DEVELOPMENT OF CRITERIA AND METHODS FOR IMPROVING THE EFFICIENCY OF SOIL MANAGEMENT AND TILLAGE OPERATIONS, WITH SPECIAL REFERENCE TO ARID AND SEMIARID REGIONS

APPENDIX 5. TO FINAL REPORT

ANALYSIS OF RAINFALL IN SOME LOCATIONS OF WEST AFRICA AND INDIA

W.B. HOOGMOED

1981

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DEVELOPMENT OF CRITERIA AND METHODS FOR IMPROVING THE EFFICIENCY OF SOIL MANAGEMENT AND TILLAGE OPERATIONS WITH SPECIAL REFERENCE TO ARID AND SEMI-ARID REGIONS.

Appendix 5.

Report on the analysis of rainfall in some locations in West Africa and India.
The effect of rainfall on runoff, infiltration and soil water movement.

W.B. Hoogmoed.

1981.

A joint project between the Tillage Laboratory, Agricultural University, Wageningen, the Netherlands, and the Department of Soils & Water, Faculty of Agriculture, Hebrew University, Rehovot, Israel.

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CONTENTS

1. INTRODUCTION

This report is the third one in a series covering the research activities of the joint research project on tillage for semi-arid regions, in Mali, 1979. (see also appendix 3 and 4).

A detailed account is given of the analysis of the rainfall, where data from Niono, Mali are compared with available rainfall data from Niger and the Hyderabad region of India.
Based on the rainfall data and the results of the rainfall simulator experiments, infiltration and runoff is calculated using various approaches. The effect of tillage and other agronomical practices on the water balance of the soil had been analysed. Since the farmer in the Sahel-Savanna zone of West Africa has only very limited financial means available, large scale solutions for the prevention of runoff are not feasible.
Fortunately, the topography and the characteristics of the majority of the soils in West Africa are such, that erosion causes less problems than expected from the high runoff values.

Solutions to runoff problems should be looked for in the form of a change or adaptation of tillage practices.

2. RAINFALL ANALYSIS.

The analysis.

For the analysis of the rainfall, data from recording raingauges were necessary: the actual analysis was done by "digitizing" the graphs from the original charts (=cumulative rainfall in time) and processing the results by computer. Digitizing was carried out both in Israel and at the computer center of the Agricultural University in Wageningen. The computerprogram for the data analysis was developed by Dr. Morin of the Soil Erosion Research Institute, Israel (Morin and Jarosch, 1977). The basic output of this program (written in FORTRAN) is a division of individual rainfall events (rainstorms) in segments with uniform rainfall intensity. Rainfall events with 'dry' intervals of less than 12 hours were considered to belong to one storm. When soil characteristics in terms of infiltration rate vs. rainfall are known, e.g. as obtained by rainfall simulator experiments (Morin and Benyamini, 1977), a calculation of infiltration and runoff for different surface storage and -detention values can be made. If no such specific soil information is available, infiltration and runoff may be estimated assuming (constant) infiltration rate values.

The original program was extended by the author to facilitate calculation of kinetic energies and various indexes used in soil and water conservation research. In addition, changes in infiltration characteristics, induced by tillage during the rainy period under consideration, can be taken into account. For the calculation of kinetic energy, the relation between intensity and kinetic energy, as proposed by Wischmeier and Smith (1958) was used. This equation is in SI units (Dexter, 1977):

$$E_k = 13.3 + 9.8 \log_{10} I \ (J.m^{-2}.mm^{-1})$$

with rainfall intensity I in $mm.hr^{-1}$. This relation however is on an emperical basis and found to fit well under North-American climatic conditions. When this relation is to be applied to tropical or subtropical conditions, it should be kept in mind that drop sizes and wind velocities during rainfall under said conditions may be considerably higher. In certain cases the E_k calculation according to the above equation will be an under-estimation.

Erosion indexes are proposed by a number of authors. In the computer-program, the following indexes are calculated:

a. The EI_{30} index, developed by Wischmeier et al (1958). This index is the product of total kinetic energy of the storm and the highest 30 minute rainfall in this storm. Dimensions $J.m^{-2}.mm.hr^{-1}$ SI units. This index is also used in the universal soil loss equation, proposed by Wischmeier.

b. The KE >25 index. This index was proposed by Hudson (1971). He suggested that, because of the difference in rainfall characteristics between USA and Africa, the EI_{30} index was not representative in estimating erosivity for conditions with high intensity rains. The KE>25 index is defined as the total kinetic energy of rain in a storm falling at intensities of more than 25mm (1 inch) per hour. This index is also in $J.m^{-2}$.

c. The AI_m index, proposed by Lal (1976). The advantage of this index is the ease of calculation, since for each rainfall event this is the summation of the products of intensity and amount of rain for each intensity class. Also, this index overcomes the limitations set by the emperical basis of the calculation of kinetic energy. Dimensions of this index: $mm^2.hr^{-1}$.

Available data.

Detailed data on rainfall in the West African Sahel are scarce; Cochemé and Franquin (1967), who did an agroclimatology survey on the area south of the Sahara, reported 35 meteorological stations to give information on an area extending over 2 million square kilometers! The intensity of rainfall (recording raingauges) is measured only at a few of these stations, so those data are even more scarce. The authors quote a study by Delorme (1963), and estimate 4 $mm.hr^{-1}$ for the average intensity of rainfall in this zone. Only very few studies have been made, investigating rainfall characteristics as effecting agriculture or agricultural practices. Charreau and Nicou (1971) did extensive research in Senegal, including observations on rainfall.

They found for the rainfall at Bambey (average precipitation between 1960 and 1968 of 550 mm) the following intensity distribution:

75% of total volume: intensity ≤ 8.6 $mm.hr^{-1}$
50% " " ≤ 26.7 "
25% " " ≤ 52.4 "

In Sefa, a station with an average annual rainfall of 1200 mm, the intensities were higher. Kowal and Kassam (1976) measured rainfall characteristics in Nothern Nigeria, using an instrument to monitor number and size of falling raindrops. Energy load and instantaneous intensity of the rainstorms could thus be assessed. No detailed data on intensities were given, but Kowal (1970) gives for the same area, over the past 45 years, the following rainstorm sizes:

85% of total volume in rainstorms < 25 mm
12% " " " betw. 25 and 50 mm
3% " " " > 50 mm

Peak intensities of over 250 $mm.hr^{-1}$ are not uncommon, but usually only for very short periods of time.

A study of rainfall characteristics with respect to erosion was carried out in Niger by Delwaulle (1973). He measured rainfall and observed runoff and erosion in an area with average rainfall of 495mm. Peak intensities reported here are as follows:

peak intensities mm/hr	nr of years out of 6 analysed	
150-174	2	Years analysed: 1966-1971
125-149	1	Average rainfall: 495mm.
100-124	1	Location: Allokoto, Niger
75- 99	2	(west of Maradi)

In this study, energies and erosivity indexes (according to Wischmeier) were calculated. These results will be discussed later in this chapter.

For our study, the following data were available:

- For Mali, data collected during three years as part of the research activities of the PPS-project (Penning de Vries, F.W.T. and M.A.

Djiteye, eds, 1981) in the environment of Niono. The data include 1977 (one location) and 1978 and 1979 (both years six locations). Of this area, information is available on some important soils and their infiltration characteristics (Hoogmoed, 1980, Stroosnijder, 1977).

- For Niger, data of 1963, 1970, 1971 and 1972 were available (location: Niamey Ville 1963, Niamey Airport 1970-1972).
- From the ICRISAT station in the Hyderabad region of Andhra Pradesh, India for the years 1974-1977.

A. Niono, Mali.

The six locations where rain was measured in 1978 and 1979 were all relatively close to each other (within a 10 kilometer range). Rainfall was measured by syphon type recording raingauges. The daily rain distribution of the locations are given in fig. 1*, 2a-f and 3a-f. Not all storms were recorded and analysed (due to malfunctioning and other problems). A summary of the number and volume of the rainstorms analysed is given in table 1*. Compared to the long term average of the rainfall, 1977 and 1979 can be regarded as dry years, with 1978 as a "normal to dry" year. Long term average for Niono is 580 mm.
In the analysis, the storms were divided into three volume classes: <10mm, between 10 and 20mm and >20mm. This discrimination was made in order to find out whether there was a correlation between contribution to runoff by the storm and storm size.
Results.
1. Intensities. Each rainstorm was divided into segments of equal intensity. A typical result is given in fig.4. Usually the storm starts with high intensities, followed by a "tail" of lower intensities. A small number of storms shows peak intensities somewhere halfway the storm. This phenomenon is also reported by Lal (1976) for Western Nigeria.
For the entire rainy season, the distribution of intensities (or intensity classes) can be given as a function of percentage of total rain. These results are given in figs. 5a-c and summarized in table 2.
* figures and tables: see Annex.

The difference in intensity distribution between storm sizes is clear: larger storms have higher intensity rain than smaller storms. Intensities measured were very high;

peak intensities found were in 1977 : 190 $mm.hr^{-1}$ (approx. 3 minutes)
in 1978 : 230 $mm.hr^{-1}$ (" 4 ")
in 1979 : 300 $mm.hr^{-1}$ (" 6 ").

Peak intensities of this order of magnitude are also mentioned by Kowal (1970) for Northern Nigeria.

2. Energies and indexes. For each rain event, kinetic energy, indexes and peak intensities were calculated: an example of the (computer) output is given in fig. 6. The cumulative values for each location per year are given in tables 3a-c. The higher intensities in the larger storms are also shown in the calculated energies and indexes, not only for the totals per storm or season, but also when expressed per mm of rainfall. In particular Lal's index, when expressed per mm rain, can be considered as a weighted mean intensity. Between the three years, there is no big difference, the larger storms (>20 mm) account for approx. 50% of the total precipitation in 1977 and 1979 and for approx. 43% in 1978 (see also table 1).

Although there is a difference between mean intensities in the three storm size classes, no correlation was found between mean intensities (Lal's index per mm of rain) and storm size.

B. Niamey, Niger.

From this location, rainfall records of 1963 (Niamey Ville) and 1970, 1971 and 1972 (Niamey Airport) were analysed.

A summary of number and volumes of the rainstorms is given in table 4. The daily rain distribution over the rainy seasons is given in figs. 7a-d. Similar to the Mali data, storms were divided into three classes: <10mm, 10-20mm and >20mm. Of the 1963 data, no records were available for storms <10mm. For the other years, all storms were analysed.

Results.

1. Intensities. The intensity distribution, expressed as percentage of total rain is given in figs. 8a-d and a summary in table 5. As for

Mali, the distribution shows that larger storms have higher intensities.
Peak intensities found in the available records:

1963: 188mm.hr^{-1} (for 6 minutes)
1970: 231mm.hr^{-1} (for 6 minutes)
1971: 150mm.hr^{-1} (for 6 minutes)
1972: 253mm.hr^{-1} (for 6 minutes)

2. Energies and indexes. The cumulative values of energies and indexes are given for all years in table 6. Although the energies (intensities) in the larger storms are higher (similar to the Mali rainfall), there is no relation between energy and storm size under 20mm. The percentage of the volume of rain, falling in storms >20mm is given in table 4 and is approx. 60%, even for a dry year with very low precipitation (1972) this is still 50%.

C. Hyderabad, India.

Hyderabad, on the Deccan Plateau in Andhra Pradesh, India also has a typical semi-arid climate. From the ICRISAT meteorological station, rainfall records of the years 1974-1977 were analysed. Daily rainfall distribution is shown in figs. 9a-d. A summary of the number and volumes of the rainstorms is given in table 7. All storms were analysed.

Results.

1. Volumes. The annual precipitation for the Hyderabad region is higher than for the two West African stations: long term average approx. 670mm. This is approx. 90 mm higher than Niono and 30 mm higher than Niamey. Precipitation in 1975 was higher, in 1977 lower than average. The number of rainstorms (assuming that one storm should not have dry periods longer than 12 hours) however, is not larger, the volumes of the individual storms are higher (see table 6). In the years '74, '75 and '76 approx. 75% of the total rain came in events of more than 20mm each, in the dry year 1977 still more than 50%. Rainfall distribution over the rainy season is also different from West Africa, the season is longer. More information on the climatology of semi-arid India is given by Virmani et al (1978).

2. Intensities. The intensity distribution as a function of volume of rain is given for each year in figs. 10a-d. The intensities are high and typical for a semi-arid region; comparison with the results from West Africa however shows that intensities in the Hyderabad region are lower. Peak intensities were as follows:

1974 : 134mm.hr^{-1} (for 6 minutes)
1975 : 155mm.hr^{-1} (" " ")
1976 : 92mm.hr^{-1} (" " ")
1977 : 57mm.hr^{-1} (" " ")

A summary of the intensities is given in table 8.

3. Energies and indexes. Similar to the other locations, the cumulative and average values of energies and indexes are calculated and given in table 9. There is a difference between the mean intensity (expressed as Lal's index per mm) of the different storm size classes, except for 1977, where the intensities are all in the same order of magnitude. The distribution of rain over the rainy season in 1977 was also without peaks, compared to the other years, with daily rainfall peaks of 108, 175 and 160mm per day respectively.

A comparison of the rainfall characteristics.

The information obtained from data of 3 and 4 years only is by far too small to permit any statistically sound conclusion, in particular for the variable rainfall pattern of a semi-arid climate. Notwithstanding this, differences are observed between the locations which may be of extreme importance for the applicability of results from agricultural research on soil tillage and management, when not performed immediately near the experimental sites.

For the optimum growth and development of a crop, the water supply to the plant should be uninterrupted during the growing season, especially in critical periods like emergence and flowering. Information on the rainfall distribution over the season is a major factor for research; together with water holding characteristics of the soils,

the risks for periods with restricted water availability to the crop can be estimated. For information on rainfall distribution and statistical analysis of occurrence of dry periods, both in India and West-Africa, reference is made to the work of ICRISAT (Virmani et al, 1978 and Sivakumar et al, 1979). Important studies on the agroclimatology for West Africa are also given in the previously mentioned W.M.O. studies of Cochemé and Franquin (1967) and Davy et al, (1976).
Information on the intensities of the rain and their distribution within the rainstorm is very important for research in soils and soil tillage. Under a high intensity rain, the infiltration rate of the soil surface may be exceeded by the rainfall intensity and water losses by runoff may occur. The infiltration rate (or -capacity) will be affected by phenomena like soil slaking and crust formation, which in turn is depending strongly on the agressiveness of the rain (inter-related characteristics like intensity, drop size, velocity etc.).
A comparison between the mean kinetic energy load of the different locations gives the following results:

Mali			Niger			India		
year	kin.en. per mm	AI_m per mm	year	kin.en. per mm	AI_m per mm	year	kin.en. per mm	AI_m per mm
1977	27	48	1970	28	59	1974	24	30
1978	25	31	1971	26	39	1975	24	30
1979	27	47	1972	26	53	1976	24	25
						1977	22	14
ave.	26	42	ave.	27	50	ave.	23	25

From these results, the rainfall in Niamey appears to be the most agressive (the 1963 data are not used for the calculation because of the absence of data of storms <10mm). The rainfall at ICRISAT is less agressive considering the kin. energy and mean intensities.
Comparing the total energy dissipated by the rain for the 3 areas gives (kin. energy in $J.m^{-2}$):

Mali	total kin.en.	total rain (mm)	Niger	total kin.en.	total rain (mm)	India	total kin.en.	total rain (mm)
1977	10146	377	1970	12849	466	1974	16983	695
1978	8195	412	1971	11297	438	1975	19414	802
1979	10539	404	1972	5995	299	1976	15014	626
						1977	8581	388

Kinetic energy, as calculated from the intensities, appears to be in India (Hyderabad region) approx. 10% lower (per mm of rain) than in locations analysed in West Africa.

Kowal and Kassam (1976) found for Samaru, Nigeria (average annual rainfall 1100mm) the average E_k load to be 34.6 $J.m^{-2}.mm^{-1}$. Elwell and Stocking (1973) found for Rhodesia (910mm rain) approx 19 $J.m^{-2}.mm^{-1}$.

Delwaulle (1973) did not present energy loads, but gave Wischmeier's EI_{30} (R) index. This index per mm rain is 788 $J.m^{-2}.mm^{-1}$, (ranging between 609 and 1030) for Allokoto (average rainfall 495mm, ranging between 289 and 515mm).

In this study, figures for Upper Volta are also mentioned;

location Dori (587mm), EI_{30} per mm is 772,

location Bobo Dioulasso (1160mm), EI_{30} per mm is 829.

Our values for Niono and Niamey are in the same order of magnitude (see figs. 3 and 6):

Niono: average 933, ranging between 686 and 1193 and

Niamey: average 995, ranging between 744 and 1432.

The values for ICRISAT (fig. 9) are not lower: average 938, ranging between 504 and 1235.

When certain soil tillage or - management systems are being developed in one region, it must be realized that, apart from differences in soils and topography (stability, erodibility etc.), the differences mentioned above in rainfall intensity will play an important role. E.g. surface roughness, created by soil tillage will be decreasing sooner under high intensity rains and also the required surface storage (in view of preventing runoff losses) will be higher.

This subject will be discussed in more detail in the next chapter.

3. INFILTRATION AND RUNOFF.

In the first report of this series (Appendix 3) , results of experiments on infiltration and runoff with a rainsimulator are reported. Some averaged curves of the S1N soil, a sandy soil typical for the Niono area, are given in figs. 11a-c. For the interpretation of these curves, it must be kept in mind, that the experiments on the "undisturbed" soil were carried out on a soil which had not been cultivated for many years. There was hardly any vegetation and virtually no surface storage on the area subjected to the artificial rain. On farmers' fields, one may expect a (slightly) higher surface storage and possibly some more plant residue, although in many cases this material had been used as fodder.

Measurements and calculations.

A. Bare, undisturbed soil.

For the calculations of runoff (or more correctly rainfall minus infiltration), two methods were used:

a. the application of the rainfallsimulator results with the rainfall analysis (computerprogram),
b. the calculation (estimation) of the sorptivity S (Stroosnijder, 1981).

With regard to sorptivity: cumulative infiltration at time t I(t) may be expressed as follows: $I(t) = S\sqrt{t} + ks_{crust}.t$, with ks_{crust}= saturated hydraulic conductivity of the crust.
The second part of the equation ($ks_{crust}.t$) is very small compared to $S\sqrt{t}$ on fine textured soils, for up to 30 minutes after the start of the rain on a dry soil. S (in $mm.min^{-\frac{1}{2}}$) has been determined on the basis of frequent soil moisture measurements. For the S1 soil, S was estimated (average for the growing season) as 0.75 for a bare soil and 1.50 for a soil with a vegetative cover.
During the rainy season of 1979, some measurements of runoff under natural rainfall on plots similar to the ones used with the rainfallsimulator were taken, both on tilled soil planted with millet (see

Appendix 3) and undisturbed, bare soil.
In table 10 the results are given of:

a. the actual runoff measured on S1N plots (natural rainfall),
b. the runoff calculated with the rainfall simulator results and the rainfall analysis,
c. the runoff calculated with the equation $I(t) = S\sqrt{t}$.

The table shows first of all that the runoff values are very high, both for the measured as well as the calculated figures, a cumulative runoff of approx. 40% of total precipitation for those showers where runoff was measured, and a calculated runoff of approx. 50% for the same storms.
From the 41 storms of 1979, 18 did not lead to any runoff on the S1N soil, total volume of rain from these storms was only 35.7 mm out of a total of 362.7 mm (10%). Thus expressed as a percentage of total rain over the season, runoff was approx.45%. Secondly the table shows that there is a small difference between calculated and measured runoff and an even smaller difference between the two methods of calculation. Cumulative runoff values are 68.2mm when calculated using $S\sqrt{t}$, 71.7mm when calculated with the computer analysis and 78.0mm when measured. Although the calculated values are smaller, this is not significant, since the differences may be attributed to a number of storms where some runoff was measured but where the calculations yielded zero runoff. The system of measuring runoff was such, that measurements tended to overestimate runoff while the accuracy of measuring runoff was such that values of one and two mm will be within the error of measurement. From the above results, it may be assumed, that the calculation of runoff, both by the computer analysis and the sorptivity estimation is fairly accurate (with an error of less than 10%).
The measurements (rainsimulator and "natural" runoff) were carried out on experimental plots bare of vegetation and a surface storage of virtually zero.
The effect of increased surface storage capacity is given by the computer analysis (see also table 10):

surface/storage	runoff (mm)	% of rain (total rain is 362mm)
0 mm	162.4	44.9
0.5mm	146.5	40.5
5 mm	97.5	27.0
10 mm	70.0	19.3

Thus, a considerable reduction of runoff losses may be achieved by just increasing the surface storage.

B. Cultivated soils.

The important impact of soil tillage on the infiltration characteristics of the S1N soil can be observed in the infiltration vs. rainfall curves determined with the rainfall simulator (see fig. 11). To quantify this effect for the whole (rainy) season, runoff was calculated using the computer rainfall analysis, with the tillage operations performed at various dates within the season. The results are given in table 11. This table shows, that the time of tillage relative to a rain event is very important; e.g. tillage after storm nr. 19 is rather late in the season, but just before the large storm of 82mm (see table 10 for the listing), so total runoff is in this case lower than from early tilled fields.
The effect of surface storage (which will be determined hereby as the surface roughness induced by tillage) is again important: fields with a storage of 10mm, will give runoff which is only 50% or less of the runoff from fields with a storage of 2 mm.
There is hardly any difference between the runoff from ridged and plowed fields, although in practice plowing will give a higher surface storage value than ridges along the slope (in particular immediately after the tillage operation). Repeated tillage operations (even superficial) during the growing season will of course improve infiltration again. The effect of hoeing the surface of a plowed (weathered) plot is given in fig. 12 (exp. 10 and 17 of rainfall simulator work).
For a possible extrapolation of the results to other areas, three important conditions should be kept in mind:

a. The <u>character of the rainfall</u> in the area of measurement. Although available data are restricted, it is clear that intensities may differ considerably from place to place. In an attempt to quantify this in terms of runoff, combinations of soil data from S1N and rainfall data from Niger (=higher intensities) and India (= lower intensities) have been used to calculate runoff, similar to the processing of the Mali data.
The results are given in tables 12 and 13. It is clear that the intensities indeed do play a role in the formation of runoff. Although the total amounts of rain in India are higher, runoff is less; for the years analysed, runoff as a percentage of total rain was 30, 31, 25 and 12% for ICRISAT, 52, 35 and 35% for Niamey and 45, 46 and 48% for Niono (assuming zero surface storage).

b. The <u>soil characteristics</u>. The S1N soil on which the simulator experiments have been carried out, is a typical fine sandy soil with a strong tendency to form a crust when being subjected to rainfall. Soils with a smaller percentage of clay or with a coarser sand fraction may keep up a higher final infiltration rate. On other soil types in the Niono area, sorptivity values were estimated (Stroosnijder, 1981: table 4.4.2):

soil (bare)	1977	1978	1979	
S1N		0.75	0.75	S values in $mm.min^{-\frac{1}{2}}$
S1S		0.75		
S2 (coarser)	2.23	2.25	1.00	
Clay D1		0.50		
Loam LIM		0.65	0.75	
Degraded soil TD		1.00	0.38	

This table indicates the differences in infiltration capacities (derived from observations under natural conditions, so taking into account phenomena like crust formation). The coarser sand S2 will have a higher infiltration, clay and loam soil will be lower. Only very few data on infiltration are available for West Africa; the crust formation is reported and quoted in the review publication by Jones and Wild (1975). Charreau and Nicou (1971) report infiltration rates on sandy Senegal soils to drop under rainfall from 50 to 5mm/hr, which indicates that the values found for the SIN soil are not exceptionally low.

c. The assumption of a bare soil throughout the growing season. The soil will become protected in the course of the growing period by the developing crop. Raindrops will be intercepted and the direct impact of the rain will be reduced. For the (climatological) region where the experiments were carried out, the protecting effect of the crop canopy is not very high, due to various reasons:

   I. Planting density and- geometry are such, that only a small percentage of the area is covered. Millet plants (in "bunches") in a pattern of 0.80 x 1.10m will not cover the surface completely.

   II. Because of the lack of fertilizers, crop development (and thus growth of protecting leaves) in the early stages is low.

   III. The millet varieties grown here are mainly with leaves oriented upright, which is not very effective in intercepting raindrops.

   IV. When a crust has been formed early in the growing season, the direct impact of the raindrops will be less important than volume and intensity of rain.

   The contribution of rainstorms appearing later in the season to runoff should however be corrected for the crop canopy development. Although no data were available, it seems probable that the LAI (Leaf Area Index: total area of leaves per unit area of land surface) is the best way to express the protecting effect of a crop.

Contribution to runoff by large rainstorms

As was pointed out by Delwaulle (1973), the larger rainstorms usually cause the largest losses as runoff. The phenomenon was also observed in the experiments in Mali. The reasons for the high runoff rates are twofold:

1. Because of the large amounts of rain, the topsoil becomes saturated, a crust may have been formed and thus the infiltration rate will decrease considerably.
2. The intensity of the rainfall in larger storms usually is higher

(chapter 2), so a crust may be formed sooner and the infiltration capacity of the soil will be exceeded easier.

Some of the available rainfall data have been used for the calculation of runoff, using the infiltration characteristics of the S1N soil from Mali (see tables 11, 12 and 13). From the results of the "no-tillage" treatment, a distinction is made between storms <20mm and >20mm. Their respective contribution to runoff is given in table 14. It is clear, that in the West African locations, just a few large storms will give a high percentage of the total runoff. For India, this figure is less pronounced, because of the fact that rain comes in large storms, but usually with lower intensities.

For surface storage values of 10mm, nearly all runoff is produced during storms >20mm.

4. MOISTURE DISTRIBUTION AND -STORAGE.

After rainwater has entered the soil, a process of redistribution in the profile will start. The amounts of water available to the plant will (in the layers where roots have developed) be determined by two values: moisture content (m.c.) at Field Capacity (FC) and m.c. at Permanent Wilting Point (PWP).
PWP is the value of m.c. where the plants are no longer able to take up water from the soil. This value is usually taken as m.c. at a suction of approx. 15 bar (=pF 4.2.). For FC, this value is less clearly determined; this value is usually assumed to be the m.c. of a soil some time (1 or 2 days) after saturation, under good drainage conditions. Since this value is not constant in the time, assumptions have to be made. In temperate climates FC is usually taken as m.c. at a suction of 0.1 bar (pF 2.0.).
Since the amounts of water in semi-arid climates are far less (hardly ever saturated flow), an FC value coupled at a certain minimum hydraulic conductivity (K) value seems more logical (Stroosnijder, 1981).
For the Mali soils of the PPS project, the following values (volume %, θ) were proposed:

soil	FC K= 10^{-1} cm/day	FC K= 10^{-2} cm/day	PWP
S1	18.0	7.5	2.5
S2	25.0	14.5	2.5
D1	25.5	24.5	17.0
LIM	26.5	19.5	3.0

It is clear that in a sandy soil the moisture profile will be quite different from a heavier soil; in a sandy soil, water will penetrate (redistribute) to a greater depth than in a heavier soil.
This has two possible effects:

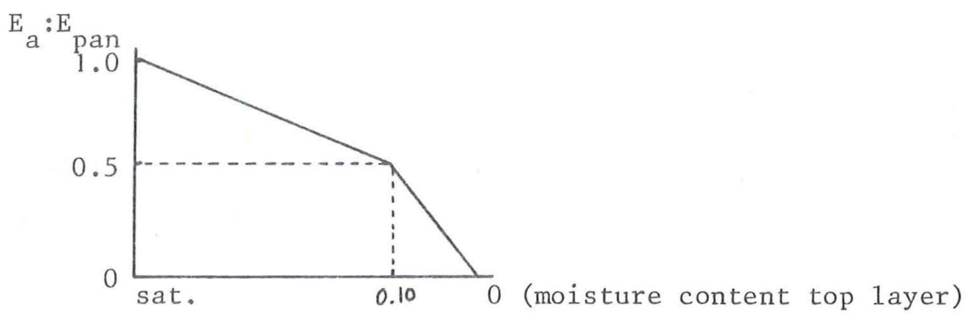
a. the moisture in the profile may be "safer" for evaporation losses in a sandy soil (although transport in the gasphase is - on the long run - important!).
b. water may be lost for the plant by deep drainage (depending on the

rooting depth of the crop).

The moisture distribution in the soil profile of SIN has been measured in 1979 (Stroosnijder, 1981: table 4.4.3. and fig. 4.4.17.). The measurements reported were carried out on a field with natural vegetation. Moisture movement in a SIN profile was also simulated by a computer model developed by the author (Hoogmoed, unpublished). The following assumptions were made:

- A bare soil, with the ψ-θ and ψ-K relations as measured for the SIN soil (Appendix 3).
- A runoff percentage calculated by the rainfall analysis program (surface storage o.5mm), which resulted in an infiltration rate of rainfall minus runoff, entering the soil in 1.2 hours.
- Evaporation as a function of available open pan evaporation data (averaged values per decade).

  The following relation between E_a:E_{pan} ratio and m.c. of the surface layer was assumed:



- A soil profile of 170cm depth, no flow of water to or from deeper layers.
- No hysteresis.

The water movement in the profile is simulated with the model using the rainfall and runoff data from 1977, 1978 and 1979.

In figs. 13a-c the volume of water in the first 10cm of the profile is given during the time of simulation (rainy season April/May - October).

Assuming a PWP of 2.5% (θ), the absolute minimum amount of water to keep a germinating seed or seedling alive, should be 0.25cm. This mi-

nimum is indicated in the figures by a dotted line.
Although rainfall in the early part of the season will wet the top layer of the soil, it is obvious that the evaporation will cause a quick drying.
E.g. in 1979, after some early periods of wetting, the dry period between day nr. 174 and 192 had caused young seedlings to die.
The importance of moisture conservation in the early part of the rainy season is shown in fig. 14 for 1977 and 1979. Here the amount of moisture in the top 10cm is given, when calculated assuming no run-off until around daynr. 200. The number of days that moisture in the toplayer is below 0.25cm is less especially when rain falls in more (smaller) events.

5. CONCLUSIONS

- Rainfall intensities in the semi-arid zone of West-Africa are high; higher than in areas with a comparable climate like parts of India or Zimbabwe (Rhodesia).
- The larger rainstorms (>20mm rain per event) have rain intensities above average. These rainstorms are the major contributors to runoff.
- Soil tillage will prevent runoff considerably, because of the improvement of the infiltration capacity. Tillage resulting in the increase of the surface storage capacity (even without significantly improving the infiltration capacity) has an even larger effect on runoff prevention.
- The critical period in terms of moisture supply to the plant or seedling is in the first month of the rainy season. In this period the moisture conservation measures are most effective; later in the season superficial drainage may even be required.
- For a reliable advice on new tillage systems or -practices based in rainfall data, many more data have to be collected and analysed.

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ANNEX

LIST OF TABLES

LIST OF FIGURES

Table 1. Rainfall near Niono, Mali, 1976 - 1979.

year	location	nr. of days with rain	total vol. (mm)	nr. of storms analysed	total vol. (mm)
1976	S1S	46	564	--	--
	D1	46	590	--	--
1977	S2	29	376	29	376
	D1	33	363	--	--
1978	S1N	36	437	30	271
	S1S	36	400	30	338
	D1	39	371	36	332
	TD	40	393	30	304
	LIM	35	448	28	341
	S2	36	429	32	398
1979	S1N	42	362	41	361
	D1	37	401	37	401
	TD	35	397	35	397
	LIM	34	398	34	398
	S2	34	431	34	430
	MIL	34	449	31	421

Distribution of rainstorm sizes; average all locations.

Volumes in mm.

year	total vol.	<10 mm		10 - 20 mm		>20 mm	
		vol.	%	vol.	%	vol.	%
1976	577	100	17.4	113	19.6	365	63.3
1977	370	57	15.5	124	33.5	189	51.1
1978	412	97	23.5	138	33.5	177	43.0
1979	403	111	27.4	74	18.3	217	54.0

Table 2. Analysis of rainfall intensities and -distribution, Niono, Mali.
All volumes in mm, intensities in mm/hr.

year	size of storm	total volume	intensities at %-level of total rain 75%	50%	25%	% rainfall with intensities higher than: 20	50	100 mm/hr
1977	all	376.5	10	28	59	60	32	12
	>20 mm	191.3	24	51	87	78	51	21
	10-20 mm	134.8	10	21	43	53	17	3
	<10 mm	50.4	4	11	21	28	2	0
1978	all	330.9	6	21	40	52	18	4
	>20 mm	141.4	9	33	57	65	33	9
	10-20 mm	101.6	5	22	38	54	13	0
	<10 mm	87.9	4	12	22	27	2	1
1979	all	396.7	12	33	67	64	39	14
	>20 mm	209.7	15	53	102	70	53	26
	10-20 mm	80.3	17	34	56	68	34	3
	<10 mm	111.3	4	10	22	30	0	0

Example: (1st line) 75% of the rain comes in intensities of 10 mm/hr or lower,
50% " " " 28 " "
25% " " " 58 " "

60% of rainfall comes in intensities higher than 20 mm/hr
32% " " " " " 50 "
12% " " " " " 100 "

Table 3. Rainfall energies and -indexes, Niono, Mali.

Dimensions: rain = mm

kin. energy = $J.m^{-2}.mm^{-1}$

Wischm. index = $J.m^{-2}.mm.hr^{-1}$

Hudson's index = $J.m^{-2}$

Lal's index = $mm^{2}.hr^{-1}$

cum. values	1977 storm size group				1978 storm size group			
	>20 mm	10-20 mm	<10 mm	total	>20 mm	10-20 mm	<10 mm	total
Rainfall (mm)	191	135	50	376	141	102	86	330
Kin. energy	5383	3658	1105	10146	3763	2476	1932	8195
Wischm. index	245478	90806	9982	346266	156637	51228	18807	226858
Hudson's index	4002	2383	259	6645	2647	1324	527	4499
Lal's index	12080	5167	741	17988	6312	2505	1416	10246
per mm rain: Kin. en.	28.1	27.1	21.9	26.9	26.7	24.3	22.3	24.8
Wischm. index	1283.2	673.6	198.1	919.7	1122.6	494.6	212.1	685.9
Hudson's index	20.9	17.7	5.1	17.6	21.4	12.8	5.9	13.6
Lal's index	63.1	38.3	14.7	47.8	46.1	24.2	16.4	31.4

	1979			
Rainfall (mm)	210	80	111	397
Kin. energy	6050	2031	2459	10539
Wischm. index	402354	44201	24466	471022
Hudson's index	4941	1069	634	6645
per mm rain: Kin en.	28.9	25.5	22.2	26.6
Wisch. index	1947.4	551.2	220.4	1192.7
Hudson's index	23.7	13.0	5.8	16.8
Lal's index	70.0	31.7	14.5	46.9

Table 4. Rainfall at Niamey, Niger.

year	location	nr. of days with rain	total vol. (mm)	nr. of storms analysed	total vol. (mm)
1963	Ville	32	512.0	17	437.1
1970	Aero	26	465.8	all	465.8
1971	Aero	30	437.8	all	437.8
1972	Aero	23	228.8	all	228.8

Distribution of rainstorm sizes:

Volumes in mm

year	total vol.	<10 mm			10-20 mm			>20 mm		
		nr.	vol.	%	nr.	vol.	%	nr.	vol.	%
1963	512.0	15	74.9	14.6	9	136.7	26.7	8	300.4	58.7
1970	465.8	11	62.2	13.3	8	104.5	22.4	7	299.1	64.2
1971	437.8	14	70.8	16.2	8	123.7	28.2	8	243.3	55.6
1972	228.8	16	78.4	34.3	3	35.6	15.6	4	114.8	50.2

Table 5. Analysis of rainfall intensities and -distribution, Niamey, Niger.
All volumes in mm, intensities in mm/hr.

year	size of storm	total volume	intensities at %-level of total rain 75%	50%	25%	% rainfall with intensities higher than: 20	50	100 mm/hr
1963	all+	437.1	18	52	85	72	52	17
	>20 mm	300.4	23	61	93	78	61	21
	10-20 mm	136.7	17	48	103	69	42	16
	<10 mm	-	-	-	-	-	-	-
1970	all	465.8	10	36	78	65	40	14
	>20 mm	299.1	23	52	95	79	51	21
	10-20 mm	104.5	6	11	34	37	19	4
	<10 mm	62.2	6	16	40	45	23	-
1971	all	437.8	8	20	44	48	23	8
	>20 mm	243.3	9	20	46	48	20	7
	10-20 mm	123.7	13	20	61	50	30	9
	<10 mm	70.8	5	13	38	44	16	5
1972	all	228.8	8	19	57	49	27	14
	>20 mm	114.8	7	10	85	31	27	24
	10-20 mm	35.6	18	33	-	74	36	-
	<10 mm	78.4	15	34	72	65	34	8

+storms smaller than 10 mm were not analysed.

Table 6. Rainfall energies and -indexes, Niamey, Niger.
Dimensions: see table 3.

cum. values	1963 storm size group				1970 storm size group			
	>20 mm	10-20 mm	<10 mm	total	>20 mm	10-20 mm	<10 mm	total
Rainfall (mm)	300	137		437	299	104	62	466
Kin. energy	8818	3906		12465	8798	2531	1521	12849
Wischm. index	584297	147943		704300	600681	41431	20531	662642
Hudson's index	7158	2696		9162	6936	1110	733	8779
Lal's index	22628	8426		5962	23023	2577	1744	27344
per mm rain:								
Kin. en.	29.4	28.6		28.5	29.4	24.3	24.5	27.6
Wischm. index	1945.0	1082.2		1611.3	2008.3	396.5	330.1	1423.6
Hudson's index	23.9	19.7		21.0	23.2	10.6	11.8	18.8
Lal's index	75.3	61.6		59.4	77.0	24.7	28.0	58.7

	1971				1972			
Rainfall (mm)	243	124	71	438	115	36	78	229
Kin. energy	6325	3255	1717	11297	2945	960	2091	5995
Wischm. index	214602	75001	36195	325798	112669	24308	49711	186688
Hudson's index	3327	1773	913	6014	1117	740	1406	3264
Lal's index	10323	4333	2469	17125	7640	1274	3284	12198
per mm rain:								
Kin. en.	26.0	26.2	24.2	25.8	25.7	27.0	26.7	26.2
Wischm. index	882.0	606.3	511.2	744.2	981.4	682.8	634.1	815.9
Hudson's index	13.7	14.3	12.9	13.7	9.7	20.8	17.9	14.3
Lal's index	42.4	35.0	34.9	39.1	66.5	35.8	41.9	53.3

Table 7. Rainfall at ICRISAT meteorological station, Hyderabad, India.

year	nr. of days with rain	<10 mm			10-20 mm			>20 mm			total volume
		nr.	vol.	%	nr.	vol.	%	nr.	vol.	%	
1974	22	4	30.2	4.3	7	93.2	13.4	11	571.7	82.2	695.1
1975	28	1	7.0	0.9	14	203.6	25.4	13	592.0	73.8	802.6
1976	23	5	29.0	4.6	9	125.4	20.0	9	471.8	75.3	626.2
1977	20	3	13.9	3.6	10	134.6	34.7	7	239.5	61.7	388.0

All storms have been analysed.

Table 8. Analysis of rainfall inetensities and -distribution, ICRISAT.
All volumes in mm, intensities in mm/hr.

year	size of storm	total volume	intensities at %-level of total rain			% rainfall with intensities higher than:		
			75%	50%	25%	20	50	100 mm/hr
1974	all	695.1	6	20	38	43	18	8
	>20 mm	571.7	6	20	41	43	22	10
	10-20 mm	93.2	6	20	25	43	4	0
	<10 mm	30.2	5	8	27	39	0	0
1975	all	802.6	5	15	38	43	18	11
	>20 mm	592.0	6	18	50	48	25	14
	10-20 mm	203.6	3	8	22	27	0	0
	<10 mm	7.0	2	3	20	25	0	0
1976	all	626.2	5	13	34	38	15	5
	>20 mm	471.8	6	16	41	46	20	5
	10-20 mm	125.4	4	10	20	25	8	8
	<10 mm	29.0	10	11	20	25	0	0
1977	all	388.0	4	11	22	27	2	0
	>20 mm	239.5	4	10	22	29	4	0
	10-20 mm	104.6	4	10	19	24	0	0
	<10 mm	13.9	14	20	0	53	0	0

Table 9. Rainfall energies and -indexes, ICRISAT, Hyderabad, India.
Dimensions: see table 3.

cum. values	1974 storm size group >20 mm	10-20 mm	<10 mm	total	1975 storm size group >20 mm	10-20 mm	<10 mm	total
Rainfall (mm)	572	93	30	695	592	204	7	803
Kin. energy	14142	2164	678	16983	14878	4394	141	19414
Wischm. index	706305	36147	7230	749683	630193	71910	930	703033
Hudson's index	6749	646	150	7544	7873	1079	0	8951
Lal's index	18526	1614	411	20552	20973	2679	55	23708
per mm rain:								
Kin. energy	24.7	23.2	22.4	24.4	25.1	21.6	20.2	24.2
Wischm. index	1235.4	387.8	239.4	1078.5	1064.5	353.2	132.9	875.9
Hudson's index	11.8	6.9	5.0	10.9	13.3	5.3	0.0	11.2
Lal's index	32.4	17.3	13.6	29.6	35.4	13.2	7.9	29.5

	1976				1977			
Rainfall (mm)	472	125	29	626	239	135	14	388
Kin. energy	11529	2811	675	15015	5245	2998	338	8581
Wischm. index	448366	38945	7497	494807	120674	43812	3793	168278
Hudson's index	5316	767	82	6165	1507	646	103	2256
Lal's index	12656	2965	368	15989	3400	1851	225	5476
per mm rain:								
Kin. energy	24.4	22.4	23.3	24.0	21.9	22.3	24.3	22.1
Wischm. index	950.3	310.6	258.5	790.2	503.9	325.3	272.8	433.7
Hudson's index	11.3	6.1	2.8	9.8	6.3	4.8	7.4	5.8
Lal's index	26.8	23.6	12.7	25.5	14.2	13.8	16.2	14.1

Table 10. Runoff amounts for 1979 on S1N soil; measured and calculated results. All amounts in mm.

storm nr.	date	rain vol.	runoff measured	runoff caluculated: using S√t	using computer analysis, surface storage values: 0	0.5	5.0	10.0 mm
2	10/5	20.6	-	8.4	8.3	6.3	0.6	0
3	22/5	14.8	-	7.6	5.9	5.4	0.9	0
5	2/6	8.3	-	3.0	2.1	1.6	0	0
8	6/6	10.6	-	4.0	4.4	3.9	0	0
10	10/6	14.4	4.0	8.8	9.9	9.4	4.9	0
11	21/6	8.8	2.5	0	0	0	0	0
12	13/7	7.0	2.0	0	0	0	0	0
14	17/7	7.9	3.0	4.3	2.3	1.3	0	0
15	21/7	7.2	1.5	0	0.3	0	0	0
16	24/7	7.5	3.0	0.4	0.7	0	0	0
17	25/7	4.0	0.3	0	0.6	0	0	0
18	28/7	32.6	22.5	21.1	19.2	18.6	14.1	9.1
19	31/7	15.3	-	8.2	6.4	5.9	1.4	0
20	4/8	82.4	-+	70.1	63.6	63.1	58.6	53.6
24	16/8	14.1	10.5	7.7	9.7	9.2	4.7	0
27	23/8	4.9	0.6	0	0	0	0	0
29	30/8	4.3	1.0	0.3	1.0	0	0	0
30	2/9	5.6	1.0	0.4	0.9	0.4	0	0
32	7/9	9.6	4.5	3.5	4.7	4.2	0	0
33	9/9	5.5	1.0	0	1.7	1.2	0	0
34	13/9	27.9	16.5	19.0	17.3	16.8	12.3	7.3
36	18/9	6.9	3.0	2.1	2.4	1.9	0	0
39	25/9	6.1	1.0	0.6	2.0	1.5	0	0
totals^o		174.3	78.0	68.2	71.7			
totals^oo		326.3		169.5	162.4	150.7	97.5	70.0

o only storms where runoff was measured

oo only storms yielding runoff as calculated (= all storms listed here)

\+ capacity of collecting barrels exceeded

total rainfall for this location: 362.0 mm

Table 11. Cumulative runoff (calculated) after a tillage operation at various dates within the season. S1N soil. Runoff expressed in mm.

tillage after: day nr.	storm nr.	runoff from plowing sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	runoff from ridging sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	
142	3	90.8	85.2	73.0	54.8	38.6	91.1	85.5	73.2	57.8	38.3	year:
160	9	95.1	89.0	75.3	54.8	38.6	95.2	89.0	75.3	54.8	38.3	1979
205	16	98.6	90.5	75.5	55.0	38.6	101.3	92.6	76.1	54.8	38.3	rain:
212	19	97.5	87.8	69.8	43.3	20.5	109.7	99.9	81.8	55.3	32.4	361 mm
no tillage		162.4	150.9	127.1	97.5	70.0	as plowing					
159	3	60.6	55.3	42.4	25.7	19.1	59.6	54.4	41.9	25.2	18.6	year:
190	6	59.8	53.0	38.5	18.8	7.3	66.0	59.3	45.2	25.6	13.9	1978
193	7	56.4	49.5	35.0	12.4	1.2	68.2	61.0	45.6	22.9	11.0	rain:
196	9	80.3	74.1	59.7	37.1	25.3	80.6	74.3	59.9	37.2	25.3	271 mm
210	13	88.0	79.5	62.1	37.3	25.3	88.2	79.7	62.2	37.3	25.3	
no tillage		125.4	113.0	91.2	58.2	32.9	as plowing					
173	5	83.2	73.7	53.5	30.0	8.2	85.8	76.2	56.0	32.9	11.1	year:
199	9	83.2	72.3	49.9	25.1	3.9	90.6	79.1	55.8	29.8	3.7	1977
220	14	103.1	92.1	69.9	45.8	19.7	105.8	94.3	70.7	45.8	19.8	rain:
223	16	128.4	117.3	94.2	69.7	43.0	131.9	120.3	97.2	71.5	43.1	376 mm+
no tillage		179.6	166.2	136.7	96.2	47.9	as plowing					

+ rainfall S2 area.

Table 12. Cumulative runoff (calculated) after a tillage operation at various dates within the season. SIN soil data, rainfall data Niamey, Niger. Runoff expressed in mm.

tillage after: day nr.	storm nr.	runoff from plowing sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	runoff from ridging sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	
190	2	127.1	119.5	101.7	83.1	58.1	127.4	119.6	101.7	83.1	58.1	year:
197	4	155.2	146.6	127.3	108.8	75.8	155.3	146.8	127.4	105.8	75.8	1970
202	6	148.3	138.8	117.0	92.5	57.5	155.0	145.5	123.7	99.1	64.1	rain:
211	9	173.1	164.9	146.2	123.9	88.9	175.4	166.0	146.1	123.9	88.9	466 mm
227	14	171.1	162.0	140.4	117.4	82.4	177.4	168.0	146.4	121.4	82.5	
no tillage		241.1	227.4	198.3	165.5	125.5	as plowing					
161	1	59.1	52.4	38.3	16.0	2.4	59.5	52.7	38.6	16.2	2.5	year:
191	6	65.3	58.4	43.6	19.4	2.4	68.0	60.6	44.2	19.7	2.5	1971
205	11	79.8	72.1	55.5	27.2	4.3	79.9	72.2	55.6	27.5	4.4	rain:
216	13	77.8	69.2	52.4	24.1	4.3	78.4	69.4	52.3	24.2	4.4	438 mm
no tillage		153.3	139.1	110.0	68.4	30.5	as plowing					
146	2	40.2	35.3	26.7	16.6	11.5	39.4	35.0	26.8	16.6	11.4	year:
182	8	40.0	32.6	20.3	8.0	0.2	45.0	38.3	26.3	14.0	6.2	1972
191	11	67.4	60.1	46.3	31.1	19.7	67.0	59.8	46.3	31.1	19.7	rain:
no tillage		80.4	70.9	51.8	31.1	19.7	as plowing					229 mm

Table 13. Cumulative runoff (calculated) after a tillage operation at various dates within the season. SIN soil data, rainfall data ICRISAT, India. Runoff expressed in mm.

tillage after: day nr.	storm nr.	runoff from plowing sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	runoff from ridging sur.storage values: (mm) 0	0.5	2.0	5.0	10.0	
165	2	69.8	64.8	54.9	42.7	28.9	78.1	73.0	63.0	50.7	31.3	year:
177	4	113.2	107.7	97.8	84.8	65.9	113.1	107.6	97.7	85.3	65.9	1974
190	7	126.8	120.0	107.2	91.2	67.4	126.7	119.9	107.1	91.8	67.3	rain:
214	10	138.1	130.4	116.2	95.2	67.4	139.4	131.6	116.7	95.7	67.3	695 mm
251	14	125.9	119.3	105.6	85.3	66.3	130.0	122.8	107.8	86.6	66.0	
no tillage		211.7	199.5	176.3	144.6	108.0	as plowing					
67	1	104.8	96.8	79.1	61.4	42.3	104.0	96.3	78.9	61.1	42.2	year:
164	4	121.0	112.6	93.4	70.4	42.3	120.2	112.0	93.1	70.2	42.2	1975
185	7	109.3	100.8	82.0	60.8	36.7	113.2	104.9	86.2	63.3	38.5	rain:
246	16	150.2	139.1	114.4	87.4	55.7	156.1	145.1	119.1	88.8	55.9	803 mm
250	17	174.5	158.6	124.7	88.5	51.1	183.2	167.1	132.0	95.4	58.1	
no tillage		247.5	228.1	183.3	133.0	85.7	as plowing					
92	1	63.4	59.9	51.0	39.9	28.3	66.4	62.9	52.6	40.8	29.1	year:
105	3	98.6	93.6	80.0	62.9	42.4	101.5	96.0	81.3	63.8	43.3	1976
199	11	78.6	71.6	53.9	34.3	16.9	87.5	80.5	62.7	40.2	18.4	rain:
220	14	85.3	74.8	56.4	35.0	15.0	94.2	82.7	61.2	37.5	17.5	626 mm
230	15	148.3	136.0	114.0	89.6	66.7	as plowing					
no tillage		159.3	144.4	117.2	89.6	66.7	as plowing					
165	2	7.1	3.9	0.1	0	0	9.0	5.0	0.1	0	0	year:
176	5	13.2	10.7	6.4	3.3	0	13.2	10.7	6.4	3.3	0	1977
205	8	24.8	20.3	12.9	6.8	0	24.8	20.3	12.9	6.8	0	rain:
no tillage		47.0	38.0	21.1	7.1	0	as plowing					388 mm

Table 14. Relation between storm size and their contribution to runoff, calculated by computer rainfall analysis: SIN soil data. Only rainfall (storms) contributing to runoff has been mentioned.

			rainfall				runoff:stor. 0.5 mm				stor. 10.0 mm	
			>20 mm		<20 mm		>20 mm		<20 mm		>20 mm	<20 mm
place	year	tot.	nr.	vol.	nr.	vol.	vol.	%	vol.	%	vol.	vol.
Niono	1977	330.2	5	191.3	12	138.9	107.6	65	58.6	35	47.9	0
	1979	326.3	4	163.5	12	162.8	104.8	70	45.9	30	70.0	0
Niam.	1970	451.0	7	299.1	12	151.9	191.3	84	36.4	16	124.6	1.0
	1971	355.0	7	202.3	15	152.7	90.1	65	49.0	35	28.5	1.9
	1972	127.3	1	39.8	12	87.5	29.2	41	41.7	59	17.9	0
ICRI	1974	586.4	10	531.6	4	54.8	211.8	92	17.8	8	108.2	0
	1975	694.8	11	544.7	10	150.1	185.3	84	35.6	16	82.8	0
	1976	550.8	8	450.8	6	100.6	126.1	87	18.3	13	66.7	0
	1977	273.8	5	199.1	5	74.7	26.6	70	11.4	30	0	0

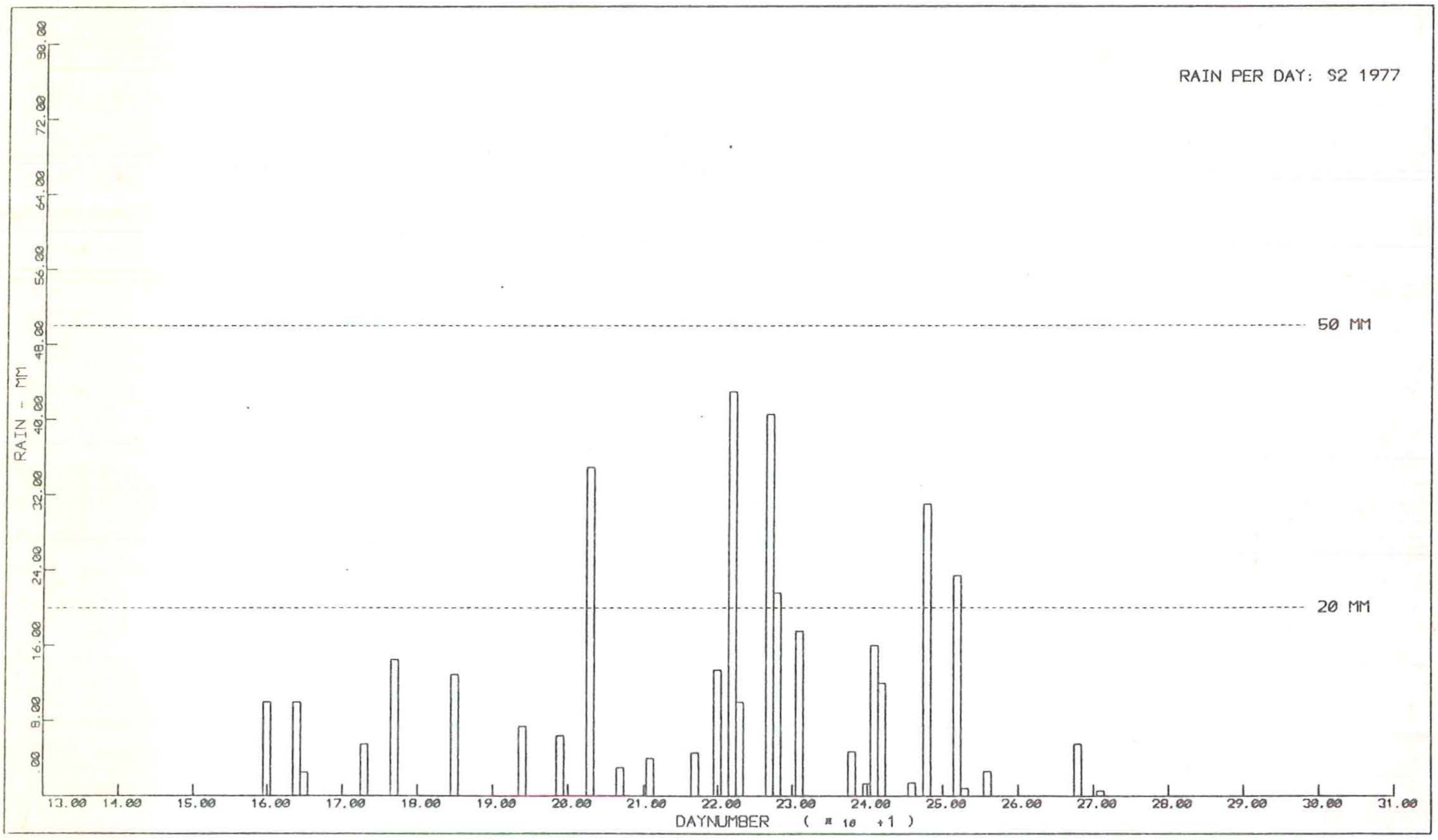


Fig. 1.

Reference table for daynumbers, used in the following figures:

date:	jan 1	daynr.: 1
	feb 1	 32
	mar 1	 60
	apr 1	 91
	may 1	 121
	jun 1	 152
	jul 1	 182
	aug 1	 213
	sep 1	 244
	oct 1	 275
	nov 1	 305
	dec 1	 335

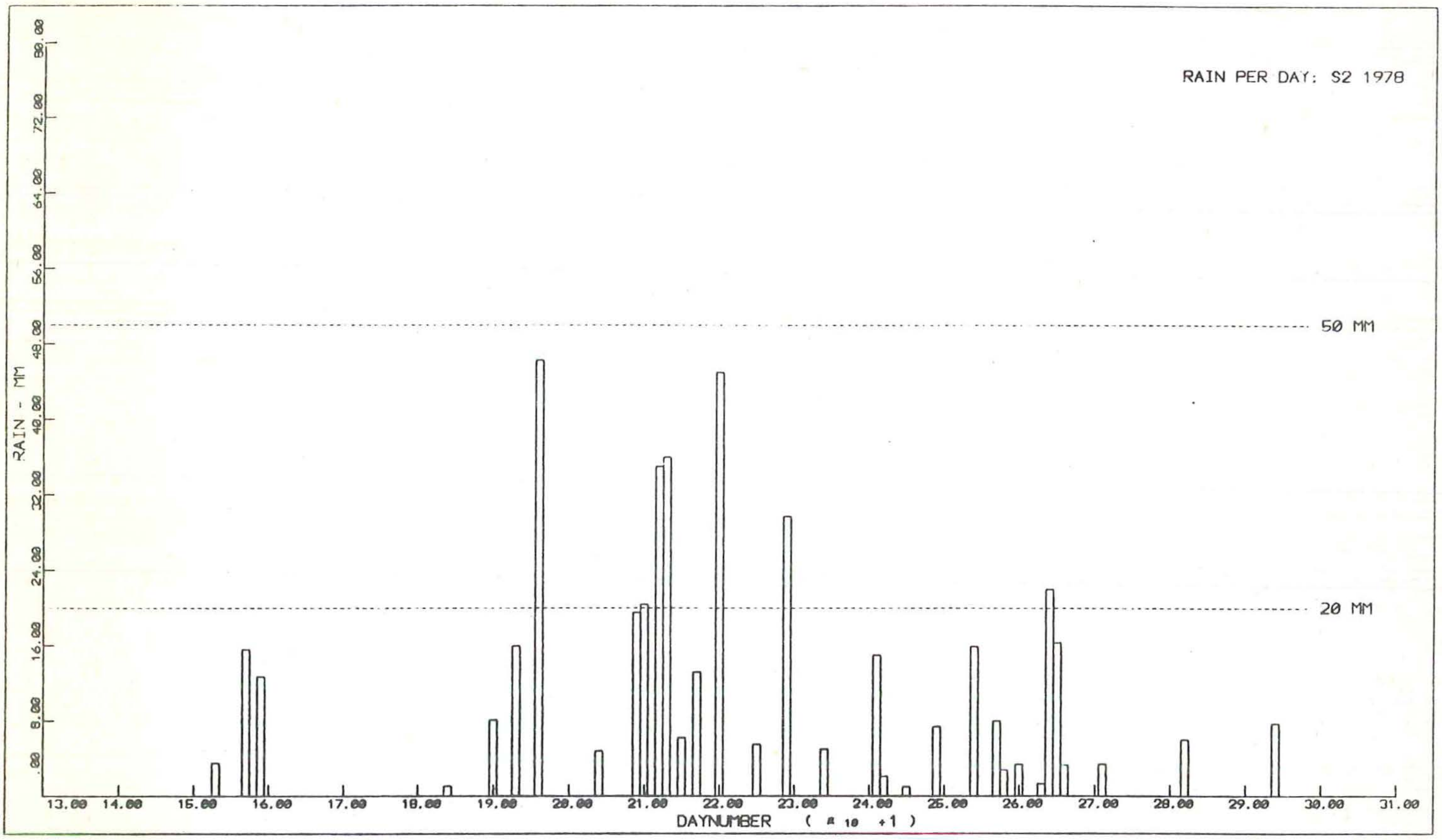

RAIN PER DAY: S2 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2a.

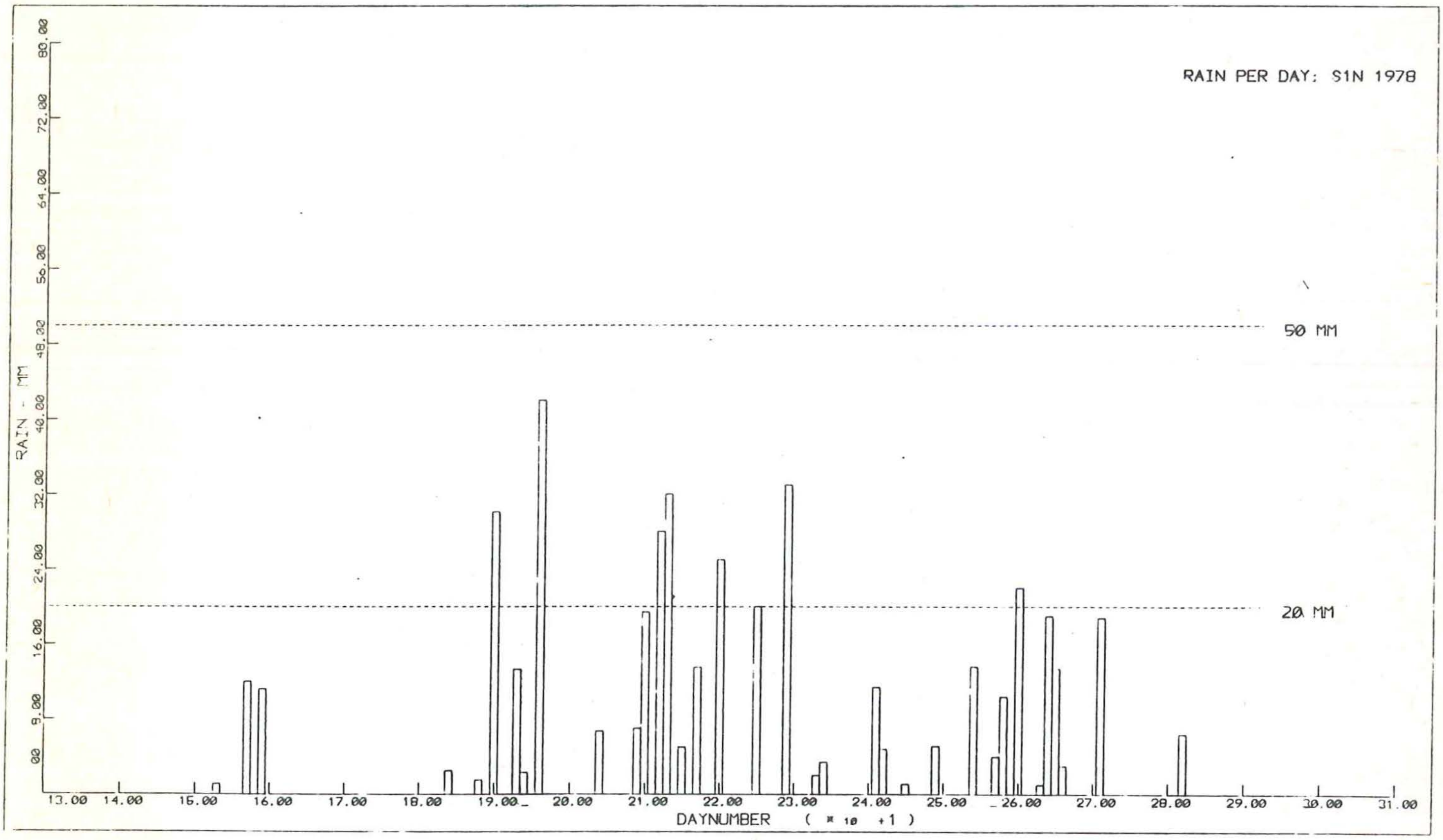

RAIN PER DAY: S1N 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2b.

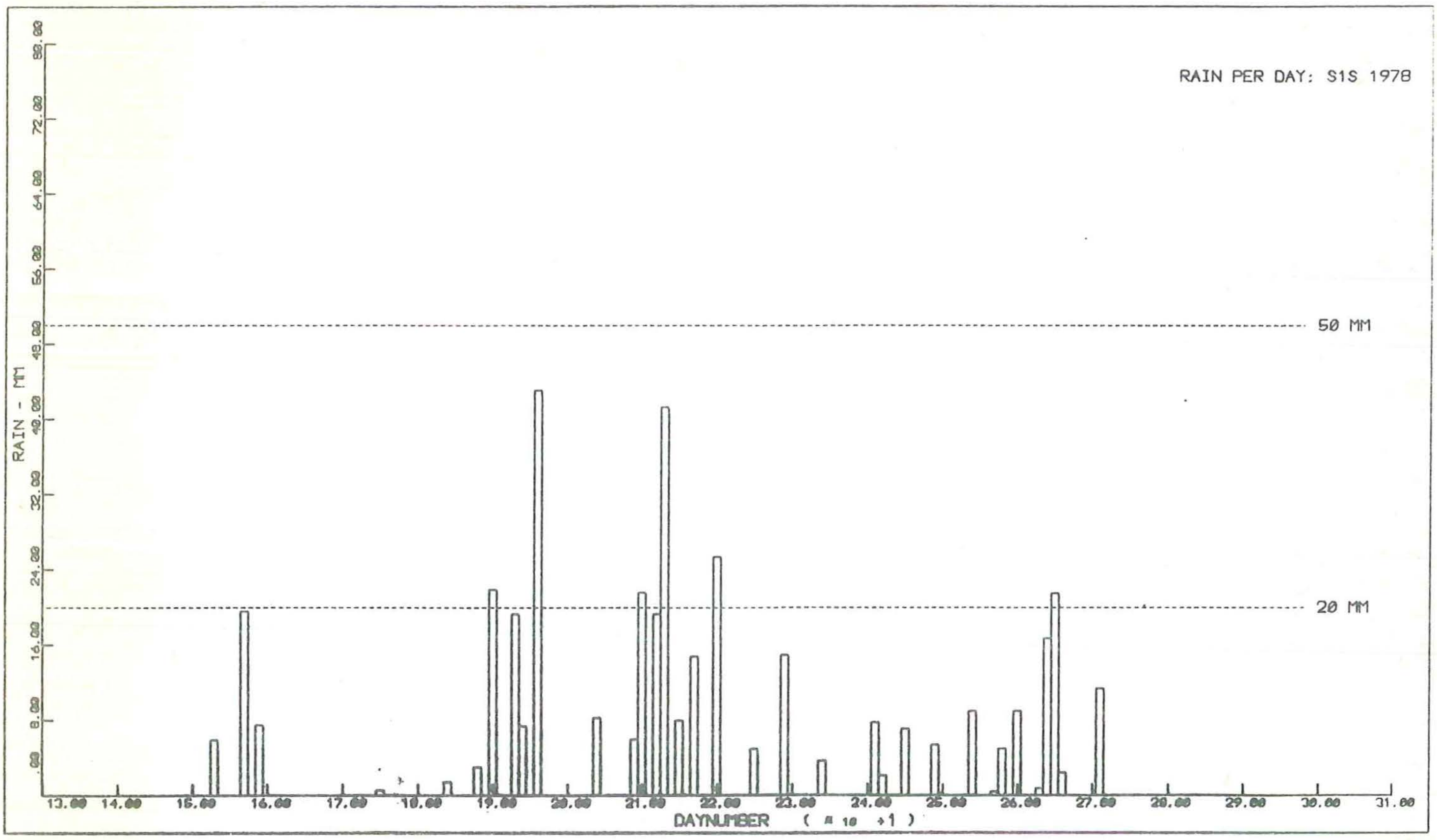

RAIN PER DAY: S1S 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2c.

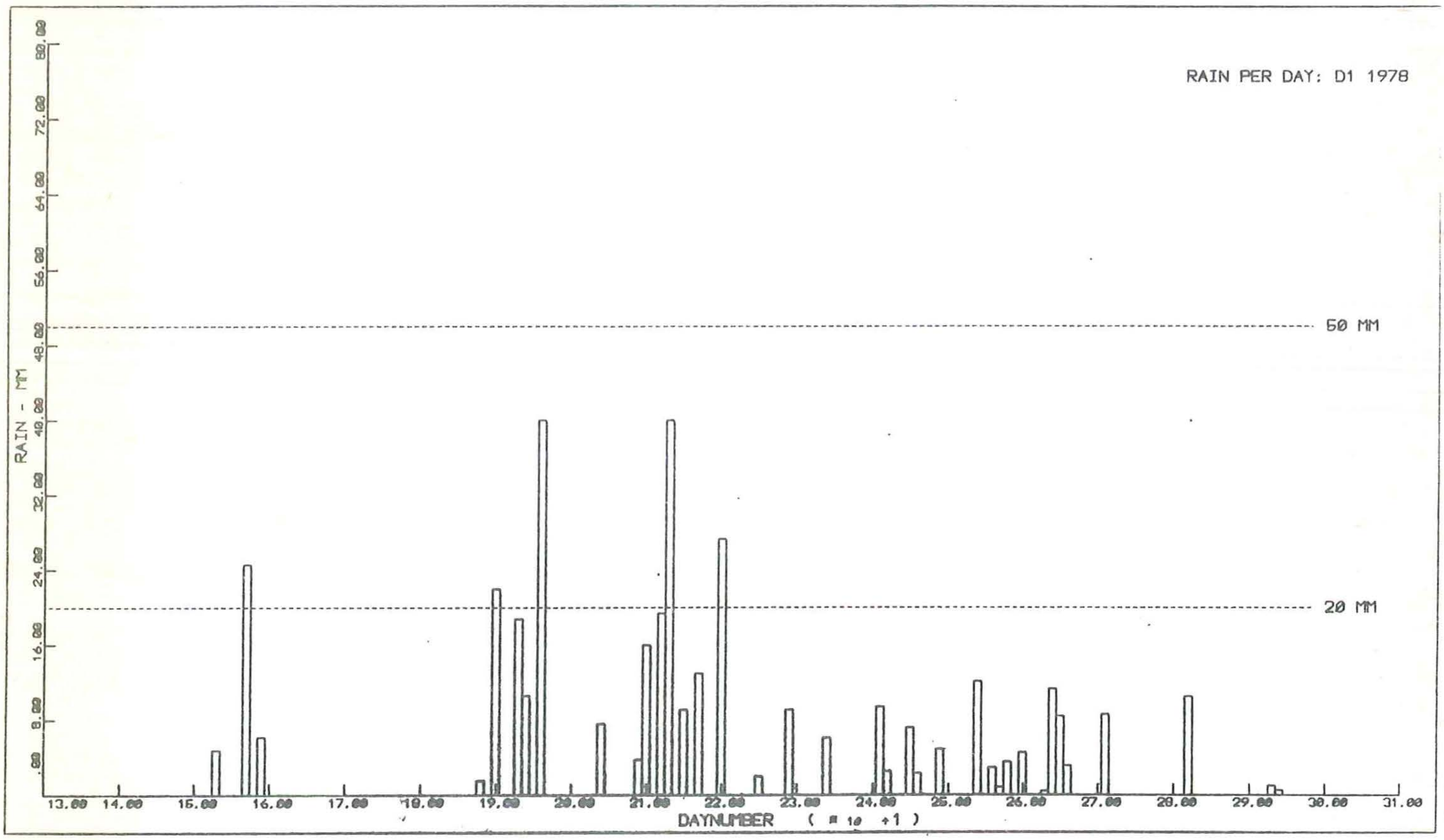

RAIN PER DAY: D1 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2d.

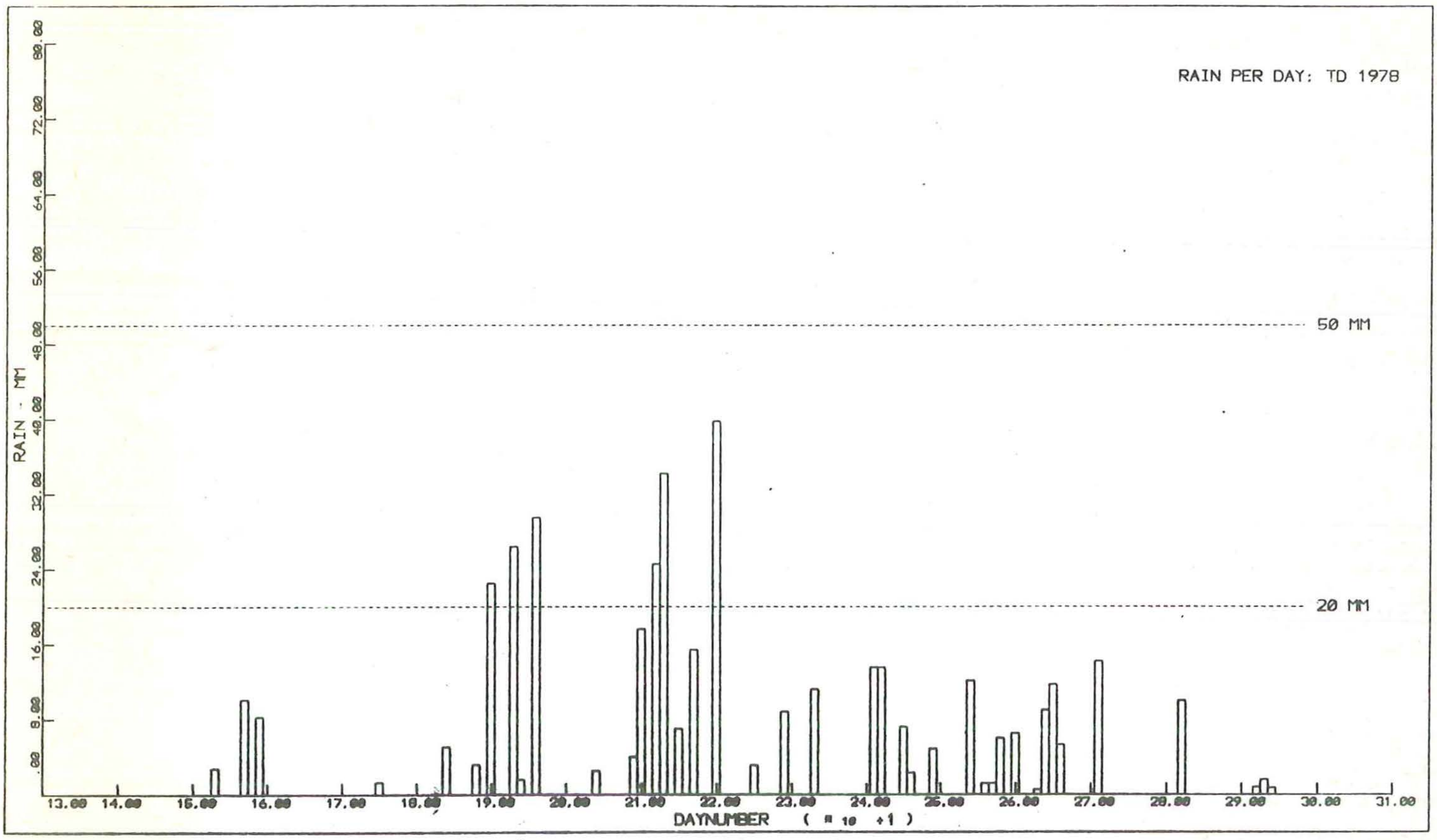

RAIN PER DAY: TD 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2e.

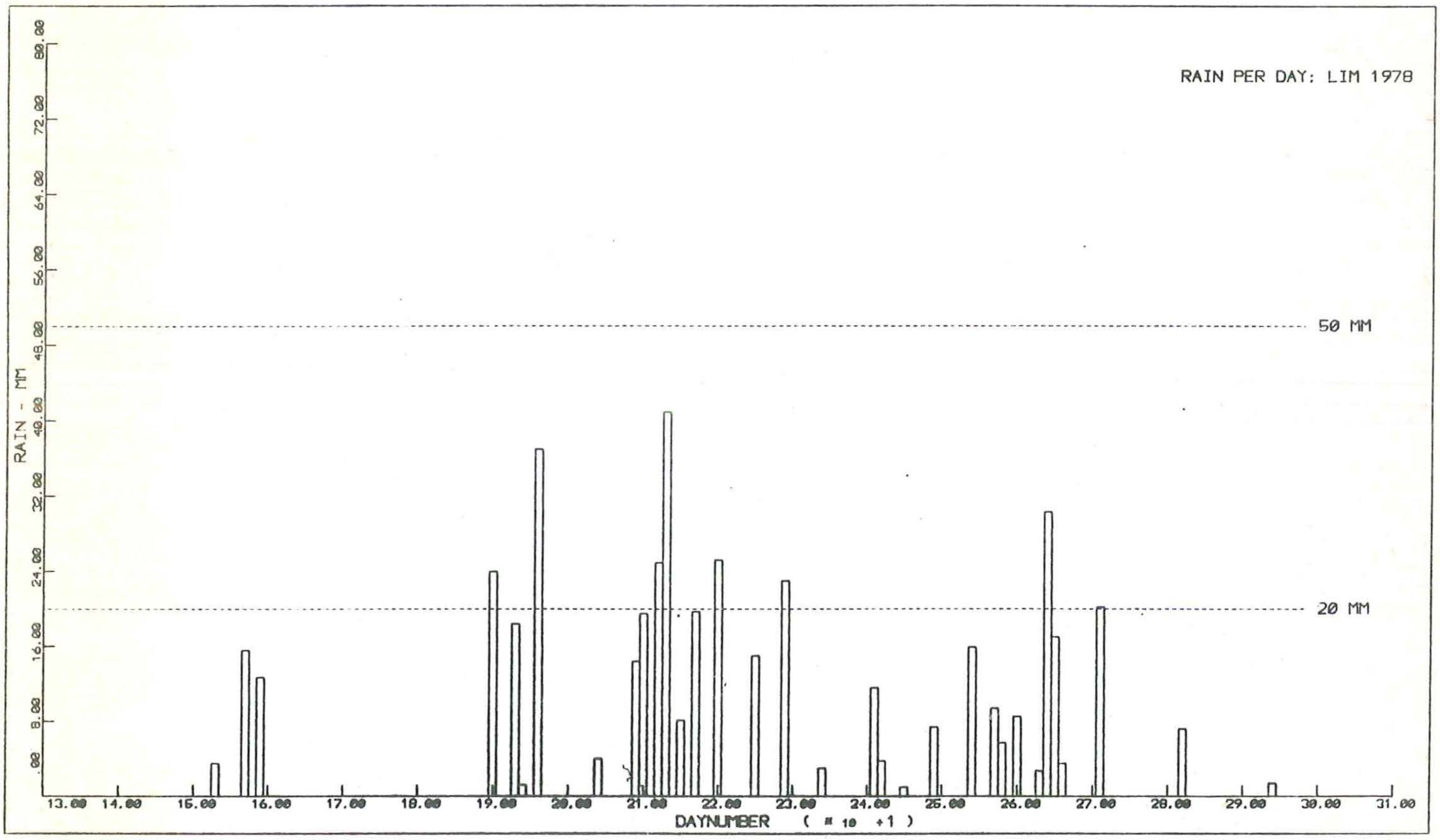
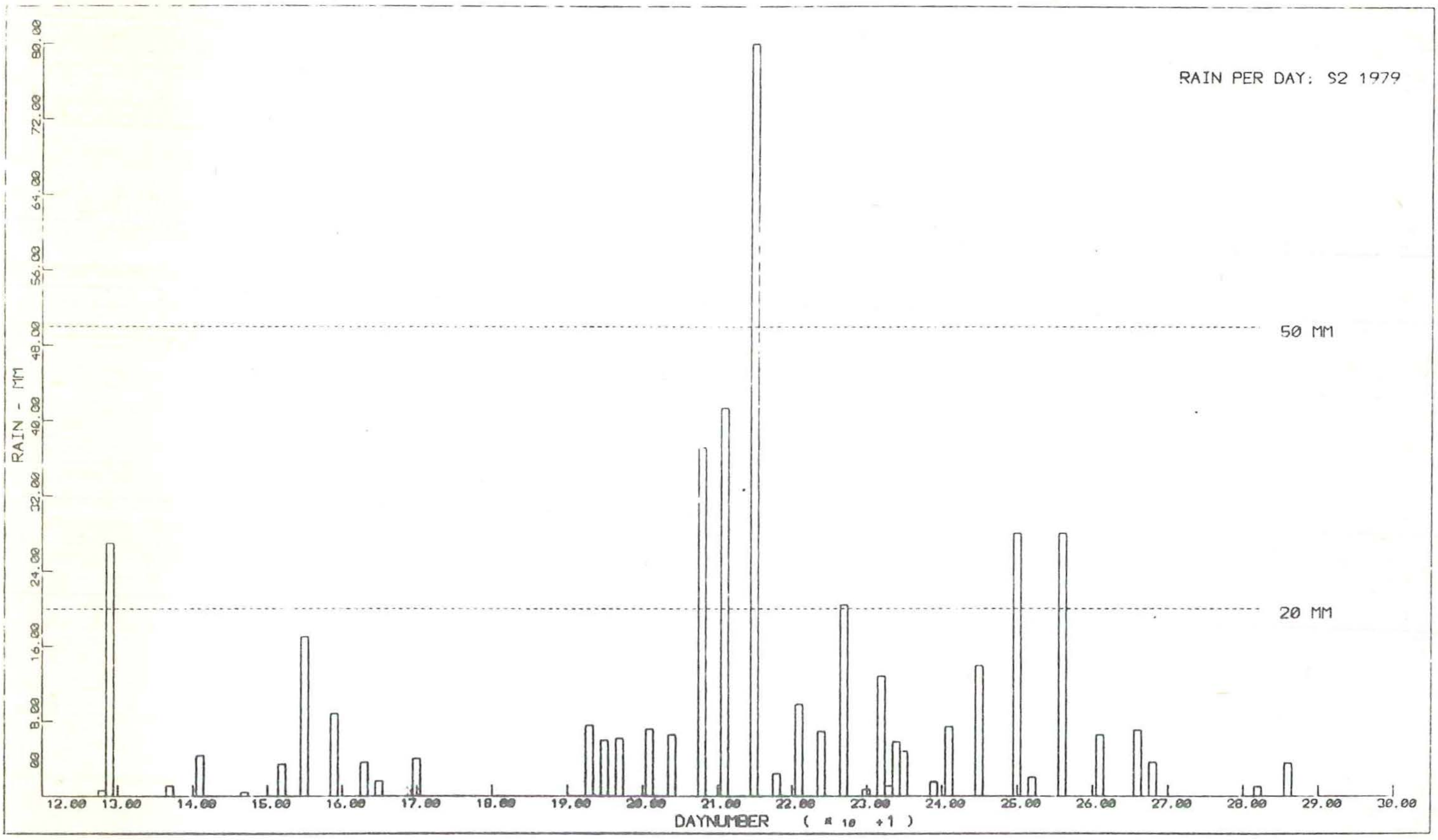
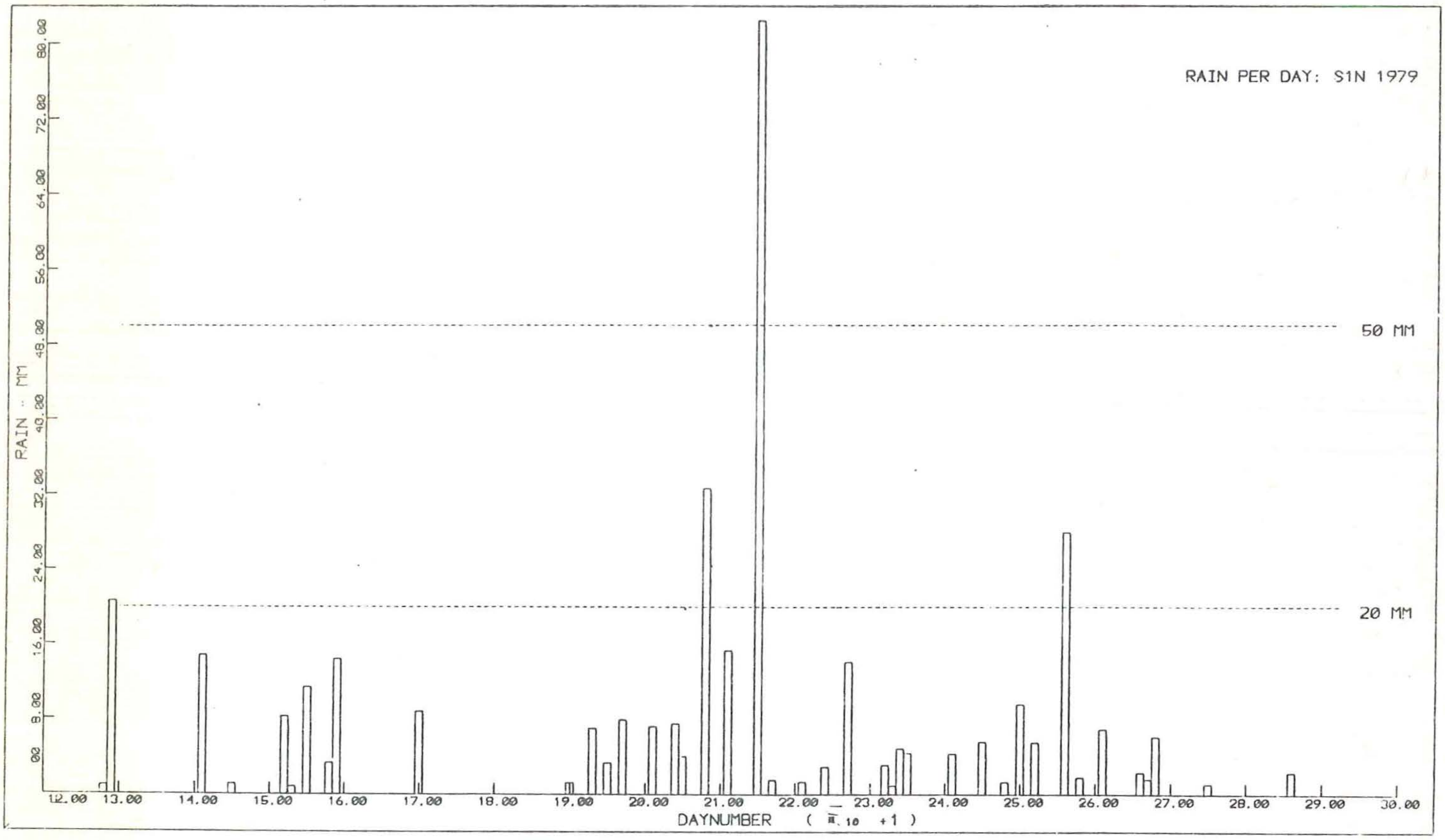

RAIN PER DAY: LIM 1978
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 2f.



RAIN PER DAY: S2 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER

Fig. 3a.



RAIN PER DAY: S1N 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER

Fig. 3b.

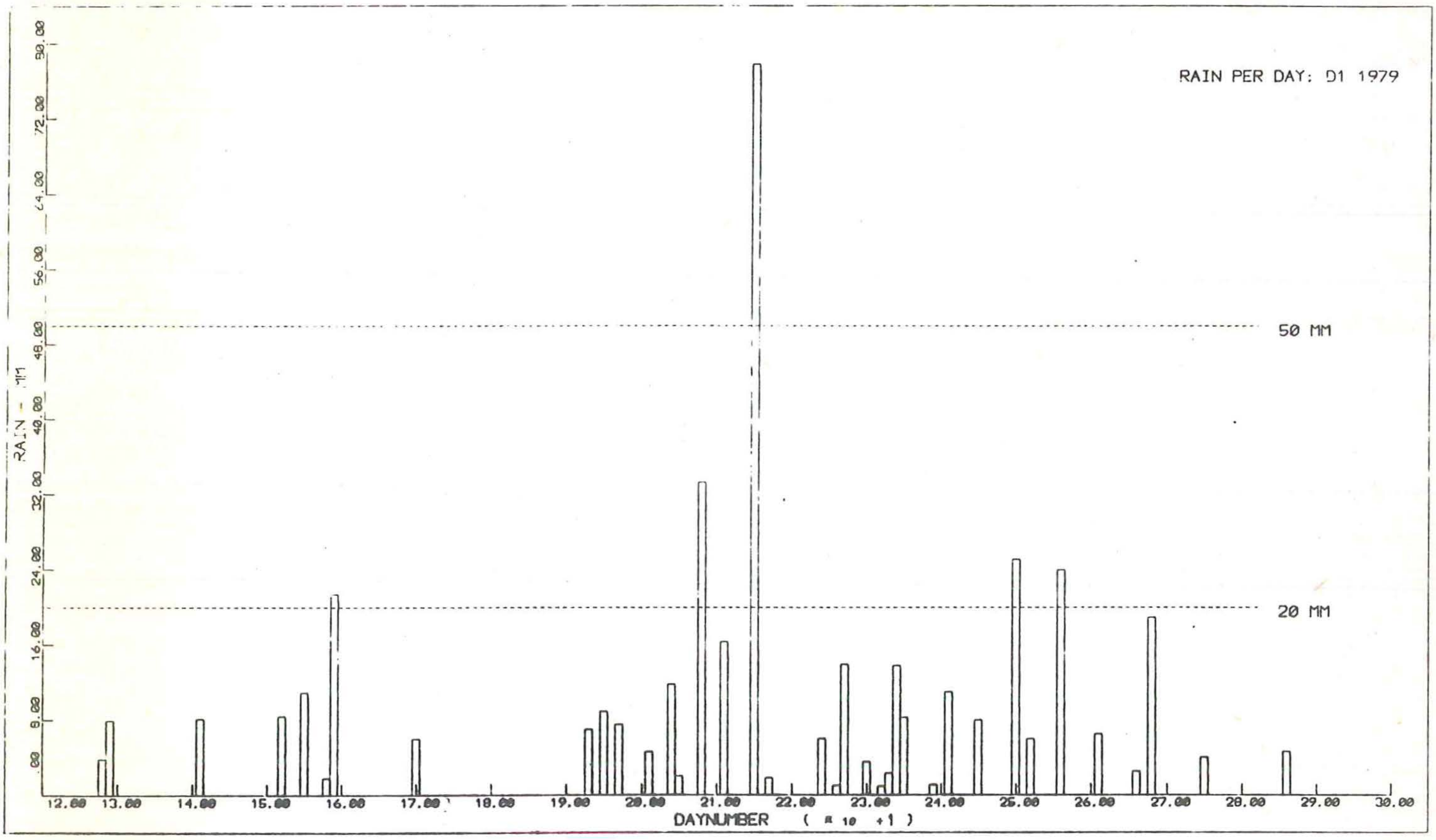

RAIN PER DAY: D1 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 3c.

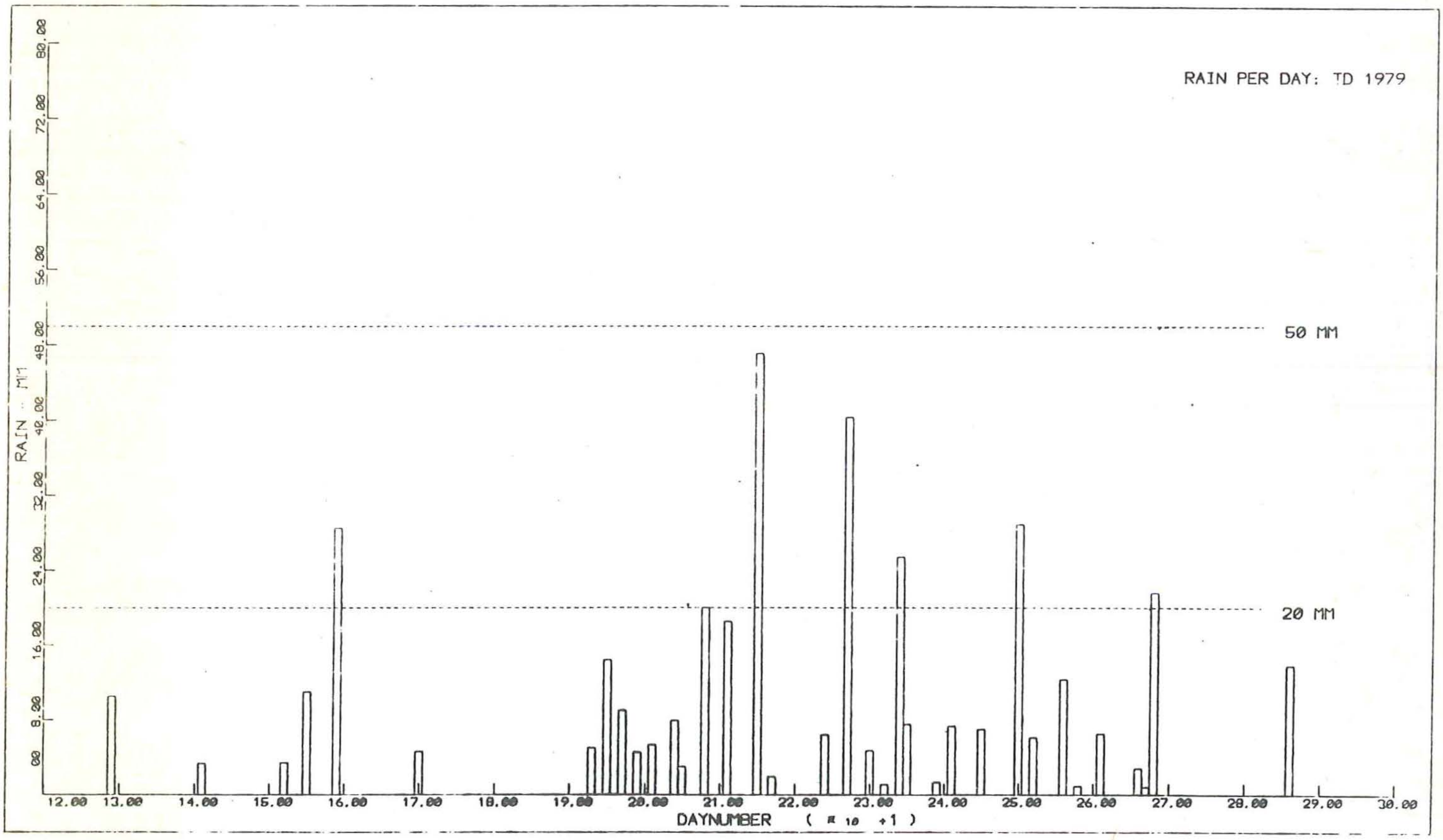

RAIN PER DAY: TD 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 3d.

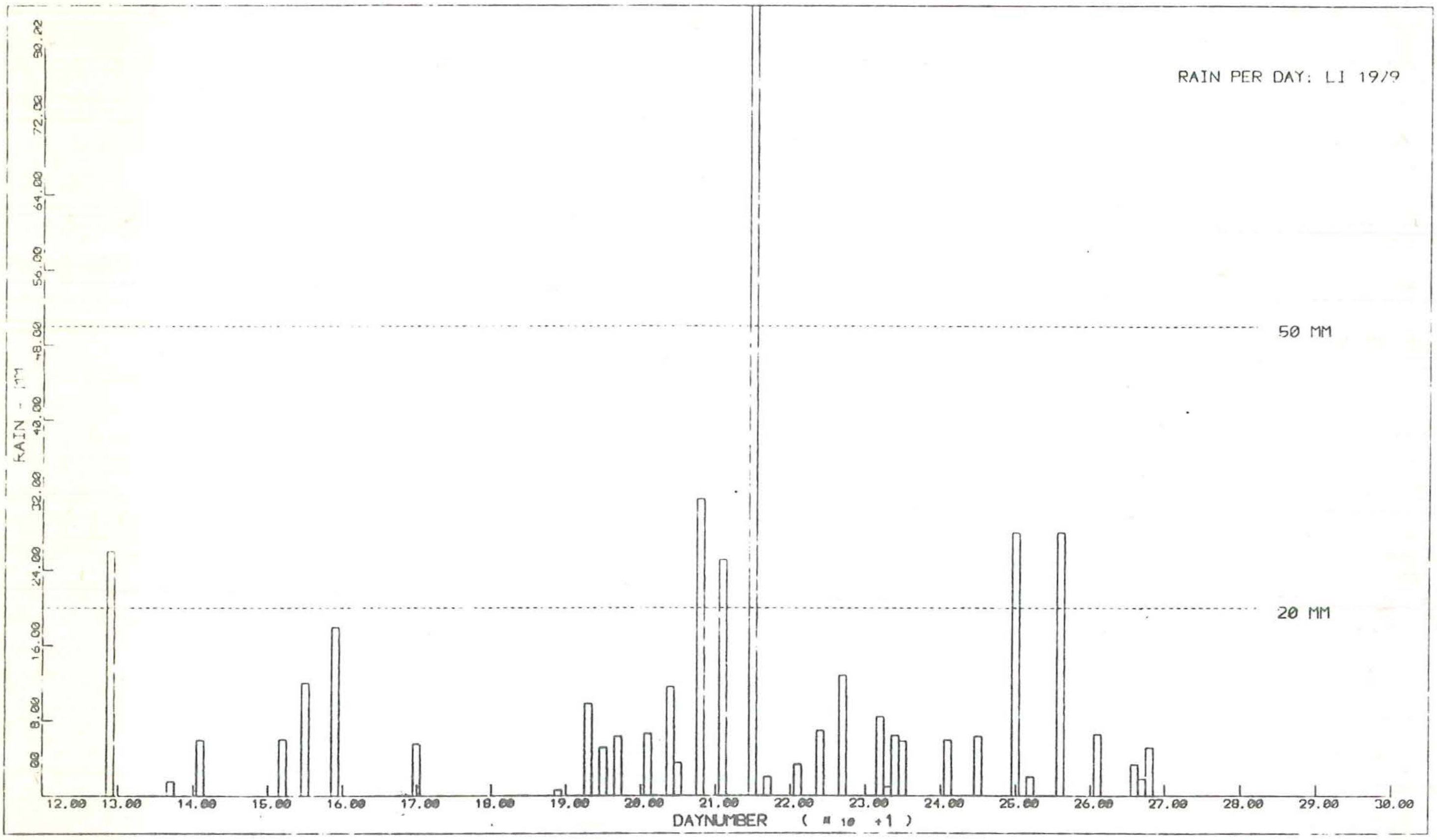

RAIN PER DAY: LI 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00
26.00
27.00
28.00
29.00
30.00

Fig. 3e.

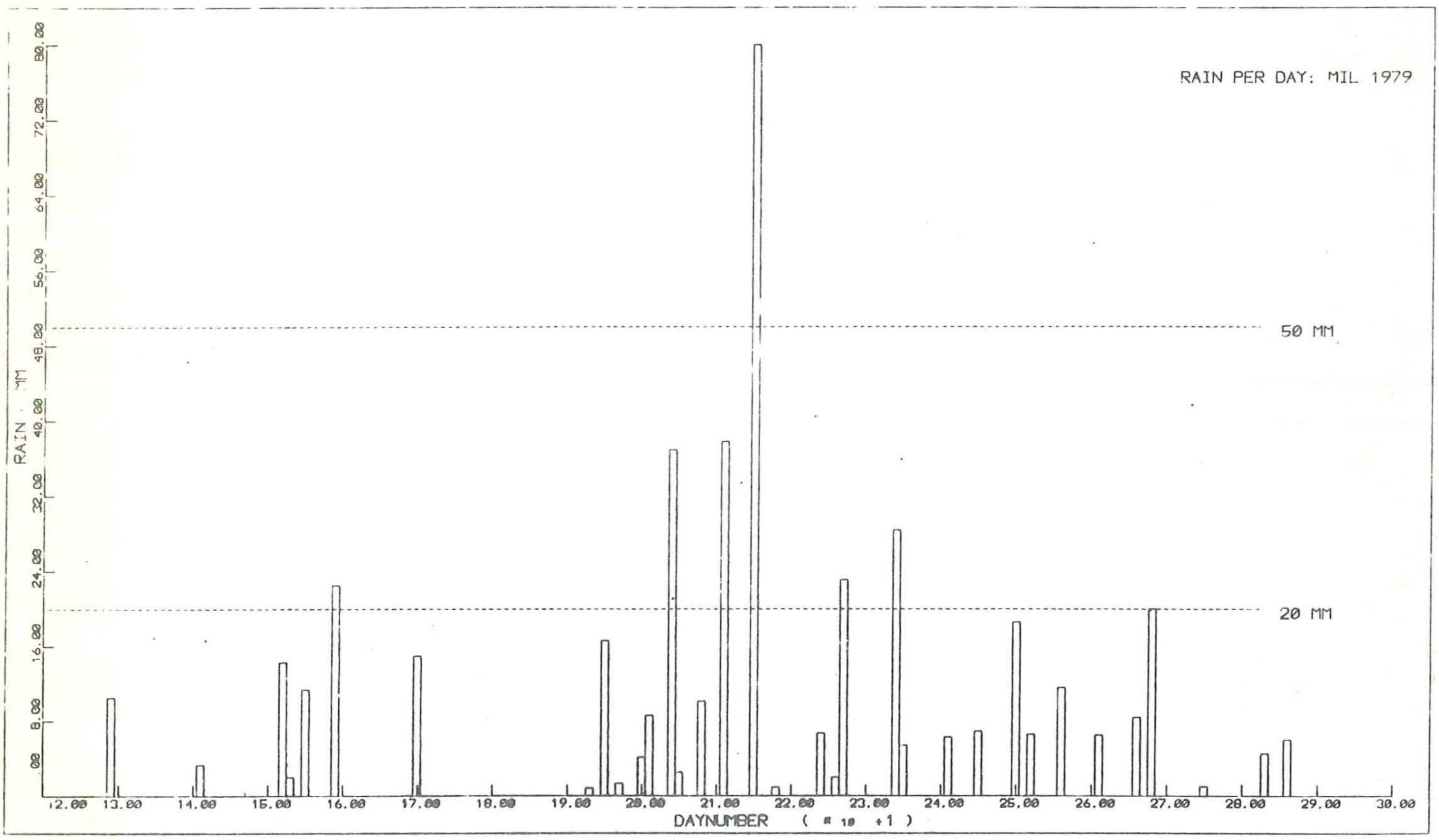
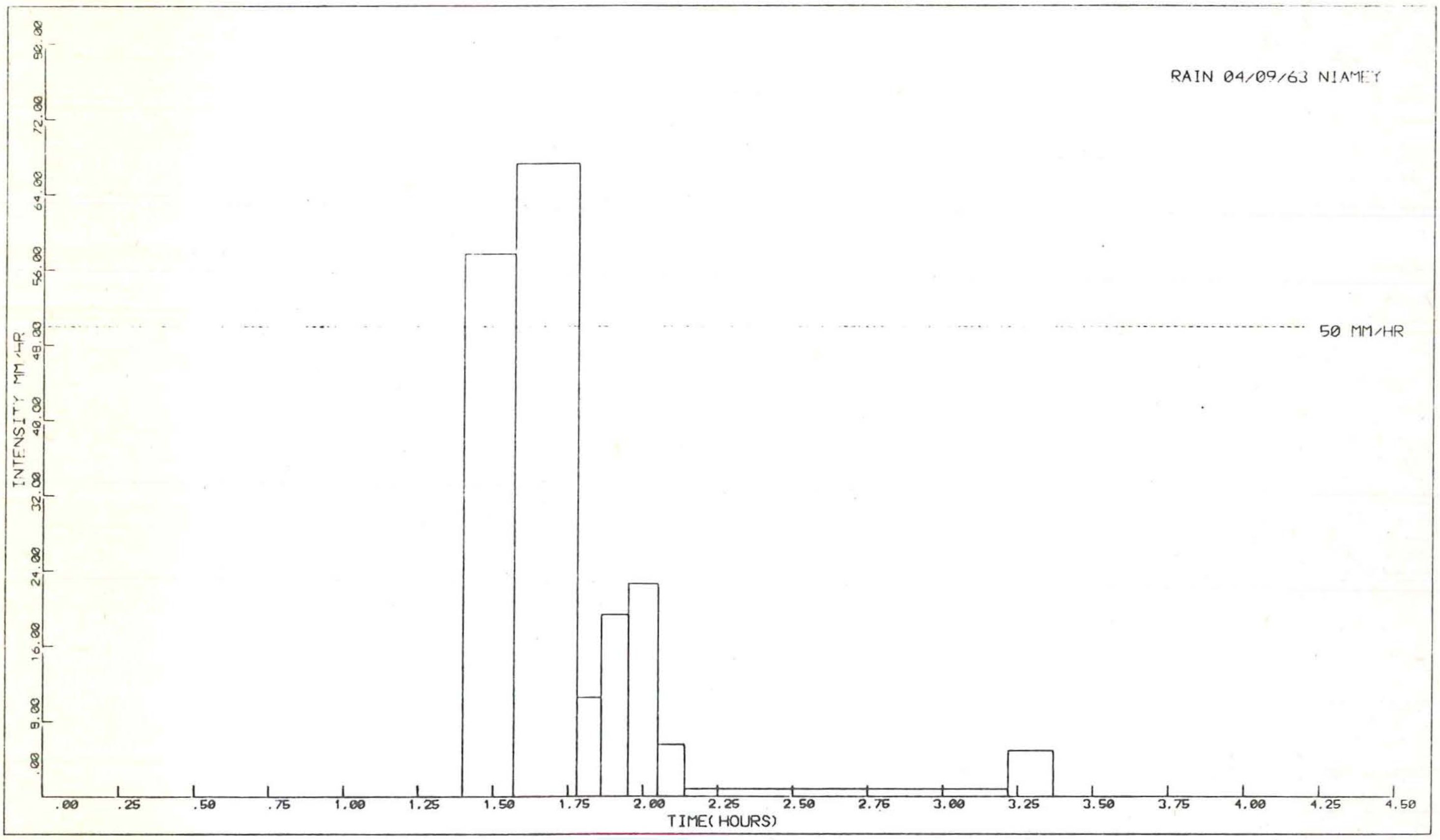

RAIN PER DAY: MIL 1979
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)
8.00
16.00
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00
26.00
27.00
28.00
29.00
30.00

Fig. 3f.

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25      NIAMEY   04 09 63  4,40      1,97      30,70      3,00
    101. 1507.   127. 1655.   170. 1812.   245. 2035.   245. 2021.   250. 2021.   245. 2007.   250. 2007.
    249. 1992.   250. 1992.   250. 1980.   258. 1980.   257. 1966.   262. 1966.   262. 1961.   266. 1960.
    266. 1946.   279. 1946.   279. 1930.   377. 1936.   375. 1925.   448. 1924.   448. 1912.   470. 1912.
    468. 1904.
ITALIAN RECORDER USED
RADIUS=-2256,0000 OFFSET= 1507,0000
      0.  828.    14.  906.    30. 1018.    32. 1025.    34. 1025.    33. 1032.    36. 1032.    37. 1039.
     38. 1039.    39. 1045.    43. 1045.    44. 1052.    46. 1052.    47. 1055.    49. 1055.    50. 1062.
     57. 1062.    58. 1066.   107. 1067.   107. 1073.   143. 1073.   145. 1079.   156. 1079.   155. 1083.
```

STORM NUMBER: 16 PLACE: NIAMEY DATE: 04 09 63

SEGMENT NR.	FROM TIME	TO TIME	INTENSITY MM/H	VOLUME MM	ACUM,VOL MM	DELT
1	4,40	4,57	57,68	9,86	9,86	0,17
2	4,57	4,78	67,29	14,00	23,86	0,21
3	4,78	4,86	10,48	0,88	24,74	0,08
4	4,86	4,95	19,29	1,70	26,43	0,09
5	4,95	5,05	22,58	2,13	28,57	0,09
6	5,05	5,14	5,48	0,50	29,07	0,09
7	5,14	6,22	0,81	0,88	29,95	1,08
8	6,22	6,37	4,94	0,75	30,70	0,15

(THIS RAINSTORM)

FR.INT.	TO INT. MM/H	VOLUME MM
0,00	1,00	0,13
1,00	2,00	0,75
4,00	5,00	0,75
5,00	6,00	0,50
10,00	11,00	0,88
19,00	20,00	1,70
22,00	23,00	2,13
57,00	58,00	9,86
67,00	68,00	14,00

(THIS RAINSTORM)

INTENSITY MM/H	VOLUME GE, MM	PERCENTAGE
0,00	30,70	100,00
1,00	30,57	99,59
4,00	29,82	97,14
5,00	29,07	94,68
10,00	28,57	93,05
19,00	27,69	90,18
22,00	25,99	84,66
57,00	23,86	77,71
67,00	14,00	45,60

Fig. 4.

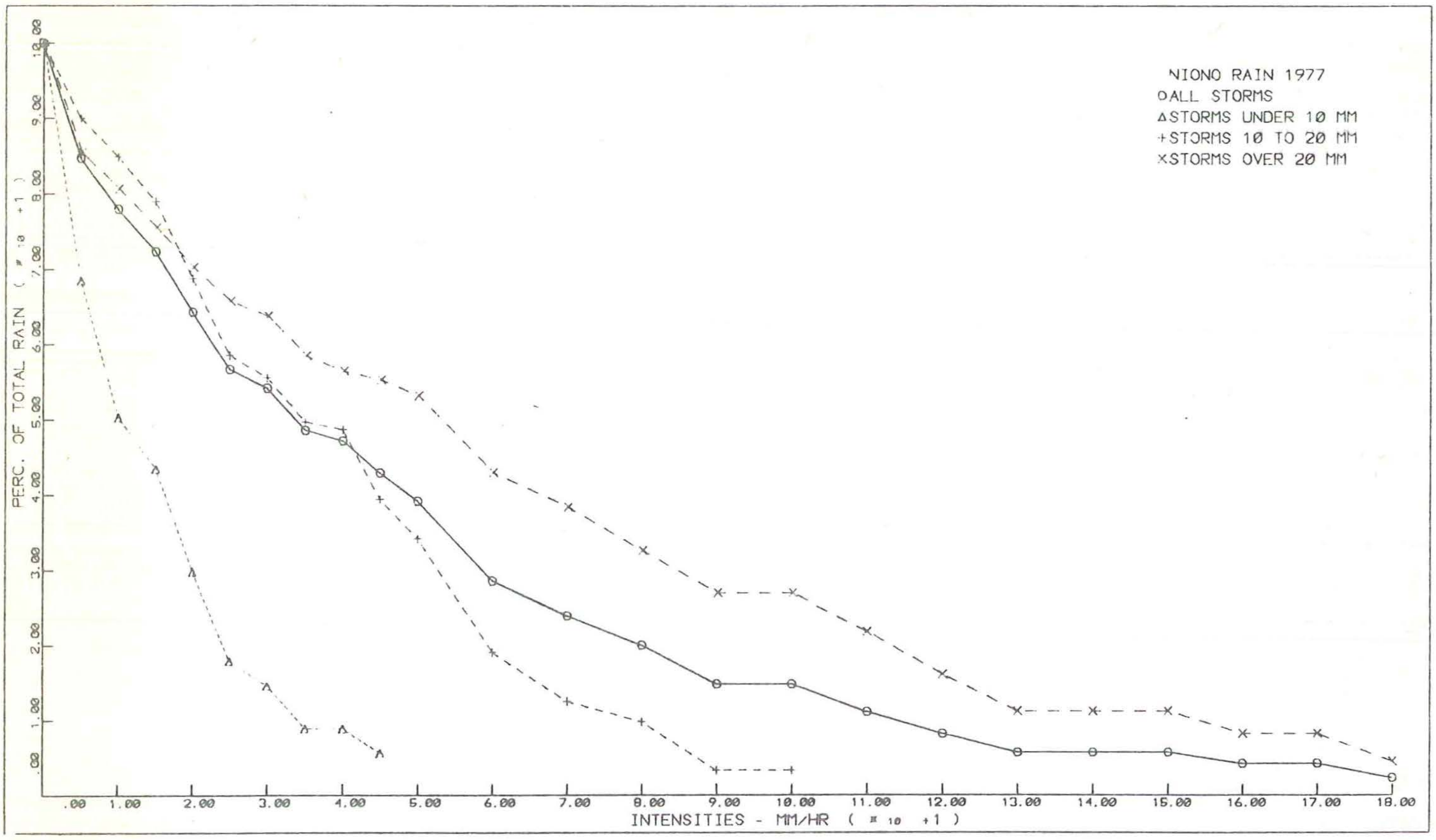

NIONO RAIN 1977
○ALL STORMS
△STORMS UNDER 10 MM
+STORMS 10 TO 20 MM
×STORMS OVER 20 MM
PERC. OF TOTAL RAIN (* 10 +1)
INTENSITIES - MM/HR (* 10 +1)

Fig. 5a.

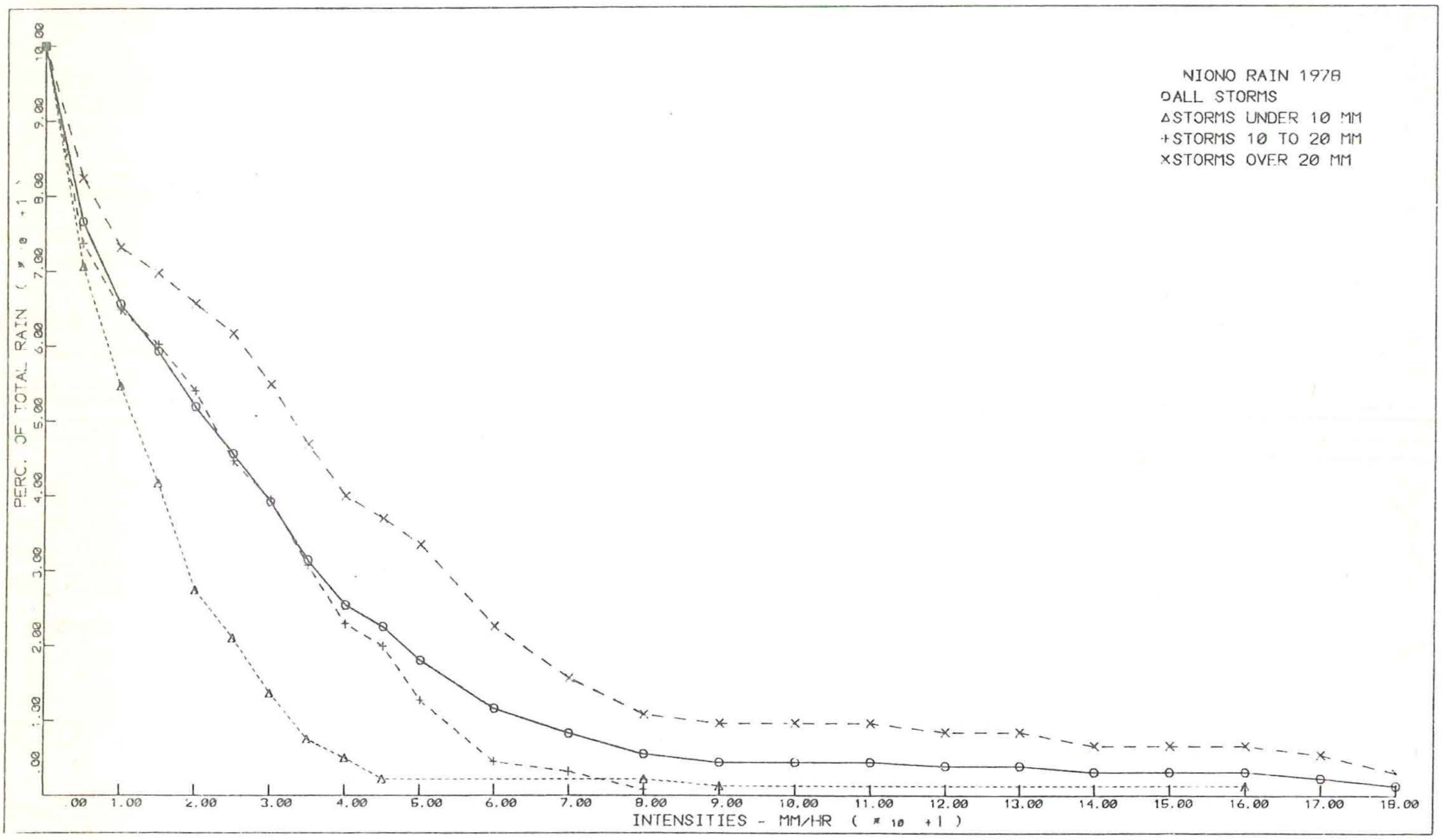

NIONO RAIN 1978
○ALL STORMS
△STORMS UNDER 10 MM
+STORMS 10 TO 20 MM
×STORMS OVER 20 MM
PERC. OF TOTAL RAIN (* 10 +1)
INTENSITIES - MM/HR (* 10 +1)

Fig. 5b.

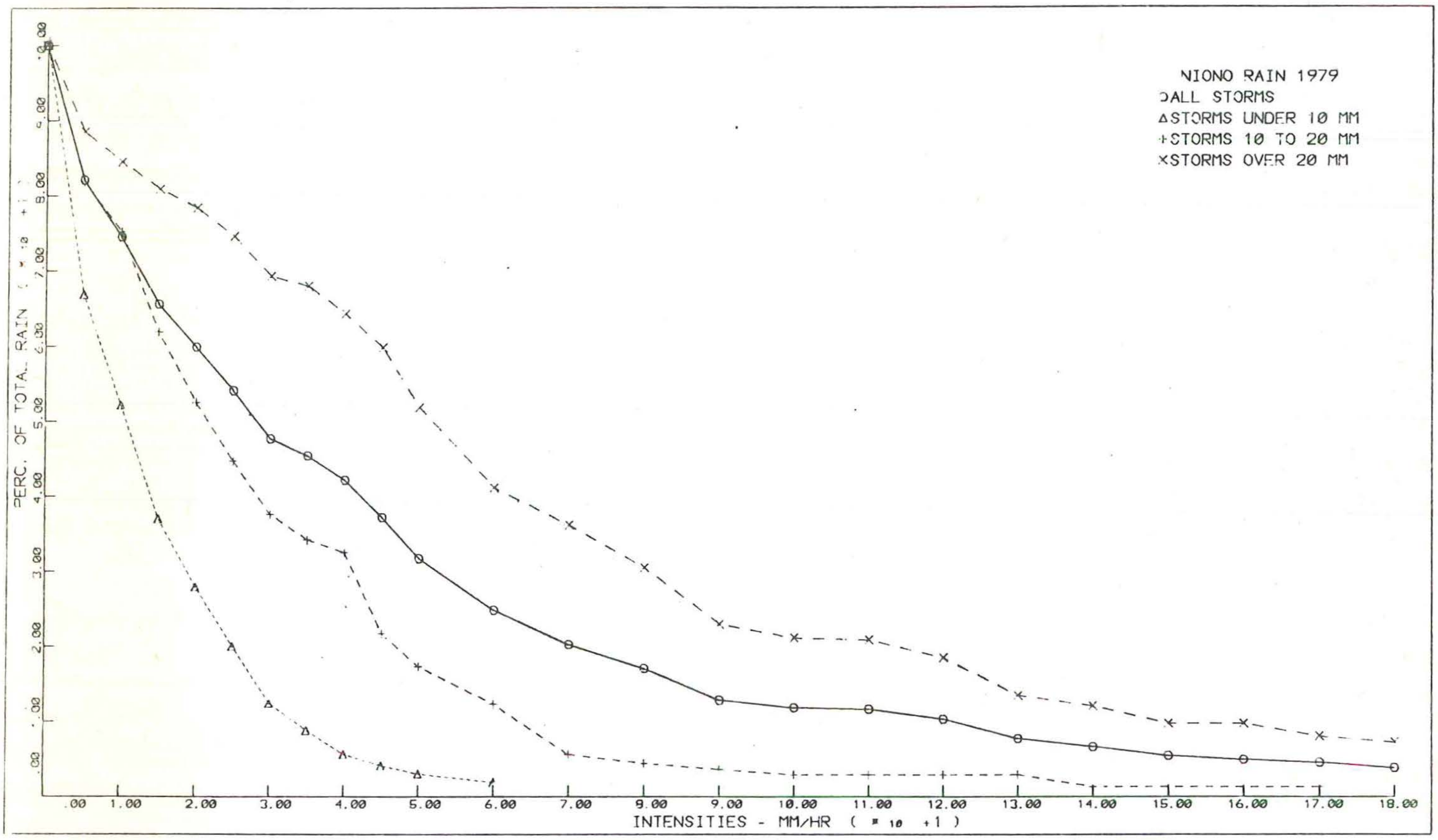

NIONO RAIN 1979
○ALL STORMS
△STORMS UNDER 10 MM
+STORMS 10 TO 20 MM
×STORMS OVER 20 MM
PERC. OF TOTAL RAIN
INTENSITIES - MM/HR

Fig. 5c.

Fig. 6.

5 ICRISAT7 25 06 74 16.80 0.60 11.50 11.00

STORM NUMBER: 3 PLACE: ICRISAT7 DATE: 25 06 74

HIGHEST RAINFALL INTENSITY DURING THIS STORM OVER DIFFERENT TIME LAPSES AND RESULTING EI VALUES

TIME LAPSE	INTENSITY	EI VALUE (E = 301.54 J/M2)
6 MINUTES	26.32 MM/HR	7935.32
12 MINUTES	25.74 MM/HR	7762.53
18 MINUTES	24.98 MM/HR	7532.15
24 MINUTES	24.25 MM/HR	7311.13
30 MINUTES	21.28 MM/HR	6416.50
36 MINUTES	19.30 MM/HR	5820.09
42 MINUTES	: STORM SHORTER THAN THIS PERIOD	
48 MINUTES	: STORM SHORTER THAN THIS PERIOD	
54 MINUTES	: STORM SHORTER THAN THIS PERIOD	
60 MINUTES	: STORM SHORTER THAN THIS PERIOD	

KINETIC ENERGY IS 301.54 JOULES PER SQUARE METER AND 26.2 J/M2.MM
WISCHMEIER"S EI30 INDEX IS 6416.50 JOULES PER SQUARE METER AND 558.0 J/M2.MM
HUDSON"S KE.GT.25 INDEX IS 114.16 JOULES PER SQUARE METER AND 9.9 J/M2.MM
LAL"S AIM INDEX IS 253.21 SQUARE MM PER HOUR AND 22.0 MM2/HR.MM

CUMULATIVE VALUES:
CUM. RAIN = 35.1 MM, CUM. KIN. EN.= 763.1 J/M2, CUM. WISCH= 10200.8 J/M2, CUM.HUDS= 207.5 J/M2, CUM. LAL= 469.4 MM2/HR
THESE VALUES PER MM RAIN: 21.7 J/M2.MM 290.6 J/M2.MM 5.9 J/M2.MM 13.4 MM2/HR.MM

22 ICRISAT7 26 06 74 23.70 4.55 63.80 1.00

STORM NUMBER: 4 PLACE: ICRISAT7 DATE: 26 06 74

HIGHEST RAINFALL INTENSITY DURING THIS STORM OVER DIFFERENT TIME LAPSES AND RESULTING EI VALUES

TIME LAPSE	INTENSITY	EI VALUE (E = 1889.34 J/M2)
6 MINUTES	108.54 MM/HR	205066.66
12 MINUTES	103.12 MM/HR	194822.29
18 MINUTES	95.19 MM/HR	179838.37
24 MINUTES	88.15 MM/HR	166544.39
30 MINUTES	82.86 MM/HR	156544.92
36 MINUTES	76.68 MM/HR	144882.76
42 MINUTES	70.13 MM/HR	132493.87
48 MINUTES	64.65 MM/HR	122139.58
54 MINUTES	60.02 MM/HR	113395.01
60 MINUTES	55.00 MM/HR	103910.88

KINETIC ENERGY IS 1889.34 JOULES PER SQUARE METER AND 29.6 J/M2.MM
WISCHMEIER"S EI30 INDEX IS 156544.92 JOULES PER SQUARE METER AND 2453.7 J/M2.MM
HUDSON"S KE.GT.25 INDEX IS 1693.22 JOULES PER SQUARE METER AND 26.5 J/M2.MM
LAL"S AIM INDEX IS 4125.78 SQUARE MM PER HOUR AND 64.7 MM2/HR.MM

CUMULATIVE VALUES:
CUM. RAIN = 98.9 MM, CUM. KIN. EN.= 2652.5 J/M2, CUM. WISCH=166745.8 J/M2, CUM.HUDS= 1900.7 J/M2, CUM. LAL= 4595.2 MM2/HR
THESE VALUES PER MM RAIN: 26.8 J/M2.MM 1686.0 J/M2.MM 19.2 J/M2.MM 46.5 MM2/HR.MM

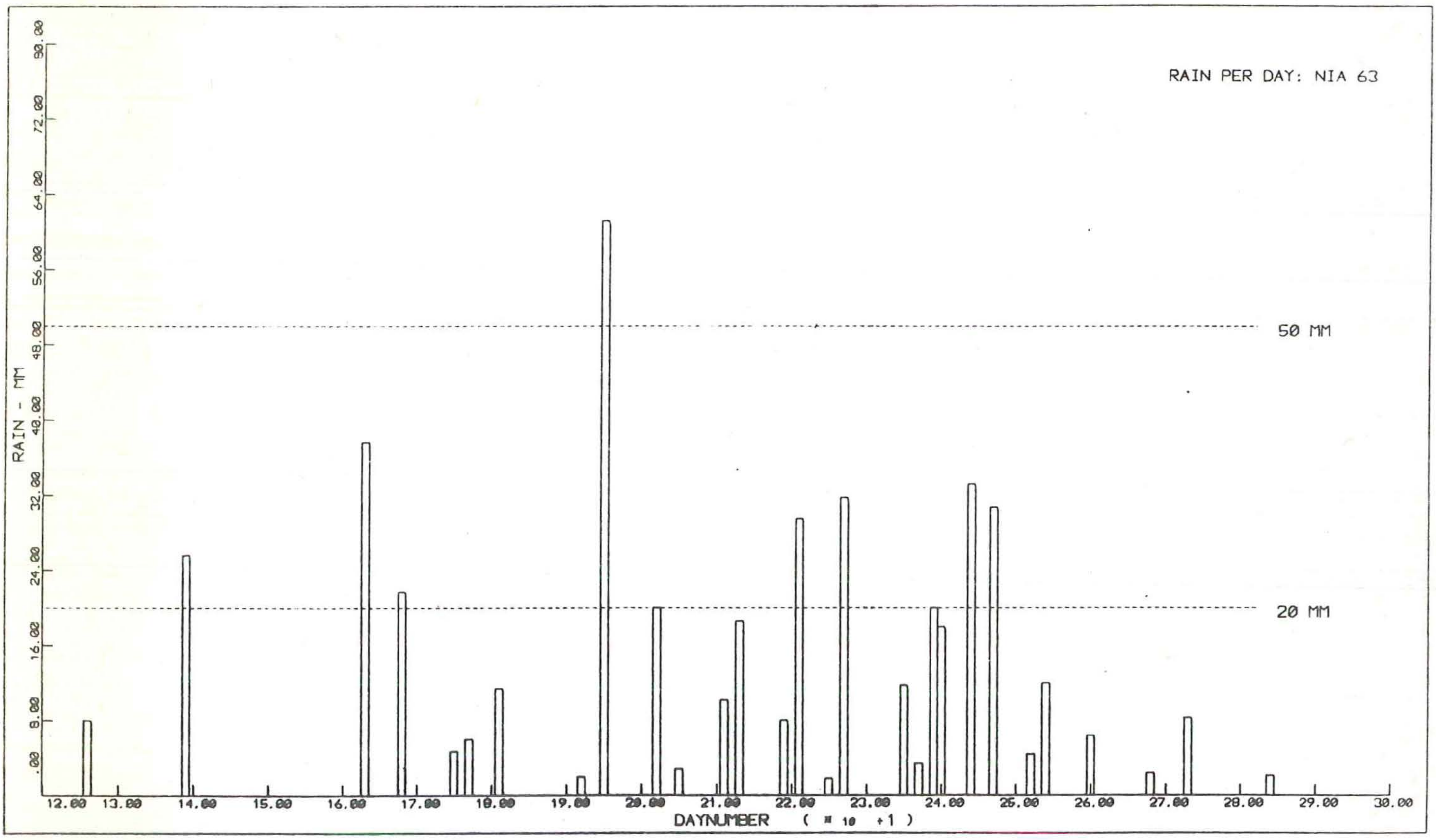

RAIN PER DAY: NIA 63
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 7a.

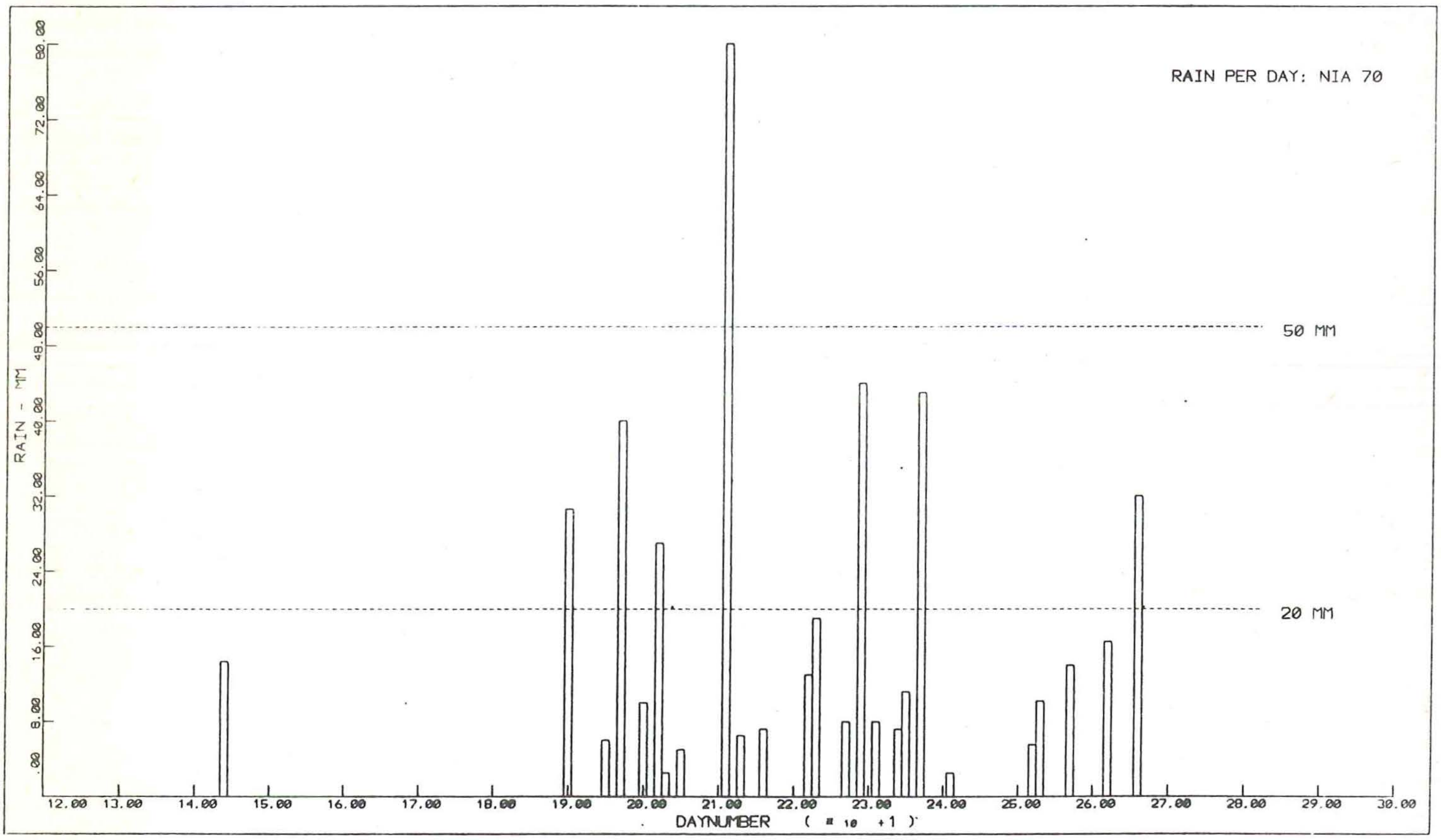

RAIN PER DAY: NIA 70
50 MM
20 MM
RAIN - MM
DAYNUMBER (* 10 +1)

Fig. 7b.

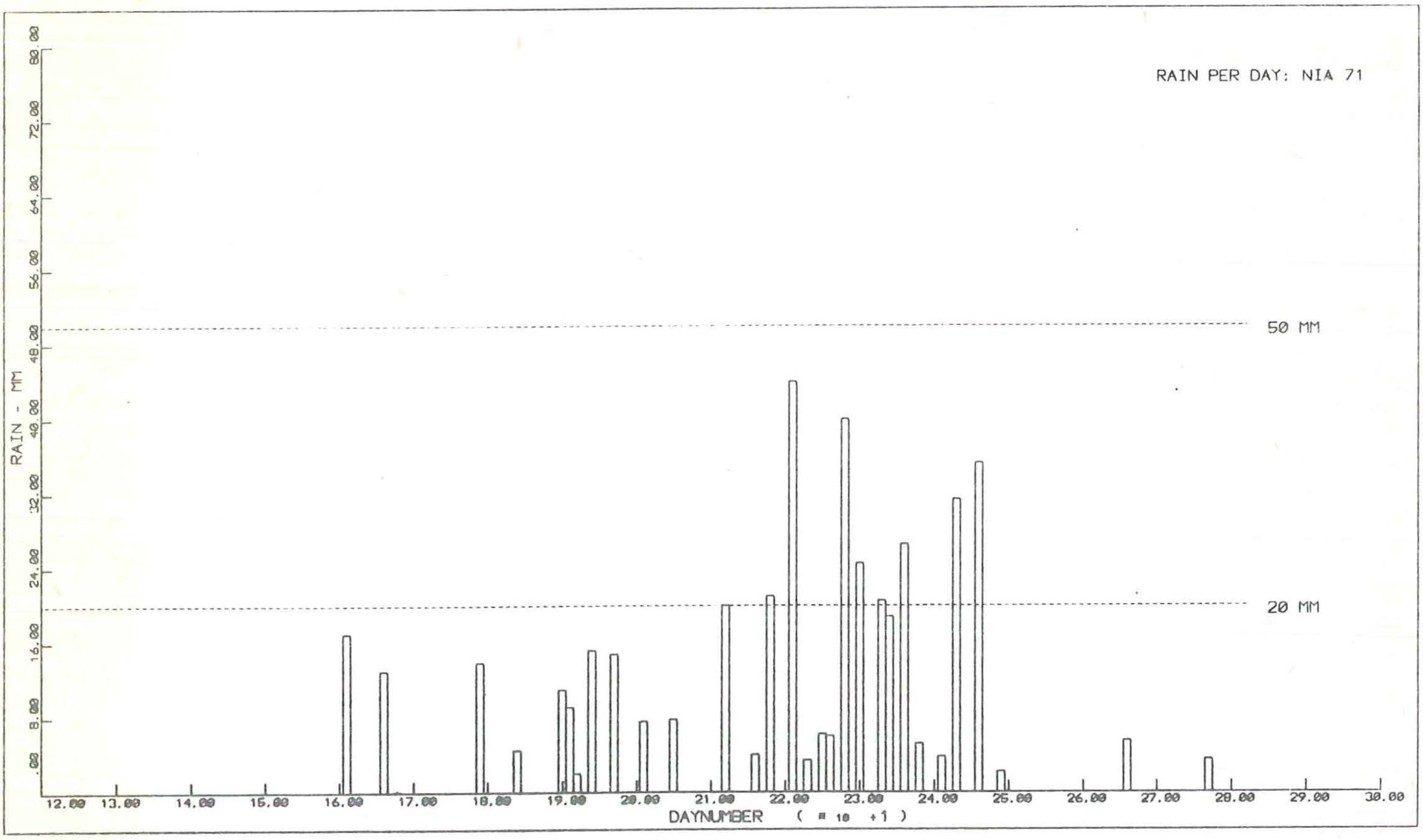

RAIN PER DAY: NIA 71
50 MM
20 MM
RAIN - MM
.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00
26.00
27.00
28.00
29.00
30.00
DAYNUMBER (* 10 +1)

Fig. 7c.

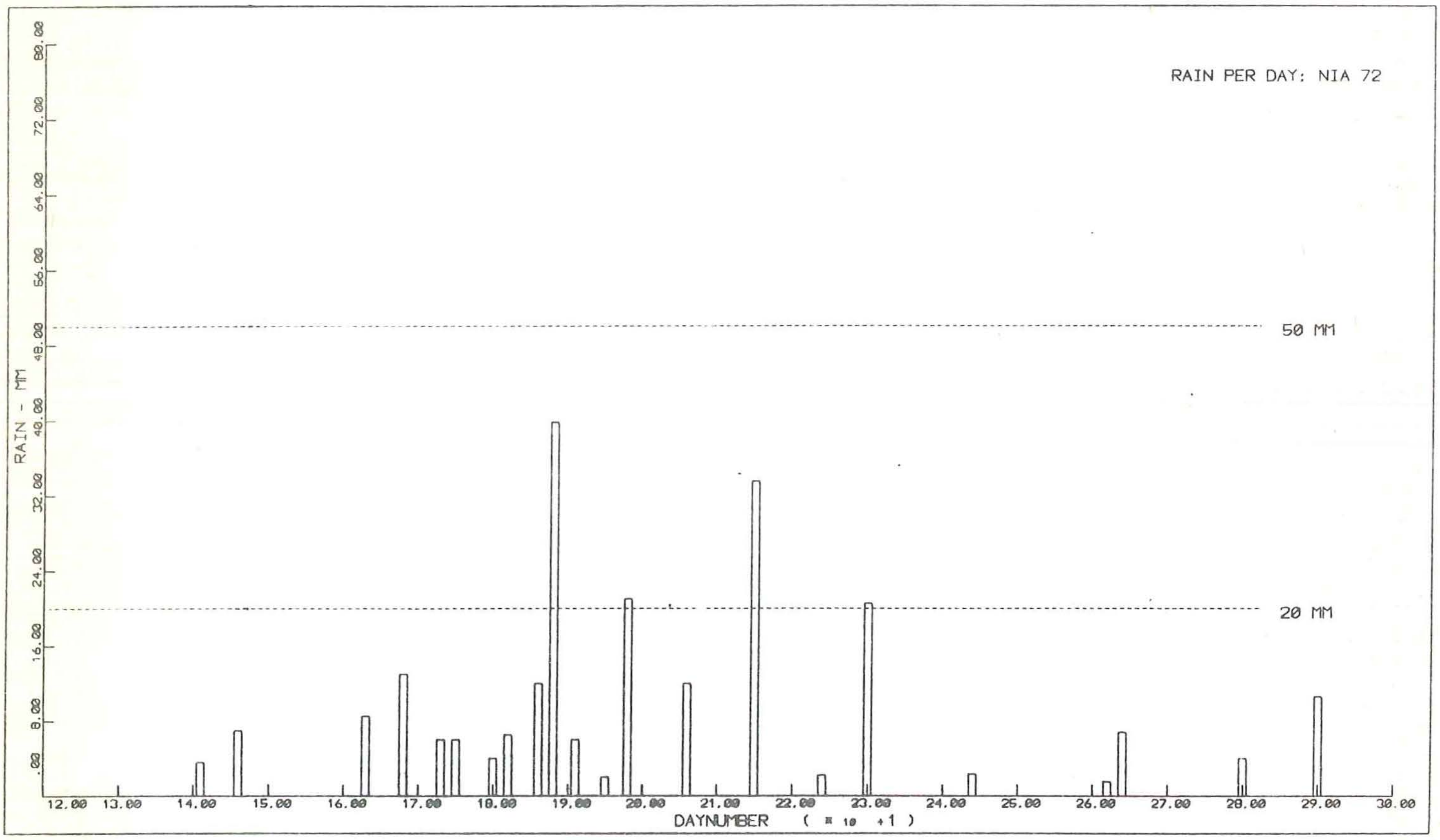

RAIN PER DAY: NIA 72
50 MM
20 MM
RAIN - MM
.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00
26.00
27.00
28.00
29.00
30.00
DAYNUMBER (* 10 +1)

Fig. 7d.

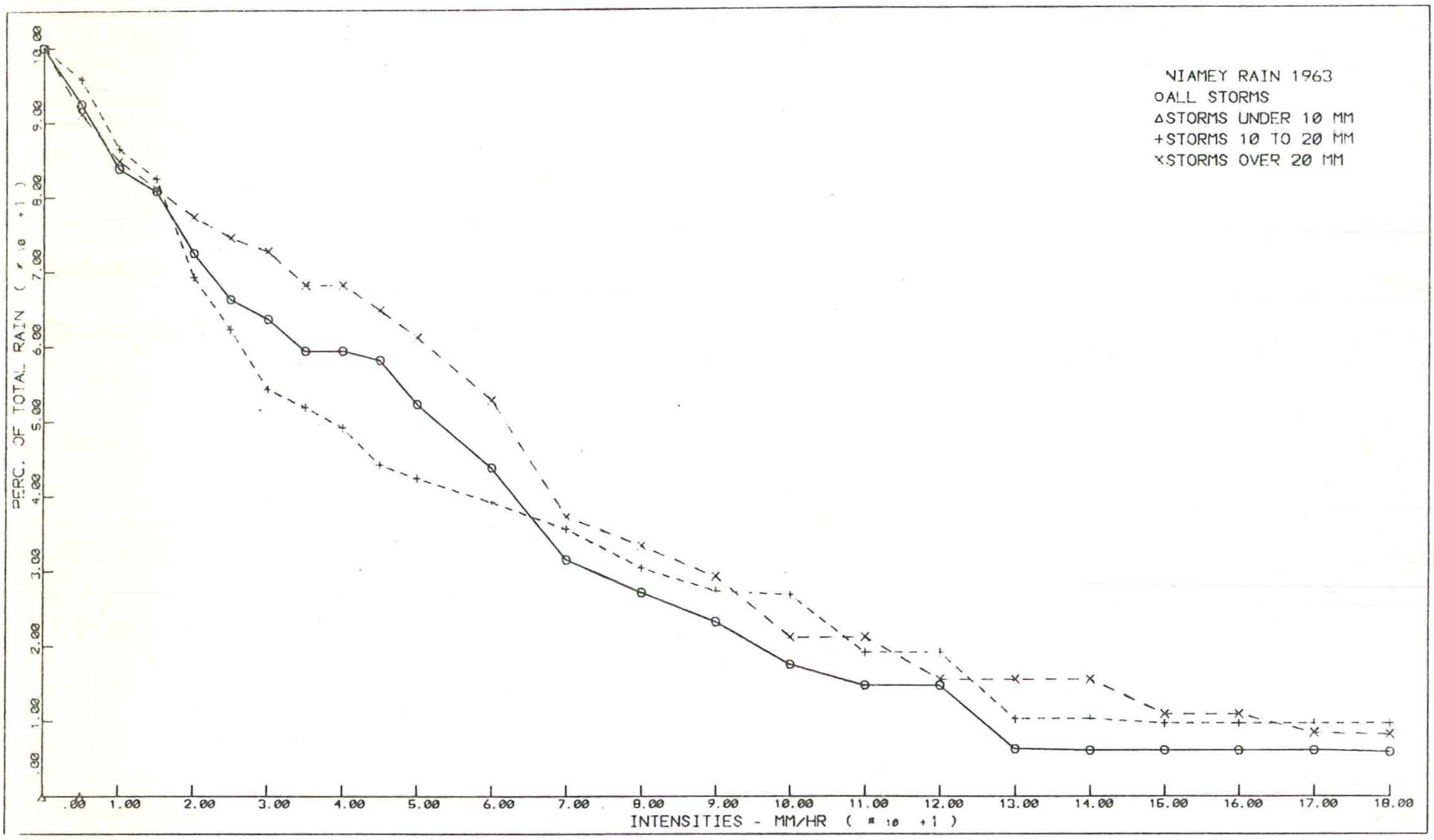

NIAMEY RAIN 1963
○ALL STORMS
△STORMS UNDER 10 MM
+STORMS 10 TO 20 MM
×STORMS OVER 20 MM
PERC. OF TOTAL RAIN (* 10 +1)
INTENSITIES - MM/HR (* 10 +1)

Fig. 8a.

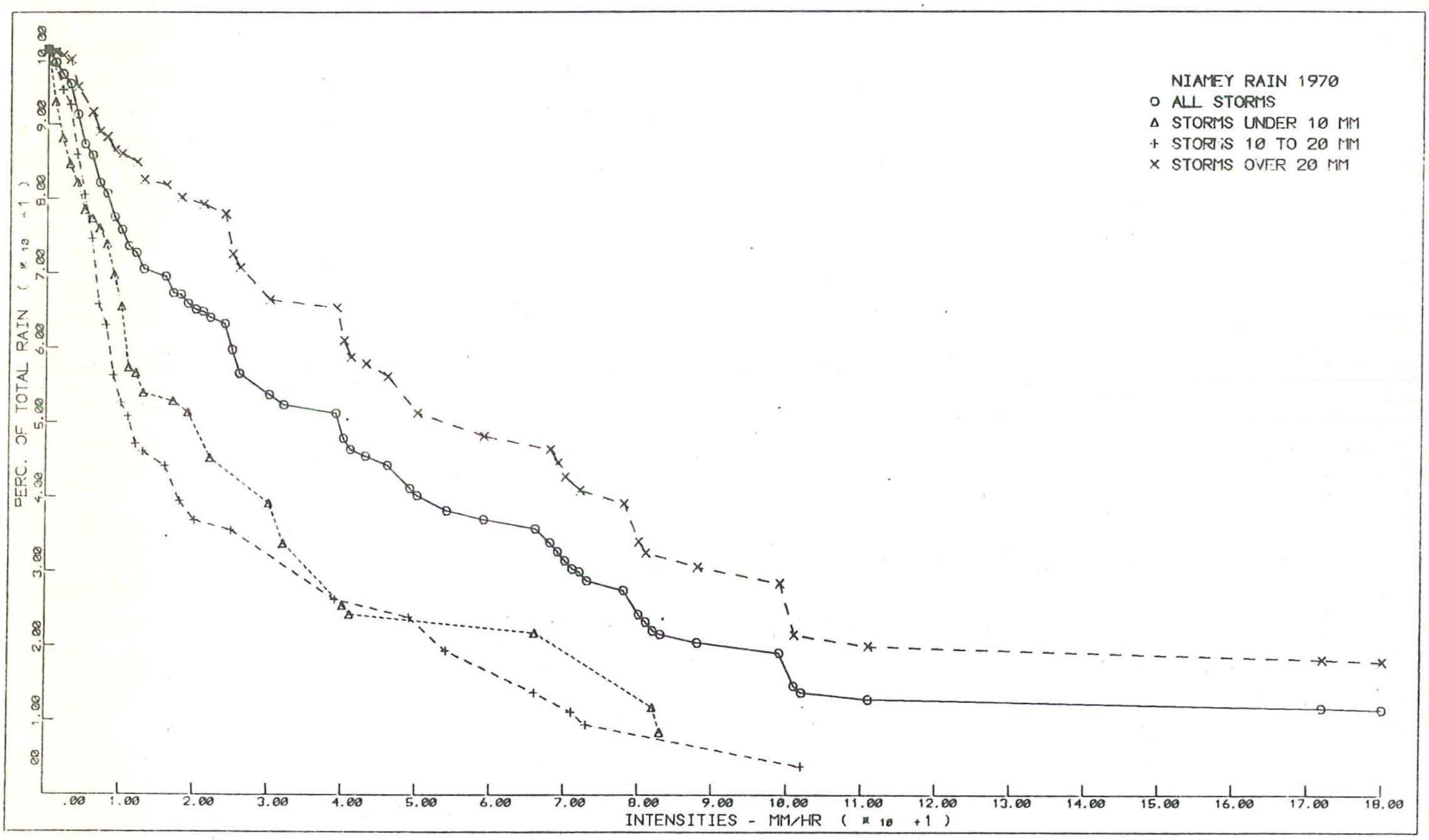

NIAMEY RAIN 1970
○ ALL STORMS
△ STORMS UNDER 10 MM
+ STORMS 10 TO 20 MM
× STORMS OVER 20 MM
PERC. OF TOTAL RAIN (* 10 +1)
INTENSITIES - MM/HR (* 10 +1)

Fig. 8b.

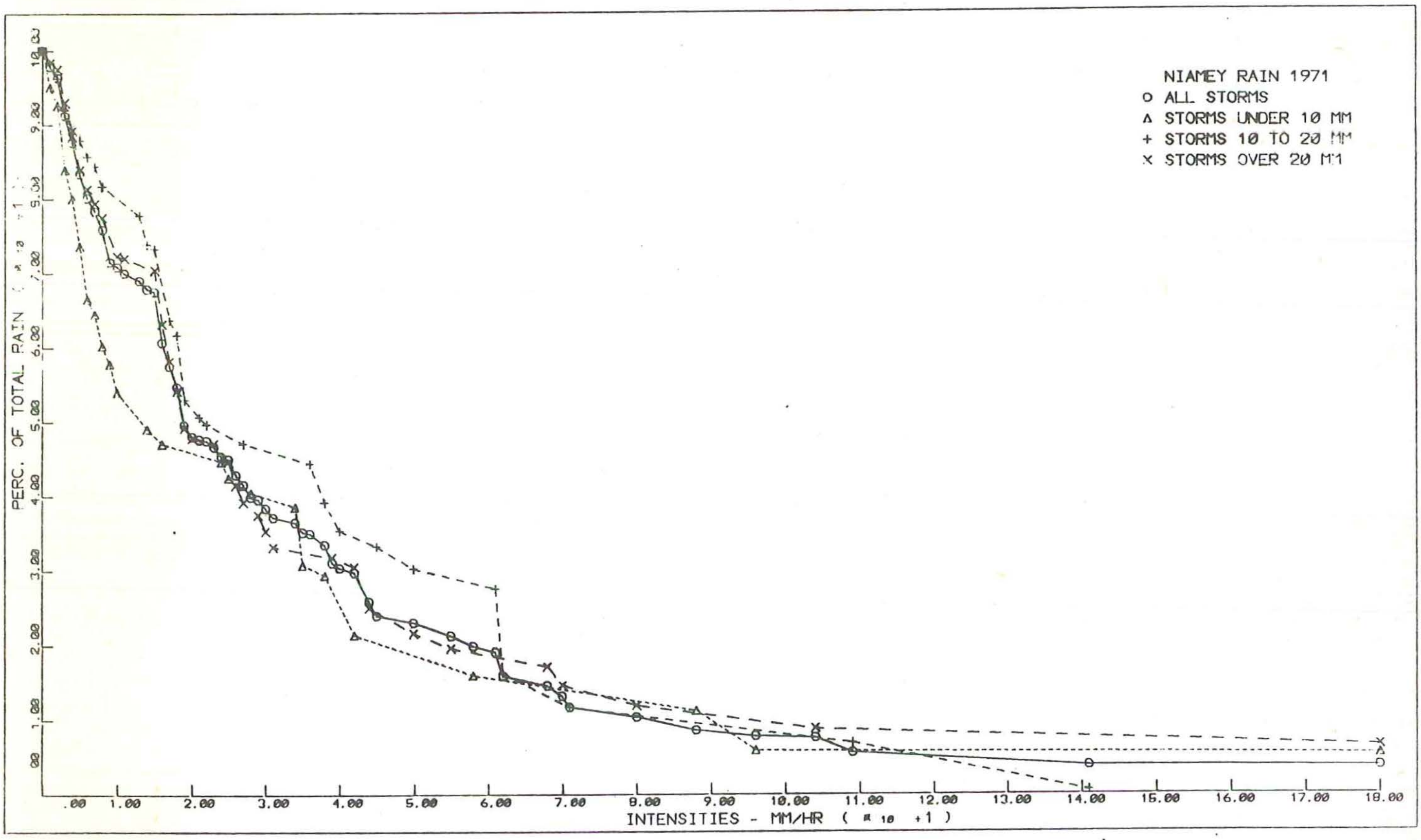

NIAMEY RAIN 1971
o ALL STORMS
Δ STORMS UNDER 10 MM
+ STORMS 10 TO 20 MM
× STORMS OVER 20 MM
PERC. OF TOTAL RAIN
INTENSITIES - MM/HR (* 10 +1)
.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00

Fig. 8c.

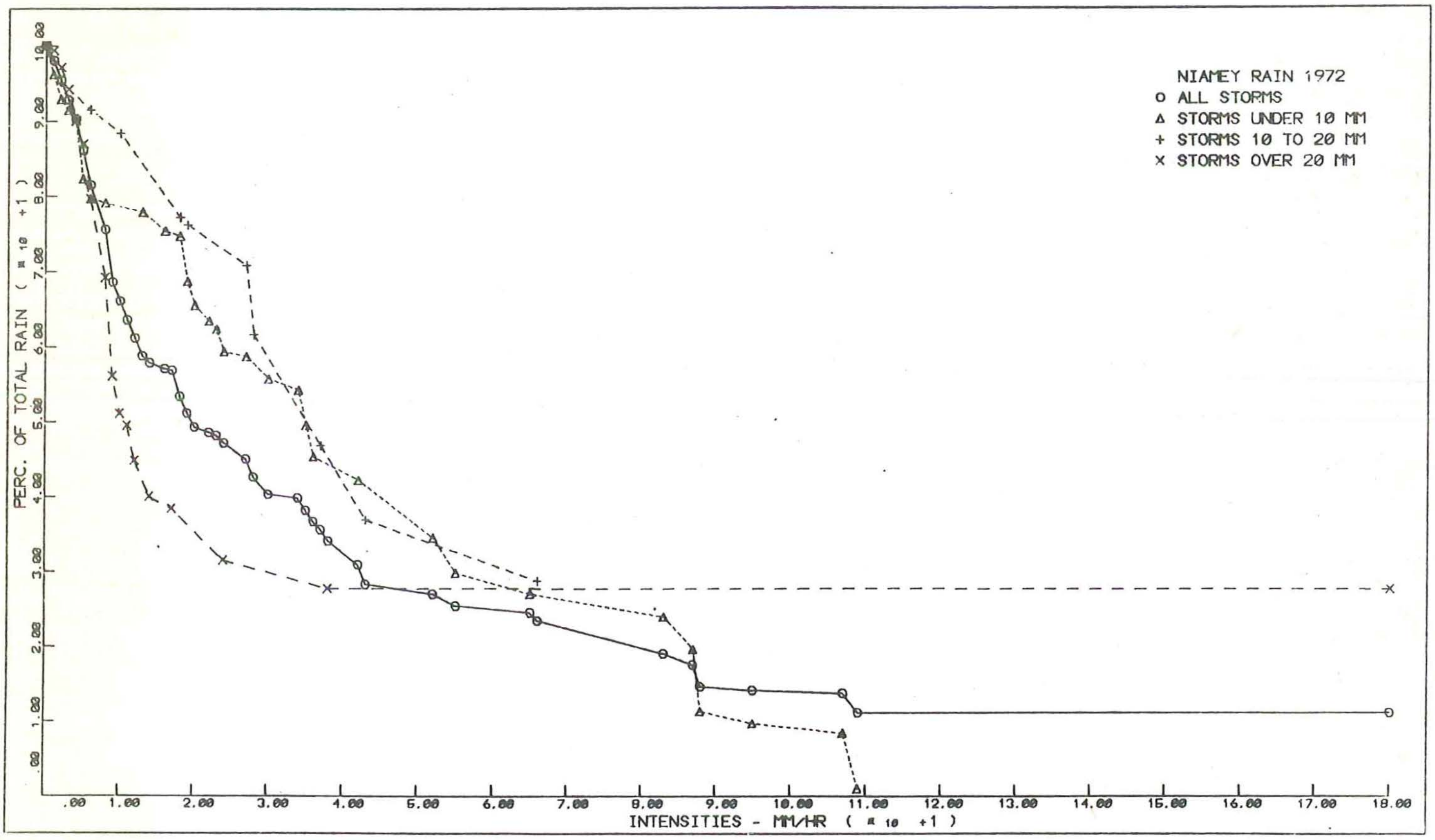
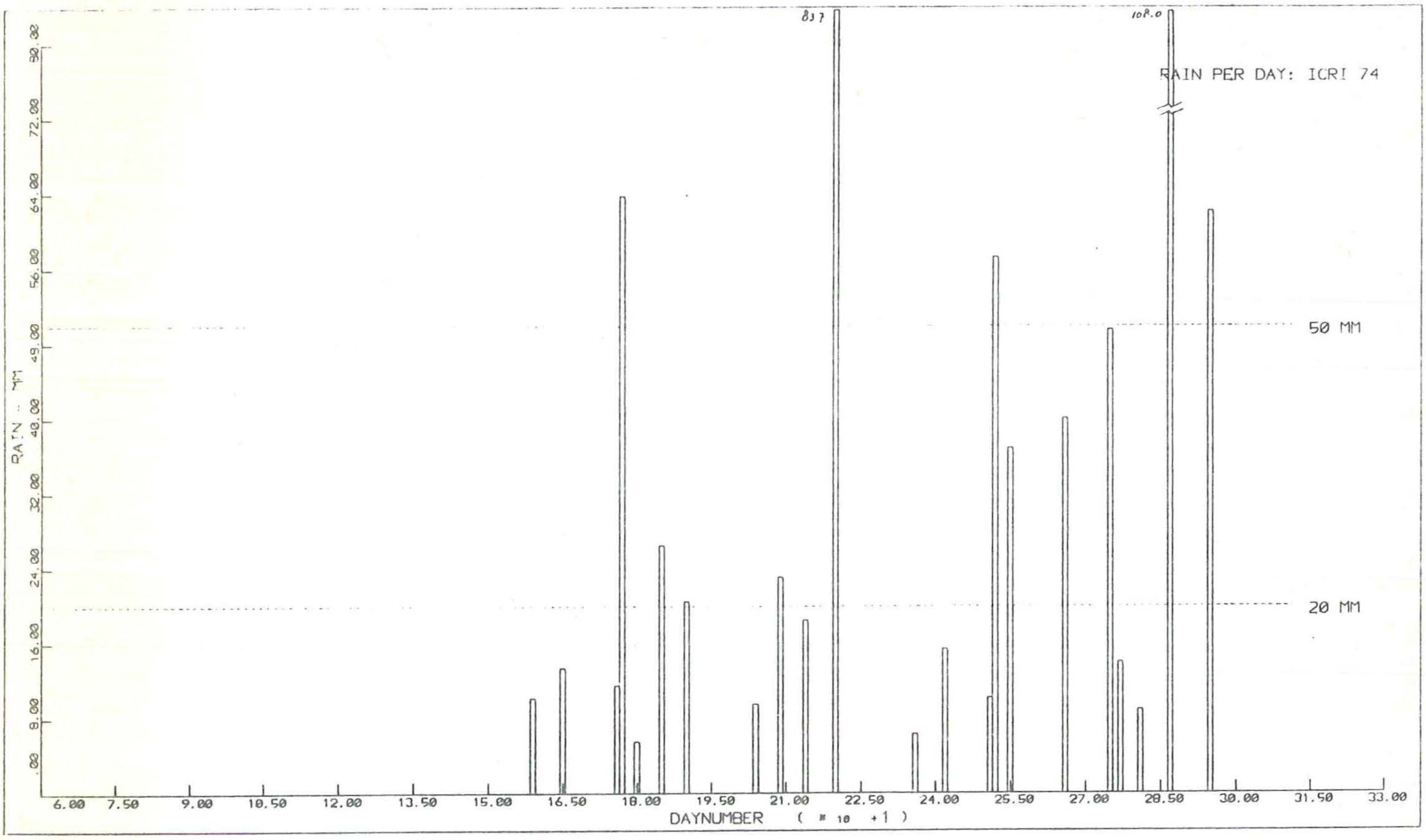
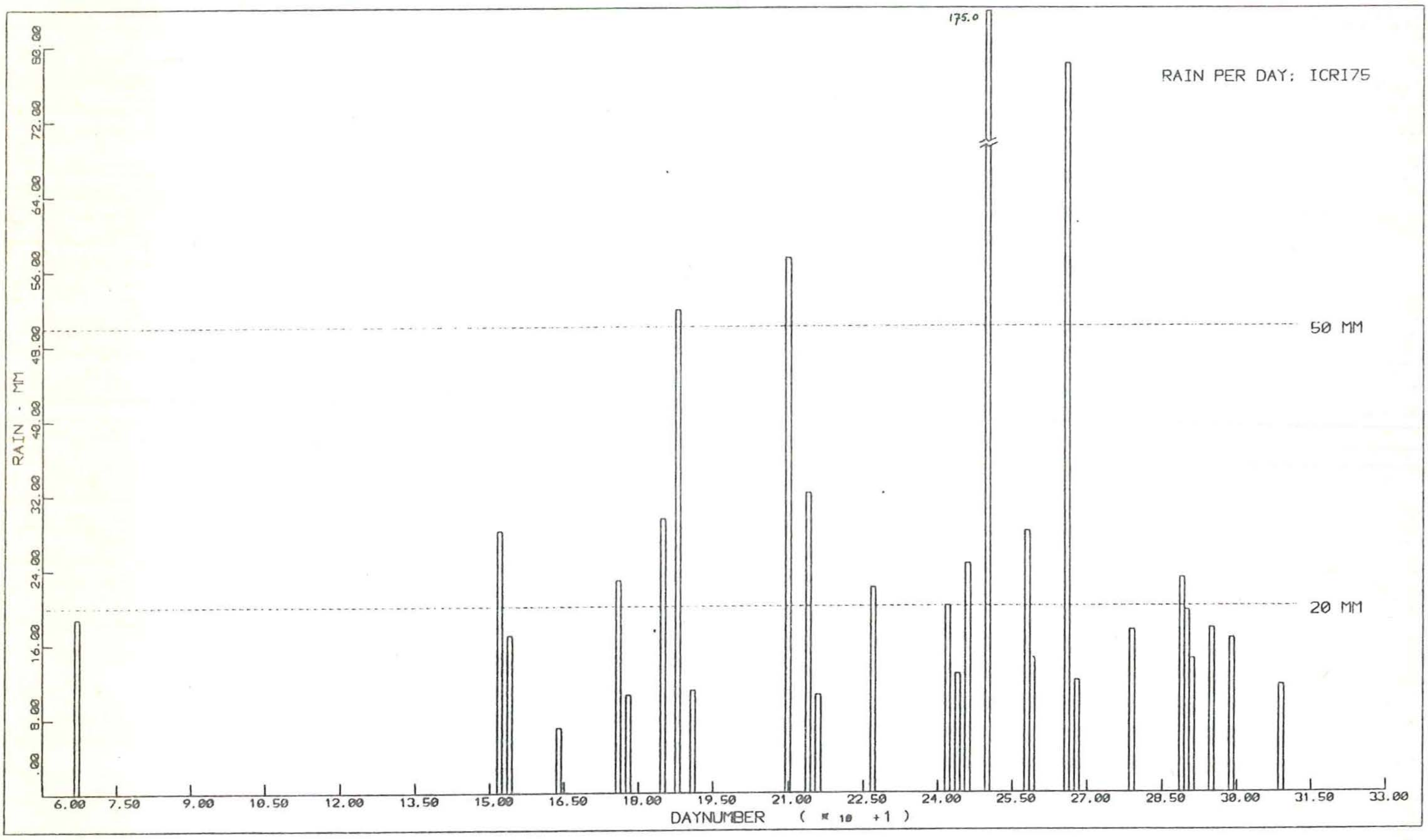

NIAMEY RAIN 1972
o ALL STORMS
Δ STORMS UNDER 10 MM
+ STORMS 10 TO 20 MM
× STORMS OVER 20 MM
PERC. OF TOTAL RAIN (* 10 +1)
INTENSITIES - MM/HR (* 10 +1)
.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00

Fig. 8d.



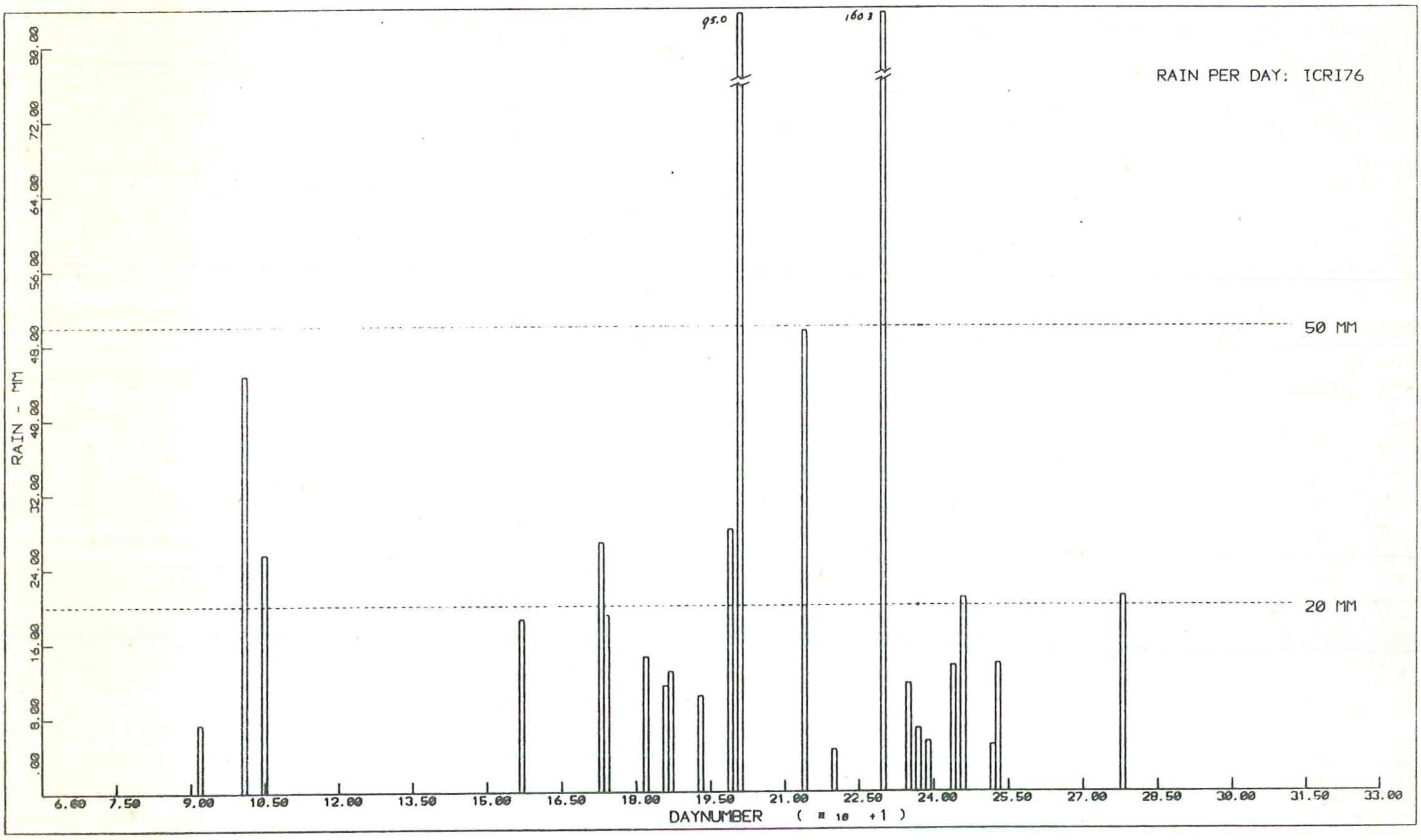
RAIN PER DAY: ICRI 74
RAIN - MM
DAYNUMBER (* 10 +1)
50 MM
20 MM
83.7
108.0

Fig. 9a.



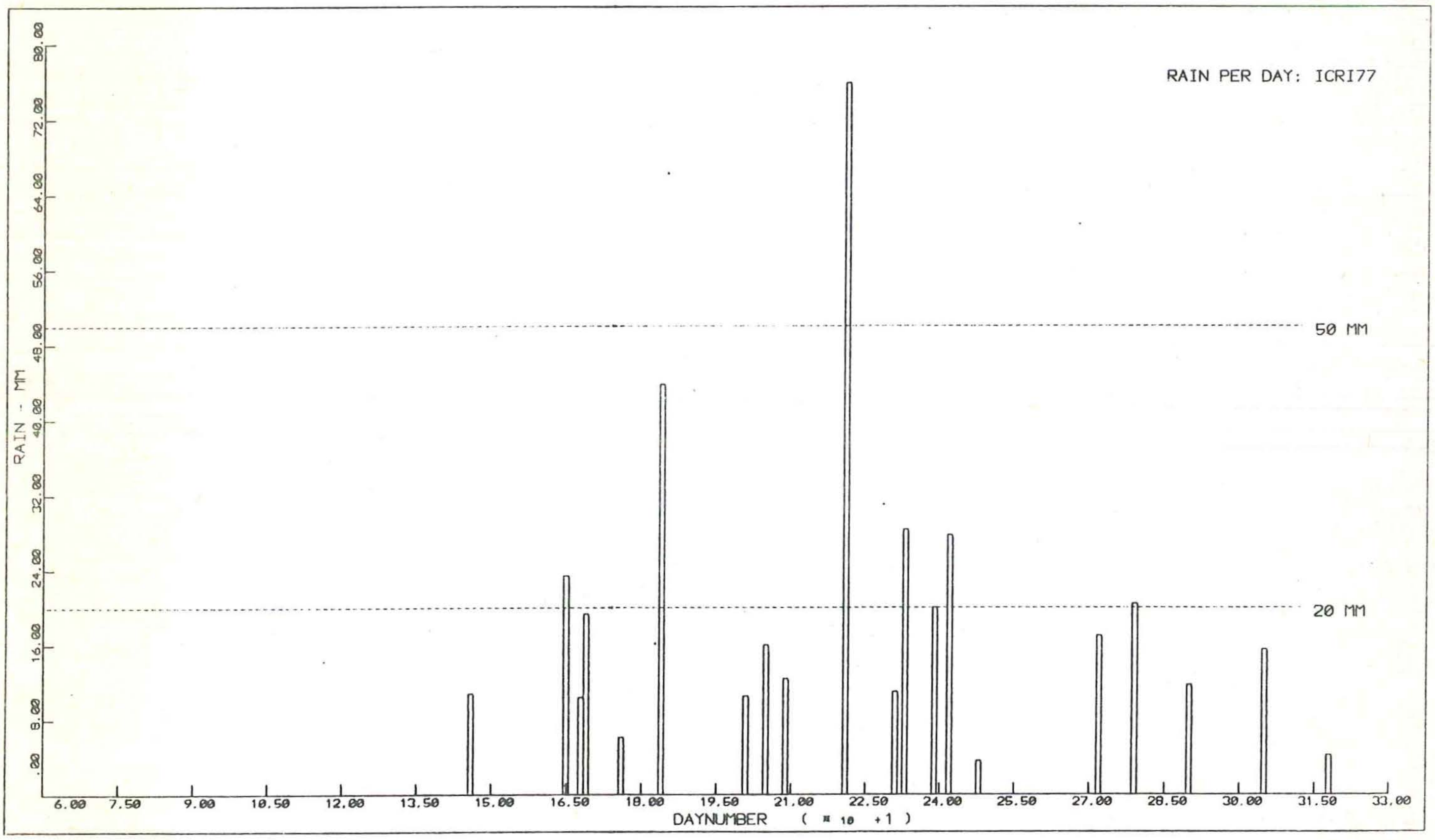
RAIN PER DAY: ICRI75
RAIN - MM
DAYNUMBER (* 10 +1)
50 MM
20 MM
175.0

Fig. 9b.



95.0
160.3
RAIN PER DAY: ICRI76
50 MM
20 MM
RAIN - MM
.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
6.00
7.50
9.00
10.50
12.00
13.50
15.00
16.50
18.00
19.50
21.00
22.50
24.00
25.50
27.00
28.50
30.00
31.50
33.00
DAYNUMBER (* 10 +1)

Fig. 9c.



RAIN PER DAY: ICRI77
50 MM
20 MM
RAIN - MM
.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
64.00
72.00
80.00
6.00
7.50
9.00
10.50
12.00
13.50
15.00
16.50
18.00
19.50
21.00
22.50
24.00
25.50
27.00
28.50
30.00
31.50
33.00
DAYNUMBER (* 10 +1)

Fig. 9d.

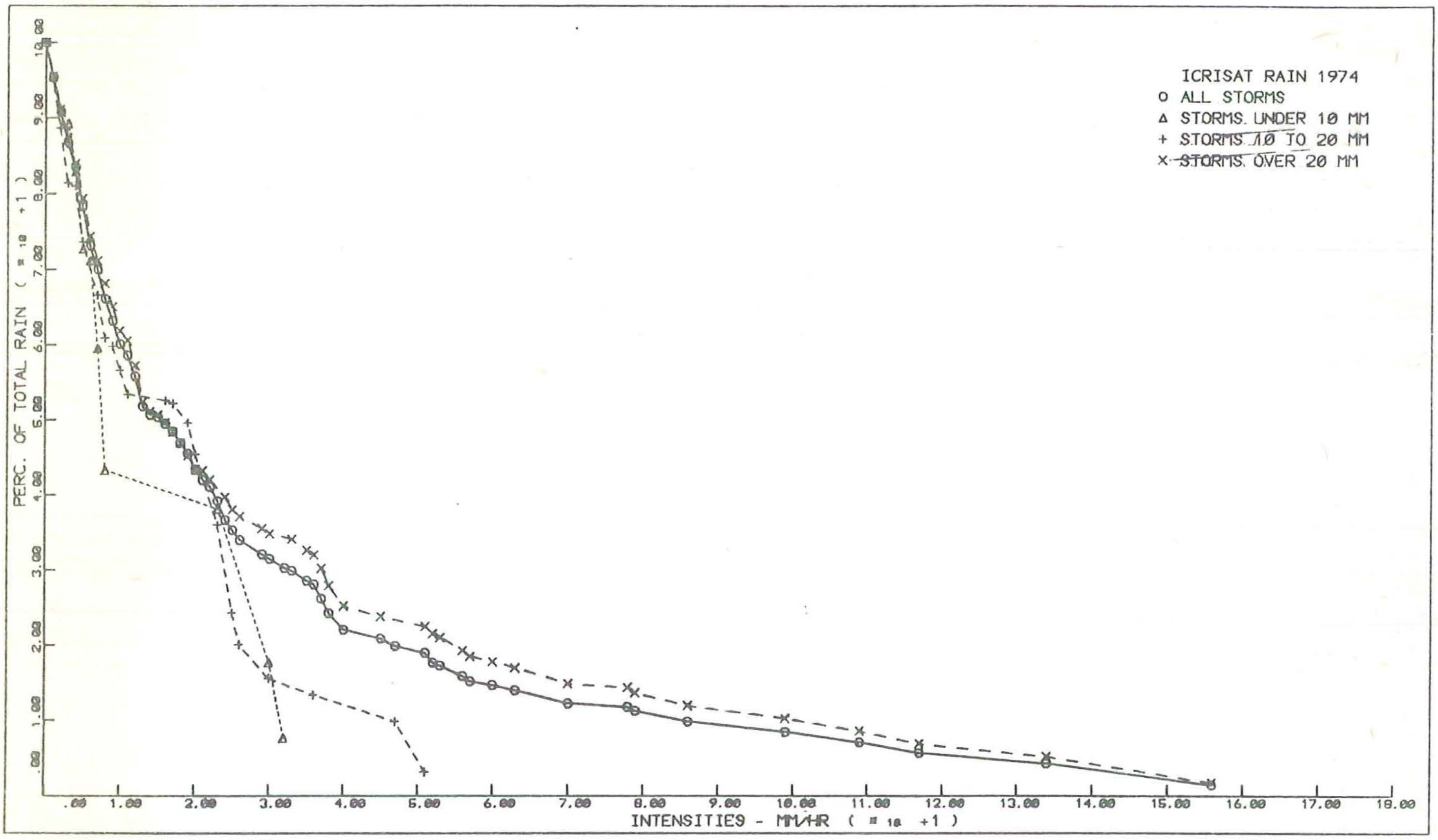


Fig. 10 a.

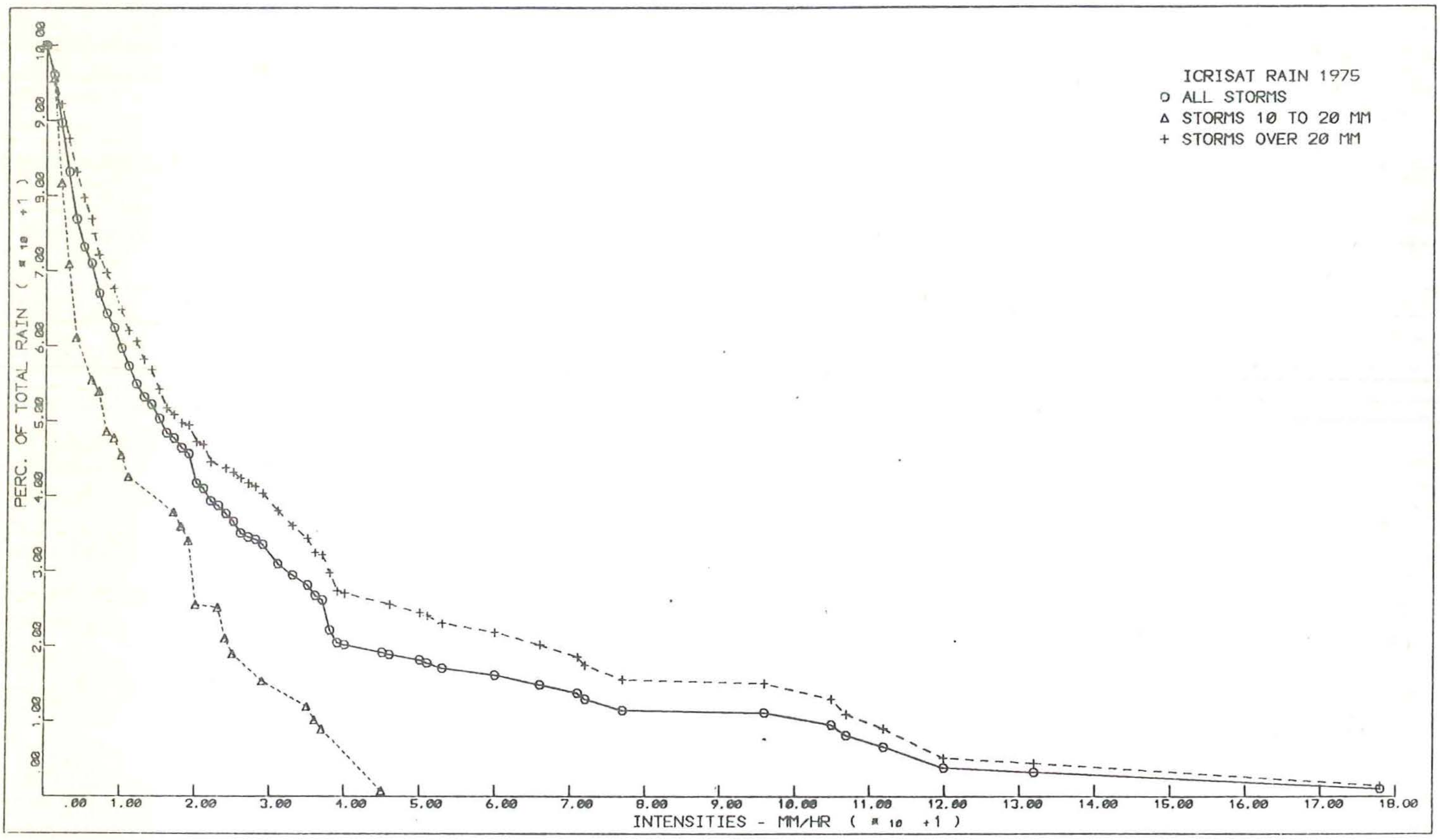


Fig. 10 b.

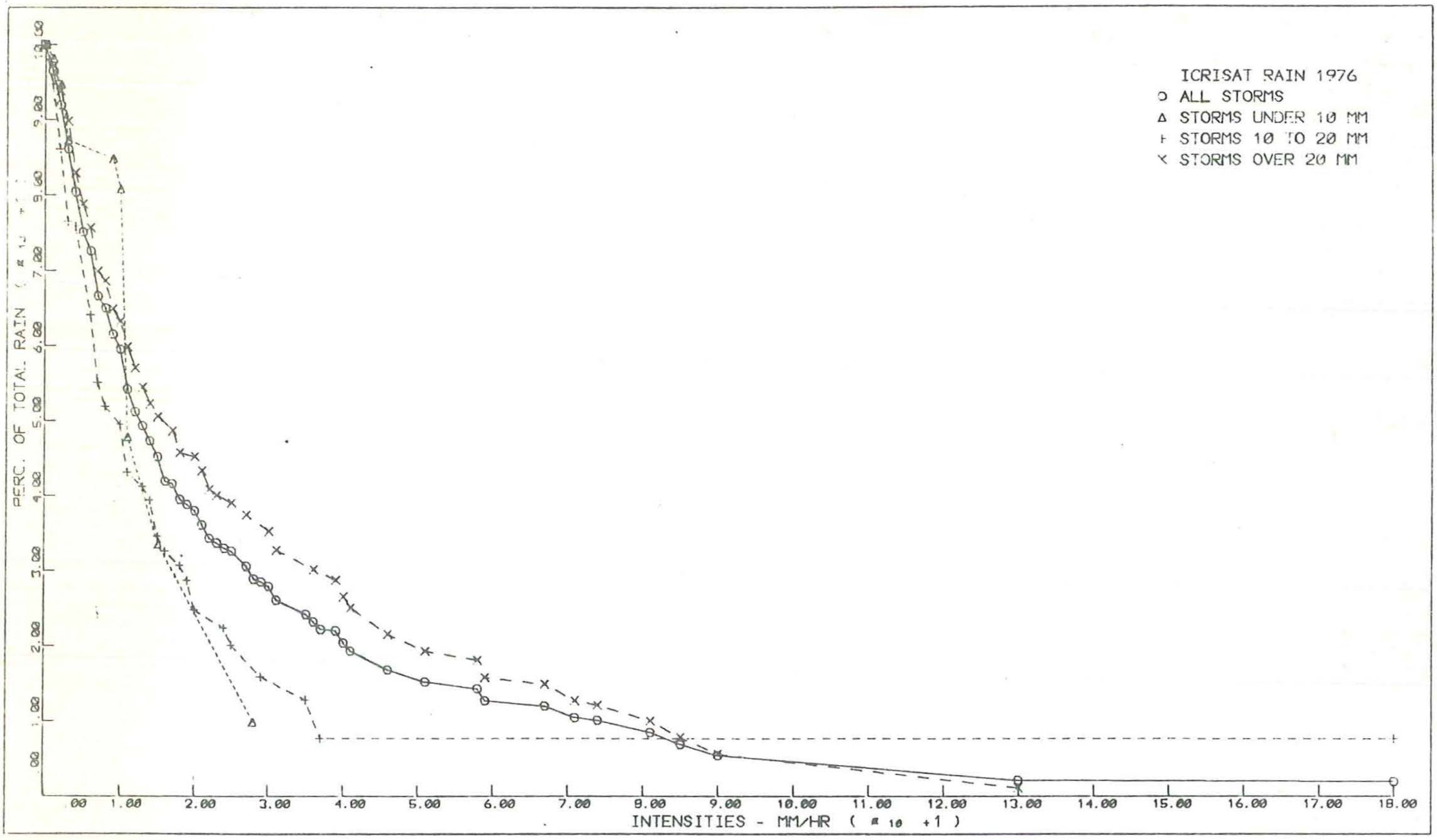


Fig. 10c.

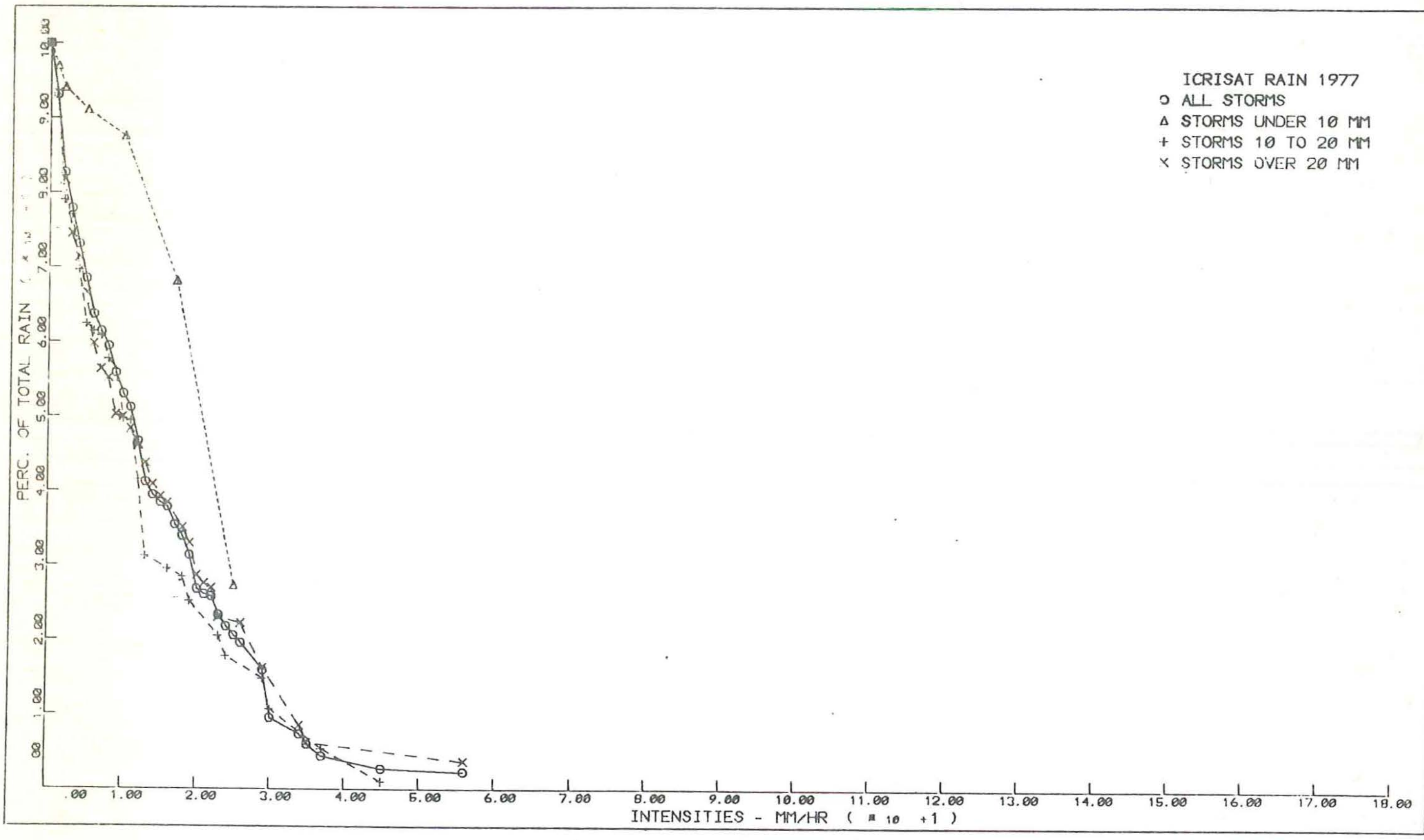


Fig. 10d.

Fig. 11a. Some infiltration rate curves from simulator work.

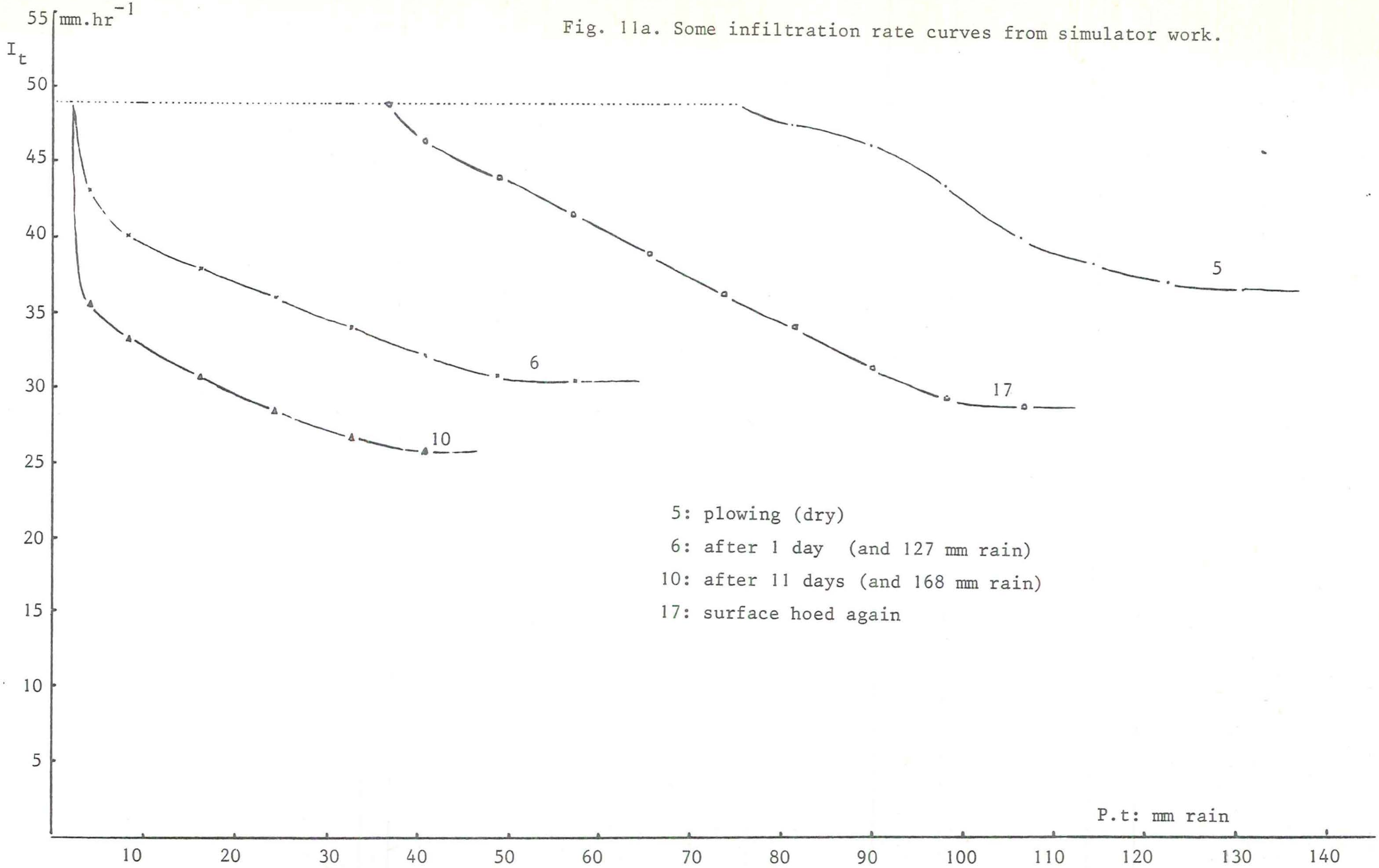
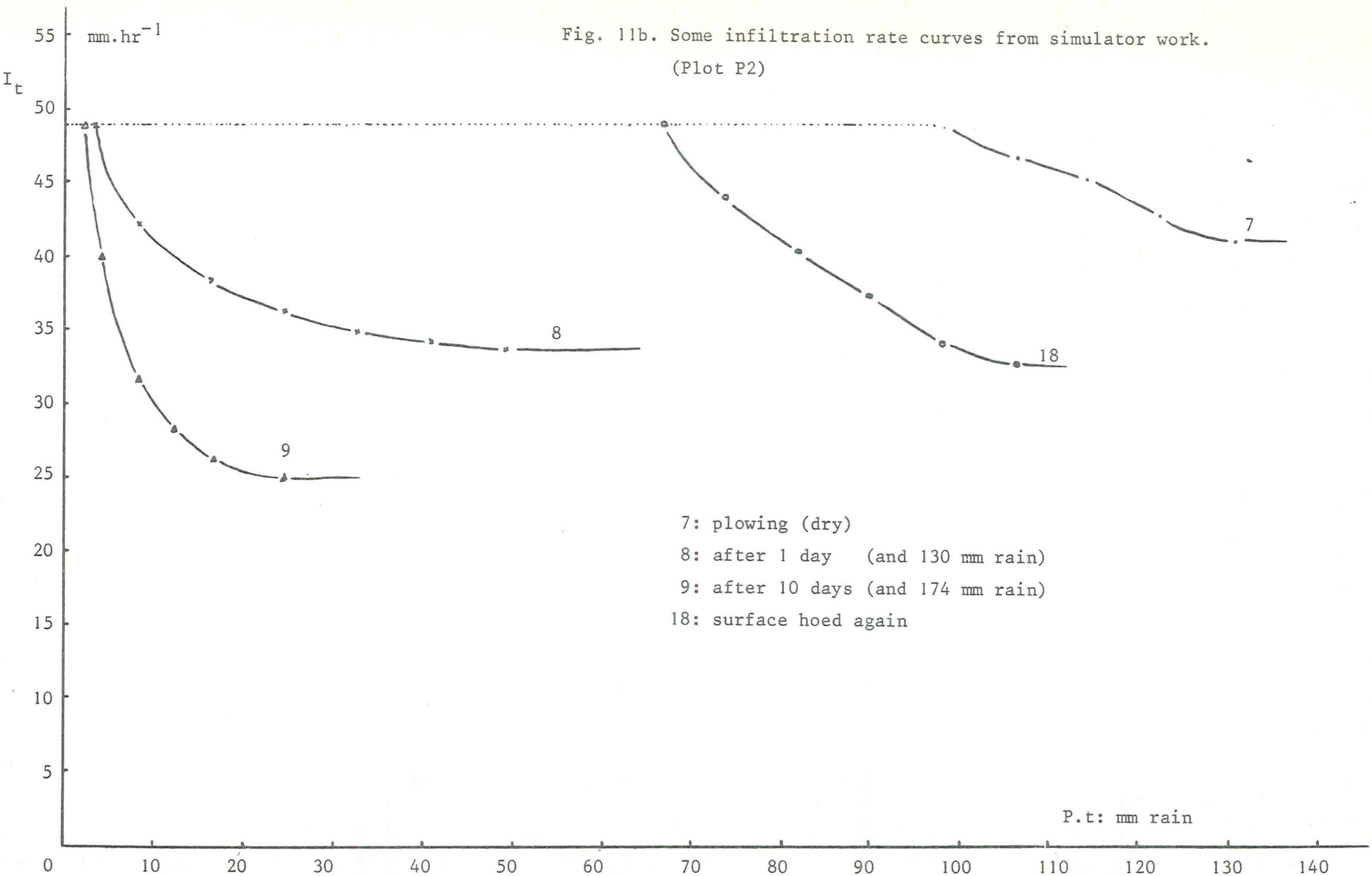


Fig. 11b. Some infiltration rate curves from simulator work. (Plot P2)



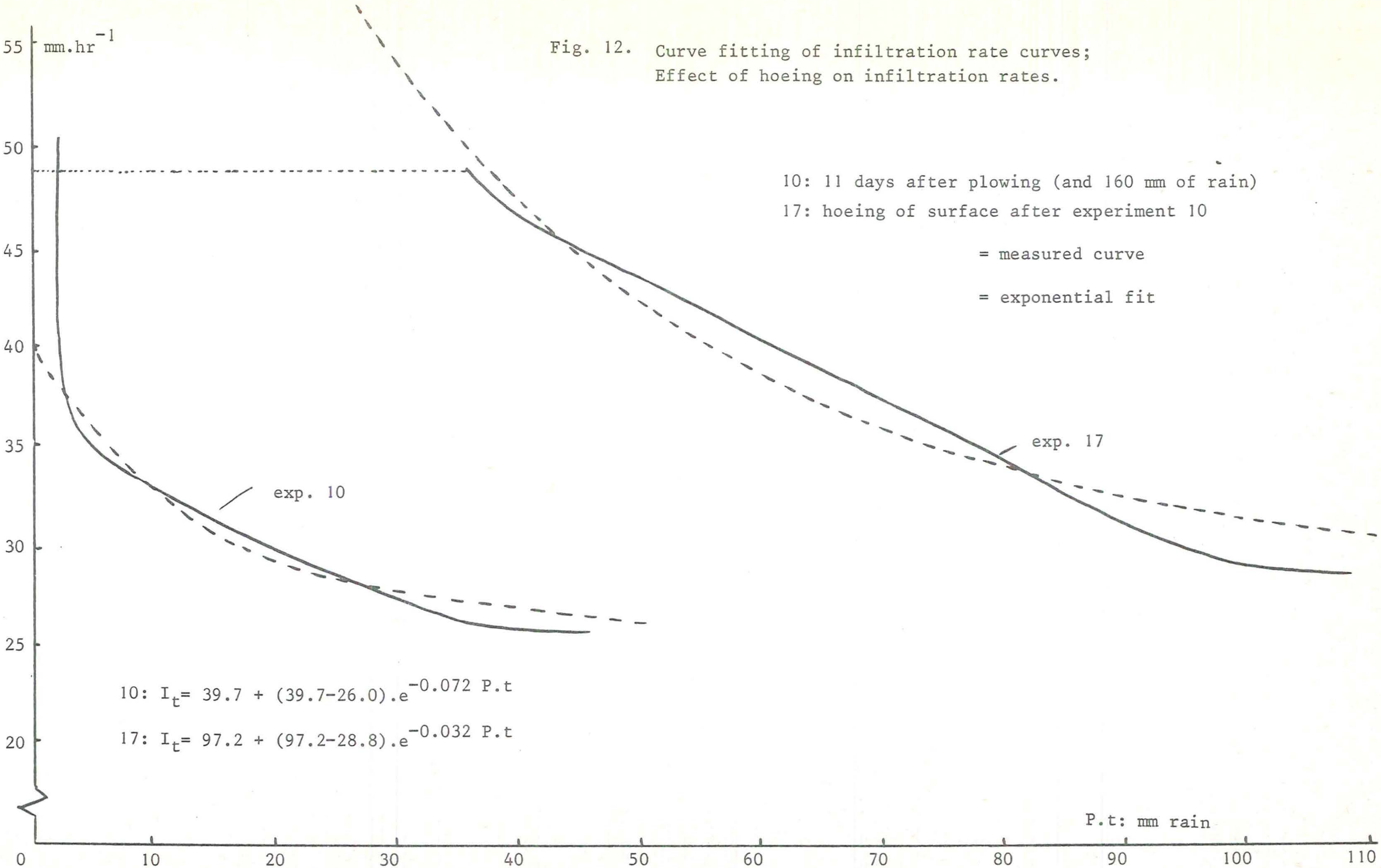


Fig. 12. Curve fitting of infiltration rate curves;
Effect of hoeing on infiltration rates.

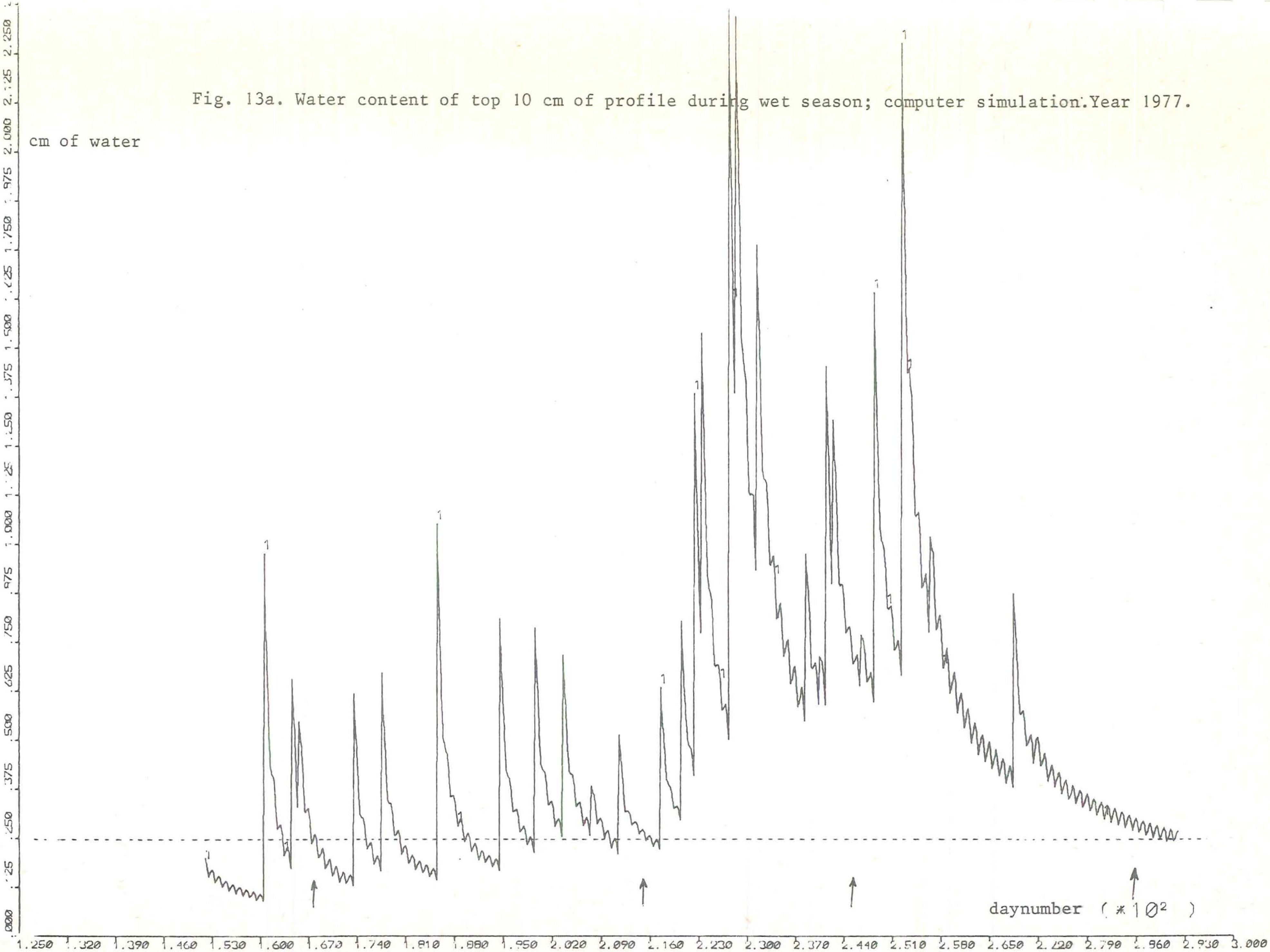


Fig. 13a. Water content of top 10 cm of profile during wet season; computer simulation. Year 1977.

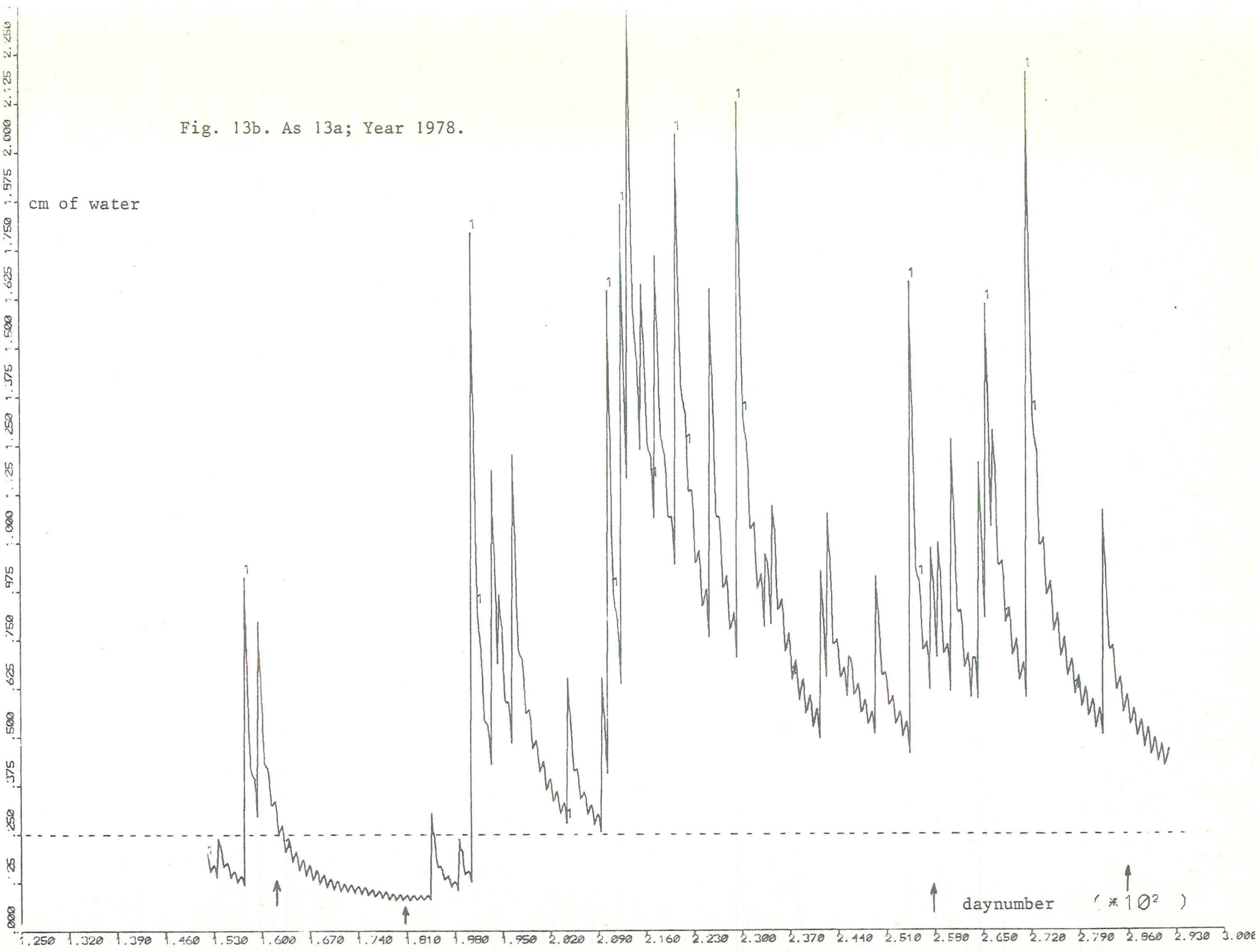


Fig. 13b. As 13a; Year 1978.

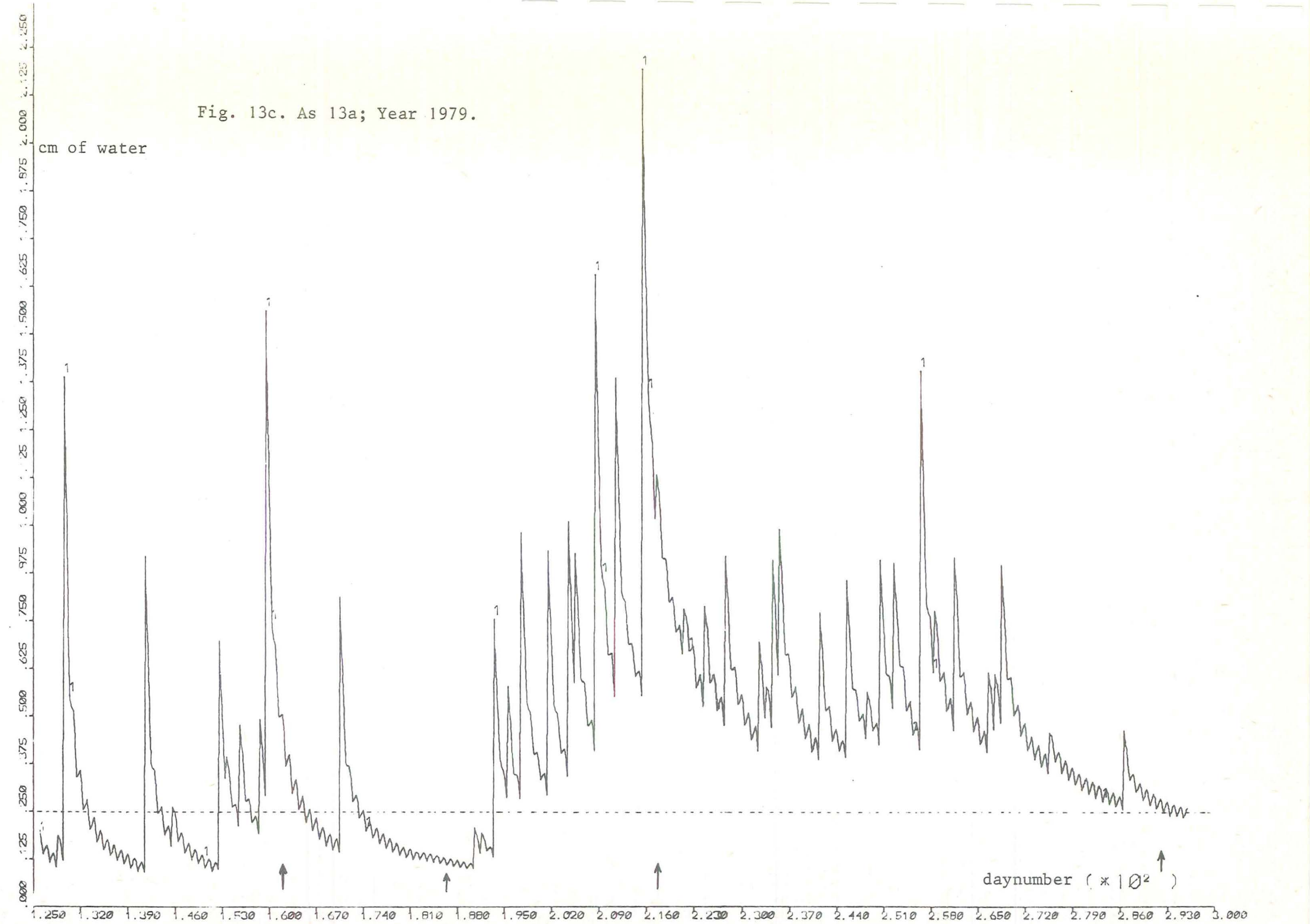
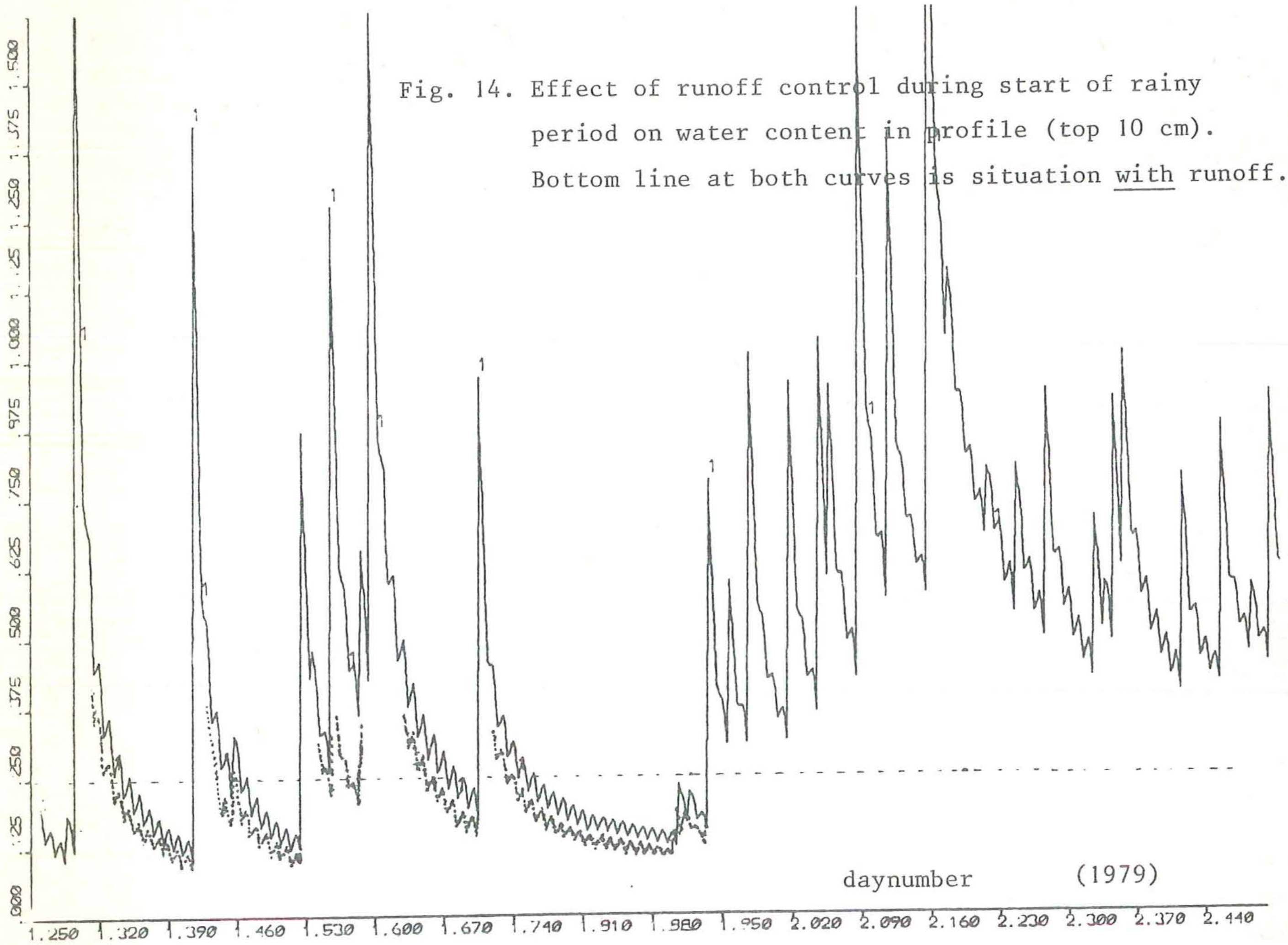


Fig. 13c. As 13a; Year 1979.
cm of water
daynumber (* 10²)
1.250 1.320 1.390 1.460 1.530 1.600 1.670 1.740 1.810 1.880 1.950 2.020 2.090 2.160 2.230 2.300 2.370 2.440 2.510 2.580 2.650 2.720 2.790 2.860 2.930 3.000

Fig. 14. Effect of runoff control during start of rainy period on water content in profile (top 10 cm). Bottom line at both curves is situation <u>with</u> runoff.



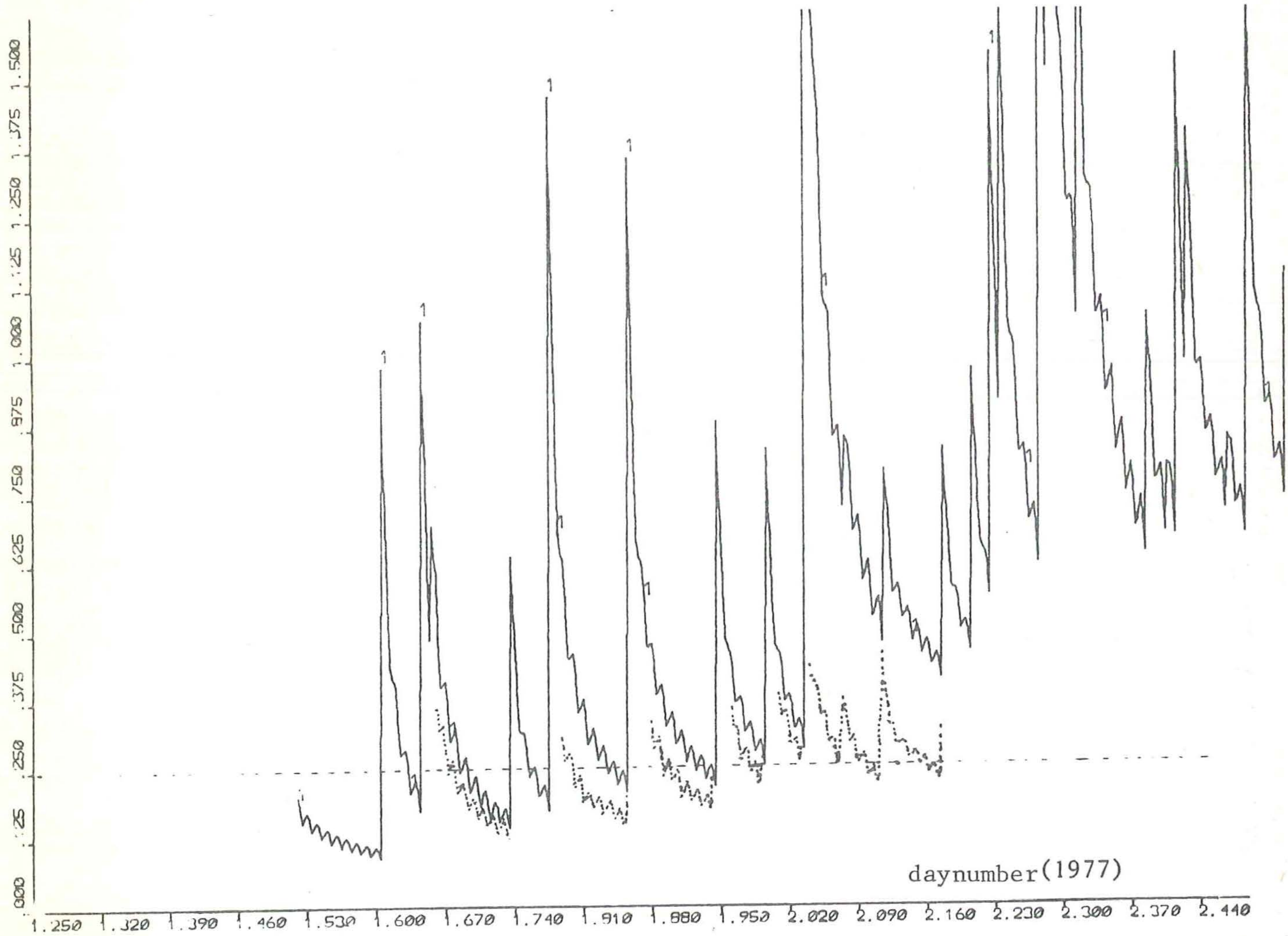


Fig. 15a. Soil moisture profiles at some periodes in the wet season; computer simulation. Year 1977.

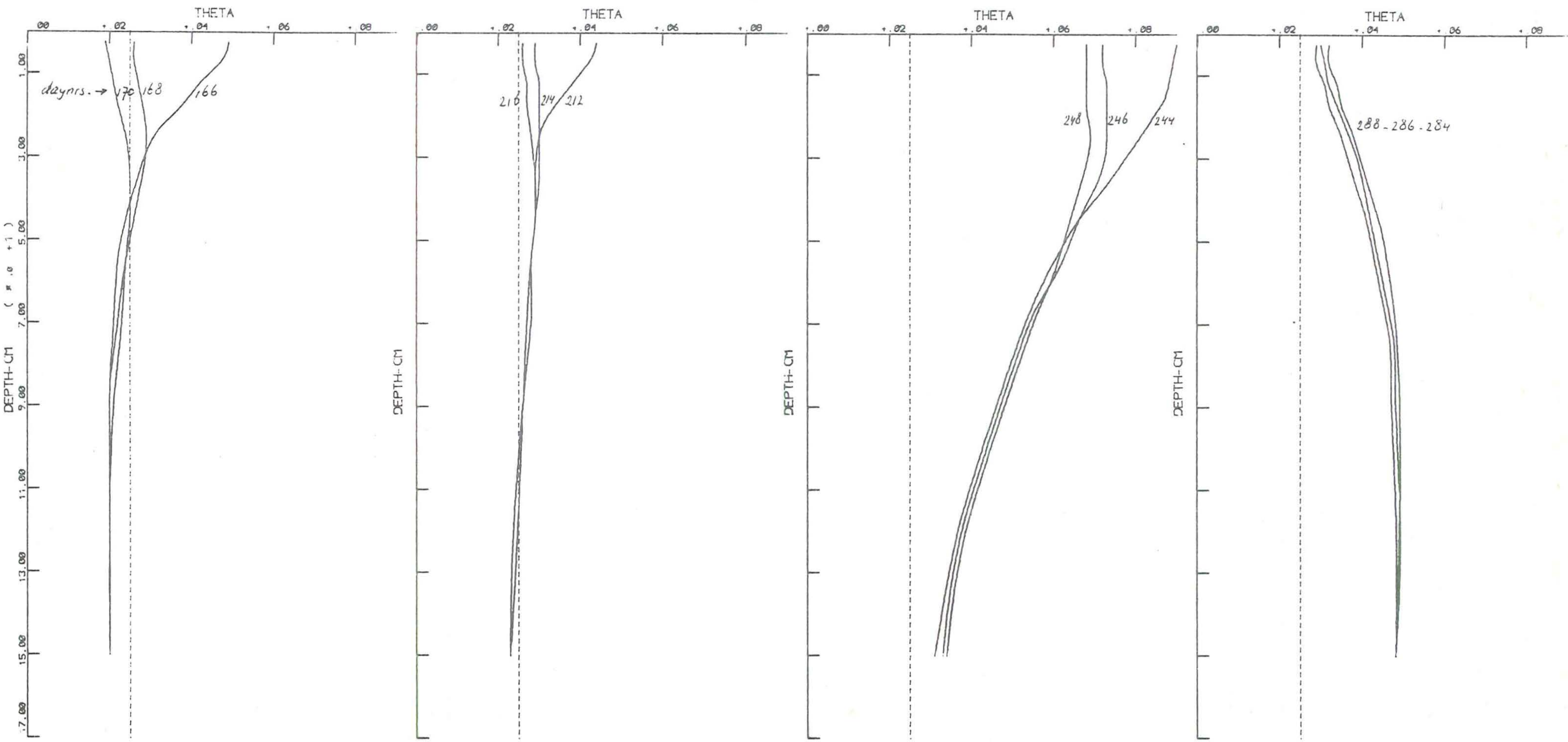


Fig. 15b. As 15a; Year 1978.

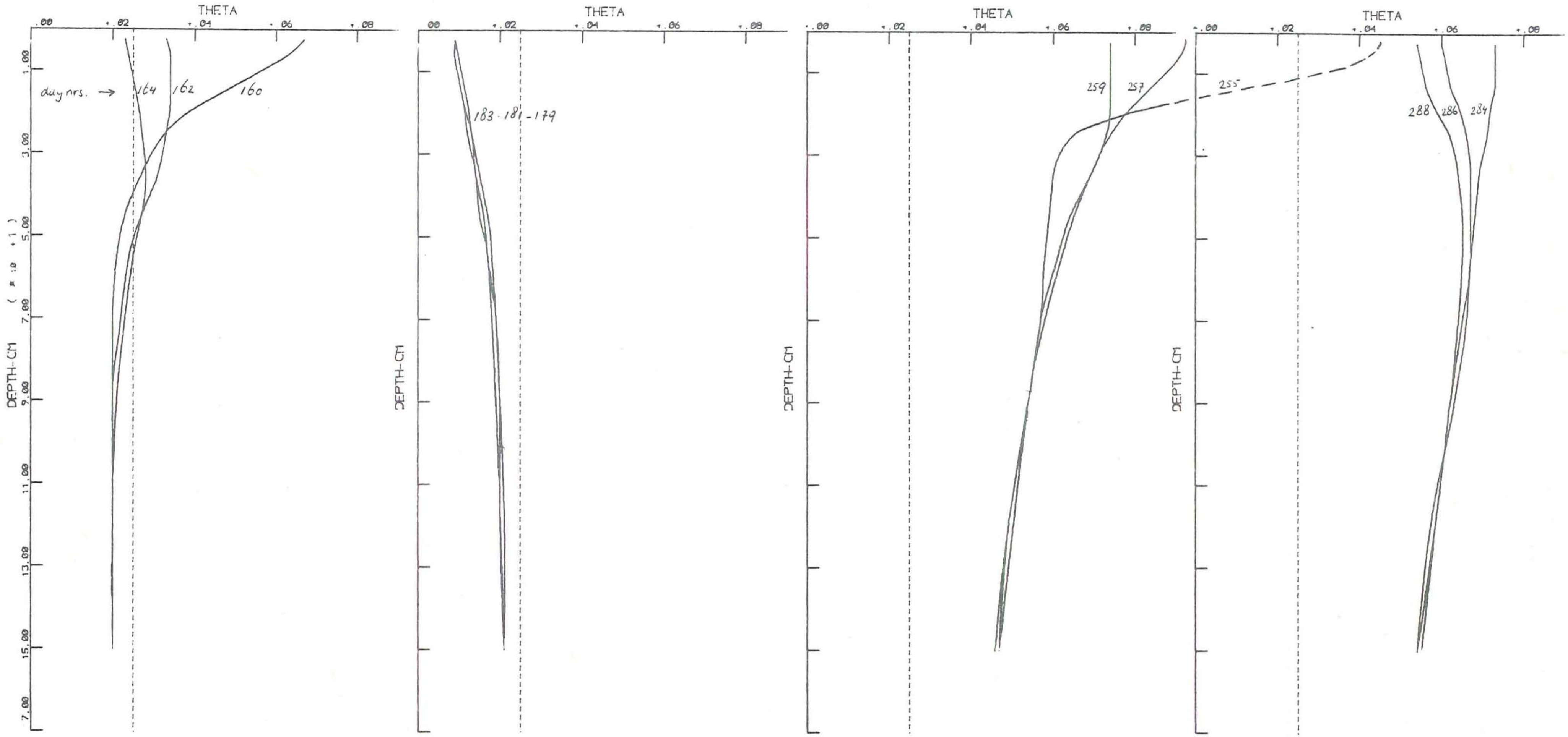


Fig. 15c. As 15a; Year 1979.