm) | Clay (%) 0-2 μm | Fine silt (%) 2-20 μm | Coarse silt (%) 20-50 μm | Fine sand (%) 50-200 μm | Coarse sand (%) 200-2000 μm | Total (%) |
|---|---|---|---|---|---|---|---|
| 1 | 0-10 | 60,0 | 15,5 | 6,7 | 7,2 | 4,4 | 94,2 |
| | 10-30 | 46,5 | 34,0 | 7,3 | 6,6 | 3,8 | 98,2 |
| | 30-70 | 45,4 | 42,2 | 3,9 | 4,1 | 4,4 | 100,1 |
| 2 | 0-10 | 47,7 | 38,1 | 3,9 | 4,3 | 2,8 | 96,8 |
| | 10-30 | 49,8 | 42,2 | 3,7 | 5,2 | 2,5 | 103,4 |
| | 30-70 | 53,6 | 25,8 | 4,1 | 5,3 | 5,9 | 94,6 |
| | >70 | 53,6 | 31,9 | 3,1 | 4,9 | 2,7 | 96,2 |
| 3 | 0-10 | 59,6 | 15,5 | 5,1 | 7,0 | 7,1 | 94,3 |
| | 10-30 | 62,8 | 13,4 | 5,5 | 7,7 | 4,8 | 94,2 |
| | 30-70 | 60,9 | 24,8 | 5,0 | 7,4 | 4,8 | 102,9 |
| | >70 | 48,7 | 30,9 | 5,2 | 7,6 | 4,2 | 96,6 |

*Table 10. Particle size distribution (Robinson's pipette).*

### 4.6 Dye- and rainfall observations

**Site 1, Plot 1:**

Dye was visible to an average depth of 0.30 m, but several deeper cracks existed, the deepest to 1.5 m. The visibility was high because the soils were light.

**Site 1, Plot 2:**

Dye was visible to an average depth of 0.30 m, but several deeper cracks existed, the deepest to 1.1 m. The visibility was high because the soils were light. The big difference in runoff between plot 1 and plot 2 depends on trouble with the equipment. At plot 2 there were soil particles in the holes where the runoff water is supposed to leave the frame, this caused larger ponding.

**Site 2, Plot 3:**

Dye was visible to an average depth of 0.17 m, and no deep cracks existed. The visibility was good in the lower parts of the profile because the soils were light. In the upper part the soil was a little bit darker but did not cause any problem according to the visibility. The runoff at this site was bigger than at site 1. The reason is probably that the clay was heavier here.

**Site 2, Plot 4:**

Dye was visible to an average depth of 0.14 m, and no deep cracks existed. The visibility was high all over the profile because the soils were light.

**Site 3, Plot 5:**

Dye was visible to an average depth of 0.26 m, and several deeper cracks existed, the deepest was about 0.96 m. The visibility was quite low here because the soils were much darker than at the other sites. The infiltration was both deep and large because of many cracks filled with sand. The soil changes its volume a lot with different water contents, this means that in summer time the cracks are bigger and in winter time, when it rains more, they are smaller. The rainfall brings bigger fractions that are deposited in the cracks.

**Site 3, Plot 6:**
Dye was visible to an average depth of 0.38 m, and several deeper cracks existed, the deepest was about 1.35 m.

In the table below, *table 11,* data from the simulations are gathered.

| | Plot 1 | Plot 2 | Plot 3 | Plot 4 | Plot 5 | Plot 6 |
|---|---|---|---|---|---|---|
| Accumulated rain (mm) | 72.08 | 72.96 | 74.42 | 76.58 | 76.08 | 72.83 |
| Accumulated runoff (mm) | 16.58 | 5.78 | 27.30 | 34.67 | 4.42 | 8.50 |
| Time required for ponding (min) | 24 | 22.5 | 20 | 20.5 | 24.5 | 22 |
| Rain required for ponding (mm) | 22.25 | 20.25 | 14.45 | 16.58 | 23.56 | 20.07 |
| Time required for runoff (min) | 32 | 32 | 24.5 | 24 | 35.5 | 28.5 |
| Rain required for runoff (mm) | 29.58 | 29.58 | 19.99 | 19.15 | 37.82 | 25.13 |
| Slope of surface (°) | 1.7 | 2 | 3.8 | 4 | 2.2 | 3 |
| Max infiltr. depth (cm) | 149 | 110 | 74 | 73 | 96 | 135 |
| Min infiltr. depth (cm) | 1 | | 2 | 1 | 1 | 1 |
| Average infiltr. depth (cm) | 30 | | 17 | 14 | 26 | 38 |

*Table 11. Experimental data from all plots.*

Already at ponding stage there is a vague tendency, both in time and rain amount required, and at runoff stage it is more clear that plot 3 and 4 will have small infiltration and big runoff compared with the other plots. Maybe not only the type of soil is vital, but also the fact that the slopes are larger on plot 3 and 4.

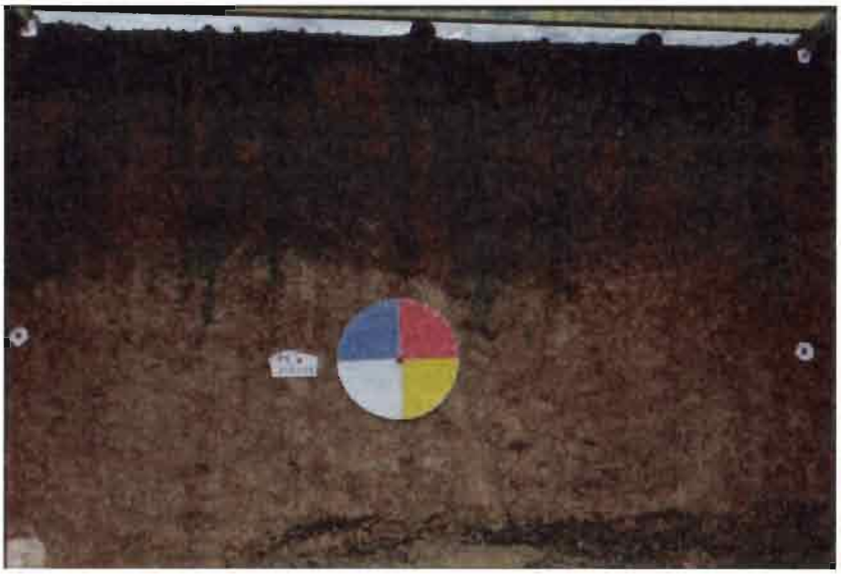


*Figure 58. Typical infiltration pattern at plot 1.*

*Figure 59. Typical infiltration pattern at plot 2.*

*Figure 60. Typical infiltration pattern at plot 3.*

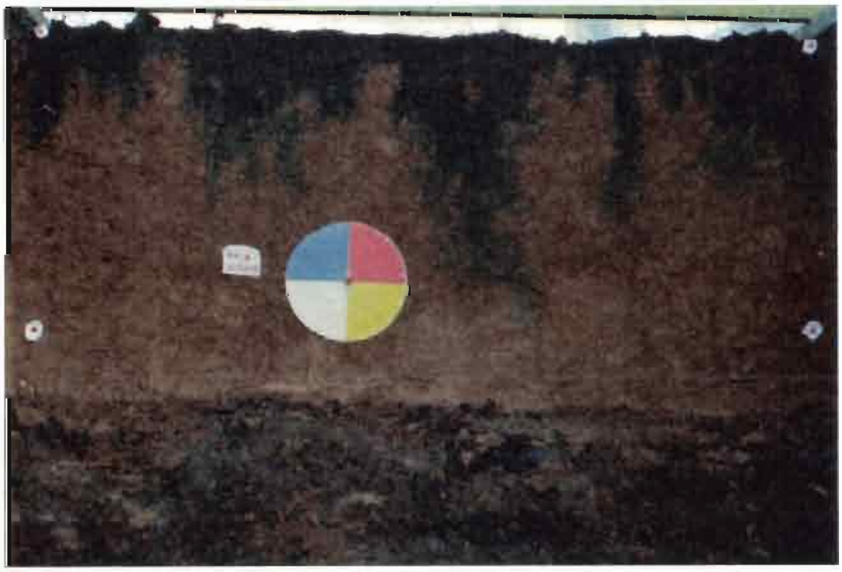


*Figure 61. Typical infiltration pattern at plot 4.*

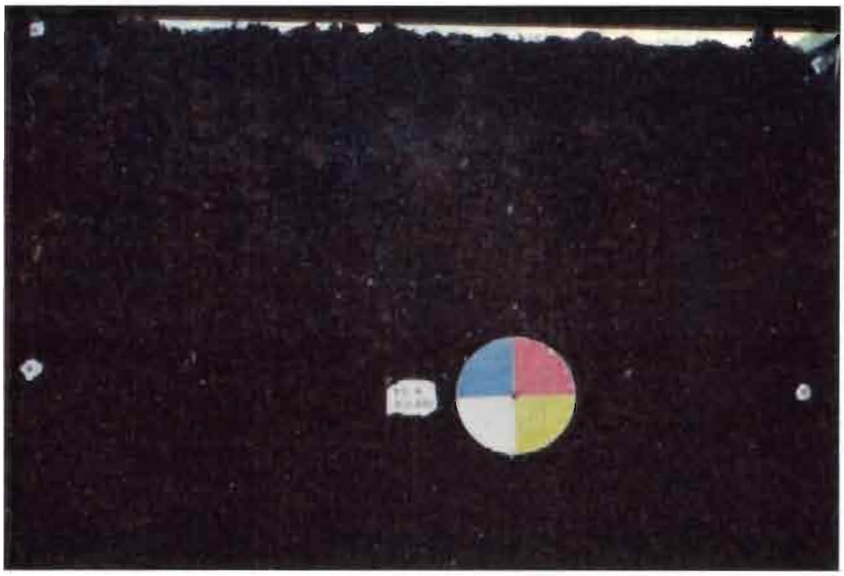


*Figure 62. Typical infiltration pattern at plot 5.*

*Figure 63. Typical infiltration pattern at plot 6.*

### 4.7 Infiltration rates measured from the graphic processing

Since we never used the method for graphic processing before described in chapter 3.2.3 it was of great interest and importance to try to figure out how well it worked. Some kind of control was necessary. We chose the following method. But, most likely, there are others working as well.

In the software used for 3-D plotting, Surfer, it is also possible to get knowledge about the plotted volume, both the total volume and the volume within certain limits. This function was used to determine how big percentage of the total volume that existed between 0-10 cm, 10-30 cm, 30-70 cm and >70 cm in the different plots, i.e. the intervals where bulk density, $\rho_b$, and true density, $\rho_c$, are known (chapter 4.6). With knowledge of $\rho_b$ and $\rho_c$ it is possible to determine the porosity, n, using $n=V_p/V$, where $V_p$=pore volume.

$$V_p = V_{tot} - V_c \Rightarrow \left[ V_{tot} = \frac{m}{\rho_b} \right] \Rightarrow \frac{m}{\rho_b} - \frac{m}{\rho_c} = m\left( \frac{1}{\rho_b} - \frac{1}{\rho_c} \right) \Rightarrow n = \frac{m}{V_{tot}}\left( \frac{1}{\rho_b} - \frac{1}{\rho_c} \right) =$$

$$= \frac{m}{m/\rho_b}\left( \frac{1}{\rho_b} - \frac{1}{\rho_c} \right) = 1 - \frac{\rho_b}{\rho_c} \Rightarrow n = 1 - \frac{\rho_b}{\rho_c}$$

Now the porosity for each plot can be calculated using:

$$n_{tot} = \frac{V_{0-10}}{V_{tot}}\left( 1 - \frac{\rho_{b,0-10}}{\rho_{c,0-10}} \right) + \frac{V_{10-30}}{V_{tot}}\left( 1 - \frac{\rho_{b,10-30}}{\rho_{c,10-30}} \right) + \frac{V_{30-70}}{V_{tot}}\left( 1 - \frac{\rho_{b,30-70}}{\rho_{c,30-70}} \right) + \frac{V_{>70}}{V_{tot}}\left( 1 - \frac{\rho_{b,>70}}{\rho_{c,>70}} \right)$$

And since infiltrated volume is equal to volume stained soil multiplied by porosity, $v_{\inf} = v_{stain} * n_{tot}$, the volume of supposed infiltrated water can be determined. The results obtained by this method compared with the results from the rainfall simulations and soil samples are listed in *table 12.*

| Plot nb | Infiltr. from rain, Is (mm) | Infiltr. from soil samples, Iss (mm) | Infiltr. from graph. Proc., Igp (mm) | Iss/Is | Igp/Is |
|---|---|---|---|---|---|
| 1 | 55.5 | 45.9<Inf<90.2 | 125.3 | 0.83<Iss/Is<1.63 | 2.26 |
| 2 | 67.2 | 29.1<Inf<51.3 | | 0.43<Iss/Is<0.76 | |
| 3 | 47.1 | 72.4<Inf<93.3 | 82.6 | 1.54<Iss/Is<1.98 | 1.75 |
| 4 | 41.9 | 88.6<Inf<119.8 | 64.5 | 2.11<Iss/Is<2.86 | 1.54 |
| 5 | 71.7 | 71.9<Inf<97.5 | 101.6 | 1.00<Iss/Is<1.36 | 1.42 |
| 6 | 64.3 | 56.3<Inf<77.6 | 136.8 | 0.88<Iss/Is<1.21 | 2.13 |

*Table 12. A comparison between different ways to calculate infiltration rate.*

The results are all over higher with the graphic processing method, than the results measured from the rainfall simulations. A comparison between the results from graphic processing and soil samples shows that: plot 1, 5 and 6 has a higher infiltration rate with graphic processing, plot 4 a lower rate and plot 3's rate is in the interval.

There are at least four sources of errors of great importance that all will lead to an overestimation of the results from the graphic processing.

1 When we digitized the stained pattern, we observed a lot of very thin but deep structures, it is difficult to digitize these structures without overestimating their importance (width).

2 We assumed the soil as saturated, this means we did not consider if the stained soil was "light blue" (probably not saturated) or "dark blue" (saturated). We only noticed if it was blue or not blue.

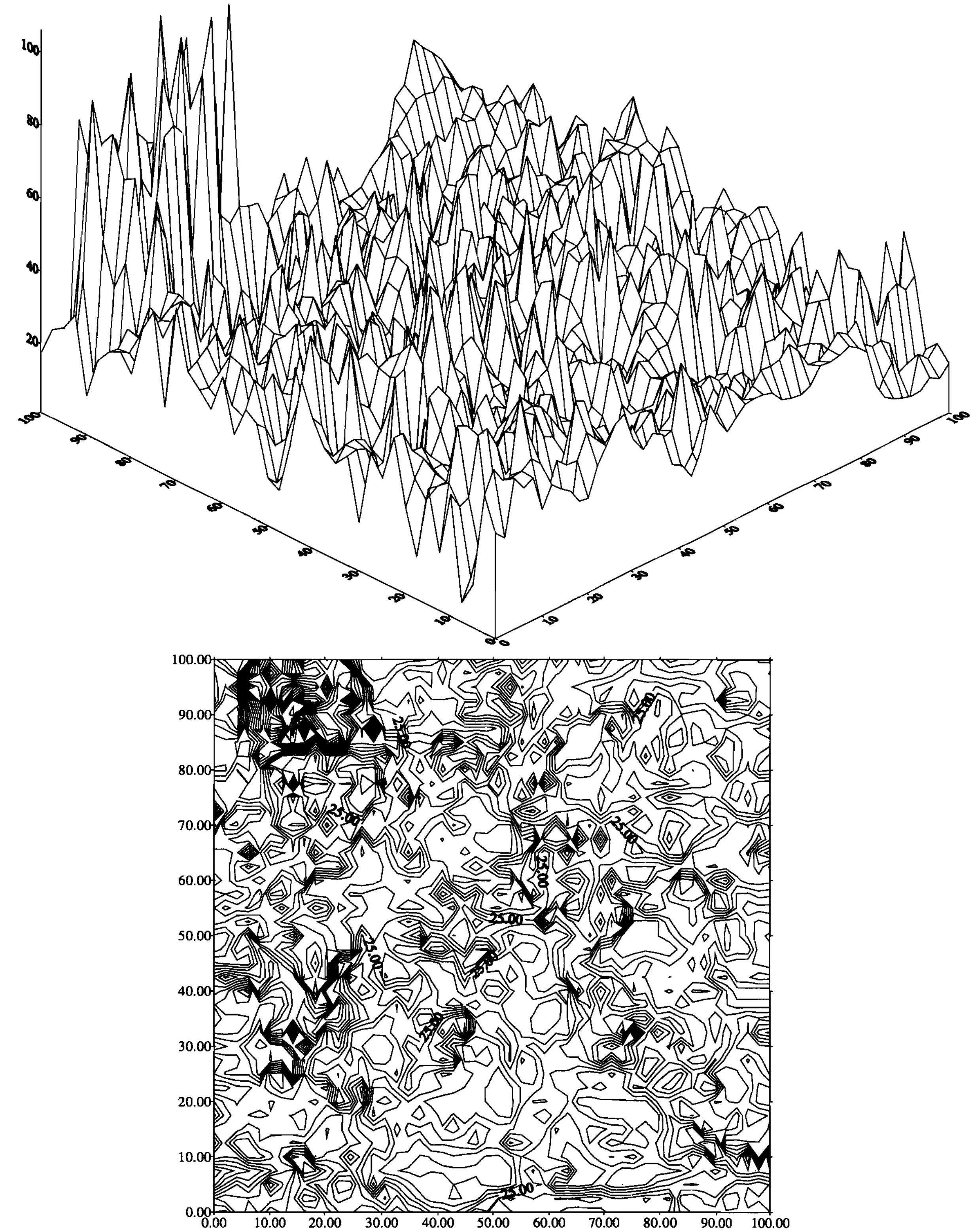
3 Within a larger area of stained soil there were always a number of small areas not stained, but very hard to exclude during the digitalization process.

4 The fact that the software plots an average if there is more than one y-value for one x-value can lead to an overestimation of the volume.

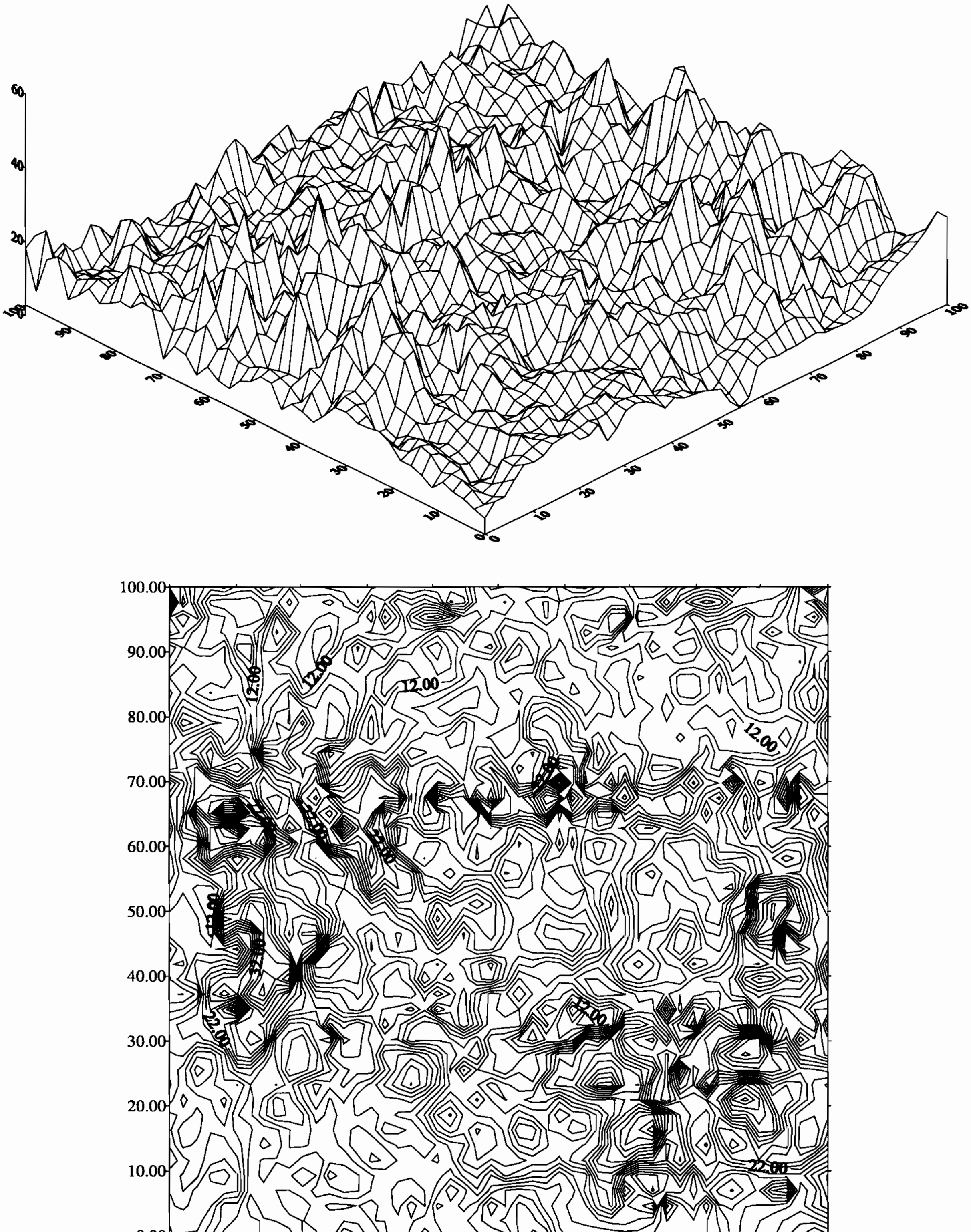
Keeping the points above in mind, the results for plot 4 and 5 seem fair. Plot 1 and 6 have quite a big error, but take a look at the *figures 64-73* and it is noticeable that there are a larger presence of high peaks and deep valleys in plot 1 and 6 compared with plot 3, 4 and 5. These facts will naturally give bigger errors. Especially in plot 6 there was a great number of structures sorting under point 1. The relatively poor result on plot 3 is more difficult to explain. The best explanation we can come up with is that it was the first plot we made, and that our technique was not fully developed at this time.

We also compared photos from different steps of the simulation with the visualization. The aim was to see if there was any connection between where we had a lot of ponding and where the infiltration was deep, but it is hard to make any general conclusions.

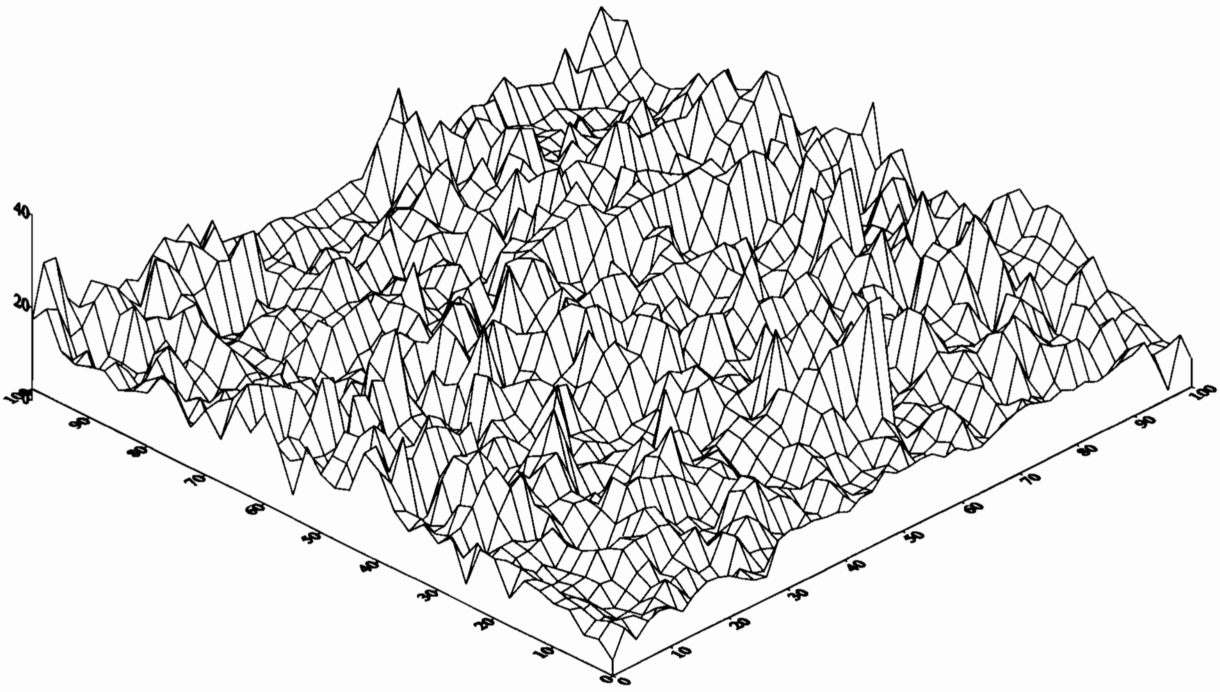
We did not have knowledge about any method to distinguish between different shades of blue, but *Aeby et.al, 1997* have used digital image analysis on a prepared sand column stained with Brilliant Blue with good results.

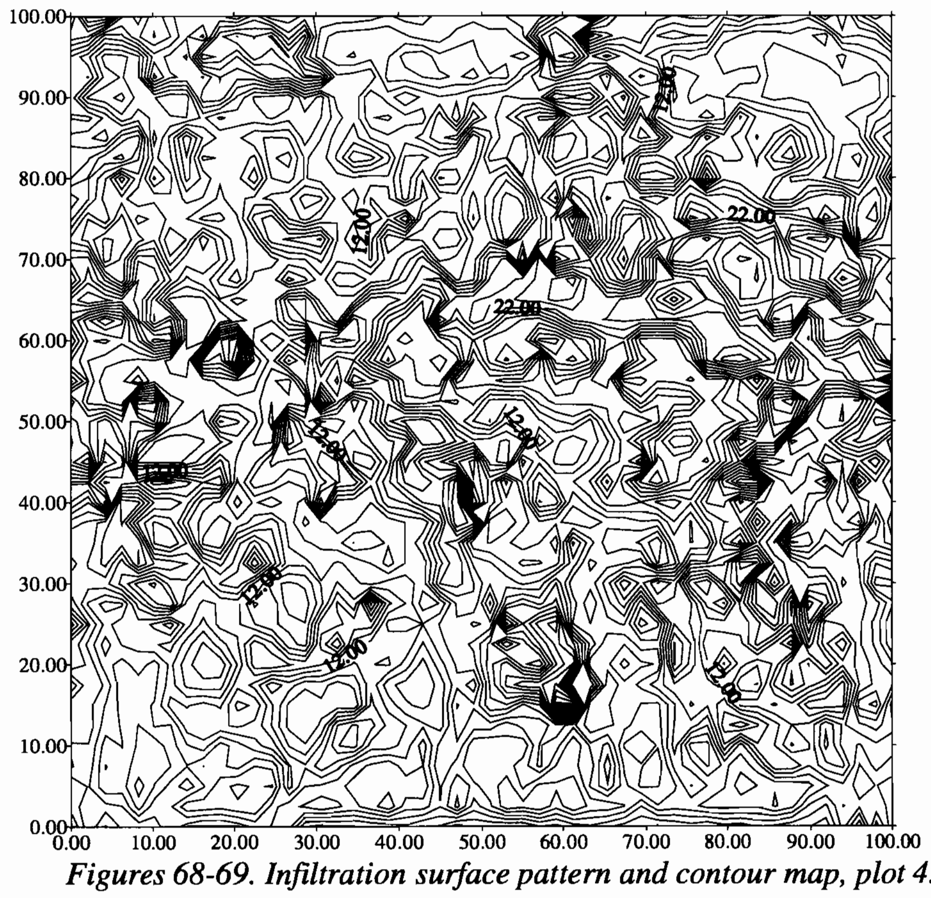



*Figures 64-65. Infiltration surface pattern and contour map, plot 1.*

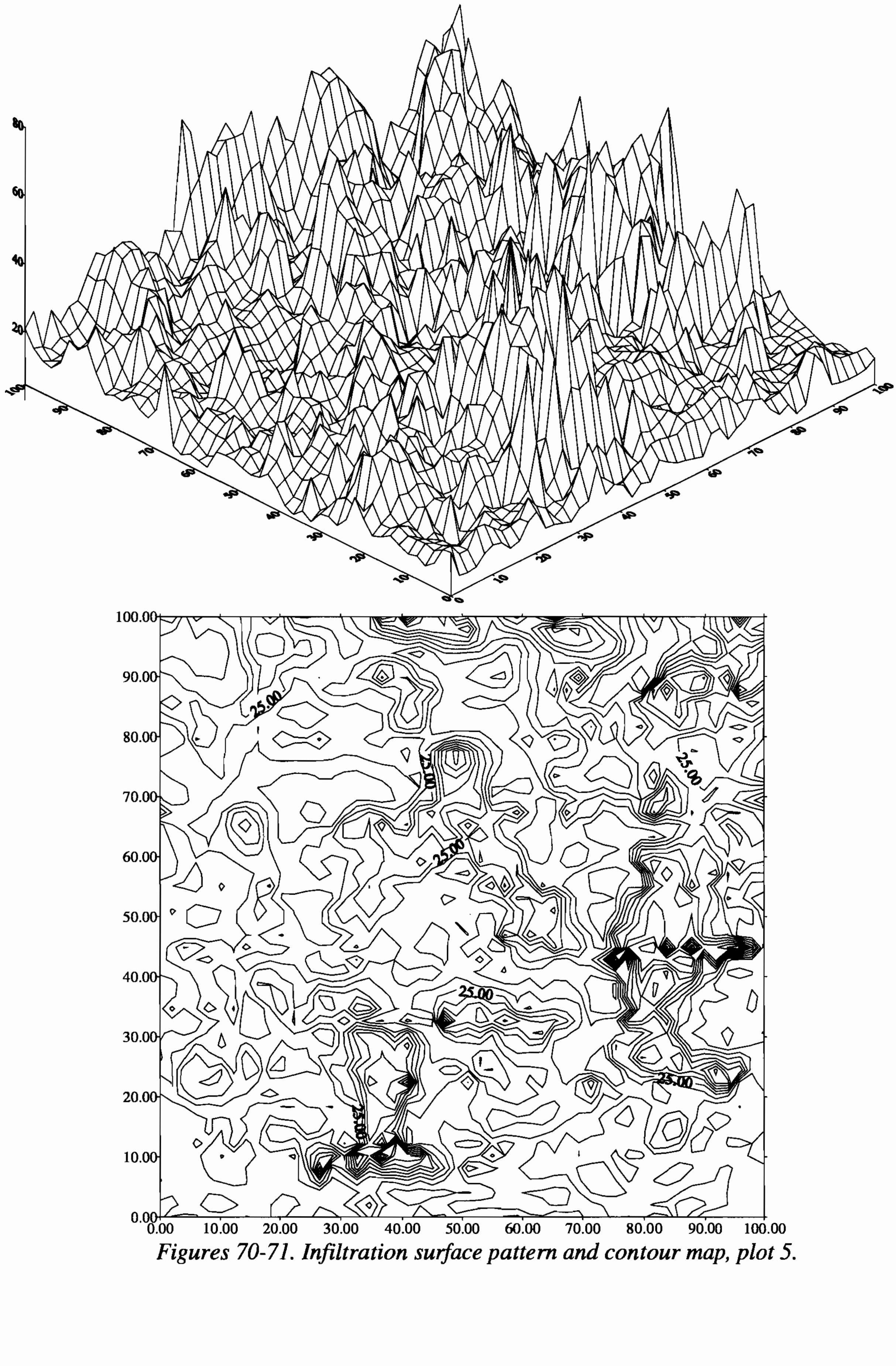



*Figures 66-67. Infiltration surface pattern and contour map, plot 3.*

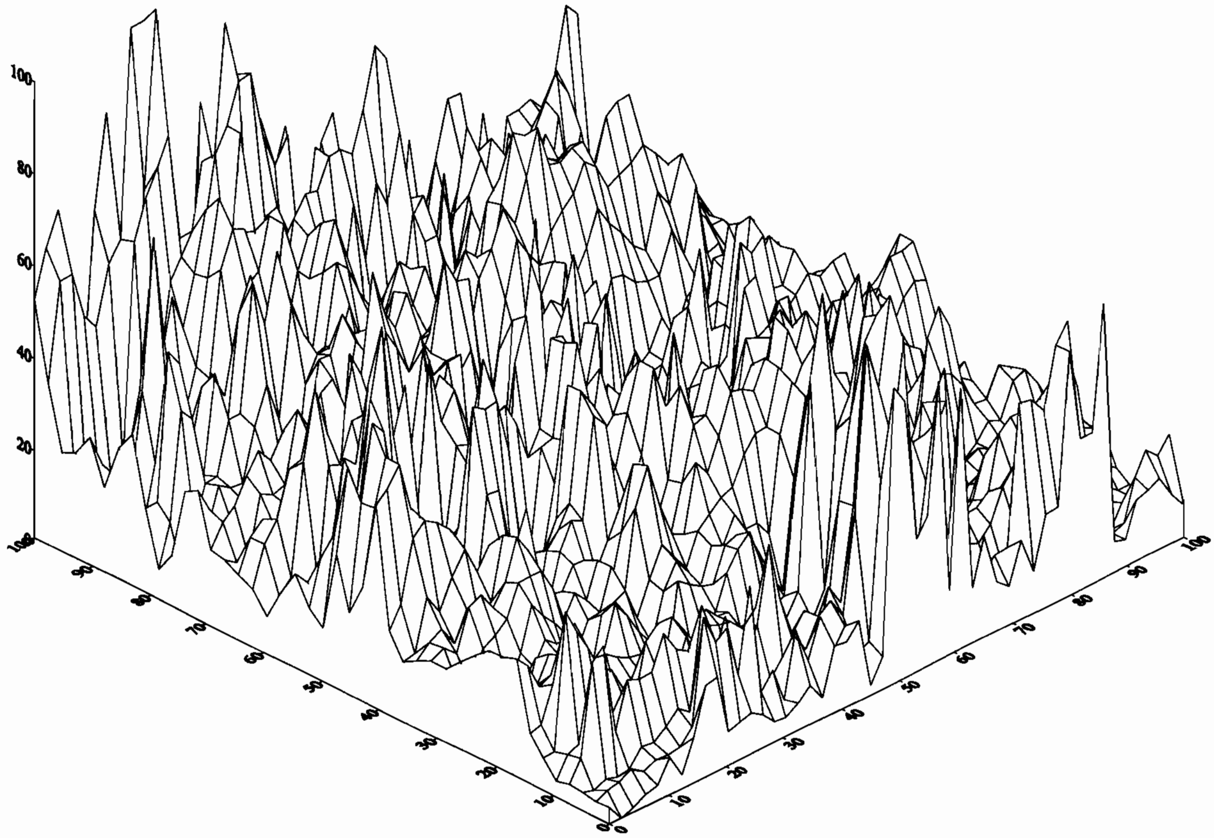


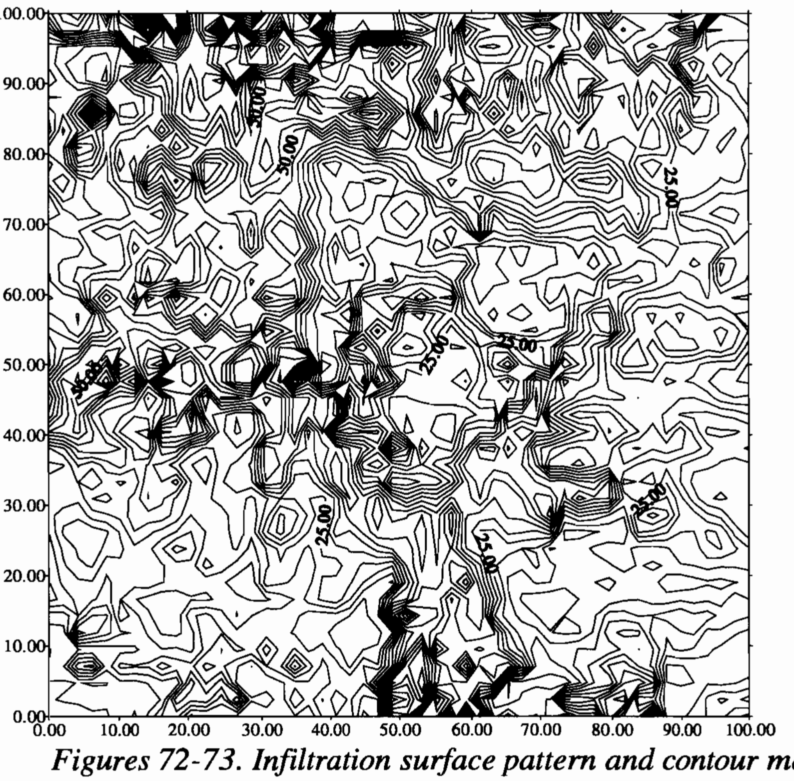



*Figures 68-69. Infiltration surface pattern and contour map, plot 4.*



Figures 70-71. *Infiltration surface pattern and contour map, plot 5.*





*Figures 72-73. Infiltration surface pattern and contour map, plot 6.*

# 5. CONCLUSIONS

After literature studies, field work, computerised work and modelling in Tunis, Bargou and Lund we are capable to give some answers about the M'Richet el Anze catchment and the different methods we used.

Preferential flowpaths do exist and are of great importance. Much of the water passes the unsaturated zone in root-channels, cracks and macro-pores. The excavation showed this clearly. It is difficult to say if pollutants can reach the groundwater since we do not have any data about the groundwater levels. We did not find any groundwater but, on the other hand, it was very dry when our experiments were carried out. Generally, the most vulnerable place must be site 1, because it is situated in a low position in the watershed not far from the brook. The excavations also showed that deep cracks existed in this soil. At site 2 the infiltration was modest and we did not find any deep cracks. At site 3 we did find several deep cracks, but the distance to the brook is quite large and the site has a high altitude in the catchment. Considering this it is not likely for short rainfall events that pollutants will contaminate the groundwater at site 2 and 3, but there is a risk at site 1. In a further more detailed investigation it could be of interest to use a tracer and see if it ever reaches the lake and, in that case, after how long time.

The water samples taken during the simulations show that there is erosion, but the very simple calculations we made indicate that the watershed is not easily eroded. The dominating soil in the watershed is Inceptisols, the soil at site 3. This soil has the lowest inclination to erode.

The Entisol, Vertic Xerorthents at site 1 contained a large number of cracks, some of them very deep. The Inceptisols, Typic or Lithic Xerochrepts at site 2 contained few cracks, which were shallow. At site 3, with Inceptisols and Vertic Xerochrepts, there were the highest number of cracks and with the maximum average depth.

We managed to visualize the infiltration in three dimensions. A comparison between infiltration measured during rainfall simulations and infiltration calculated from our models shows that our method overestimates the infiltration. We believe that a better software can decrease this error. Worth to mention is also that we did not take into account different intensities of blue soil.

The other method used to calculate infiltration, using soil samples, was also not reliable. To reach good results in a soil with a great deal of preferential flowpaths a lot of samples have to be taken, which was beyond our time limits.

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# APPENDIX

## Contents

**Pedological classification by Patrick Zante**

**Site 1**

**Location :** Oued M'Richet el Anze watershed, gouvernorat de Siliana, Délégation de Bargou, Tunisia
**Physiograpic position :** Downstream in the watershed, near the lake, on the slope of a calcareous outcrop
**Topography :** gently undulating with a slope between 3 and 8 percents.
**Classification :** Soil Taxonomy : ENTISOL, vertic Xerorthents
CPCS : SOL PEU EVOLUE d'érosion, régosolique, à facies vertique

**0 - 5/10 cm** : Ap , Dry, dark brown, clayey, some organic matter, not very clear subangular blocky structure with angular blocky substructure. Small lime soft nodules and pieces of snail shells. Fine roots. Discontinued plough pan. Gradual wavy boundary.

**5/10 - 30** cm : AC Moisty, dark brown, clayey, few organic matter, fine angular blocky structure, some small lime soft nodules and pieces of snails shells, some fine roots, closed porosity in aggregates, some small vertical cracks, gradual boundary.

**30 - 70 cm** : IIAC Moisty, light brown, clay loam, no organic matter, massive structure, low porosity with vesicular voids and random tubular pores. Gradual boundary.

**70 - 120 cm** : IIC Moisty to wet, yellowish brown, clay loam, platy thick to very thick structure with horizontal to oblique orientation, some concentration of soft powdery lime and mycelium on the surface of the small plates. At the bottom, parent rock of calcareous marl in small plates with soft powdery lime.

**Site 2**

**Location :** Oued M'Richet el Anze watershed, gouvernorat de Siliana, Délégation de Bargou, Tunisia

**Physiograpic position :** in the middle of the general slope of the watershed, near a limestone outcrop

**Topography :** gently undulating with a slope between 3 and 8 percents.

**Classification :** Soil Taxonomy : INCEPTISOLS Typic or Lithic Xerochrepts
CPCS : SOL BRUN CALCAIRE sur marno-calcaires

**0 - 10/15 cm** : Ap, Dry, light brown, clay loam, organic matter with numerous sheep dung, prismatic structure with polyedric substructure (1-2 mm), vertical cracks, plenty of fine roots, small pieces of snail shells, small random tubular pores, gradual boundary.

**10/15 - 30 cm** : A2, Moisty, light yellow-brown, clay, organic matter and some sheep dung, massive structure with fine angular blocky substructure, vesicular porosity, some pieces of shells, cobbly, gradual boundary.

**30 - 70 cm** : B3, Moisty, yellow-brown, silty clay, massive structure with medium angular blocky peds, few roots, few pores, some pieces of shells, soft powdery marl.

**> 70 cm** : C, Embedded marl, very firm coarse platy blocks weakly cemented, some white salt mycelium on the platy blocks.

This soil can have a shallow lithic contact, with a cambic horizon that is interrupted by protrusions of tuffaceous and marl bedrock.

**Site 3**

**Location :** Oued M'Richet el Anze watershed, gouvernorat de Siliana, Délégation de Bargou, Tunisia

**Physiograpic position :** Upstream in the watershed

**Topography :** in the mid part of a fan which begin on a limestone layering, when the slope become (between 3 and 8 percents).

**Classification :**Soil Taxonomy : INCEPTISOLS Vertic Xerochrepts (not far from VERTISOL Pelloxererts)
CPCS : SOL BRUN CALCAIRE vertique

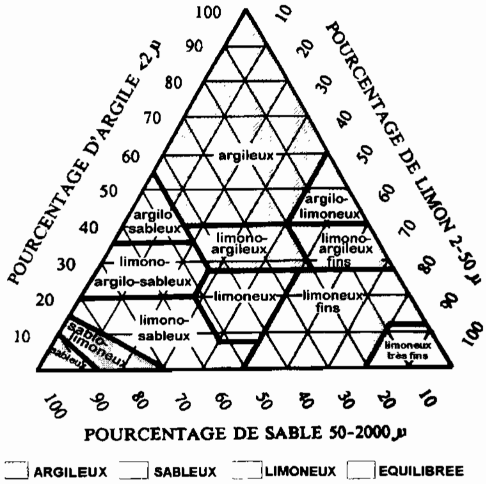
**0 - 10/15 cm** : Ap, Dry, dark brown, clay, diffuse organic matter, cracks, 2 to 5 mm width, very coarse subangular blocky structure, numerous soft nodules of lime (1-2 mm diam.), pieces of shells, plenty of fine roots, clear boundary

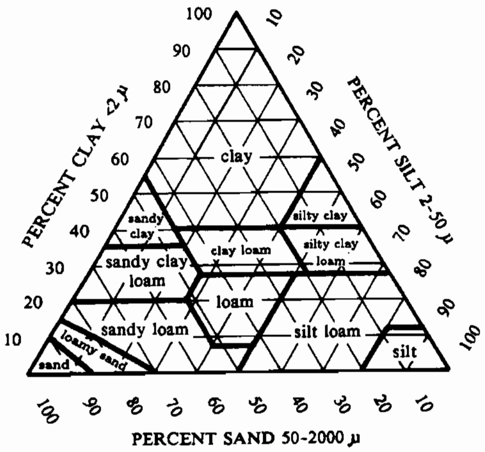
**10/15 - 30/40** cm : A2, Moisty, dark brown, clay, diffuse organic matter, fine angular blocky structure, some platy peds, fine gravel, few medium gravel, smooth and angular, some fine roots, some snail shells, diffuse boundary.

**30/40 - 70 cm** : B Moisty, dark brown, clay, angular blocky structure with little slickensides, some wedge-shaped structural aggregates, some fine roots.

**> 70** : Same characteristics but more developed wedge-shaped aggregates, few roots.

## TEXTURAL CLASSES




(From Clés de la Taxonomie des sols US AID,
Monographie Technique n° 13, 1986)

*Figure 1. The textural classes in french and english.*

| Depth (cm) | Plot 1 porosity, n | Plot 3 porosity, n | Plot 4 porosity, n | Plot 5 porosity, n | Plot 6 porosity, n |
|---|---|---|---|---|---|
| 0-10 | 0.562 | 0.515 | 0.515 | 0.460 | 0.460 |
| 10-30 | 0.489 | 0.434 | 0.434 | 0.482 | 0.482 |
| 30-70 | 0.496 | 0.445 | 0.445 | 0.430 | 0.430 |
| >70 | 0.496 | | | 0.408 | 0.408 |
| Average n | 0.519 | 0.481 | 0.492 | 0.468 | 0.464 |

*Table 1. Porosities at the different plots and depths.*

$n = 1 - \frac{\rho_b}{\rho_k}$ and $V_{inf} = V_{blue} * n$

| Depth (cm) | Maximum clay+loam (%) | Average of aggregates (%) | Coarse sand*0.9 (%) | Index of structural stability of the soil | Observation |
|---|---|---|---|---|---|
| S1, 0-10 | 12.36 | 35.31 | 4.73 | 0.40 | stable |
| S1, 10-30 | 12.36 | 39.74 | 7.52 | 0.38 | stable |
| S1, 30-70 | 31.94 | 43.14 | 4.78 | 0.83 | stable |
| S2, 0-10 | 9.27 | 48.72 | 14.60 | 0.27 | stable |
| S2, 10-30 | 12.36 | 58.13 | 3.10 | 0.22 | stable |
| S2, 30-70 | 45.33 | 36.89 | 6.86 | 1.51 | medium-stable |
| S2, >70 | 20.60 | 42.67 | 8.34 | 0.60 | stable |
| S3, 0-10 | 46.36 | 24.27 | 7.37 | 0.99 | stable |
| S3, 10-30 | 45.33 | 63.46 | 10.10 | 0.85 | stable |
| S3, 30-70 | 61.81 | 59.13 | 13.33 | 1.35 | medium-stable |
| S3, >70 | 24.72 | 52.39 | 14.18 | 0.65 | stable |

*Table 2. Index, Is, of structural stability of the soil (Henin´s method).*

$$I_s = \frac{(Clay + Loam)\ \max.(\%)}{Av.of.agg.(\%) - 0.9 * C.S(\%)}$$

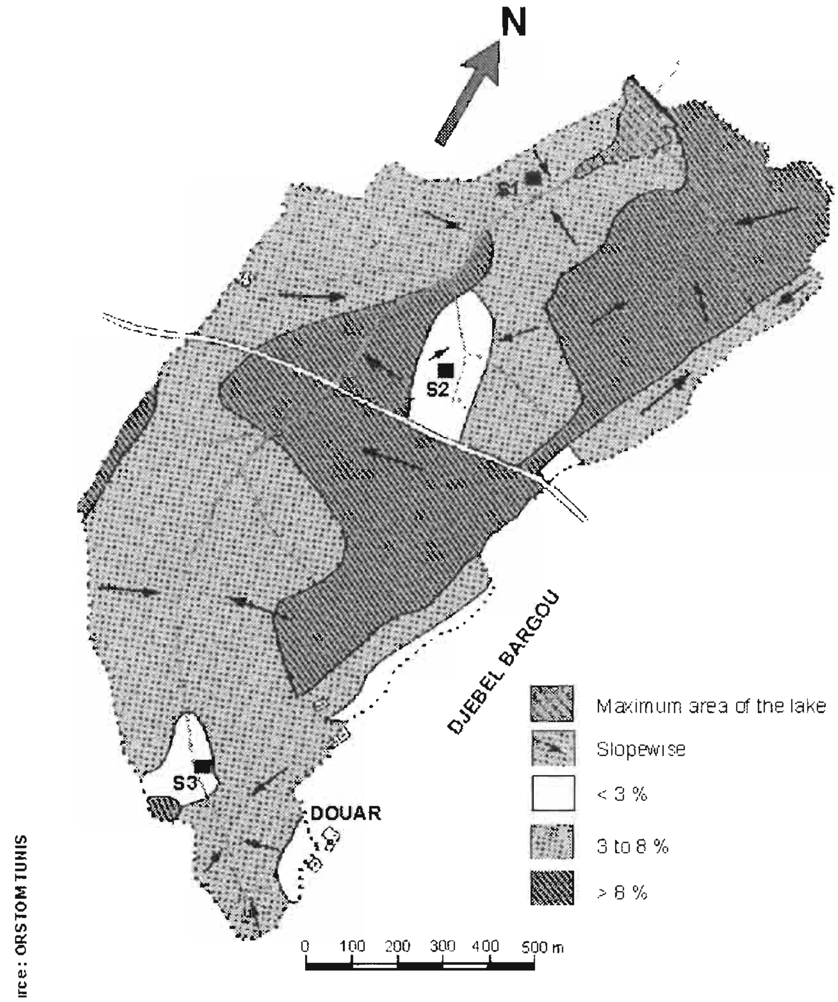



*Figure 2. Map of the slopes in the catchment (Snoussi, 1993).*

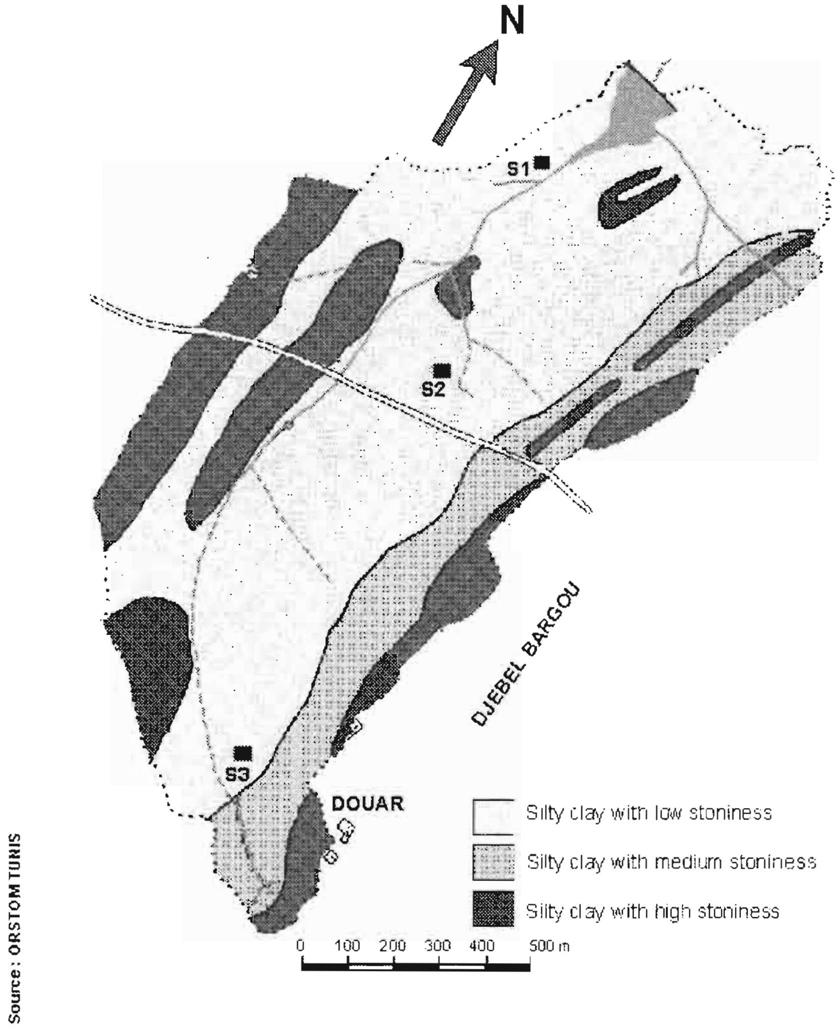
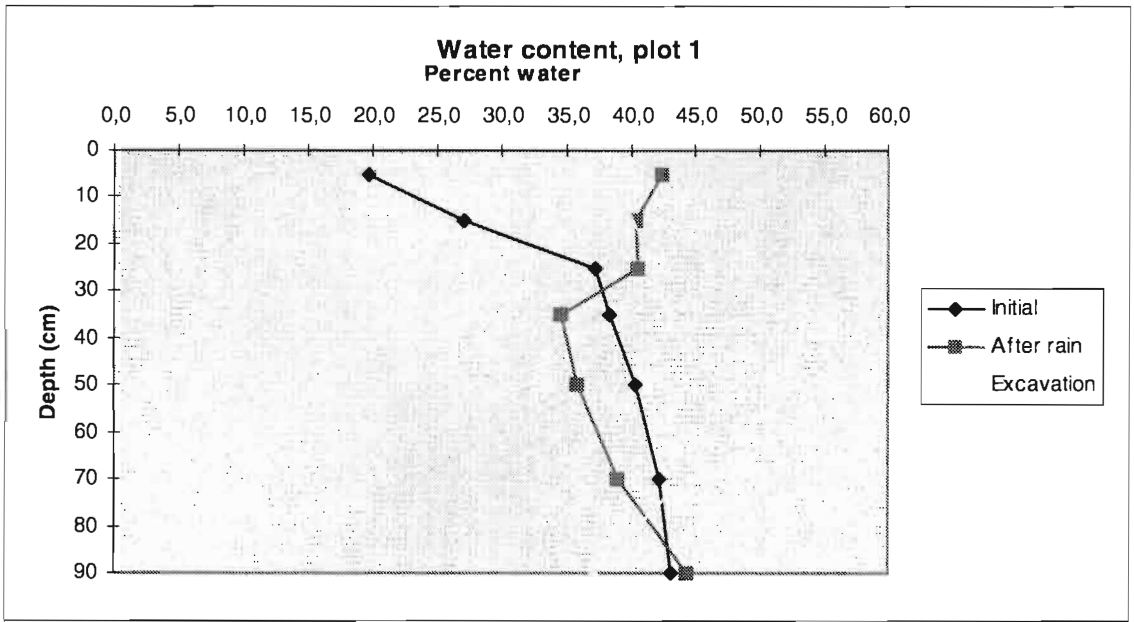
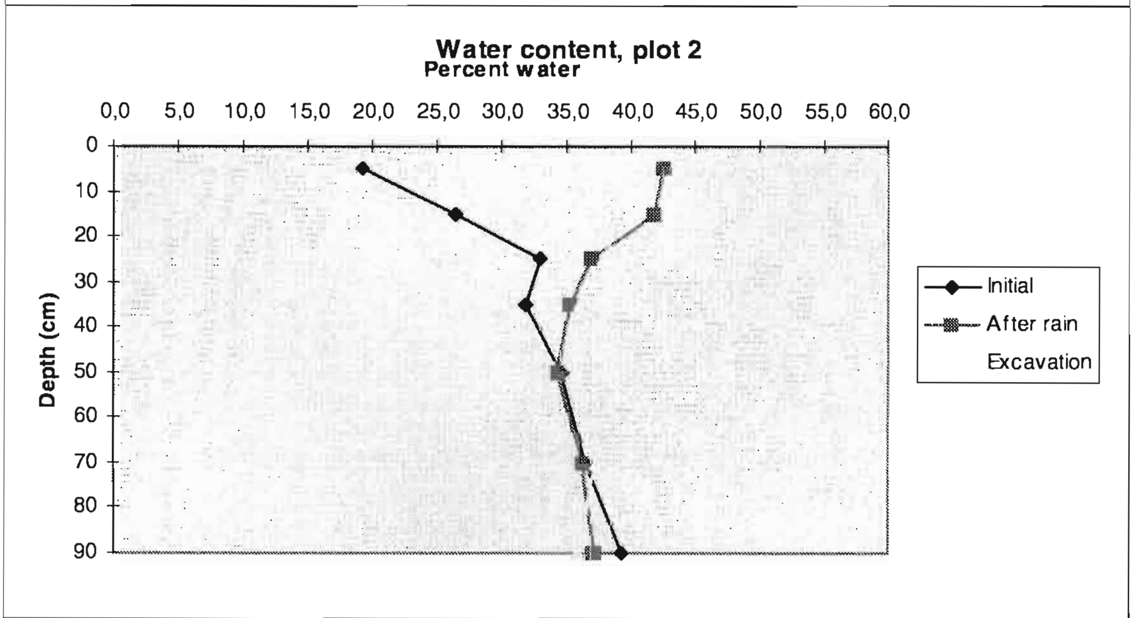
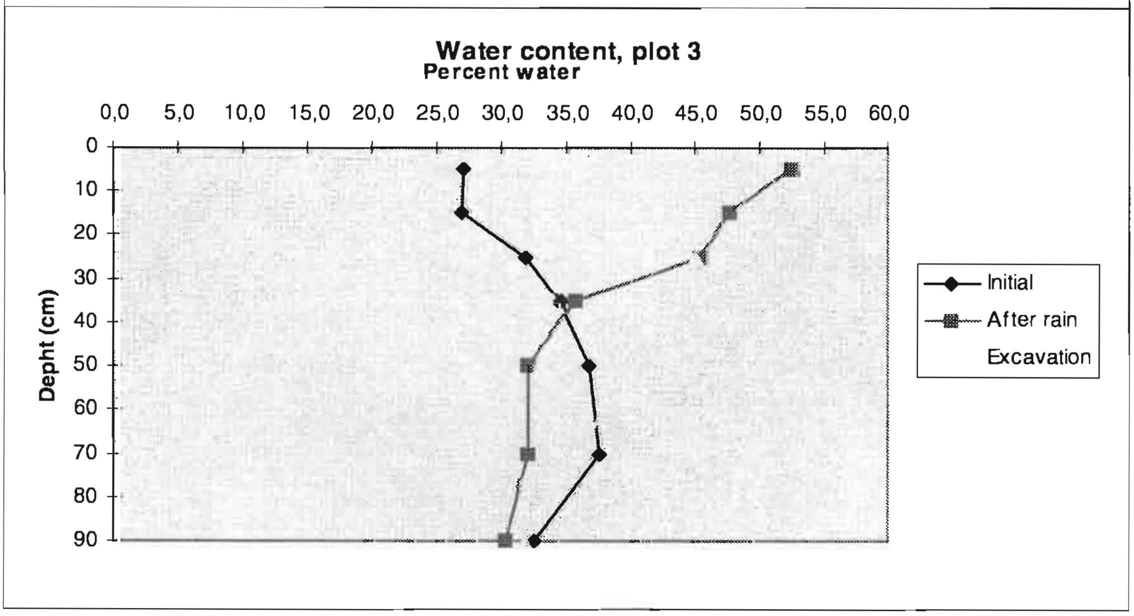


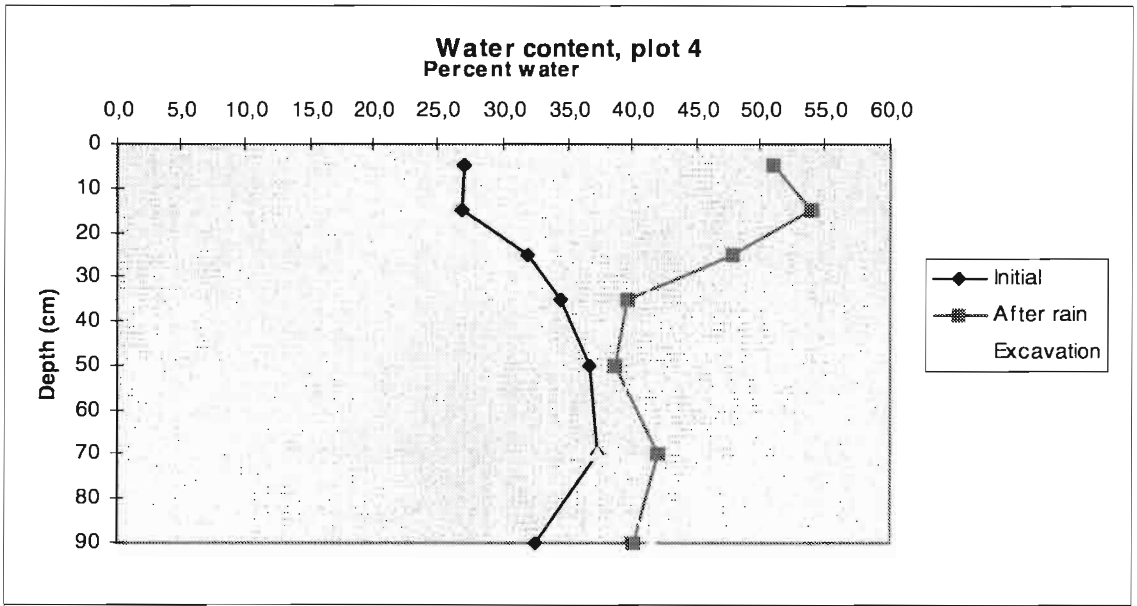

*Figure 3. Map of the stonieness in the watershed (Snoussi, 1993).*

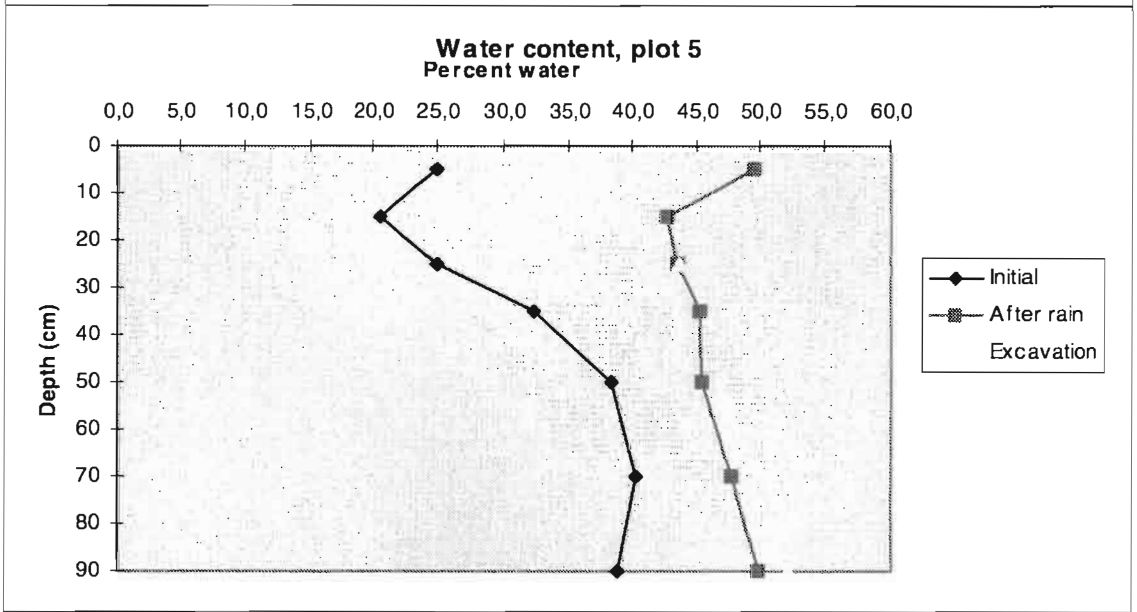


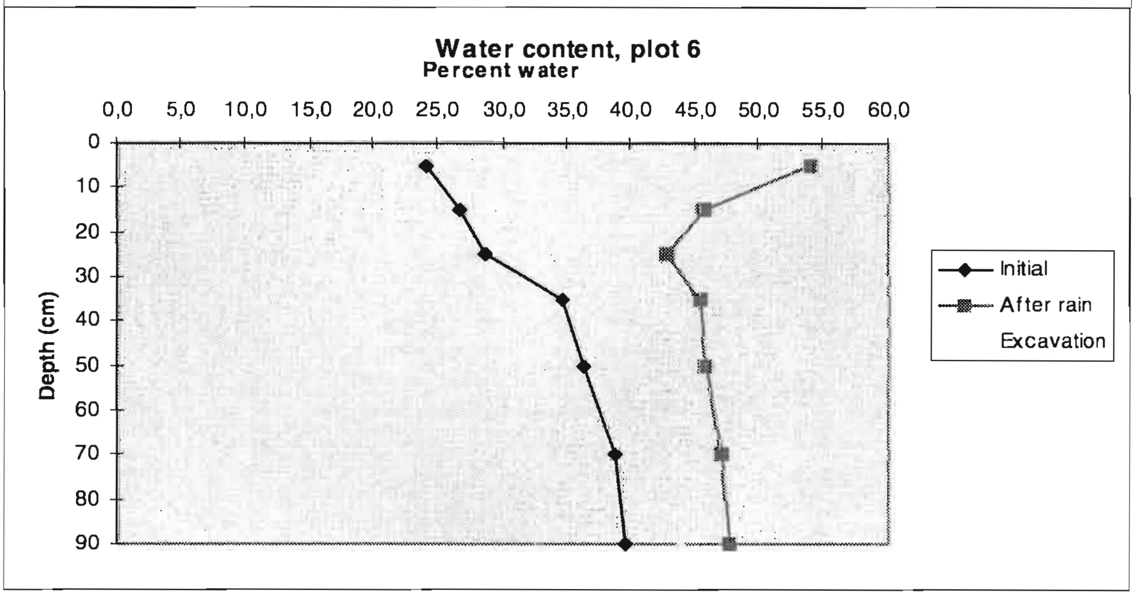



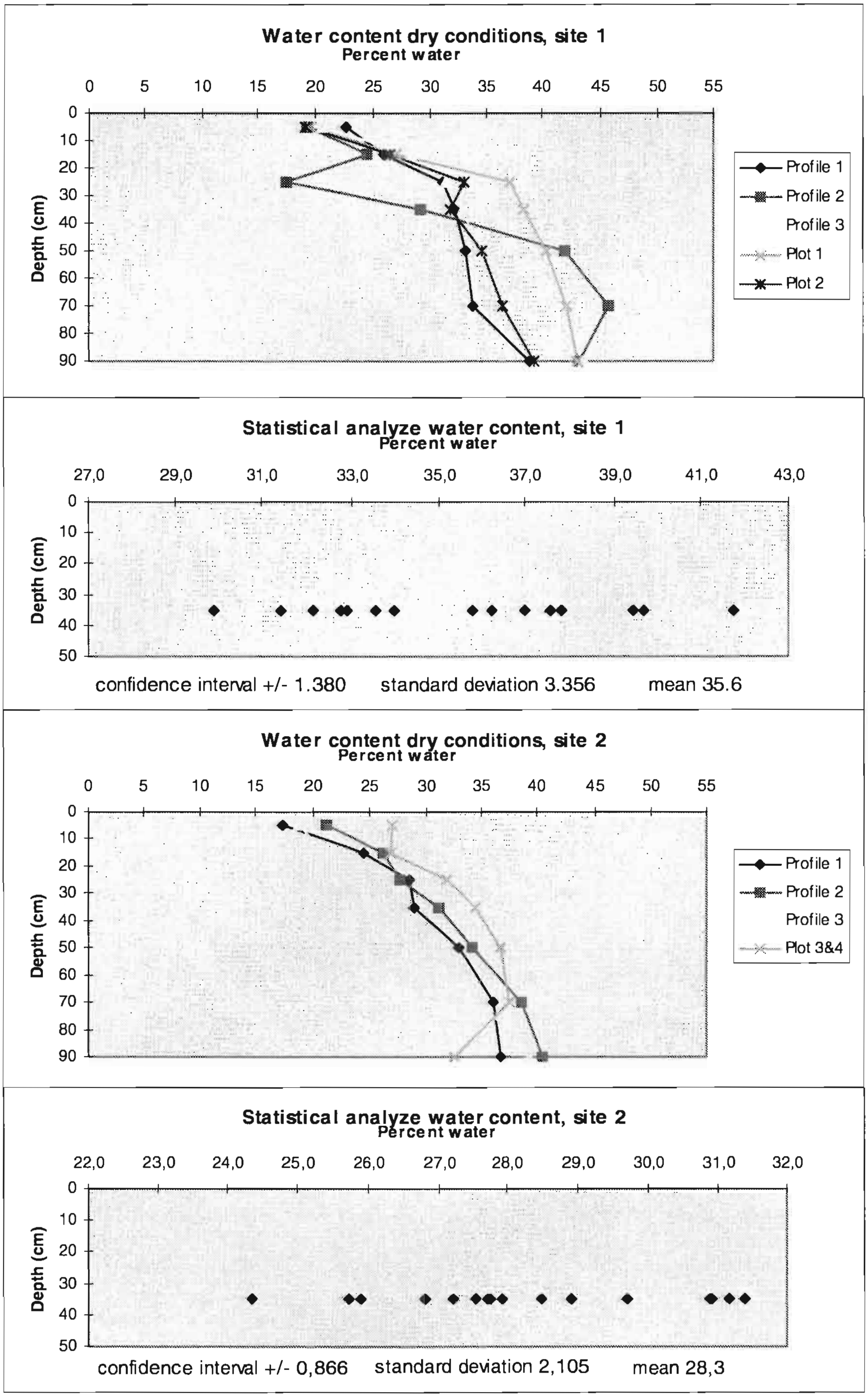

*Figures 4-6. Water contents, plot 1-3.*



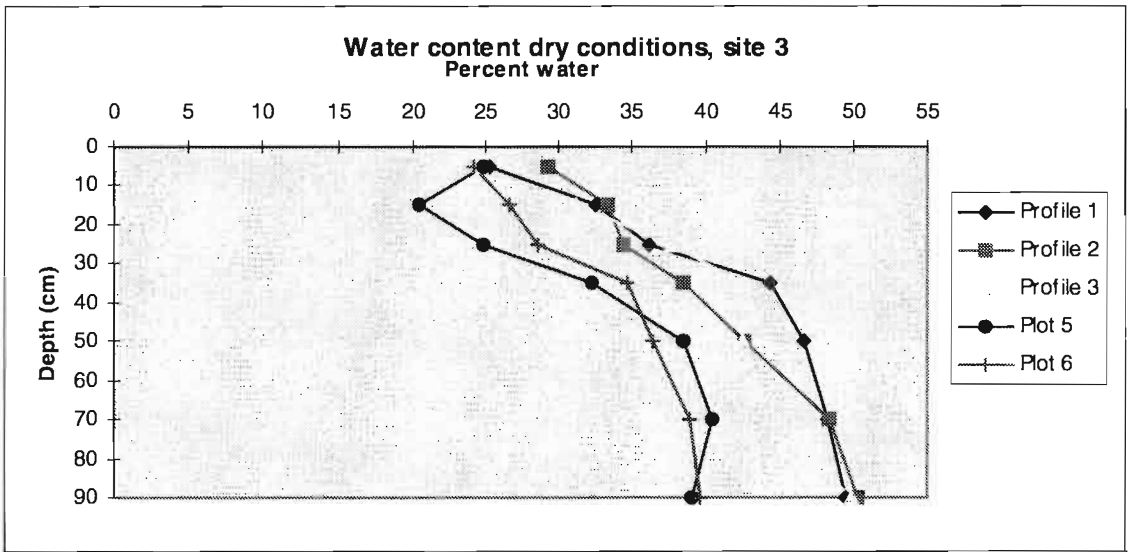



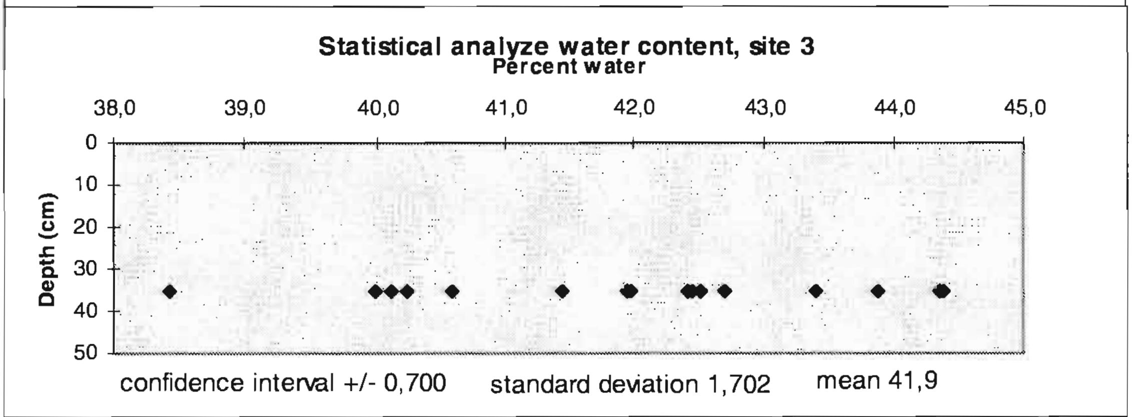




*Figures 7-9. Water contents, plot 4-6.*




*Figures 10-13. Statistical analyzes, site 1-2.*




*Figures 14-15. Statistical analyzes, site 3.*

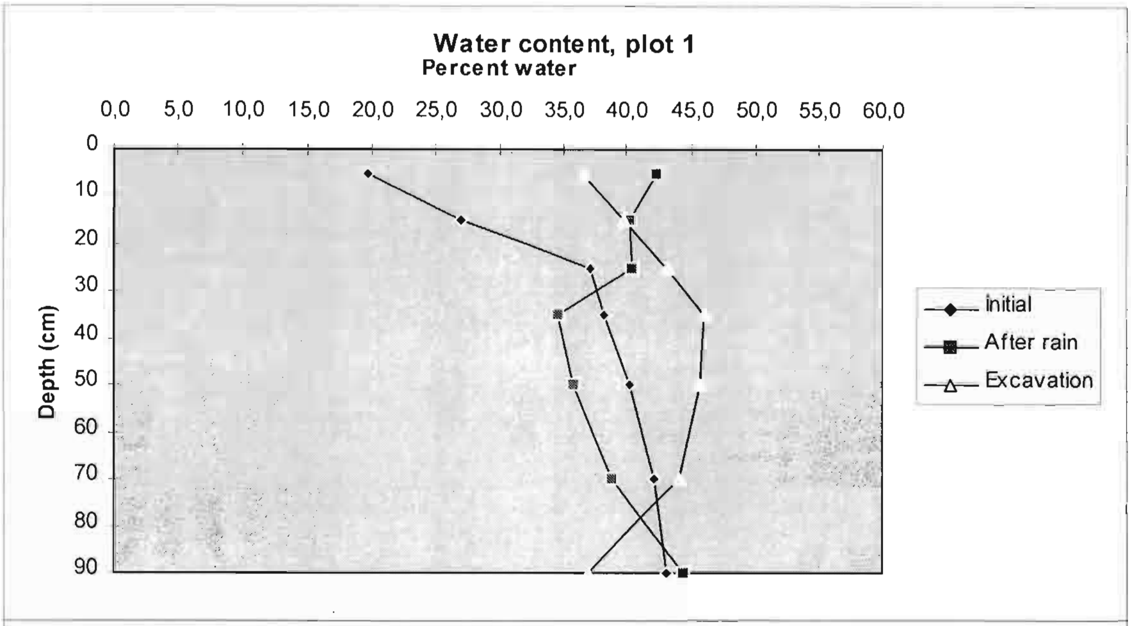
## PASCAL PROGRAM FOR TRANSFORMING THE PHOTOS

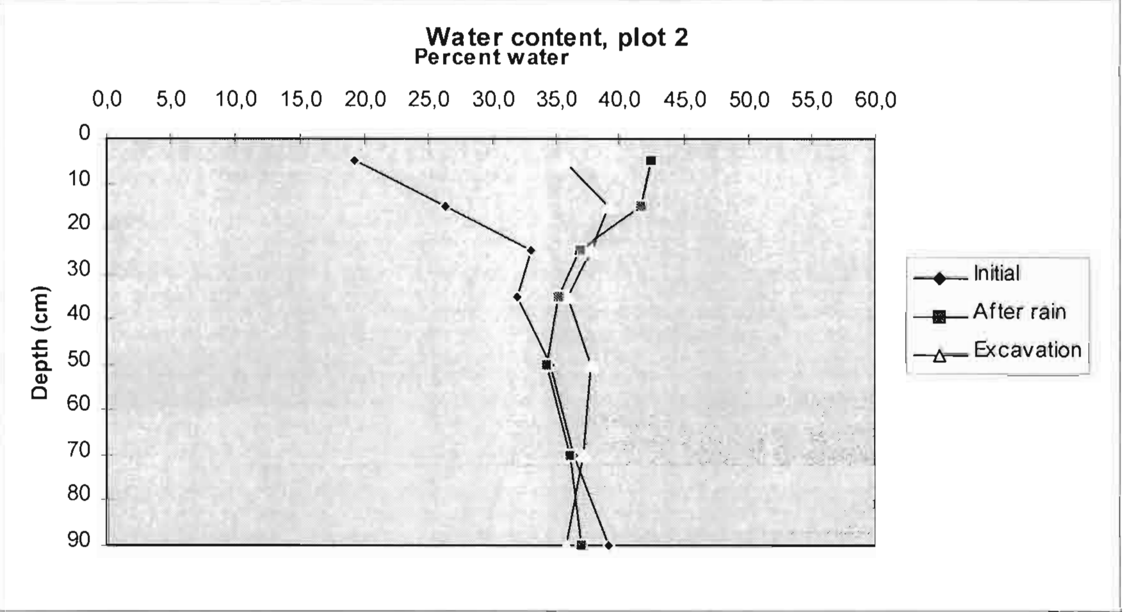
```
program Koordinatandringsprogram (Infil,Utfil,input,output);

const infile=(* 'A:\';*)    'C:\ola&olof\';
      outfile=(* 'A:\';*)  'C:\ola&olof\';

var  vektor: array[1..1000] of real;
     p,a,Svar,t: integer;
     v,beta,z,korr1,skalfaktor: real;
     Infil,Utfil1,Utfil2: text;
     bild,plot: string;

begin
  writeln('Vilken plot?');
  readln(plot);
  assign(Utfil2, outfile + 'plot' + plot + 'dat');
  rewrite(Utfil2);

  writeln('Hur m†nga indata filer?');
  readln(Svar);

  for t:=1 to Svar do
  begin
    writeln('Vad heter infilen?');
    readln(bild);
    bild:=('k' + plot + 'z' + bild + '.vec');
    writeln ('Ange z-koordinat!');
    readln (z);

    assign(Infil, infile + bild);
    reset(infil);
    assign(Utfil1, outfile + 'l' + bild);
    rewrite(Utfil1);

    p:=0;
    while not eof (infil) do
    begin
      p:=p+2;
      readln(Infil);
      readln(Infil,vektor[p-1],vektor[p]);
    end;

    korr1:=100/(sqrt(sqr(vektor[3]-vektor[1])+sqr(vektor[4]-vektor[2])));
    skalfaktor:=korr1;


  for a:=1 to p do
```

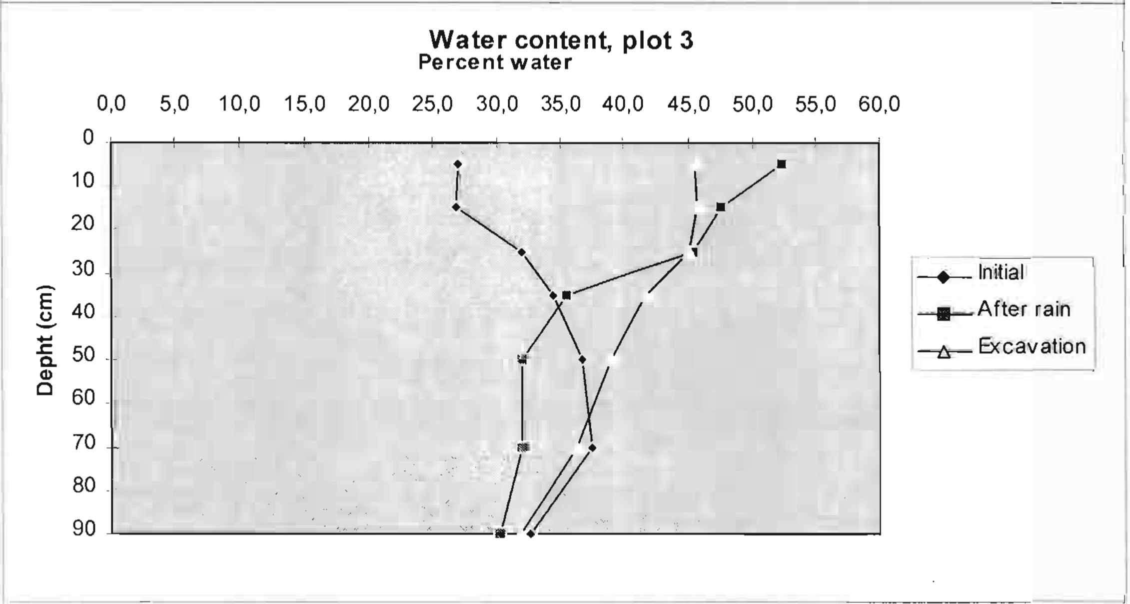
```
 vektor[a]:=vektor[a]*skalfaktor;
a:=3;

while a<=p do
begin
 vektor[a]:=vektor[a]-vektor[1];
 a:=a+2;
end;

a:=4;
while a<=p do
begin
 vektor[a]:=vektor[a]-vektor[2];
 a:=a+2;
end;

vektor[1]:=0;
vektor[2]:=0;

beta:=arctan((vektor[2]-vektor[4])/(vektor[3]-vektor[1]));

a:=3;
while a<= p do
begin
 v:=cos(beta)*vektor[a]-sin(beta)*vektor[a+1];
 vektor[a+1]:=sin(beta)*vektor[a]+cos(beta)*vektor[a+1];
 vektor[a]:=v;
 a:=a+2;
end;

a:=1;
while a<= p do
begin
 if a<8 then
  writeln(Utfil1,vektor[a]:8:1,z:8:1,vektor[a+1]:8:1)
 else
  writeln(Utfil2,vektor[a]:8:1,z:8:1,vektor[a+1]:8:1);
 a:=a+2;
end;

a:=1;
while a<=8 do
begin
 writeln(vektor[a]:8:1,z:8:1,vektor[a+1]:8:1);
 a:=a+2;
end;

close (utfil1);
close (infil);
```

```
  end;
  close (utfil2);
end.
```

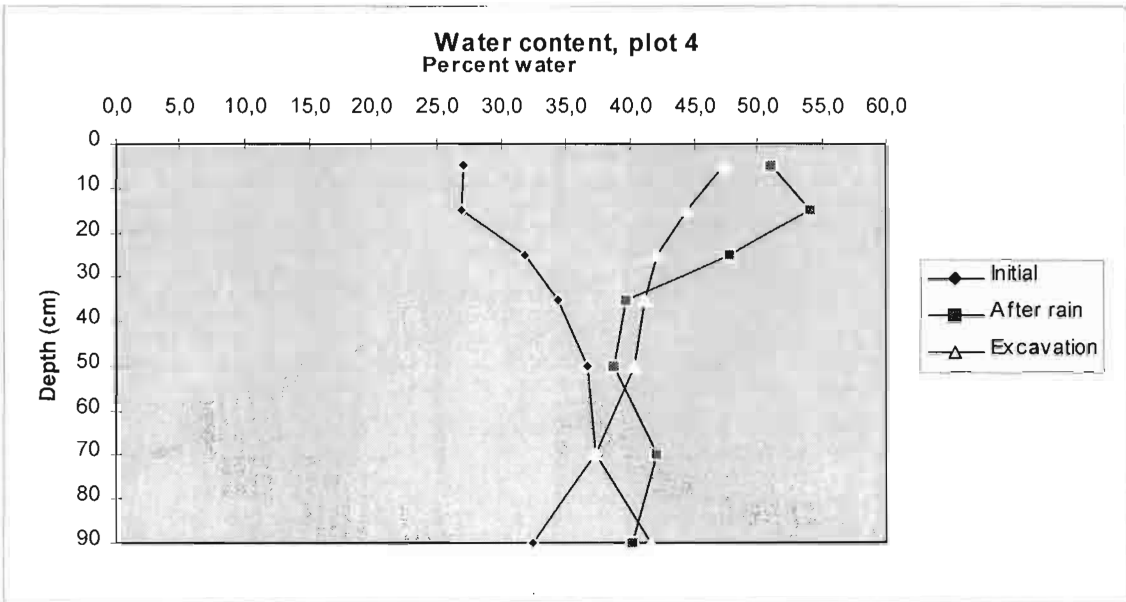
## Corrections to the Fig. 4-15 in Appendix.

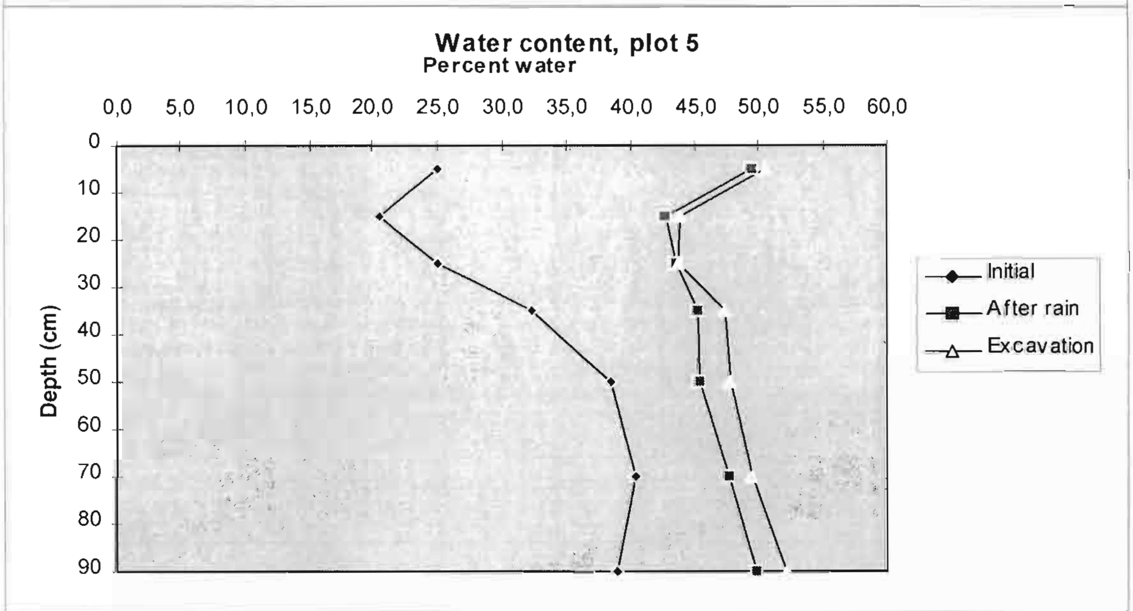


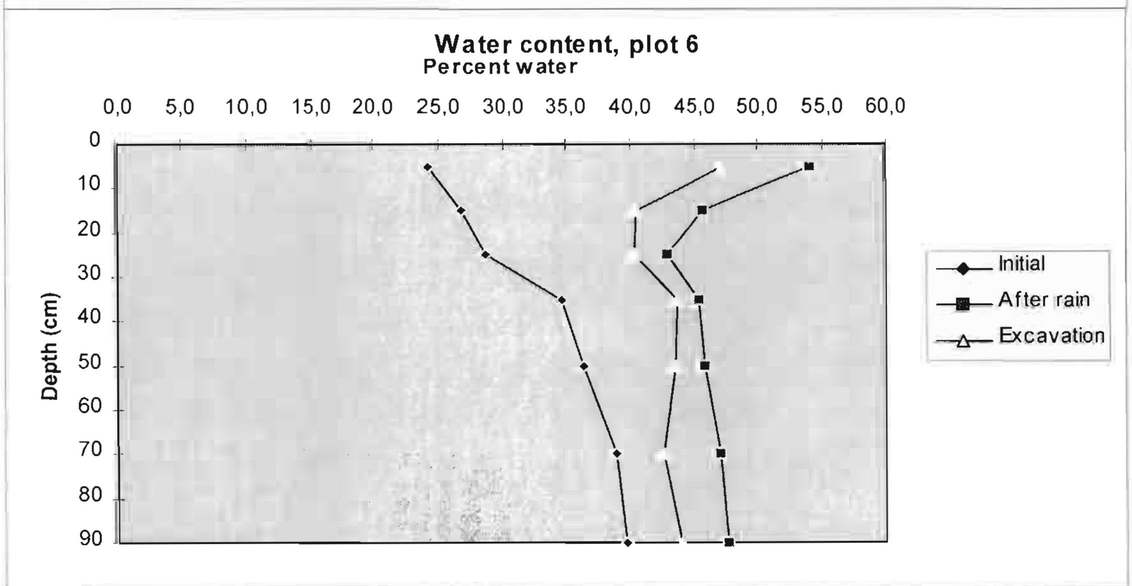



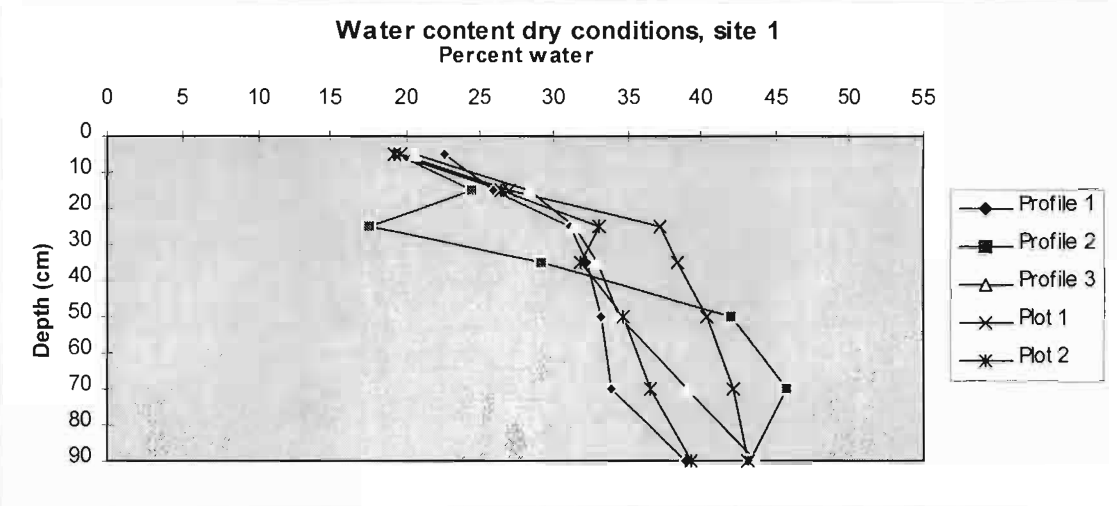

*Figures 4-6. Water contents, plot 1-3.*

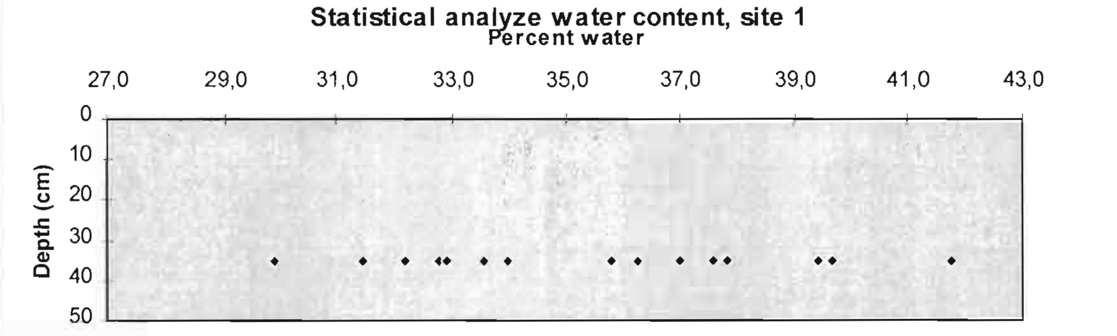


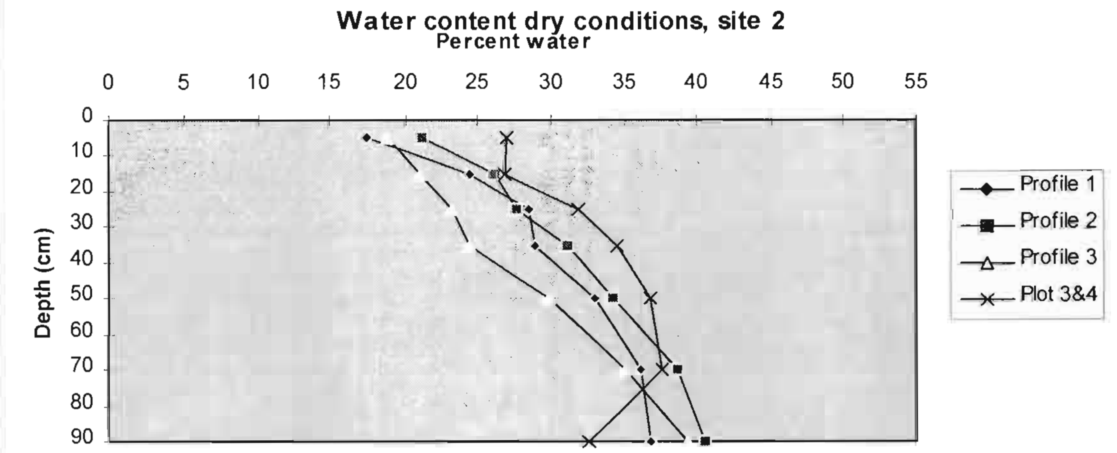



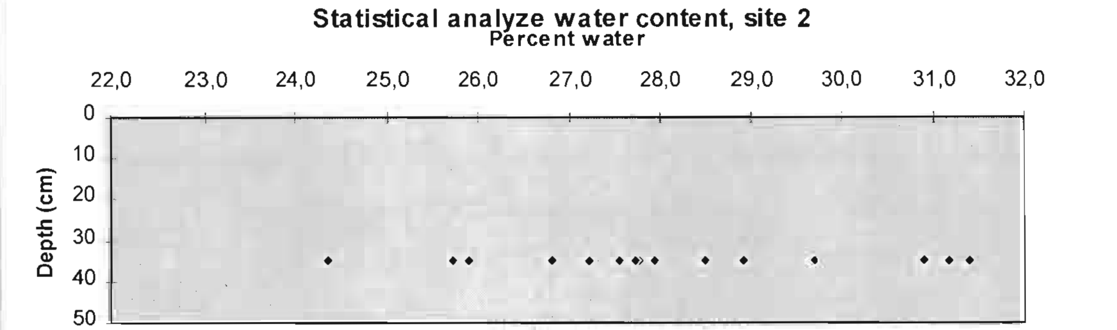

*Figures 7-9. Water contents, plot 4-6.*



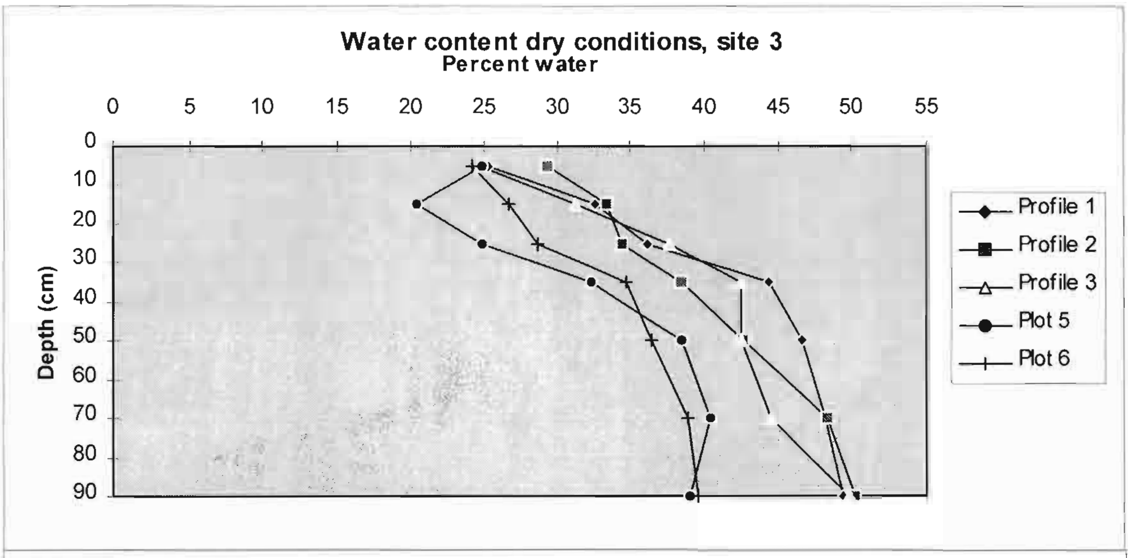

confidence interval +/- 1.380 standard deviation 3.356 mean 35.6

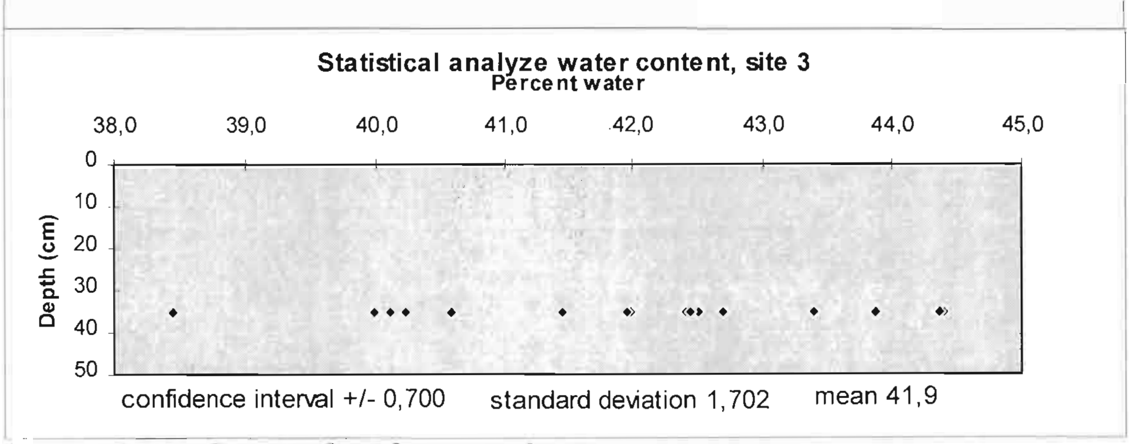



confidence interval +/- 0,866 standard deviation 2,105 mean 28,3

*Figures 10-13. Statistical analyzes, site 1-2.*




*Figures 14-15. Statistical analyzes, site 3.*