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THE VARIATION OF SOIL PHYSICAL PROPERTIES IN FERTILE WELL-DRAINED SOILS UNDER BANANA

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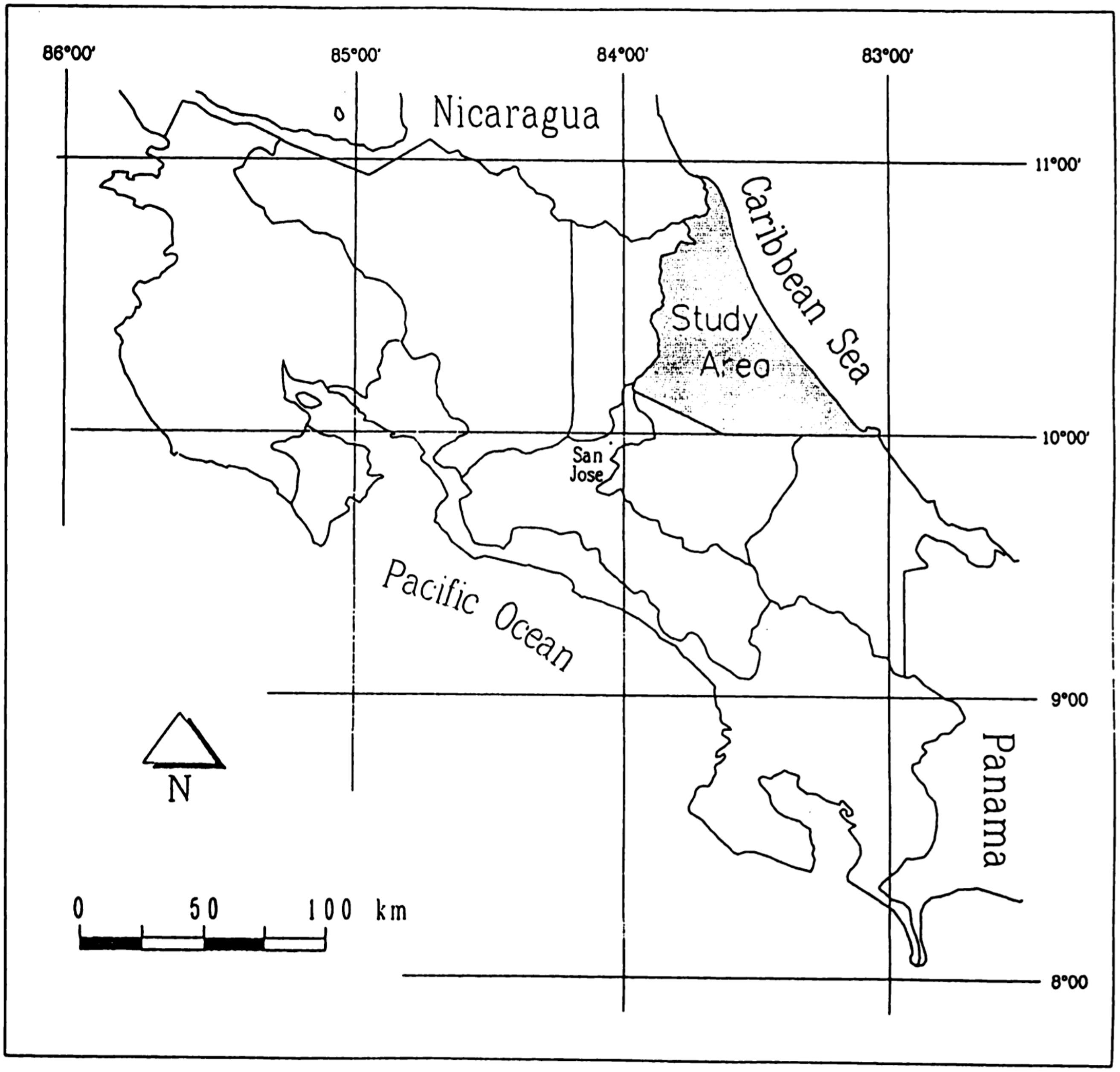
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PREFACE

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

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

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

This report describes the variation of soil physical characteristics in the fertile, well drained soils. To determine the level of accuracy in the results of the simulation models, the knowledge on variation of the input parameters is vital. Additionally this report includes a thorough discussion on the methodology used for the determination of the soil physical parameters and the functionality of the parameters.

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Harald Leummens
Wageningen, june 1993

SUMMARY

Making use of simulation modelling for the development of a methodology for analysis and planning of sustainable land use requires the availability of sufficient basic data of reliable quality. Often however gathering of data is difficult, costly and time consuming, resulting in the extrapolation of the available data. Attention should be paid to the effect of extrapolated, or grouped, data on the reliability of simulations results, and decisions should be taken if extrapolation is acceptable considering the costs and level of accuracy of both alternatives.

This study focuses on possible differences in soil physical properties of 3 soil types out of one major soil group of fertile, well-drained soils. The study, part of the Agricultural Research Program as developed in cooperation between CATIE, MAG and WAU, was carried out in the atlantic zone of Costa Rica, a region with an average temperature of 25°C and an average yearly precipitation of 3000-4000 mm. Most soils in this region briefly can be characterized as originating from volcanic deposits, either andosols or soils with andic properties. As it was the objective only to study differences in physical properties caused by intrinsic soil properties, research was restricted to the land utilization type commercial banana plantations. Because observed differences in soil physical properties are not always reflected in crop growth and sustainability of land use, determined physical characteristics were used in a soil-water-crop model. In this way differences in physical properties could be expressed as differences in functional properties, properties that can be related more directly with the sustainability of a land use system. The obtained results were used to decide whether using one set of physical data for the soil types in the major soil group, for the same land utilization type, was acceptable considering differences in functional properties or that using different sets for subgroups or individual soil types would be more appropriate.

Soil physical characteristics for three soil types were obtained using the One-Step Outflow method, in which sample outflow data were used to optimize parameters in continuous equations for soil water retention and hydraulic conductivity, as described by van Genuchten. Input data on saturated hydraulic conductivity and independent control measurements in the lowest pressure head range were obtained using the modified crust method. Results of the modified crust method, laboratory analyses and field profile descriptions show typical characteristics for soils developed in volcanic deposits, very high conductivities of 300-400 cm/day near saturation, high porosities including macroporosity, high saturated water contents, high organic matter contents and low bulk densities.

The parameter optimalization procedure resulted in acceptable equations for soil water retention curves but showed discrepancies in hydraulic conductivity in the lowest pressure head range, using the measurements of the modified crust method as an independent check. The discrepancy is partly caused by the basic equations of van Genuchten, which are based on theories developed in soils with higher bulk densities and without a strong macroporosity. Partly the discrepancy also is caused by not using measured data in the optimalization procedure. The different parameters obtained did not convert to unique results for distinguished soil layers, different sets of parameters showed rather comparable equations for the physical characteristics. In general the parameter estimation procedure resulted in useful data, because following simulation runs showed that daily pressure heads fluctuate within the range of 0.05-0.6 bar, the range that was used to obtain sample based outflow data, serving as input for the fitted physical characteristics.

The obtained equations for soil water retention and hydraulic conductivity were used as only variable input in the dynamic simulation model LEACHM, to simulate water storage, percolation, transpiration and evaporation for 3 growing seasons with different precipitation quantities. Because running a simulation model for a perennial crop still is not possible, use was made of data for the crop maize. Calculated were the functional properties "relative evapotranspiration deficit", "relative transpiration deficit" and "quantity of percolating water", all expressed as a cumulative value at the end of the growing season. Results of the simulation runs show that for one growing season differences between soil types are rather small, smaller than differences observed between the three growing seasons. Differences between the functional properties "relative evapotranspiration deficit" and "relative transpiration deficit" are an indication that anaerobiosis is a more important cause of crop growth reduction in costarican conditions.

The obtained results are an indication that observed differences in physical properties are of less importance on the final results of simulation modelling. Based on the soil types studied, it therefore may be concluded that grouping soiltypes in the major group of fertile, well-drained soils with an identical land utilization type is acceptable.

Briefly, also effort is put in obtaining pedotransfer functions, functions that relate easily obtainable basic soil properties with more difficultly measurable soil physical characteristics. Use was made of a linear regression technique, relating "van Genuchten" parameters with bulk density, organic matter content and soil texture. Although some relations are promising, confidence intervals are rather wide which is at least partly caused by the limited amount of data points.

For the future use of soil physical characteristics as basic input for simulation modelling, some extra research is necessary. More attention should be paid on the simulation of crop response on water availability and water excess, by using a model better capable of integrating crop growth with simulated soil water flow. Also the statistical significance of differences in soil physical characteristics between soil types and between repetitions needs to be quantified. Because of the observed differences between fitted and measured hydraulic conductivity in the lowest pressure head range, more research is necessary on the outcome of simulation runs using measured data. The observed high macroporosity is expected to be important for the transport of water under costarican conditions, where precipitation quantities up to 200 mm/day may occur. Measured data may be used in tabulated format or expressed as another type of equation. Before pedotransfer functions can be used to extrapolate physical properties to different locations and soil types, more effort is necessary in studying the possibilities to reduce confidence intervals. This requires the availability of more data, measured and fitted, also for more different soil and land utilization types.

CHAPTER 1 INTRODUCTION

Whenever it is decided to follow a quantitative analysis by means of simulation modeling, the amount of quantitative data is crucial to allow realistic planning and decision making. Because in practice gathering of certain data is difficult and time consuming, assumptions are made about the spatial variability of these data, while they often are extrapolated to areas where no measurements have taken place. An important question is whether these assumptions are allowed, considering the goals and demanded accuracy of the study, or that more detailed studies are necessary to identify smaller areas with different values.

The study described in this report was designed as a part of the Agricultural Research Program in the atlantic zone of Costa Rica. The central theme of the second part of this program was to develop a methodology for analysis and planning of ecological and economical sustainable land use (anonymous, 1991). The program is carried out in cooperation between the Centro Agronomico Tropical de Investigación y Enseñanza (CATIE), the Ministerio de Agricultura y de Ganaderia (MAG) and Wageningen Agricultural University. To reach the ultimate goal the study was divided into three main parts, Land Use System Analysis on crops and soils, Farm System Analysis on decision taking at farm household level and Regional System analysis on agroecological and socio-economical boundary conditions.

Looking more closely to the research setup, the Land Use Systems Analysis is carried out by analyzing the relations between 9 different crops and three major soil groups. The major soil groups were created after soil mapping and classification, which has taken place in the first phase of the Research Program. The major soil groups can be characterized as fertile/well-drained, fertile/poorly drained and non-fertile/well-drained. The crops are selected on their use in the study region and the perspectives for their use in future. They crops studied are maize, cassava (yucca), plantain, pine apple, palmheart, grassland and forest.

To define the relationships between crops and soil, use will be made of simulation modeling, in which special attention will be paid to sufficiency of nutrients, the change in physical soil properties and pollution by fertilizers and biocides. However, to allow for realistic scenario simulation sufficient data are needed and knowledge must be gathered on the variability within "homogeneous" groups used in the analysis, to decide whether making use of these groups is justified considering the aim of the study.

Part of the information needed in the simulation procedure consists of data on soil physical properties of the different major soil groups. Although on a high level these groups are defined homogeneous, they are the result of reclassifying and grouping 74 distinguished soil types. Therefore the major groups contain the variability in soil physical properties present in the atlantic zone. However, the physical behavior of a soil is not only characterized by its intrinsic properties but also by the type of land use, influencing soil structure. Therefore a study was designed to determine the effect of soil type and land use on physical properties, to characterize these properties and to investigate the range in differences in order to study the appropriate level of aggregation, considering the use of the data in Land Use System Analysis and ultimately in determining sustainability.

The main study described above was split up into parts carried out by different persons. Data on soil physical properties for different types of land use on one soil type out of the major groups fertile, well-drained and unfertile, well-drained soils were gathered by Weitz (WEITZ, 1992), while general data on the fertile, poorly drained soils were gathered by Mantel (MANTEL, 1993). To complete the analysis for the major soil group of the fertile, well-drained soils the underlying study was developed, characterizing the soil physical properties of 3 different soil types with one type of land use. The resulting physical characteristics were analyzed on their effect on functional properties, properties that are more directly related with the sustainability of a land use system. The results were used to decide whether grouping of soil types with identical land use type into the major soil group of fertile, well-drained soils is acceptable, or that the internal variability in physical characteristics is so large that subgroups need to be defined, in order to obtain realistic results in Land Use System Analysis.

The study is described in different parts. First a description of the general settings of the study, the area, the climate, the soil types and measurement locations, the core sampling procedures and analyses is given in chapter 2. In chapter 3 the use and results of the modified crust test, used to characterize saturated and unsaturated hydraulic conductivities in the lowest pressure head range, is described. In chapter 4 the One-Step Outflow method is explained, including the parameter estimation procedure to obtain continuous functions for soil water retention and hydraulic conductivity. In chapter 5 the obtained physical characteristics are used in a dynamic simulation model for the calculation of functional properties of the different soil types. In chapter 6 measured physical characteristics and more easily obtained data are linked using pedotransfer functions. Existence of good relationships can be useful in checking measurement results and obtaining knowledge of hydrological parameters without using laborious techniques.

CHAPTER 2 METHODOLOGY

General settings

The research of the Atlantic Zone Program is concentrated in the northern part of the province of Limon in Costa Rica, with the research station situated in Guapiles (figure 1). The area is bordered by the caribbean sea in the northeast and a mountain chain, the Cordillera Central, in the southwest. The major part of the area is a lowland sedimentation basin belonging to a large tectonic unit which continues to the north in the Nicaragua depression. The unit is formed by the subduction of an oceanic crust, the Cocos plate, under a continental plate, the Caribbean plate, and is one of the two typical morphologic features in an area with subduction processes.

Whenever an oceanic plate is subducing under a continental plate island arcs and back-arc basins can be found. In Costa Rica the Cordillera Central is part of the island arc, a chain of stratovolcanoes formed out of magma from the molten parts of the subducing plate. The chain of volcanoes is continued in the neighboring countries Panama and Nicaragua and continues into El Salvador and Mexico. The sedimentation basin in the atlantic zone is part of a back-arc basin, formed behind an island arc by crustal thinning, a process caused by tensional stresses in the overriding plate due to a faster rate of sinking of the subducing plate over the forward motion of the overriding plate. Eventually this may lead to the outflow of basaltic magma, a process which in the atlantic zone has lead to the formation of the Cerro del Tortuguero and Lomas de Sierpe, the only elevations in the basin (SKINNER & PORTER in SEETERS, 1992). A map with the different geomorphological units in the atlantic zone is added in figure 2.

Because of the volcanic origin of most of the sediments, the soils in the sedimentation basin mainly consist of andosols or soils with andic properties. More closely towards the chain of volcanoes more sandy and gravelly material transported by lahars can be found, while going northeast textures become more clayey. After identification, mapping and classification in the first phase of the research program the soils in the atlantic zone were grouped in three major groups which can be described as :

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

The distribution pattern of the major group of fertile, well-drained soils is printed in figure 3, expressed as a percentage within the distinguished mapping units.

Soils and sampling locations

To characterize soil physical properties and to investigate the necessity for identifying subgroups, within one major soil group and for one land utilization type, three soils out of the major soil group fertile/well-drained soils were selected. To cover the variation occurring in the defined group, soils with different types of parent material and age were selected, using the set up in figure 4, in which all the identified soil types are gathered.

figure 1 : Research area of the Altantic Zone Programme in Costa Rica.

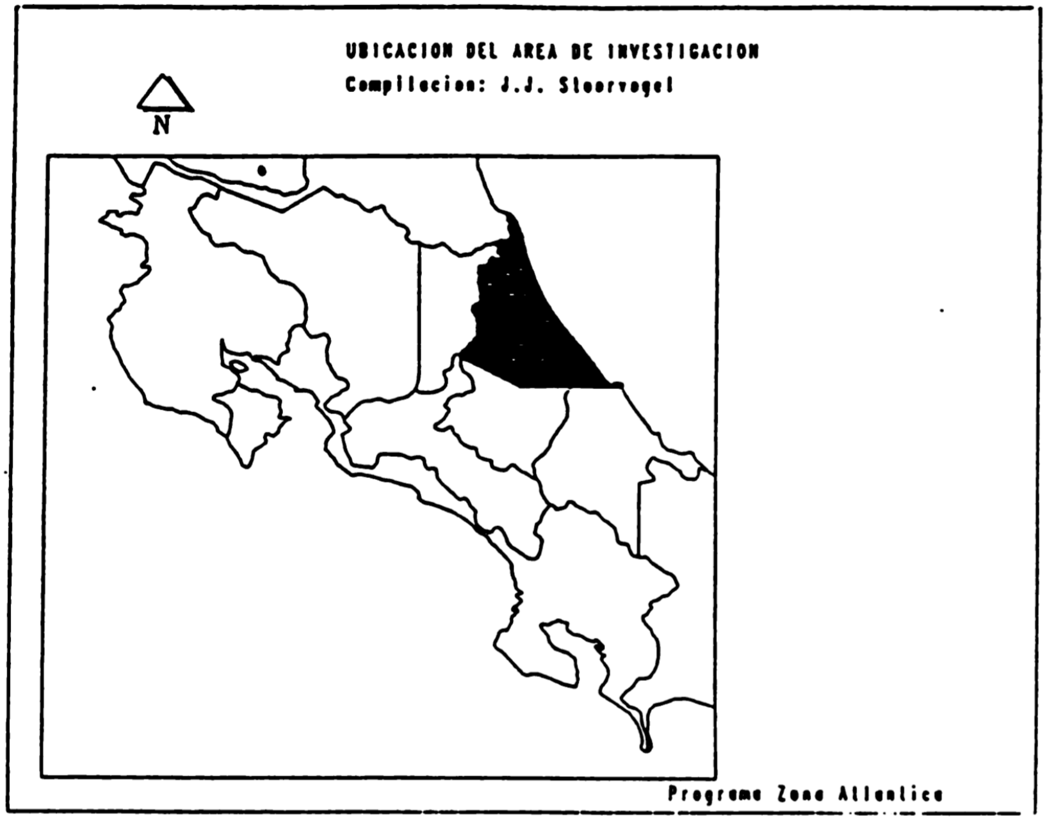


figure 2 : Geomorphological units in the atlantic zone of Costa Rica.

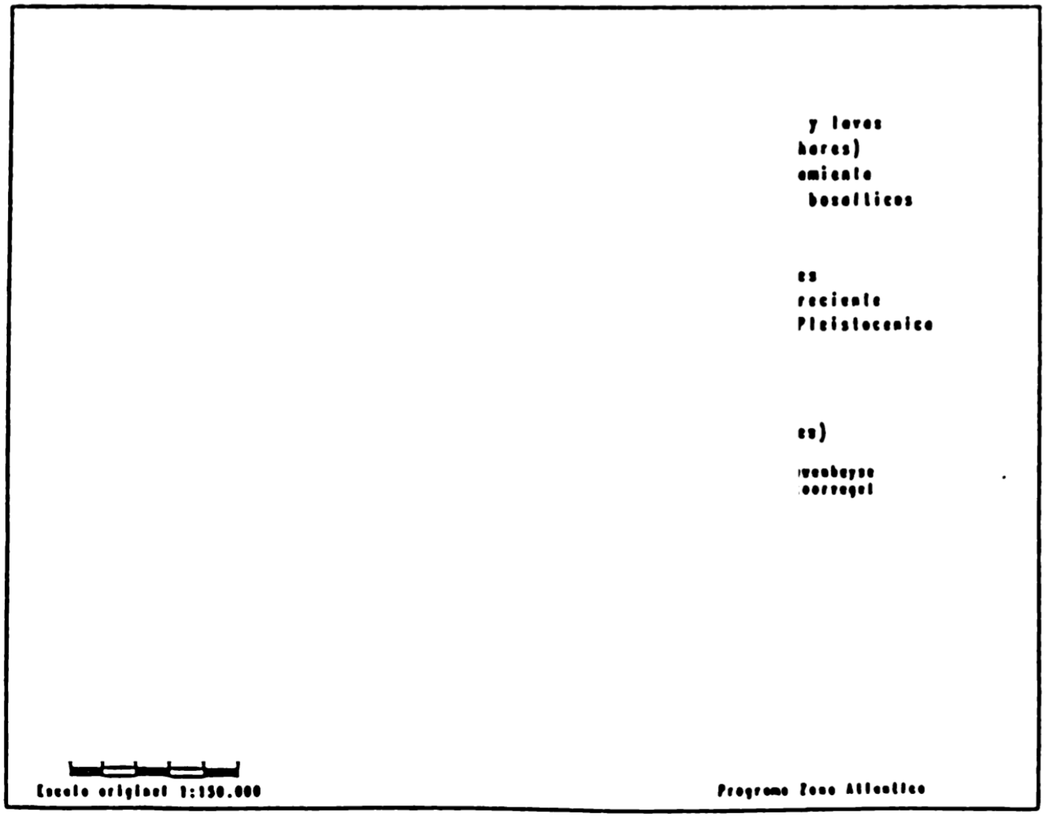
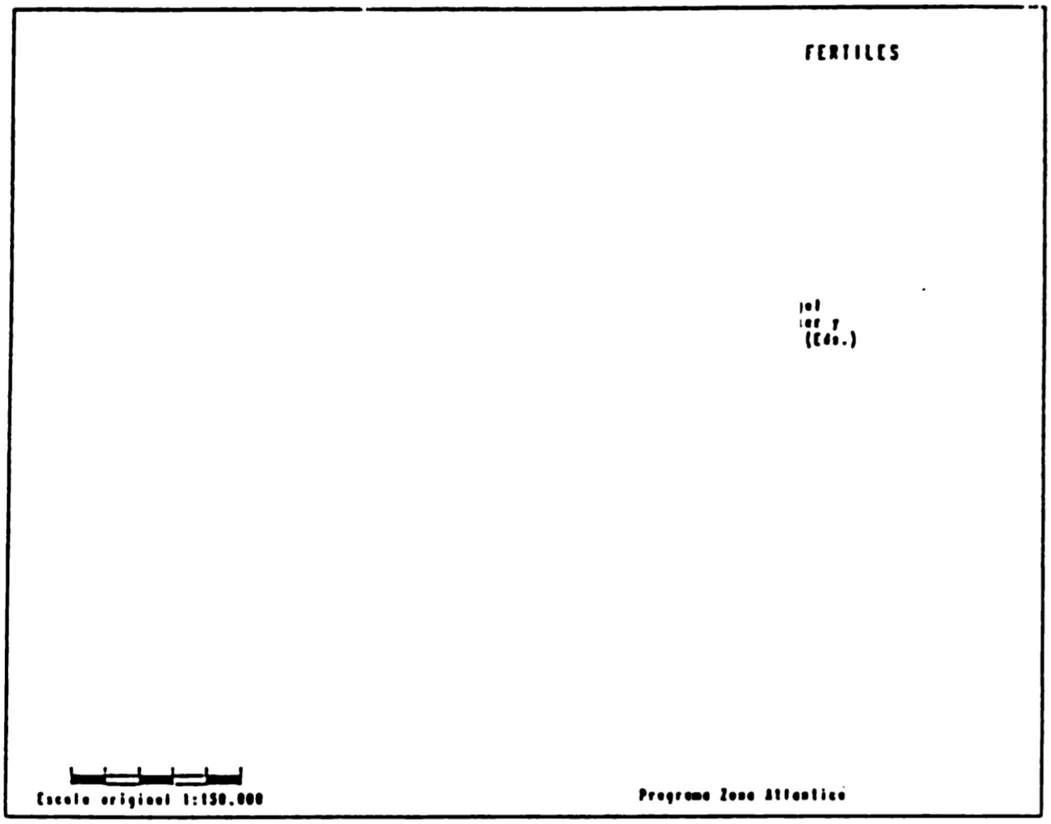


figure 3 : Distribution of the major group fertile, well-drained soils in the atlantic zone of Costa Rica, expressed as a percentage of the mapping unit



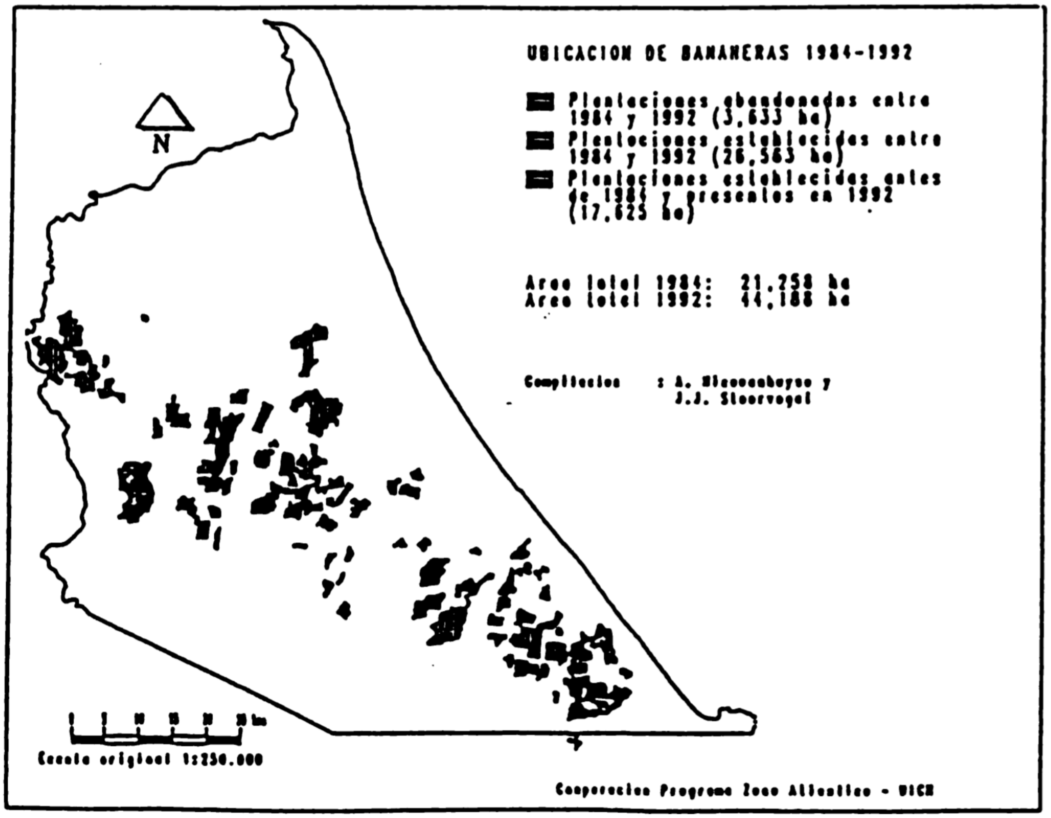
Chosen were the soil types Los Diamantes (Eutric Hapludands), Ligia (Typic Dystropepts) and Montelimar (Pseudo Vitrudands). The Ligia type can be characterized as the oldest soil, with the deepest profile development. This soil type still has some andic properties, while it has a clayey texture as a result of sedimentation processes in a river terraces environment. However, due to these sedimentation processes the parent material of Ligia is sometimes variable in texture. The soil profile of Los Diamantes is developed on sandy parent material, sedimentated closer to the mountain ridge, while it is not so far developed as the Ligia soil type, resulting in a less profound profile and a thinner A-horizon. The soil Montelimar is the youngest, clearly having andic properties, light colors in a sandy topsoil and volcanoklastic material still present in the subsoil. More detailed information on the sampled soils is given in appendix 1, containing the soil profile descriptions.

Because commercial banana production is a common practice in the province of Limon, covering an extended area with different soil types (figure 5), this land utilization type was chosen. Using SIESTA, a Geographical Information System developed for the Atlantic Zone Program (scale 1:150000) the soil types and their occurrence in compound mapping units were combined with the location of banana plantations in the year 1984. Although more recent information was available, only sites covered with banana for more than 8 years were chosen, to avoid variation in soil physical behavior due to differences in soil structure as a result of usually intensive land clearing operations.

figure 4 : Set-up of the distinguighed soiltypes and their relation with development stage and physical environment. (WIELEMAKER & KROONENBERG, 1992).

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

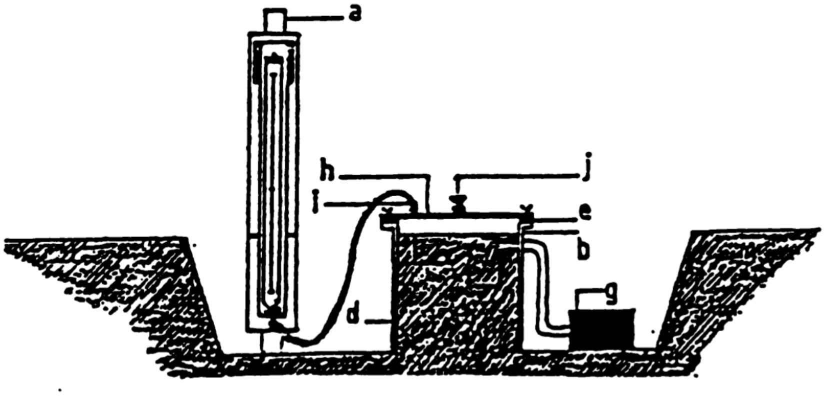
figure 5 : Location of banana plantations in the atlantic zone of Costa Rica, in 1984 and 1992.



The sampling procedure

On the selected location a soil pit was dug and a profile description according to the FAO guidelines was made. Soil profile descriptions can be found in appendix 1. After characterization of the horizon build-up samples for the determination of soil texture, organic matter content and moisture content in the high suction ranges were collected. Textures were analyzed in the laboratory of the MAG in San José, using the hydrometer method. Use was made of field moist samples to prevent textural changes which are known to occur in soils with andic properties (NIEUWENHUYSE, personal comment). Because the hydrometer method yields unreliable results for the sand fraction and a partitioning in more texture fractions was desired separate analyses using sieves were done. The results of these analyses were used to correct the hydrometer results. Also corrections for the occurrence of organic matter were made. The organic matter content was determined in the same laboratory, measuring the loss in weight after glowing. Soil water contents were measured using pressure cookers, applying pressures of 3 and 15 bar. In the field also 300 cm^3 cylindrical rings with undisturbed soil were sampled for One-Step Outflow analyses in the laboratory at the research center. Before taking these samples a horizontal plane was made on the selected depth, somewhat above the center of the sampled horizon. At the same depth 100 cm^3 cylindrical rings were sampled for the determination of the saturated water content using the traditional procedure with the water level one centimeter below the top of the ring. Although an extra set of samples was necessary and the results obtained did not refer to the same samples used for the One-Step Outflow procedure, still it was considered to yield results more in accordance with the methods used when the theory for the relation between soil water content and suction was developed (see also the comment by WEITZ, 1992). Also it proved to be difficult to adjust exactly the outflow level at the top of the sample in the One-Step Outflow set-up. Although smaller samples are more sensitive to measurement errors, comparison of bulk densities resulting from both sample series showed that results were comparable. For every soil layer 5 samples for the One-Step Outflow analysis and 5 samples for the saturated water content were taken.

figure 7 : Schematic diagram of the field installation of the modified crust method (WEERTS, 1992).



a = mariotte stand
b = ring infiltrometer
c = crust
d = cemented soil wall
e = rubber ring
f = tensiometers
g = pressure transducer
h = plastic cover
i = water intake port
j = air outlet

Installation

A cylindrical ring with a diameter of 30 cm and a height of 10 cm was pushed into the soil at the specified depth. The soil surface should be horizontal, which in the subsoil can be arranged easily using a knife. For the topsoil carefully the upper organic layer is removed, to prevent it from interfering with the crust and to remove small irregularities in the soil surface. A soil column of approximately 30 cm was carved out and the wall was coated with Pegamix, a sand-cement product, to prevent lateral flow and evaporation losses. Afterwards a crust made of a mixture of fine sand, cement (10% by weight) and water (also 10% by weight) was applied on top of the soil surface. The texture of the sand used is added in appendix 4. The thickness of the crust was about 1 cm, while good contact between crust and soil surface was reached by compressing the crust material. After hardening for one day the column was closed with a plastic cover and rubber ring to prevent air entry. A vertical stand with a movable mariotte device was installed next to the soil column, in such a way that the level of outflow of the mariotte was at the same level as the crust. Afterwards water was put into the mariotte device and on the crust surface while air was removed out of the system. After the measurements at different mariotte levels the crust was removed and the saturated hydraulic conductivity was measured.

Application

Theoretically the installation of two tensiometers on different depths below the crust is necessary to measure the pressure head and to check whether unit gradient is reached. Due to the absence of a pressure transducer during the field work period measuring tensiometers was not possible and installation did not take place. In stead of this unit gradient was assumed whenever a constant infiltration rate was reached while corrected values for the subcrust pressure heads were obtained using a correction factor. The correction factor was calculated using tensiometer readings of earlier crust measurements in Costa Rica (WEERTS, 1992). The results are added in appendix 2.

Due to low bulk densities and high biological activity in the used soil types high fluxes were obtained, therefore time interval of 15 sec was used. To be able to compare the results of the measurements with formerly measured conductivities the same procedure for crust preparation was used, although the maximal subcrust value reached was only -12 cm. The standard procedure after air leakage through the crust was to remove the cap and water and to seal the spot with silicone to be able to continue the measurements. However, when the silicone surface coverage became more than 25% the measurements were stopped.

Also in accordance with previous measurements the upper 60 cm of the soil were characterized. Rings were installed at 0 and 30 cm, characterizing the layers 0-30 and 30-60 cm. Because conductivity were expected to be heterogeneous all measurements were repeated 3 times in the topsoil layer and 2 times in the subsoil layer.

Results and discussion

The averaged measured values for the different soil types and depths are summarized in table 1, while the measurements are visualized in the figures 8 and 9 for respectively the topsoil and the subsoil. Results of the individual measurements are added in appendix 3.

table 1 : averaged hydraulic conductivities (cm/day) of 3 soil types for different sub-crust pressure heads.

	Los Diamantes		Montelimar		Ligia	
cm/day	0-30	30-60	0-30	30-60	0-30	30-60
no crust	624.3	177.8	193.0	227.3	685.4	229.7
h= -7	326.6	214.1	336.8	285.7	328.1	207.7
h= -8	308.4	188.4	275.6	249.3	229.7	207.0
h= -9	251.3	181.5	249.0	276.7	222.4	194.3
h=-10	218.8	168.2	226.5	221.8	141.6	169.3
h=-12	136.9	149.7	169.6	189.5	84.2	153.8
h=-13	101.7	127.7	107.6	166.2	32.3	116.1
h=-14	54.7	115.7	80.7	127.7	16.0	85.0
h=-16		82.4				

figure 8 : Measured hydraulic conductivities in the layer 0-30 cm of 3 different soil types.

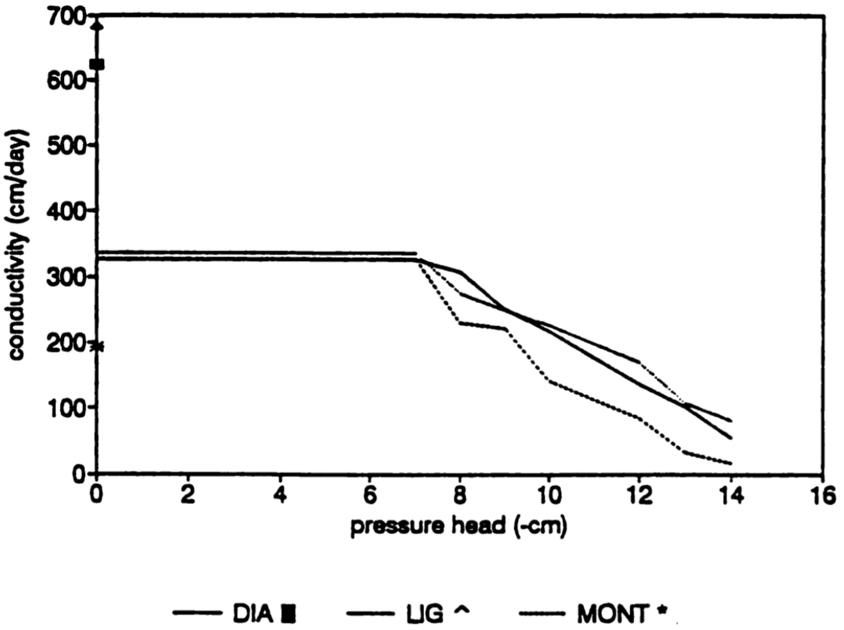


figure 9 : Measured hydraulic conductivities (cm/day) in the layer 30-60 cm of 3 different soil types.

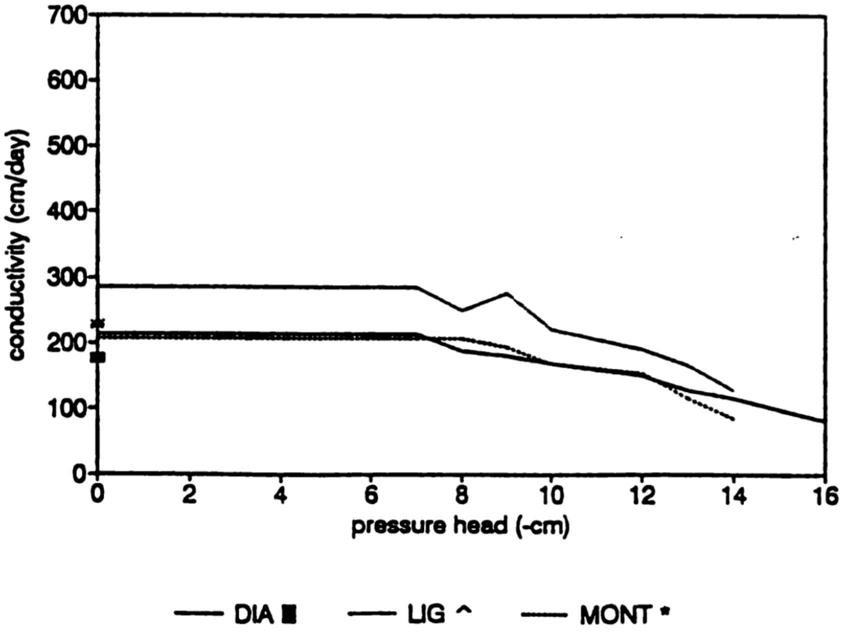


Figure 8 shows that for the topsoil roughly 2 trends can be distinguished, with Ligia on one and Los Diamantes and Montelimar on the other hand. An explanation for this distinction can be found in textural differences between these soils, of which Los Diamantes and Montelimar both contain less clay in the topsoil than Ligia (appendix 4) while the soil structure for the 3 soils is more or less the same (appendix 1). The relationship between conductivity and soil texture/structure is less clear in the subsoil, although in figure 9 also 2 trends can be distinguished. Now Los Diamantes and Ligia show almost the same conductivity curve, while the Ligia soil contains twice as much clay as Los Diamantes. Also differences in structure exist, weak sub-angular blocky to granular for Los Diamantes and moderate angular to sub-angular blocky for Ligia.

A problem not reported before but visible in the measured soil types was the lower K_s after removal of the crust, which is in contradiction with the theory of totally filled macropores causing a higher flux. One possible explanation is that during crust compaction, to ensure good contact between crust and soil, the upper soil layer is compacted, resulting in lower values for K_s after removal of the crust. Careful preparation of the soil surface however did not result in higher values. Another possible explanation is that in soil systems with low bulk densities and many macropores, the fast flow of water in nearly saturated conditions may cause instability and breakdown of macropores, strongly reducing the flow of water (WEITZ, personal comment). Separate measurements of new installed columns without using a crust resulted in two of the three topsoils in much higher values for K_s than measured after removal of the crust. Due to time limits an extra measurement for the Montelimar soil was not possible. Also for the layer 30-60 cm no extra measurements were done, although also here lower saturated conductivities after removal of the crust can be seen. Although according to the soil profile descriptions in this layer pore structure and size are different, there are still macropores which should cause higher conductivities without crust. Because no further data on the observed problem are available, it is not possible to provide a final answer to the question.

Conclusions

The crust method showed that it can be a useful method to obtain data on saturated and unsaturated hydraulic conductivity in the field, taking the presence of macropores and small scale spatial variability into account. Although installation of columns is quite time consuming, measurements are fast due to high fluxes resulting in fast reached steady state infiltrations. The results of the measurements with a crust show for all soil types very high absolute values, a result of low bulk densities, high organic matter contents and a high biological activity. However, problems were observed measuring the K_s after removal of the crust, measured values were too low compared with values for unsaturated hydraulic conductivity, while separately columns only for measuring K_s showed clearly higher values. The cause of the problem is not clear, whether it is caused by intrinsic soil properties of by installation errors.

For the use of the measured data in the parameter estimation procedure the observed problem of too low K_s values is of less importance, because use is made of the values for $K_{(sat)}$, the saturated hydraulic conductivity measured with a crust on top of the soil. This excludes bypass flow, necessary because van Genuchten's expressions for $\Theta(h)$ and $K(h)$ do not take bypass flow into account. Although it is expected that the order of magnitude of the measured $K_{(sat)}$ is sufficient to be used in the parameter estimation procedure, an uncertainty in these data is caused by the procedure followed to correct for the absence of measured tensiometer data.

CHAPTER 4 ONE-STEP OUTFLOW ANALYSIS

Parameter estimation

A way of handling the complex system of soil and water, without the use of laboratory or field experiments with rather restricting initial and boundary conditions to determine the soil hydraulic functions, is to use a parameter estimation technique (VAN DAM et al, 1990). The advantage of this so called inverse approach is that mathematical problems can be solved in all cases with an appropriate analytical or numerical method, while necessary experiments can be selected on their practical application. Basic knowledge is used to develop the system relations, expressed in a parameterized form. Parameters can be optimized according to an optimalization algorithm minimizing an objective function. As a consequence the optimalization approach does not put restrictions on the form or the complexity of the model. Disadvantage of the procedure is that used model formulations are fixed, it must be assumed that the degree of approximation is good enough considering the objective of the study. Another kind of uncertainty is caused by non-uniqueness of many parameter estimation techniques, multiple parameter sets giving the same minimum in the objective function, which makes it impossible to decide on the correct solution. The problem can be caused by the correlation among parameters of the model, changes in one parameter are balanced by a change in the correlated parameter, leading to large estimation variances and impossibility to determine parameters accurately (KOOL et al, 1985).

In this study a parameter estimation procedure was used, based on the results of a "one step" pressure outflow experiment, measuring the cumulative outflow after applying a step change in air pressure on top of a soil column. Use is made of Van Genuchten's expressions for soil hydraulic functions $\Theta(h)$ and $K(h)$ (VAN GENUCHTEN, 1980).

One-step outflow experiment

experimental design

Measuring cumulative outflow data in time is possible using an experimental setup as displayed in figure 10. Ten undisturbed soil samples (300 cm^3 cylinders, 7.25 cm diameter and height) are placed in pressure cells (figure 11) on a ceramic plate with an air entry value of 1 bar. The contact between the soil sample and the plate should be as good as possible, therefore careful sampling and surface preparation is important. Air entry from the sides is prevented by using greased rubber O-rings. After installation and testing on air leakages the sample is saturated from below moving an overflow level above the top of the pressure cell. When all samples are saturated and air is removed from the system, measurements are started by applying an air pressure on top of the sample, using a pressure regulation unit consisting of a compressor, a pressure regulation valve and a pressure transducer. During the measurements the level of the outflow tube is situated halfway the height of the core.

figure 10 : Schematic overview of the One-Step Outflow set-up as developed by TFDL, Wageningen, The Netherlands. (BOOLTINK et al, 1991)

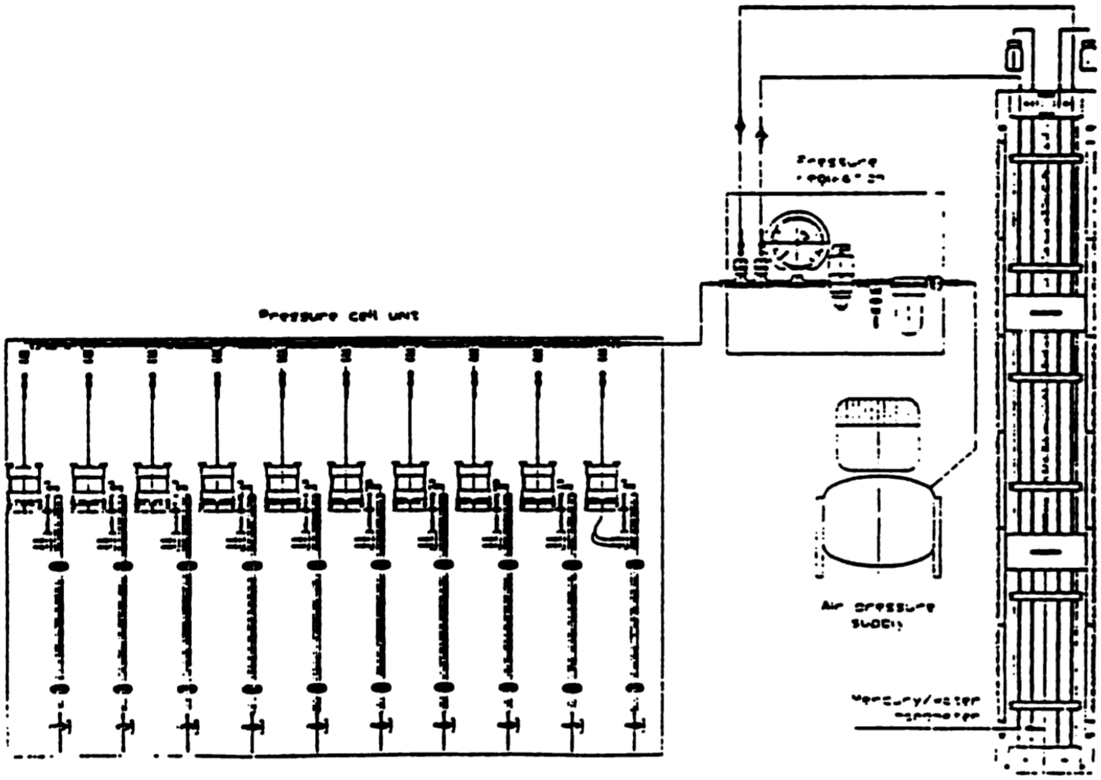
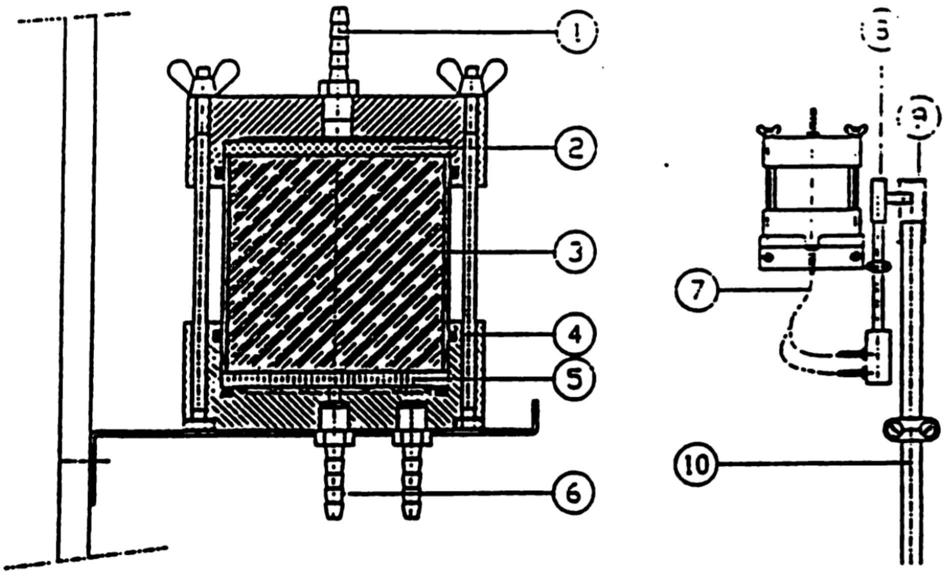


figure 11 : Details of a pressure cell as used in the One-step Outflow set-up (BOOLTINK et al, 1991)



1 - air pressure supply
2 - synthetic filter
3 - iron sample ring
4 - rubber O-ring
5 - ceramic filter
6 - water discharge/air exclusion
7 - polyethylene tubing
8 - flow over
9 - cap to prevent evaporation
10 - buret

data collection

Input data for the parameter estimation procedure are collected in two stages. First the moisture content for two points in the wet part of the soil water retention curve are determined, for the pressures 0.03 and 0.05 bar. Total outflow is measured after equilibrium is reached and the outflow of water stopped. Afterwards the pressure is increased to 0.6 bar. Application of a higher pressure is not recommended because problems may rise with dissolving and releasing air in soil water (BOOLTINK et al, 1991). Outflow is measured as a function of time, first in very short intervals, later in larger time steps up until at least 72 hours. After finishing the outflow experiment the samples are removed from the pressure cells, weighted and dried at 105°C to determine dry bulk density. After drying the samples are analyzed visibly to see whether there are characteristic features which eventually could explain a specific outflow or deviations between samples.

SFIT analysis

Theory

For simulation of the flow of water through the soil, measured as outflow in time, a solution of the Richards' equation is required. For one-dimensional flow with vertical distance x taken positive downward this equation may be written as

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x}[K(h)(\frac{\delta h}{\delta x} - 1)] \qquad (2)$$

in which Θ is the moisture content, t the time, h the pressure head, K(h) the hydraulic conductivity and x the vertical distance (KOOL et al, 1985, VAN DAM, 1991). This equation is solved for a two-layer system of soil column and porous plate, in which the air-entry value of the porous plate is high enough to assure saturated conditions throughout the experiment. Subsequently the cumulative outflow can be calculated as

$$Q(t) = A\int_0 [\theta(x,0) - \theta(x,t)]\,dx \qquad (3)$$

in which Q(t) is the cumulative outflow at time t, A the surface area of the core, L the vertical length of the sample. Simulation of the outflow is possible when soil hydraulic functions are known. As it is the objective of the experiment to obtain these functions, it is assumed that the hydraulic functions are described by the analytical functions of van Genuchten (VAN GENUCHTEN, 1980), of which the unknown parameters are determined and optimized (BOOLTINK et al, 1991, VAN DAM et al, 1991).

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

$$K = K_s S_e^{\gamma} [1 - (1 - S_e^{1/m})^m]^2 \tag{5}$$

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \tag{6}$$

$$m = (1 - \frac{1}{n}) \tag{7}$$

In these formulas Θ_r is the residual water content, Θ_s the saturated water content, h the pressure head (cm), K_s the saturated hydraulic conductivity (cm/hour), S_e the relative saturation, α approximately the reciprocal of the air entry value (cm^{-1}) and n, m and γ dimensionless fitting parameters. N determines the rate with which the S-shaped retention curve turns towards the ordinate at high negative values of h, while γ influences the decrease of the hydraulic conductivity at higher negative pressure heads (WÖSTEN & VAN GENUCHTEN, 1985). The K_s is based on the drying conductivity curve. When the effective saturation S_e is taken into account the formula can be written in terms of the soil water pressure head as

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

(WEITZ, 1992, WÖSTEN & VAN GENUCHTEN, 1985).
Using the above mentioned formulas for $\Theta(h)$ and $K(h)$ with a chosen set of the empiric parameters it is possible to calculate the hypothetical outflow according to formula 2. The optimal combination of parameters that minimizes the differences with the experimentally measured outflow data is found using an optimalization algorithm. The SFIT program makes use of an algorithm based on Marquardt's maximum neighborhood method. A reduction of prediction errors is possible when not only measured outflow data are used but also selected $\Theta(h)$ points are incorporated into the analysis (PARKER et al, 1985b). The objective function which has to be minimized is

$$E(b) = \sum_{i=1}^{n} \{w_i[Q(t_i) - \hat{Q}(t_i,b)]\}^2 + \sum_{j=1}^{m} \{v_j[\theta(h_j) - \hat{\theta}(h_j,b)]\}^2 \tag{9}$$

in which w_i and v_i are weights assigned to measured and predicted outflow or moisture content respectively. To assure that the above mentioned procedure leads to sufficiently accurate results it is important that

(1) the pressure increment is large enough to reach a final water content that is less than half of the initial quantity between saturated and residual water content.
(2) the duration of the outflow experiment is long enough, so that data contain cumulative outflow that is at least half of the equilibrium outflow.
(3) initially guessed parameter estimates are close to their real values.
(4) the experimental error in measurements is relatively small (PARKER et al, 1985).

Input of the SFIT analysis

To run the SFIT program, parameters such as dimension of the soil column, number of elements and timestep used in the finite element procedure, number of observations, maximum number of iterations allowed and number of repetitions need to be known. Besides this, also data on initial and boundary conditions of the experiment, on model parameters, measured outflow and soil water retention are needed. More details can be found in the SFIT user's guide (KOOL & PARKER, 1987).

In total 8 parameters can be optimized but because no data were gathered on hysteresis and values for K_s and Θ_s were determined using independent measurements, these parameters are not optimized. Therefore only values for the parameters α, n, γ and Θ_r are obtained. In the analysis Θ_r is a strictly empirical fitting parameter of which the upper boundary is assumed to be equal to the soil water content at pF 4.2 (KOOL et al., 1985). Initial values for α, n and γ are obtained from soil texture data following a standard procedure used in the Netherlands. According to this procedure parameters are chosen out of the "Staring series", in which measured water retention and hydraulic conductivity characteristics of most top- and subsoils of Holland are described and grouped based on soil texture, while the averaged curves are also expressed with the appropriate "van Genuchten" parameters (WöSTEN et al, 1987). The used range for α was 0.001-5.0 while n varied between 1.001-7.5. Because γ is only considered as a fitting parameter the range varied from 0-100 (BOOLTINK et al, 1991).

Values for the saturated hydraulic conductivity (in cm/day) are obtained with the modified crust method (WEERTS, 1992) at zero pressure head, using a crust to eliminate bypass flow. Bypass flow is excluded because the basic assumptions of the model of van Genuchten do not take bypass flow into account (BOOLTINK et al, 1991). Calculated $K_{(sat)}$-values can be found in chapter 3. The fixed values for the saturated water content θ_s (in vol%) are an average 5 separately taken samples of 100 cc. Calculations of these values are added in appendix 5.

The measured data needed for the SFIT analysis consist out of cumulative outflow data in time and 4 points of the soil water retention curve. Data on cumulative outflow and two points in the lower range of the retention curve are collected making use of the One-Step Outflow method as described before. For all samples a time series of 3 days was used, while the applied pressure was fixed at 0.6 bar. Of the accepted samples the different outflow curves were averaged and also used as input in the parameter estimation procedure, to investigate whether it was possible to obtain average conductivity and water retention curves. The retention points in the high suction range, 3 and 15 bar were determined on disturbed field moist samples in pressure cells of the laboratory of the Ministry of Agriculture in San José.

After having analyzed all samples, it was noticed that for some samples fitted soil water retention curves did not match with the measured points, while outflow curves were acceptable. The problem was caused by the low amount of water retention measurements compared to the amount of outflow measurements. An improvement was obtained using extra weights for the retention points, although sometimes the fitted outflow curve was somewhat worse.

Output of the SFIT analysis

Using the initially chosen parameter values, the SFIT program proceeds with the iterative optimalization procedure until the relative change in each parameter becomes < 1% (KOOL et al, 1985), with the maximum number of iteration fixed at 20. This process is repeated twice with randomly chosen set of parameter values within the specified range, to check whether the optimalization procedure converts to unique values. The final result therefore consists of 3 sets of parameter estimations for each measured soil sample. The quality of the obtained sets can be evaluated using the summed squared differences (R^2) between measured and fitted curves.

Apart from the R^2 the quality of the fits can be checked visually, which is even necessary because for calculation of the R^2 only differences between the measured and predicted outflow and retention are used. One check is to compare the measured retention points with the fitted soil water retention curve. Another check is comparing the calculated hydraulic conductivity curve with the independently measured conductivities of the modified crust method. Although the crust method only gives results for the lowest pressure heads, it can be used to judge the level of the fitted conductivity curve.

In total, parameter sets for 45 samples are available, divided over 3 soiltypes with each 3 layers, each layer containing 5 replications. Due to air leakages some samples are not taken into account in the further analysis, resulting in less samples for certain layers. The results of the fitting procedure, the estimated parameters and the R^2 for the best fit, are summarized in table 2, together with the results for fitting the parameters using the average outflow curve.

Results and discussion

After the parameter estimation for all layers, the best fit was selected based on the R^2 and visual checks. For the first 2 layers the obtained parameter sets are summarized in table 2. Using the parameter sets in combination with the equations of van Genuchten, continuous curves for soil water retention and hydraulic conductivity are plotted in figure 12 and 13. Measured and fitted outflow curves are visualized in appendix 6. The results for the third layer are added in appendix 7. Because field measurements for hydraulic conductivity only took place in the layers 0-30 and 30-60 cm, no independent checks are available. Results of water retention and bulkdensity measurements are added in appendix 8.

figure 12 : Water retention curves obtained by parameter estimation for the best fits per sample for the top- and subsoil of 3 soil types, including average-outflow data.

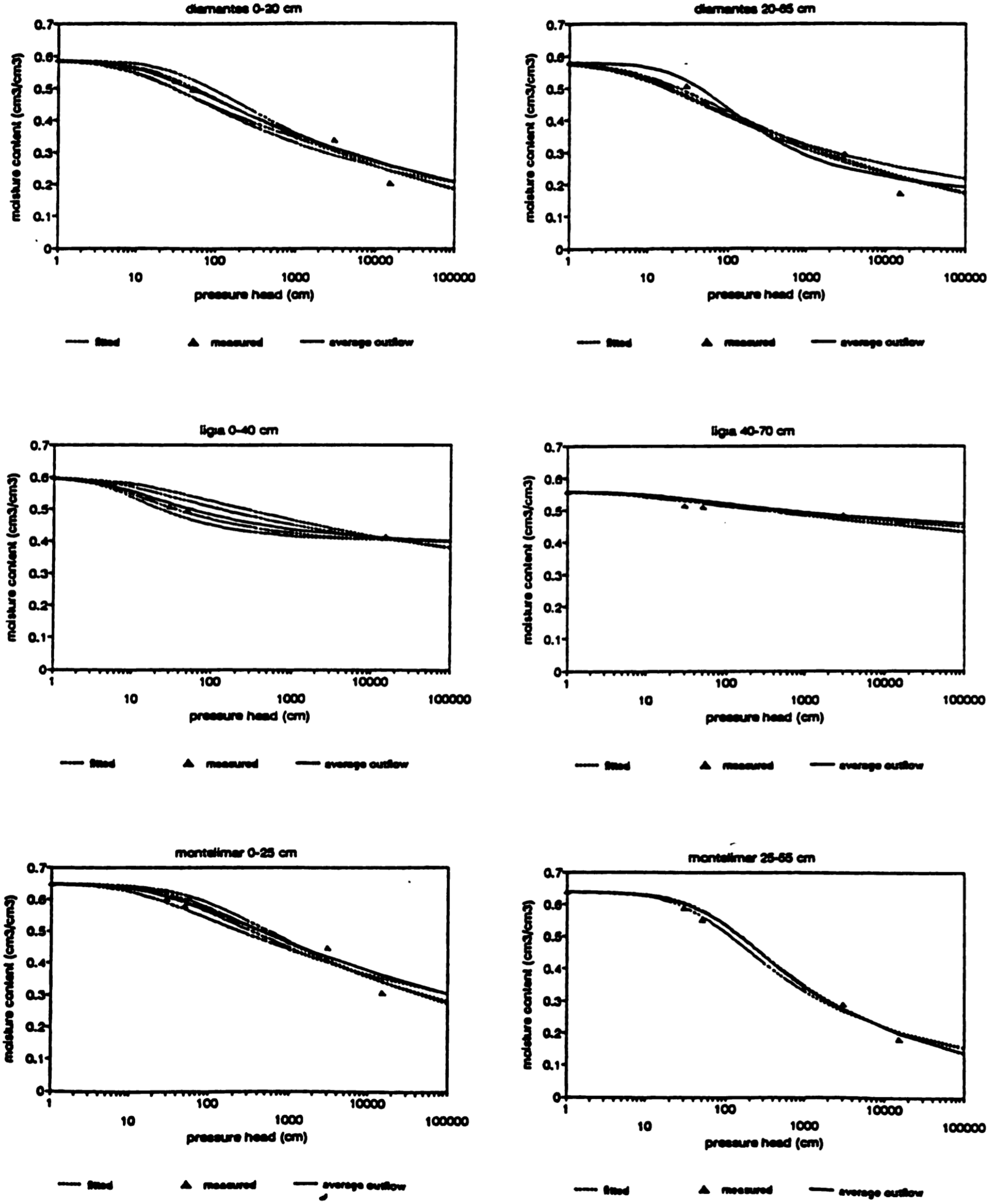


table 2 : VAN GENUCHTEN parameter sets for 3 soils in Costa Rica, best fit per sample

		ALFA	N	θ_r	GAMMA	R2
d0-20	1	0.0901	1.1668	0.094	4.0249	0.9867
	2	0.1341	1.1110	0.001	0.1139	0.9895
	3	0.0271	1.1503	0.001	14.1890	0.9939
	4	0.0498	1.1353	0.001	9.2900	0.9930
	av.outfl	0.0739	1.1187	0.005	3.5920	0.9926
	average	0.0753	1.1409	0.024	6.9045	
	st.dev.	0.0408	0.0205	0.040	5.3188	

		ALFA	N	θ_r	GAMMA	R2
d20-65	1	0.1418	1.1286	0.001	1.4316	0.9900
	2	0.1648	1.1240	0.001	1.0882	0.9940
	3	0.1017	1.1301	0.001	6.3268	0.9937
	4	0.1183	1.1870	0.143	0.5591	0.9882
	av.outfl	0.0269	1.3769	0.172	5.4629	0.9797
	average	0.1317	1.1424	0.037	2.3514	
	st. dev.	0.0239	0.0258	0.062	2.3161	

		ALFA	N	θ_r	GAMMA	R2
L0-40	1	0.1450	1.1397	0.304	0.0001	0.9905
	2	0.1837	1.3382	0.390	0.0008	0.9954
	3	0.1767	1.4726	0.400	0.0001	0.9952
	4	0.0996	1.0824	0.185	0.0001	0.9985
	5	0.1465	1.1632	0.338	0.0001	0.9992
	av.outfl	0.1703	1.2796	0.387	0.0001	0.9979
	average	0.1503	1.2396	0.323	0.0002	
	st. dev.	0.0298	0.1442	0.077	0.0003	

		ALFA	N	θ_r	GAMMA	R2
l40-70	1	0.2227	1.0443	0.201	0.0310	0.9911
	2	0.2235	1.0508	0.242	0.0001	0.9899
	3	0.2549	1.0477	0.252	0.0219	0.9933
	4	0.2616	1.0551	0.265	0.0001	0.9935
	5	0.2195	1.0661	0.325	0.0564	0.9900
	av.outfl	0.0955	1.1331	0.415	0.0128	0.9915
	average	0.2364	1.0528	0.257	0.0219	
	st. dev.	0.0180	0.0075	0.046	0.0211	

		ALFA	N	θ_r	GAMMA	R2
m0-25	1	0.0361	1.1015	0.001	4.0338	0.9936
	2	0.0662	1.1105	0.095	0.0097	0.9918
	3	0.0721	1.1229	0.146	0.0001	0.9911
	4	0.0229	1.1086	0.001	7.0090	0.9950
	5	0.0145	1.1194	0.001	17.4147	0.9958
	av.outfl	0.0359	1.0924	0.002	3.0393	0.9960
	average	0.0424	1.1126	0.049	5.6935	
	st. dev.	0.0230	0.0077	0.061	6.4279	

		ALFA	N	θ_r	GAMMA	R2
m25-55	1	0.0148	1.2419	0.034	14.8487	0.9893
	2	0.0208	1.2632	0.081	12.3302	0.9881
	3	0.0166	1.2126	0.001	16.1861	0.9928
	4	0.0138	1.2846	0.077	15.5521	0.9895
	av.outfl	0.0158	1.2390	0.034	15.4067	0.9060
	average	0.0165	1.2506	0.048	14.7293	
	st. dev	0.0027	0.0266	0.033	1.4637	

Water retention

In the graphs of figure 12, fitted soil water retention curves for all accepted samples, including the computed average outflow sample, are plotted. Also the measured retention points are plotted, of which the water content at 0.03 and 0.05 bar are average values.

Most fitted curves are in agreement with the measured points, showing only small variations between samples of one soil layer, although it should be stated that the measured points are used in the optimalization procedure to obtain the fitted curves. The fits based on an average outflow curves show, except for the Los Diamantes subsoil, good agreement with the individual samples and can be used as average fitted curves for all layers. The problem reported by Weitz (WEITZ, 1992), saturated water contents that were too high compared to water content values at slightly lower pressure heads, is not seen in this study, possibly due to the use of independently measured saturated water content as described before. However, some graphs show water contents at 3 bar that are too high compared to measured values at 15 bar (d0-20, d20-65, m0-25). The cause of this problem is not known, maybe another pressure was installed, maybe also equilibrium was not yet reached.

Probably due to intrinsic soil properties saturated and unsaturated water contents of all soils are very high, even at 15 bar. Extreme examples are the layers of the Ligia soil with water contents of 45-50 % in the high pressure range, indicating non-realistic available water contents. A possible explanation that equilibrium was not yet reached for these samples at the end of the experiment. Texture is not expected to be the cause of this problem, because the Ligia layers 40-70 and 70-90 cm showed the same texture as layers of Los Diamantes and Montelimar.

Número del perfil:	HL01
Clasificación	
PZA:	Los Diamantes
USDA Soil Taxonomy:	Eutric Hapludand
Fecha de la observación:	07-09-1992
Autor de la descripción:	H. Leummens
Ubicación:	Finca Los Diamantes
Hoja topografia:	Guapiles, hoja 3446N
Aproximadamente N:	248.10
E:	561.70
Altitud:	175 m
Unidad geomorfológica:	abanico aluvial
Forma del terreno circundante:	Casi plano
Microtopografía:	no
Pendiente:	casi llano, 2%
Vegetación o uso actual:	Banana, antes de 1984

INFORMACION GENERAL ACERCA DEL SUELO

Material de partida:	aluvion de composición andesitica
Drenaje:	4 (bien drenado)
Humedad del suelo:	Humido
Capa freática (in cm):	>120 cm
Fauna del suelo:	Lombrices, hormigas
Piedras en la superficie:	clase 0, muy pocas piedras.
Rocos en la superficie :	clase 0, muy pocas rocos.
Salis o álcalis en el perfil:	clase 0, libre de exceso de sales o álcali.
Erosión:	erosión hídrica, laminar, ligeramante
Sedimentación:	No

DESCRIPCION DE LOS HORIZONTES DEL SUELO

Horizonte 1:

Profundidad:	0-5
Color en húmedo:	(10 YR 2/2)
Manchas:	No
Textura:	Franco
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Moderada, fino, bloques sub angulares
Consistencia:	Ligeramente adherente y ligeramente plástico en mojado.
Poros:	Muchos, muy finos y finos, caoticos continuos, intersticiales, vesiculares y tubulares.
raíces:	abundantes, muy finas, finas, medianas y gruesas.
límite - anchura:	Neto
- topografía:	Plano
observación:	Ligaremente tixotropico

Horizonte 2:

Profundidad:	5-20 cm
Color en húmedo:	(10 YR 3/2)
Manchas:	No
Textura:	Franco a franco arenoso
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Moderada, en bloques sub-angulares muy fino.
Consistencia:	Ligeramente adherente y ligeramente plástico en mojado.
Poros:	Frecuentes a muchos, micro, muy finos y finos, caótic, continuos, vesiculares, intersticiales y tubulares.
raíces:	abundantes, muy finas, finas,medianes y grueses.
límite - anchura:	gradual
- topografía:	Ondulado
observación:	Ligeramente tixotropico

Horizonte 3:

Profundidad:	20-65
Color en húmedo:	(10 YR 3/3 a 4/3)
Manchas:	No
Textura:	franco arenoso
Grava y piedras - abundancia:	poca grava, sin piedras.
- forma:	roco, redondeado
Estructura:	débil, en bloques sub-angulares muy fina a migajose
Consistencia:	No adherente y ligeramente plástico en mojado.
Poros:	Frequentas, micro, muy finos y finos, caótic, continuos, intersticiales y tubulares.
raíces:	comunas a pocas, muy finas y finas
límite - anchura:	gradual
- topografía:	Ondulado
observación:	Ligeramente tixotropico

Horizonte 4:

Profundidad:	65-105
Color en húmedo:	(10YR 4/3)
Manchas:	No
Textura:	Areno francoso
Grava y piedras - abundancia:	poco grava, sin piedras
- forma:	roco, meteorizado
Estructura:	Débil, en bloques sub-angulares muy fino
Consistencia:	no adherente y no plástico en mojado
Poros:	Frequentas, micro, muy finos y finos, continuos, intersticiales y tubulares.
raíces:	Pocas a muy pocas, muy finas.
límite - anchura:	gradual
- topografía	ondulado
observación:	Ligeramente tixotropico

Horizonte 5:

Profundidad:	105-120
Color en húmedo:	(10YR 3/2)
Manchas:	No
Textura:	Arenoso grueso
Grava y piedras - abundancia:	con grava, pedregoso a muy pedregoso
- forma:	Roco, redondeado
Estructura:	Sin estructura, granular fina
Consistencia:	No adherente y no plástico en mojado.
Poros:	Observar la porosidad esta dificil.
raíces:	no raíces
límite - anchura:	
- topografía:	
observación:	Ligeramente tixotropico

Studying the obtained parameter sets in table 2 it can be seen that N converges to rather unique values, showing only small variations with small standard deviations, while α for some layers shows larger variations, for example d0-20 and m0-25. From the values for Θ_r it can be seen that this parameter does no longer represent the water content at 15 bar, because very low values are obtained. Also the standard deviations of this parameter are high indicating non-uniqueness, for example for d0-20, d20-65, m0-25 and m25-55. Statistical analyses still need to be done to study whether water retention curves for different layers and within one layer are significantly different.

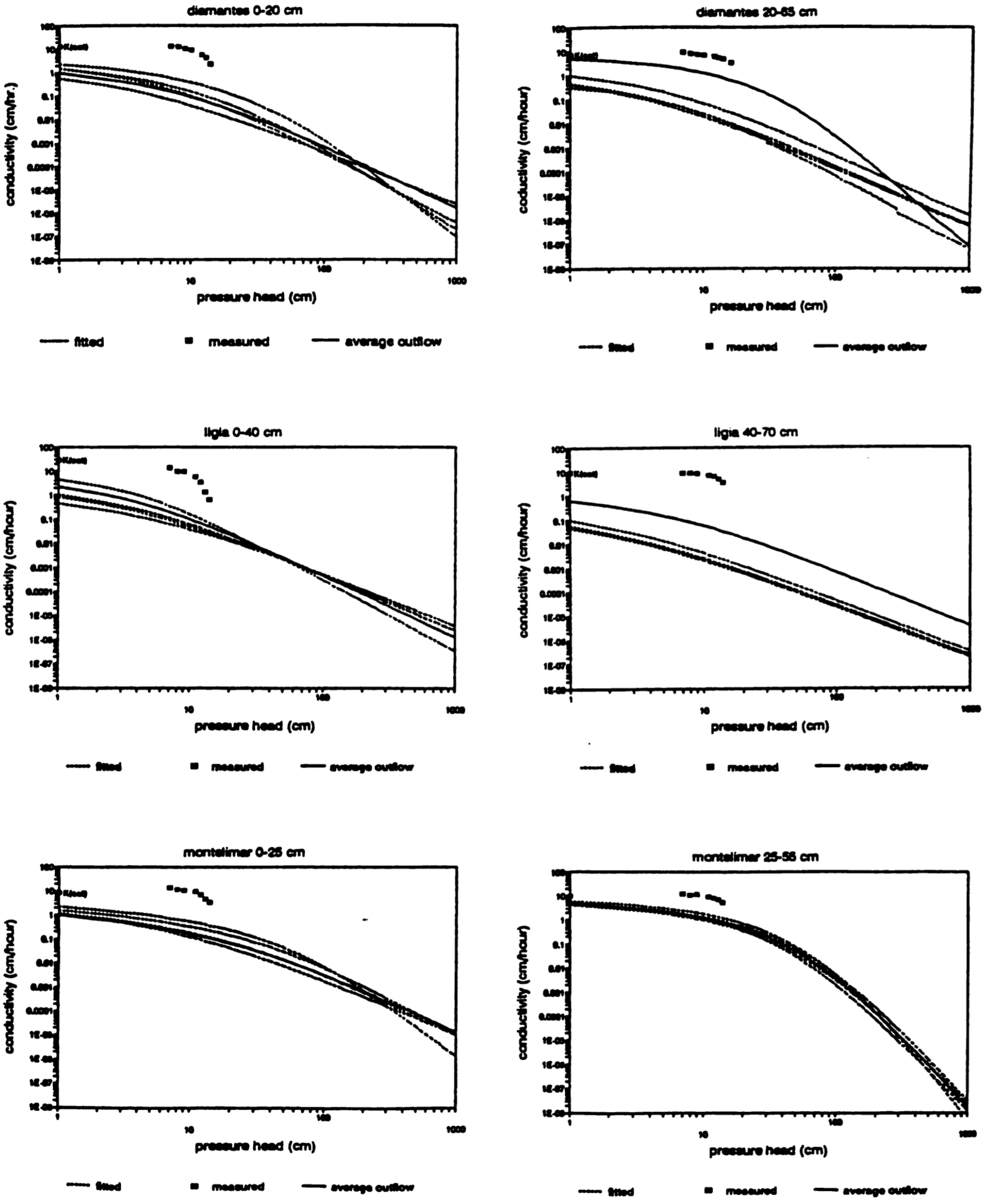
Hydraulic conductivity

In the graphs of figure 13 the hydraulic conductivity curves for all accepted samples, including the hypothetical sample with computed average outflow are plotted. Also included are the results of the modified crust method. For most layers fitted curves for individual samples show almost the same trend with increasing pressure head, although differences between curves are bigger than observed for the water retention curves. For the Los Diamantes and the Ligia subsoil layers the fits based on average outflow curves are not in agreement with the individual samples. The cause for this discrepancy is not known.

For all layers fitted curves show lower conductivities than independently measured points. Also for most layers the point of inflection of the fitted curves is found at higher pressure heads than for the measured points. Both problems are also visible in the results obtained by Weitz (WEITZ, 1992). However, it should be kept in mind that fitted curves are based on outflow data measured after a one-step change in pressure from 0.03 to 0.6 bar. Therefore, curves are only valid between these pressures, while for lower and higher pressure head ranges the obtained curves are extrapolated, also in the wettest part of the curve for which the field measurement are available. Probably differences in this wet part are caused by the strong macroporosity observed in the studied soils. Because almost all studied soils in the atlantic zone of Costa Rica show differences between fitted curves and measured points, it might be better to divide conductivity curves into two parts, based on field measurements for the range 0-0.03 bar and based on One-Step Outflow-data and parameter optimalization for the range 0.03-0.6 bar. Doing so, fitted curves resemble the empirical relations developed by Rijtema (RIJTEMA, 1969, in DRIESSEN & KONIJN, 1992), using a texture-specific suction boundary to make a division into a curved part for lower pressure heads and a linear part for higher pressure heads. Using measured data for simulation modeling can be done in a tabular form, or in a continuous form by fitting another type of curve through the points.

Looking at the obtained parameter sets in table 2, for N and α the conclusions are already discussed. For the parameter γ it can be seen that obtained values also show large fluctuations, resulting in high standard deviations, indicating the non-uniqueness of this fitting parameter.

figure 13 : hydraulic conductivity curves obtained by parameter estimation for the best fits per sample for the top- and subsoil of 3 soil types, including the average outflow. Field measurements are included (modified crust test).



How the underestimation of the obtained conductivity curves in the lowest pressure head range will influence the results of the soil-water-crop simulation model and the functional properties between the soil types is not known, because it is still difficult to import measured conductivity data into the model. An evaluation of these effects is only be possible when both methods can be used in the simulations. As with the water retention curves, a statistical analysis on significant differences between layers and within one layer still needs to be done.

comment

In general the One-Step Outflow experiment combined with the nonlinear parameter estimation procedure is useful to obtain continuous functions on soil water retention and hydraulic conductivity for a relatively large range in pressure head. Compared to other methods, input data are obtained fast while the number of samples handled simultaneously easily can be increased. To assure good input data, the sampling procedure and sample preparation are of crucial importance, to obtain good contact between sample and ceramic plate and to avoid a break in pore continuity.

In this study, fitting curves using measured outflow and water retention data was no problem, considering the outflow curves in appendix 6, the retention curves in figure 12 and the high R^2-values printed in table 2. Also the use of average outflow curves showed to give good results, although not for all layers. Making use of this average outflow could strongly reduce the amount of parameter estimation calculations necessary. However, the study showed problems fitting conductivity curves in agreement with independently measured field data, obtained by using the modified crust method. These problems might be caused by the specific soil types used, andosols and soils with andic properties. In these soils low bulk densities and high macroporosities leading to high values for water content and conductivity are observed, deviations from the circumstances for which the equations of van Genuchten were developed. The effect of the differences between fitted curves and measured points should be studied, to be able to decide to ignore it or to replace in the lowest pressure range fitted curves with measured curves.

There are some possible explanations for the problem that fitted outflow and retention curves are in good agreement with measured outflow and retention data, while fitted conductivity curves clearly do not follow measured points. First, only outflow and retention points are used in the fitting procedure. Second, only one parameter set is used to describe two curves with partly the same parameters, parameters which are also correlated. Therefore completely satisfying results are hard to obtain. Possibly the use of measured K(h) data may cause improvements in the fitting procedure, which also could influence the decision to replace the fitted curve with measured points in the lower pressure head range.

Studying the obtained parameter sets it can be concluded that unique sets are not obtained, although the fitted graphs show for all layers rather unique results for water retention are obtained. An explanation for this difference might be the correlation between the parameters. Still the statistical significance of differences between soil layers and within one layer needs to be studied.

CHAPTER 5 ANALYSIS OF FUNCTIONALITY

Introduction

Once for different soil types soil hydraulic properties are characterized, the variation between soil types can be studied using parameters relevant in the scope of the assessment of sustainable land use. Knowledge of variation is important to judge whether grouping of soil types is acceptable, to allow realistic scenario analyses.

To investigate the effect of variation of physical characteristics on simulation results, the determined hydrological characteristics are used as the only variable input parameter in the dynamic soil water simulation model LEACHW. The effect is analyzed regarding calculated functional properties which are directly related to practical applications (WÖSTEN, 1986) and of which it is expected that they play an important role in determining the suitability and sustainability of a particular type of land use. In this study the functional properties "relative evapotranspiration deficit", "relative transpiration deficit" and "quantity of percolating water" are used. Because running a simulation model for a perennial crop still is difficult, the analysis is done for maize, also grown in the atlantic zone although on a rather small scale.

The functional property "relative evapotranspiration deficit" is quantified by calculating the difference between potential and actual evapotranspiration during the growing period. This relative deficit can be expressed using the following relationship (DOORENBOS & KASSAM, 1979)

$$relative\ deficit = (1 - \frac{ET_a}{ET_m}) \qquad (10)$$

In this formula ET_a is the actual evapotranspiration and ET_m the maximum evapotranspiration of the crop. The obtained results can not be related to actual production losses as they occur in the atlantic zone, they only express the differences caused by differences in soil physical properties between the soil types. Because not actual evapotranspiration but actual transpiration is the factor directly related with the uptake of water by the crop (DRIESSEN & KONIJN, 1992), this factor is also expressed as a relative deficit compared with the potential transpiration.

To stress the environmental impact of a land utilization type in terms of possible leaching of nutrients and pesticides, the functional property "quantity of percolating water" is determined. Quantifying the amount of water passing the lower boundary of the soil profile is only part of the analysis, more information is required on land use and management, interactions between the solid and the liquid phase, solute concentrations and the flow of water in the saturated zone. This information was not gathered in this study, therefore also these results should be treated only as a general indication of differences between soil types.

Material and methods

The LEACHW model

The used model is part of the more general model LEACHM (Leaching Estimation And CHemistry Model, WAGENET & HUTSON, 1989, 1991), a simulation model describing dynamically the quantity and flow of water and the chemistry and transport of solutes in unsaturated or partly saturated soils. The different calculations on nitrogen transport and transformation, pesticide displacement and degradation, the movement of inorganic ions, the microbial population dynamics and the water regime can be used independently by making use of separated subroutines. In this study only the water regime is simulated.

Using a deterministic model like LEACHM requires the availability of a wide range of input data, most of which were not directly measured for the soils and the region under observation. Still running this simulation model is useful to study the effect of variance in soil hydraulic properties on properties of more practical significance, to decide on the level of aggregation of soil types used in simulation modeling. However, the background of the model calculations should always be kept in mind, because the assumptions done strongly influenced the final results. Using different assumptions or field measurements may lead to different results and therefore to different conclusions.

To simulate dynamically the flow of water through the soil, the subroutine LEACHW calculates the water balance equations in variable time steps of maximal 0.1 day, for thin layers of 5 cm. Actual transpiration and evaporation are calculated using water potential in the root, flow coefficient in the plant, matrix potential, conductivity, the fraction of roots present in the specific soil layer and the maximal evaporative flux density possible from the soil surface. Interactively, using finite differencing techniques the Richard's equation is solved, describing the change in water content and fluxes for all small layers in the soil. Starting point of the calculations are initial soil water pressure heads and equations for soil water retention and conductivity. More details on the differencing technique and the solution procedure can be found in the reference manual (WAGENET & HUTSON, 1989, 1991).

To be able to run LEACHW for the soils under observation three types of general information are needed. First, information on local soil conditions and the behavior of water is necessary, on boundary conditions, water retention and hydraulic conductivity. Second, information on the climate, the potential evapotranspiration of a grass reference crop (ET0) and precipitation. Third, information on the crop maize is needed, about the growing period, root development, ground coverage and the number of plants per m^2.

Soil data

In the simulation runs performed for the costarican soils free drainage was used as lower boundary condition. This assumption is in accordance with a groundwater table at great depth, as observed during field investigations. To simulate the upper boundary flux of water, information on precipitation rates is necessary. Because this information was not available from meteorological data, it was assumed that precipitation rates were 10 times as high as the quantity, resulting in a concentration of the day's precipitation in one time step. Because information on the hour of precipitation also was not available, use was made of a random generator to define the precipitation to one specific time step.

In the original LEACHW version Campbell's equations for retentivity and conductivity are used. These equations were replaced by the closed-form equations of van Genuchten (VAN GENUCHTEN, 1980), to be able to use the parameters, obtained with the SFIT procedure, for the different soil types.

To assure a good dynamic equilibrium between the soil water status and precipitation and evapotranspiration, model simulations are started two months before the growing season. Regarding the absence of a distinct dry period the initial water status was set at field capacity, -0.12 bar.

Climate data

In order to be able to simulate the waterflow in the soil, input is needed on precipitation and potential evapotranspiration in mm/day, for a reference crop (ET0). Because ET0-data were not directly available from meteorological records, basic climatological data were used to calculate ET0 according to the Penman-Montheith-equation (SMITH, 1991).

$$ETO = \frac{(0.408 * \Delta * R_n) + (\gamma * (\frac{900}{T_{gem}+273}) * U_2 * (e_a - e_d))}{\Delta + \gamma * (1 + 0.34 * U_2)} \tag{11}$$

In this equation R_n is the net radiation ($MJ.m^{-2}.day^{-1}$), Δ the slope of the vapor pressure curve ($KPa.°C^{-1}$), γ the psychrometric constant ($kPa.°C^{-1}$), T_{gem} the average daily temperature (°C), U_2 the average windspeed at 2 m height ($m.s^{-1}$), e_a the saturated vapor pressure (KPa) and e_d the actual vapor pressure (KPa).

Basic climatic data of the station "Hacienda el Carmen" were used in the simulation procedure. Although this station is situated more close to the coast then the sites under investigation, it is the closest station with sufficient data over an extensive period of time. Due to the availability of 20 year record average and extreme years could be selected. Using the data of El Carmen it should be kept in mind that differences in climate exist within the atlantic zone, mainly for windspeed and precipitation. Windspeed decreases going from the coast to the inland. Precipitation varies from one place to another and from year to year, governed by temporals with a more regional character and heavy downpours acting more locally (VAN SEETERS, 1992). Notwithstanding this restriction the quantitative results of the simulation procedure still can be used to compare the different soil types.

Used datafiles contained missing values which needed to be replaced in order to obtain a usable inputfile for calculation of the ET0. Because windspeed was only measured in 1991, these values were considered to be representative for all selected years. Finally, calculated ET0 values where grouped into weekly totals to serve as input for LEACHW.

To correct ET0-values into potential evapotranspiration for the actual crop a "pan factor" is used, equal to 1, referring to empirical data for the period of vegetative growth to yield formation. Weekly data of potential evapotranspiration for a reference crop are used to calculate daily potential evaporation and transpiration, using the pan factor and a crop-cover factor. Daily potential evaporation and transpiration values are transformed into values per time step, assuming that evapotranspiration only takes place during the day and follows a sinusoidal progression. Integration between time limits yields the potential evaporation and transpiration flux per time step. Calculated weekly values for the ET0 are added in appendix 10, together with the yearly total and the total during the growing season.

To evaluate the effect of the calculated soil hydraulic properties years with different climatic conditions were used. Three years were selected: the relative wet year 1991, the dry year 1985 and the intermediate year 1988. Looking more closely to the rainfall quantities showed that in 1988 the growing season was dryer than 1985. The values are presented in table 3 while the rainfall distribution during the growing season is added in appendix 9.

Table 3 : Amount of precipitation and evapotranspiration for three years and growing seasons (from may, 1st until september, 15nd).

year	total prec. (mm)	prec. in growing season (mm)	total evapo-transp. (mm)	evapotransp. in growing season (mm)
1985	2810.1	1393.1	1800.5	560.0
1988	3602.2	1022.4	1843.6	677.2
1991	4077.4	2088.2	1763.8	588.3

Crop data

To be able to investigate the effect of soil hydrological characteristics on crop production, the growth of maize was simulated, assuming that the crop was sown on may 1st, that germination took place on may 9nd (day 8), that the crop was mature on august 19nd (day 110) and was harvested on september 3nd (day 125). Assumed was a crop density of 25.000 plants/ha (DOORENBOS & KASSAM, 1979). Crop cover was considered as a fraction varying between zero at the start of the growing season and 1 at maturity.

The cover fraction was described by an empirical sigmoidal curve, depending on the length of the growing period (t_2) and the time elapsed since germination (t_1) (WAGENET & HUTSON, 1991).

$$Crop\ cover = \frac{Crop\ cover\ at\ maturity}{1+\exp\left(6-\left(\frac{12\,t_1}{t_2}\right)\right)} \tag{12}$$

Together with the calculated weekly, crop-specific ET0 the fractional crop cover is used to calculate the potential daily transpiration, according to

$$T_{day} = \left(\frac{ET0_{week}*panfac}{7}\right)*crop\ cover \tag{13}$$

Potential evaporation from the soil surface is calculated as the difference between the daily crop-specific ET0 and the daily potential transpiration.
Root growth was simulated, using equations for maize root growth (DAVIDSON et al, 1978). Root density in these equations is considered as a function of time and depth. In these equations the effect of water content, soil strength and availability of nutrients on the development of roots and shoots are not taken into account, but considered to be optimal. The relative rooting depth, used to compress or expand the root distribution was taken equal to 1, in accordance with the value used by Davidson.

Simulation results

Simulation results for different soil types and growing seasons can be expressed in terms of the water balance, as presented in appendix 11. Quantitative results are grouped in table 4. The results will be studied in more detail using evapotranspiration and transpiration deficits and the quantity of leached water.

Analyzing the results for one growing season shows that potential evaporation and transpiration are soiltype independent, in accordance with the calculation procedure. Potential transpiration depends only on the evapotranspiration of a reference crop (ET0), the pan factor and the crop development factor, which are assumed equal for the three soil types and only depends on the day in the growing season. Potential evaporation is calculated as the difference between ET0 and potential transpiration. Actual evaporation and transpiration, however, are soil type dependent, because the availability of water for the crop is influenced by soil water retention and hydraulic conductivity. Table 4 shows that differences in actual transpiration after one growing season are very small, indicating that differences in soil physical properties are not translated to differences in uptake of water. More differences can be seen in actual evaporation, of which the cause is not known, because precipitation is constant and differences in transpiration and percolation are small. For all seasons actual evaporation is the lowest for the Ligia soil and the highest for the Montelimar soil. Actual evaporation, however, is the highest in 1991.

table 4 : LEACHM simulations of cumulative potential and actual transpiration and evaporation (mm), for 3 growing seasons and 3 soil types.

		dia	lig	mont		dia	lig	mont
1985	T-act	278.9	278.2	279.4				
	E-act	201.3	184.8	215.7	ET-act	480.2	463.0	495.1
	T-pot	295.8	295.8	295.7				
	E-pot	290.4	290.4	290.4	ET-pot	586.2	586.2	586.2
1988	T-act	327.2	326.4	327.7				
	E-act	204.5	179.7	236.6	ET-act	531.7	506.1	564.3
	T-pot	343.6	343.6	343.6				
	E-pot	324.4	324.4	324.4	ET-pot	668.0	668.0	668.0
1991	T-act	273.0	270.1	262.3				
	E-act	234.5	220.8	251.2	ET-act	507.5	490.7	513.5
	T-pot	296.1	296.1	296.1				
	E-pot	281.5	281.5	281.5	ET-pot	577.6	577.6	577.6

Between the growing seasons, differences in actual and potential evaporation and transpiration can be seen. The potential evapotranspiration differs due to variations in incoming radiation, while pan factor, sowing date and crop development are constant factors and the calculation is soil type independent. The highest potential transpiration and evaporation can be seen in 1988, the driest season with probably less clouds and consequently more direct radiation, while there is no difference between 1985 and 1991. Also differences in actual transpiration and evaporation can be seen, due to differences in precipitation between the growing seasons. Precipitation influences the moisture status of the soil and therefore also the availability of water for the crop, the evaporation at the surface and percolation to the subsoil. As with potential transpiration, also actual transpiration is the highest in 1988, the driest growing season, while 1985 and 1991 show almost identical results. The obtained differences are used to calculate the functional properties "relative evapotranspiration deficit", "relative transpiration deficit" and "quantity of percolating water".

To obtain the relative evapotranspiration deficit, the simulated daily actual transpiration and evaporation values are summed to obtain one cumulative value per growing season. Using the daily values is not considered, because no information is available on the possibility of plants to correct a short transpiration deficit with an increased uptake of water (BOOLTINK, pers. comment). The simulated relative evapotranspiration deficits are summarized in table 5.

table 5 : relative cumulative evapotranspiration deficit for maize in Costa Rica as simulated with LEACHM, for 3 soil types and 3 growing seasons (fraction)

	1-(ET-act/ET-pot)		
	Diamantes	Ligia	Montelimar
1985	0.18	0.21	0.16
1988	0.20	0.24	0.16
1991	0.12	0.15	0.11

Relative evapotransporation deficits in table 5 show the lowest value for the Montelimar soil, in all growing seasons, while the highest deficits are observed in the Ligia soil. Differences between soil types are somewhat smaller than differences between growing seasons. Studying the differences between the growing seasons it can be concluded that a lower evapotranspiration deficit is observed in growing seasons with higher amounts of precipitation, indicating an effect of droughtness. In general the deficits are rather high, 15-20%, regarding the high precipitation quantities in the atlantic zone.

Because plant assimilation and therefore crop production is only a function of transpiration and not of evapotranspiration (DRIESSEN & KONIJN, 1992), also a relative transpiration deficit is calculated. Results of these calculations are added in table 6.

table 6 : Relative transpiration deficit for maize in Costa Rica, as simulated with LEACHM for 3 soils and 3 growing seasons (fraction).

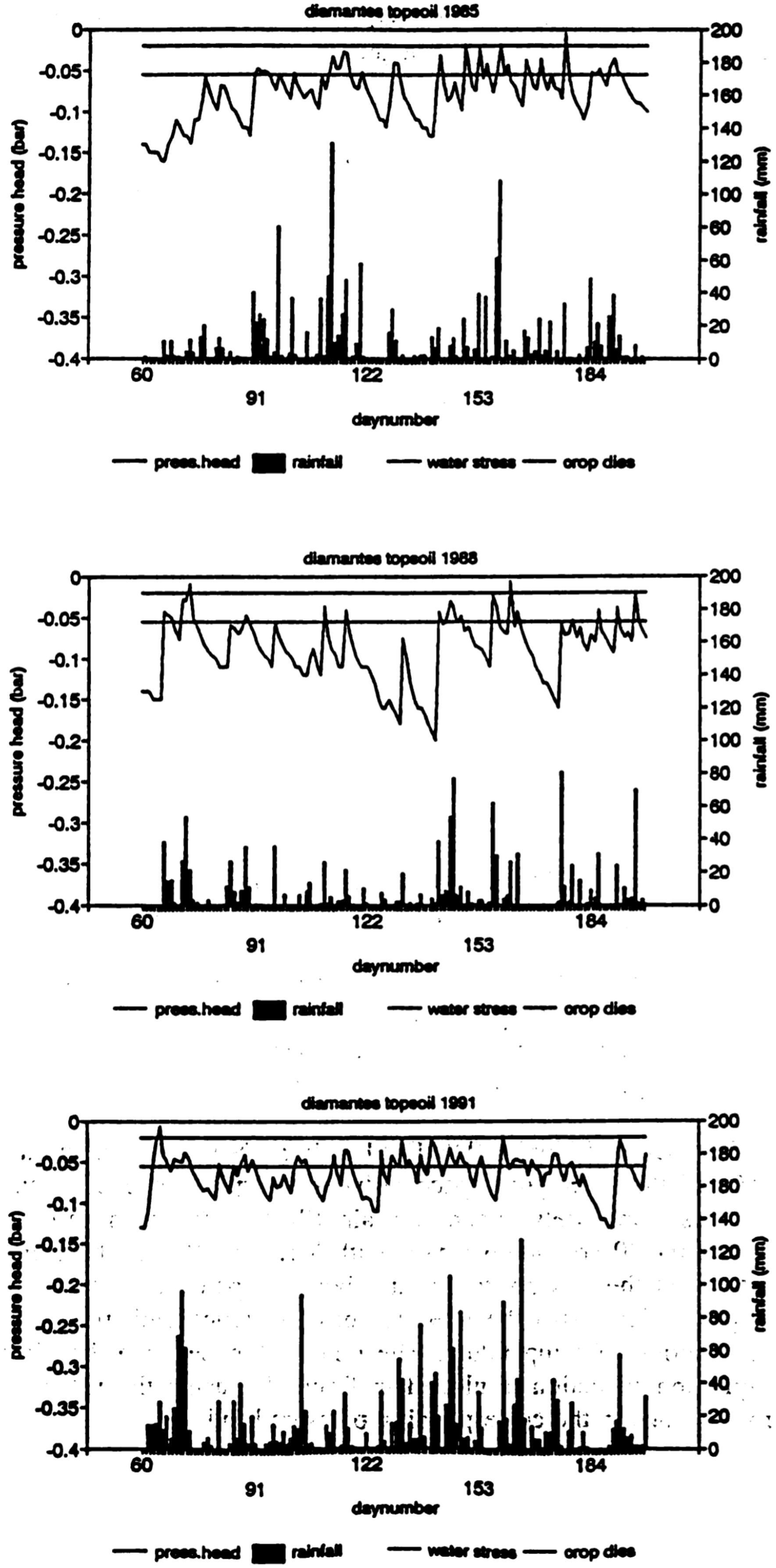
year	soil type Diamantes	 Ligia	 Montelimar
1985	0.057	0.059	0.055
1988	0.048	0.050	0.046
1991	0.078	0.088	0.077

Relative transpiration deficits in table 6 show much smaller values than the evapotranspiration deficits, due to the fact that evaporation added most to the observed differences in evapotranspiration. Again clearly differences between soil types are smaller than differences between growing seasons. However, now seasons with the lowest amount of precipitation give the lowest deficit, indicating that not water shortage but anaerobiosis determines the final deficit. Combined with much lower absolute values for the deficit, this conclusions seems more realistic for the costarican situation, regarding the high amount of precipitation and the high hydraulic conductivities in the lowest pressure range.

The conclusion that a relative reduction in transpiration is caused by anaerobiosis is supported by the simulated daily soil water pressure heads in the different topsoils. In figure 14 values for the soil type Los Diamantes are plotted, for 3 growing seasons. Results for the soil types Ligia and Montelimar can be found in appendix 11.

According to Driessen and Konijn (DRIESSEN & KONIJN, 1992), an air filled pore space lower than 8% of the total pore space reduces transpiration due to anaerobiosis, while transpiration stops completely when the air filled pore space falls below 4%. Also assumed is that after 20 consecutive days with less than 4% air the plant will be dead. It should be noted that there is no consensus about the percentage of oxygen necessary for optimal crop production. Also the need for oxygen varies with root activity in time, for example as a function of temperature. The relationship between the air filled pore space and the transpiration reduction is plotted in figure 14, using the fitted average soil water retention curves to obtain the corresponding pressure head.

figure 14 : Pressure head variation in 3 growing seasons, as simulated with LEACHM, for the soil type Los Diamantes.



Fom figure 14 it can be concluded that within one growing season pressure head values range from 0.04 to 0.2 bar, influenced by the time and amount of precipitation. During the growing season transpiration is reduced due to anaerobiosis, for periods up to 7 days.For shorter periods of 1-2 days transpiration even stops completely. Studying differences between growing seasons, it shows that higher amounts of precipitation result in more days with reduced transpiration and therefore also in a higher cumulative transpiration deficit at the end of the season. Combining figure 14 and appendix 11, for one growing season differences between soil types are rather small, although the Ligia soil type shows slightly wetter soil conditions throughout the growing season, while the Montelimar soil type is somewhat dryer. The differences between growing seasons and soil types support the calculated results of table 6, the amount of precipiitation being more important than soil type specific physical properties.

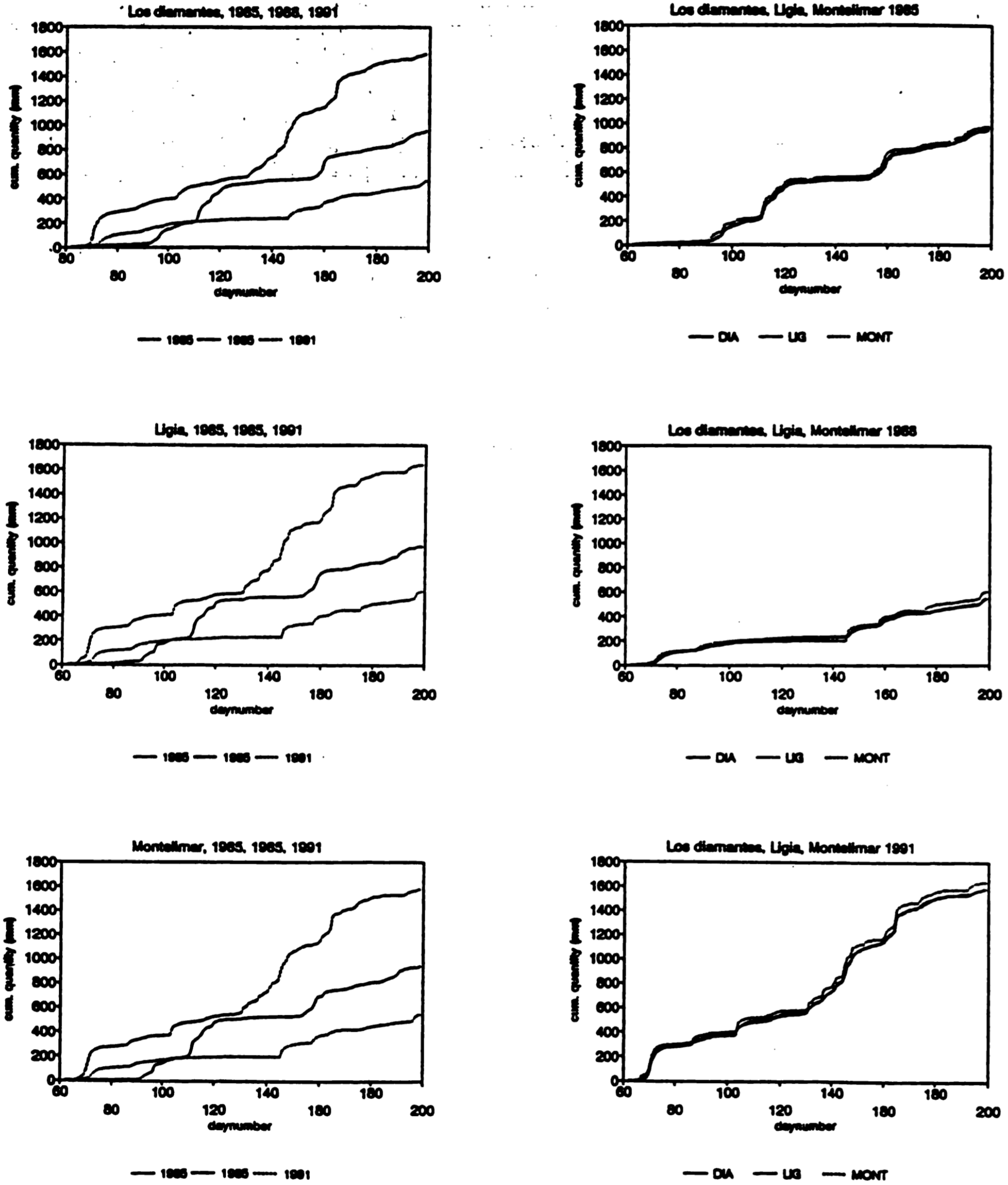
The second functional property that was analyzed using the LEACHW model is the "quantity of percolating water" at the lower boundary of the profile. Values for the cumulative quantities in mm can be found in table 7 while figures for the different growing seasons and soil types are grouped in figure 15.

table 7 : Quantity of percolating water as simulated with LEACHM for 3 soil types and 3 growing seasons (mm).

	soil type		
year	Diamantes	Ligia	Montelimar
1985	952	968	944
1988	544	602	544
1991	1580	1636	1577

Table 7 shows a clear relationship between the amount of rainfall in the growing season and the leaching quantity below the profile, being the lowest in 1988 and the highest in 1991. Again differences between soil types in one growing season are very small, although for the calculated seasons the Ligia soil shows slightly higher values than the Diamantes and Montelimar soil. It should be kept in mind that for the different soil types the profile depth for percolation is not the same, due to the concept of soil horizons as it was used in the simulation model. Therefore part of the differences will be caused by differences in water storage in the profile, although this is expected to be of minor importance, considering the high percolation quantities and the moist soil conditions. Figure 15 shows that rainfall distribution strongly influences the pattern of leaching over the growing season, although there is a shift in time of peaks and valleys due to the necessary time water needs to flow through the soil.

figure 15. : Simulated quantities of percolation water for 3 soil types and 3 growing seasons.



Comment

This study showed the possibilities of using quantified soil physical characteristics in a soil-water-crop simulation model, to characterize soil types on functional properties, to be used as a tool in decision taking.

It showed that for the soils used in this study differences in functional properties were small, compared with differences observed between growing seasons with a range in amount of precipitation. Therefore for physical characteristics it may be concluded that the 3 soil types with the same type of land use can be grouped into one major soil group, with uniform physical characteristics. Although only 3 soil types out of the major group of fertile, well-drained soils are studied, the results are an indication that for one type of land use grouping of soil types into this major group is acceptable.

However, it should be stated that the effect of water in the soil on transpiration and evaporation in the LEACHW model is not completely understood, especially the situation of excessive wetness as was the most important for the costarican situation. The calculation procedure is however of crucial importance for a proper interpretation of the final results, and should therefore be studied. Possibly also another model with more clearly defined crop growth and stress factors needs to be used.

Also the significance of observed differences in soil physical properties still needs to be investigated, between different curves for one soil type as well as between soil types.

CHAPTER 6 PEDOTRANSFER FUNCTIONS

Introduction

Because obtaining and interpreting soil physical characteristics is rather laborious and time consuming, it is difficult to expand measurements to larger areas or more different soil types. Therefore effort is put in relating soil physical characteristics with easily measured basic soil characteristics, creating so-called "pedotransfer functions" (BOUMA & VAN LANEN, 19.., WöSTEN & VAN GENUCHTEN, 1988). The choice between using measured or calculated soil physical characteristics will depend on the amount of extra effort for measurements compared with the improvement of the results obtained (BOUMA, 1988).

Because in this study the soil physical properties hydraulic conductivity and water retention are expressed using van Genuchten's equations and parameters, it is tried to find individual continuous pedotransfer functions between easily obtainable basic soil data and the parameters. Use is made of standard regression techniques.

Theory

Finding linear relations between fitted "van Genuchten" parameters and easily obtainable soil data is done using a multiple regression technique based on the Ordinary Least Square approach (OLS). The linear multiple regression model involving the dependant variable Y and p independent variables $X_1, X_2, ..., X_p$ can be written as (DILLON & GOLDSTEIN, 1984)

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_p X_{pi} + e_i \qquad i = 1,2,\ldots,n \qquad (14)$$

where β_0 denotes the intercept, $\beta_2,...,\beta_p$ are the partial regression slope coefficients and ε_i is the residual term associated with the i-th observation. The OLS procedure consists of choosing values for the unknown β parameters so that the residual or error is as small as possible. The OLS method rest on a number of assumptions which, when they are satisfied, make the OLS estimators the "best linear unbiased estimators" (BLUE), estimators that are linear, are unbiased and that have minimum variance. Those assumptions are (DILLON & GOLDSTEIN, 1984)

1 - The expected value of the residual vector ε is zero.
2 - There is no correlation between the i-th and the j-th residual term.
3 - Residuals exhibit constant variance.
4 - The covariance between the X's and the residual terms ε are zero.
5 - The rank of the regression equations is less than the number of observations, so that an exact linear relationship is not possible.

In this study it is assumed that the estimators may be considered as BLU.

To examen the goodness of fit, use is made of the squared multiple correlation coefficient, R^2, which represents the proportion of total variability that is accounted for by the regression model. The R^2 is defined as

$$R^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{\sum (Y_i - \bar{Y})^2} \qquad (15)$$

in

which Y is the mean of the measured dependant variable, Y_i is the measured value of Y at point i and $\hat{Y}$ is the estimated value at the same point i.

Because the R^2 in general only gives the appropriate value for the limited number of data used, but overestimated the goodness of fit for the infinite population, and also can be increased artificially by increasing the number of variables included in the regression model, it is preferred to make use of the adjusted squared multiple correlation coefficient R_a^2 (NORUSIS, 1988). The R_a^2 is defined as

$$R_a^2 = R^2 - \frac{p(1-R^2)}{n-p-1} \qquad (16)$$

where n is the number of observations and p is the number of parameters in the model, including the intercept term.

The obtained estimates for the β's, the partial regression coefficients b_0, b_1,...b_p, individually can be tested on their statistical significance using a Student's t-test, with the H_0 hypothesis that $\beta_i = 0$. Also the 95% confidence interval can be calculated, according to (DILLON & GOLDSTEIN, 1984)

$$b_i \pm t(\frac{\alpha}{2}; n-p) s \sqrt{c_{ii}} \qquad (17)$$

where s is the standard error, the square root of the estimated variance σ^2, and c_{ii} is the variance of the i-th point estimate

Apart from testing individual partial regression coefficients also the overall significance of the sample-based regression model can be tested, using a simultaneous hypothesis $H_0 : \beta_1 = \beta_2 = ... = \beta_p = 0$. In words this test evaluates the linear relationship between Y and the set of X's, which can be done comparing a calculated F-value with the tabulated value of the F-distribution with p-1 and n-p degrees of freedom. To calculate the F-value use can be made of the relationship with the R^2, according to

$$F = \frac{R^2/(p-1)}{(1-R^2)/(n-p)} \qquad (18)$$

If the calculated F-value exceeds the critical tabulated value at the α-percent level of significance, H_0 is rejected, otherwise it is accepted.

Also the 95% confidence interval for a predicted value of Y, given a predetermined set of values for the X's. The mean value of this Y is estimated using the determined b-values, while the variance can be calculated according to

$$var(\hat{\mu}) = (X_E(X'X)^{-1}X_E')\sigma^2 \tag{19}$$

The 95% confidence interval for the mean value of Y at X_E can than be calculated according to

$$\hat{\mu}_0 \pm t(\frac{\alpha}{2};n-p)s\sqrt{X_E(X'X)^{-1}X_E'} \tag{20}$$

Materials and methods

To build a multiple linear regression model with minimum error, use was made of the statistical package SPSS/PC+ (NORUSIS, 1988). To obtain the best model different variables were introduced "stepwise", using the calculated simple correlation coefficients between each explanatory variable and the dependent variable. The explanatory variable with the highest correlation coefficient was entered first, followed by one variable at each successive stage, according to their squared partial correlation coefficient in which the effect of the variables already made part of the model has been removed. The variable with the largest squared partial correlation coefficient is entered at a given step, as long as the calculated F-value exceeds the predetermined tabulated 95% F-value. The process is terminated when no remaining variable can be entered, according to its computed F-value and the critical F-to-enter value.

To do the analyses, use is made of bulk density measurements, resulting from the One-Step Outflow analyses, organic matter content and texture analyses on % clay, % silt, % sand. All used explanatory and dependent variables were also used in logarithmic and squared form. Due to the fact that for all layers only one analysis on texture and organic matter was available, it was possible to relate only one set of "van Genuchten" parameters with these results. Therefore no use could be made of the observed range in VG-parameters within one soil layer.

Use was made of the following data set, with the VG-parameters obtained using the average outflow quantity in time.

figure 16 : Linear regression and confidence intervals between "van Genuchten" parameters and basic soil properties.

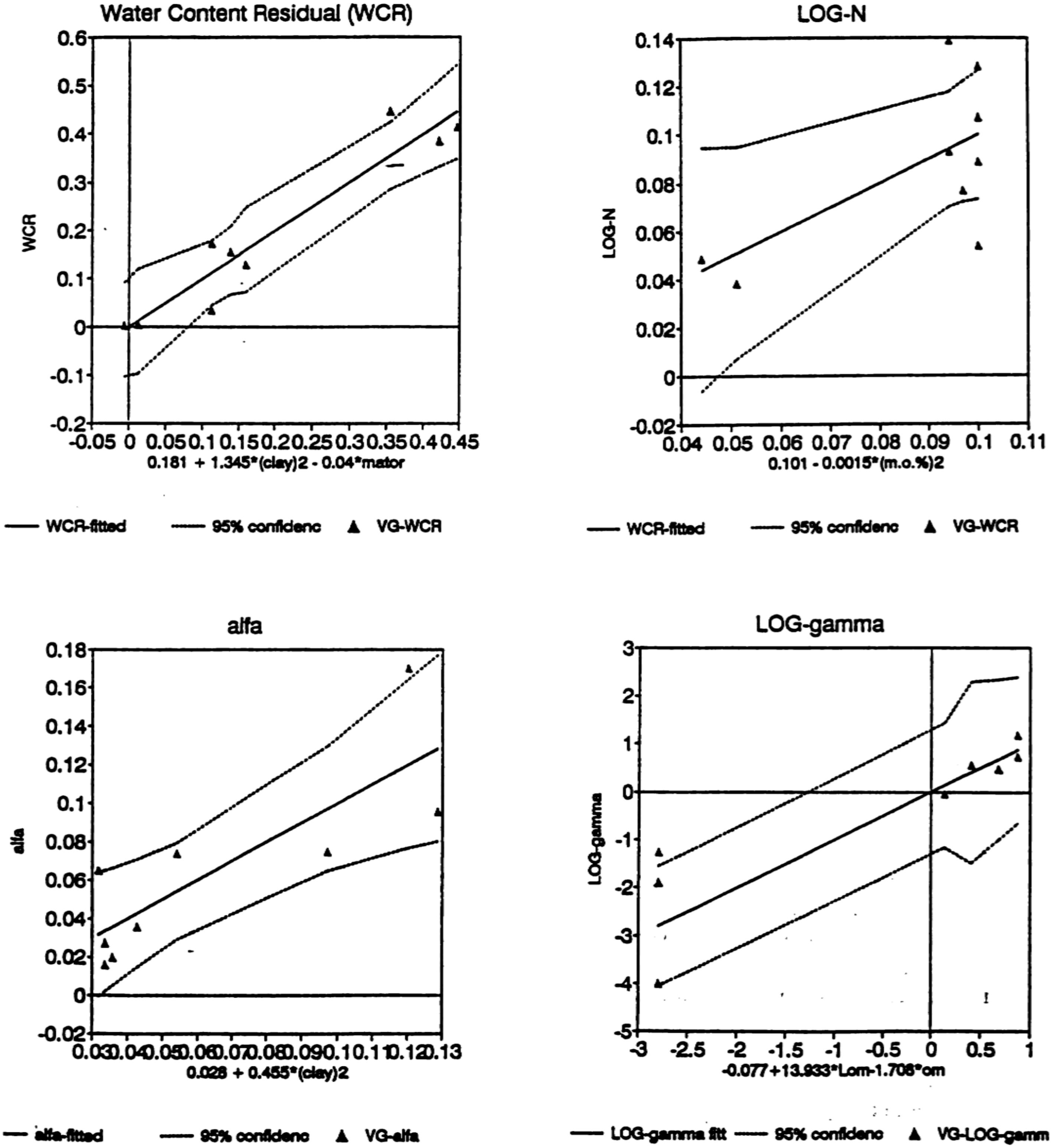


table 8 : Data set used to generate pedotransfer functions

soil type	"van Genuchten" parameters				soil data				
	alfa	N	Θ(s)	τ	bulk dens.	% o.m.	% clay	% silt	% sand
D 0- 20	0.0739	1.1187	0.0049	3.5920	0.81	6.16	0.24	0.09	0.67
D 20- 65	0.0269	1.3769	0.1720	5.4629	0.91	2.14	0.11	0.14	0.75
D 65-105	0.0652	1.3435	0.1290	0.0001	1.17	0.80	0.09	0.09	0.82
L 0- 40	0.1703	1.2796	0.3867	0.0001	0.86	0.80	0.45	0.31	0.24
L 40- 70	0.0955	1.1331	0.4147	0.0128	1.12	0.80	0.47	0.13	0.40
L 70- 90	0.0748	1.2266	0.4454	0.0554	1.12	0.80	0.39	0.05	0.56
M 0- 25	0.0359	1.0924	0.0021	3.0393	0.72	5.77	0.18	0.22	0.60
M 25- 55	0.0158	1.2390	0.0342	15.4067	0.71	2.14	0.11	0.25	0.64
M 55- 80	0.0199	1.1941	0.1552	0.9013	1.16	1.65	0.13	0.27	0.60

Results and discussion

The approach of stepwise introducing explanatory variables resulted in the best model equations as given in table 9. For the parameters α, WCR and LOG(γ) the linear relations are obtained with a reliability of 95%. For N however this was not possible, therefore a reliability of 90% was accepted. The goodness of fit and the significance of the obtained regression functions are given in table 10, while the 95% confidence intervals for the b's are given in table 11. The 95% confidence intervals for the whole curves are visualised in figure 16.

table 9 : Best linear continuous pedotransfer functions relating "van Genuchten" parameters with measured basic soil properties.

$$\alpha = 0.028 + 0.455*(\text{clay }\%)^2$$

$$WCR = 0.181 + 1.345*(\text{clay}\%)^2 - 0.040*(\text{o.m.}\%)$$

$$LOG(\gamma) = -0.077 + 13.933*LOG(\text{o.m.}\%) - 1.709*(\text{o.m.}\%)$$

$$LOG(N) = 0.101 - 0.0015*(\text{o.m.}\%)^2$$

table 10 : Obtained squared and adjusted squared correlation coefficients, and calculated and tabulated F-values for the different VG-parameters.

	n	p	df	R^2	R_a^2	F_{calc}	F_{tab}
ALFA	9	2	7	0.67	0.62	14.14	5.59
WCR	9	3	6	0.91	0.89	32.13	5.14
LOG(γ)	9	3	6	0.80	0.74	12.31	5.14
LOG(N)	9	2	7	0.43	0.34	5.19	3.59

table 12 : Regressed b-values and their 95% confidence intervals (90% for N) for the different VG-parameters.

	β_0	β_1	β_2
ALFA	0.028 ± 0.033	0.455 ± 0.286	--
WCR	0.181 ± 0.107	1.345 ± 0.646	-0.040 ± 0.026
LOG(γ)	-0.077 ± 1.927	13.933 ± 9.272	-1.709 ± 1.569
LOG(N)	0.101 ± 0.027	-0.0015 ± 0.0016	--

As can be seen from table 12, confidence intervals are rather wide, due to large standard errors used to calculate the intervals. Table 10 shows that the overall obtained regression functions however are significant at the applied confidence level. The value for the adjusted R^2 shows that for the Water Content Residual (WCR) the used variables explain for most of the variance observed in this dependent variable. For the LOG(γ) also a satisfying result is obtained, but for α and especially LOG(N) no variables could be found to obtain linear relations that describe the variation in the dependent variable sufficiently.

Figure 12 confirms the results from the different tables, the confidence intervals for the VG-parameters described with a linear relation are rather wide. Together with the wide intervals for the individual β's this means that using more easily obtainable soil data does not give unique VG-parameters, the same combination of basic soil properties can be expressed as a range in VG-parameters. More investigations are necessary to obtain information on the influence of the range in VG-parameters on the functions for hydraulic conductivity and water retention and consequently the simulation of crop growth. One also should remember the correlation between different VG-parameters, different combinations may show the same type of functions for hydraulic conductvity and water retention. For the use of pedotransfer functions on regional level it is necessary that more data points are gathered and that also more different soil and land use types are used in the regression analyses, in which attention should be paid to the need for and possibilities of creating subgroups. Also attention should be paid to the range in basic soil properties and VG-parameters within one soiltype or soil layer.

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APPENDICES

APPENDIX 1 : Profile descriptions of 3 soil types

1 - Los Diamantes
2 - Ligia
3 - Montelimar

Número del perfil:	**HL03**
Clasificación	
PZA:	**Ligia**
USDA Soil Taxonomy:	**Typic Dystropept**
Fecha de la observación:	**06-10-1992**
Autor de la descripción:	**H. Leummens**
Ubicación:	**Finca Teresa, 50 m oeste del camino, cerca de un cobertizo pequeño. Mapa Guapiles, hoja 3446 IV**
Hoja topografia:	**Guapiles, hoja 3446 IV**
Aproximadamente N:	**253.70**
E:	**557.00**
Altitud:	**103 m**
Unidad geomorfológica:	
Forma de terreno:	
Forma del terreno circundante:	**Casi plano**
Microtopografía:	**no**
Pendiente:	**casi llano, 2%**
Vegetación o uso actual:	**Banana**
observación:	

INFORMACION GENERAL ACERCA DEL SUELO

Material de partida:	**((aluvion de composición andesitica))**
Drenaje:	**4 (bien drenado)**
Humedad del suelo:	**Humido**
Capa freática (in cm):	**>120 cm**
Fauna del suelo:	**Lombrices, hormigas**
Piedras en la superficie:	**clase 0, muy pocas piedras.**
Salis o álcalis en el perfil:	**clase 0, libre de exceso de sales o álcali.**
Erosión:	**erosión hídrica, laminar, ligera**
Sedimentación:	**No**
observación:	

DESCRIPCION DE LOS HORIZONTES DEL SUELO

Horizonte 1:	
Profundidad:	**0-10**
Color en húmedo:	**(10 YR 2/2)**
Manchas:	**No**
Textura:	**Franco Argillo Limoso**
Grava y piedras - abundancia:	**sin grava, sin piedras**
Estructura:	**Fuerte, en bloques angulares, muy fino**
Consistencia:	**Ligeramente adherente y plástico en mojado.**
Poros:	**Muchos, muy finos y finos, medianos y gruesos, caoticos continuos, vesiculares interstitiales y tubulares.**
raíces:	**abundantes, muy finas, finas y medianas.**
límite - anchura:	**Neto**
- topografía:	**Plano**
observación:	**Ligaremente tixotropico**

Horizonte 2:	
Profundidad:	**10-40 cm**
Color en húmedo:	**(10 YR 3/3)**
Manchas:	**No**
Textura:	**Franco Argillo Limoso**
Grava y piedras - abundancia:	**sin grava, sin piedras**
Estructura:	**Fuerte, en bloques sub angulares, muy fino.**
Consistencia:	**Ligeramente adherente y plástico en mojado.**
Poros:	**Muchos, muy finos y finos, medianos y greusos, caótic, continuos, intersticiales y tubulares.**
raíces:	**abundantes, muy finas, finas,medianes.**
límite - anchura:	**gradual**
- topografía:	**plano**
observación:	**Ligetamente tixotropico**

Horizonte 3:

Profundidad:	40-70
Color en húmedo:	(10 YR 4/4)
Manchas:	No
Textura:	Franco arenoso
Grava y piedras - abundancia:	Poco grava, sin piedras.
Estructura:	Moderada, en bloques angulares a sub-angulares muy fina a fina.
Consistencia:	Ligeramente adherente y ligeramente plástico en mojado.
Poros:	Frequentas a muchas, finos, medianos y gruesos, caótic, continuos, intersticiales y tubulares.
raíces:	comunas a pocas, muy finas y finas
límite - anchura:	neto
- topografía:	plano
observación:	Ligeramente tixotropico

Horizonte 4:

Profundidad:	70-90
Color en húmedo:	(10YR 4/4)
Manchas:	No
Textura:	areno francoso
Grava y piedras - abundancia:	con grava, ligeramente pedregoso
Estructura:	Débil, en bloques sub-angulares a migajose, muy fino a fino.
Consistencia:	no adherente y ligeramente plástico en mojado.
Poros:	Frequentas, finos y medianos, continuos, tubulares.
raíces:	Pocas a muy pocas, muy finas.
límite - anchura:	Brusco
- topografía	Plano
observación:	Ligeramente tixotropico

Horizonte 5:

Profundidad:	90-120
Color en húmedo:	(10YR 4/2)
Manchas:	No
Textura:	Arenoso
Grava y piedras - abundancia:	Mucho grava, muy pedregoso
Estructura:	Sin estructura, fina, migajose.
Consistencia:	No adherente y no plástico en mojado.
Poros:	Observar la porosidad esta dificil.
raíces:	no raíces
límite - anchura:	
- topografía:	
observación:	Ligeramente tixotropico

Número del perfil:	HL02
Clasificación	
PZA:	Montelimar
USDA Soil Taxonomy:	Pseudo Vitrudand
Fecha de la observación:	18-09-1992
Autor de la descripción:	H. Leummens
Ubicación:	Finca Urania, cerca de Sangrada familia, 50 metros a la derecho del camino a empackadora, 300 m antes Sangrada familia
Hoja topgrafia:	Agua Fria, hoja 3447 II
Aproximadamente N:	259.75
E:	568.65
Altitud:	45 m
Unidad geomorfológica:	
Forma del terreno circundante:	Casi plano
Microtopografía:	Zanjas de drenaje
Pendiente:	Casi llano (0-1%)
Vegetación o uso actual:	Banana, antes de 1984
observación:	

INFORMACION GENERAL ACERCA DEL SUELO

Material de partida:	((aluvion de composición andesitica))
Drenaje:	3 (moderamente bien drenado)
Humedad del suelo:	Humido
Capa freática (in cm):	>120 cm
Fauna del suelo:	Lombrices, hormigas
Piedras en la superficie:	clase 0, sin piedras y rocos
Salis o álcalis en el perfil:	clase 0, libre de exceso de sales o álcali
Erosión:	erosión hídrica, laminar, ligeramente
Sedimentación:	No
observación:	

DESCRIPCION DE LOS HORIZONTES DEL SUELO

Horizonte 1:	
Profundidad:	0-5
Color en húmedo:	Negro pardoso (10 YR 3/2)
Manchas:	No
Textura:	Franco
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Moderada, en bloques angulares a sub-angulares, muy finos a finos.
Consistencia:	Ligeramente adherente y plástico en mojado.
Poros:	Frequentas a muchos, muy finos, finos, medianos y gruesos, continuos, vesiculares, intersticiales y tubulares.
raíces:	Muy abundantes, finas a medianas
límite - anchura:	
- topografía:	
observación:	Ligaremente tixotropico

Horizonte 2:	
Profundidad:	5-25 cm
Color en húmedo:	Pardo oscuro (10 YR 3/3)
Manchas:	No
Textura:	Franco
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Moderado, en bloques sub-angulares, muy fino a fino
Consistencia:	Ligeramente adherente y plástico en mojado.
Poros:	Precuentes a muchos, muy finos, finos, medianos y gruesos, caótic, continuos, vesiculares, tubulares y intersticiales
raíces:	Abundantes, muy finas, finas y medianas
límite - anchura:	
- topografía:	
observación:	moderamente tixotropico

Horizonte 3:

Profundidad:	25-55
Color en húmedo:	Pardo oscuro (10 YR 3/3)
Manchas:	No
Textura:	franco arenoso
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Débil, en bloques sub-angulares a migajosa, muy fina a fina
Consistencia:	Ligeramente adherente y ligeramente plástico en mojado.
Poros:	Frequentas, muy finos, finos y medianos, caótic, continuos, intersticiales y tubulares.
raíces:	Abundantes, muy finas, finas y medianas
límite - anchura:	
- topografía:	
observación:	Moderademente tixotropico

Horizonte 4:

Profundidad:	55-80
Color en húmedo:	(10YR 4/3)
Manchas:	pocas, pequeñas,indistintas
Textura:	areno francoso
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Débil, migajose, fino
Consistencia:	no adherente y no plástico en mojado
Poros:	Frequentos, muy finos y finos, continuos, intersticiales y tubulares.
raíces:	Pocas, finas y medianas
límite - anchura:	
- topografía	
observación:	muy tixotropico

Horizonte 5:

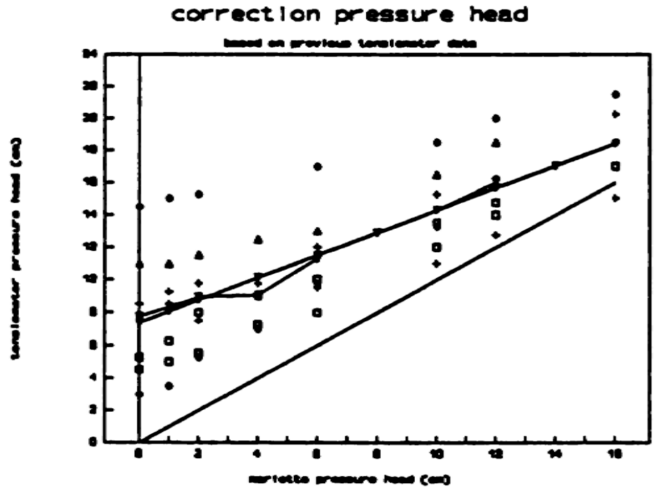
Profundidad:	80-105
Color en húmedo:	(10YR 4/3)
Manchas:	Pocas a frequentas, pequeñas, indistintas
Textura:	Arena
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Debil, migajose a bloques sub-angulares, muy fino a fino
Consistencia:	No adherente y no plástico en mojado.
Poros:	Pocos, muy finos y finos, continuos, tubulares.
raíces:	no raíces
límite - anchura:	
- topografía:	
observación:	muy tixotropico

Horizonte 6:

Profundidad:	105-120
Color en húmedo:	(10YR 4/3)
Manchas:	Frequentas a muchos, pequeñas a medianos, destacadas
Textura:	Franco arenoso
Grava y piedras - abundancia:	sin grava, sin piedras
Estructura:	Debil, migajose , fino
Consistencia:	Ligemente adherente y ligeramente plástico en mojado.
Poros:	Muy pocos, muy finos y finos, continuos, tubulares.
raíces:	no raíces
límite - anchura:	
- topografía:	
observación:	muy tixotropico, pseudo-gley

APPENDIX 2 : DETERMINATION OF THE SUBCRUST PRESSURE HEAD

To compensate for missing tensiometer data to determine the correct subcrust pressure head belonging to a certain level of the mariotte outflow level, use was made of tensiometer readings of Weerts (WEERTS, 1991), who measured saturated and unsaturated hydraulic conductivities also on the soil type Los Diamantes, under forest and pasture. The following relationship was found, out of the averages of about 10 measurements. Using lineair regression the relationship was best described by Y = 0.69X + 7.39. This resulted in the corrected subcrust pressure head as given in the table.



installed mariotte level	corrected pressure head
0	-7.4
-1	-8.1
-2	-8.8
-4	-10.2
-6	-11.5
-8	-12.9
-10	-14.3
-12	-15.7

APPENDIX 3 : CRUST TEST MEASUREMENTS OF THE HYDRAULIC CONDUCTIVITIES OF THE DIFFERENT SOIL TYPES

All of the following calculated unsaturated hydraulic conductivities are corrected for the use of silicone to seal places where air leaks through the crust. Crust coverage with silicone was not more than 30% and occured in all measurements at mariotte levels -8, -10, -12. Assumed was that the influence of silicone was neglectible.

HYDRAULIC CONDUCTIVITY SUELO LOS DIAMANTES

Summary of 5 measurements on different depths, mariotte levels
Depths 0-30 cm (1..3) and 30-60 cm (4..5)

	1	2	3	4	5
with crust					
h= 0	313.4	308.2	358.1	228.6	199.6
h= -1	292.5	299.3	333.5	191.5	185.2
h= -2	285.7	180.4	287.7	188.1	175.0
h= -4	268.9	177.0	210.5	177.8	158.6
h= -6	92.3	155.8	162.7	157.9	141.5
h= -8		101.7		139.3	116.2
h=-10		54.7		113.2	118.2
h=-12				82.4	
without crust					
h= 0	--	129.5	--	213.4	142.1
ponding	720.0	96.0	285.0	--	--
sep. measure					
h= 0	624.3				

HYDRAULIC CONDUCTIVITY SUELO MONTELIMAR

summary of 4 measurements on different depths, mariotte levels
depths 0-30 cm (1..3) and 30-60 cm (4).

	1	2	3	4	5
with crust					
h= 0	381.8	291.8		285.0	
h= -1	359.8	259.9	207.1	249.3	
h= -2	333.0	230.7	183.2	276.7	
h= -4	291.6	201.9	186.0	221.8	
h= -6	188.8	162.7	157.2	189.5	
h= -8	129.8	105.8	87.1	166.2	
h=-10	75.2	79.7	87.1	127.7	
h=-12					
without crust					
h= 0	230.6	257.5	90.9	227.3	

Remark : no separate measurement without crust done, no second subsoil measurement due to destrucion of the installed column.

HYDRAULIC CONDUCTIVITY SUELO LIGIA

Summary of the 5 measurements on different depths, mariotte levels.
Depths 0-30 cm (1..3) and 30-60 cm (4..5).

	1	2	3	4	5
with crust					
h= 0	292.5	402.7	289.1	212.9	202.6
h= -1	260.7	244.5	183.8	192.3	221.8
h= -2	235.1	220.1	211.9	185.4	203.3
h= -4	177.9	153.8	93.1	162.1	176.5
h= -6	123.6	93.6	35.2	144.2	163.4
h= -8	44.8	34.6	17.4	132.5	99.6
h=-10		16.0			85.0
h=-12					
without crust					
h= 0	335.0	315.4	223.7	244.5	214.9
sep. measure					
h= 0	685.4				

APPENDIX 4 : Texture analyses

sample number	horizont	% o.m.	uncorr. MAG-lab values % sand	% clay	% silt	corrected values % sand	% clay	% silt
1-1	D 0- 5	7.77	55.4	20.8	23.8	0.67	0.23	0.10
1-2	D 5- 20	6.16	59.4	22.8	17.8	0.67	0.24	0.09
1-3	D 20- 65	2.14	65.4	10.8	23.8	0.75	0.11	0.14
1-4	D 65-105	0.8	75.4	8.8	15.8	0.82	0.09	0.09
1-5	D105-120	0.53	93.4	4.8	1.8	0.94	0.05	0.01
2-1	M 0- 5	6.16	39.4	18.8	41.8	0.55	0.20	0.25
2-2	M 5- 25	5.77	47.4	16.8	35.8	0.60	0.18	0.22
2-3	M 25- 55	2.14	41.4	10.8	47.8	0.64	0.11	0.25
2-4	M 55- 80	1.65	45.4	12.8	41.8	0.60	0.13	0.27
2-5	M 80-105	0.53	59.4	12.8	27.8	0.71	0.13	0.16
2-6	M105-120	6.16	45.4	14.8	39.8	0.28	0.16	0.56
3-1	L 0- 10	2.14	25.4	30.8	43.8	0.22	0.31	0.47
3-2	L 10- 40	0.8	19.4	44.8	35.8	0.24	0.45	0.31
3-3	L 40- 70	0.8	21.4	46.8	31.8	0.40	0.47	0.13
3-4	L 70- 90	0.8	41.4	38.8	19.8	0.56	0.39	0.05
3-5	L 90-120	0.53	91.4	8.8	1.2	0.90	0.09	0.01
0-0	crust	0.53	95.4	4.8	1.2	1.00	0.00	0.00

sample number	horizont	separation of the sand fraction (gr) 1000-2000	500-1000	250-500	100-250	53-100	total	starting weight moist. corr. incl.	o.m. corr. incl.
1-1	D 0- 5	0.46	2.55	7.77	8.40	9.45	28.63	46.30	42.70
1-2	D 5- 20	0.55	2.47	7.53	8.49	10.04	29.08	46.19	43.34
1-3	D 20- 65	0.49	2.80	9.04	10.38	11.75	34.46	47.13	46.12
1-4	D 65-105	0.61	3.82	11.86	11.63	11.31	39.23	48.43	48.04
1-5	D105-120	6.63	16.05	14.76	5.73	2.65	45.82	48.75	48.49
2-1	M 0- 5	0.16	0.20	1.03	4.16	17.37	22.92	44.77	42.01
2-2	M 5- 25	0.02	0.21	1.39	4.97	19.02	25.61	45.13	42.53
2-3	M 25- 55	0.01	0.16	1.39	8.11	19.72	29.39	46.59	45.59
2-4	M 55- 80	0.01	0.17	1.39	5.49	20.64	27.70	46.65	45.88
2-5	M 80-105	0.01	0.30	4.98	13.56	15.41	34.26	48.24	47.98
2-6	M105-120	0.37	1.35	2.17	2.26	5.68	11.83	44.96	42.19
3-1	L 0- 10	0.19	0.81	1.59	1.74	5.22	9.55	44.58	43.63
3-2	L 10- 40	0.15	1.12	2.61	2.50	4.06	10.44	44.78	44.42
3-3	L 40- 70	1.32	3.90	5.69	3.61	3.32	17.84	45.00	44.64
3-4	L 70- 90	0.04	0.14	1.18	4.94	18.62	24.92	45.00	44.64
3-5	L 90-120	5.89	13.22	11.61	6.32	3.29	40.33	45.00	44.76
4-1	C 0- 10	0.22	0.51	1.48	2.32	6.33	10.86	81.52	
4-2	C 10- 40	0.09	0.37	1.12	2.04	6.99	10.61	82.36	
4-3	C 40- 65	0.12	0.53	1.58	2.31	5.04	9.58	78.71	
4-4	C 65- 90	0.31	2.77	9.27	12.79	18.44	43.58	79.40	
4-5	C 90-110	1.26	7.46	15.38	15.76	18.38	58.24	62.75	
0-0	crust	0.01	0.11	21.63	19.23	8.62	49.60	50.00	49.74

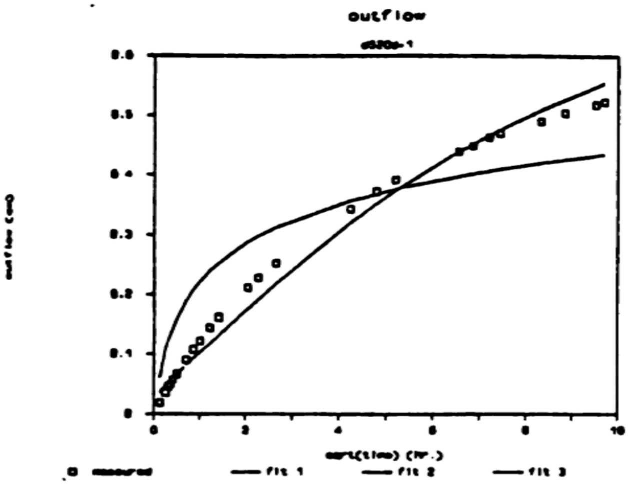
REMARKS :
- The sand fraction measured with the hydrometer method is replaced by the results of hand sieving, corrected for organic matter content and moisture content.
- The clay fraction measured with the hydrometer method is replaced with a corrected value corrected for the organic matter content. Assumed was that the results of the lab were already corrected for the moisture content.

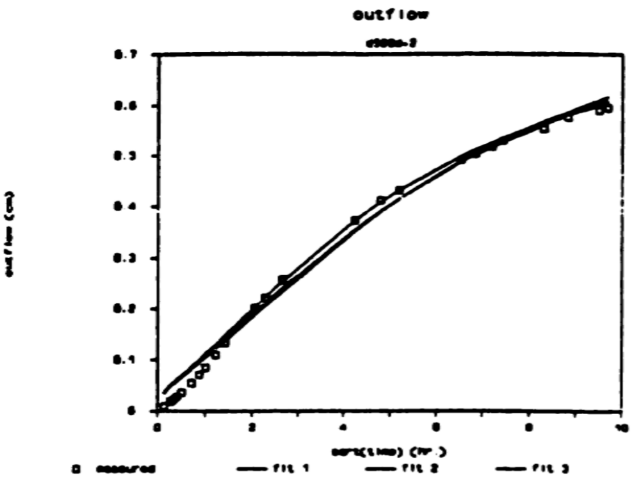
APPENDIX 5 : Calculated saturated water contents

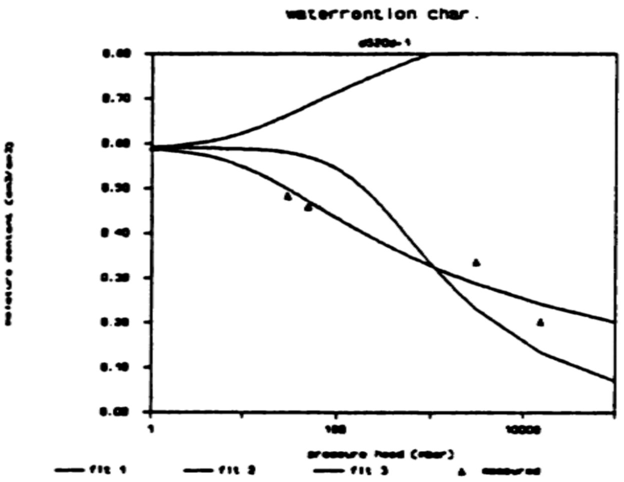
SATURATED WATER CONTENT AND BULK DENSITY, 100 cc samples

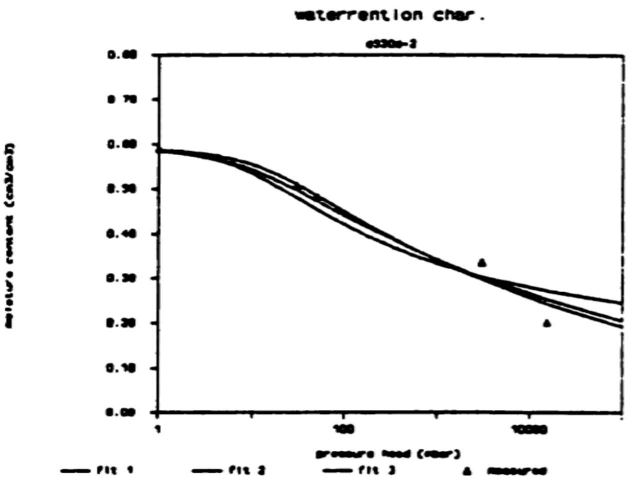
LOS DIAMANTES			LIGIA			MONTELIMAR		
layer	bulk dens.	theta sat	layer	bulk dens.	theta sat	layer	bulk dens.	theta sat
0- 20	0.937	0.572	0-40	0.884	0.601	0-25	0.733	0.667
	0.863	0.621		0.849	0.611		0.688	0.660
	0.860	0.636		0.859	0.593		0.734	0.661
				0.895	0.591		0.708	0.644
				0.887	0.585		0.794	0.643
mean	0.887	0.610		0.875	0.596		0.731	0.655
20-65	0.898	0.575	40-70	1.075	0.559	25-55	0.645	0.651
	0.929	0.567		1.065	0.564		0.716	0.630
	0.892	0.580		1.086	0.554		0.597	0.657
	0.951	0.580		1.101	0.562		0.753	0.610
	0.905	0.615		1.077	0.549		0.615	0.652
mean	0.915	0.583		1.081	0.558		0.665	0.640
65-105	1.139	0.547	70-90	1.114	0.557	55-80	1.158	0.544
	1.107	0.520		1.100	0.561		1.124	0.540
	1.085	0.532		1.107	0.565		0.989	0.564
				1.133	0.544		1.089	0.555
				1.108	0.554			
mean	1.110	0.533		1.112	0.556		1.090	0.551

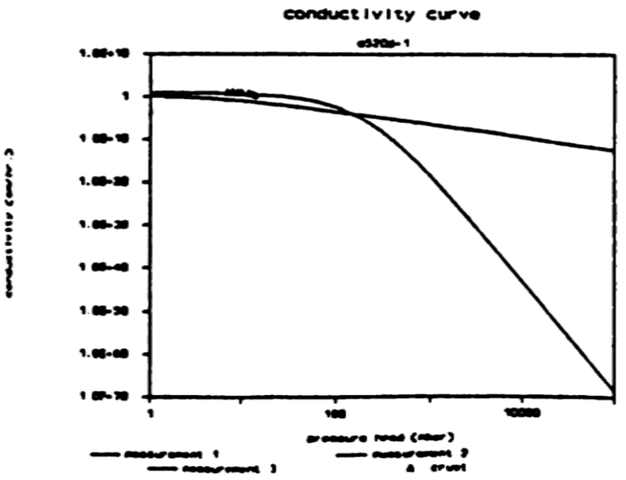
APPENDIX 6 : Fitted outflow, retention and conductivity curves for all accepted soil samples

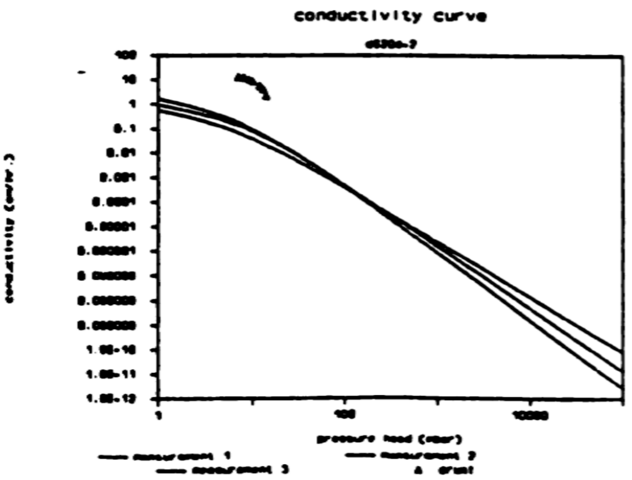


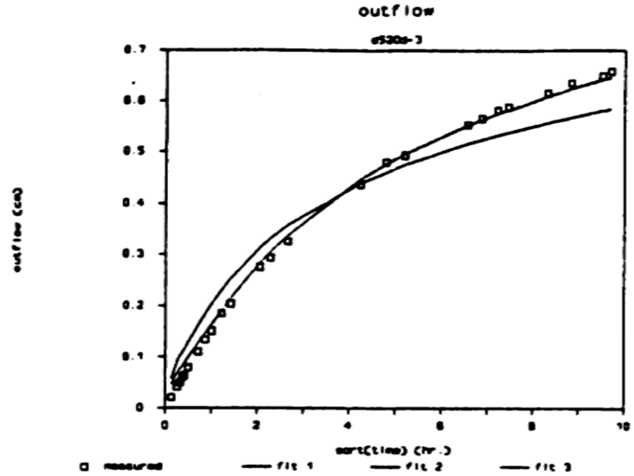


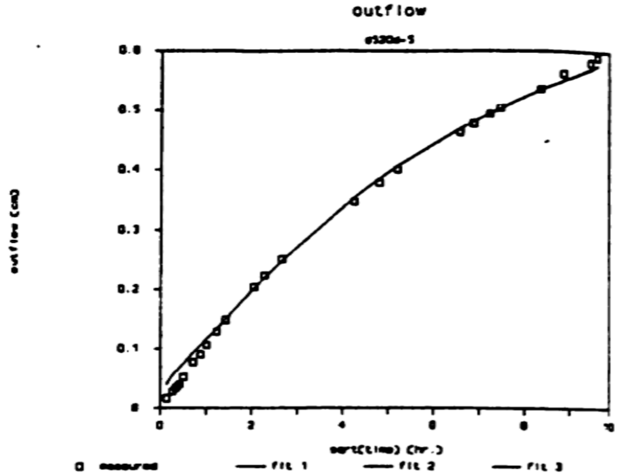


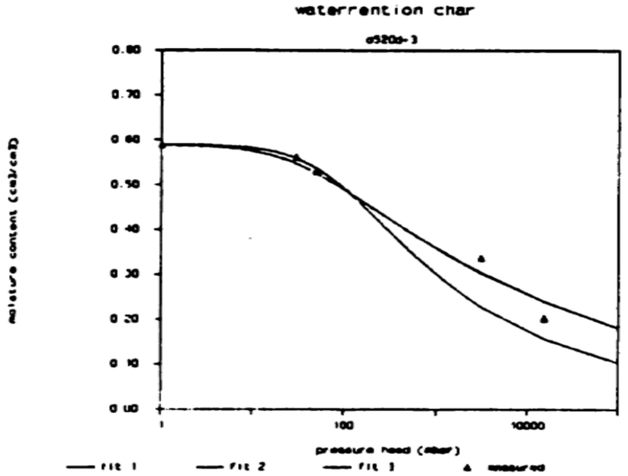


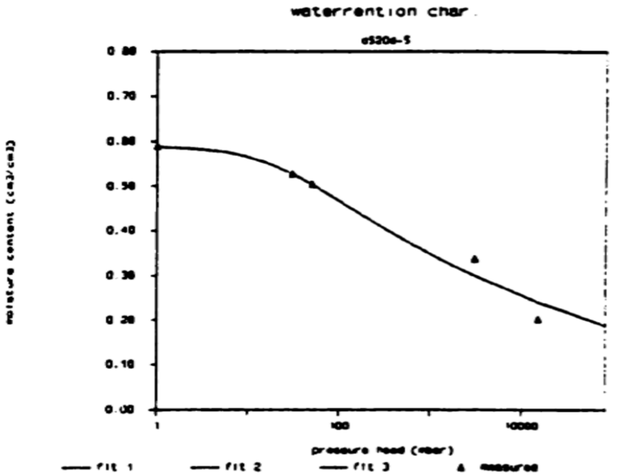


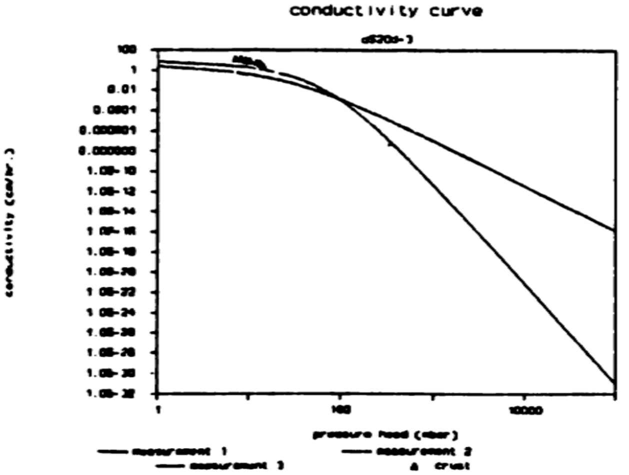


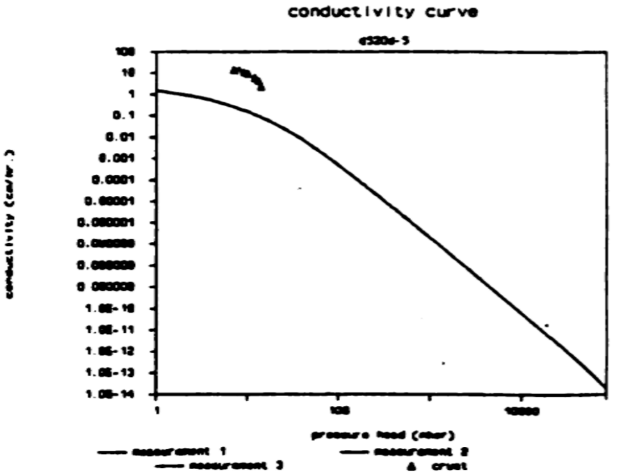

outflow
d520s-3
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

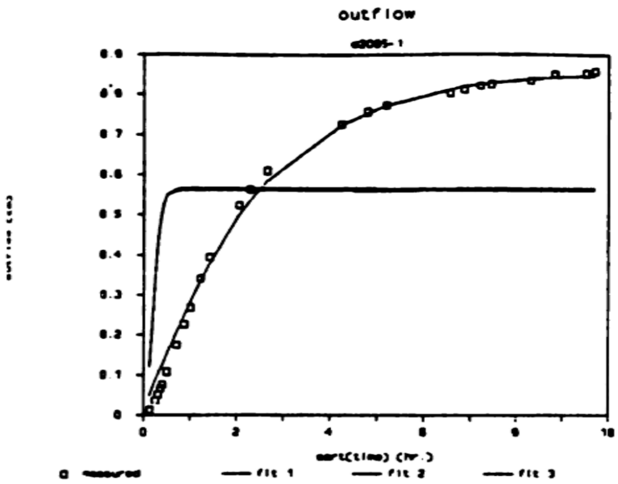

outflow
d520s-5
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

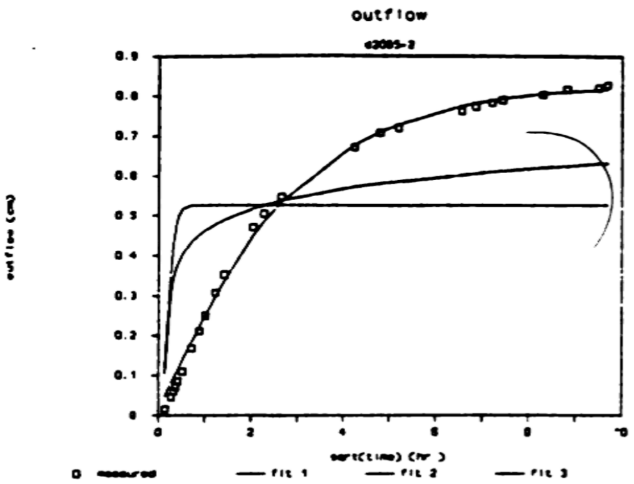

waterrention char
d520s-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
▲ measured

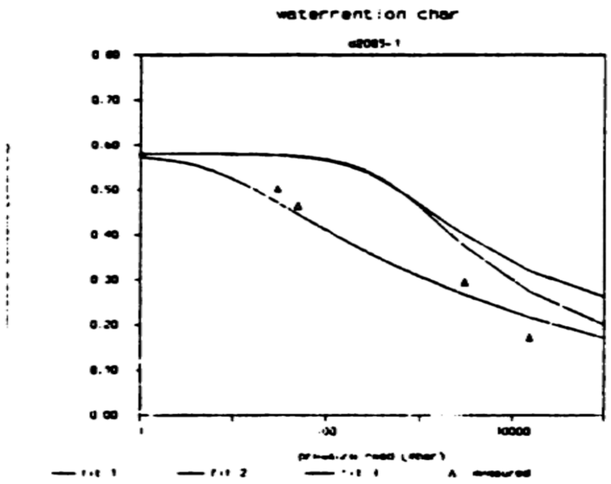

waterrention char
d520s-5
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
▲ measured

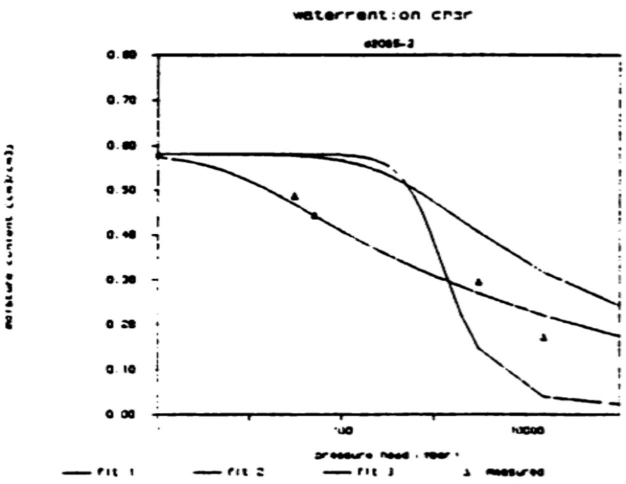

conductivity curve
d520s-3
conductivity (cm/hr.)
100
1
0.01
0.0001
0.000001
0.00000001
1.0E-10
1.0E-12
1.0E-14
1.0E-16
1.0E-18
1.0E-20
1.0E-22
1.0E-24
1.0E-26
1.0E-28
1.0E-30
1.0E-32
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
▲ crust

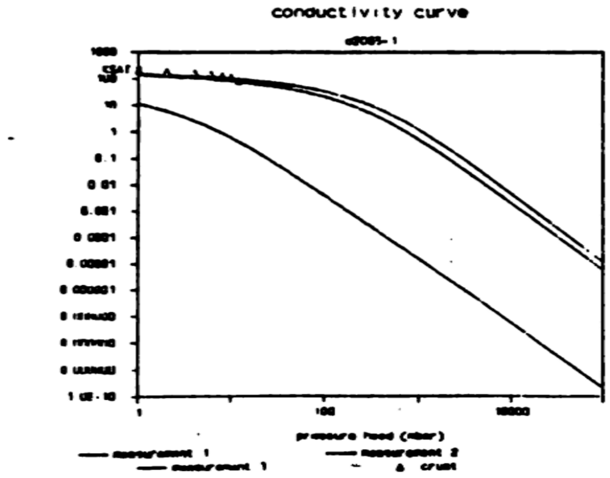

conductivity curve
d520s-5
conductivity (cm/hr.)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
▲ crust

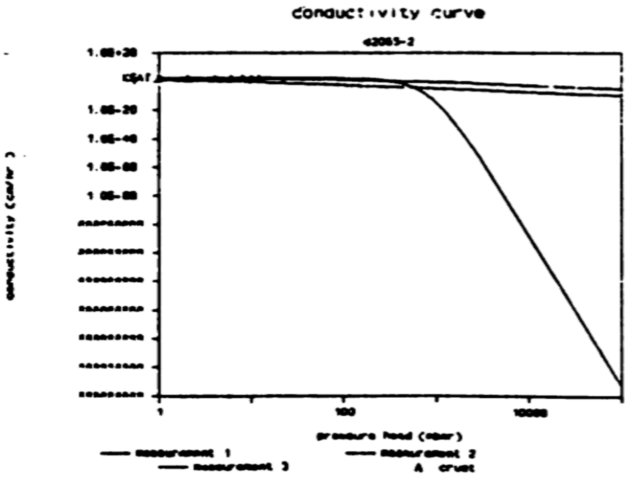

outflow
d2085-1
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

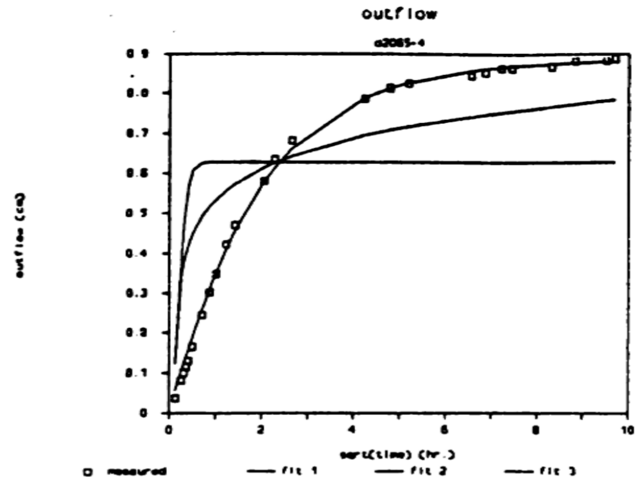

outflow
d2085-2
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

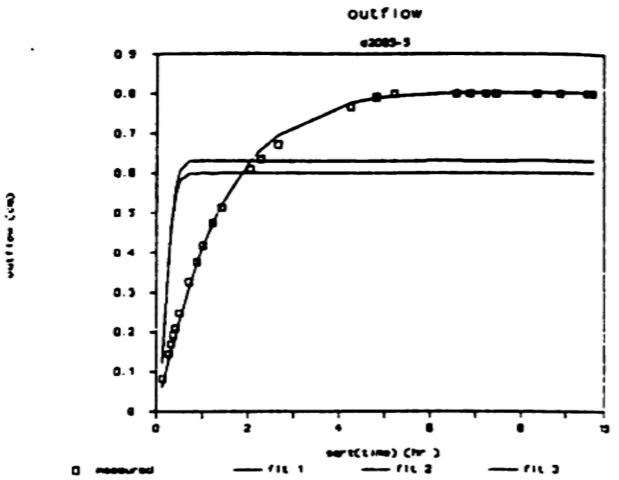

waterrention char
d2085-1
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

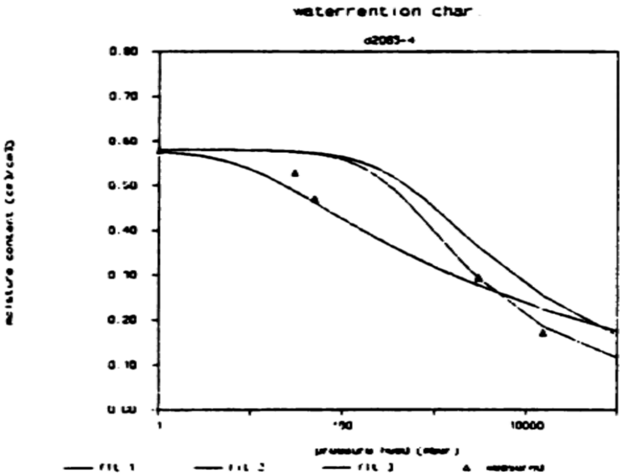

waterrention char
d2085-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

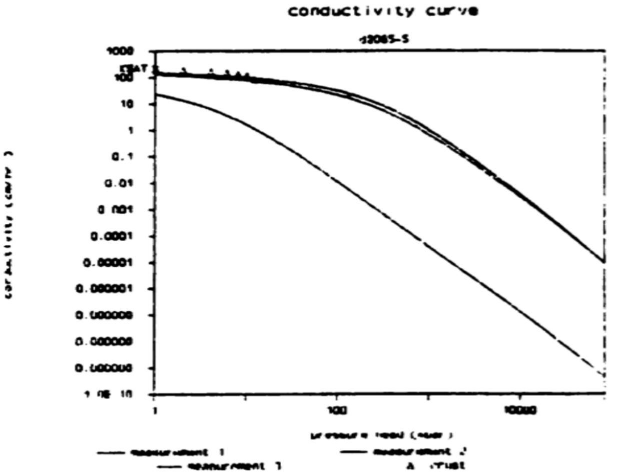

conductivity curve
d2085-1
1000
KSAT
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 1
crust

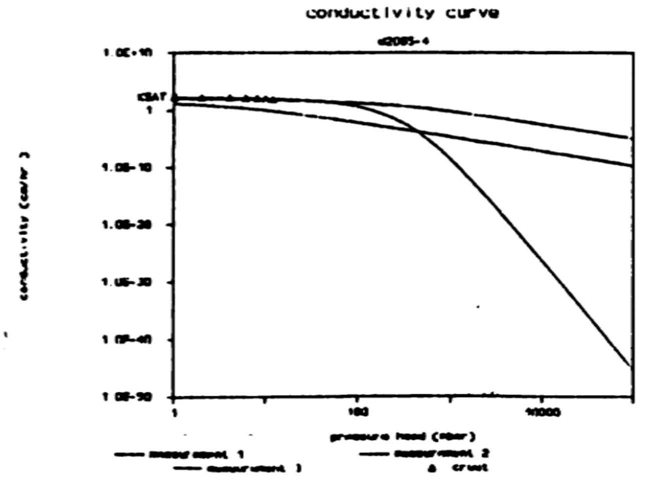

conductivity curve
d2085-2
conductivity (cm/hr)
1.0E+20
KSAT
1.0E-20
1.0E-40
1.0E-60
1.0E-80
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

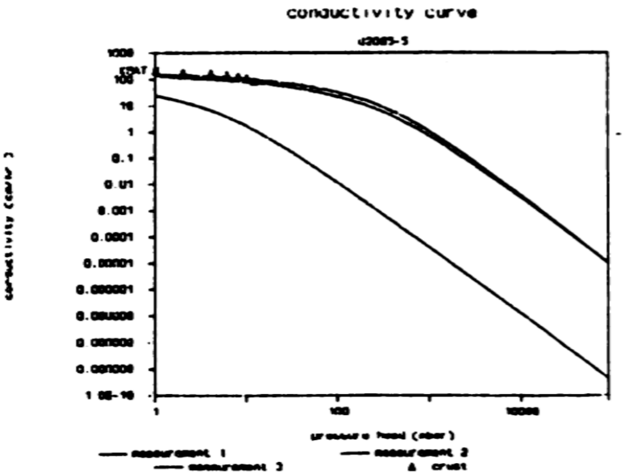

outflow
d2085-4
outflow (cm)
sqrt(time) (hr.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
2
4
6
8
10
measured
fit 1
fit 2
fit 3

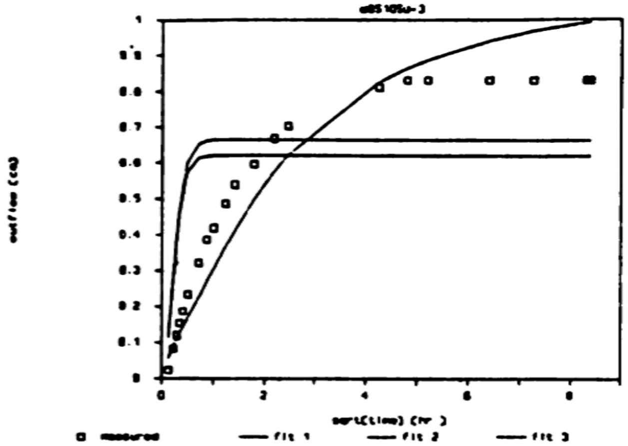

outflow
d2085-5
outflow (cm)
sqrt(time) (hr.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
2
4
6
8
10
measured
fit 1
fit 2
fit 3

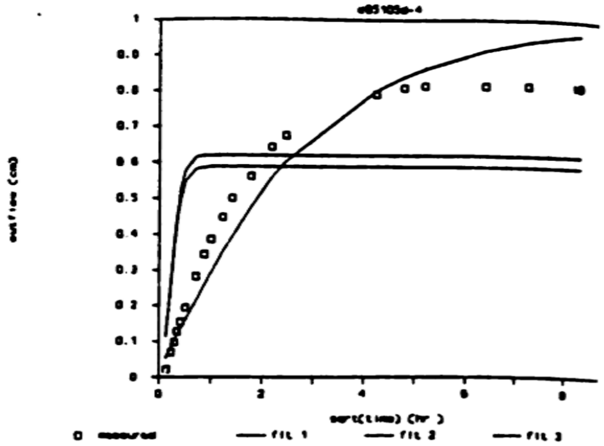

waterrention char.
d2085-4
moisture content (cm3/cm3)
pressure head (mbar)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
fit 1
fit 2
fit 3
measured

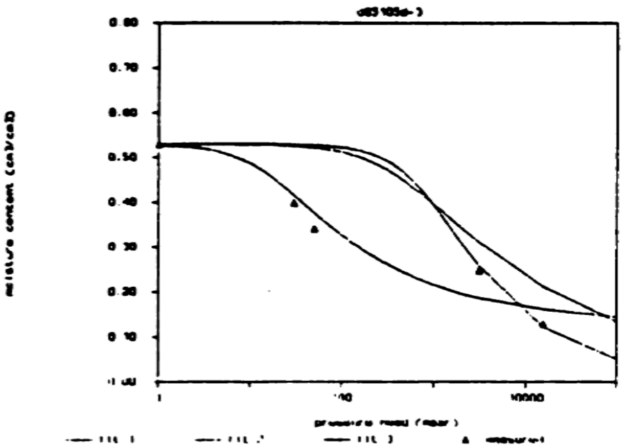

conductivity curve
d2085-5
conductivity (cm/hr)
pressure head (mbar)
KSAT
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1
100
10000
measurement 1
measurement 2
measurement 3
crust

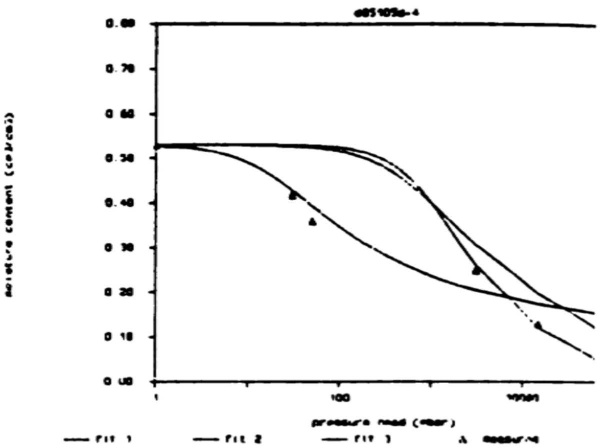

conductivity curve
d2085-4
conductivity (cm/hr)
pressure head (mbar)
KSAT
1.0E+10
1
1.0E-10
1.0E-20
1.0E-30
1.0E-40
1.0E-50
1
100
10000
measurement 1
measurement 2
measurement 3
crust

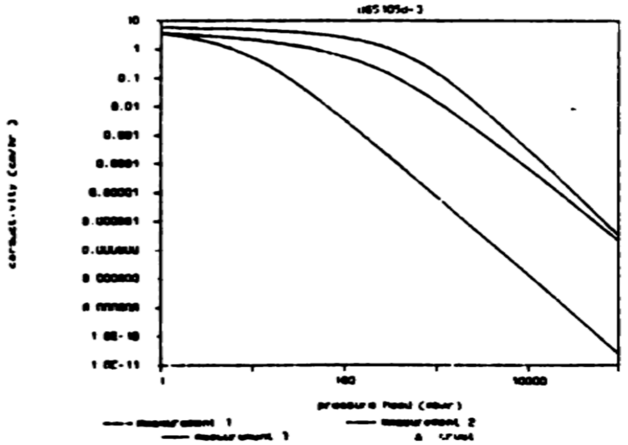

conductivity curve
d2085-5
conductivity (cm/hr)
pressure head (mbar)
KSAT
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1
100
10000
measurement 1
measurement 2
measurement 3
crust

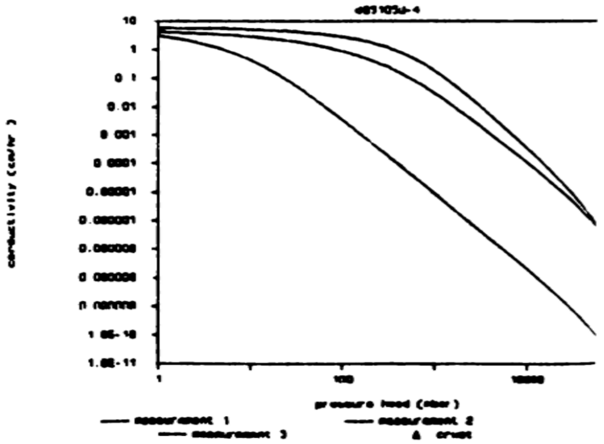




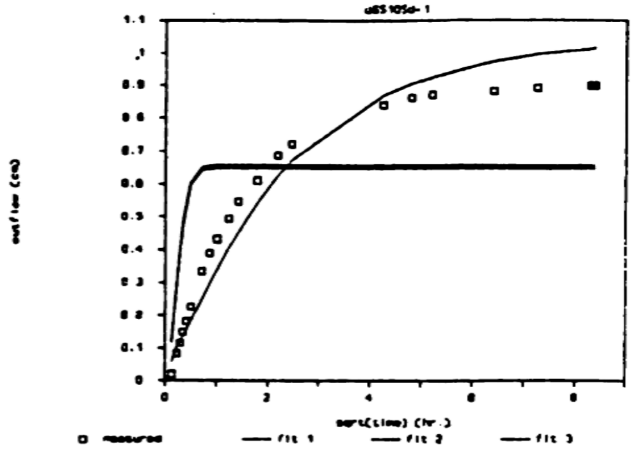

waterrention char


waterrention char

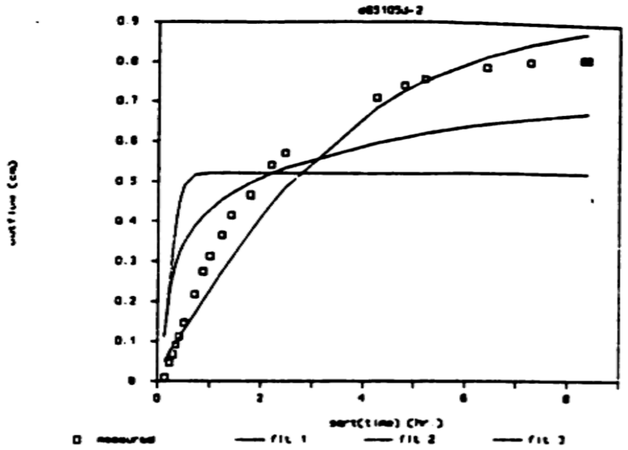

conductivity curve


conductivity curve

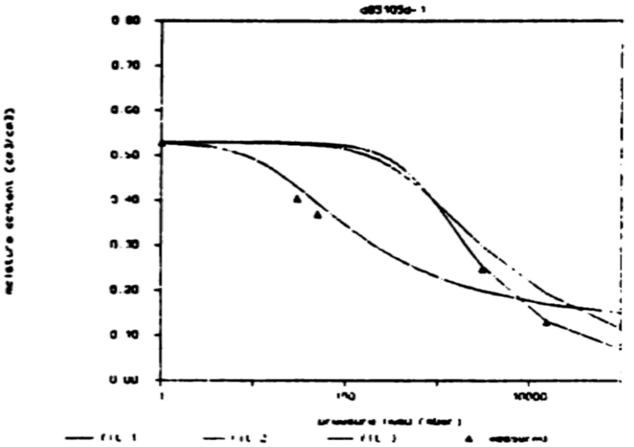
outflow



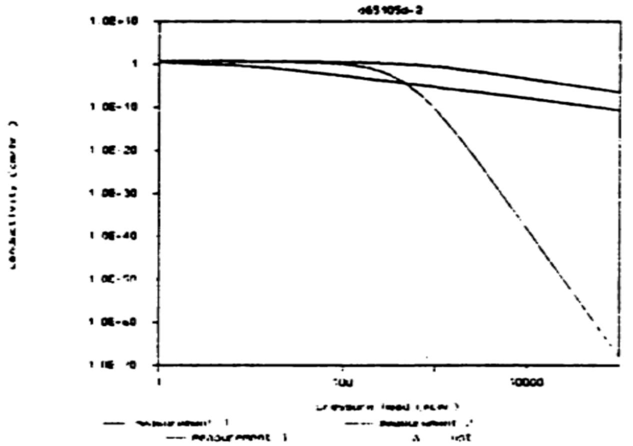
outflow



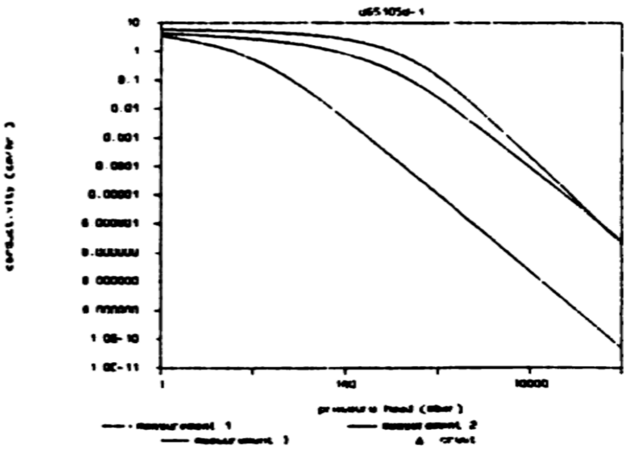
waterrention char.



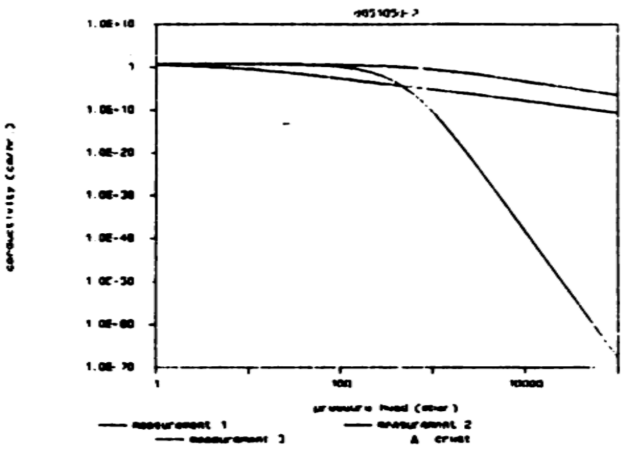
conductivity curve

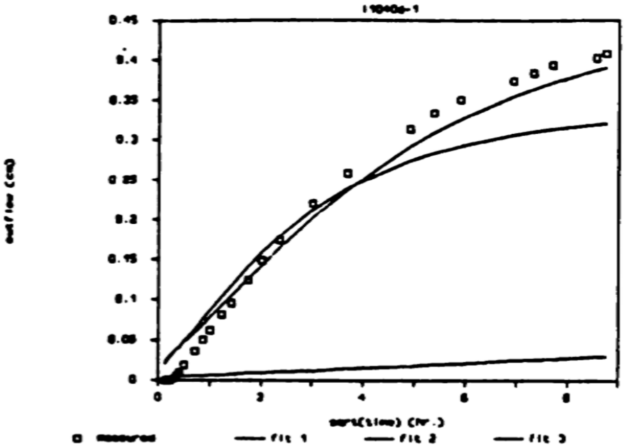


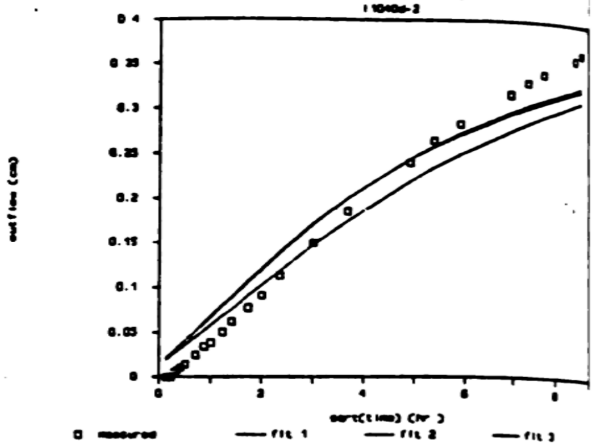
conductivity curve

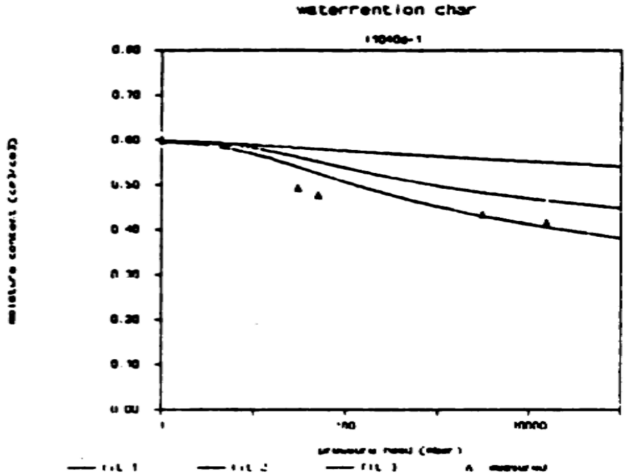


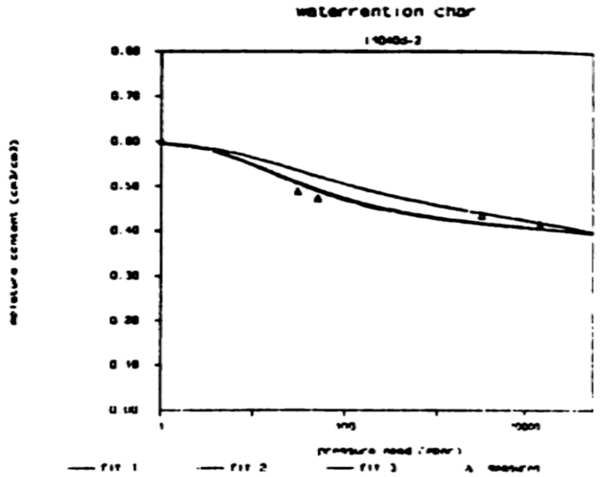
conductivity curve

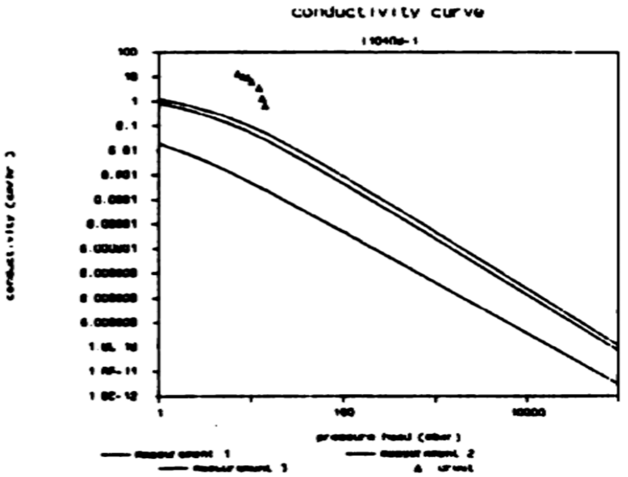


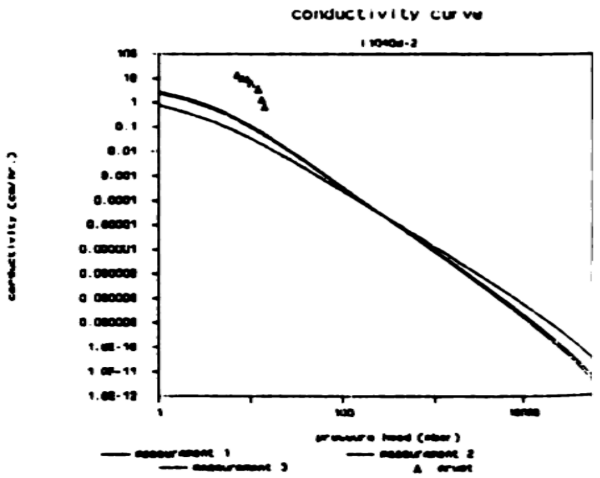

11040a-1
outflow (cm)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

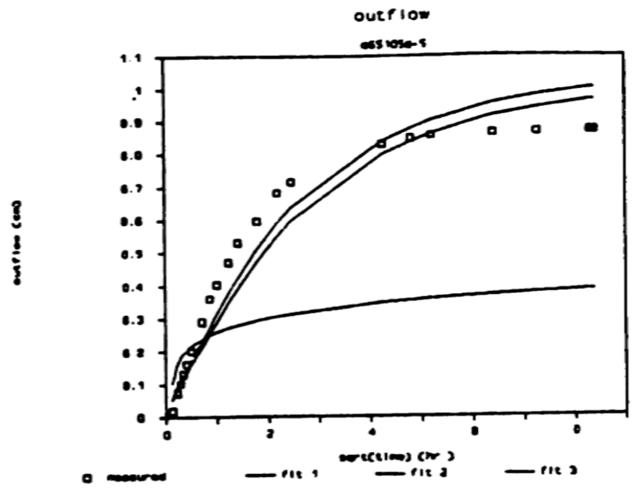

11040a-2
outflow (cm)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

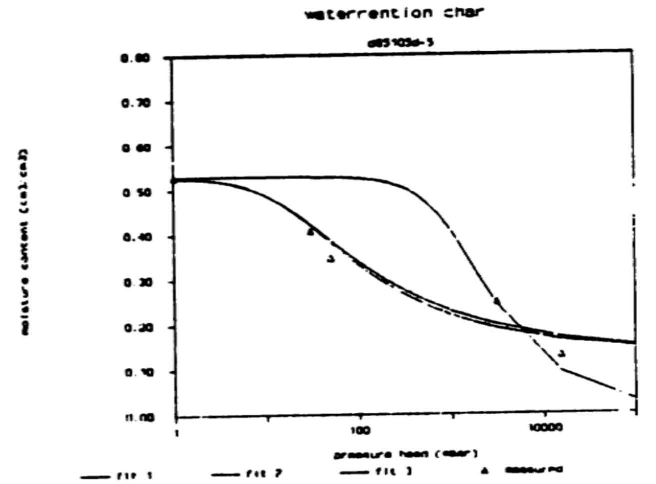

waterrention char
11040a-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

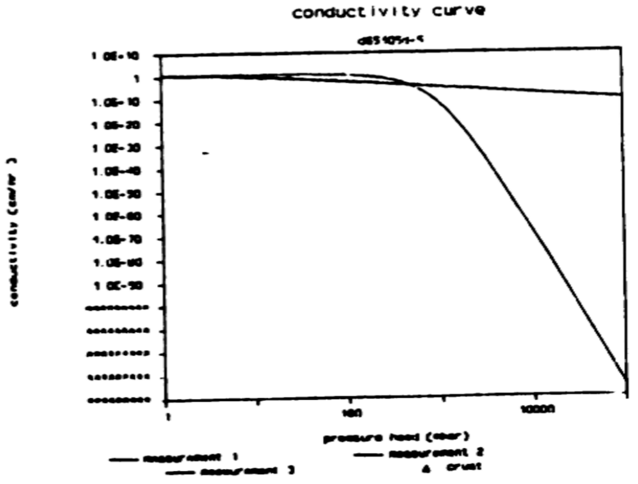

waterrention char
11040a-2
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

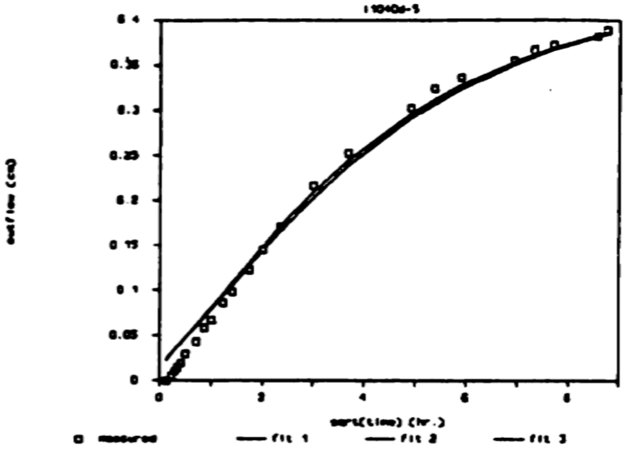

conductivity curve
11040a-1
conductivity (cm/hr.)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ drukt

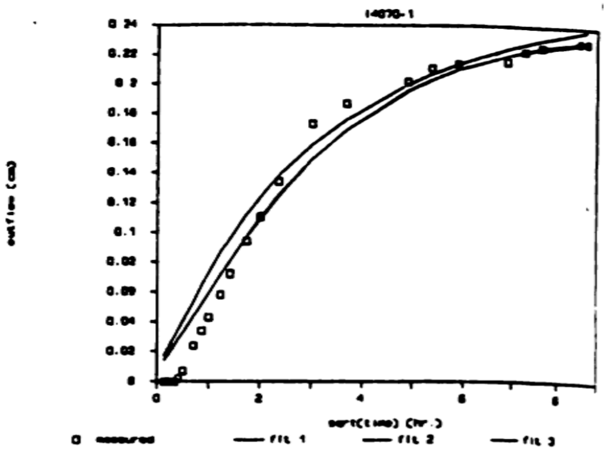

conductivity curve
11040a-2
conductivity (cm/hr.)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ drukt

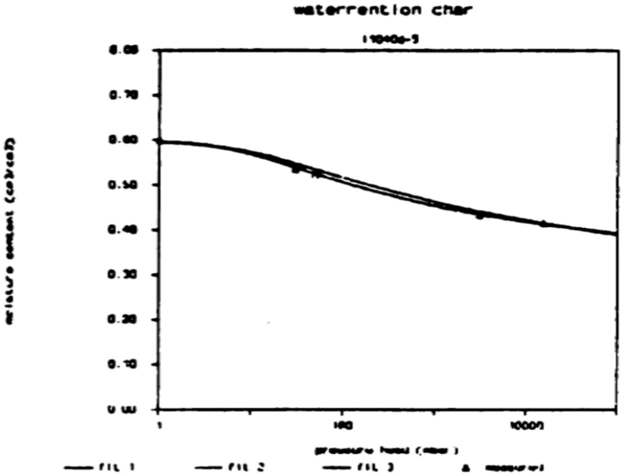

outflow
d85105o-5
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
2
4
6
8
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

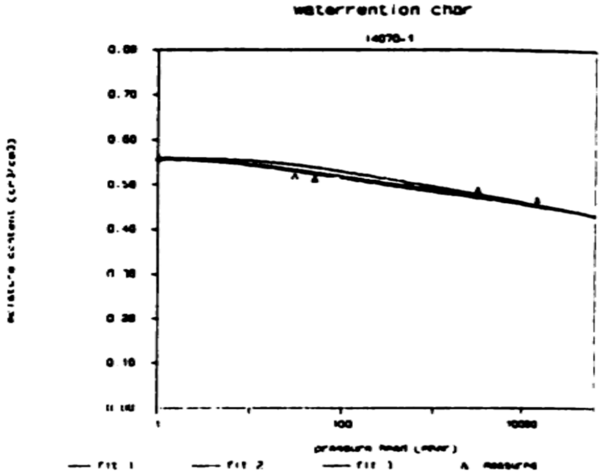

waterrention char
d85105d-5
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

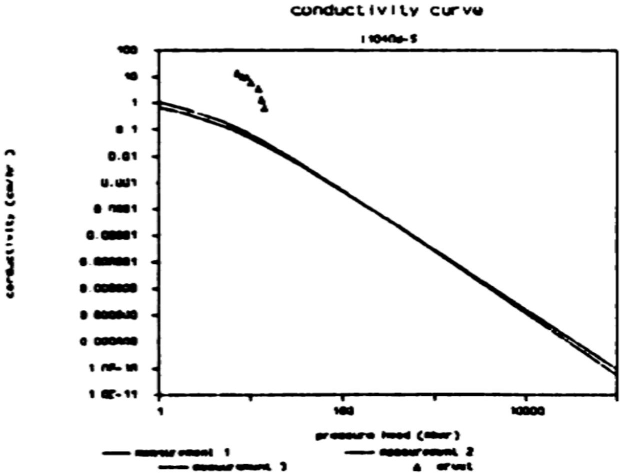

conductivity curve
d85105i-5
conductivity (cm/hr)
1.0E+10
1
1.0E-10
1.0E-20
1.0E-30
1.0E-40
1.0E-50
1.0E-60
1.0E-70
1.0E-80
1.0E-90
#########
#########
#########
#########
#########
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

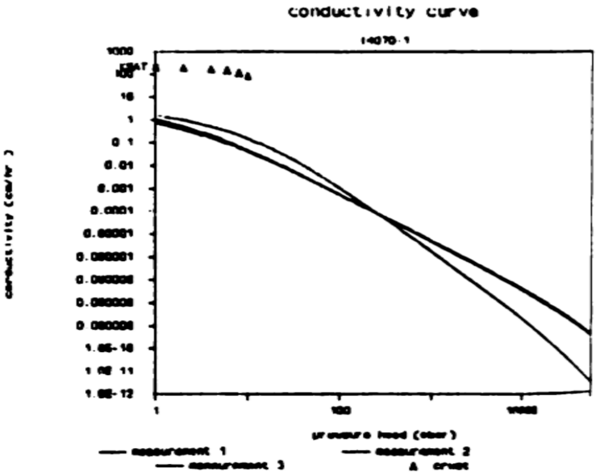

11040a-5
outflow (cm)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

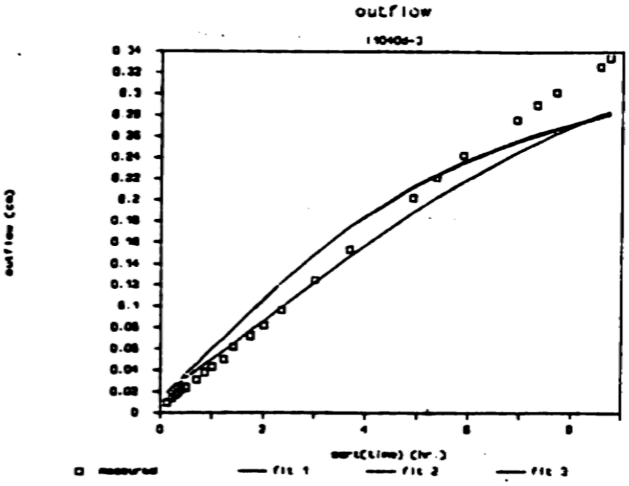

14070-1
outflow (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

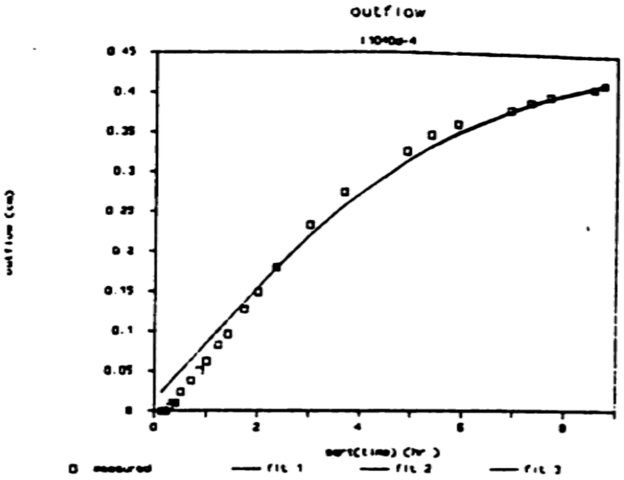

waterrention char
11040a-5
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

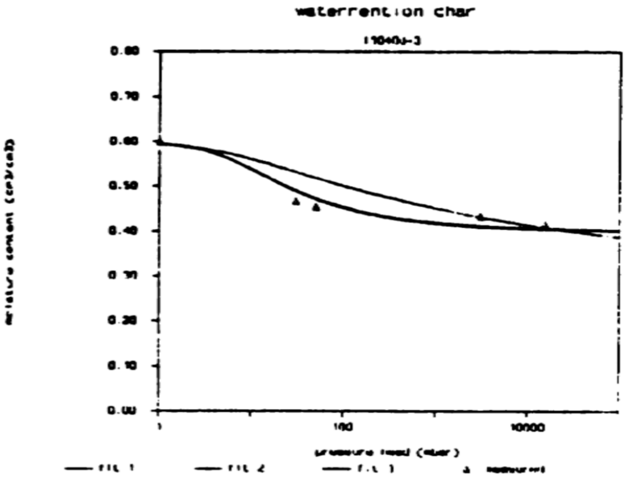

waterrention char
14070-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

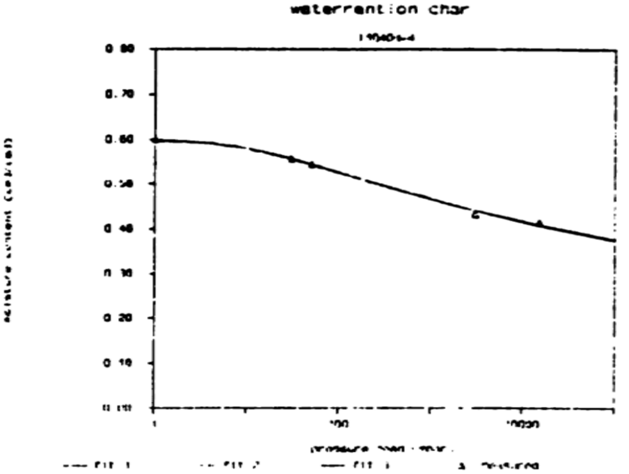

conductivity curve
11040a-5
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

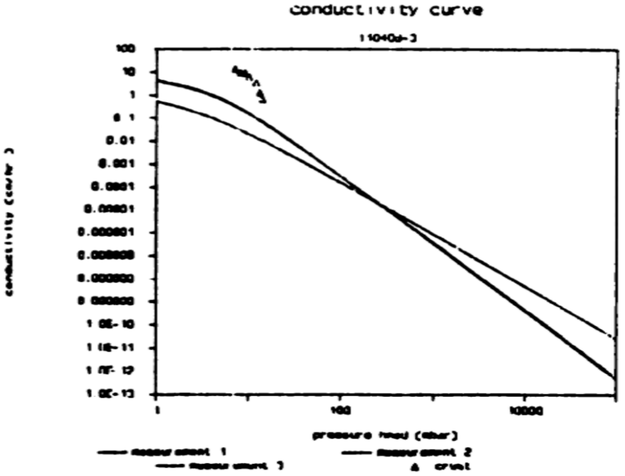

conductivity curve
14070-1
conductivity (cm/hr)
1000
KSAT
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1.0E-12
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

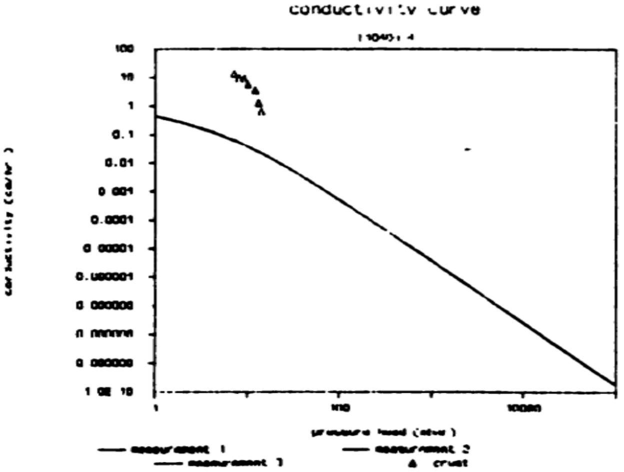

outflow
11040d-3
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

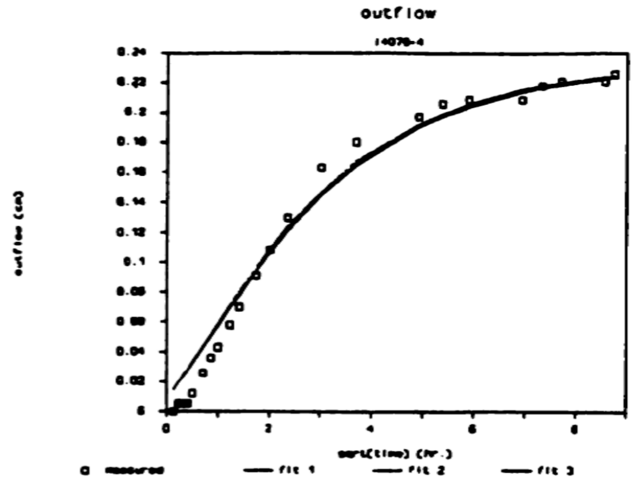

outflow
11040d-4
outflow (cm)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

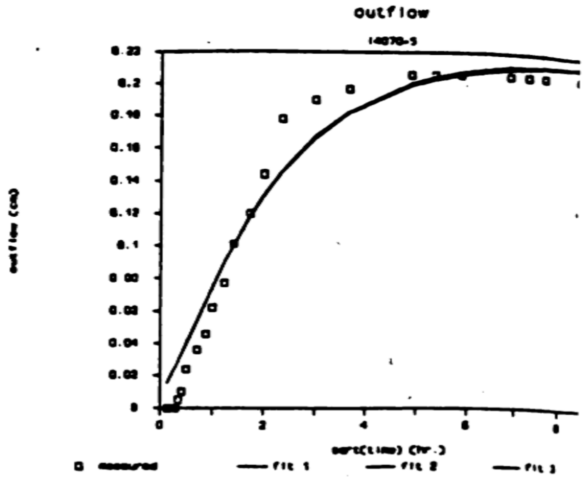

waterrention char
11040d-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

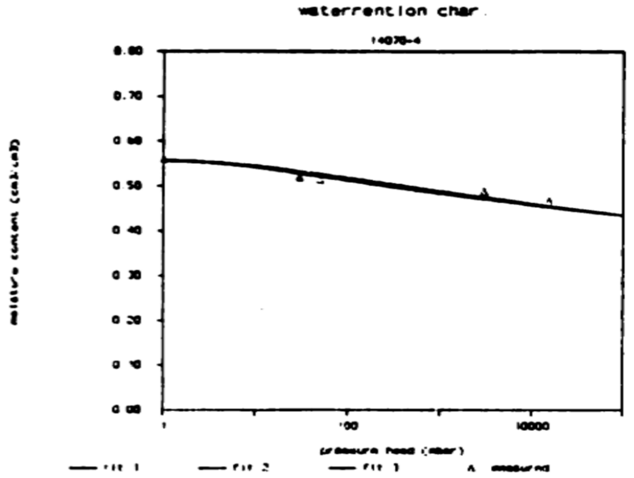

waterrention char
11040d-4
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

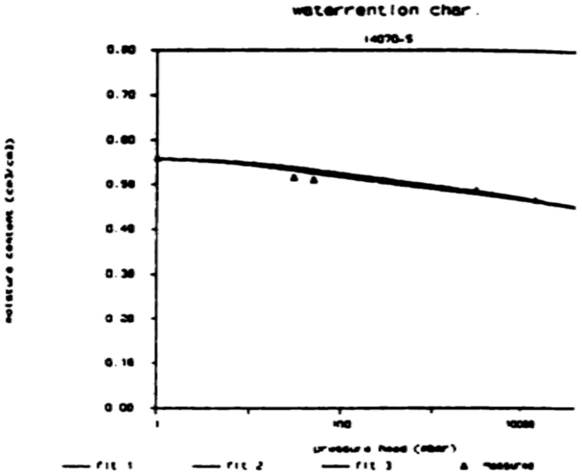

conductivity curve
11040d-3
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

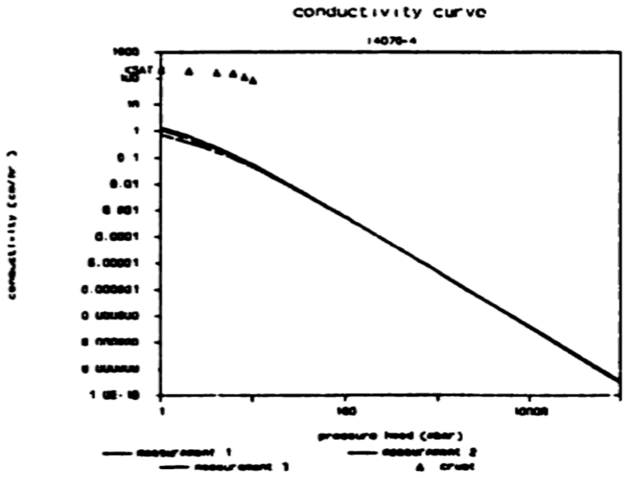

conductivity curve
11040d-4
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

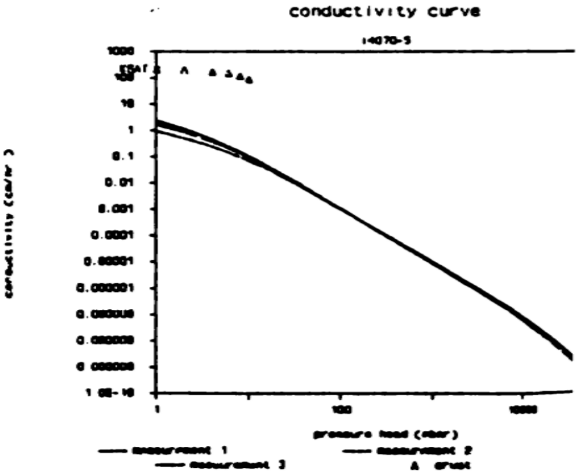

outflow
14070-4
outflow (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

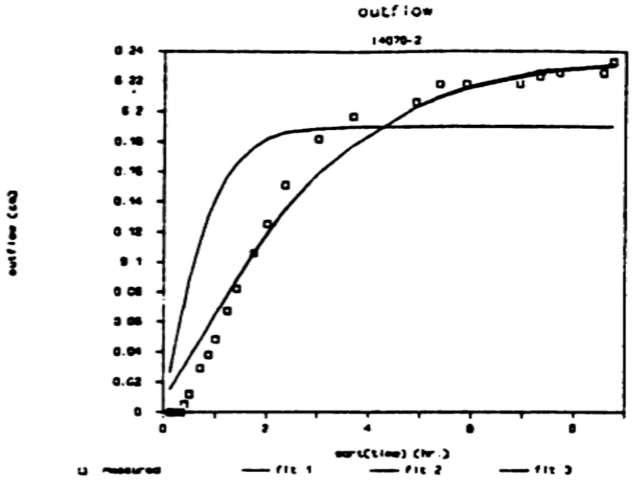

outflow
14070-5
outflow (cm)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

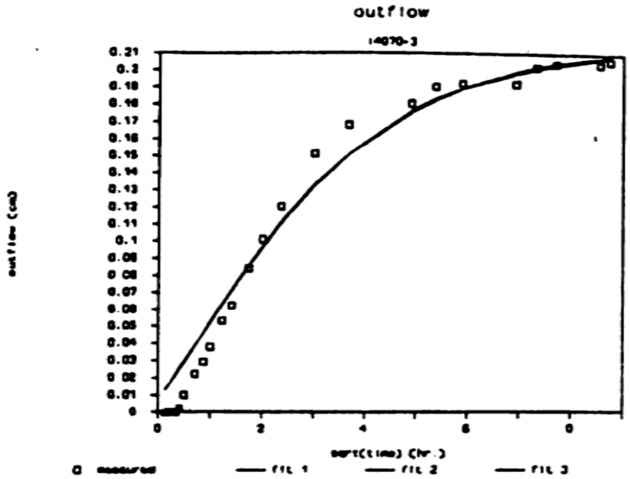

waterrention char.
14070-4
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

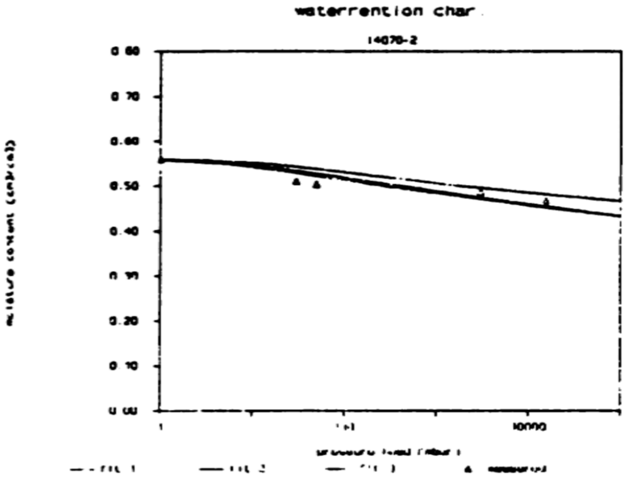

waterrention char.
14070-5
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

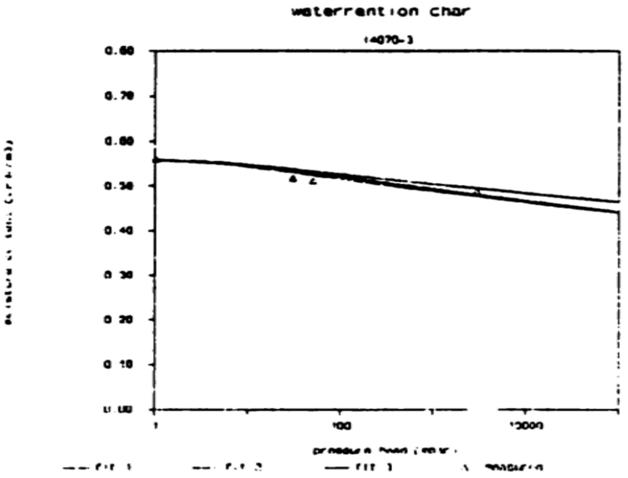

conductivity curve
14070-4
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
KSAT
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

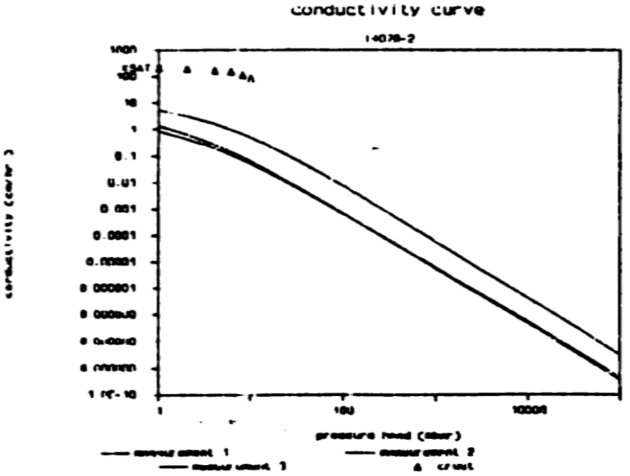

conductivity curve
14070-5
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
KSAT
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

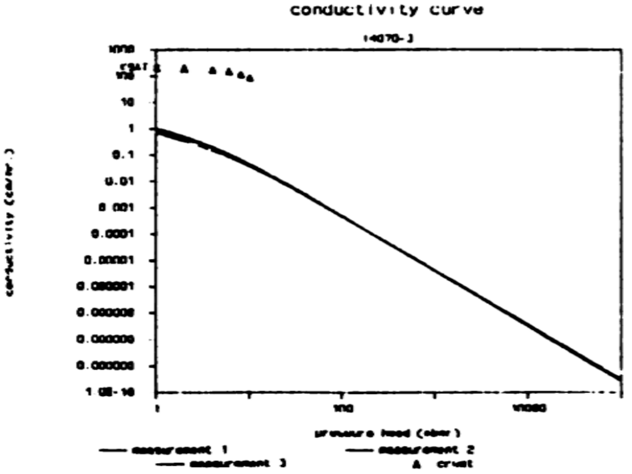

outflow
14070-2
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

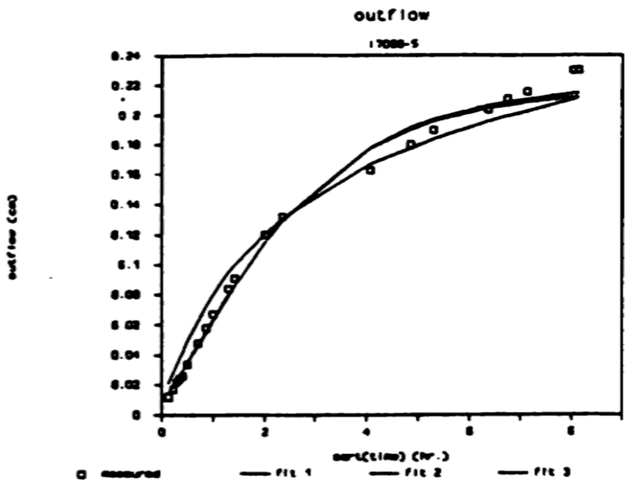

outflow
14070-3
outflow (cm)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0.21
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

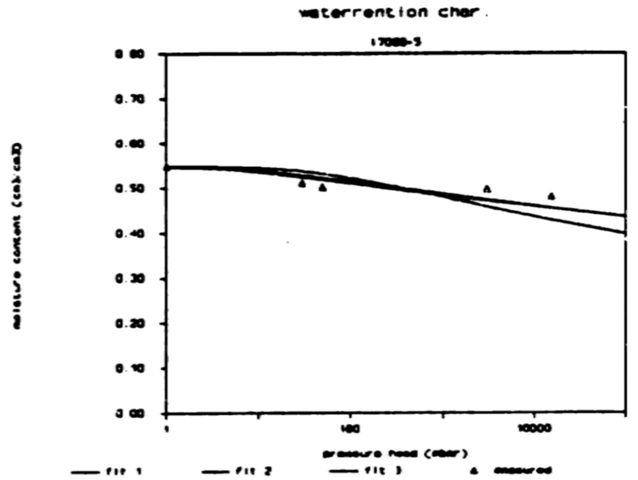

waterrention char
14070-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

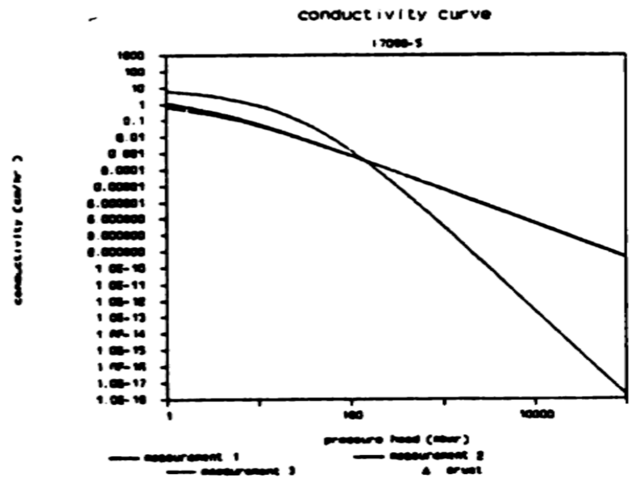

waterrention char
14070-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

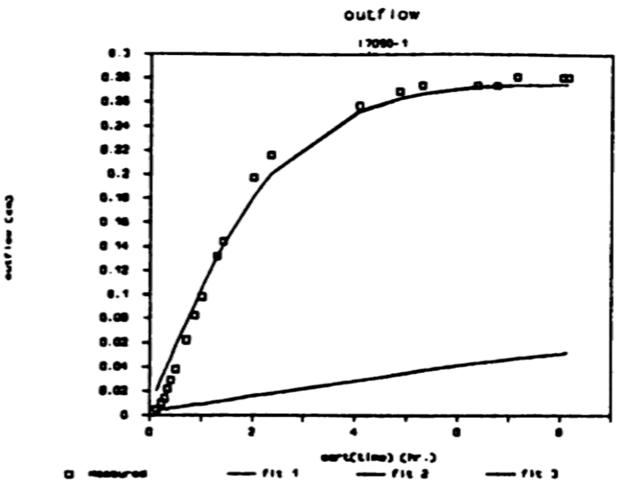

conductivity curve
14070-2
conductivity (cm/hr)
1000
ksat
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

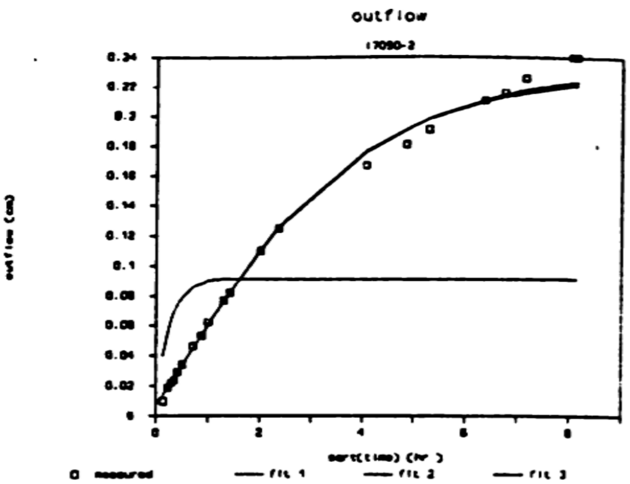

conductivity curve
14070-3
conductivity (cm/hr)
1000
ksat
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

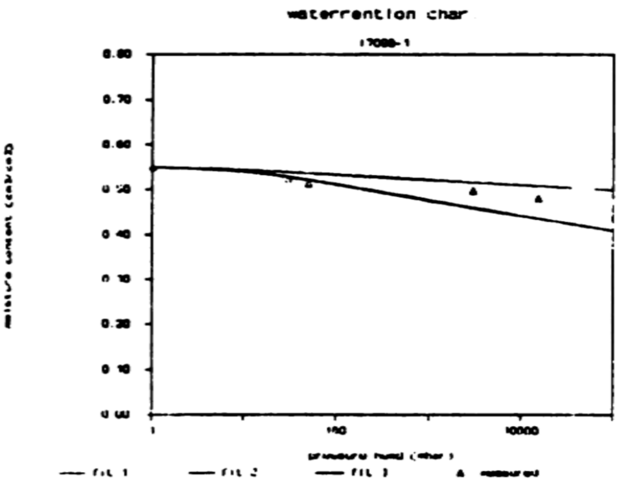

outflow
17088-5
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

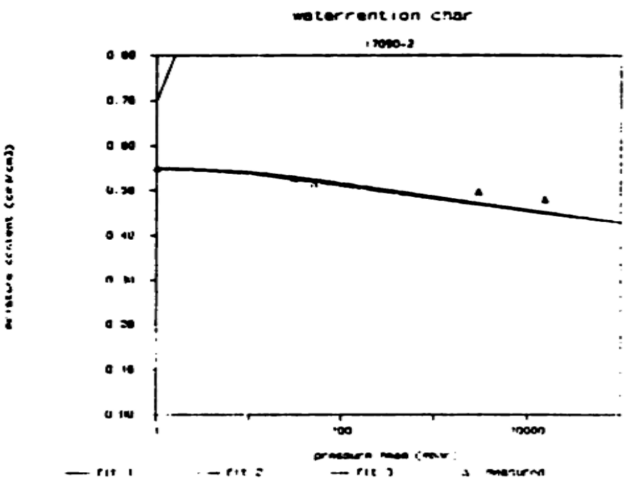

waterrention char.
17088-5
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

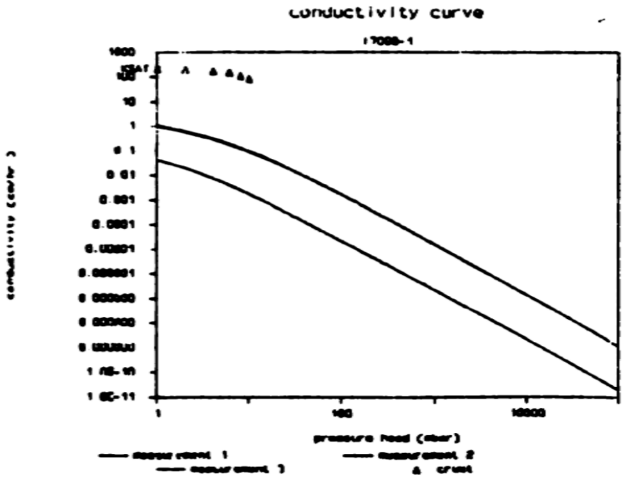

conductivity curve
17088-5
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

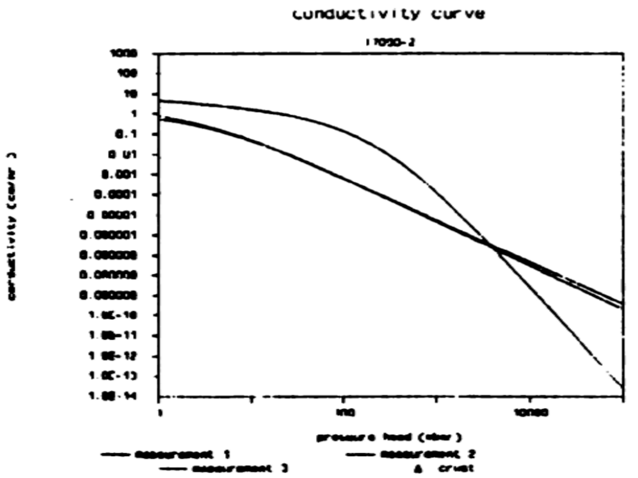

outflow
17090-1
outflow (cm)
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

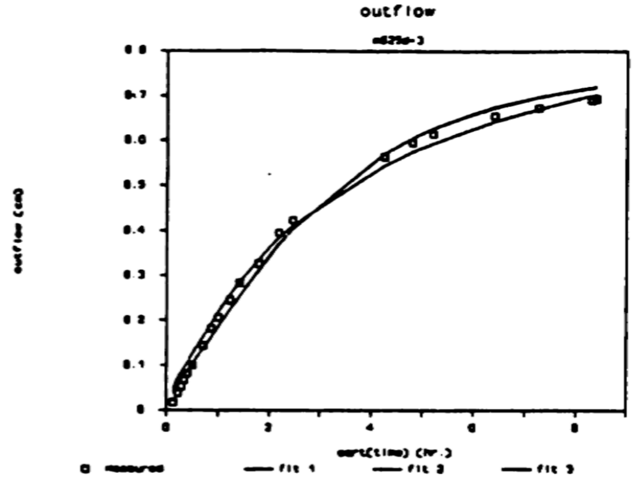

outflow
17090-2
outflow (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

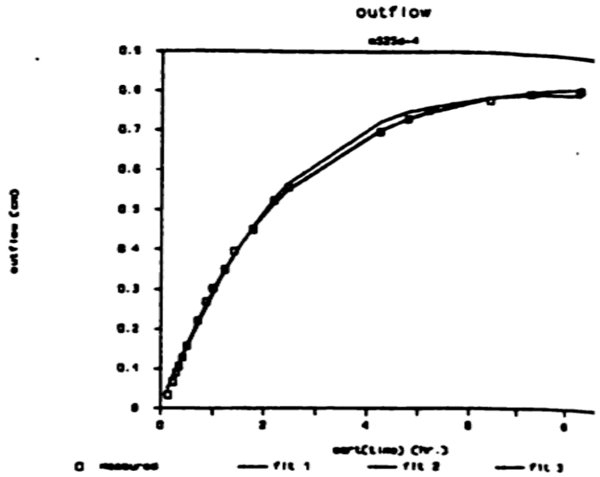

waterrention char
17090-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

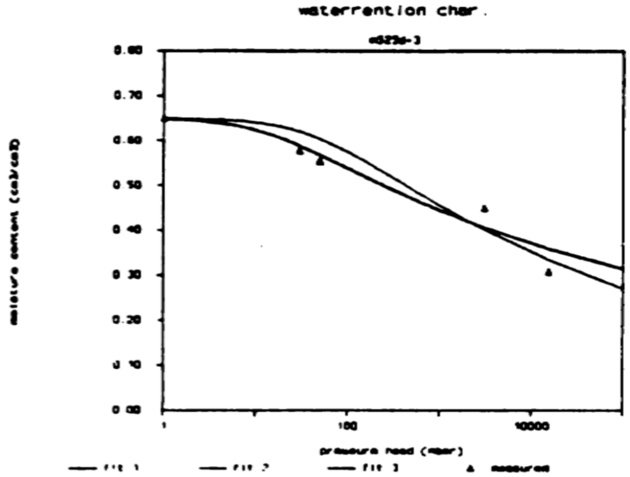

waterrention char
17090-2
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

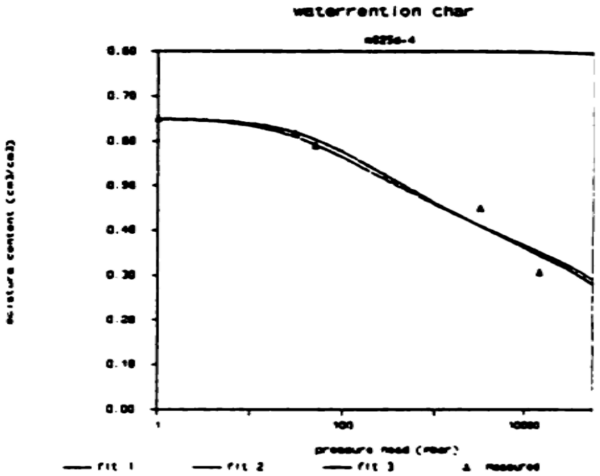

conductivity curve
17090-1
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1.0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust

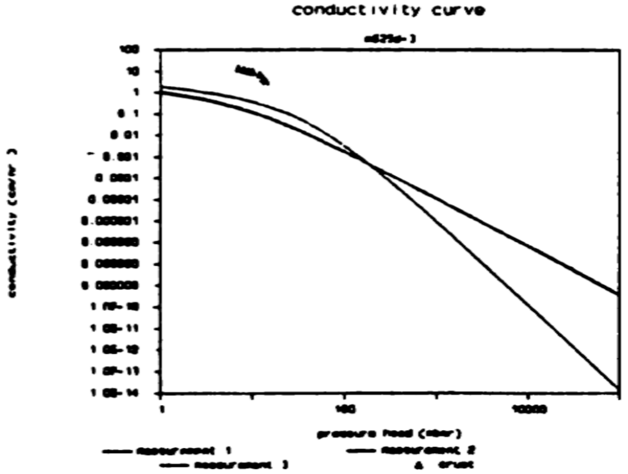

conductivity curve
17090-2
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust

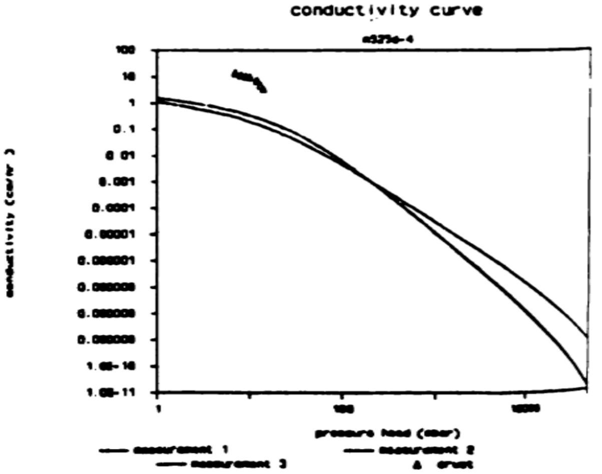

outflow

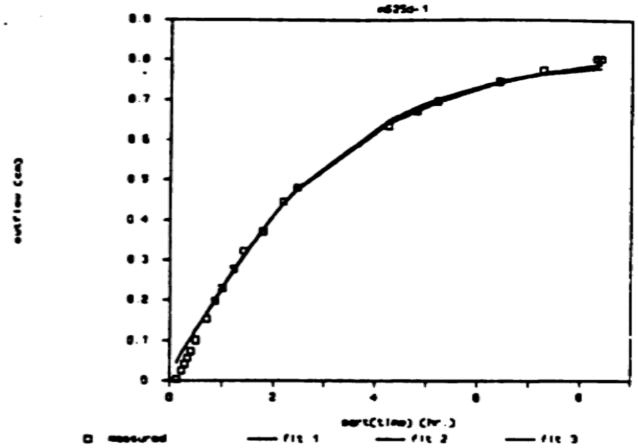

outflow

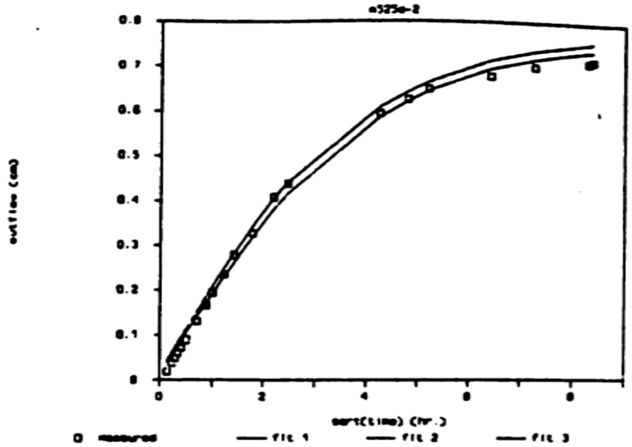

waterrention char.

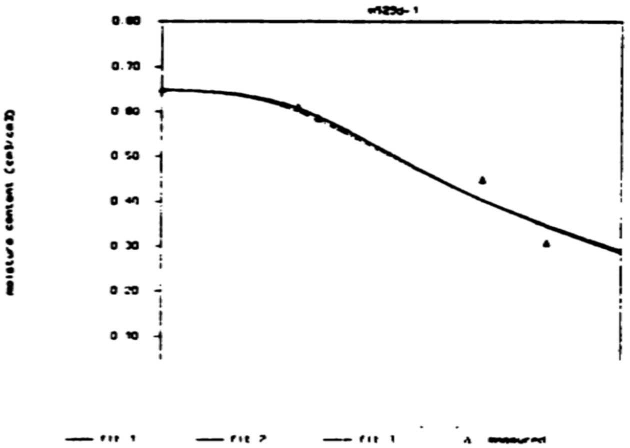

waterrention char

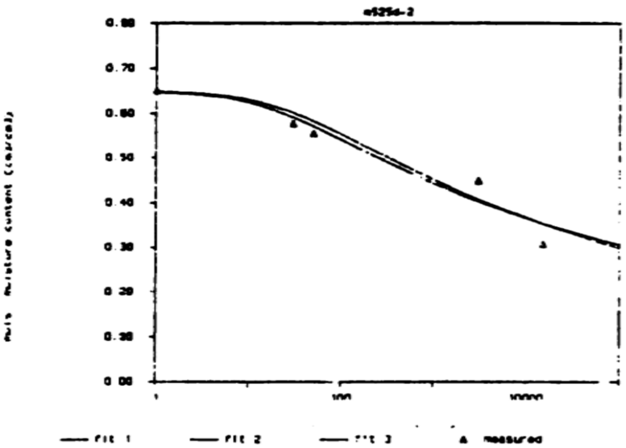

conductivity curve

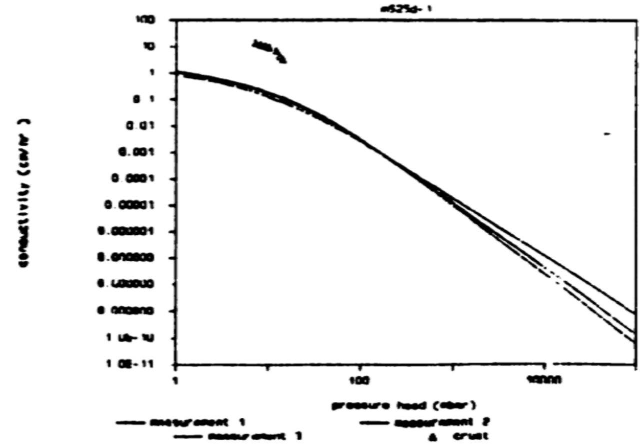

conductivity curve

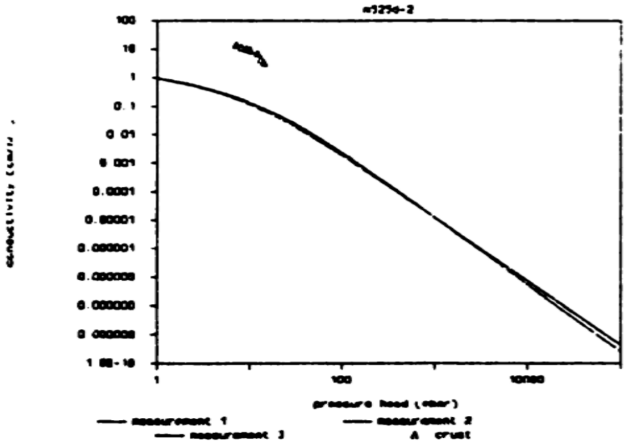

outflow

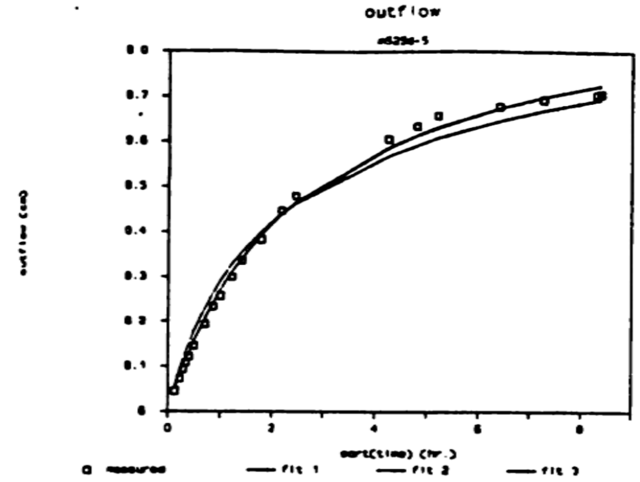

outflow

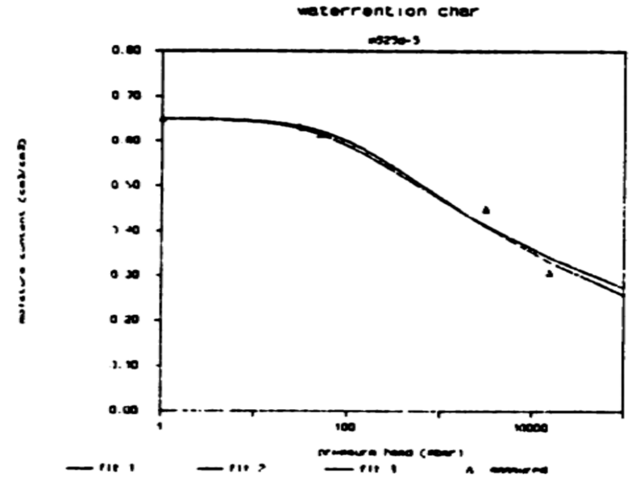

waterrention char

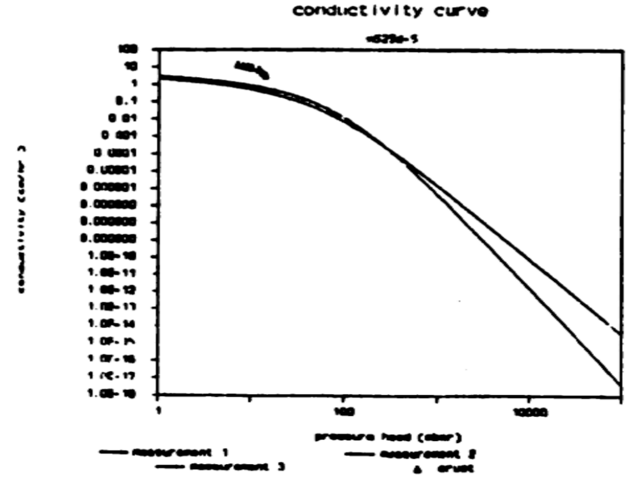

waterrention char

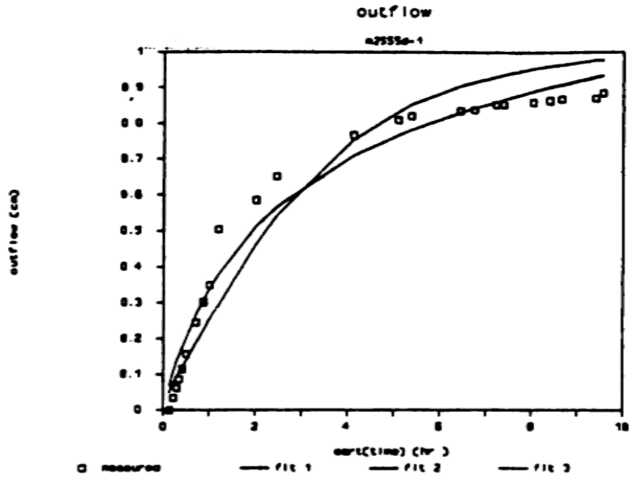

conductivity curve

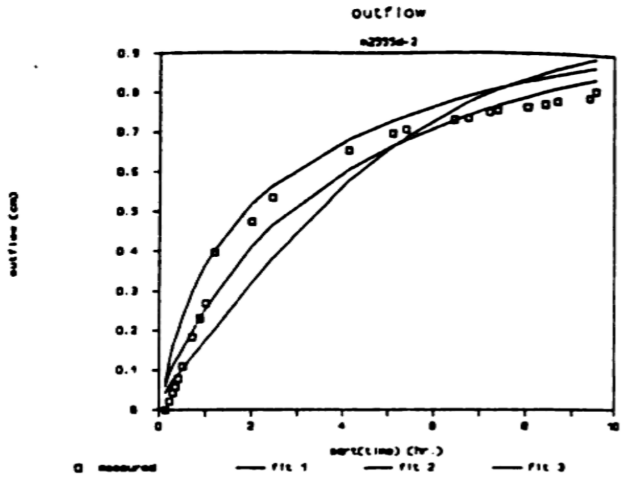

conductivity curve

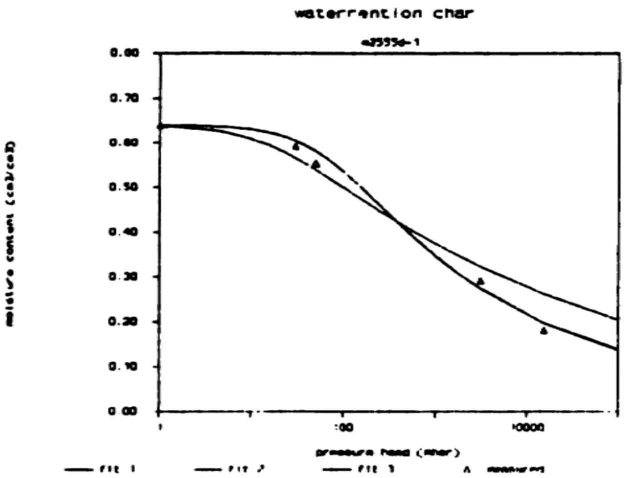

outflow
m529e-5
outflow (cm)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

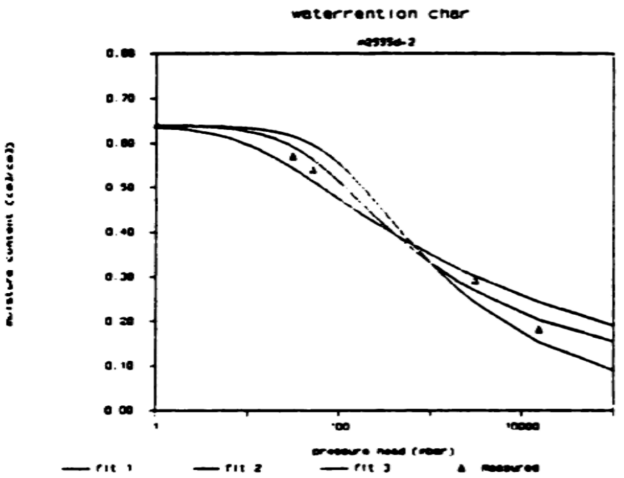

waterrention char
m529e-5
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

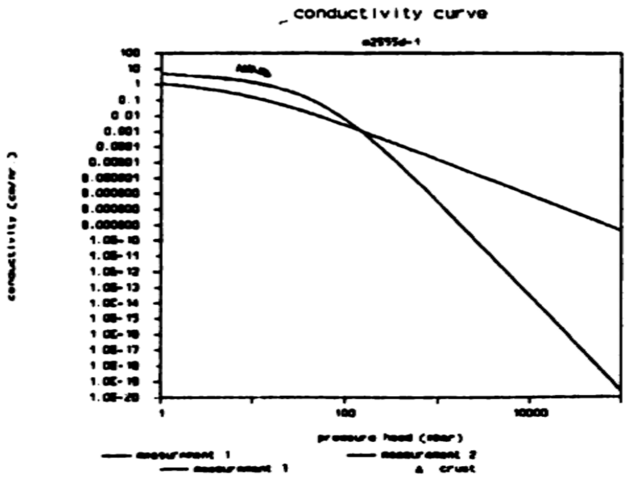

conductivity curve
m529e-5
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

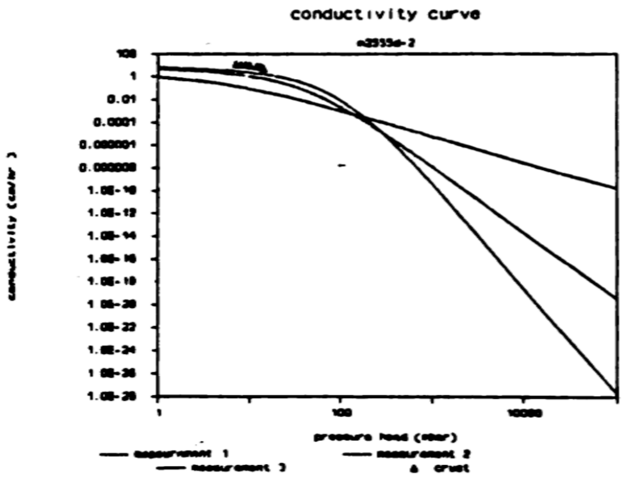

outflow
m2595d-1
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

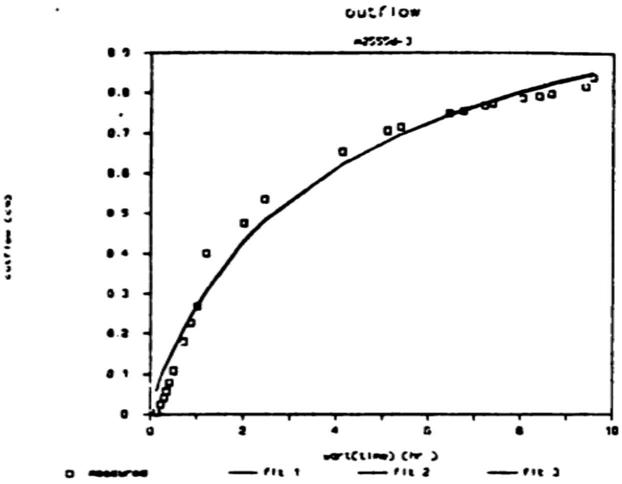

outflow
m2595d-2
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3


waterrention char
m2595d-1
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

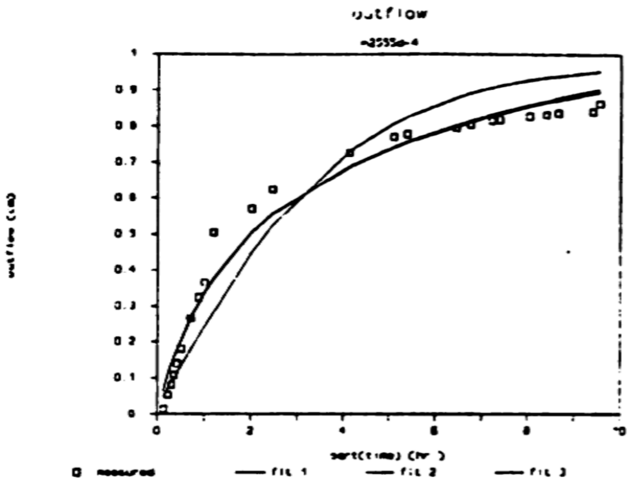

waterrention char
m2595d-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured


conductivity curve
m2595d-1
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
1.0E-20
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

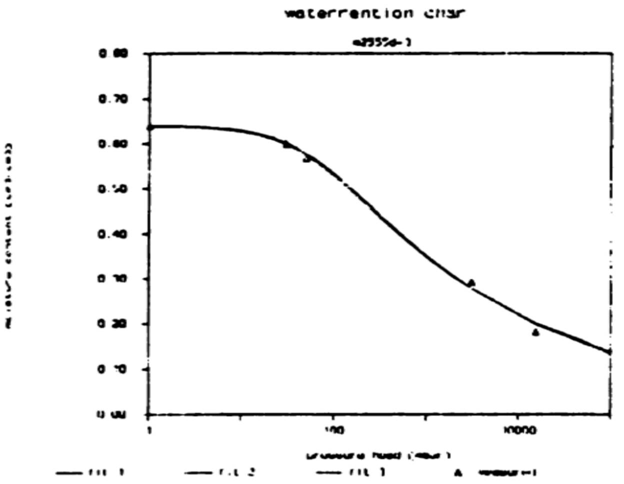

conductivity curve
m2595d-2
conductivity (cm/hr)
100
1
0.01
0.0001
0.000001
0.00000001
1.0E-10
1.0E-12
1.0E-14
1.0E-16
1.0E-18
1.0E-20
1.0E-22
1.0E-24
1.0E-26
1.0E-28
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust


outflow

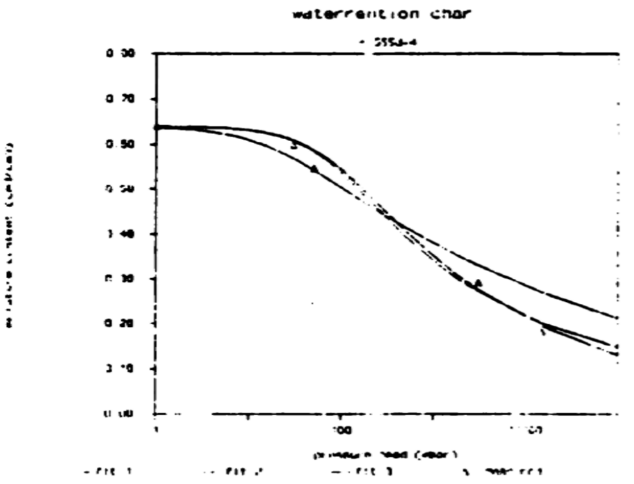
m2555a-3


outflow

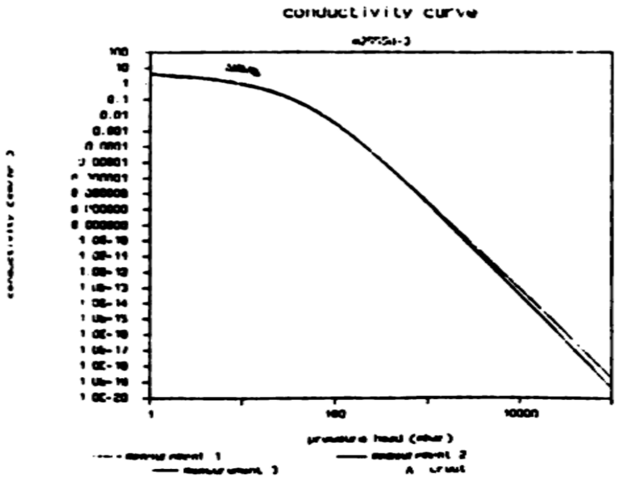
m2555a-4


waterrention char

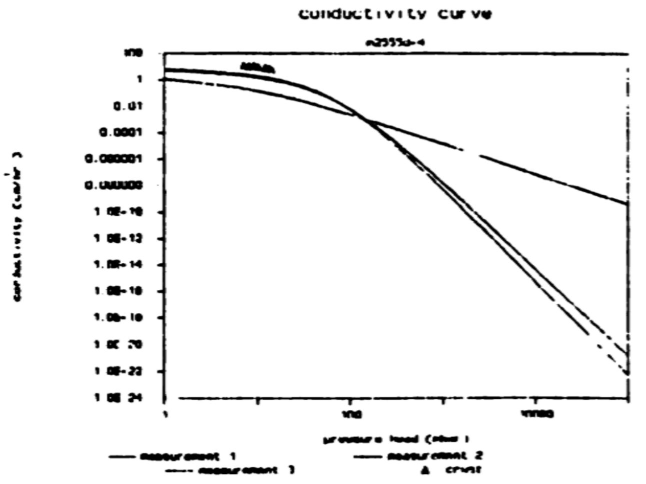
m2555a-3


waterrention char

m2555a-4

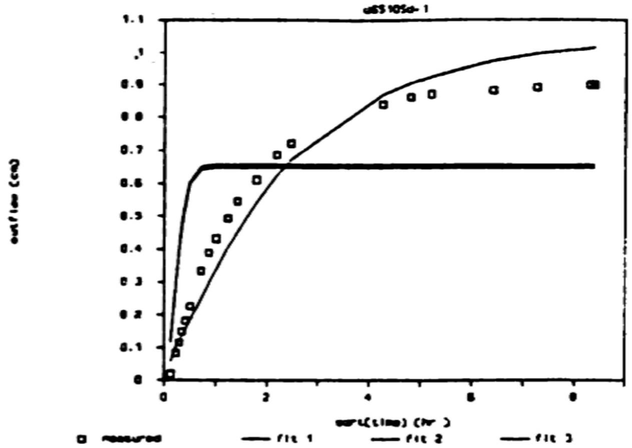

conductivity curve

m2555a-3

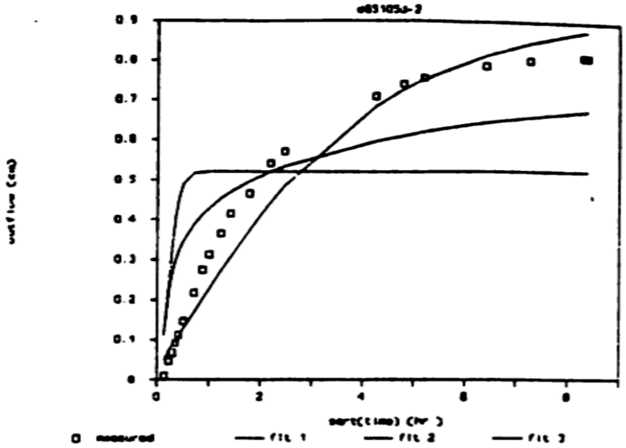

conductivity curve

m2555a-4

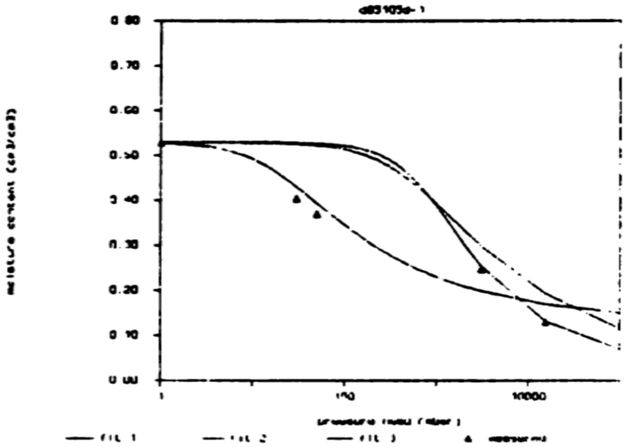
outflow



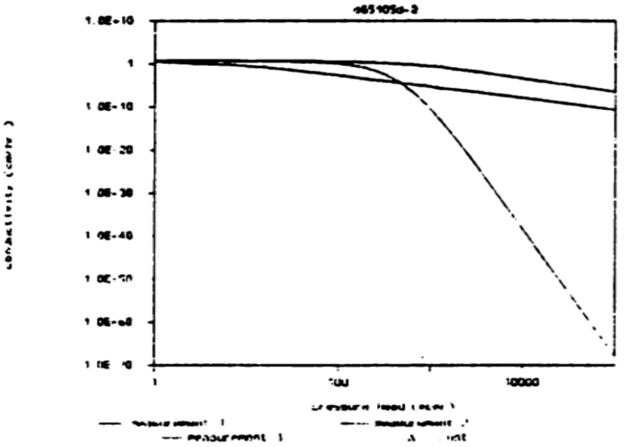
outflow



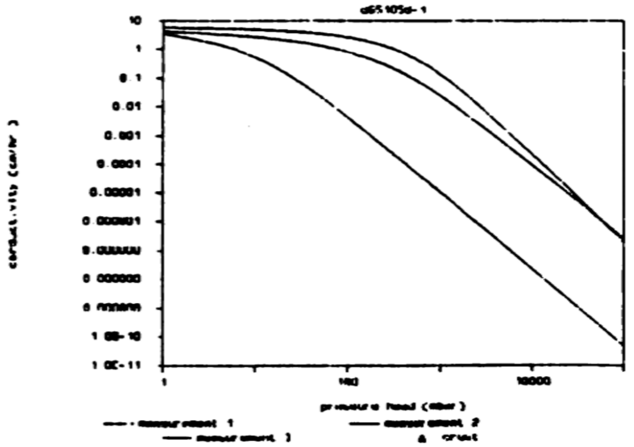
waterrention char.



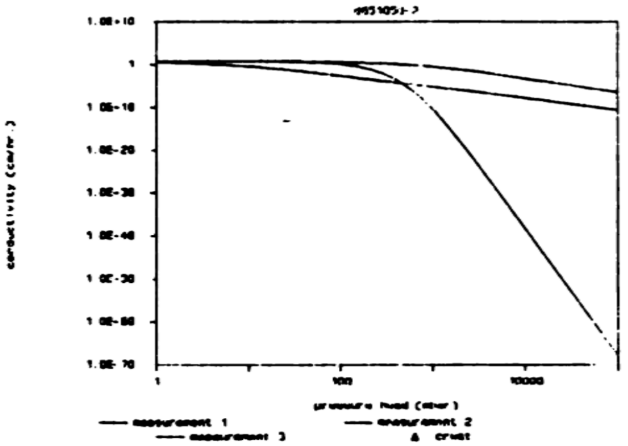
conductivity curve



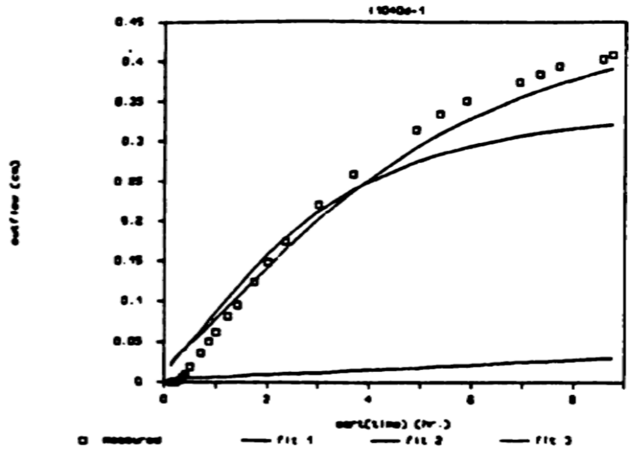
conductivity curve

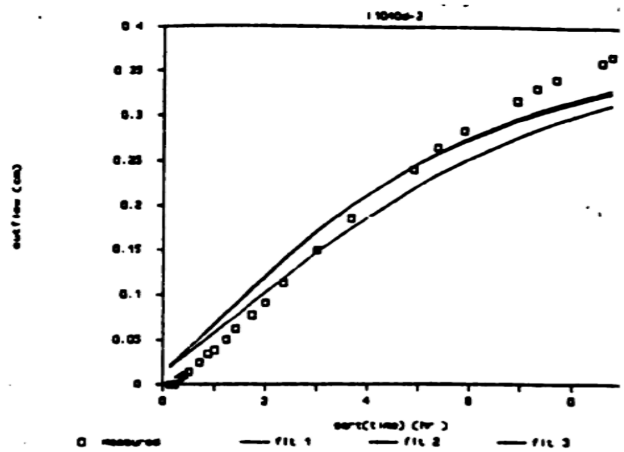


conductivity curve

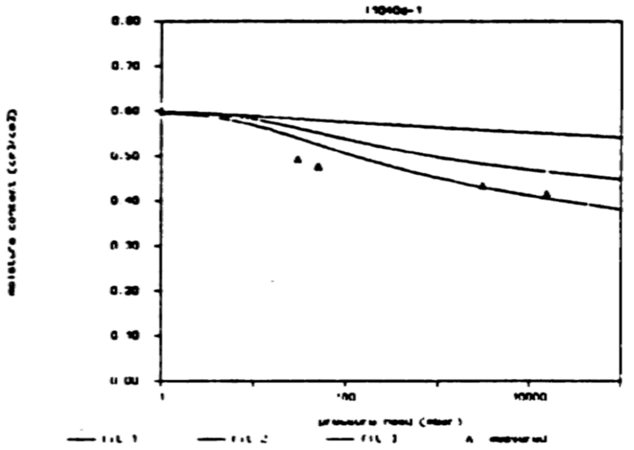


outflow

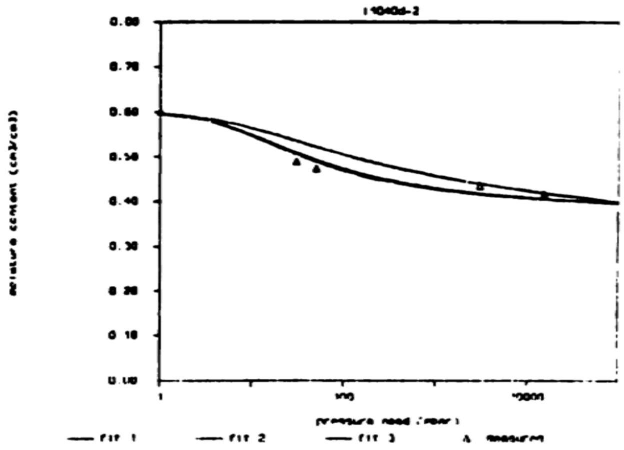




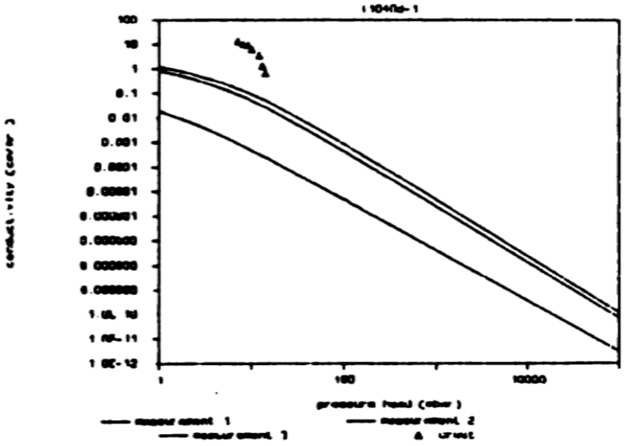
waterrention char



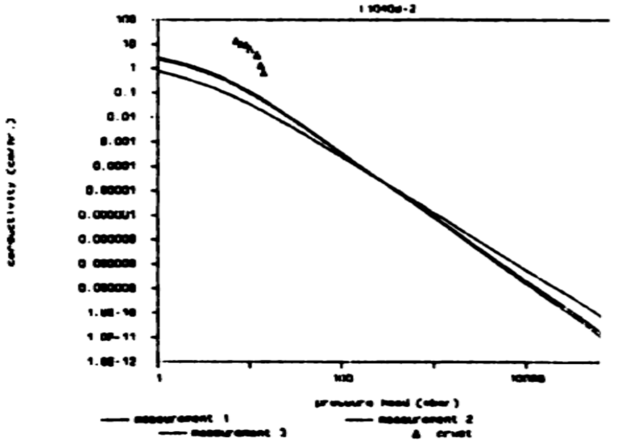
waterrention char

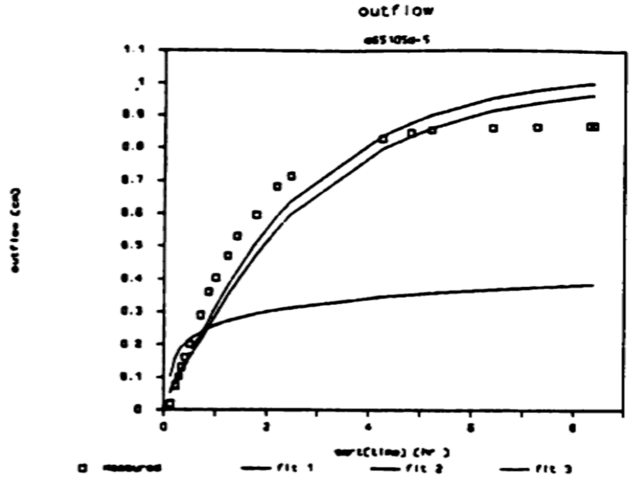


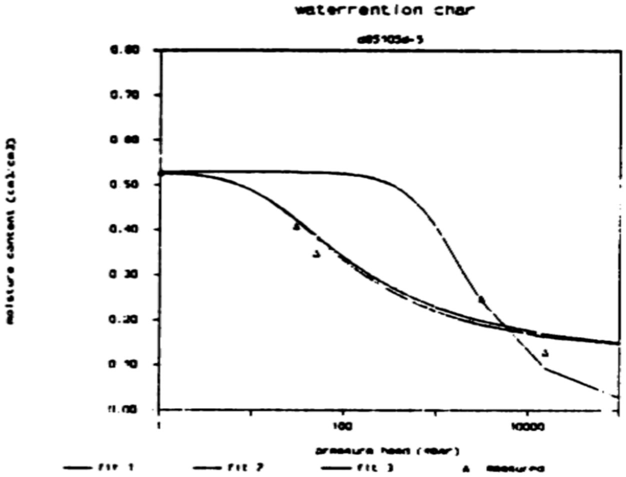
conductivity curve

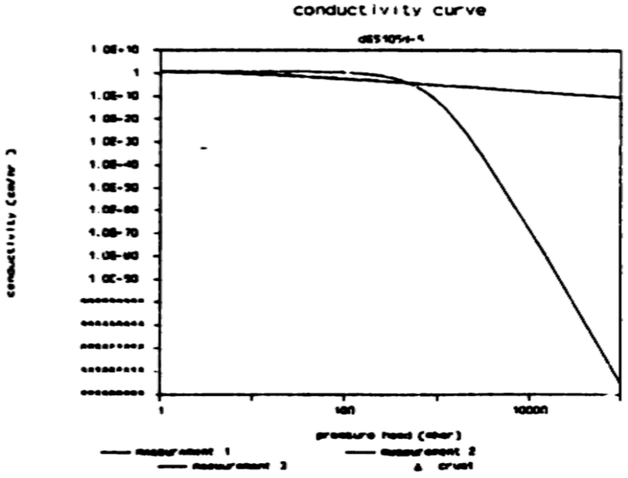


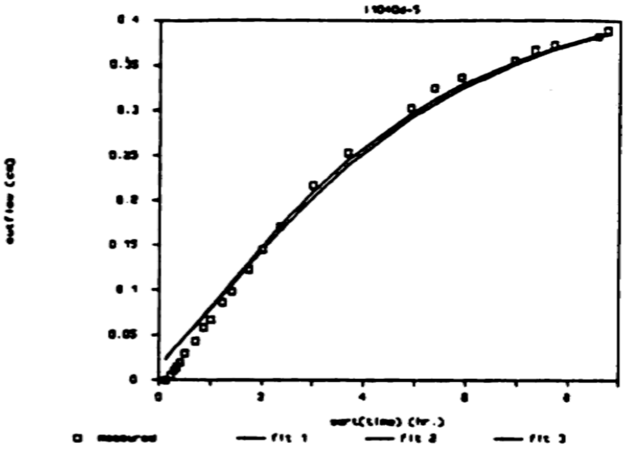
conductivity curve

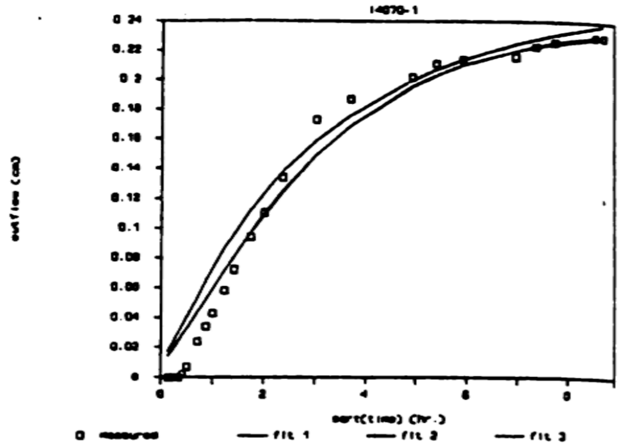


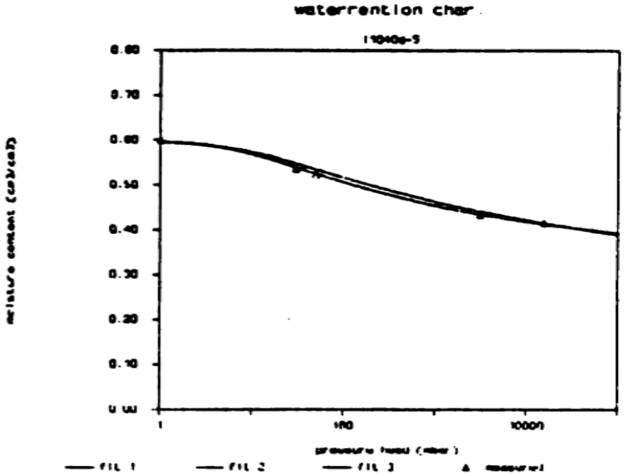

outflow
d85105a-5
outflow (cm)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

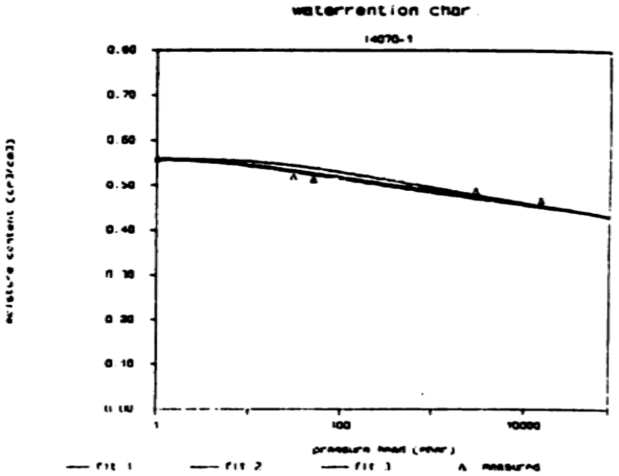

waterrention char
d85105a-5
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

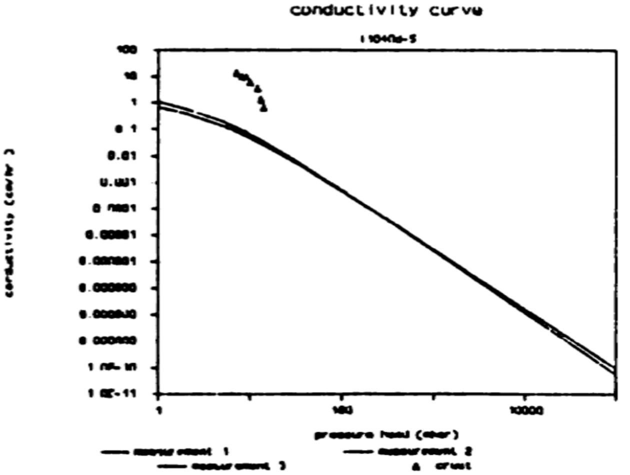

conductivity curve
d85105a-5
conductivity (cm/hr)
1.0E+10
1
1.0E-10
1.0E-20
1.0E-30
1.0E-40
1.0E-50
1.0E-60
1.0E-70
1.0E-80
1.0E-90
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

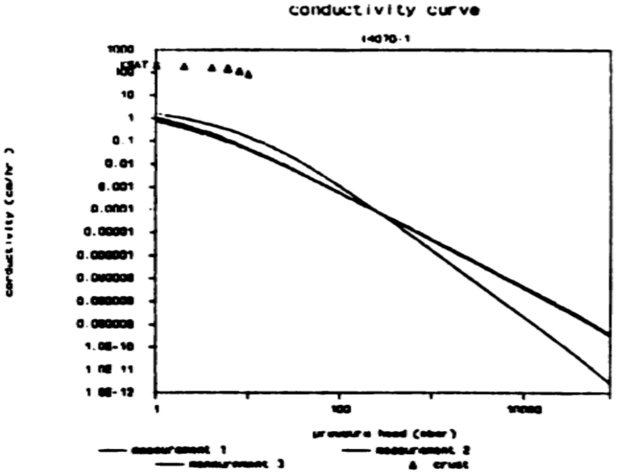

11040d-5
outflow (cm)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
sqrt(time) (hr.)
0
2
4
6
8
measured
fit 1
fit 2
fit 3


14070-1
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
sqrt(time) (hr.)
0
2
4
6
8
measured
fit 1
fit 2
fit 3

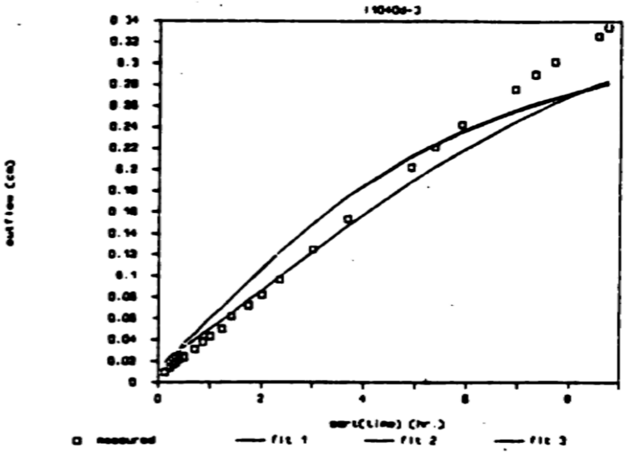

waterrention char.
11040d-5
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
pressure head (mbar)
1
100
10000
fit 1
fit 2
fit 3
measured


waterrention char.
14070-1
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
pressure head (mbar)
1
100
10000
fit 1
fit 2
fit 3
measured

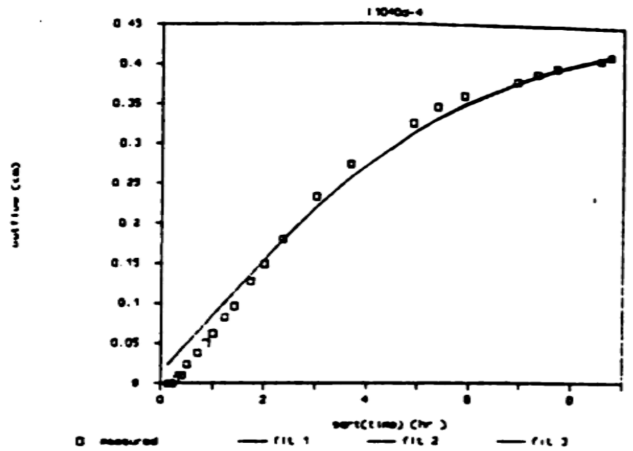

conductivity curve
11040d-5
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1 0E-10
1 0E-11
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
crust


conductivity curve
14070-1
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1.0E-12
KSAT
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
crust

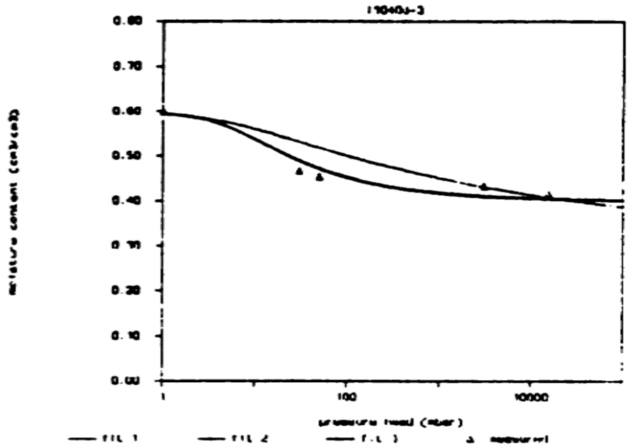
outflow



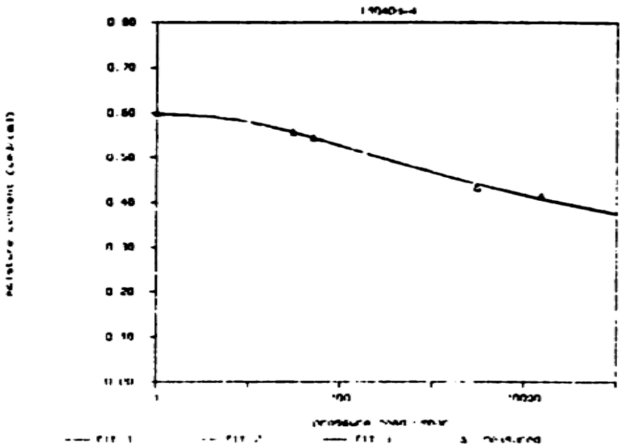
outflow



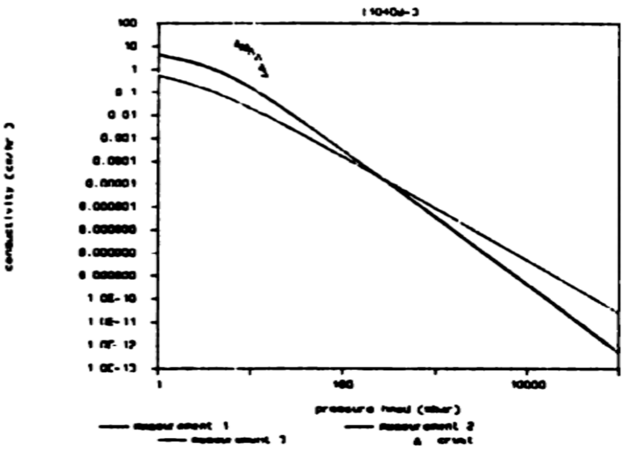
waterrention char



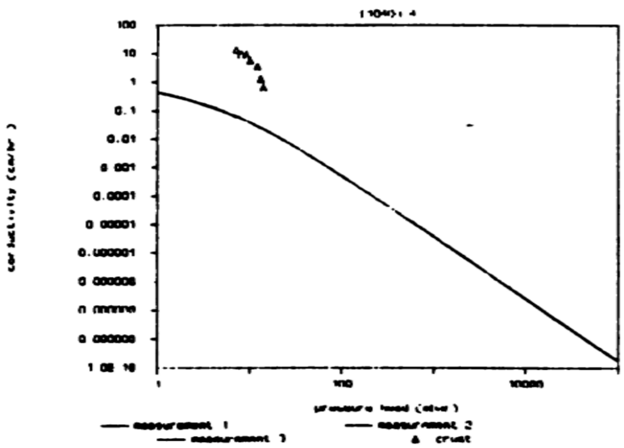
waterrention char

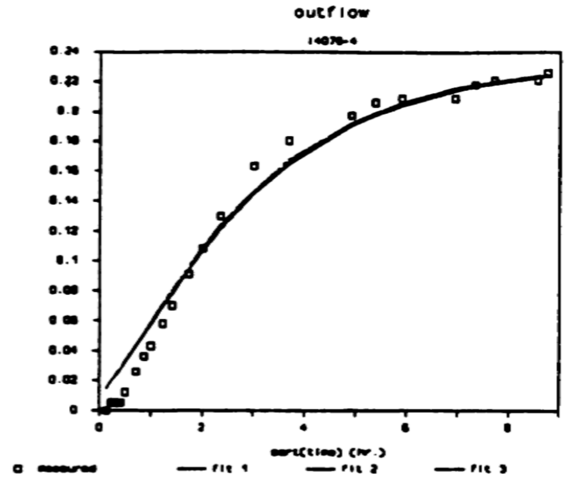


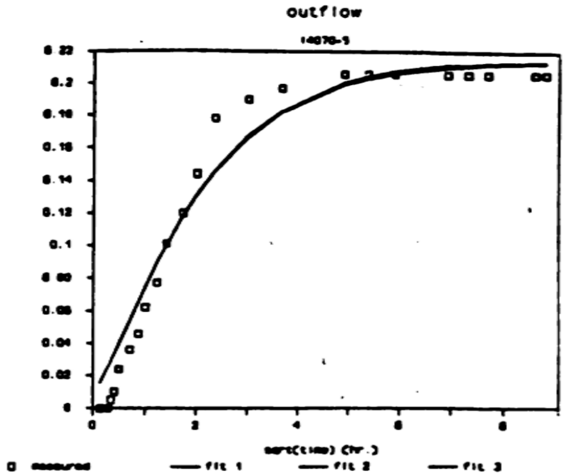
conductivity curve

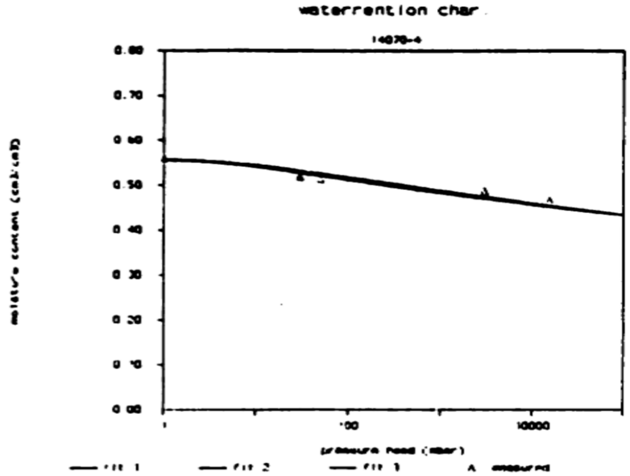


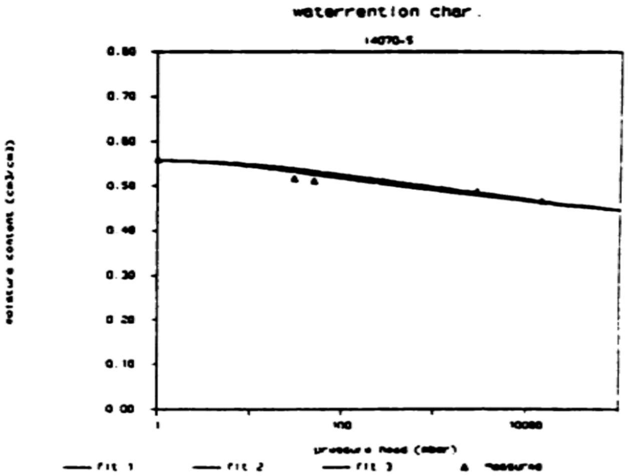
conductivity curve

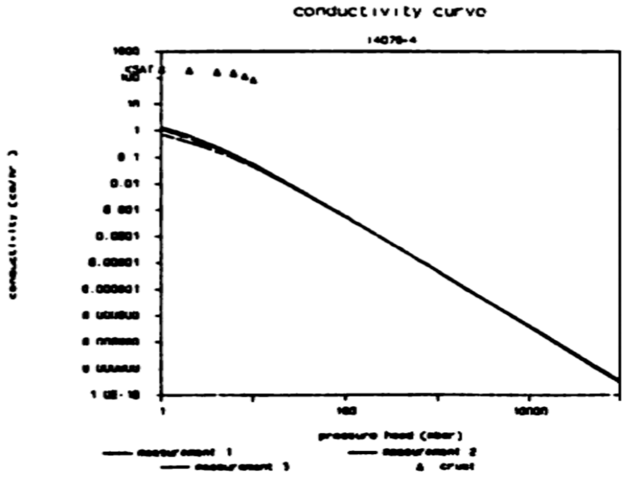


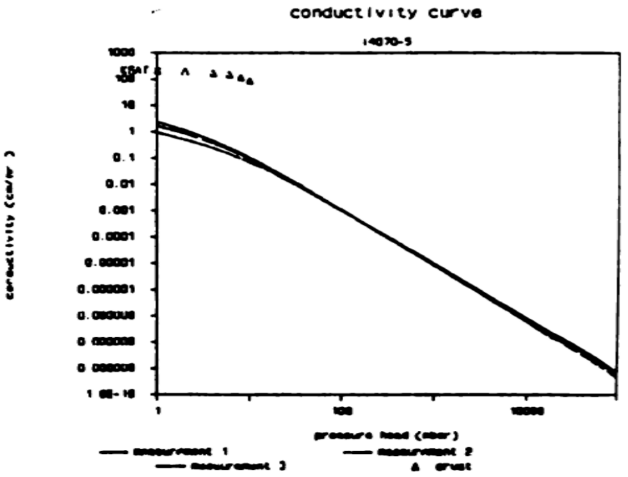

outflow
14070-4
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
sqrt(time) (hr.)
0
2
4
6
8
□ measured
fit 1
fit 2
fit 3

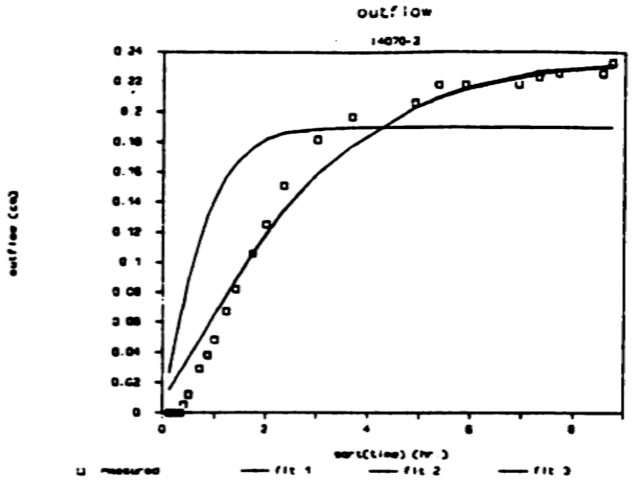

outflow
14070-5
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
sqrt(time) (hr.)
0
2
4
6
8
□ measured
fit 1
fit 2
fit 3

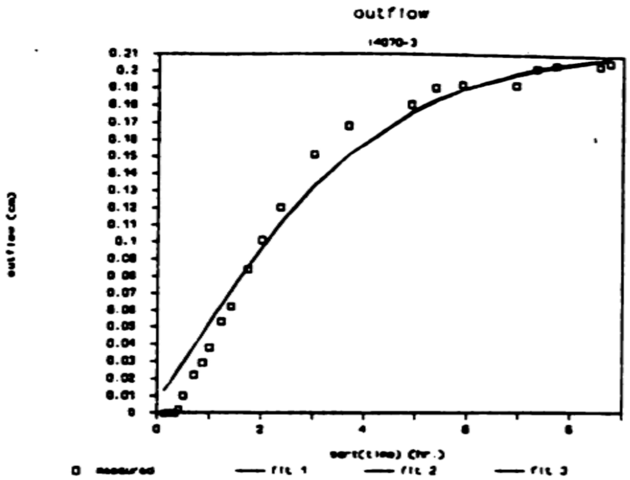

waterrention char.
14070-4
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
pressure head (mbar)
1
100
10000
fit 1
fit 2
fit 3
Δ measured

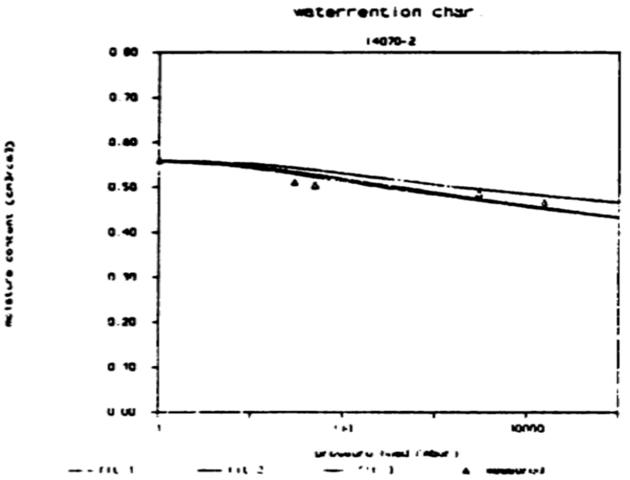

waterrention char.
14070-5
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
pressure head (mbar)
1
100
10000
fit 1
fit 2
fit 3
Δ measured

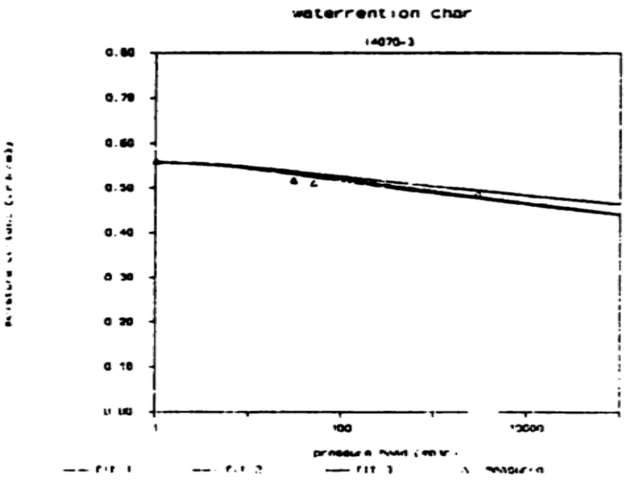

conductivity curve
14070-4
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1 0E-10
KSAT
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
Δ crust

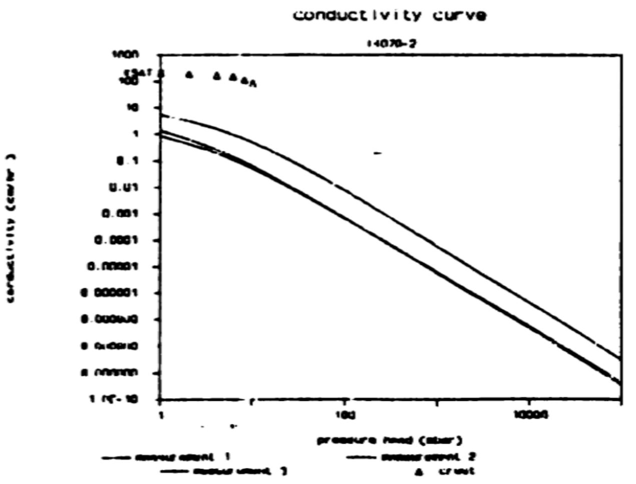

conductivity curve
14070-5
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1 0E-10
KSAT
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
Δ crust

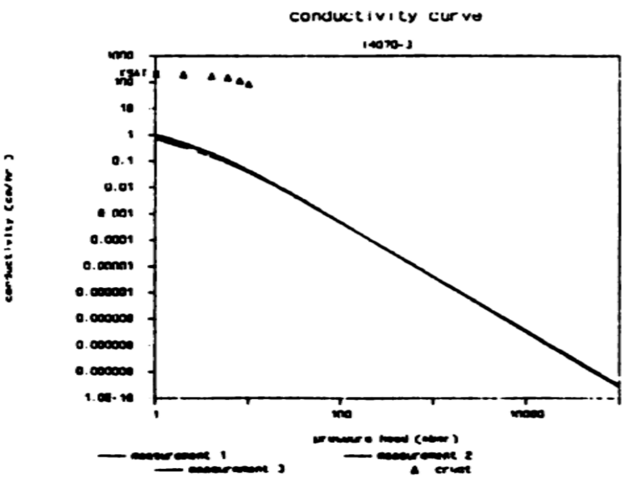

outflow
14070-2
outflow (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3


outflow
14070-3
outflow (cm)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0.21
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

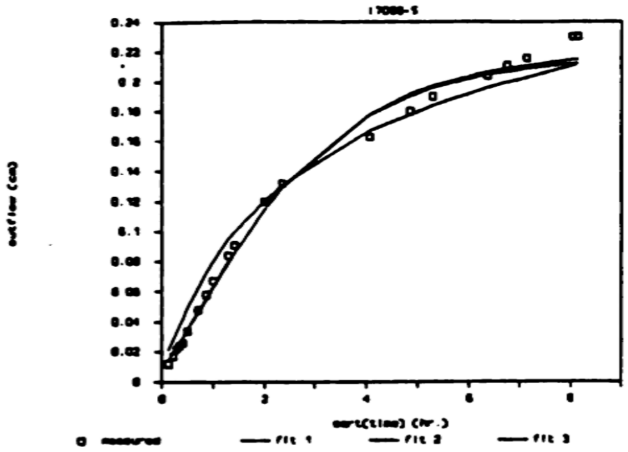

waterrention char
14070-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured


waterrention char
14070-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

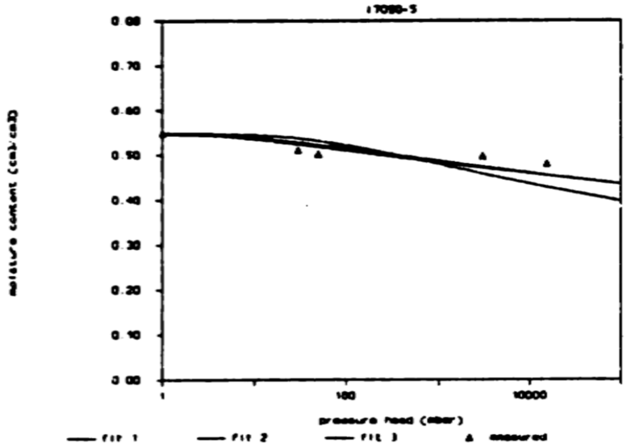

conductivity curve
14070-2
conductivity (cm/hr)
1000
100
KSAT
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust


conductivity curve
14070-3
conductivity (cm/hr)
1000
100
KSAT
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

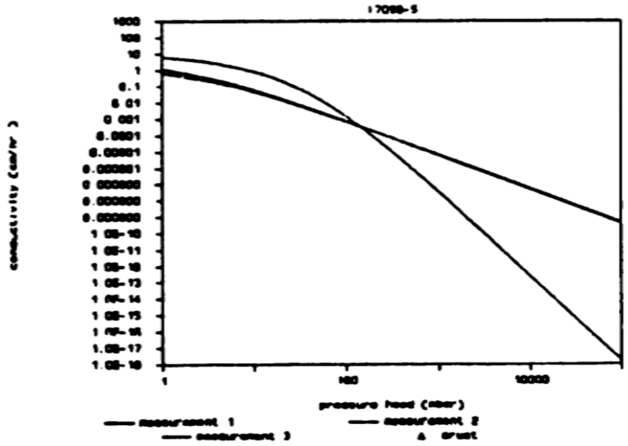
outflow

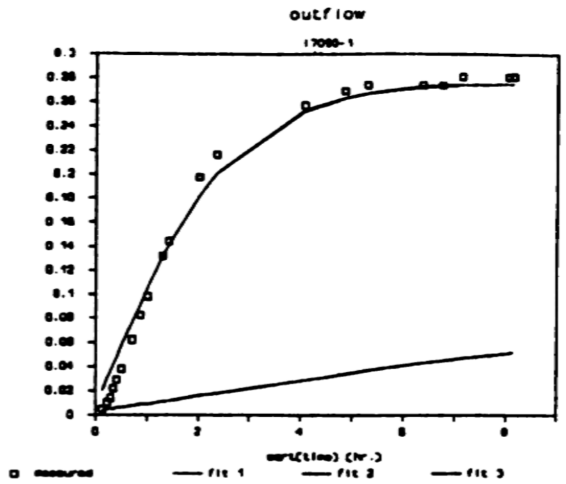


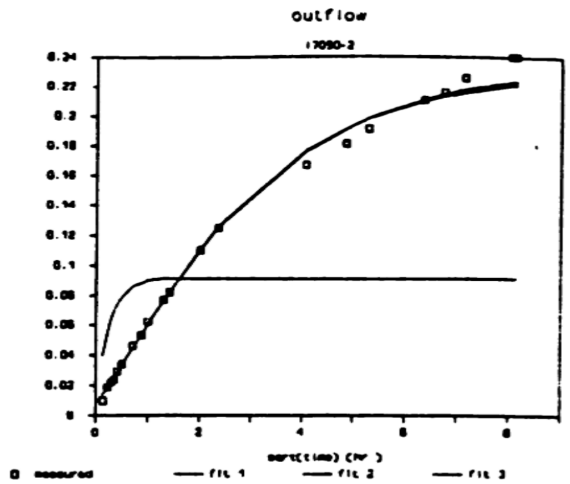
waterrention char.

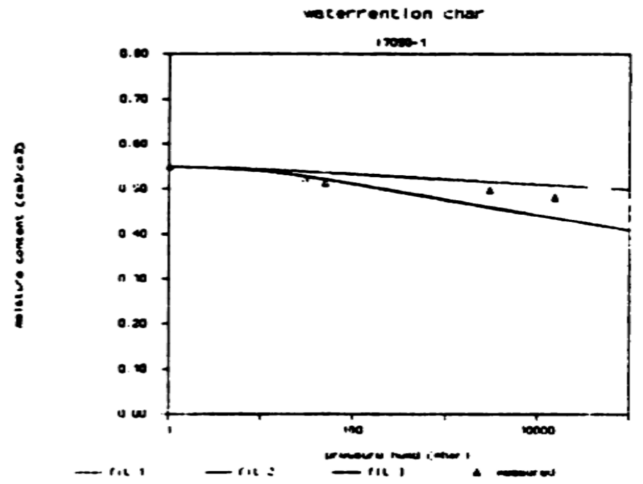


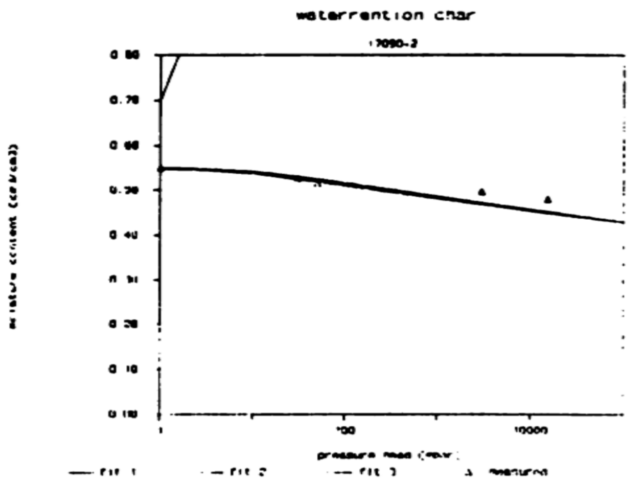
conductivity curve

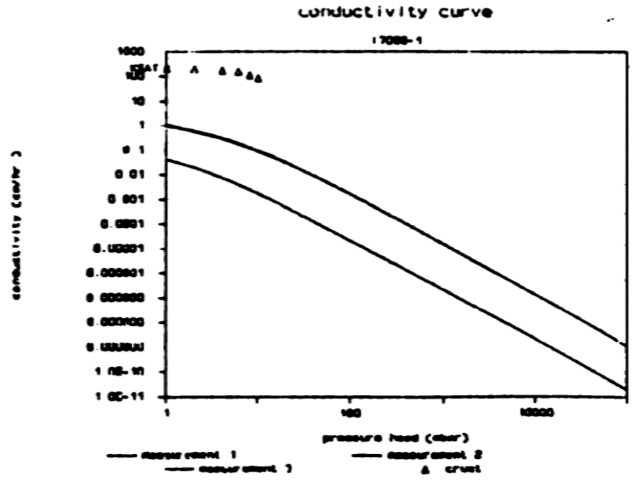


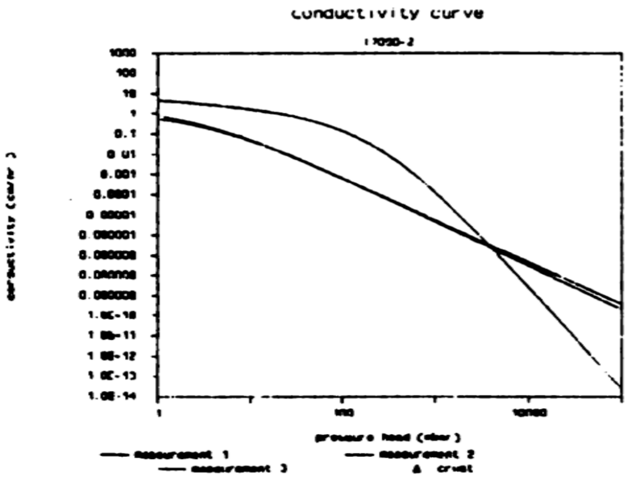

outflow
17090-1
outflow (cm)
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

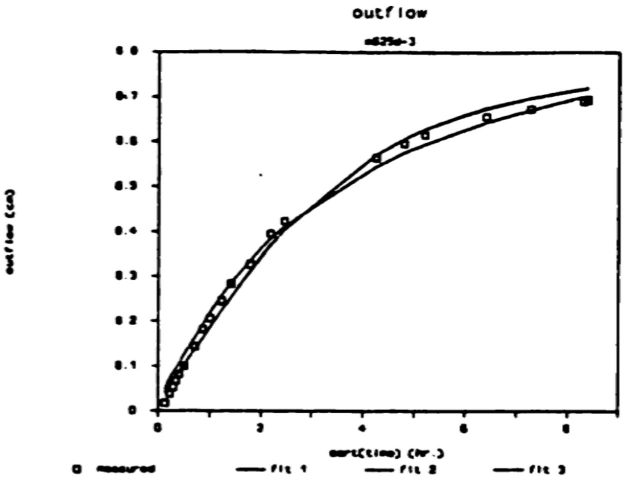

outflow
17090-2
outflow (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

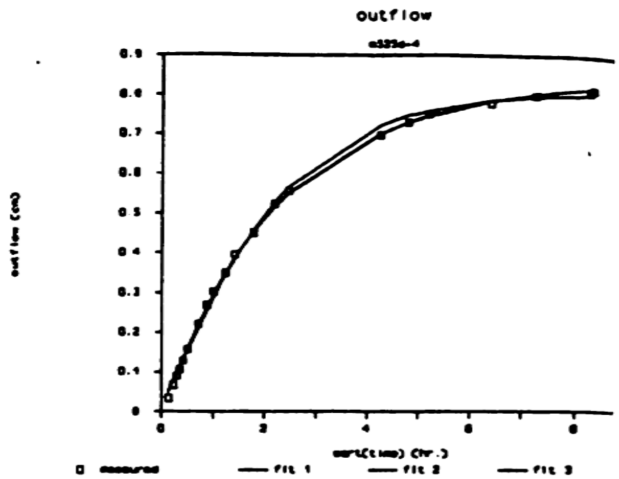

waterrention char
17090-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

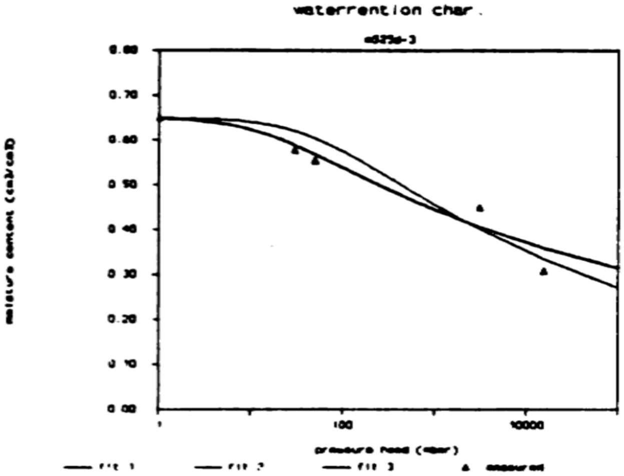

waterrention char
17090-2
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

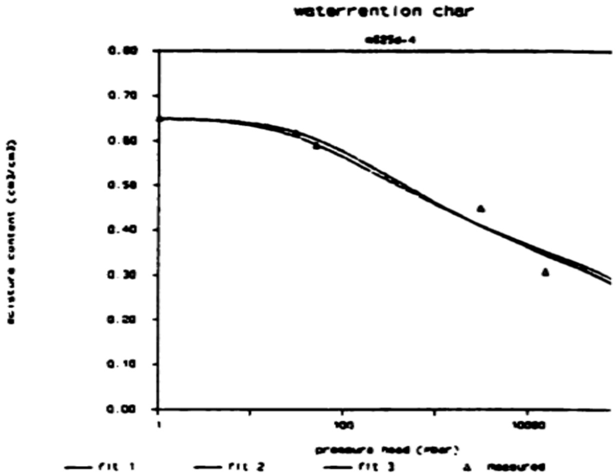

conductivity curve
17090-1
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust
KSAT

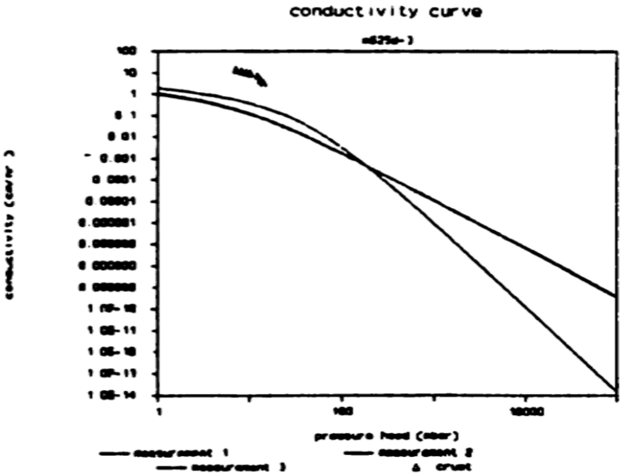

conductivity curve
17090-2
conductivity (cm/hr)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust

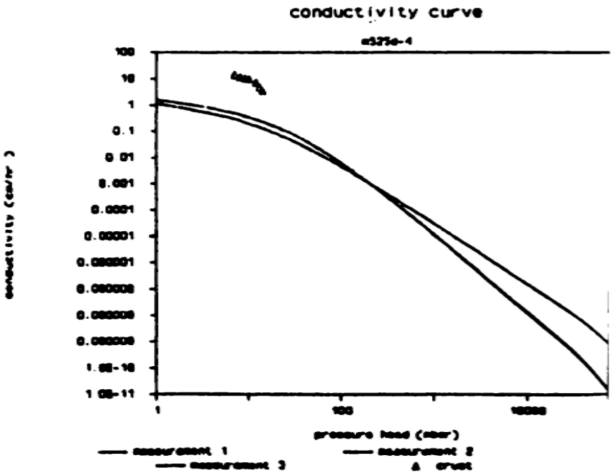

outflow
m525d-3
outflow (cm)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

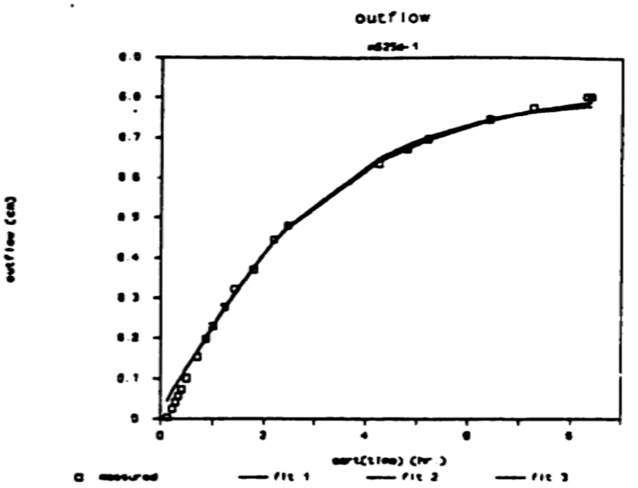

outflow
m525d-4
outflow (cm)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

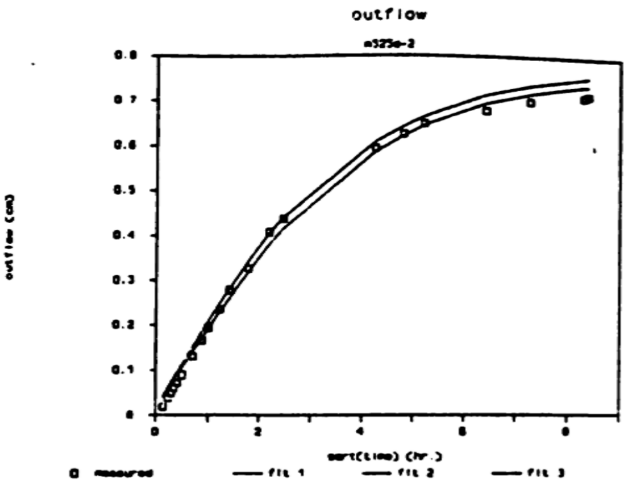

waterrention char.
m525d-3
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

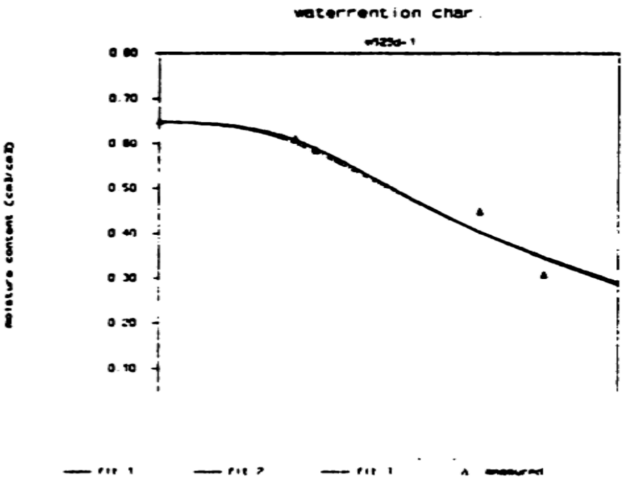

waterrention char
m525d-4
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
△ measured

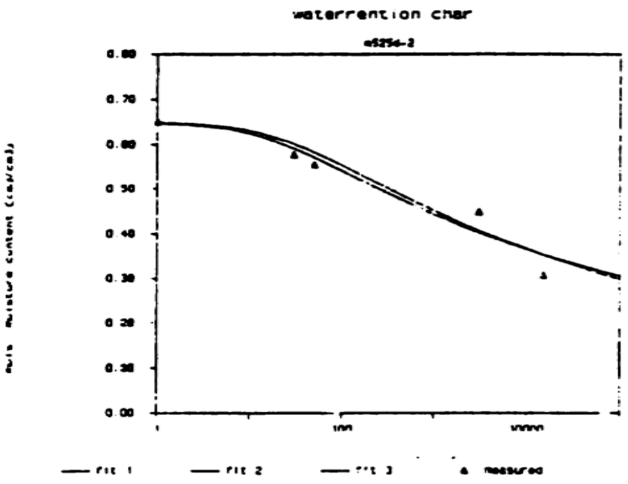

conductivity curve
m525d-3
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust

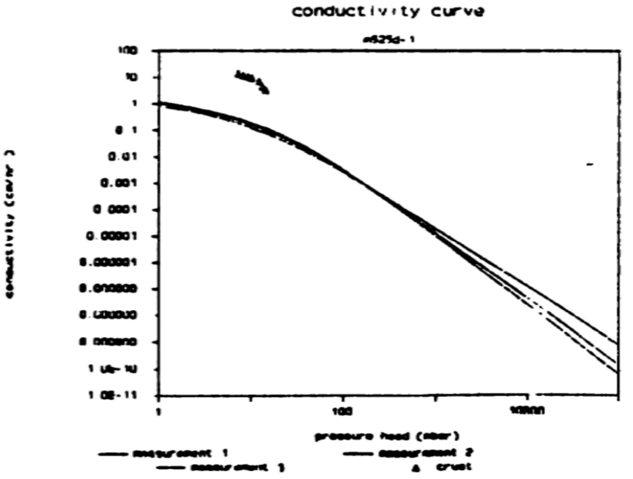

conductivity curve
m525d-4
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
△ crust

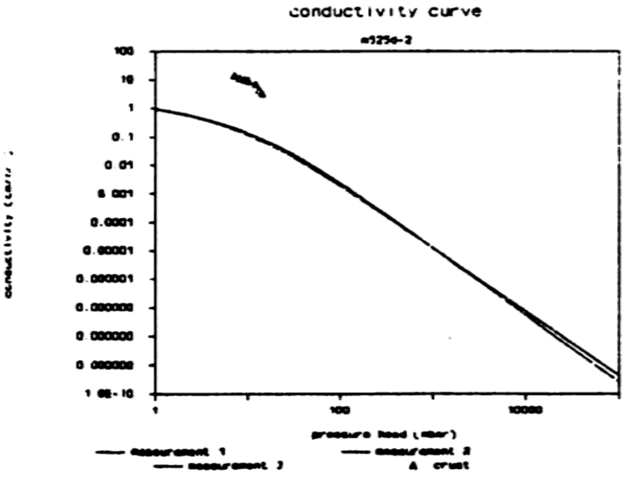

outflow
m525d-1
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
sqrt(time) (hr.)
0
2
4
6
8
measured
fit 1
fit 2
fit 3

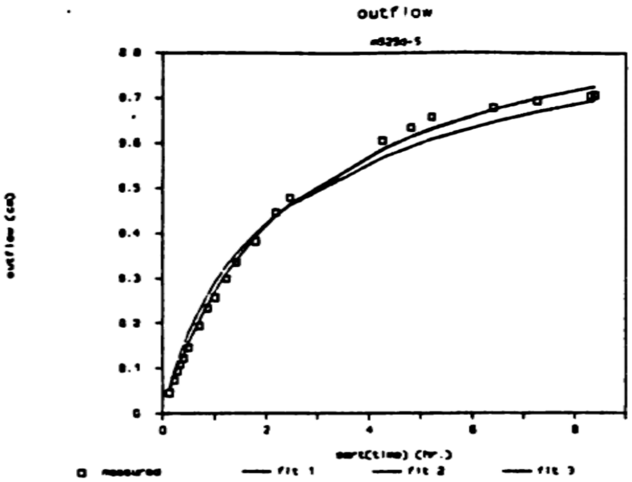

outflow
m525d-2
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
sqrt(time) (hr.)
0
2
4
6
8
measured
fit 1
fit 2
fit 3

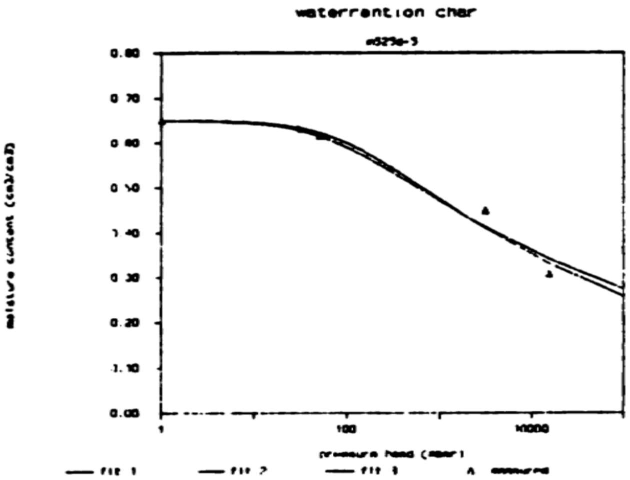

waterrention char
m525d-1
moisture content (cm3/cm3)
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
fit 1
fit 2
fit 1
measured

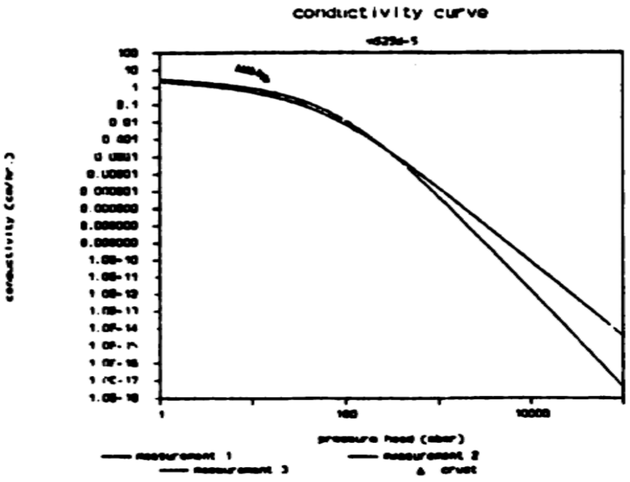

waterrention char
m525d-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
fit 1
fit 2
fit 3
measured

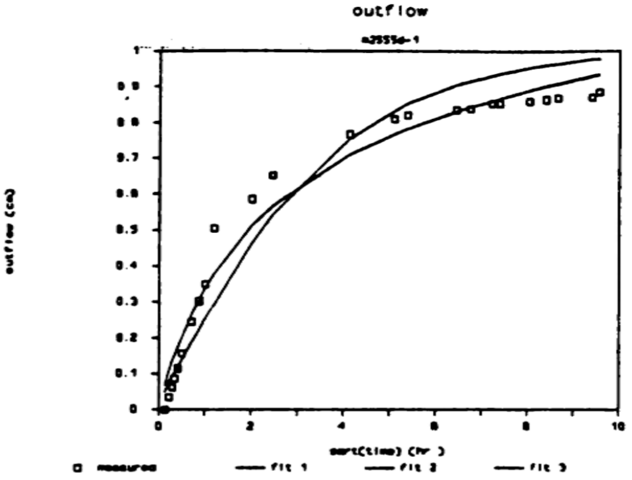

conductivity curve
m525d-1
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1 0E-10
1 0E-11
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
crust

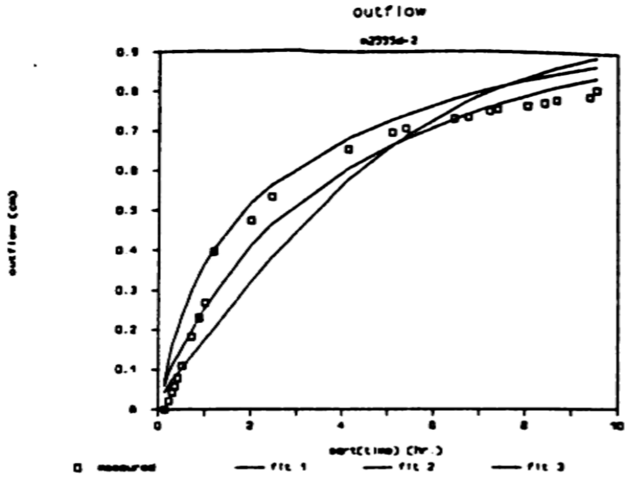

conductivity curve
m525d-2
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1 0E-10
pressure head (mbar)
1
100
10000
measurement 1
measurement 2
measurement 3
crust

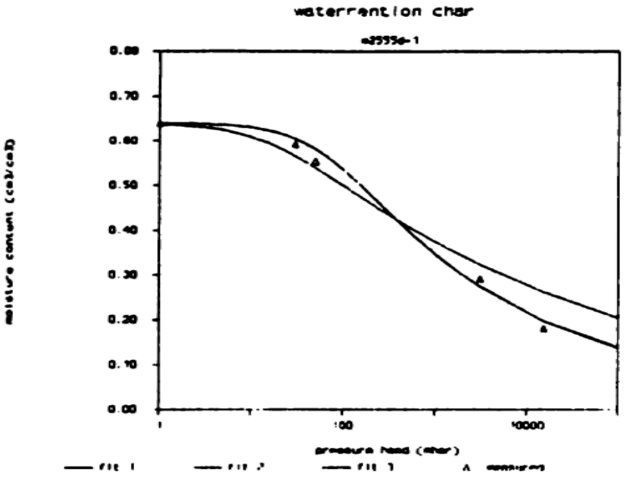

outflow
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
outflow (cm)
0
2
4
6
8
sqrt(time) (hr.)
measured
fit 1
fit 2
fit 3

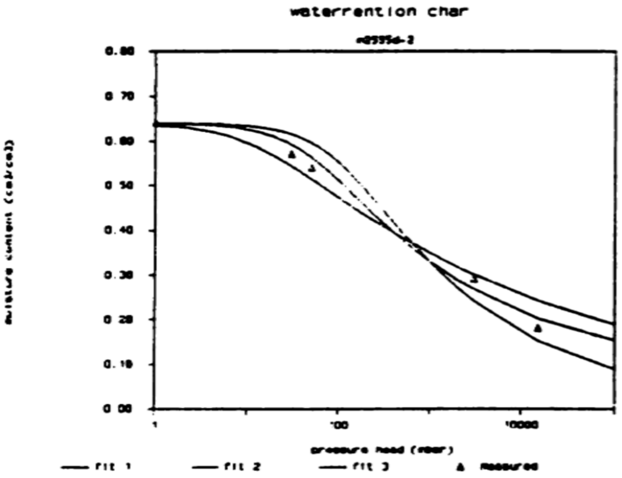

waterrention char
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
moisture content (cm3/cm3)
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
measured

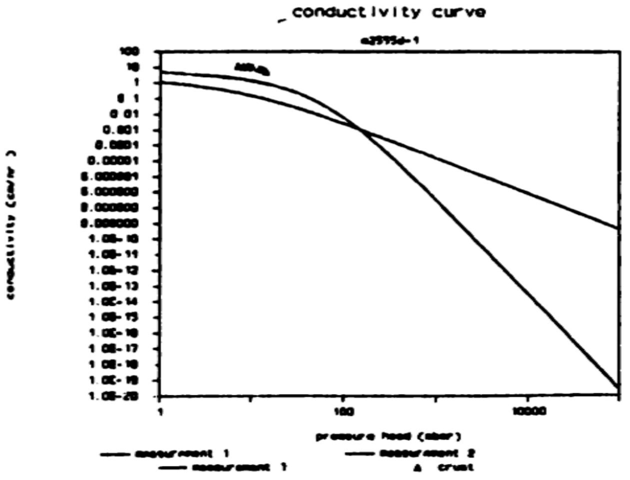

conductivity curve
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
conductivity (cm/hr.)
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
crust

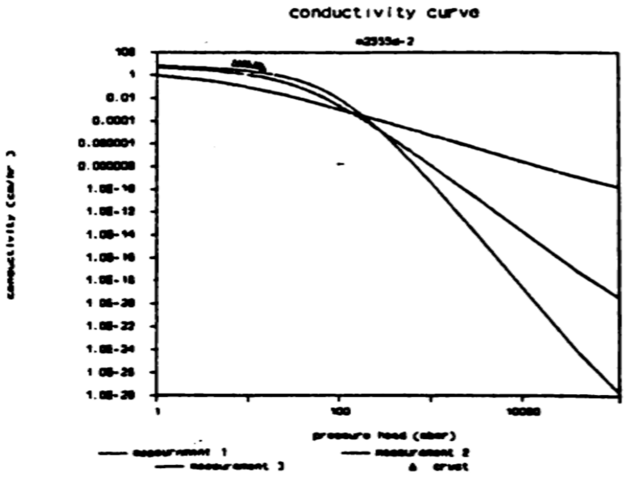

outflow
m2555d-1
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

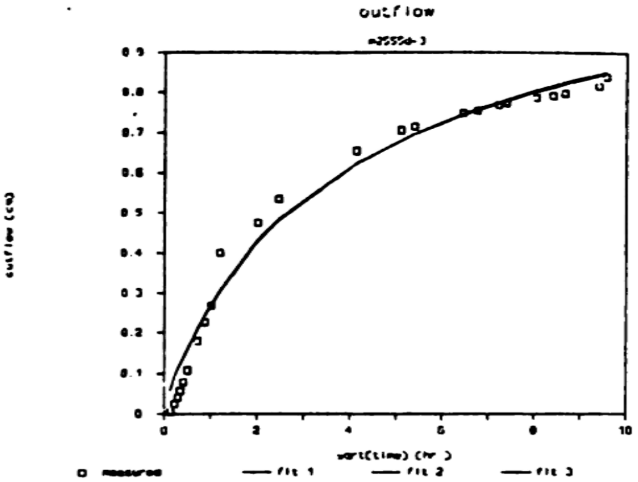

outflow
m2555d-2
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

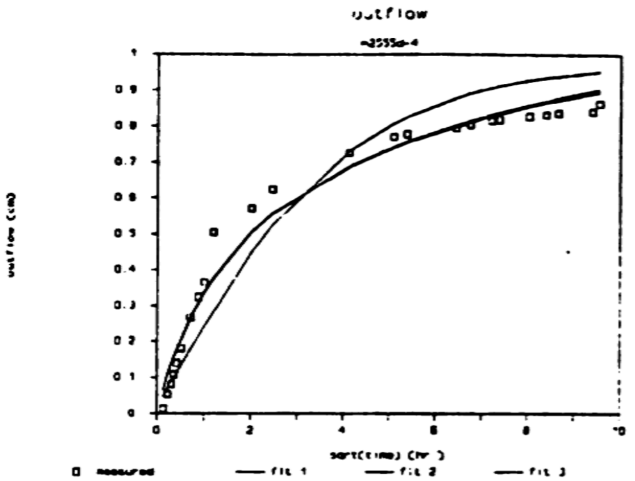

waterrention char
m2555d-1
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

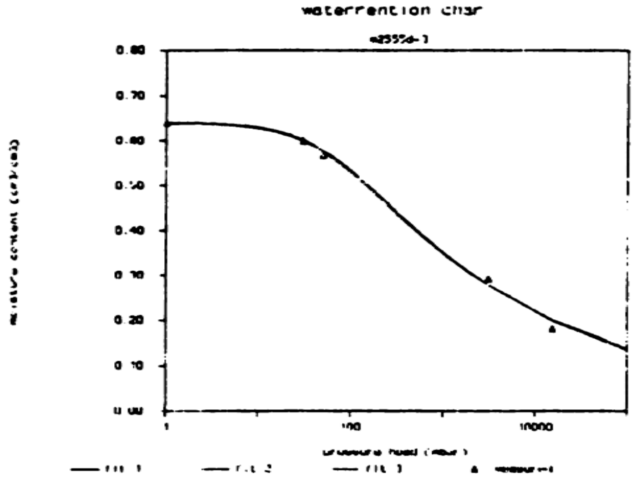

waterrention char
m2555d-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

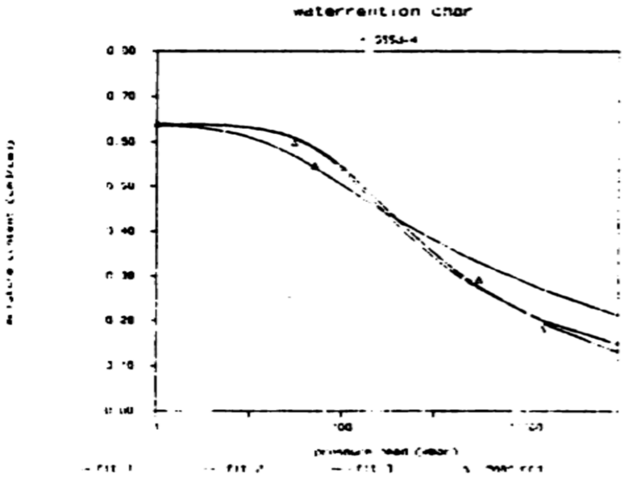

conductivity curve
m2555d-1
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.000000
0.000000
0.000000
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1.0E-19
1.0E-20
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

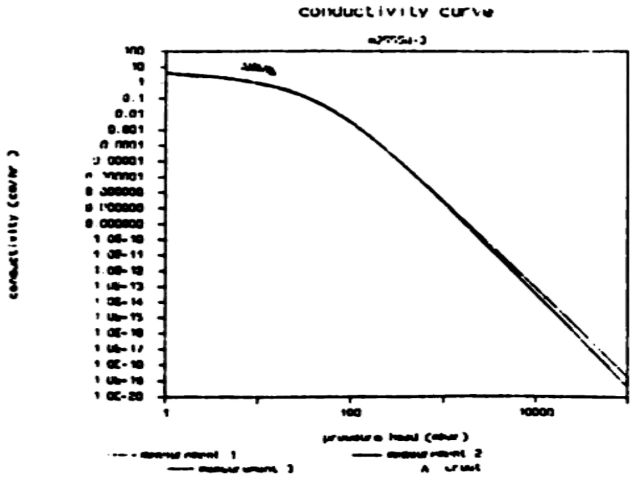

conductivity curve
m2555d-2
conductivity (cm/hr)
100
1
0.01
0.0001
0.000001
0.000000
1.0E-10
1.0E-12
1.0E-14
1.0E-16
1.0E-18
1.0E-20
1.0E-22
1.0E-24
1.0E-26
1.0E-28
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

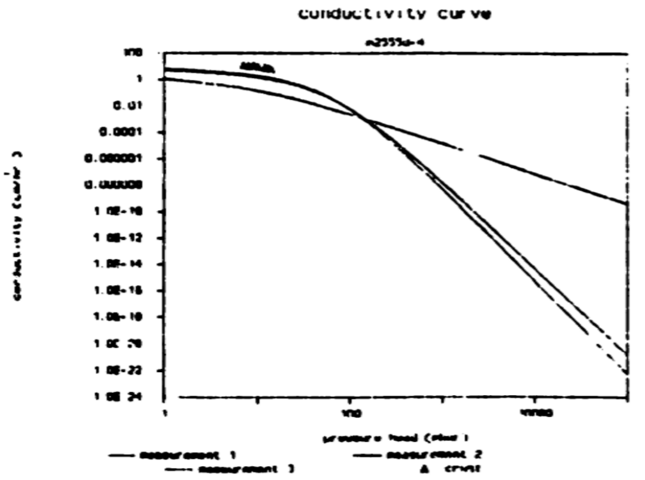

outflow
m2555d-3
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

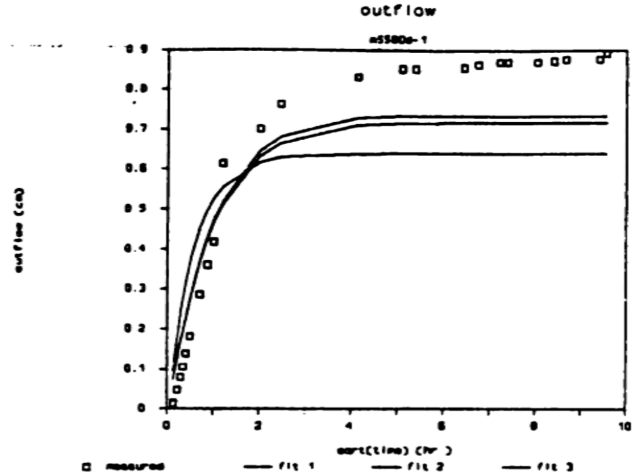

outflow
m2555d-4
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

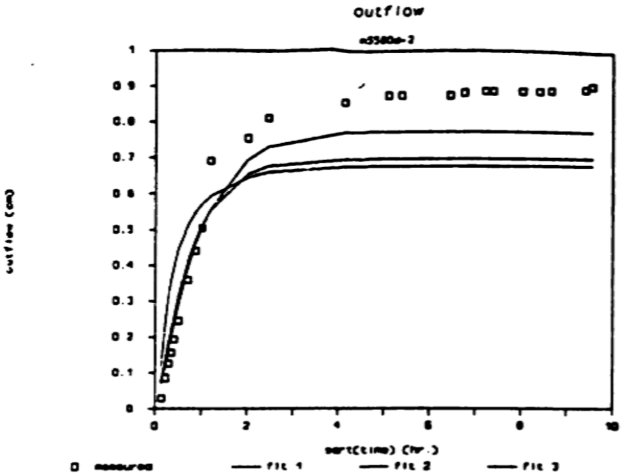

waterrention char
m2555d-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
▲ measured

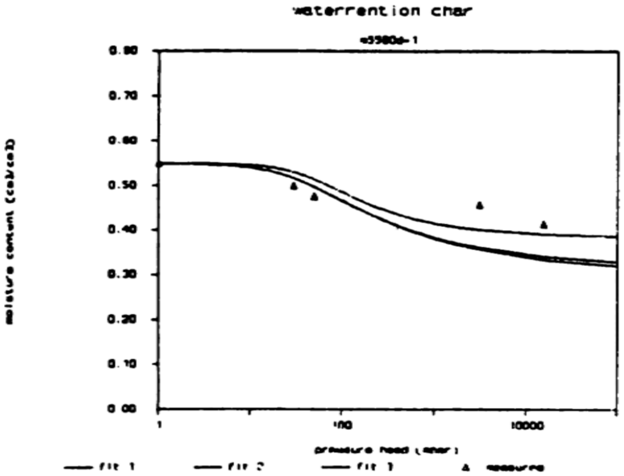

waterrention char
m2555d-4
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
▲ measured

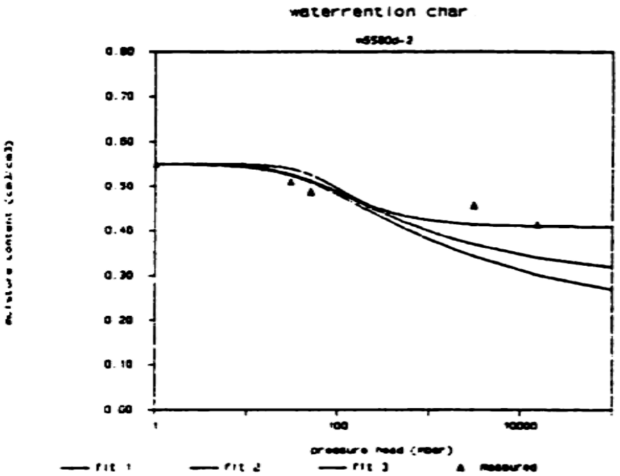

conductivity curve
m2555d-3
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
1.0E-20
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
▲ crust

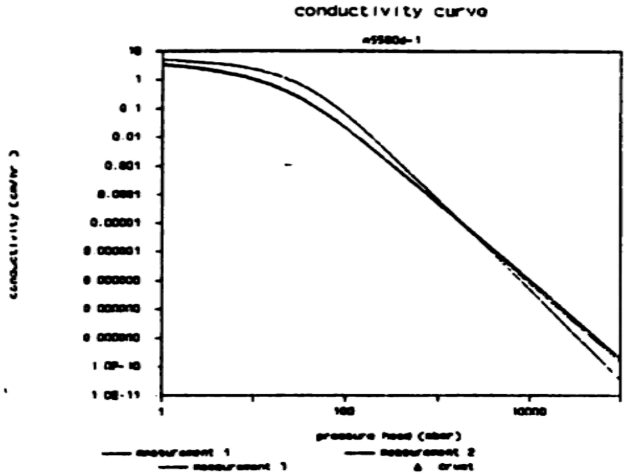

conductivity curve
m2555d-4
conductivity (cm/hr)
100
1
0.01
0.0001
0.000001
0.000001
1.0E-10
1.0E-12
1.0E-14
1.0E-16
1.0E-18
1.0E-20
1.0E-22
1.0E-24
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
▲ crust

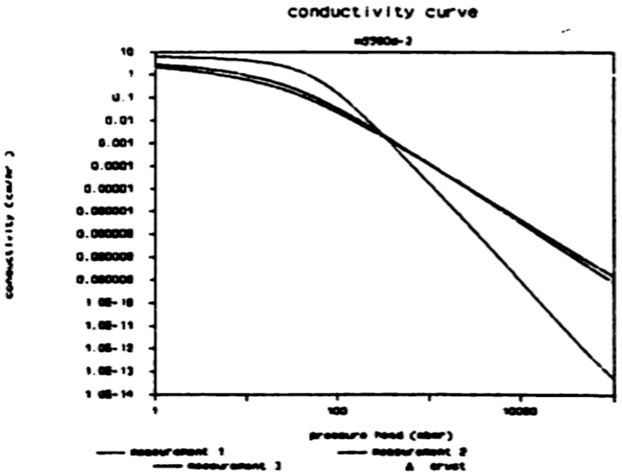

outflow
m5580d-1
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
2
4
6
8
10
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

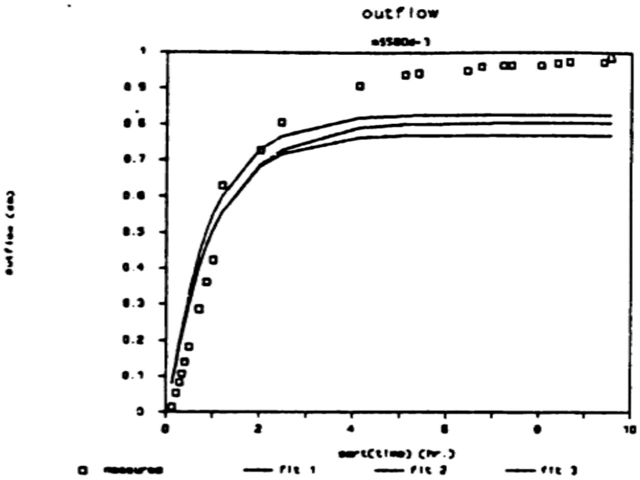

outflow
m5580d-2
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

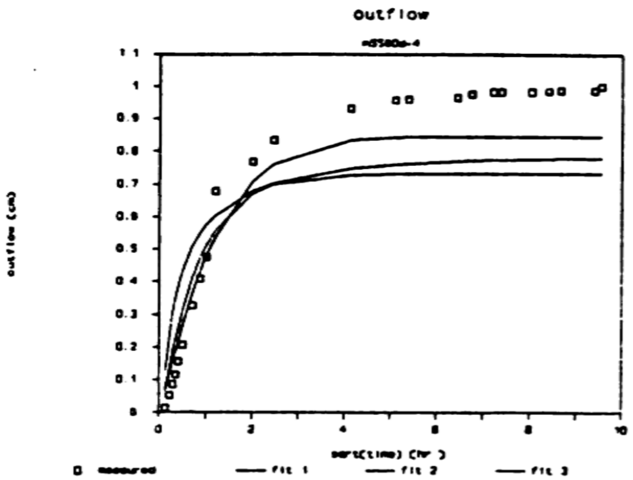

waterrention char
m5580d-1
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

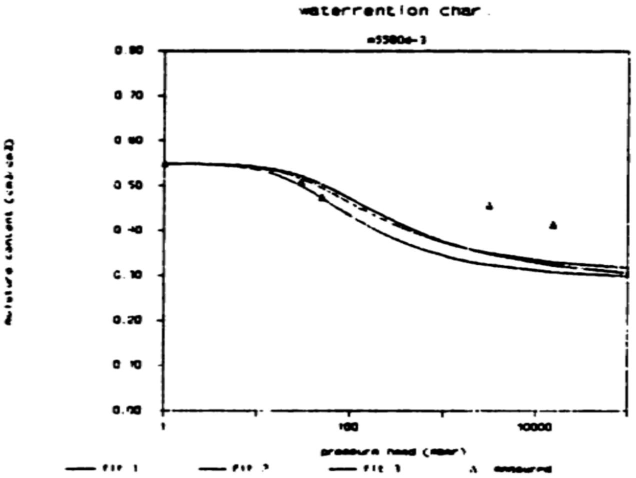

waterrention char
m5580d-2
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

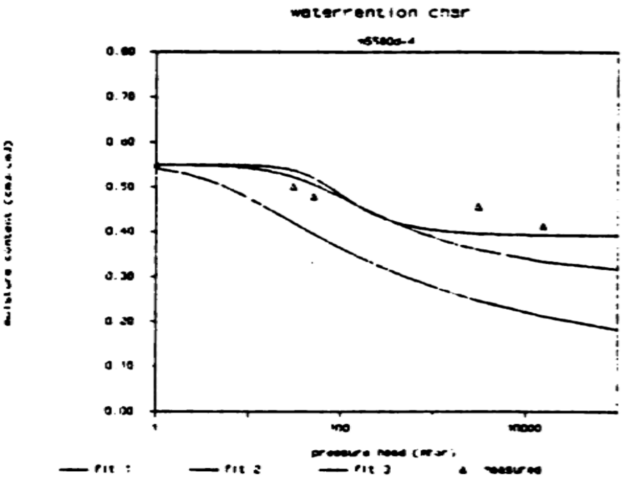

conductivity curve
m5580d-1
conductivity (cm/hr)
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3

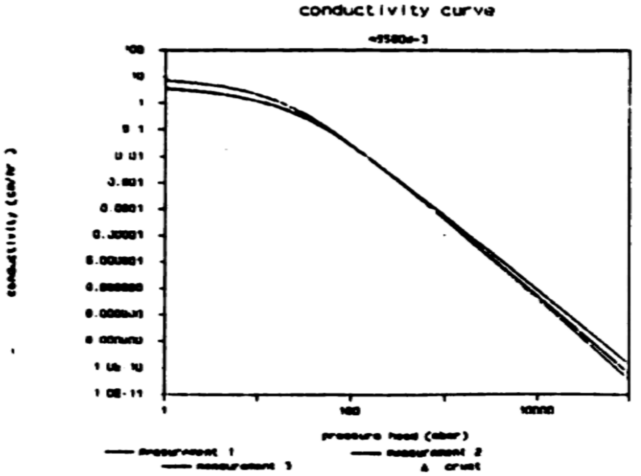

conductivity curve
m5580d-2
conductivity (cm/hr)
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3

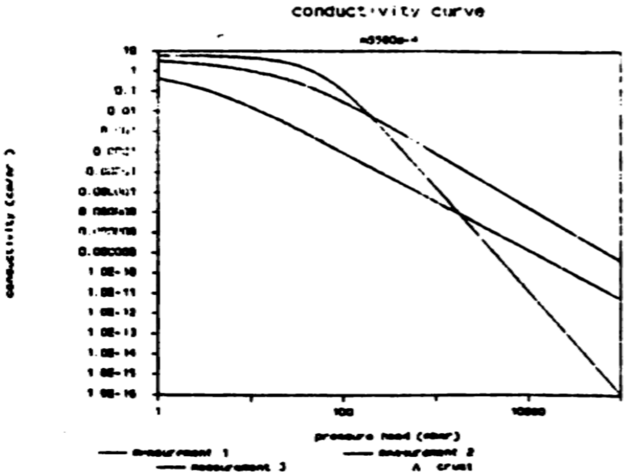

outflow
m5580e-3
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3


outflow
m5580e-4
outflow (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
2
4
6
8
10
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

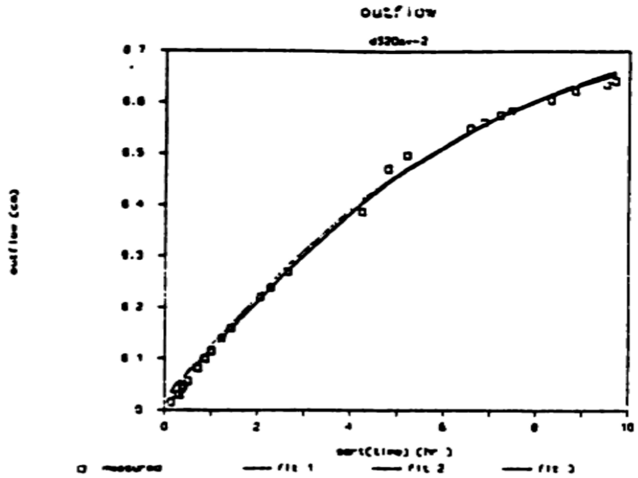

waterrention char.
m5580e-3
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

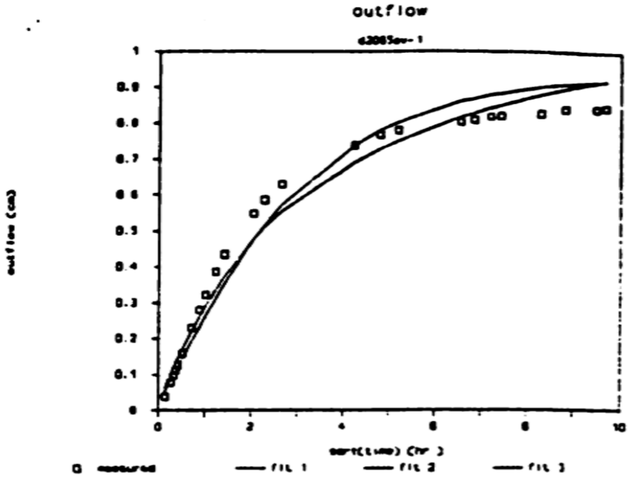

waterrention char
m5580e-4
moisture content (cm3/cm3)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

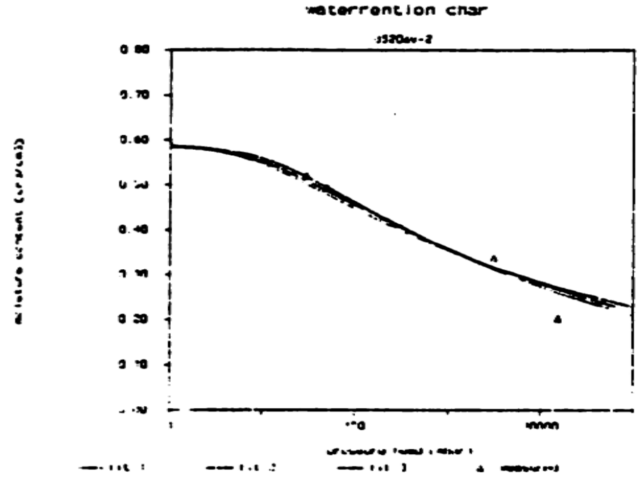

conductivity curve
m5580e-3
conductivity (cm/hr)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1 0E-10
1 0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

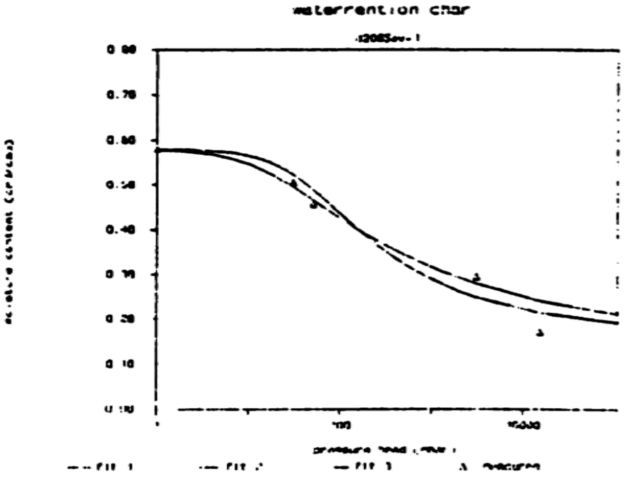

conductivity curve
m5580e-4
conductivity (cm/hr)
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
0.000000001
1 0E-10
1 0E-11
1 0E-12
1 0E-13
1 0E-14
1 0E-15
1 0E-16
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

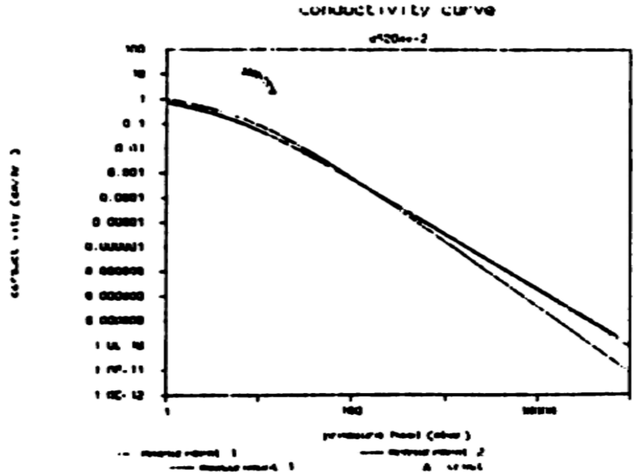
APPENDIX 6A : Fitted outflow, retention and conductivity for averaged outflow curves.

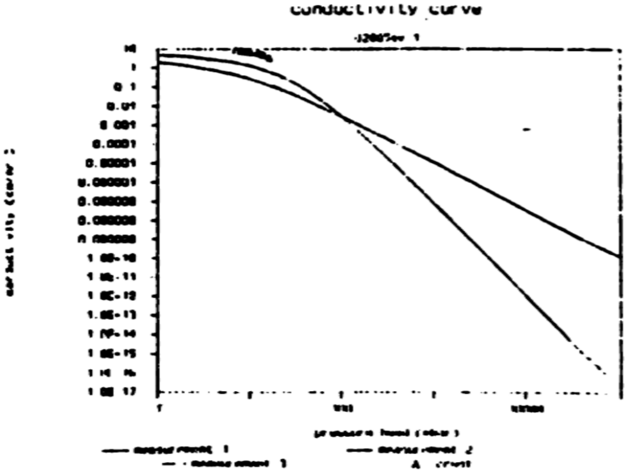


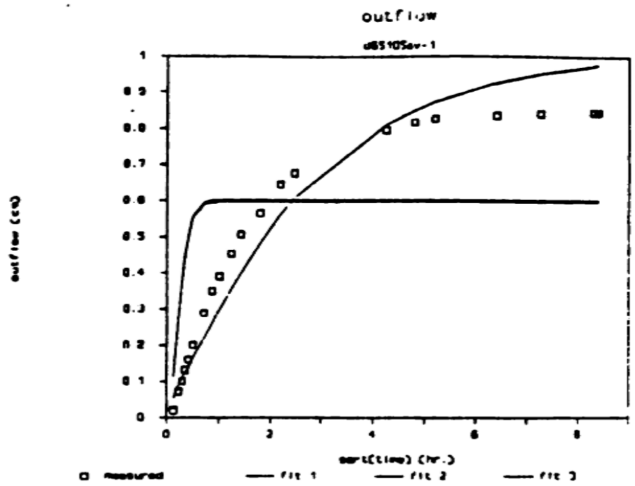






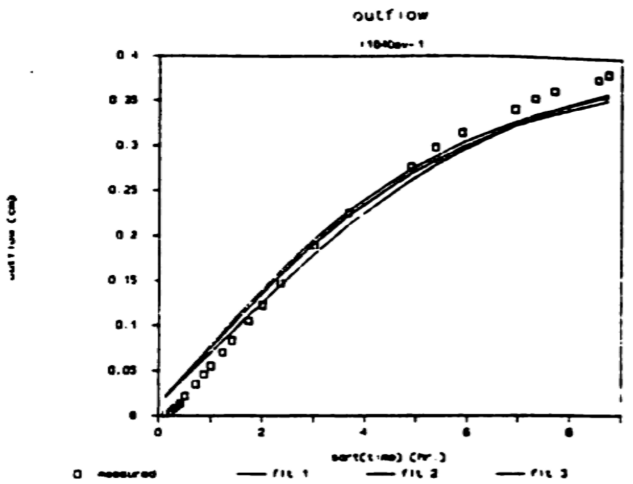






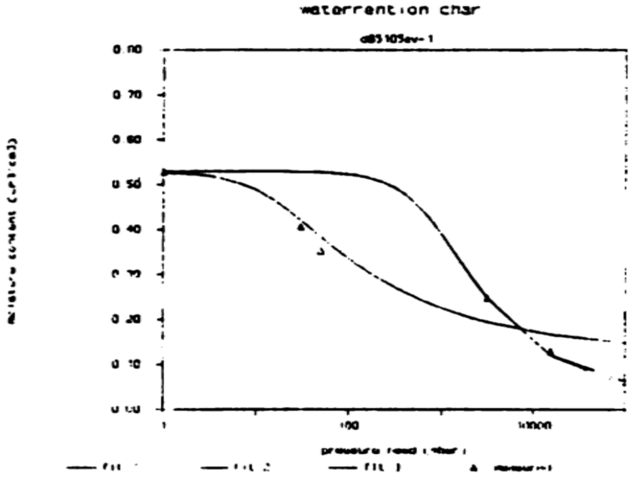
outflow

d85105ev-1



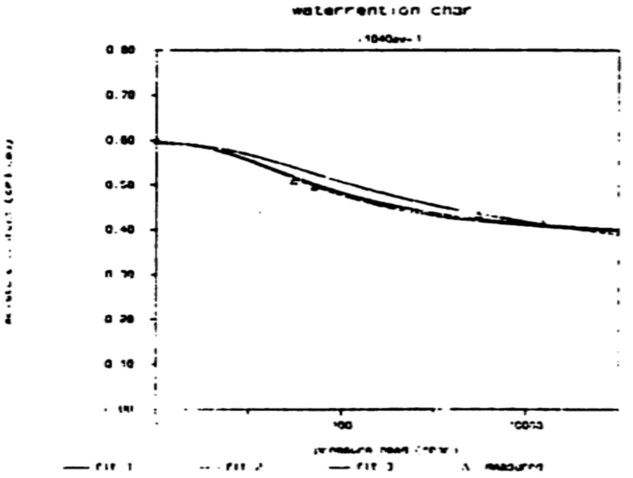
outflow

i1040ev-1



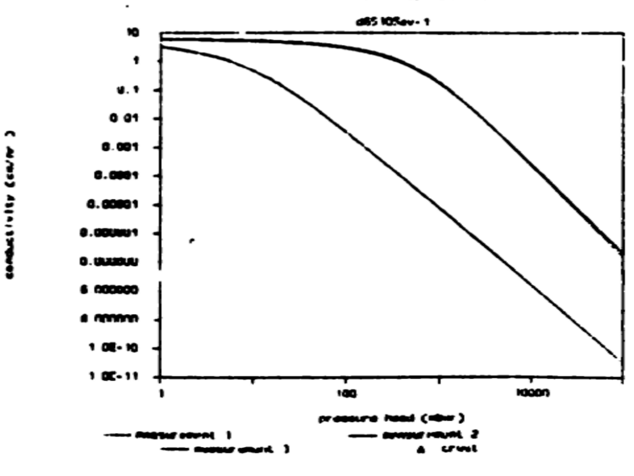
waterrention char

d85105ev-1



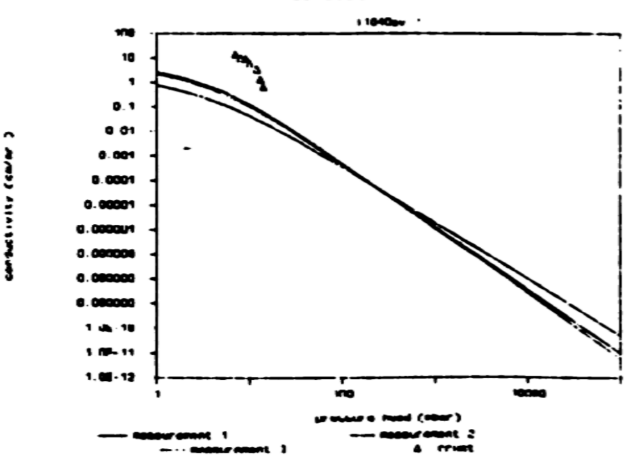
waterrention char

i1040ev-1



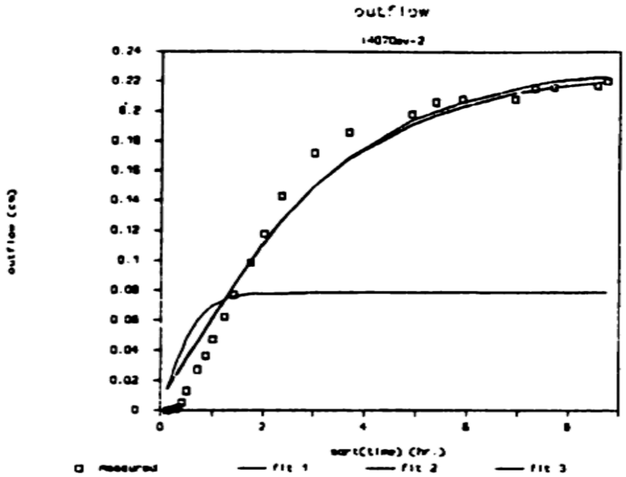
conductivity curve

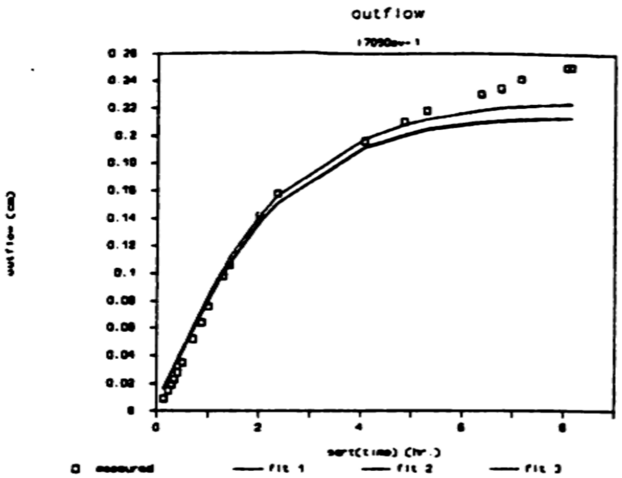
d85105ev-1

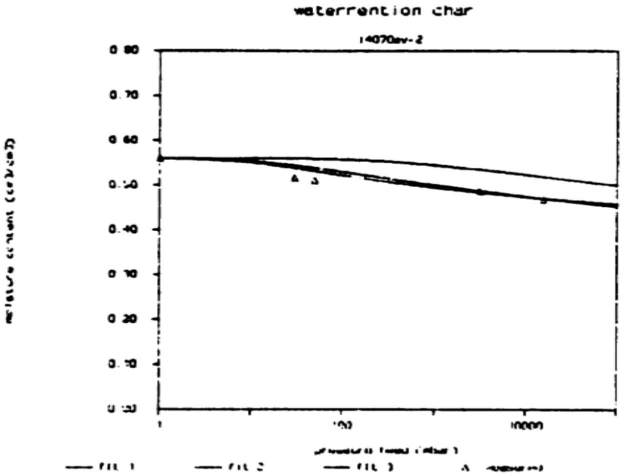


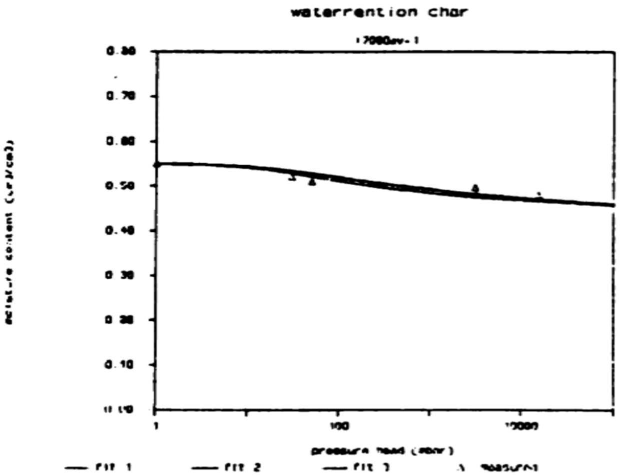
conductivity curve

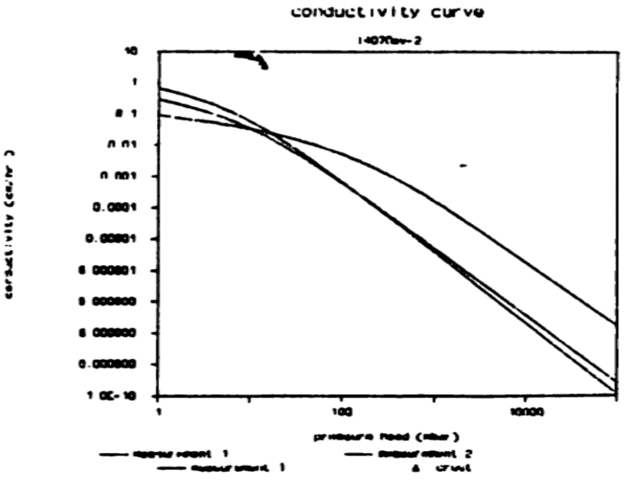
i1040ev-1

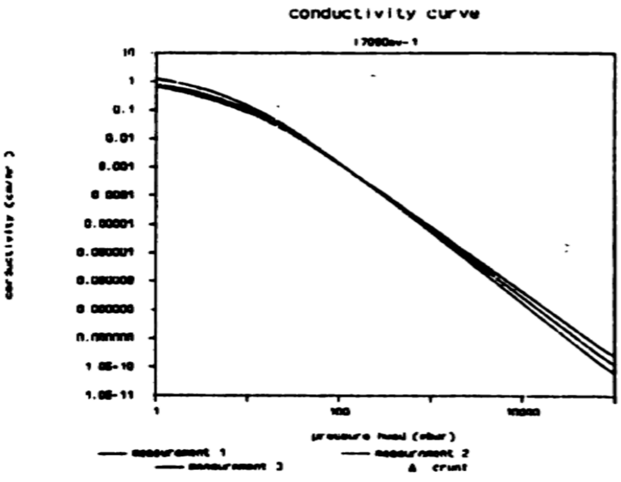

outflow
14070av-2
outflow (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

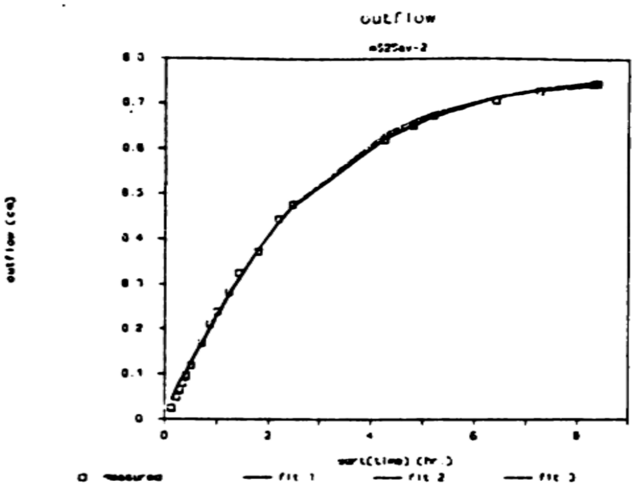

outflow
17090av-1
outflow (cm)
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
sqrt(time) (hr.)
□ measured
fit 1
fit 2
fit 3

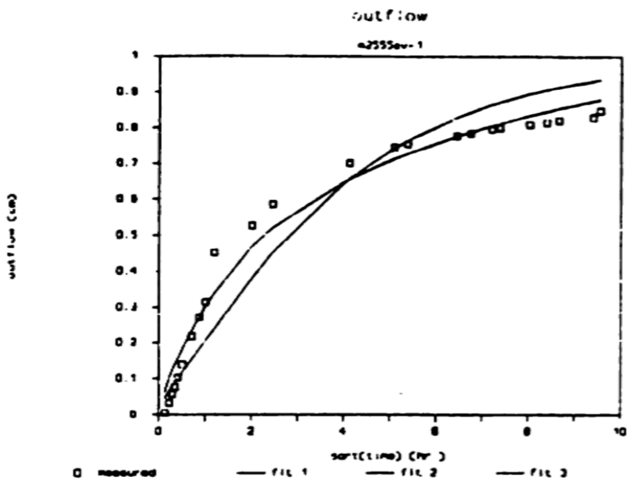

waterrention char
14070av-2
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

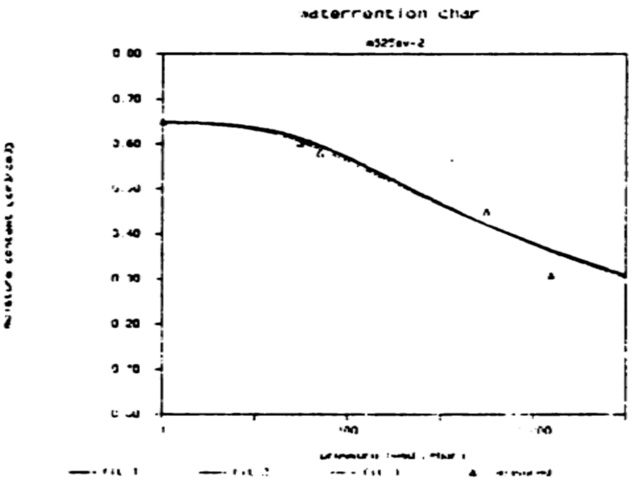

waterrention char
17080av-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

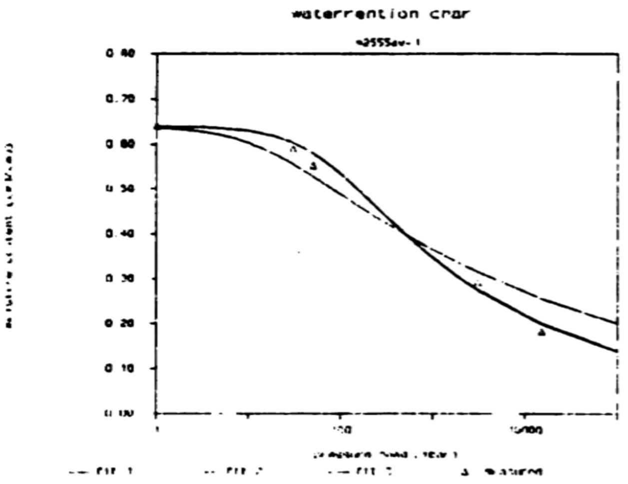

conductivity curve
14070av-2
conductivity (cm/hr)
10
1
0.1
0.01
0.001
0.0001
0.00001
1.0E-10
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

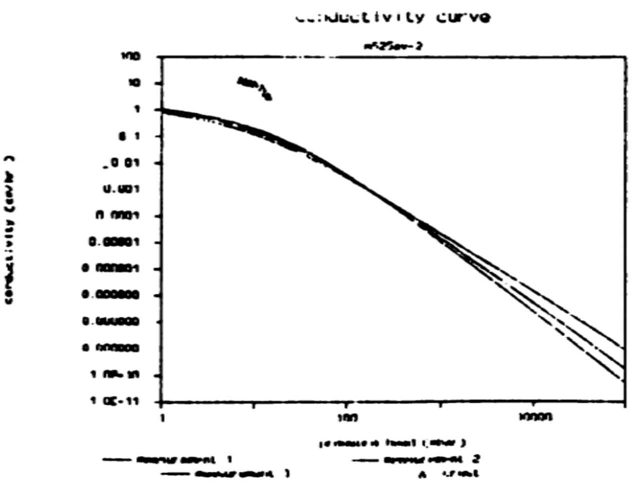

conductivity curve
17080av-1
conductivity (cm/hr)
10
1
0.1
0.01
0.001
0.0001
0.00001
1.0E-10
1.0E-11
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ crust

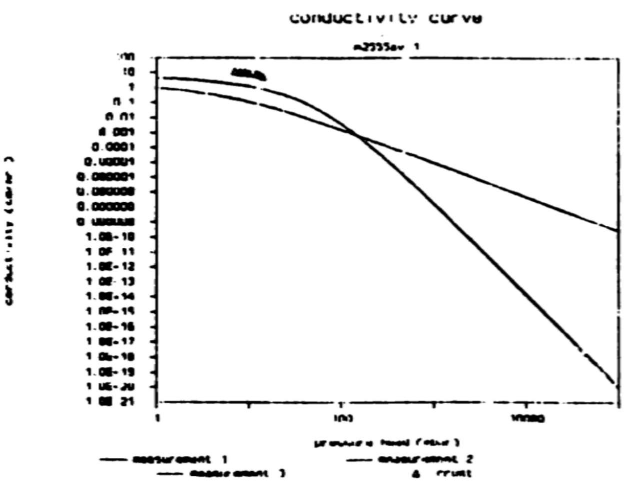

outflow
m525av-2
outflow (cm)
sqrt(time) (hr.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
Measured
fit 1
fit 2
fit 3

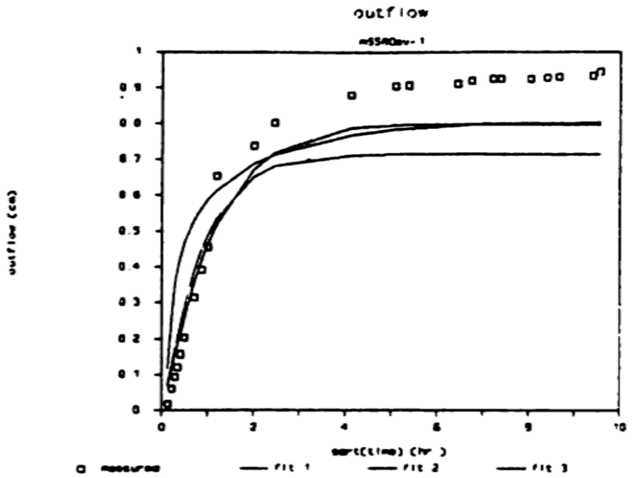

outflow
m2555av-1
outflow (cm)
sqrt(time) (hr.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
Measured
fit 1
fit 2
fit 3

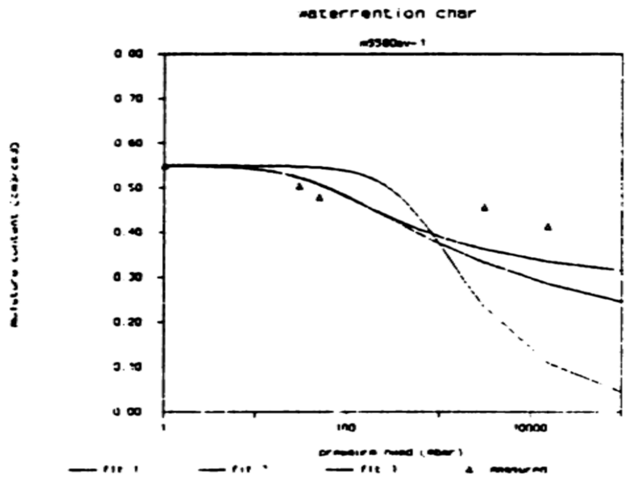

waterrention char
m525av-2
moisture content (cm3/cm3)
pressure head (mbar)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
fit 1
fit 2
fit 3
measured

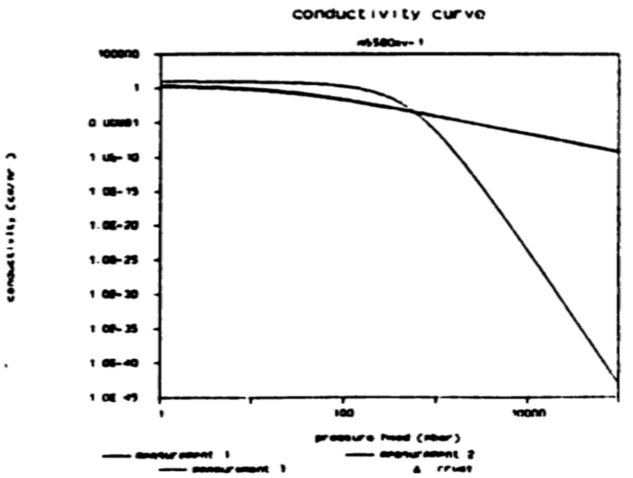

waterrention char
m2555av-1
moisture content (cm3/cm3)
pressure head (mbar)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
100
10000
fit 1
fit 2
fit 3
measured


conductivity curve
m525av-2
conductivity (cm/hr)
pressure head (mbar)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1
100
10000
measurement 1
measurement 2
measurement 3

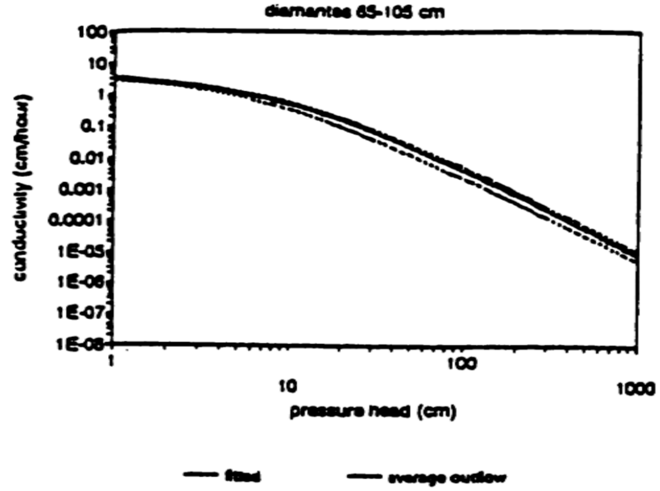

conductivity curve
m2555av-1
conductivity (cm/hr)
pressure head (mbar)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1.0E-19
1.0E-20
1.0E-21
1
100
10000
measurement 1
measurement 2
measurement 3

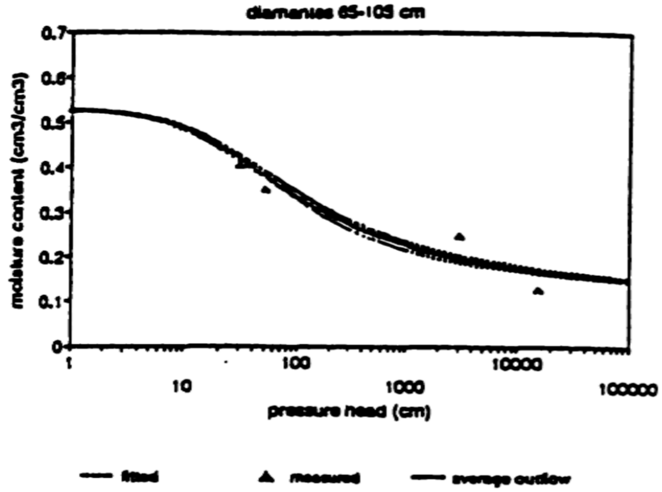

outflow
m5540av-1
outflow (cm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
sqrt(time) (hr)
□ measured
fit 1
fit 2
fit 3

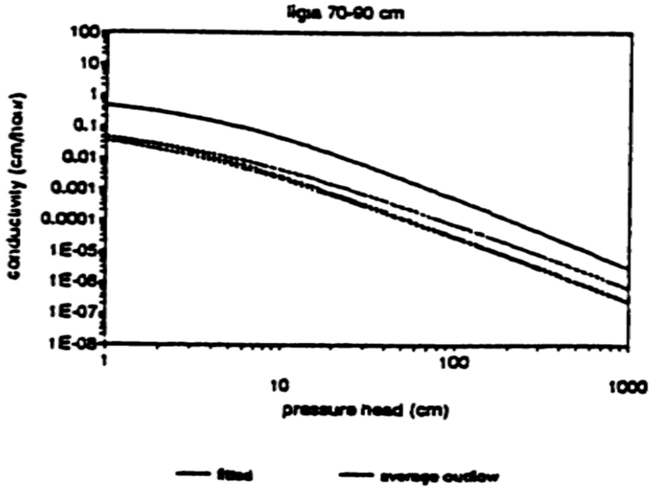

waterrention char
m5580av-1
moisture content (cm3/cm3)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
100
10000
pressure head (mbar)
fit 1
fit 2
fit 3
Δ measured

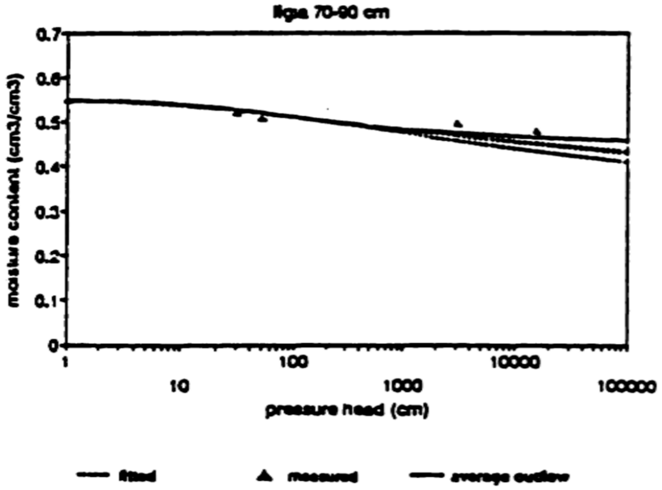

conductivity curve
m5580av-1
conductivity (cm/hr)
100000
1
0.00001
1.0E-10
1.0E-15
1.0E-20
1.0E-25
1.0E-30
1.0E-35
1.0E-40
1.0E-45
1
100
10000
pressure head (mbar)
measurement 1
measurement 2
measurement 3
Δ Kfit

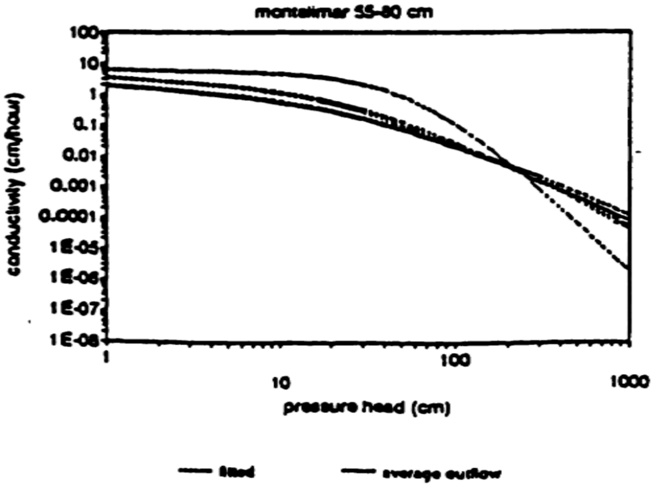
APPENDIX 7 : Best fits for hydraulic conductivity and water retention : third layer

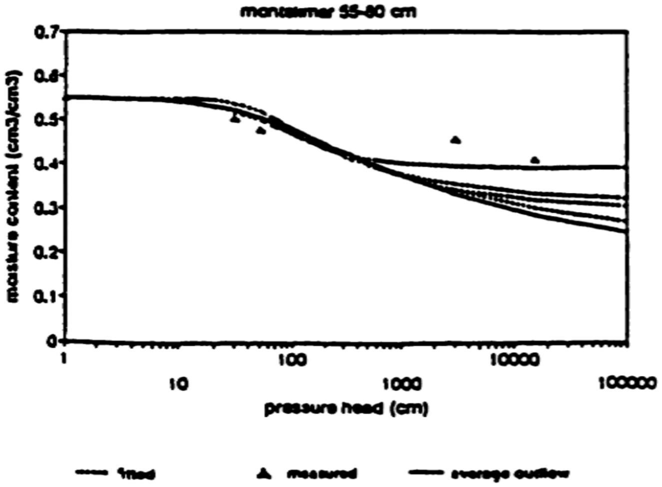












APPENDIX 7 vervolg

VAN GENUCHTEN PARAMETERS VOOR DIVERSE BODEMTYPEN IN COSTA RICA
beste set per monster, diepste horizonten
tevens het gemiddelde en de standaard deviatie per parameter en per laag

D 65-105	AlFA	N	theta(r)	GAMMA	R2
1	0.0583	1.3386	0.129	0.0001	0.9620
2	0.0798	1.3185	0.129	0.0008	0.9641
3	0.0649	1.3679	0.129	0.0001	0.9413
4	0.0645	1.3163	0.129	0.0001	0.9560
5	0.0659	1.3323	0.129	0.0001	0.9536
av.outfl	0.0652	1.3435	0.129	0.0001	0.9570
average	0.0667	1.3347	0.129	0.0002	
st. dev.	0.0071	0.0186	0.000	0.0003	

L 70-90	ALFA	N	theta(r)	GAMMA	R2
1	0.0907	1.0354	0.041	0.0130	0.9896
2	0.1644	1.0395	0.172	0.1008	0.9950
3	0.1806	1.0489	0.251	0.0117	0.9953
av.outfl	0.0748	1.2266	0.445	0.0554	0.9985
average	0.1452	1.0413	0.155	0.0418	
st. dev.	0.0391	0.0057	0.087	0.0417	

M 55-80	ALFA	N	theta(r)	GAMMA	R2
1	0.0273	1.3564	0.306	0.0236	0.9262
2	0.0212	1.2221	0.206	0.0032	0.9215
3	0.0217	1.3577	0.287	0.8494	0.9118
4	0.0145	1.979	0.392	1.1637	0.8949
av.outfl	0.0199	1.1941	0.155	0.9013	0.9061
average	0.0212	1.4780	0.298	0.5100	
st. dev.	0.0045	0.2940	0.066	0.5089	

APPENDIX 8 : Measured One-Step Outflow retention points and bulk density

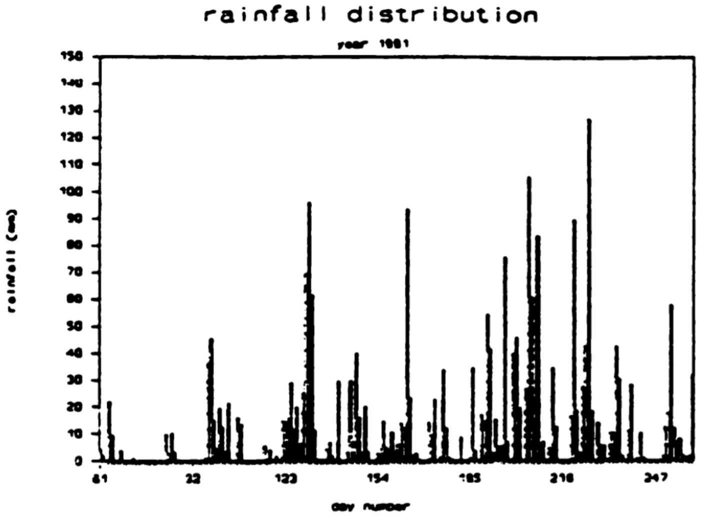
ONE STEP OUTFLOW RESULTS

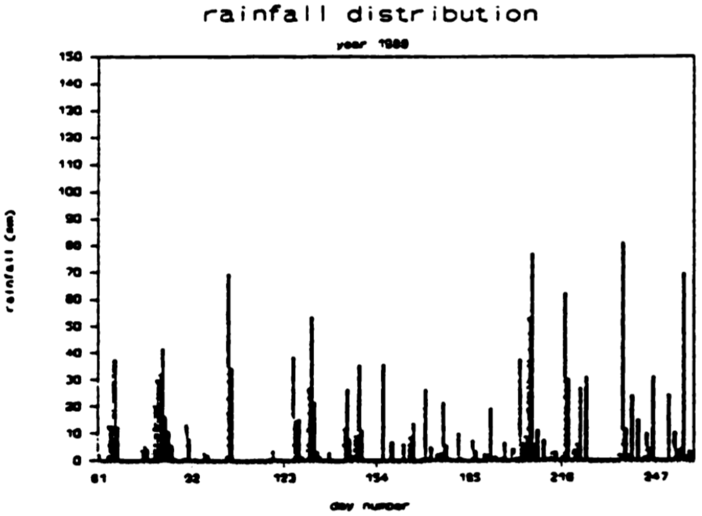
	LOS DIAMANTES				LIGIA				MONTELIMAR		
		moisture %				moisture %				moisture %	
	bulk dens	0.03 (bar)	0.05		bulk dens	0.03 (bar)	0.05		bulk dens	0.03 (bar)	0.05
0-20	0.82	0.484	0.459	0-40	0.86	0.495	0.478	0-25	0.65	0.611	0.585
	0.86	0.507	0.482		0.82	0.489	0.474		0.74	0.577	0.555
	0.77	0.562	0.531		0.78	0.468	0.454		0.74	0.577	0.555
	0.80	0.528	0.504		0.94	0.556	0.545		0.67	0.616	0.590
					0.90	0.537	0.524		0.77	0.631	0.616
average	0.81	0.520	0.494		0.86	0.509	0.495		0.71	0.602	0.580
20-65	0.93	0.502	0.465	40-70	1.11	0.519	0.513	25-55	0.76	0.593	0.555
	0.87	0.488	0.444		1.12	0.511	0.505		0.75	0.570	0.540
	0.98	0.529	0.470		1.15	0.518	0.512		0.66	0.601	0.568
	0.87	0.505	0.452		1.10	0.519	0.513		0.65	0.598	0.546
					1.12	0.517	0.512				
average	0.91	0.506	0.458		1.12	0.517	0.511		0.71	0.591	0.552
65-105	1.19	0.405	0.369	70-90	1.15	0.523	0.513	55-80	1.19	0.500	0.476
	1.16	0.417	0.348		1.11	0.526	0.515		1.16	0.510	0.487
	1.14	0.399	0.342		1.09	0.512	0.502		1.13	0.506	0.475
	1.16	0.418	0.360						1.14	0.502	0.479
	1.20	0.408	0.348								
average	1.17	0.409	0.353		1.12	0.520	0.510		1.16	0.505	0.479

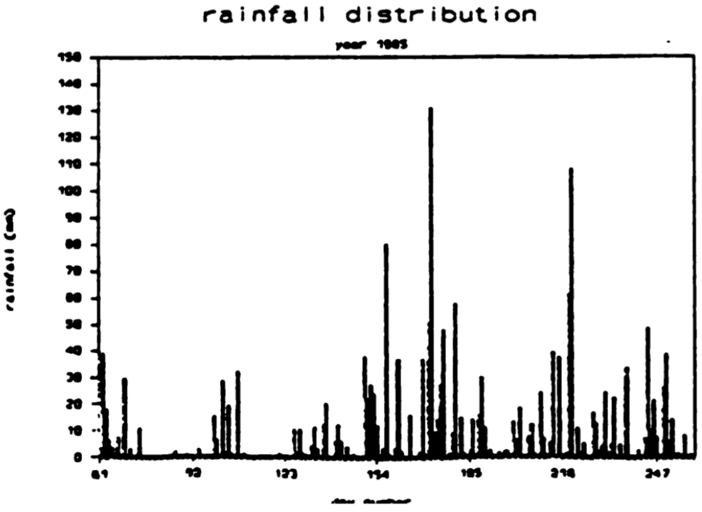
PRESSURE COOKER RESULTS

	LOS DIAMANTES			LIGIA			MONTELIMAR	
	3 bar	15 bar		3 bar	15 bar		3 bar	15 bar
0- 20	0.337	0.203	0-40	0.434	0.416	0-25	0.449	0.308
20- 65	0.294	0.172	40-70	0.487	0.467	25-55	0.292	0.182
65-105	0.248	0.129	70-90	0.496	0.480	55-80	0.458	0.414

APPENDIX 9 : Rainfall distribution in 3 growing seasons







APPENDIX 10 : Calculated weekly ET0 values (mm) for 3 growing seasons

	1985	1988	1991
	42.82	44.12	27.62
	30.75	30.64	26.32
	41.07	41.16	32.90
	37.64	34.43	41.52
	29.03	38.27	36.51
	27.07	43.19	37.71
	37.59	36.31	30.39
	24.63	37.02	31.46
	29.12	35.48	32.07
	30.05	34.74	33.08
	31.47	35.93	29.70
	28.73	36.17	31.23
	30.90	25.36	26.79
	28.17	34.18	30.03
	33.49	32.56	26.12
	25.98	45.71	33.45
	39.07	42.88	31.88
	35.58	36.71	39.21
total growing season	583.2	664.9	578.0
yearly total	1800.5	1843.6	1763.8

APPENDIX 11 : Simulated pressure heads for the soil types Ligia and Montelimar