THE DEVELOPMENT OF PROFILE AVAILABLE WATER CAPACITY MODELS

by

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WATER RESEARCH COMMISSION

PRETORIA 98/1/88 JANUARY 1988

Final report to the Water Research Commission on the research project:

The determination of the profile available water capacities of soils.

98/1/85

A B S T R A C T

Profile available water capacities for a selection of important crops (maize, wheat, cotton, peas) on a variety of soils and under different evaporative demands were determined in the Ciskei and at the Vaalharts and Loskop irrigation schemes. This was done following the guidelines proposed by Hensley & De Jager (1982). The validity of the _in situ_ determination of the upper and lower limit of profile available water was clearly illustrated. Final extraction patterns depended on soil profile characterisitcs. Similar soils in different regions under different evaporative demands showed identical extraction patterns. Severe doubts arose regarding the validity of pre-dawn leaf water potential measurements as a correct parameter to indicate the onset of stress in crops under high evaporative demand. Visual stress symptoms were used for determining first stress during the Vaalharts summer experiments.

During the PAWC determinations changes in soil profile water content were monitored at regular intervals. This permitted to observe the evolution of the extraction

pattern with time, in detail. Three typical extraction patterns were found: (a) shallow "fan", (b) deep "fan" pattern, (c) "parallel-block" pattern. The very specific "parallel-block" pattern found on the deep, sandy Hutton soils of the Vaalharts region are due to the changes in textural composition of these soils with depth.

The regular monitoring of soil water content with neutron hydroprobes during the drying cycles also helped to examine the problem of availability of soil water between irrigations. Crop factors for different periods of the drying cycle could be calculated. Observations were contradictory to the current opinion that soil water is equally available for a certain period after irrigation has been applied. It was found that the availability of soil water is decreasing with time after irrigation from the first day after the water was applied onwards.

Irrigation scheduling experiments, based on the PAWC concept, were carried out at the Vaalharts and Loskop irrigation schemes. The effect of irrigation, at extraction of different fractions of PAWC, on seasonal water use, yield and water use efficiency was tested. The PAWC concept seem to provide a consistent base on which to conduct irrigation scheduling experiments. Seasonal water use was depressed by stretching the irrigation intervals but water use efficiency was only slightly improved. There seems to be a certain threshold value of extracted water below which yields are not seriously affected. Past this value yields drop to economically unacceptable levels. Relative yield/Relative ET relationships must be viewed with caution: at different sites identical relative relationships were found but actual relationships between yield and evapotranspiration and water use efficiencies differed widely.

During the irrigation scheduling experiments the unreliability of pre-dawn leaf water potential measurements for indicating first stress under high evaporative demand was confirmed.

A deficit irrigation treatment applied during the irrigation scheduling experiments at Fort Hare gave exciting results. Extremely high water use efficiencies were obtained without depressing yield significantly. The crops extracted a high percentage of water from the lower soil layers and at the end of the season a dry soil profile was obtained.

The PAWC concept, as proposed by Hensley & De Jager

(1982) was critically evaluated. Some of the irrigation scheduling experiment results do not fit in with the current PAWC concept: at a certain threshold value of PAWC yields dropped significantly. This threshold value of PAWC was calculated from production functions obtained during the scheduling experiments with the "Cate and Nelson" method for partioning soil correlation data in two groups. The term PEW (Profile extractable water) was introduced to accommodate this concept of "amount of water that can be extracted from a soil profile by a specific crop without causing significant yield reductions". The term PAD (Profile allowable depletion) is used to describe the maximum fraction of PEW that can be consumed if one is aiming for maximizing yield.

Models for estimating PAWC and PEW for maize and wheat were developed. Physical and chemical properties of the soils, obtained during the field experiments and in the laboratory, combined with the effective rooting depth and the depth at which specific pedogenetic horizons are occuring, were used as variables in multiple regression equations for predicting PAWC and PEW at untested sites. Depth index and silt + clay content are the dominant independent variables influencing PAWC and PEW of a specific pedogenetic horizon in soils containing less than 20% silt + clay. For soils containing more than 20% (silt + clay) depth index was found to be the dominant variable. Structure index was influencing the PEW and PAWC values for a specific pedogenetic horizon to a lesser extent.

Some practical recommendations for future research in the field of profile available water and irrigation scheduling are made in the last chapter.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude towards the following persons and bodies:

The Water Research Commission, for sponsoring the project.

The Council and Rector of the University of Fort Hare, for permission to undertake the project.

The project steering committee, and especially Mr. D.S. van der Merwe, the chairman, for their extremely valuable support and criticisms.

The Director of the Orange Free State Region of the Department of Agriculture, for permission to do part of the research at Vaalharts and for valuable support by his staff.

The Director of the Tobacco and Cotton Research Institute, for permission to do part of the research at Loskop and for valuable support by his staff.

The Director of the Soil and Irrigation Research

Institute, for permitting Mr. C. le Maire to co-operate on the project.

Dr. M. Hensley for advice and many hours of discussion regarding the research.

Prof. J.N. Marais and his staff for providing agronomic advice and for the co-operation with the lysimeter experiments.

Mr F.M.G. van Assche and Mr. C. le Maire for the diligent way in which they took responsibility for the irrigation scheduling experiments.

Prof. A.T.P. Bennie of the Department of Soil Science at the University of the Orange Free State for arranging the determination of rooting densities in that Department and Mrs. R.P. Hunt for doing these determinations.

Mr. S. Nofemele, Mr. C. Roelofse, Mr. L.J. van Heerden, Mr. A. Nell and Ms. De Zeutter for the enthusiasm with which they co-operated in the field work.

Mr. I.R.F. Trollip for the numerous hours that he helped with the computer assimilation of the collected data.

Mrs. F.A. Lees, Mrs. J. Holcroft, Mrs. K. Tutt, Mrs. V. D'Huyvetter and Mrs. M. Boedt for their assistance with typing and drawing of the diagrams.

Mr. A.B.D. Joubert, of the Department of Agricultural Engineering, University of Fort Hare, for designing the rainsheds.

Mr. S.T. Levy, of the Department of Genetics, University of Fort Hare for his advice on the statistical assimilation of the data.

Prof. C.E.J. Botha, of the Department of Botany, University of Fort Hare, for the use of some of the Department's computer equipment.

Mr. van der Linde, Mr. du Preez and Mr. Venter for providing sites on their farms for the conducting of the experiments.

CONTENTS

CHAPTER 1

PLANT-AVAILABLE WATER

1.1 INTRODUCTION

For various technical and economic reasons detailed knowledge of soils within an existing or potential irrigation scheme is essential. The high costs involved in running or developing the necessary infrastructure justify intensive research in this field.

Storie (1964) listed a dozen reasons (technical as well as economical) for detailed soil investigations in irrigation studies. The most important one is undoubtedly the need to acquire information on the factors and processes controlling the movement, storage and plant-availability of soil water. These factors will ultimately influence all aspects of irrigation development (land suitability, crop production, irrigation systems, layout of irrigation schemes, economic rendability of a scheme, engineering.....). An estimate of how much water is available in a soil profile helps to solve the most crucial problems in irrigation scheduling: how much water should be applied to a crop and when that water should be applied.

More recently the increasing need for water conservation and improving water use efficiencies became additional reasons for soil investigations related to irrigation. The shortages in irrigation water encountered in many parts of the world (and specifically in Southern Africa during recent years), due to climatic factors including drought hazards and/or competition from urban users, stress the need for detailed research into the matter. Hanks & Rasmussen (1982) stated that:

> "the possibility of dealing with water shortages will become more of a reality in the future. This will be in contrast to the practice of much of the irrigated regions of the world where irrigation previously was supplied to meet maximum demands."

The situation described here was already reality for most irrigation schemes in South Africa during the last two years!

1.2 REVIEW OF LITERATURE

1.2.1 Classical concepts of available water

Viehmeyer & Hendrickson (1927) introduced the concept of "soil available water" as the amount of water that can be consumed by crops between an upper limit (field capacity) and a lower limit (permanent wilting point). In this concept the upper and lower limits are considered as soil constants that are unique for a certain soil. Later these two soil constants were defined in soil physical terms: field capacity was the soil water content at a soil moisture tension of 10kPa or 33kPa (depending on soil texture); permanent wilting point was the soil moisture content at a soil water potential of -1500kPa. Both values were determined in the laboratory on disturbed or undisturbed soil samples with water extraction equipment.

This definition was popular among workers in the field of irrigation research until recently. Tables were drawn up that gave the values of the upper and lower limits of available moisture for soils belonging to different textural classes so that a quick assessment of available water for a soil profile could be made.

During the last two decades this traditional approach was severely criticized by several authors (e.g. Hillel, 1980; Ritchie, 1981). Both field capacity and wilting point were considered to be imprecise limits for available soil water: Plants may remove water from a wet soil before it drains to field capacity and some crops can extract soil water to potentials considerably below -1500kPa (Richards & Wadleigh, 1952; Wilcox, 1962; Miller & Aarstad, 1971, 1973; Ritchie, 1981; Hensley & De Jager, 1982).

1.2.2 The upper limit of plant-available water

Field capacity is usually considered to be the upper limit of plant available soil water. Various definitions for field capacity have been developed since the term was introduced by Viehmeyer & Hendrickson (1931). They defined "field capacity" as the amount of water held in the soil after all "free" or "gravitational" water has drained from the soil and downwards movement of water in the soil profile has materially ceased. A well-watered soil takes about three days to reach this stage, at which the macropores are emptied and water is retained only in the micropores (Buckman & Brady, 1969). This is usually considered to be equivalent to the soil water content at a soil water potential of -10kPa or -33kPa (Skaggs, Miller & Brooks, 1981; Doorenbos & Kassam, 1979).

As research advanced it became clear that it is meaningless to consider field capacity as a soil constant (Hillel, 1980). Drainage continues for a long time after a profile has been wetted and drainage, although it becomes negligible after some time, probably never stops. This was demonstrated by Robins, Pruitt & Gardner (1954), Ogata & Richards (1957) and Miller & Aarstad (1974). Stone, Horton & Olson (1973) showed that the soil (Great Bend silt loam) on which they conducted a field experiment with sorghum, kept on draining for more than 12 days after water was applied. Ritchie (1981) found that drainage became negligible only ten days after irrigating an Adelanto clay loam soil. He therefore introduced a new term: "drained field capacity".

Besides soil texture, organic matter, soil porosity and depth of wetting, field capacity also depends on layering and the sequence of pedogenetic horizons in a soil profile (Robins, 1959; Miller, 1973). The thickness and the contrast in textures of horizons within the soil profile will influence the moisture holding capacity of a soil in the field (F.A.O., 1979).

For these reasons it is clear that field capacity determined by laboratory measurements cannot give reliable results. Skaggs et al (1981) therefore recommend that field capacity values at -10kPa or -33kPa soil water potential should only be used as rough estimates. Ratliff, Ritchie & Cassel (1983) evaluated the relationships between in situ measured field capacity (drained field capacity) and soil moisture content at -33kPa (laboratory determined). They found that laboratory estimates of the upper limit obtained by -33kPa water content were significantly less than the field-measured drained upper limit for sands, sandy loams, and sandy clay loams and were significantly more than field measurements for silt loams, silty clay loams, and silty clays.

Hillel (1980) described in detail how field capacity should be determined. He stressed that a useful field capacity value can only be determined in the field under conditions that normally exist during the growing season.

He continues: "the profile should be wetted as deep as possible and the measurement of soil-moisture content and depth distribution should be made repeatedly rather then only once at an arbitrary time such as 2 days. Periodically repeated measurements, preferably by a non-destructive method such as neutron gauging, will provide information on the dynamic pattern of internal drainage and allow evaluation whether any single value of soil moisture at any specifiable characteristic time can be designated as the field capacity".

1.2.3 The lower limit of plant-available water

Early researchers (Briggs & Shantz, 1921) suggested that the soil water content now known as the permanent wilting point, was a limit below which any water that could be extracted by plants was insufficient for the crop growth. Richards & Weaver (1944) found that the water content in a soil subjected to a pressure potential of -1500kPa was closely related to the permanent wilting percentage, as determined with sunflower, for a wide range of soils. Permanent wilting point was considered to be at the same water potential for all soils and for all crops.

It was, however, found that this definition of the lower limit of the available water range was misleading (Hillel, 1980; Skaggs *et al*, 1982):

- some crops wilt or some physiological functions are disturbed long before a soil water potential of -1500kPa is reached.
- some crops can easily function at soil water potentials below -1500kPa.

It was therefore clear that a single soil constant, like water content at a soil water potential of -1500kPa, could not characterize the lower limit of soil water availability for all crops and all soils. The lower limit varies with soil depth, soil profile characteristics, evapotranspiration, crop and the growth stage of the crop (Skaggs *et al.*, 1982).

Lately several researchers have tried to establish a scientifically sound and practically useful lower limit. It was obvious that a crop related stress index was required because plant performance is the ultimate reflection of the plant-available soil water status. When plants are wilting and show stress symptoms two main reasons may be responsible: either the available soil water is depleted or the atmospheric demand is so high that, temporarily, the soil-plant system cannot deliver the necessary water to keep the plant cells at full turgor. It is, however, difficult to separate soil-induced from atmospheric-induced stress. Soil-induced stress can be cured by supplying water to the crops and is closely related to the whole soil water availability problem. Atmospheric-induced stress is unavoidable. The fact that different plant physiological functions respond differently to soil moisture makes the establishment of a valuable plant stress index even more complicated: While transpiration rate may be, for a time, relatively independent of soil water content changes in the root zone, other forms of plant activity may not be. Photosynthesis, vegetative growth, flowering, fruiting and seed production may be related quite differently to the content of soil water (Hillel, 1980; see also Figure 1.1).

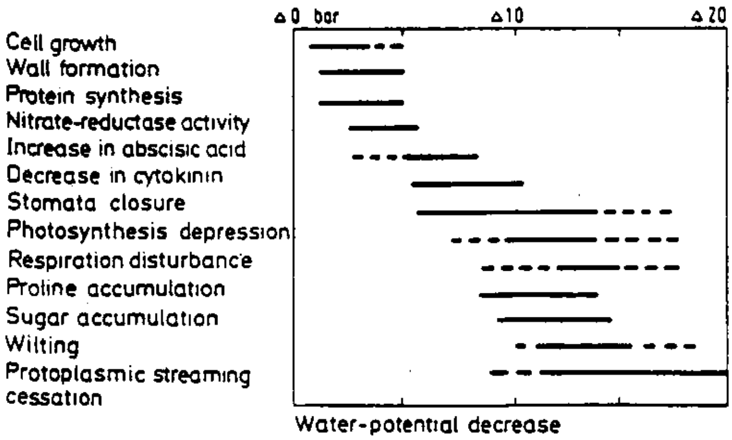


FIG.1.1 Sensitivity of cell functions to water deficiency, and changes in the plant as it dries out. The lines indicate the range in which a clear effect begins to appear in most plant species. The measure of desiccation stress used here is the change in water potential as compared with that when there is a good supply of water (from Larcher, 1980).

Barrs (1968), gives a review of the different techniques that have been developed to assess water stress in plants: relative water content determinations, measurements of leaf, stem and fruit thickness, monitoring of the rate of growth of leaves, determinations of leaf water potential by means of a pressure bomb or thermocouple psychrometer, measurement of stomatal aperture, monitoring of leaf diffusive resistance, recording of visual stress symptoms. Recording of leaf temperatures by means of infra-red thermometers could also be used (Berliner, Oosterhuis & Green, 1984). All these techniques could with a certain degree of success detect the onset of stress in plants, but failed to give a clear distinction between soil- and atmospheric-induced stress.

Idso, Jackson, Pinter, Reginato & Hatfield (1981) were successful in separating soil- from atmospheric-induced stress by combining infrared thermometer readings with vapour pressure deficit determinations. This concept, named "Crop water stress index" (CWSI), was further developed by Reginato (1983). Laker (1983) suggests that this concept could also be valuable in combination with other crop water stress detection techniques.

1.2.4 New concepts in available water

As a consequence of the above mentioned arguments new definitions of available water were proposed by various authors. Most of them recognised the need for <u>in situ</u> determinations of field capacity. The dependency of the lower limit on effective rooting depth, root ramification, soil profile characteristics, evapotranspiration, crop (cultivar, root system...) and growth stage were also accepted.

Gardner (1983) explains the philosophy of the new concepts of available water on the basis of two figures (see Figures 1.2 and 1.3). In these figures the hypothetical rate of water loss from the soil profile is plotted as a function of the average water content (Figure 1.2) or water potential (Figure 1.3) of the soil profile. Curves for a few important soil textural classes are shown. At the right hand side of each curve the rate of water loss from the soil profile is very high due to transpiration and, dominantly, drainage. This will lead to water loss through deep percolation if the water content is kept at a too high level. At a lower

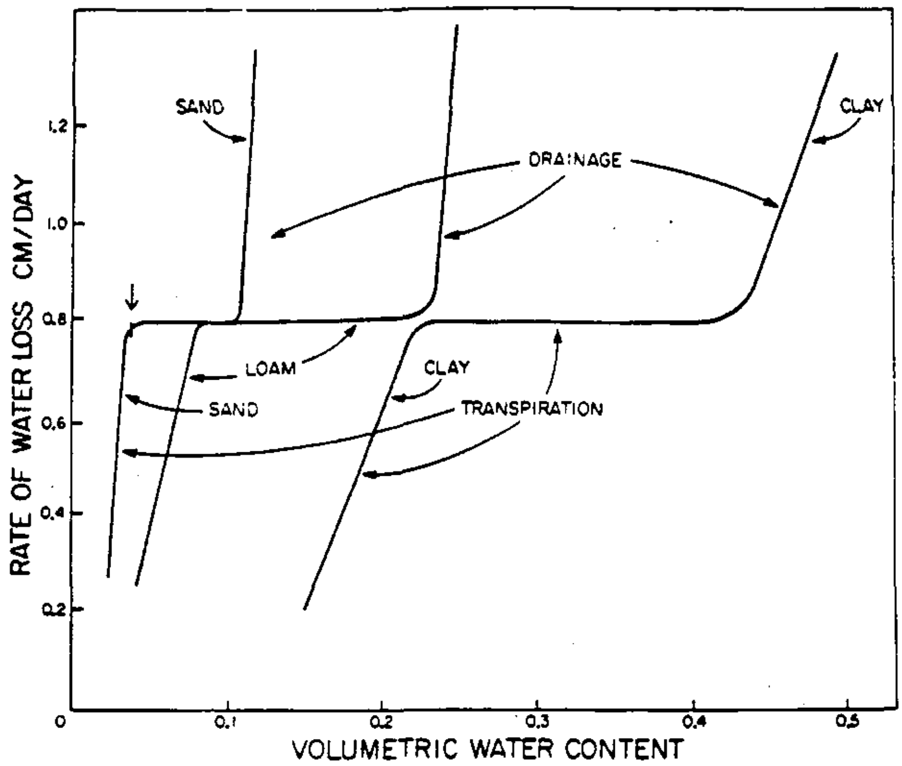


FIG.1.2 Hypothetical rate of water loss from a soil profile due to drainage and transpiration as a function of soil water content (from Gardner, 1983).

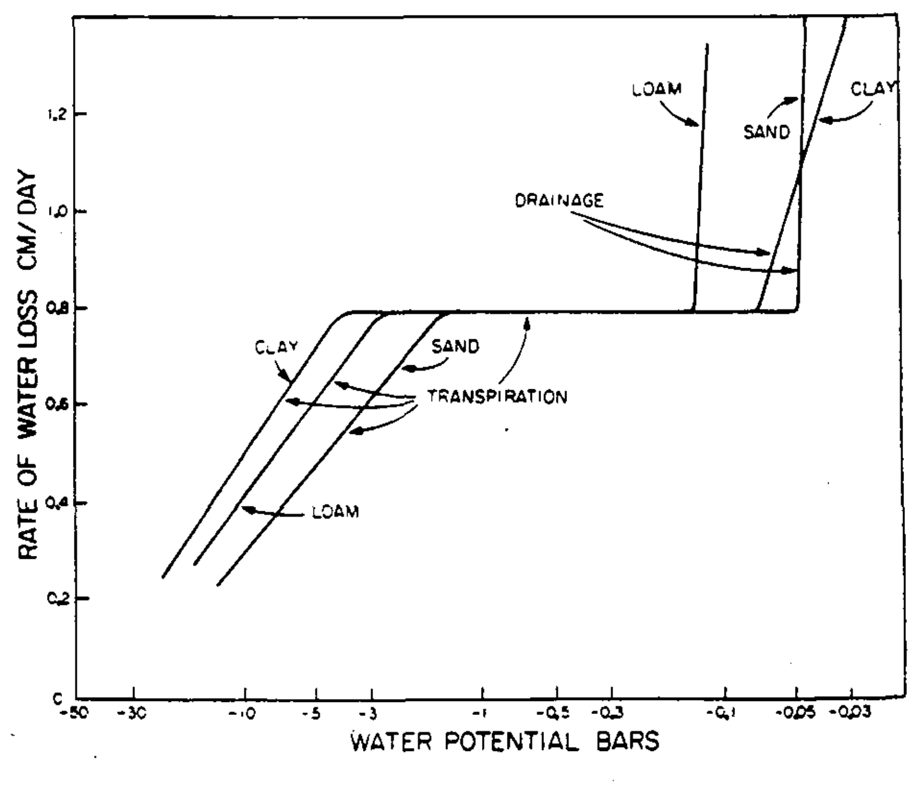


FIG.1.3 Hypothetical rate of water loss from a soil profile due to drainage and transpiration as a function of soil water potential (from Gardner, 1983).

water content (potential) the rate of extraction becomes constant (horizontal part of the curve) and drainage is negligible. When the soil water content is very low there is a sharp drop in transpiration rate due to stomatal closure and the crop is under stress. The exact position of the break point will depend upon plant and atmospheric factors and there is no single value that will apply to all soils. The plateau on each curve represents the available water range.

Ratliff _et al_ (1983) introduced the term "potential extractable soil water" (PLEXW). It is defined as the difference between _in situ_ measurements of both the upper and lower limits. The upper limit is defined as the "drained upper limit" (DUL). The in situ measured DUL is attained when the drainage rate in a thoroughly wetted soil profile becomes negligible and at that stage the decrease in soil water content is about 0,1 to 0,2% water content per day. The _in situ_ measured lower limit (LOL) is the field measured soil water content when plants become permanently wilted, die prematurely or become dormant as a result of soil water deficit. This concept of available water is very well illustrated in Figure 1.4: DUL (after 248 hrs) and LOL are compared with the traditional upper and lower limits of available water.

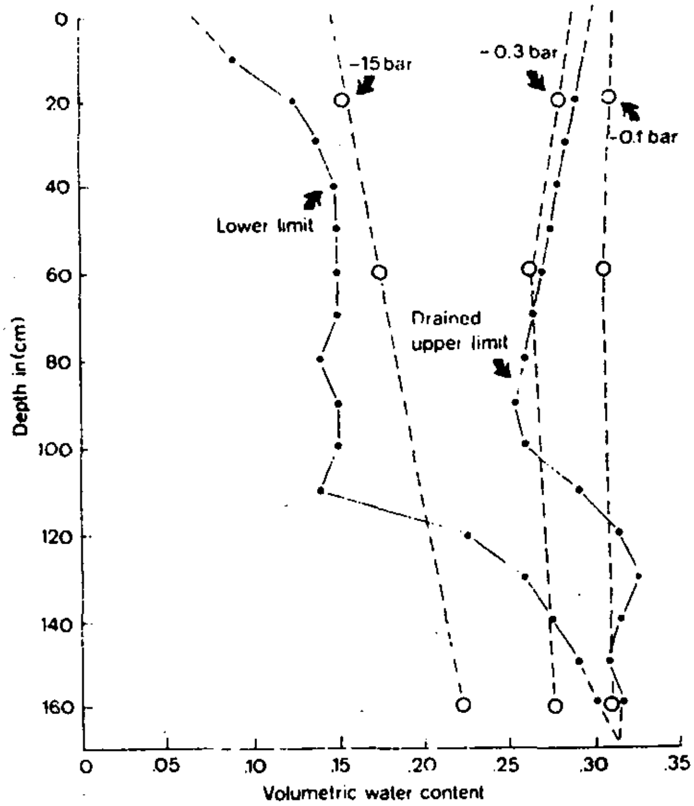


FIG.1.4 Soil water content profiles for various estimates of the lower and upper limits of water availability for a sorghum crop on Adelanto clay loam (from Ritchie, 1981).

Although this PLEXW-concept is very useful for dryland conditions it has serious limitations for use in irrigated agriculture. The upper and lower limits of PLEXW are both too low for irrigated crops: For drought sensitive crops the irrigation intervals are sometimes smaller than the time needed to reach DUL, and LOL is obviously too strict a criterion in a situation where high economic rendability is expected.

Hensley & De Jager (1982) developed a definition for available water that was applicable to an irrigation situation. They defined "profile available water capacity" (PAWC) for a specific crop (cultivar, growth stage) and soil under a certain evaporative demand as "the amount of water which is held in the effective root zone between field capacity and first material stress". The lower limit (first material stress) was defined as: "the quantity of water in the soil profile at the degree of crop water stress at which the next irrigation should be applied if optimum yield is to be obtained". Later this definition of the lower limit was somewhat changed to equate first material stress with well defined stress (Hensley, 1984). "First material stress can be defined as the soil water content at which plant physiological processes have been reduced by 25% of their

normal rate. This is considered to be the stage at which the next irrigation should be applied if optimum yield is to be obtained" (Hensley, 1984). Visual symptoms, leaf diffusive resistance, leaf water potential or the ratio between actual evapotranspiration and pan evaporation were used to define first stress.
The PAWC concept was tested out for several crops at full canopy development on a variety of soils and reproducable results were obtained. Hensley & De Jager (1982) and Laker (1982) proposed models for predicting PAWC at untested sites.

1.2.5 Relative availability of plant-available water

There exist wide differences of opinion as to the relative availability of soil water between the upper and lower limits of profile available water. New concepts of available water do not give a solution to this problem, which is of crucial importance in irrigation scheduling.

It was once generally accepted that soil water was equally available to plants from field capacity to wilting point (Viehmeyer & Hendrikson, 1927, 1949, 1950). This was disputed by Richards & Wadleigh (1952). Hsiao, O'Toole & Tomar (1980) stated: "if this principle of equal availability throughout the available water range would have been faithfully followed, much of irrigated agriculture would have been ruined".

Richards & Wadleigh (1952) produced evidence indicating that soil-water availability to plants decreases with decreasing soil water content. Other researchers (Doorenbos & Kassam, 1979) believe that, for a certain time after the soil has been brought to field capacity, plants can obtain water with equal facility. The higher the evaporative demand the shorter the period of "readily available water" (see Figure 1.5). The different opinions are graphically represented in Figure 1.6.

It is obvious that the relative availability of soil water will have a tremendous influence on the optimum length of irrigation intervals and it is therefore strange that so little research has been done in this field. In practice irrigators used what Hsiao <u>et al.</u> (1980) calls a "fudge" factor: allowable depletion of the available water range. Depending on the sensitivity of the crop and its growth stage a fraction of the total available water is the allowable depletion. For wheat this is supposed to be 55% of the amount of water between

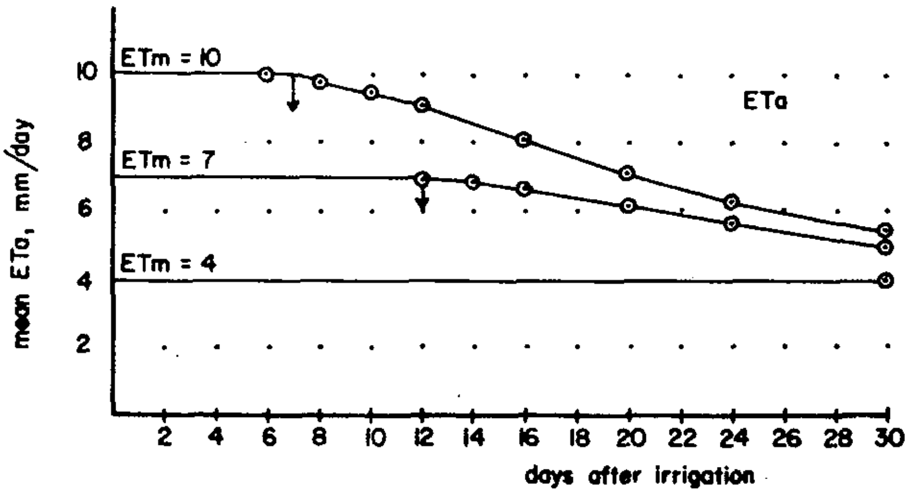


FIG.1.5 Mean actual evapotranspiration (ETa) over time after irrigation for different values of maximum evapotranspiration (ETm) (from Doorenbos & Kassam, 1979).

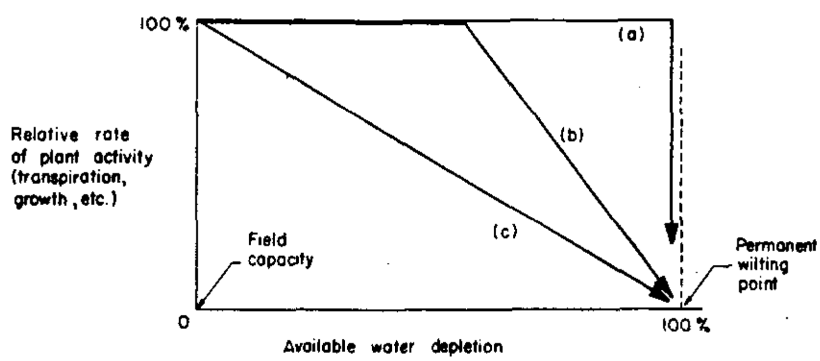


FIG.1.6 Three classical hypotheses regarding the availability of soil water to plants: (a) equal availability from field capacity to wilting point, (b) equal availability from field capacity to a "critical moisture" beyond which availability decreases, and (c) availability decreases gradually as soil moisture content decreases (from Hillel, 1980).

33kPa and 1500kPa soil moisture tension during the reproductive stage and 90% at ripening (Doorenbos & Pruitt,1977). The depletion levels were chosen very arbitrarily (safe-playing, one is afraid of given insufficient water) and are therefore unsatisfactory for irrigation scheduling purposes.

CHAPTER 2

DETERMINATION OF PROFILE AVAILABLE WATER CAPACITIES

2.1 INTRODUCTION

2.1.1 Upper limit of PAWC

Hensley & De Jager (1982) defined field determined field capacity as the upper limit of PAWC. Many researchers (F.A.O., 1979; Hsiao *et al*, 1980 and others) consider this as a suitable upper limit for available water. It has recently been emphasized that, whenever possible, field capacity should be determined in the field (Ratliff *et al*, 1983; Hillel, 1980; Miller & Aarstad, 1973). Miller (1963) and Hillel (1980) give guidelines for the *in situ* determination of field capacity.

Hensley & De Jager (1982) defined field capacity as the amount of water retained in a soil profile when free drainage has materially ceased.

During the present study field capacity was always determined in the field on a plot as close as possible to the site where the actual PAWC-experiments were conducted. The plots were approximately 3mx3m. In the centre of the plot a neutron probe access tube was installed so that regular water content measurements were possible. The plot received an abundant amount of water (a surplus to what was expected to refill the profile) and the soil was then allowed to drain. When all surface water was infiltrated the plot was covered with black plastic sheeting so that evaporation from the soil surface was avoided.

As a general guideline the soil moisture content 72 hours after the water was applied, was considered as field capacity. This was done in accordance with the current opinion that by that time drainage has dropped to a negligible rate. There are serious disadvantages to the use of such an arbitrary limit. Firstly the water that is consumed by the crop and water loss by evaporation during the period of drainage towards "field capacity" is not taken into account. Secondly this limit does not take the dynamic nature of soil water into account. Drainage, especially unsaturated flow out of the rooting zone, can continue for much longer than 72 hours (Stone *et al.*, 1973; Ritchie, 1981).

The first problem was recognised by Wilcox (1962) and Miller & Aarstad (1973). Hensley & De Jager (1982) use the term "expanded" PAWC to accommodate this "additional" water consumed by evapotranspiration. Miller & Aarstad (1973) estimate this amount with the following formula:

$$Evt = \frac{Et \times d}{K} \qquad [2.1]$$

where Evt = evapotranspiration before field capacity is reached (mm)

Et = mean consumptive use (mm/day)

d = effective rooting depth (mm)

K = mean rate of movement of the wetting front (mm/day)

If this amount was taken into account it would make the definition of available water directly dependent on evaporative demand. This can be clearly seen from the formula. If one considers:

$$\frac{d}{K} = 3$$

(three days to reach field capacity) and a mean consumptive use of 10mm/day, an additional 30mm can be added to the profile available water of soils in regions with a high evaporative demand.

Water content determinations at regular intervals in pre-wetted covered plots will not give the information that is applicable to practical field conditions in a cropped plot: evaporation, transpiration and drainage are occurring simultaneously! Drainage will be much lower in a soil where a crop is actively growing than in a bare, covered plot.

Although Hensley & De Jager (1982) recognised the importance of consumptive use during drainage towards "field capacity" they did not include it in the upper limit of PAWC. For this reason and because it would introduce an inconsistent variable to the PAWC concept it was also not included in the present study.

Drainage rate per day on day n (Dn) can be calculated with the equation:

$$\theta_n z = \theta_{n\ 1} z + Pn - ETn - Dn \qquad [2.2]$$

whereby θ_n is the average water content of an entire profile of depth z at the end of any day n, θ_{n-1} is the corresponding water content on day n-1, Pn is recorded precipitation or irrigation and ETn is the evapotranspiration.

Ritchie (1981) uses this equation for the calculation of unsaturated flow out of the rooting zone in a field where a crop is growing.

Figure 2.1 shows drainage rates found for several soils in the Vaalharts area during the present study. It can be concluded from this figure that in the cases of Kamp I and Kamp II 72 hours was sufficient to allow for free drainage. For the very deep, sandy Mangano soils at the Van der Linde I and II and Demonstration plot sites 96 to 120 hours were needed to allow for free drainage in cropped plots. Figures 2.2 (a, b, c, d) illustrate soil moisture profiles at several days after water application to plots on which no crops were growing. It can be seen that after three to five days there is still considerable drainage taking place. It is possible that part of this drainage is in fact lateral flow to the much drier soil surrounding the test plot.

In the Ciskei and the Loskop area the internal drainage of the soils was much slower than in the more sandy soils

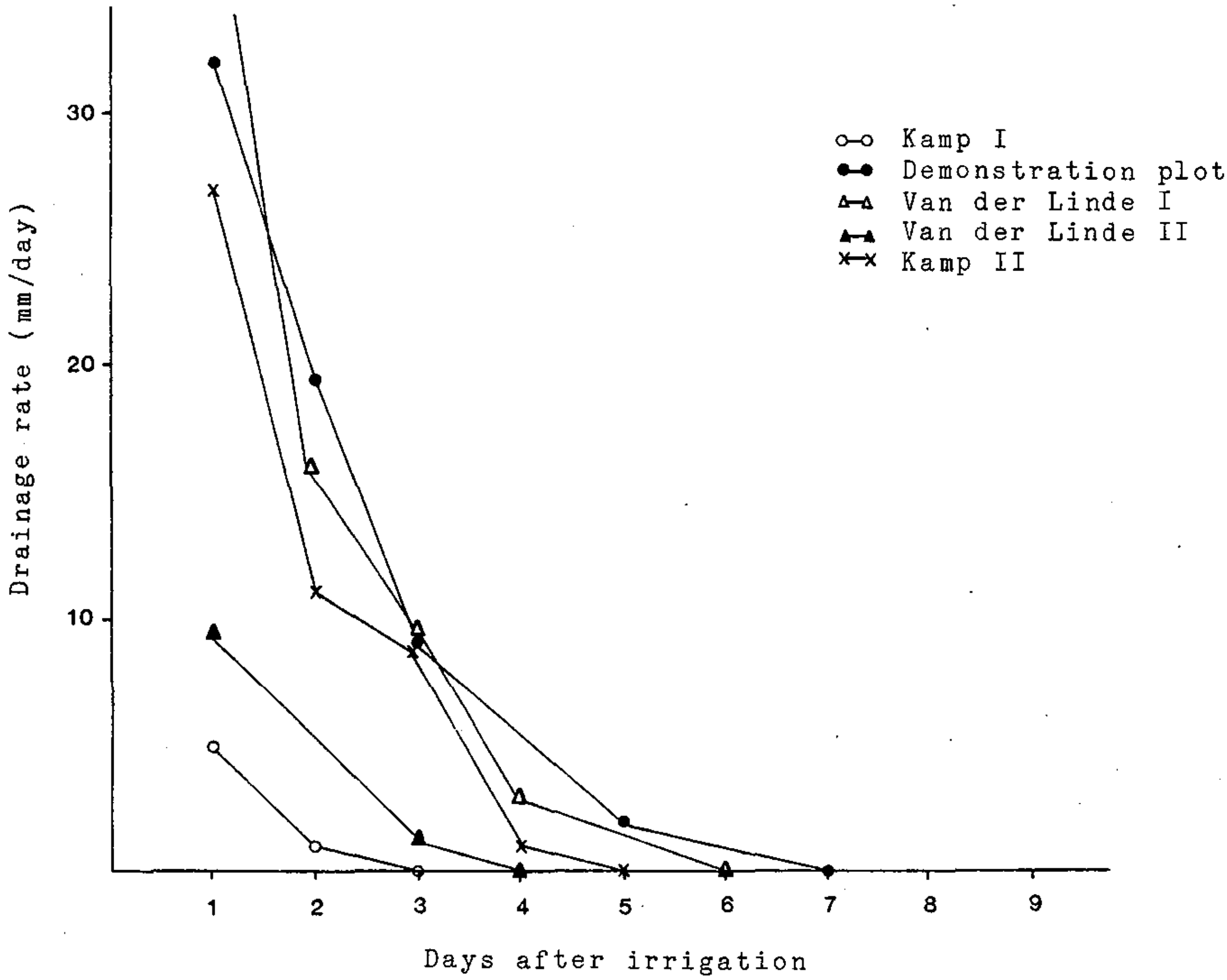


FIG.2.1 Drainage rates for some experimental sites at the Vaalharts irrigation scheme (uncovered plots, wheat at flowering). The drainage rates were calculated with equation 2.2.

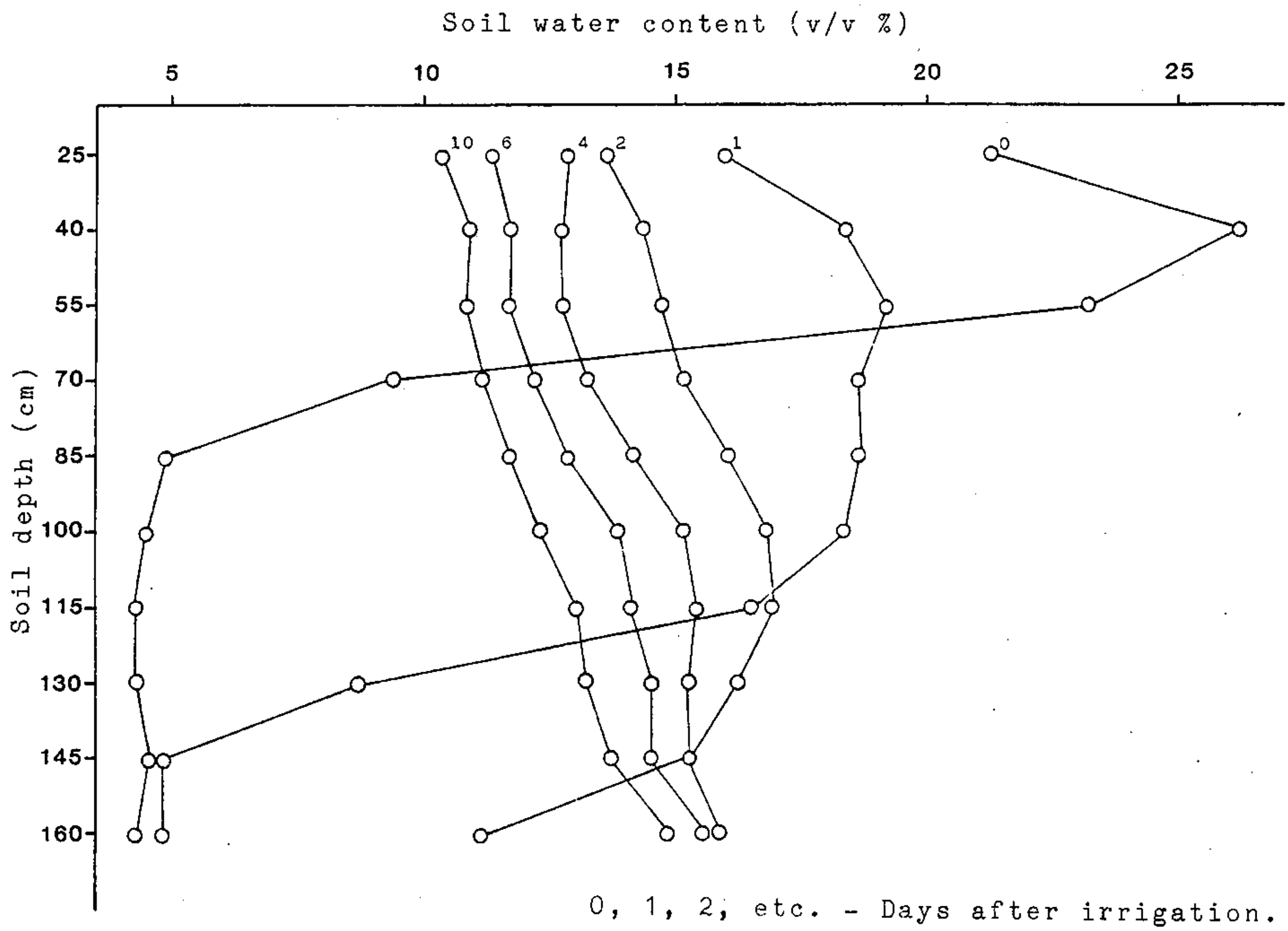


FIG.2.2 (a) Soil profile water contents at different days after irrigation (uncropped, covered plot at Demonstration plot).

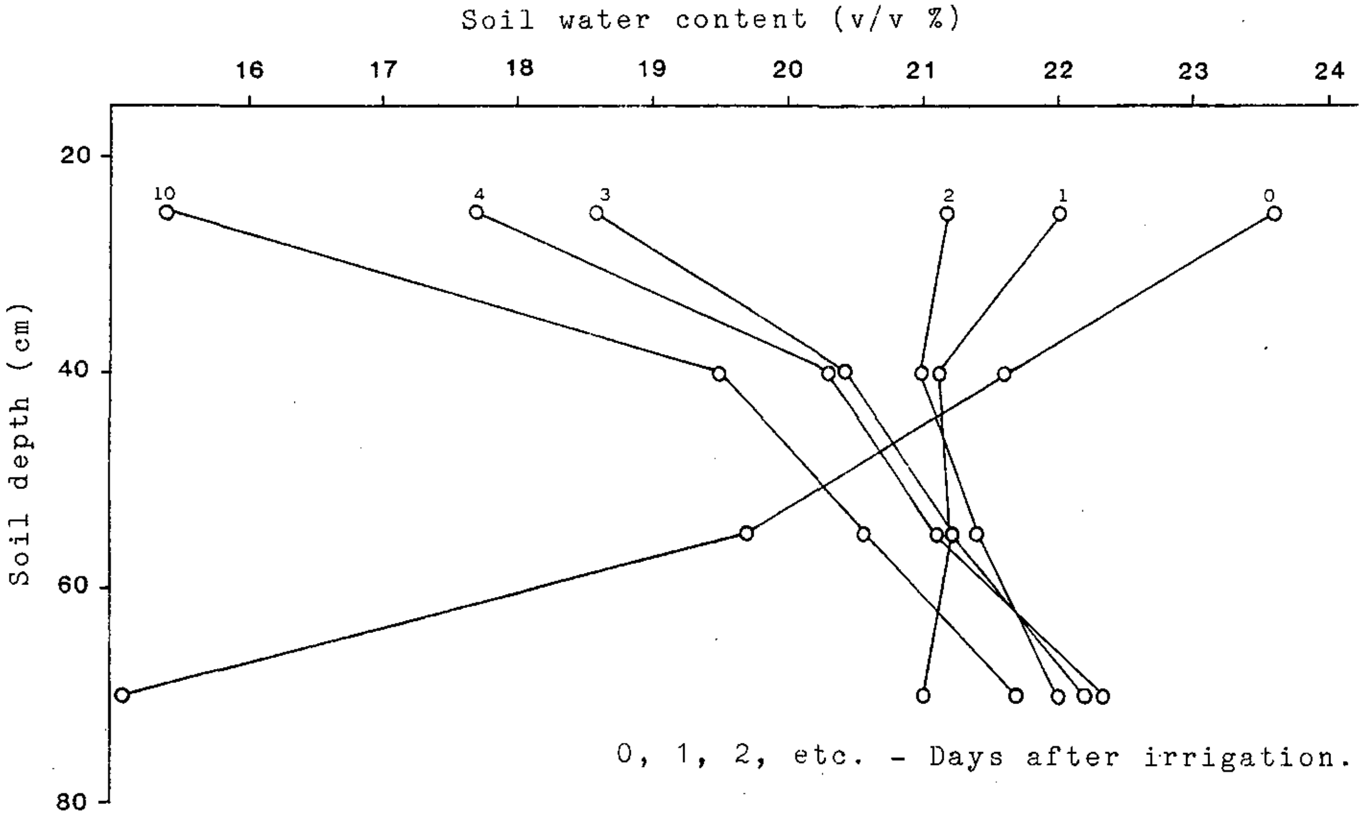
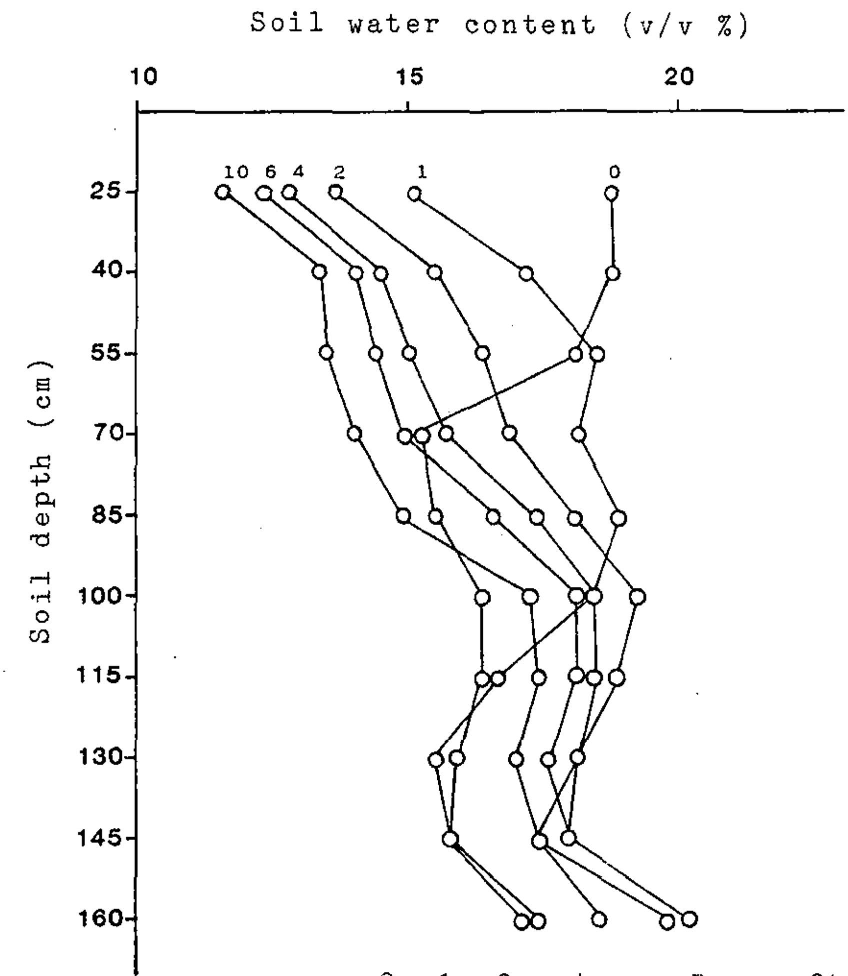
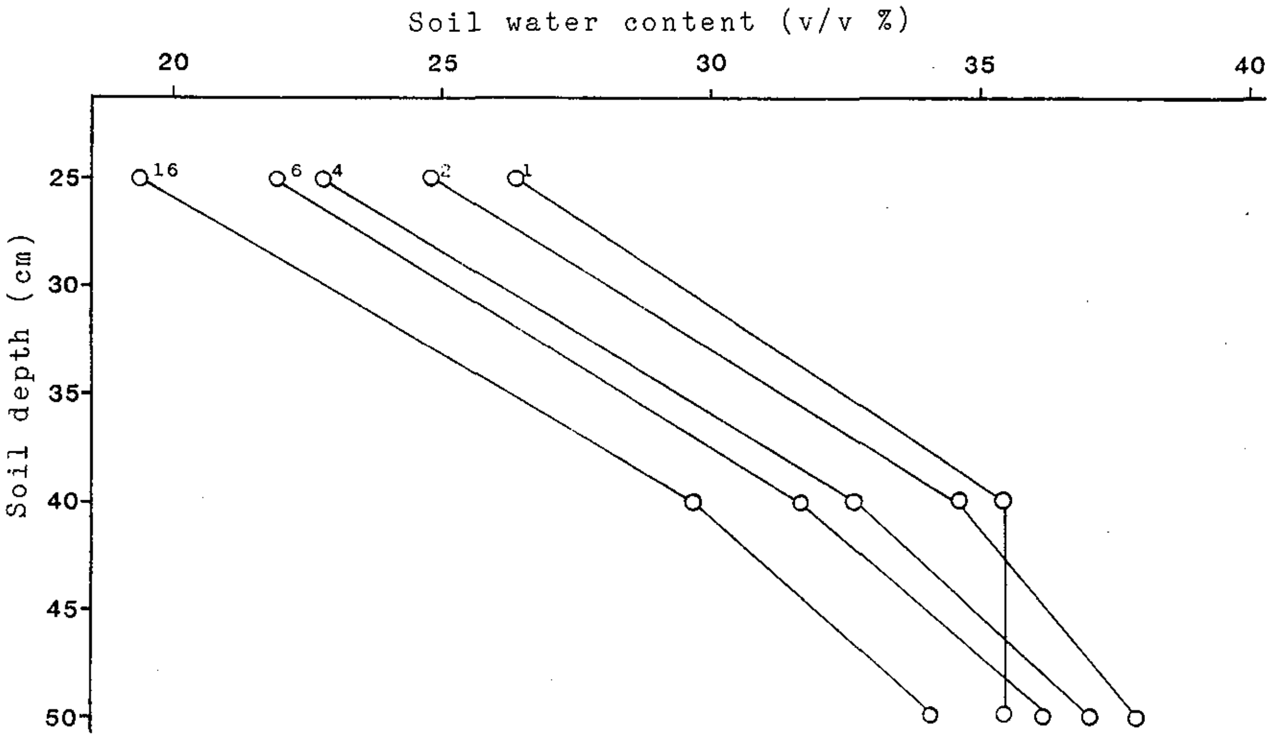


FIG.2.2 (b) Soil profile water contents at different days after irrigation (uncropped, covered plot at Kamp I)



0, 1, 2, etc. - Days after irrigation.

FIG.2.2 (c) Soil profile water contents at different days after irrigation (uncropped, covered plot at Van der Linde II).



1, 2, 4, etc. - Days after irrigation.

FIG.2.2 (d) Soil profile water contents at different days after irrigation (uncropped, covered plot at Kamp II).

of the Vaalharts area. Also the medium-textured Stanford soil in the Vaalharts area drained quickly to field capacity. No considerable water loss through deep percolation could be noted with the formula presented by Ritchie (1981). The layers occurring low in the soil profile took much more than 72 hours to be brought to field capacity. Observation of the extraction patterns by the different crops helped to decide on the upper limit of available water in these cases. This will be discussed in detail when the different test sites are treated separately.

2.1.2 Lower limit of PAWC

Hensley & De Jager (1982) and Hensley (1984) defined the lower limit of PAWC in terms of plant performance. From this it must be concluded that the lower limit of PAWC is a variable, which will vary according to the crop (growth stage, cultivar, rooting habit..). Sensitivity to drought varies with crop and, additionally, the physiological processes taking place in a plant are affected in different ways when the crop is water stressed (Hsiao, 1982).

An ideal situation for determining the lower limit of available water would be where abundant yield data, combined with data regarding the quantities of water extracted by the crop, are available. Information regarding both water extraction between successive irrigations and total seasonal consumptive use are relevant. This is unfortunately non-existent for most irrigation schemes of the world. In irrigated agriculture crops cannot be allowed to be severely stressed (except in special cases for initiating fruiting or promoting other desirable physiological processes) because productivity, and consequently economic rendability would be harmed. Crop water stress can, therefore, be used to indicate the lower limit of PAWC.

Several techniques were developed to detect crop water stress (see literature review). During the present research preference was given to leaf water potential determination to indicate stress. Hensley & De Jager (1982), Green (1982), Ritchie & Hinckley (1975) and others found this method reliable and usable in the field. Pre-dawn readings were used in an effort to separate soil- from atmospheric-induced stress.

Ψ pd (leaf water potential measured before dawn) is a function of soil moisture availability only, if it is assumed that during the night low atmospheric demand for water and stomatal closure prohibit transpiration. The water potential gradient which existed in the plant during the previous day has been equalized and equilibrium has been established with the soil (Ritchie & Hinckley, 1975). Hsiao _et al_ , (1980) stress the value of pre-dawn leaf water potential as a stress indicator since: "as transpiration is greatly reduced (or even eliminated) at night, the tissue refills with water until dawn. At that time, leaf water potential approaches equilibrium with the soil water potential and hence is indicative of the soil water status in the rhizosphere".

The principle is explained in Figure 2.3

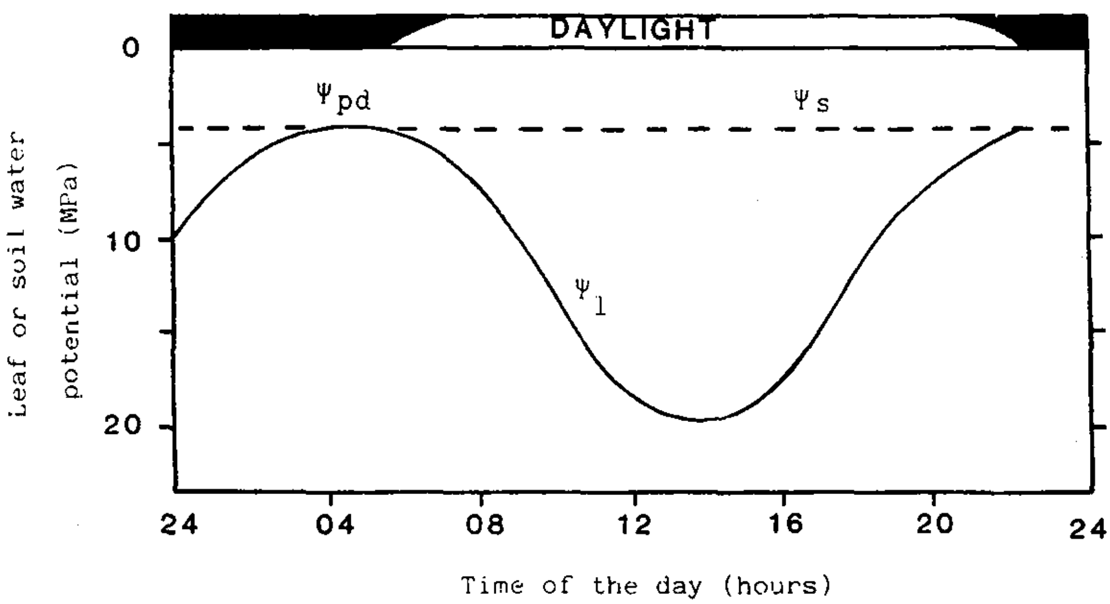


FIG.2.3 An idealized diurnal curve showing the change in leaf water potential (Ψl) with time. Just before dawn the leaf water potential (Ψpd) equals the soil water potential Ψs. During the day time the leaf water potential drops considerably to reach a minimum around midday. During the afternoon and the night the leaf water potential equilibrates again with the soil water potential.

It is important to realise that pre-dawn leaf water potential reflects the soil water potential close to the roots and not of the soil profile as a whole. Therefore, as the crops are growing, pre-dawn leaf water potential will remain constant until a certain threshold value (initial stress indication) is reached and the potential will start to decline significantly while, at the same time, the soil water content in the profile will gradually decrease (see Figure 2.4).

According to Hensley (1984) identification of the threshold value for first stress, and thus for the lower limit of available water, on the pre-dawn leaf water potential curves can be problematic. Consider the hypothetical curves in Figures 2.5 and 2.6: No problems are encountered in cases represented by Figure 2.5. The pre-dawn leaf water potential drops dramatically after point A and a clear indication of the onset of crop water stress is obtained. In Figure 2.6 the situation is somewhat different: it is not sure whether the slight drop in leaf water potential at point B is significant. Once point C is reached the crops may be under too much stress already. Hensley (1984) predicted maximum yield/unit land if B is used as lower limit, but

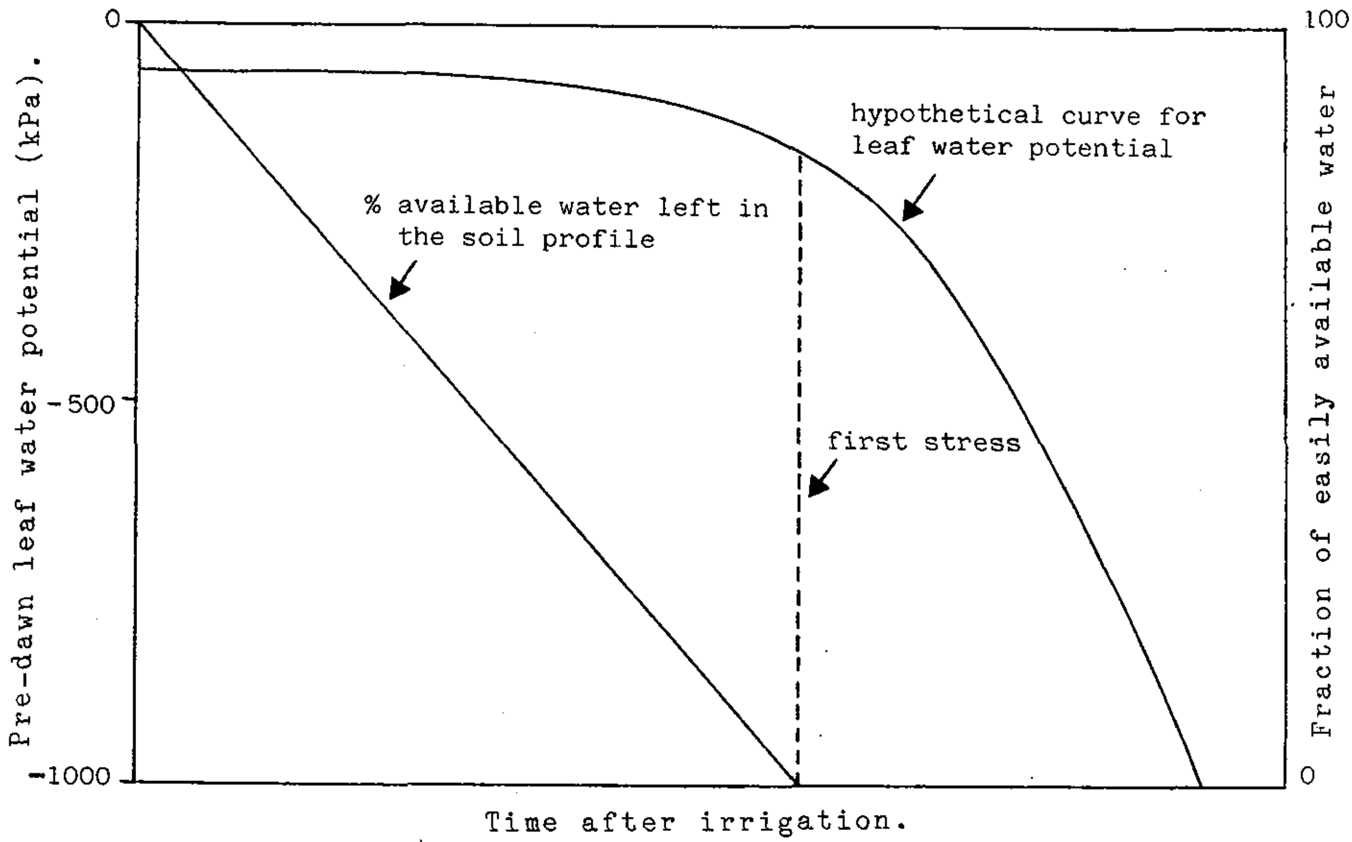


FIG.2.4 Schematical diagram of the leaf water potential - available water relationships (available water is considered here to be the amount of water that can be extracted from the soil profile without reducing yields significantly).

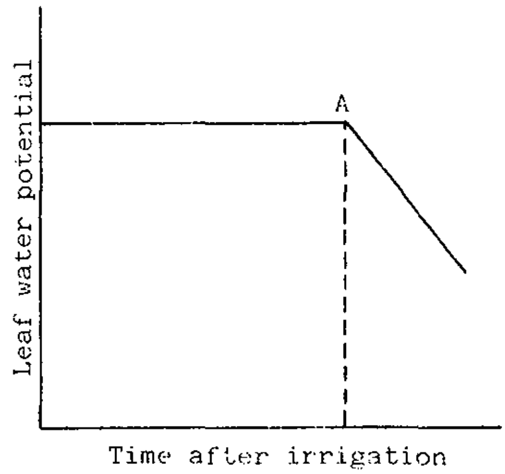


FIG.2.5 Characteristic curve showing the change in leaf water potential as a drying cycle progresses. After Hensley & De Jager (1982).

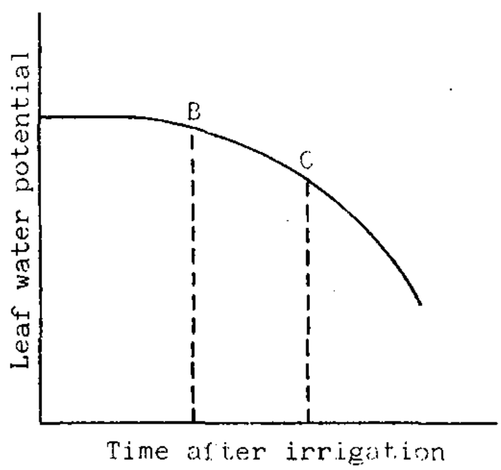


FIG.2.6 Characteristic curve showing the change in leaf water potential as a drying cycle progresses. After Hensley & De Jager (1982).

increased water use efficiency (yield/unit water) if C is used as lower limit. Hensley (1984) used point C as "first material stress".

Generally it appears that pre-dawn leaf water potential measurements give satisfactory indications of first stress, and consequently of the lower limit of available water, if the evaporative demand of the atmosphere is not too high. During summer time, under very high evaporative demand (often class A-pan readings of up to 14mm/day were found), it was in the present study found that this technique was not reliable. Under such extreme conditions visible wilting was observed during early morning, while pre-dawn leaf water potential readings were still at a high level. Under these conditions visual stress symptoms at 09h00 were arbitrarily used as an indication of first stress. The usual visual stress criterion of wilting at 10h00 or 10h30 (Hensley & De Jager, 1982) could not be used under these extreme conditions since at this time of the day plants would wilt even in soils at field capacity.

The relatively wide range of soil and climatic conditions for which PAWC determinations were made in the present study, the use of very efficient neutron hydroprobes, and the collection of extensive yield data, facilitated some revision and major refinements in the identification of the lower limit of PAWC by means of pre-dawn leaf water potential measurements. This will be discussed in detail later.

2.2 RESEARCH PROCEDURES

The research was conducted in three important irrigation regions of Southern Africa during four growing seasons. During the winter season of 1982 PAWC-determinations were done in the Ciskei. During the following summer ('82-83) and winter ('83) seasons the research was conducted at the Vaalharts irrigation scheme. PAWC-determinations were done at the Loskop irrigation scheme during the summer of '83-'84.

This geographical distribution of the experiments allowed a study of the influence of interactions between different soils, crops and evaporative demands on PAWC. The prime objective of the research was to assess profile available water capacities and to develop models for predicting PAWC at unknowm sites. Hanks (1982) stressed the need for identical experimental procedures at different locations. Data from different regions, under different climatic conditions are more comprehensive and consequently more useful in model testing than if only one site had been tested.

2.2.1. Site description and soils

Figure 2.7 indicates the localities of the three regions where the research was conducted. More precise location of the individual experimental sites in the three areas is given in Figures 2.8, 2.9, 2.10.

The original PAWC research was conducted in the Ciskei (Hensley & De Jager, 1982). Several projects, aimed at agricultural development, are presently being conducted in the region, many in the field of irrigated agriculture. For these reasons the Ciskei was the obvious place to start the experiments reported here. The soils in the area are formed on grey mudstone, shales and sandstones of the Balfour Formation (Beaufort group). In the area where the experiments were done the grey mudstones are most dominant, which is reflected in the relatively high silt contents in many of the soils. The study area has an average rainfall that ranges between

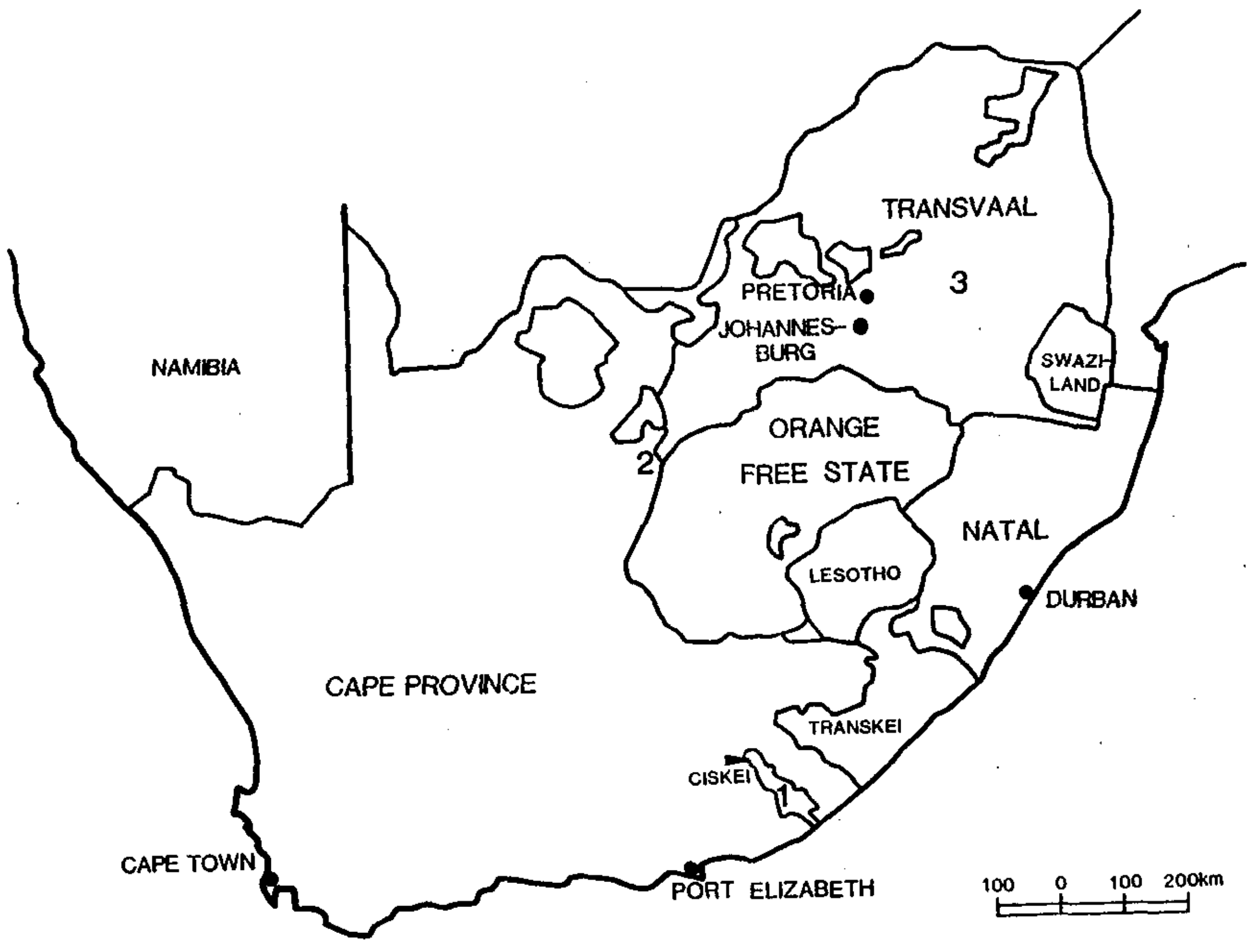


FIG.2.7 Situation of the regions where the study was conducted

1. Ciskei.
2. Vaalharts Irrigation Scheme.
3. Loskop Irrigation Scheme.

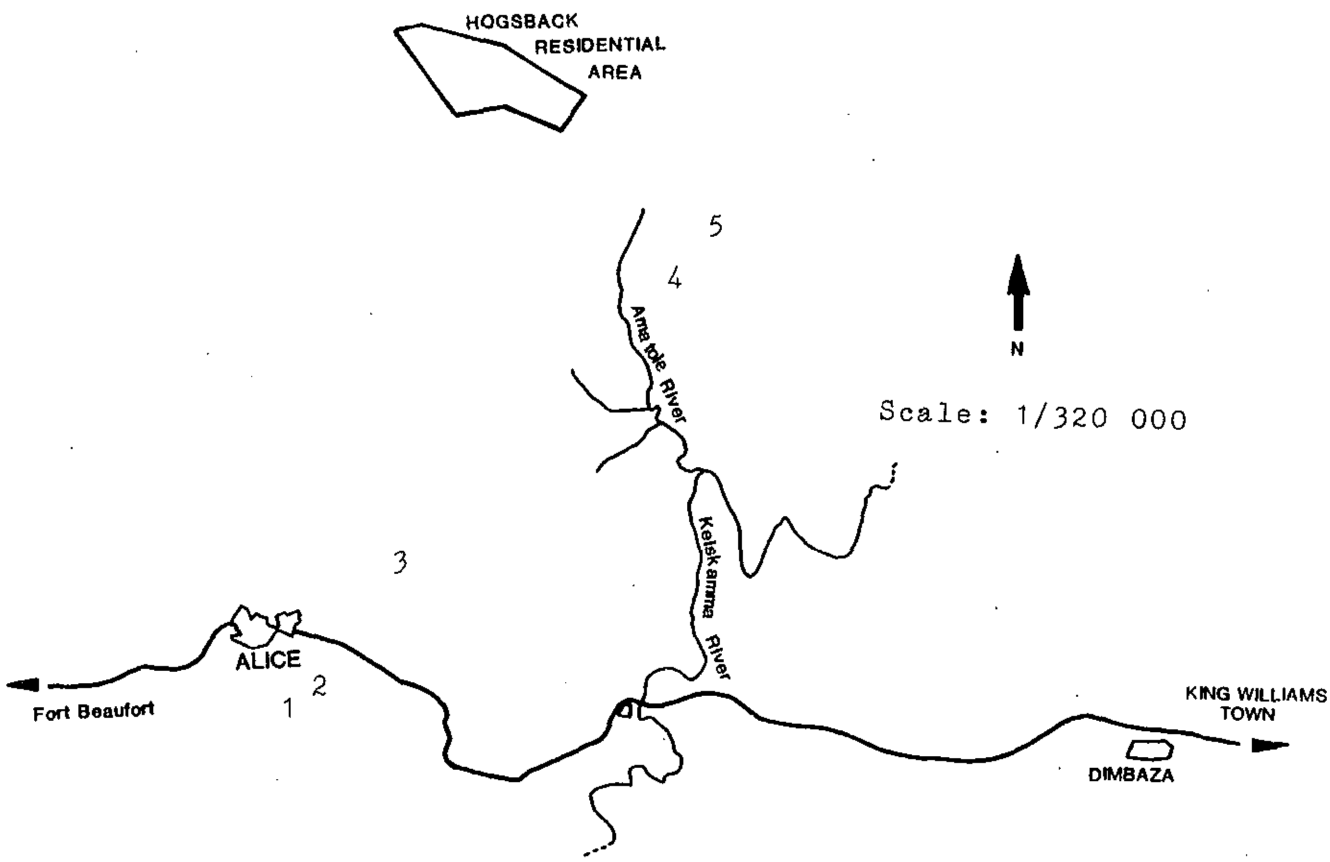


FIG.2.8 Situation of the experimental sites in the Ciskei.

1. Jozini
2. Sterkspruit
3. Kinross
4. Marikana
5. Arniston

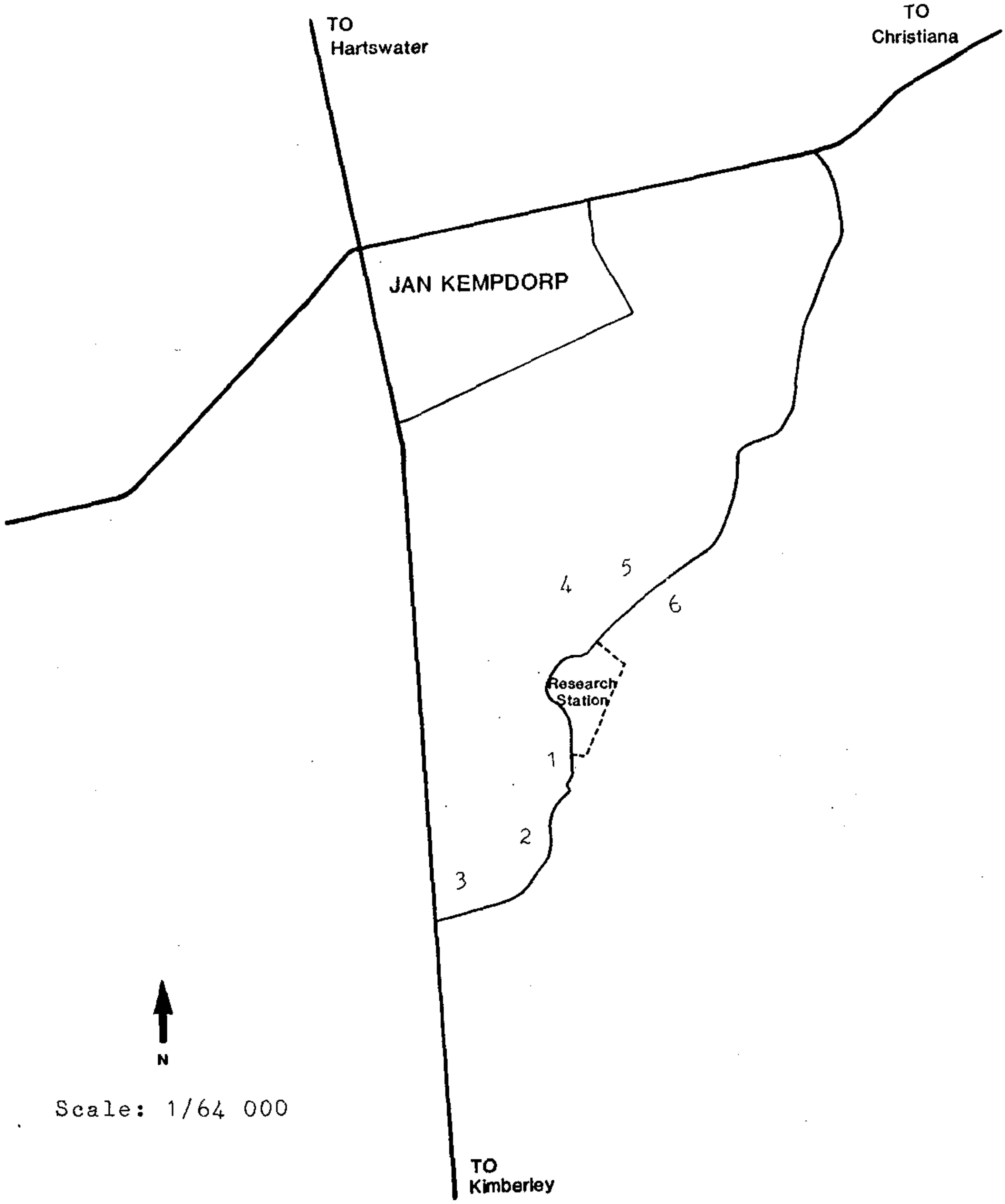


FIG.2.9 Situation of the experimental sites at the Vaalharts Irrigation Scheme.

1. Kamp I.
2. Kamp II.
3. Kamp III.
4. Demonstration plot.
5. Van der Linde I.
6. Van der Linde II.

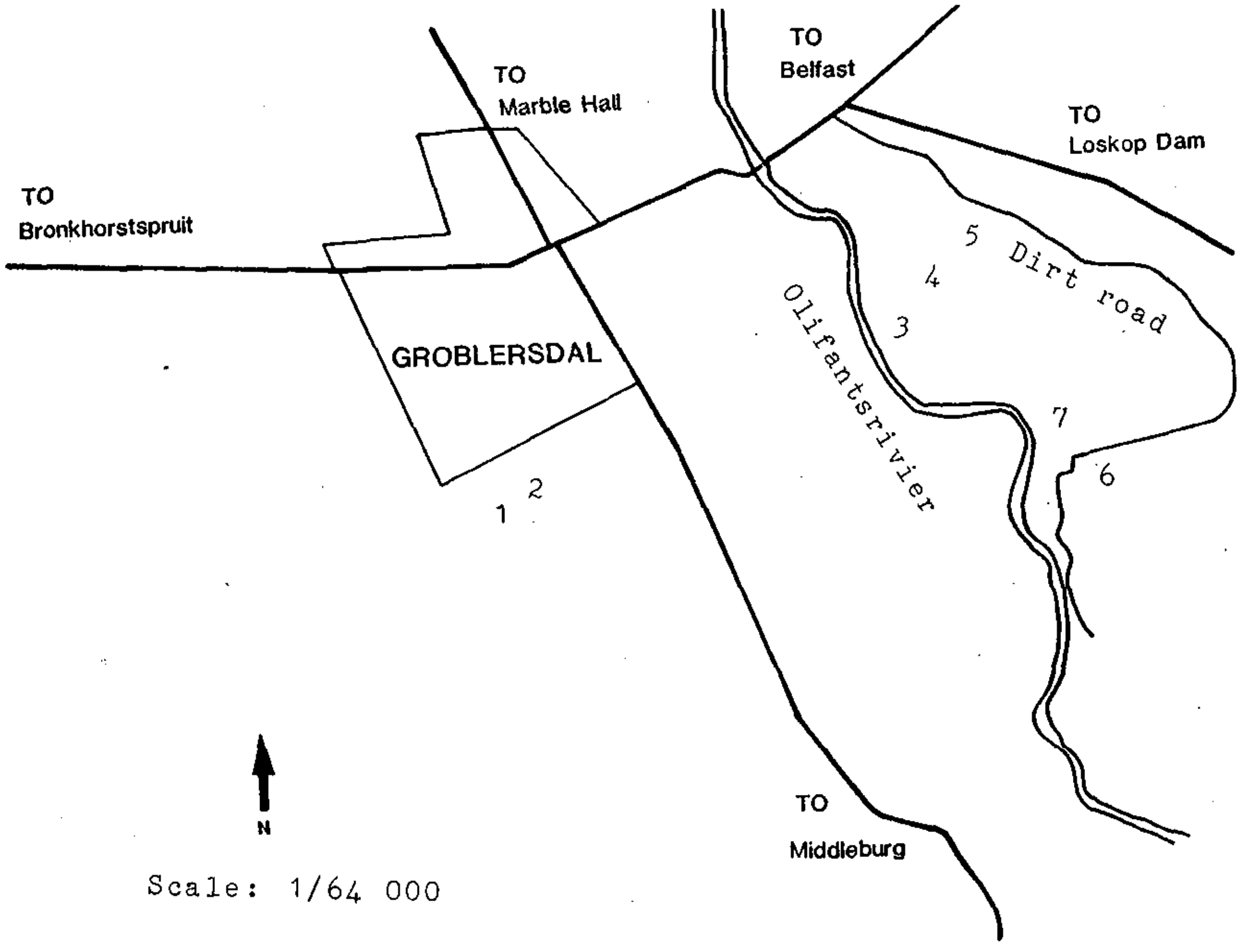


FIG.2.10 Situation of the experimental sites at the Loskop Irrigation Scheme.

1. Contour 5
2. Contour 10
3. Du Preez I.
4. Du Preez II.
5. Du Preez III.
6. Venter I.
7. Venter II.

550mm and 650mm and throughout the year potential evapotranspiration exceeds precipitation (Laker, 1978). The altitude of the experimental areas is about 500 to 900m above sea level.

The Vaalharts irrigation scheme is situated in the nothern Cape Province, close to the point where the boundaries of the Transvaal, Cape Province and Orange Free State intersect. Vaalharts is the largest irrigation scheme in South Africa and comprises about 35 000 hectares. There is a great need for information regarding plant-water relationships under the extreme climatic conditions of this region. The climate is distinctly aridic with a mean annual rainfall of 446mm and potential evapotranspiration figures of 850mm per year. The soils in this area are formed on the red, aeolian continental Kalahari sands and have therefore an extremely high fine sand content (Eloff, 1984). The scheme is at an altitude of about 1150m above sea level.

The Loskop irrigation scheme is situated in the centre of the Transvaal province. The scheme is situated on soils formed on igneous rocks of the Bushveld Complex. The region is of extreme economic importance because of its tobacco, cotton and maize seed production. It has, in addition, great potential for vegetable production as the scheme is close to the most densily populated area of the country. The area has an average annual of 667mm. The potential evapotranspiration is 1030mm per year. The area is at an altitude of about 1050m.

According to their texture and diagnostic horizons a selection of important, dominant soils was made for the research in the different regions. The aim of the selection was to present an, as wide as possible variety of textures, diagnostic horizons and effective rooting depths.

Because of the specific nature of the experiments it was sometimes very difficult to find suitable sites. Occurrence of a permanent or periodic watertable had to be avoided. Whenever possible the sites were situated away from irrigated fields to prevent influences of water applications by other irrigators. Additionally, the sites had to be close together so that pre-dawn leaf water potential readings were possible within a short time interval. Finally 5 experimental sites were selected in the Ciskei, 7 at Vaalharts and 7 at Loskop. According to the South African binomial soil classification system (Macvicar, De Villiers, Loxton, Verster, Lambrechts, Merryweather, Le Roux, Van Rooyen, Harmse, 1977) these soils are classified as follows:

Area	Site name	Soil classification Series	Form
<u>Ciskei</u>	Jozini	Jozini	Oakleaf
	Sterkspruit	Sterkspruit	Sterkspruit
	Hutton	Marikana	Hutton
	Shortlands	Kinross	Shortlands
	Valsrivier	Arniston	Valsrivier
<u>Vaalharts</u>	Kamp I	Maitengwe	Hutton
	Kamp II	Stanford	Sterkspruit
	Kamp III	Mangano	Hutton
	Demonstration plot	Mangano	Hutton
	Van der Linde I	Mangano	Hutton
	Van der Linde II	Mangano	Hutton
	Joubert	Swaerskloof	Sterkspruit
<u>Loskop</u>	Contour 5	Glendale	Shortlands
	Contour 10	Kinross	Shortlands
	Du Preez I	Shorrocks	Hutton
	Du Preez II	Sunvalley	Shortlands
	Du Preez III	Shigalo	Hutton

Venter I	Kinross-Glendale	Shortlands
Venter II	Shorrocks	Hutton

The soils cover a texture range from sand to heavy clay (5% to 60% clay). The most important diagnostic subsoil horizons are represented and the effective soil depths vary from 700mm to more than 2000mm. Detailed profile descriptions and analyses of the soils are given in Appendices 1.1 to 1.19.

The Jozini and Sterkspruit soils from the Ciskei region were the same ones that were used by Hensley & De Jager (1982) in their PAWC research. These sites were included as a control on the reproducibility of PAWC values. Soils similar to the Arniston series (Valsrivier form) often occur on low lying river terraces of the Ciskei where water can easily be diverted onto them for irrigation. The Shortlands and Hutton soils are important, high potential soils in the Ciskei region.

Deep soils of the Hutton form and soils from this form underlain by a $CaCO_3$ layer occur abundantly in the

Vaalharts region. The Sterkspruit soil at Vaalharts was included in order to compare the extraction patterns on this soil with the extraction patterns of the Sterkspruit soil in the Ciskei.

The soils used in the Loskop area are important, dominant soils for that region which were selected in consultation with local researchers.

2.2.2 Protection against rain

Rainsheds were constructed over plots to avoid influences of rain water at critical stages of the experiments (when the mature plants are just about to show stress).

In the Ciskei it was necessary to construct permanent covers because the sites were at considerable distances from each other and it would have been impossible to cover all the plots if a sudden rainstorm would have occurred. A relatively cheap type of wooden construction, covered with uvidek plastic was used (see Figures 2.11 and 2.12). The sides of the shed were left open to permit free movement of air. The sheds were built sufficiently wider and longer than the experimental areas to prevent rain being driven onto the plots through

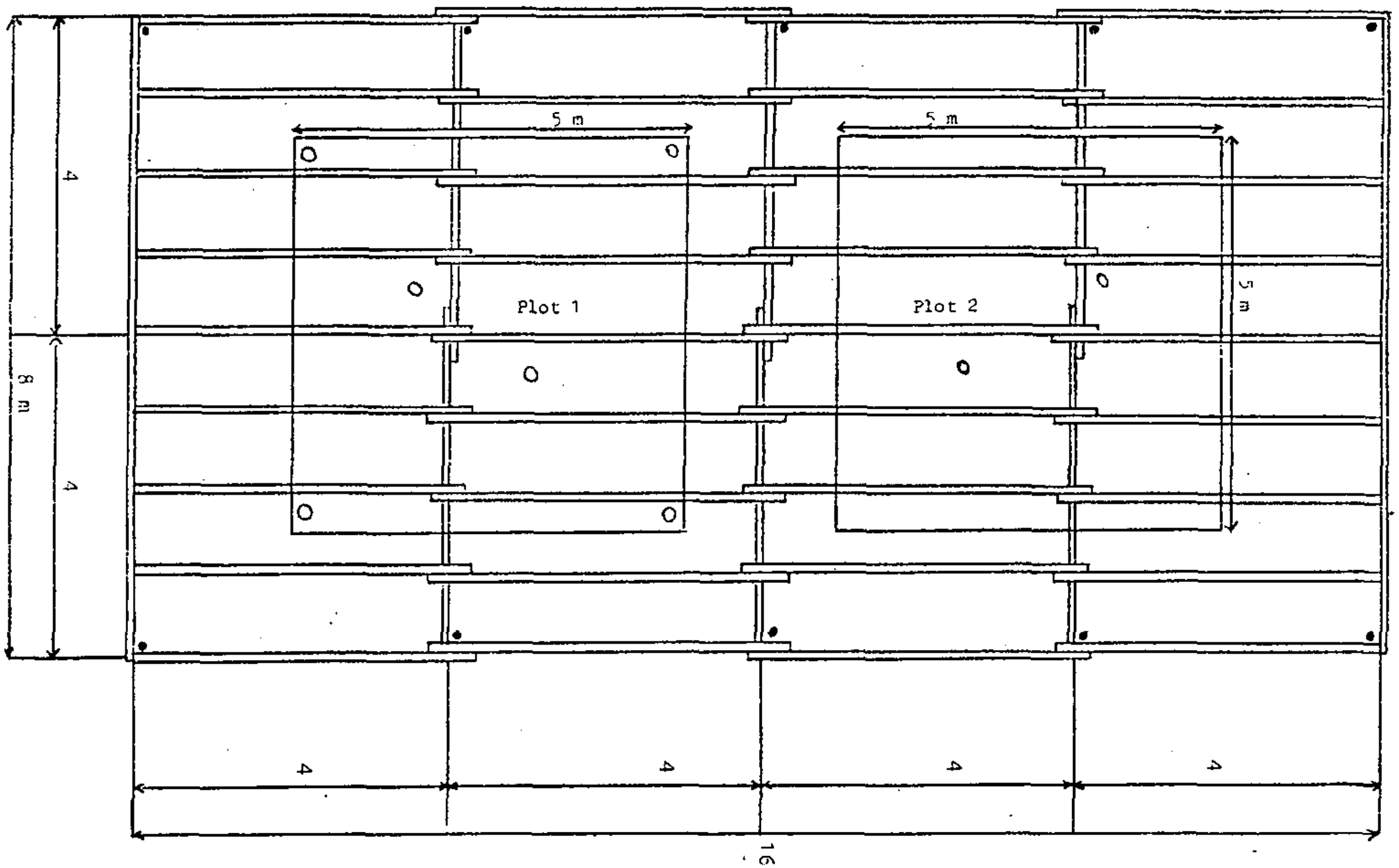


FIG.2.11 Top-view of a rainshed used during the field experiments conducted in the Ciskei.

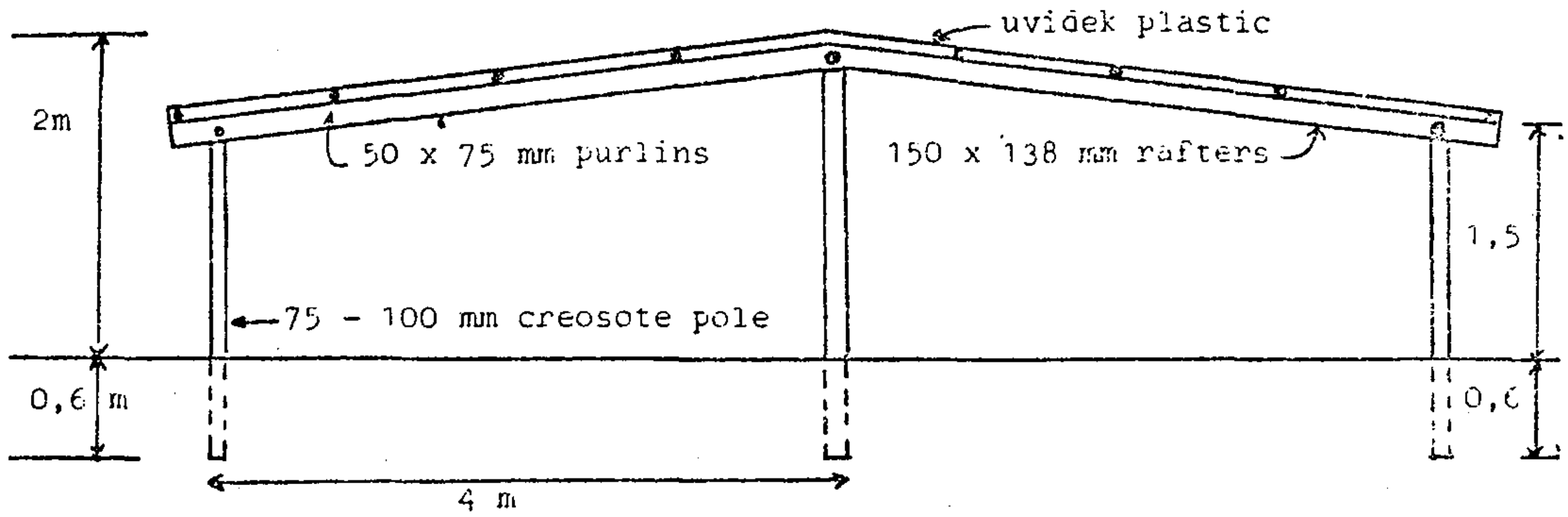


FIG.2.12 End-vieuw of a rainshed used during the field experiments conducted in the Ciskei.

the open sides by wind. Small ditches were dug to carry off water that ran off from the plastic cover. Ground walls around the experimental area prevented run-on of water. The height of the sheds was such that free movement of air between the top of the crop (wheat or peas) and the roof of the shed was permitted.

No permanent cover was mounted over the crops during the Vaalharts experiments with wheat, peas and cotton because it was considered that there would be ample warning of any possible rainstorm. The sites were fairly close together and access roads very good so that quick action was posible. Frameworks were built over the plots so that uvidek plastic roofs could be rolled over the sites in case of threatening rain (see Figure 2.13). These constructions were thought to be impracticable for tall plants such as maize. A low, permanent shed (see Figure 2.14) was therefore constructed which left the majority of the maize leaves open to the atmosphere. The soil was shielded from rain by mounting strips of uvidek plastic between the rows and sealing the strips between the plants in the row by means of tape.

At Loskop the experimental sites were again far apart but time did not allow for the construction of permanent

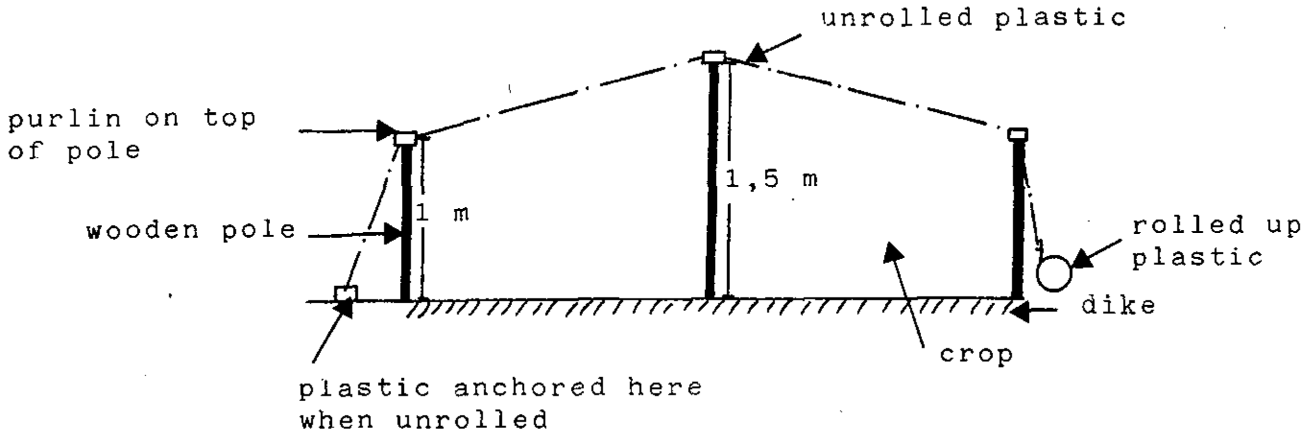


FIG.2.13 Semi-permanent rain cover used during the Vaalharts winter experiments.

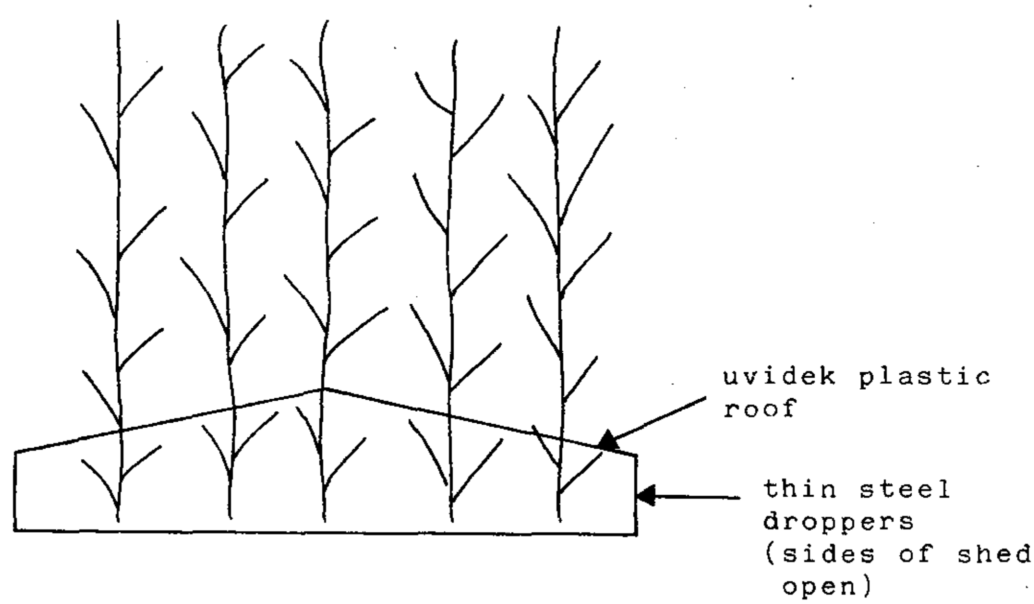


FIG.2.14 Permanent rain cover for maize experiments at Vaalharts.

sheds, such as described for the Ciskei experiments. Frameworks similar to the ones used for cotton, peas and wheat at Vaalharts were made. Fortunately the researcher was assisted by two fieldworkers at this stage and quick covering of the plots was possible in case of rain.

Hail netting was installlled as a precaution at the Loskop and Vaalharts experiments because both regions are subject to hailstorms, especially during early summer. This measure proved to be valuable at Vaalharts and the summer experiments were undamaged after a severe hailstorm. At Loskop it could not prevent the complete destruction of young cotton plants and replanting of cotton had to be done at almost all sites.

At Vaalharts severe damage to young crops was caused by rabbits during the 1983 winter. A chicken wire fence had to be erected around the experimental sites to avoid further losses.

2.2.3 Experimental design

Throughout the field work it was tried to keep as much uniformity as possible in the layout and execution of the experiments. However, as the project advanced, and more knowledge and experience were gained, changes were made to the experimental procedures.

Wheat and maize were selected as the major crops for winter and summer seasons respectively. During the winter seasons peas were planted as an additional crop while cotton was used as second crop for the summer seasons. At each of the nineteen sites two plots, one for each crop, were layed out. In the Ciskei the size of the plots was 5mx5m because the plots were also used for the calibration of the neutron hydroprobe. In the other regions 4mx4m plots were used because the calibration of the neutron hydroprobe was done on separate plots.

At the Sterkspruit and Valsrivier sites (Ciskei) wheat was planted on both plots and no peas were planted. This was (a) to gain more information on how irrigated wheat is behaving on these soils, which are not considered to be well suited for irrigation and (b) because peas are considered to do very badly on such soils.

During the '82-'83 summer season cotton failed to germinate on the second plot at the Joubert site (Vaalharts) and eventually maize was planted on this plot also. During the following season this site was abandoned because it was found that salinity in the soil was excessive, resulting in poor crop stands.

At all the other sites all crops germinated well and PAWC determinations could be done on both plots during each growing season. Table 2.1 summarizes what crops were planted at each site during the different growing seasons.

2.2.4 Agronomic practices

As a guideline cultivars, fertilizer application and planting densities recommended by local researchers and extension officers in the different areas were used.

The cultivars and planting dates for the different experiments are shown in Table 2.1. In the Ciskei wheat was sown in rows 300mm apart at a sowing rate of 100kg/ha. Prior to sowing, 3:2:1(Zn)(22) was applied broadcast at a rate of 700kg/ha and incorporated in the soil. The seed was treated with Vivatex to prevent rust during later growth stages.

Peas were sown in rows, 600mm apart, at a sowing rate of 100 kg/ha. The plants were later thinned to give a

TABLE 2.1 Cultivars and planting dates of the crops at the different sites

SITE	PLOT	CROP	CULTIVAR	PLANTING DATE
CISKEI				
JOZINI	1	wheat	SST44	15-6-1982
	2	peas	Green feast	2-7-1982
MARIKANA	1	wheat	SST44	6-7-1982
	2	peas	Green feast	6-7-1982
KINROSS	1	wheat	SST44	5-7-1982
	2	peas	Green feast	5-7-1982
STERKSPRUIT	1	wheat	SST44	26-6-1982
	2	wheat	SST44	6-7-1982
VALSRIVIER	1	wheat	SST44	25-6-1982
	2	wheat	SST44	6-7-1982
VAALHARTS				
KAMP I	1	maize	Pioneer 542	14-10-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	27- 5-1982
	2	peas	Green feast	27- 5-1982
KAMP II	1	maize	Pioneer 542	27- 5-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	27- 5-1982
	2	peas	Green feast	27 -5-1982
KAMP III	1	maize	Pioneer 542	14-10-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	27 -5-1982
	2	peas	Green feast	27 -5-1982
VAN DER LINDE I	1	maize	Pioneer 542	14-10-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	26- 5-1982
	2	peas	Green feast	26- 5-1982
VAN DER LINDE II	1	maize	Pioneer 542	14-10-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	26- 5-1982
	2	peas	Green feast	26- 5-1982
DEMONSTRATION PLOT	1	maize	Pioneer 542	14-10-1982
	2	cotton	Acala 1517/70	29-10-1982
	1	wheat	SST44	26- 5-1982
	2	peas	Green feast	26- 5-1982
JOUBERT	1	maize	Pioneer 542	14-10-1982
	2	maize	Pioneer 542	30-10-1982

(continued)

TABLE 2.1 (continued)

LOSKOP

CONTOUR 5	1	maize	SNK 2232	13-10-1983
	2	cotton	Acala 1517/70	14-11-1983
CONTOUR 10	1	maize	SNK 2232	13-10-1983
	2	cotton	Acala 1517/70	14-11-1983
DU PREEZ I	1	maize	SNK 2232	14-10-1983
	2	cotton	Acala 1517/70	14-10-1983
DU PREEZ II	1	maize	SNK 2232	14-10-1983
	2	cotton	Acala 1517/70	14-11-1983
DU PREEZ III	1	maize	SNK 2232	21-10-1983
	2	cotton	Acala 1517/70	14-11-1983
VENTER I	1	maize	SNK 2232	15-10-1983
	2	cotton	Acala 1517/70	14-11-1983
VENTER II	1	maize	SNK 2232	21-10-1983
	2	cotton	Acala 1517/70	21-10-1983

spacing of 500mm between plants. Prior to sowing 3:2:1(Zn) (22) was applied at a rate of 700kg/ha.

At Vaalharts both maize and cotton were planted in rows 900mm apart. Maize plants were 200mm apart in the row, resulting in a plant density of 55 000 plants/ha. At planting 3:2:1(22) at a rate of 500kg/ha and ammonium sulphate at a rate of 280kg/ha was applied broadcoast. At the time of the first irrigation after planting a topdressing of ammonium sulphate was given at a rate of 240kg/ha. Cotton was thinned so that there was 400 to 500mm between plants in a row. In addition to 500kg/ha 3:2:1(22) at planting the cotton also received 240kg/ha ammonium sulphate at the first irrigation after planting.

The wheat and peas experiments during the 1983 winter season at Vaalharts were planted in the same manner and at the same density as in the Ciskei. At planting wheat and peas received a fertilizer application of 550kg/ha 4:1:0(30). For peas this amount was supplemented with 300kg/ha superphosphate. The wheat was pre-treated with bayleton to avoid rust damage.

A fertilizer application equivalent to 220kg/ha 4:1:0(30) was applied at sowing for maize and cotton at Loskop.

Planting densities and spacings were as at Vaalharts.

Weed and pest control were applied as advised by local researchers. During the Ciskei experiments the department of Agronomy of the University of Fort Hare and at Vaalharts and Loskop local, experienced researchers were consulted on this matter.

2.2.5 Irrigation practices

At all sites the soil profiles were brought to field capacity immediately before planting. As a general rule soil moisture contents were kept at a high level during the vegetative growth stages to avoid harmful effects of water stress on the crops before the actual PAWC determination at flowering (when the plants were fully grown) were done. Hsiao (1982) has indicated that vegetative growth is very sensitive to water stress. Only maize was allowed to be mildly stressed during early growth stages because it is believed that water stress at these stages brings about a well established root system in the lower layers of the soil profile. For wheat it was confirmed that a high soil moisture level at crown root initiation is essential (Michael,1978). The argument that by that time there is still sufficient water available in the soil profile proved to be misleading. Tillering was stimulated considerably after a light irrigation was applied at that stage of the crop development. The soil close to the surface, where the crown roots are formed, is at that stage probably very dry because of surface evaporation. At flowering all profiles, for each crop, were filled to field capacity and determination of PAWC was started.

Where the sites were located on level terrain, water could be applied by means of flooding. Fortunately this was the case for most sites. Little dikes were constructed around the plots and water was pumped onto the plots.

However, in the Ciskei the Sterkspruit, Kinross and Marikana sites were on fairly sloping terrain and difficulties were encountered to obtain uniformity of water application. Finally a technique was designed that allowed for even water distribution: microjets were mounted in plastic pipe suspended on angle iron supported on stands of different heights to ensure that the microjets were all on exactly the same level (see Plate 2.1). Because of low infiltration rate of the soils at these sites care had to be taken that no run-off occured. The water applications had to be interrupted at regular intervals to ensure this.

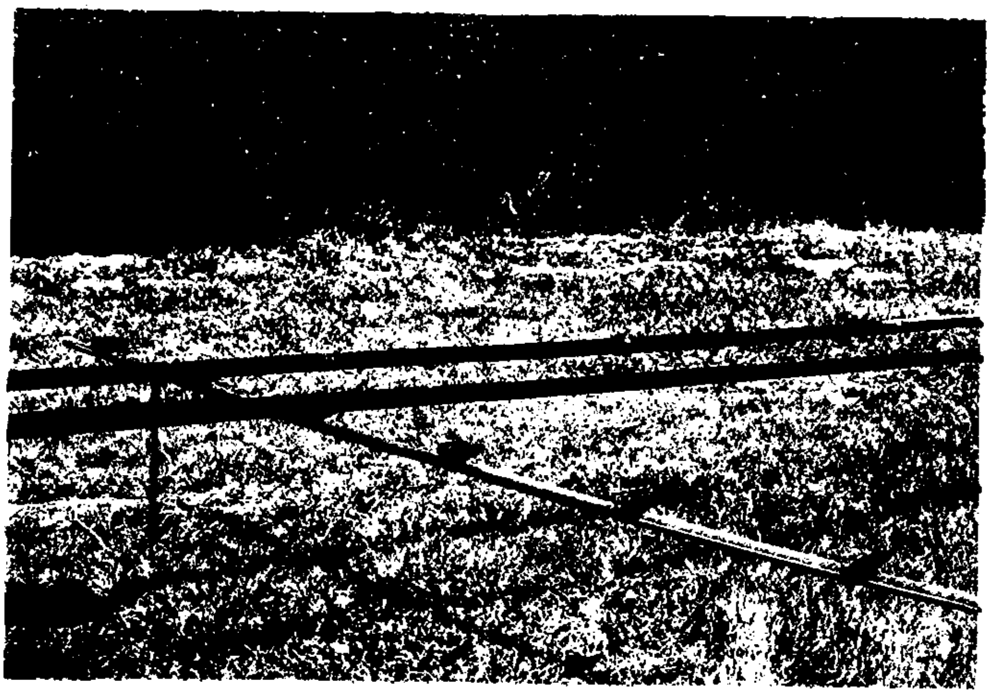


Plate 2.1 Photograph of the small irrigation system that was developed to ensure equal water distribution on plots that were situated on sloping terrain. Microjets mounted in plastic pipe suspended on angle iron supported on stands of adjustable height ensured that the microjets were all on exactly the same level.

At Loskop some sites were situated on slightly sloping ground. Uniformity of water distribution was obtained by constructing little ridges at right angles to the direction of the slope.

2.2.6 Moisture determinations

2.2.6.1 Soil moisture determinations

At field capacity (arbitrarily taken as 3 days after water has been applied) and at first material stress, samples were taken at 100mm intervals in the profile to do gravimetric moisture content determinations of the upper and lower limit of available water.

The evolution of soil moisture extraction patterns during drying cycles was observed by means of soil moisture determination with a Campbell Pacific Nuclear (CPN 503) neutron hydroprobe. Two access tubes were installed in each plot. Calibration of the neutron hydroprobe against volumetric water content determined gravimetrically was done for each diagnostic horizon at each site.

Neutron hydroprobe measurements started at 250mm depth and were made at 150mm depth intervals deeper in the soil profile. Measurements were made to a depth of 1600mm. This was done because previous experiments in the Ciskei indicated that wheat and maize were not extracting water below 1500mm depth (Hensley & De Jager, 1982). When the crops were approaching first stress daily readings were made. During the winter experiments at Vaalharts and the summer experiments at Loskop water content was determined daily throughout the drying cycles.

In the very deep, well drained soils of the Vaalharts region (Van der Linde I and II, Demonstrasie eenheid) access tubes were installed to a depth of 2000mm during the 1983 winter experiments in order to determine whether water was effectively extracted by crops at this depth from these soils.

2.2.6.2 Leaf water potential measurements

Pre-dawn leaf water potential, measured with a pressure chamber similar to the one described by Scholander, Hammel, Hemmings & Bradstreet (1964) and Waring & Cleary (1967), was used as an indicator of crop water stress. Four to eight measurements on different plants in a plot were made each time.

Standardization of the procedures of leaf water potential determinations are essential for reproducible results (Ritchie & Hinckley, 1975). For wheat four leaf water determinations were done at each site. Well-exposed flag leaves were selected and each leaf was cut at 20mm from the base. The determination was made on the main vein. For maize well-exposed top leaves were used for leaf water potential determinations. Two or three leaves were chosen at each site and two determinations were done on each leaf. A centre piece of the leaf was used and the determination was made on the veins parallel to the main vein. Youngest mature leaves were used for cotton and peas. The reading was done on the central vein of the leaf. Four to eight leaves were selected per plot.

Pre-dawn leaf water potential determinations were done at regular intervals at all sites. When lower leaf water potentials were observed, or when it was suspected that first stress was approaching, daily readings were taken. Pre-dawn leaf water potential was a fairly good indicator of the onset of stress in wheat during the winter seasons.

Unfortunately severe doubts regarding the validity of this parameter under extreme climatic conditions, such as those that were prevailing at Vaalharts during the

1982/83 summer season, arose. It was found that when the maize and cotton plants clearly showed visual stress symptoms around mid-morning, no drop in pre-dawn leaf water potential was noted. It was eventually decided to define first stress as the day on which practically all leaves of the plants in a plot showed visual stress symptoms at 09h00 in the morning. This time differs from that specified by Mallet & De Jager (1971) and Hensley & De Jager (1982), viz. 10h00 Or 10h30. It was found at Vaalharts, however, that complete stress symptoms occurred at 10h00 even on the first day after irrigation, while the soil moisture level was still very high.

For maize the visual symptoms described by Mallet & De Jager (1971) and Hensley & De Jager (1982) were used as indicator of stress:"when stressed the portions of a maize leaf on either side of the midrib tend to fold together. This causes the leaves to stiffen and to stand up at a relatively steep angle to the stem, rather than droop in a gracious arc away from the plant. The stressed plants have a spiky appearance from a distance and leaves lost their luscious green colour and developed a greyish tinge with whitish stripes on the back of the leaves".

For cotton the following observations were made: when soil moisture is ample, the leaves have a fresh green colour. The five main veins of the leaf are rigid and the centre of the leaf, where these veins meet, is below the top of the leaf. At initial stress the edges of the leaf curls up and the leaf has a "fringy" appearance. At wilting the leaves look "limp". The green colour becomes dull and the tip of the leaf is now below the leaf centre.

During the following summer season (1983-1984)at Loskop it was decided, upon advice of Prof. Impens (Antwerp, Belgium), to continue registering pre-dawn leaf water potential until a significant drop occurred. This finally happened long after visual symptoms indicated first stress. The crops were visibly too severely stressed when this drop in pre-dawn leaf water potential occurs. It became clear that re-interpretations of pre-dawn leaf water potentials as indicators of the onset of stress were required. This will be discussed in detail later.

Covered plant water potential measurements were tested, but were found to be more variable and consequently less reliable than pre-dawn leaf water potential measurements. Additionally it was realized that pre-dawn leaf water potential readings were more feasible than covered plant water potential determinations. The latter practice demands for two visits a day to each plot, which was impractical because of the relatively large distances between the different plots in the Ciskei and at Loskop.

2.3 RESULTS AND DISCUSSION

2.3.1 Pre-dawn leaf water potentials

A decrease in pre-dawn leaf water potential to below -1000kPa was taken as the lower limit of profile available water. This point, described by Hensley & De Jager (1982) as "well defined stress", was used in order to compare the data of this study with their data. It was expected that a significant increase in water use efficiency, without a significant decrease in yield, would be obtained if this value was used for irrigation scheduling (Hensley & De Jager, 1982).

2.3.1.1 Wheat

In general two basic pre-dawn leaf water potential patterns were found as water was extracted between field capacity and first stress. On the more structured, medium-textured to clayey soils pre-dawn leaf water potential stayed more-or-less constant at values around -400kPa. Then, suddenly, in a matter of a few days, the readings dropped to values below -1000kPa, indicating first stress. A typical example of this pattern, which was found at the Jozini, Marikana, Sterkspruit and Arniston sites from the Ciskei, is illustrated in Figure 2.15. See Appendices 2.20 and 2.21 for details.

On the very weakly structured to apedal, sandy soils from Vaalharts pre-dawn leaf water potentials gradually decreased from around -200kPa or -300kPa to values in the order of -600 to -700kPa, after which the readings quickly dropped to below -1000kPa. This pattern is illustrated by the data for wheat at the Kamp I site (Figure 2.16). The patterns for wheat at Van der Linde I, II and Demonstration plot are presented in Appendices 2.22 and 2.23. The patterns were somewhat disturbed by a heavy rain storm . The rains shields were ripped off and

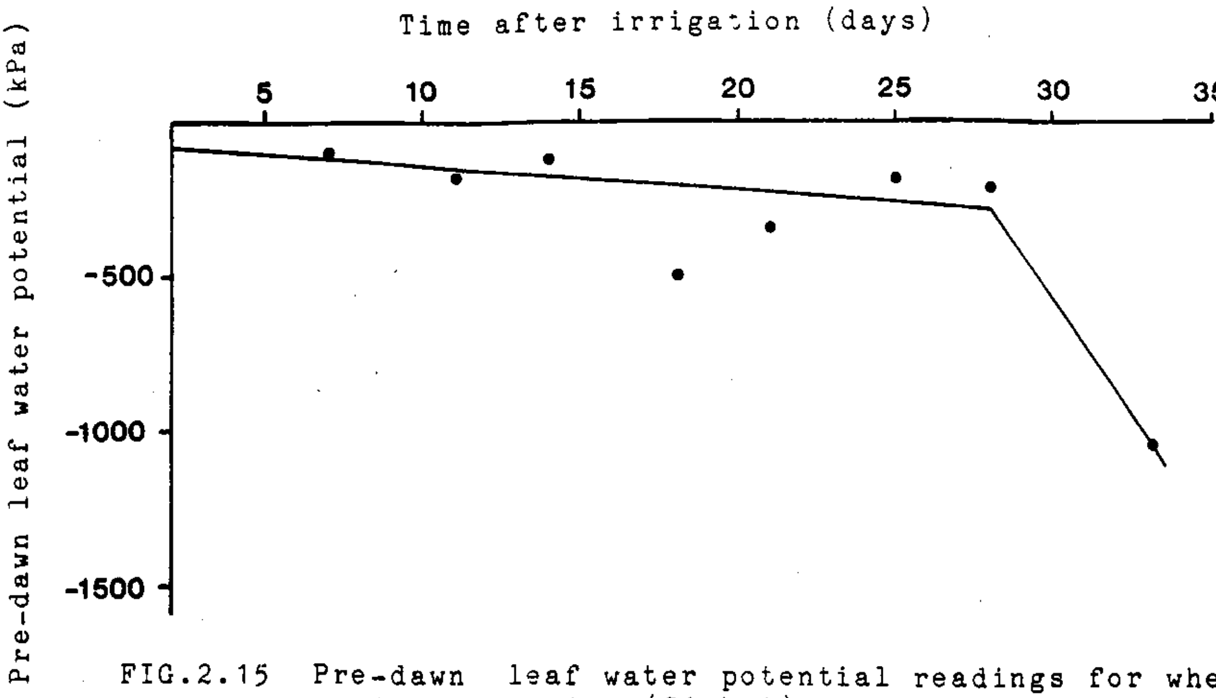


FIG.2.15 Pre-dawn leaf water potential readings for wheat on Arniston site (Ciskei).

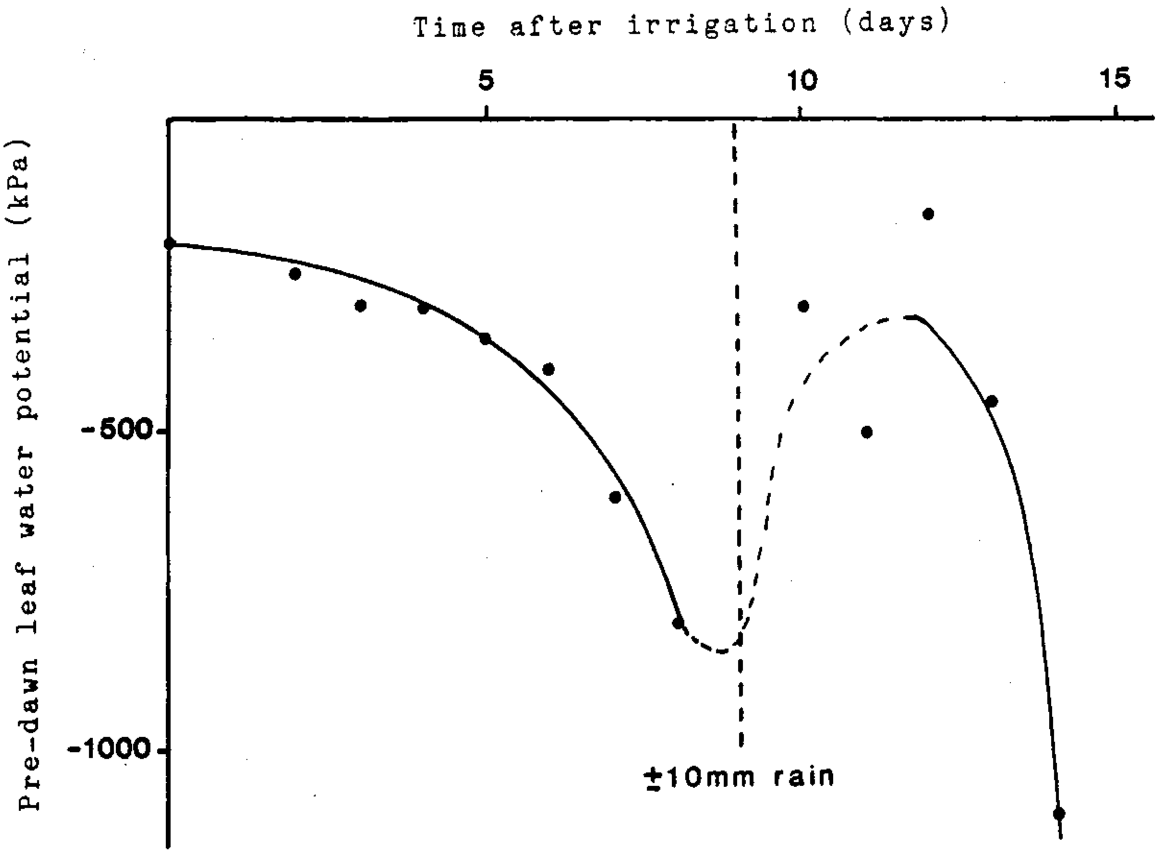


FIG.2.16 Pre-dawn leaf water potential readings for wheat on the Kamp I site (Vaalharts).

the plots received some rain, which caused the pre-dawn leaf water potential to rise again (see Figure 2.16). Normal patterns followed thereafter.

It is notable that at Kamp II in the Vaalharts region (a structured soil of the Sterkspruit form) a pre-dawn leaf water potential pattern similar to those for the moderate to strongly structured soils from the Ciskei was found (Figure 2.17). Unfortunately the pattern at Kamp II was also disturbed by the rain storm mentioned in the previous paragraph. The observation of this pattern at Kamp II confirms that the difference between the two basic patterns can be attributed to differences in soil characteristics and not to the climatic differences between the Ciskei and Vaalharts.

The leaf water potential pattern found for wheat on the red structured Kinross soil does not seem to fit in with the general trend for structured soils. (See Appendix 2.20).

2.3.1.2. Peas

During the 1982 winter season in the Ciskei it was impossible to detect first stress in peas by means of

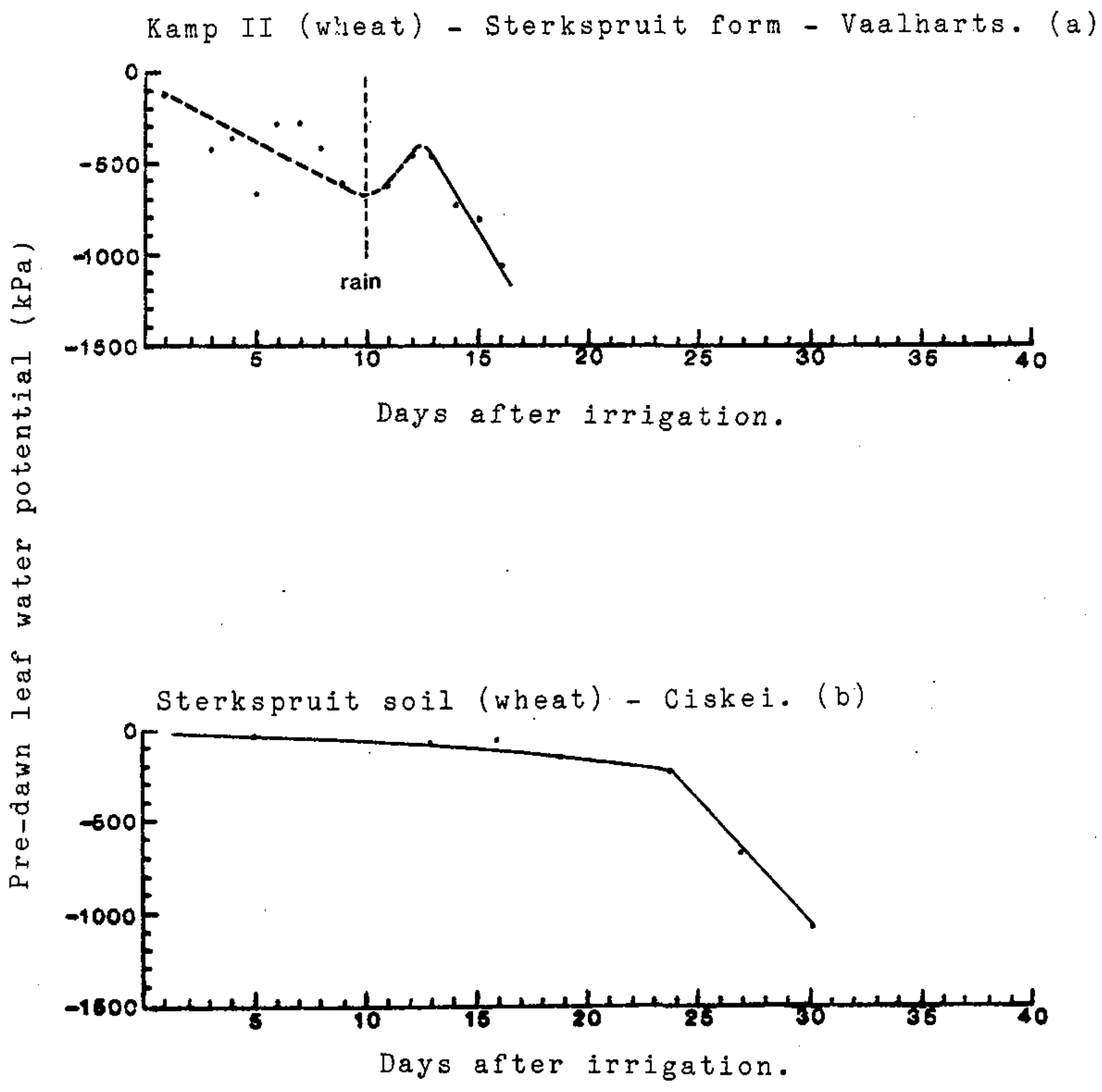


FIG.2.17 Pre-dawn leaf water potential patterns for wheat on Sterkspruit form soil at Vaalharts (a) and in the Ciskei (b).

pre-dawn leaf water potential monitoring. No clear pattern emerged. Leaf water potentials quickly dropped to -600kPa and then remained around that value for a very long period until the plants matured and eventually reached natural senescence without any further decrease in leaf water potential.

On the sandy Vaalharts soils the following pattern was found: pre-dawn leaf water potential gradually decreased to about -700kPa, after which there was a fairly clear drop to below -1000kPa (see, for example, Figure 2.18). On the more structured, clayey soil of Kamp II, pre-dawn leaf water potential readings again (as in the Ciskei) decreased gradually over a long period, with no definite drop at any stage (see Figure 2.19). Eventually pre-dawn leaf water potential approached -1000kPa and this was taken as first stress. Peas seem to be a drought tolerant crop which seems to have a high water regulating capacity (see Appendix 2.24).

2.3.1.3 Maize

During the 1982/83 summer season at Vaalharts pre-dawn leaf water potential monitoring failed to indicate the onset of stress under the prevailing extremely high

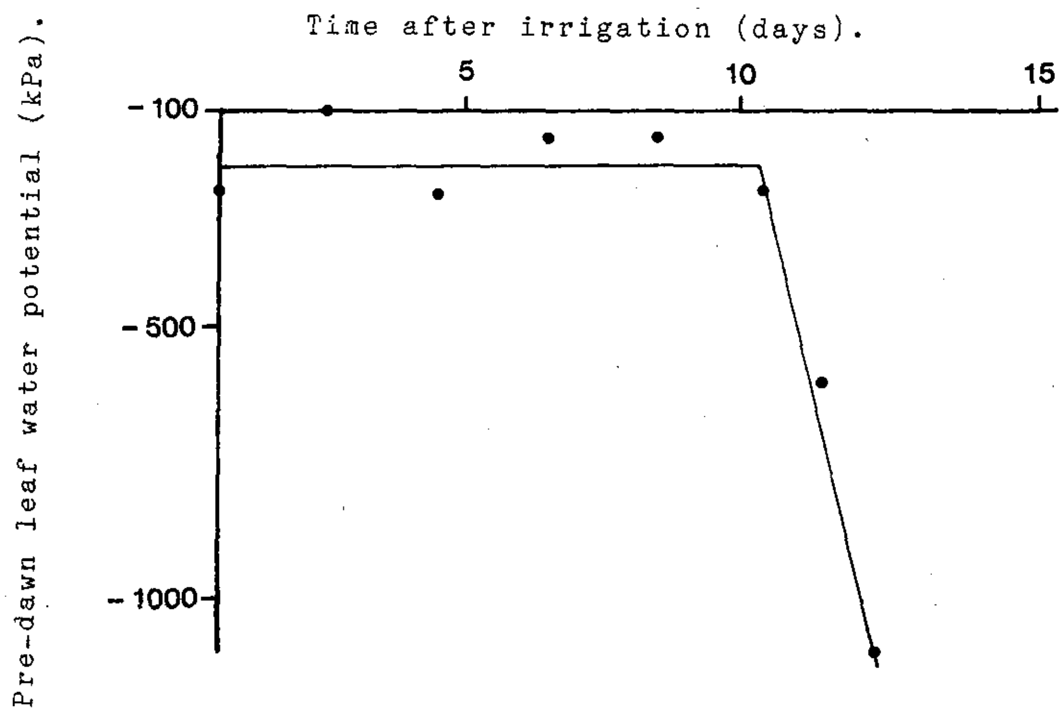


FIG.2.18 Pre-dawn leaf water potential pattern for peas at Kamp II (Vaalharts).

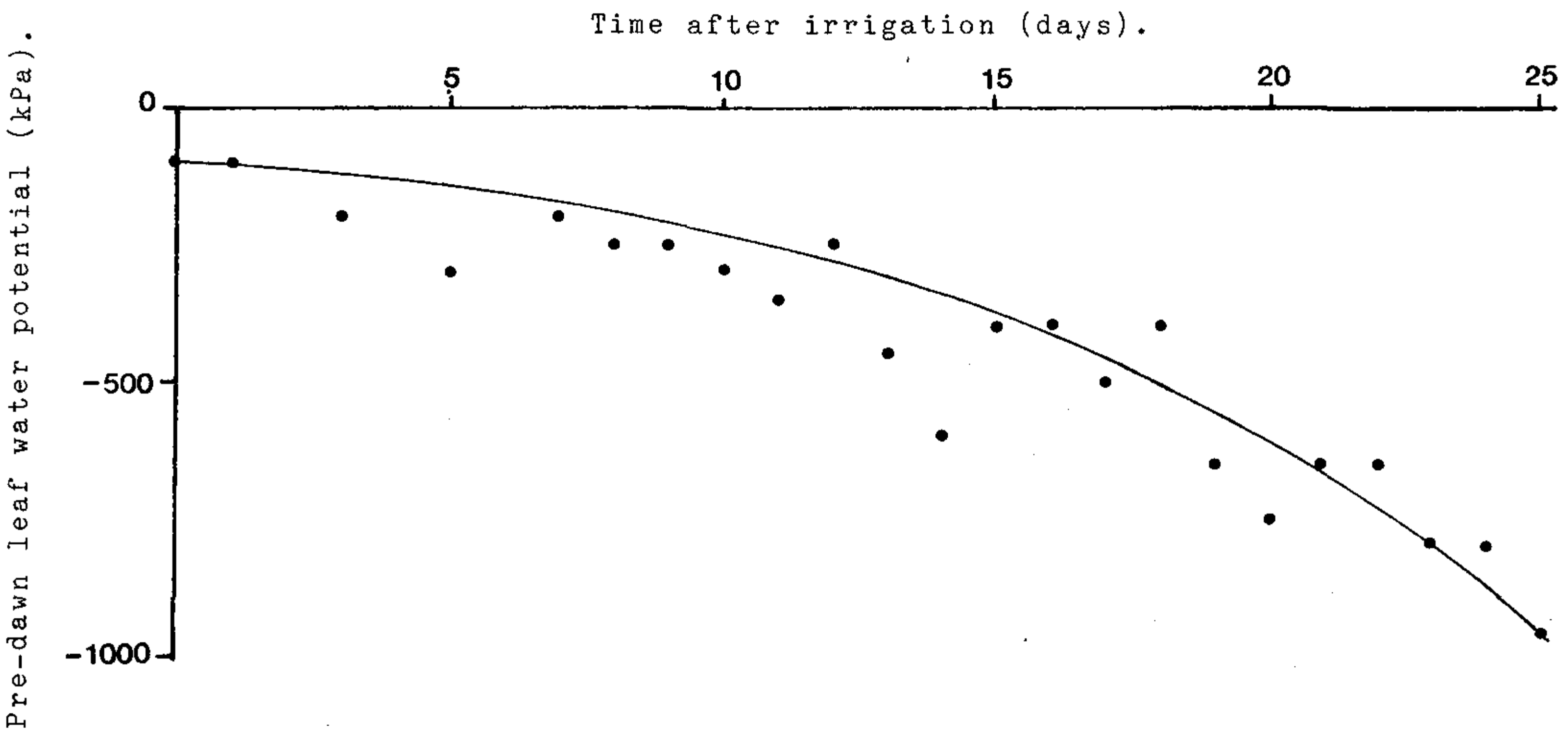


FIG.2.19 Pre-dawn leaf water potential pattern for peas at Van der Linde II (Vaalharts).

evaporative demand. Visual stress symptoms were, therefore, used to indicate the onset of stress for maize during that season. These were found before decreases in pre-dawn leaf water potential to below -1000kPa occurred. On advice of Prof. I. Impens, Plant Physiologist at the University of Antwerp, (1983, personal communication) it was decided to continue pre-dawn leaf water potential measurements during the following summer season at Loskop until a significant drop in leaf water potential occurred, irrespective of observed visual symptoms.

At all sites pre-dawn leaf water potentials stayed relatively constant at values around -200 to -300kPa during the first part of the drying cycle between field capacity and first stress (12 to 24 days). Then pre-dawn leaf water potential readings started to fluctuate: the leaf water potential dropped repeatedly to values between -600kPa and -1000kPa but recovered to high values the subsequent day. It was decided that the initial drop in pre-dawn leaf water potential was not sufficient to give a clear indication of stress and the readings were continued until pre-dawn leaf water potential dropped clearly below -1000kPa (see Figure 2.20 and Appendices 2.25 and 2.26). Only at Contour 10 this "fluctuating" pattern was not observed. After a long period of

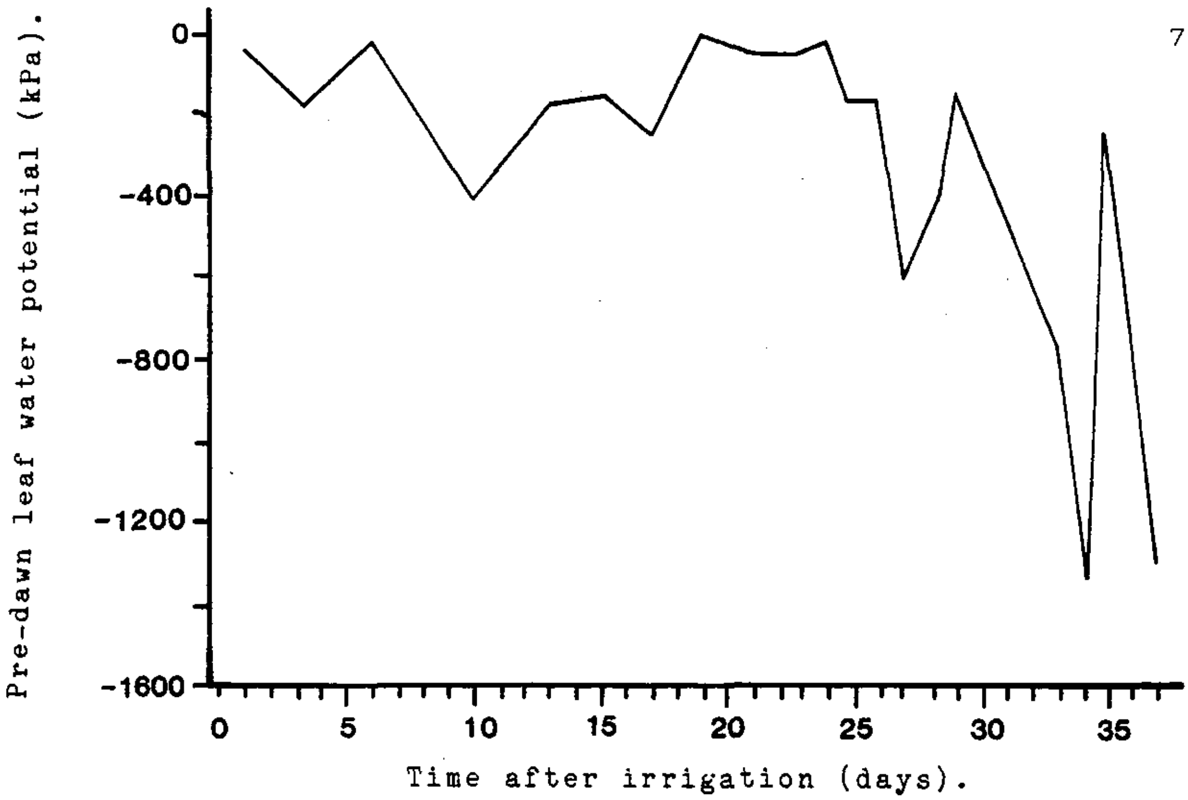


FIG.2.20 Pre-dawn leaf water potential pattern for maize at Venter II (Loskop).

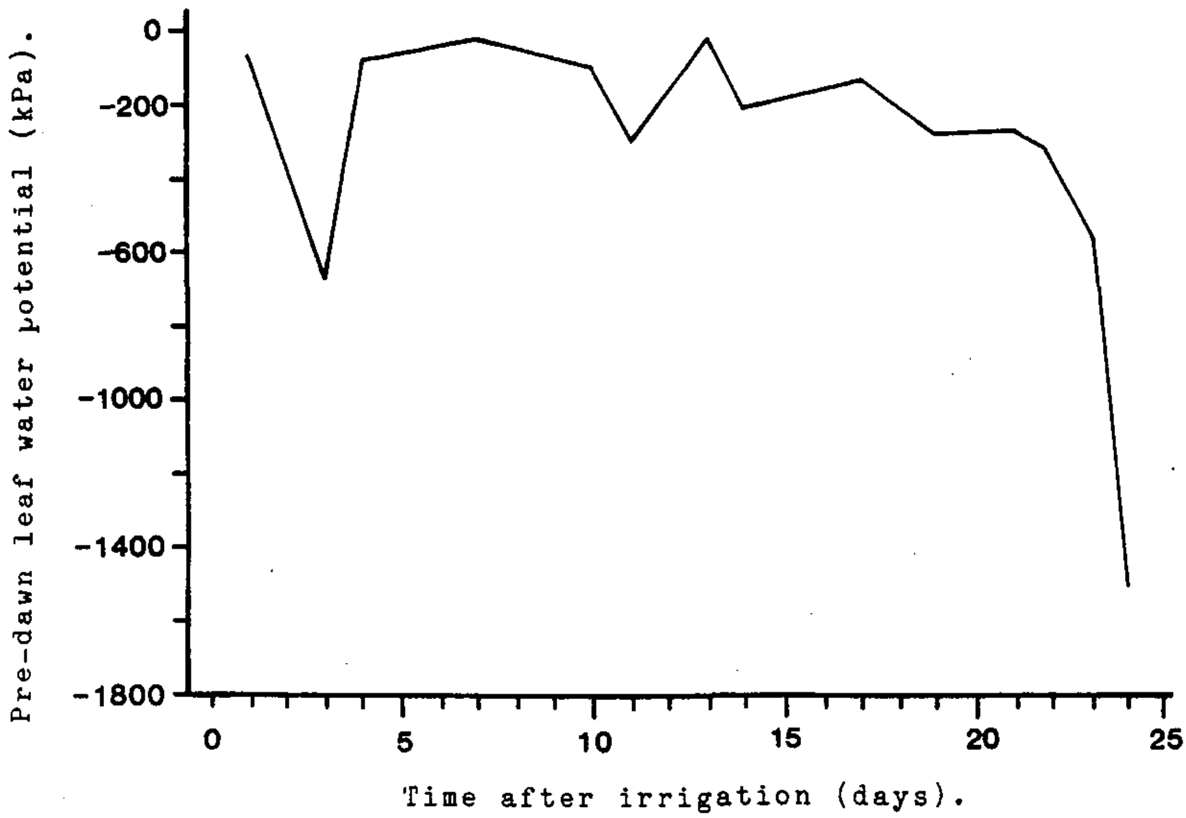


FIG.2.21 Pre-dawn leaf water potential pattern for maize at Contour 10 (Loskop).

constant high values the pre-dawn leaf water potential readings fell to below -1000kPa in a matter of a few days (see Figure 2.21).

As far as possible pre-dawn leaf water potential was determined at daily intervals during the final stages of the drying cycles. Simultaneously observations of visual stress symptoms were made at 09h00 in the morning. At most sites (Du Preez I,II, III and Contour 5) severe visual stress was observed long before leaf water potential was indicating stress. This was concordant with findings for the Vaalharts region where maize was also wilting around 09h00 without this being expressed in the pre-dawn leaf water potential readings. At all sites the impression was gained that the prolonged pre-dawn leaf water potential monitoring stretched the drying cycle too far and severe stress was occurring before being indicated by a clear decrease in leaf water potentials.

The fluctuations in pre-dawn leaf water potential readings towards the end of the drying cycle was initially assumed to be due to experimental error, i.e. due to insensitivity of the measuring technique. An "average" line was constructed to represent this part of the curve (Figure 2.22.a). Close inspection revealed that the fluctuations did not represent random variations - as would be expected if it was due to inherent errors in the measuring technique. The pre-dawn leaf water potential readings during this part of drying cycle represented a more-or-less rhythmic oscillation between low and relatively high values (Figure 2.22.b). This represents oscillation between temporary stress and temporary recovery, until a point is reached when the plants do not recover again.

The general trend for pre-dawn leaf water potential for the "temporary stress" days is to decrease fairly consistently. A "stress curve" could be constructed through these "temporary stress" points (Figure 2.22.c). The possible implications of such "stress curve" in regard to interpretations of pre-dawn leaf water potentials and identification of the lower limit of PAWC will be discussed in Chapter 5.

Close scrutiny of the results of Hensley & De Jager (1982) revealed that they have obtained similar oscillating (or "cyclic") patterns for covered leaf water potentials towards the end of drying cycles for maize in the Ciskei. (See their Figures 5.7, 5.8 and

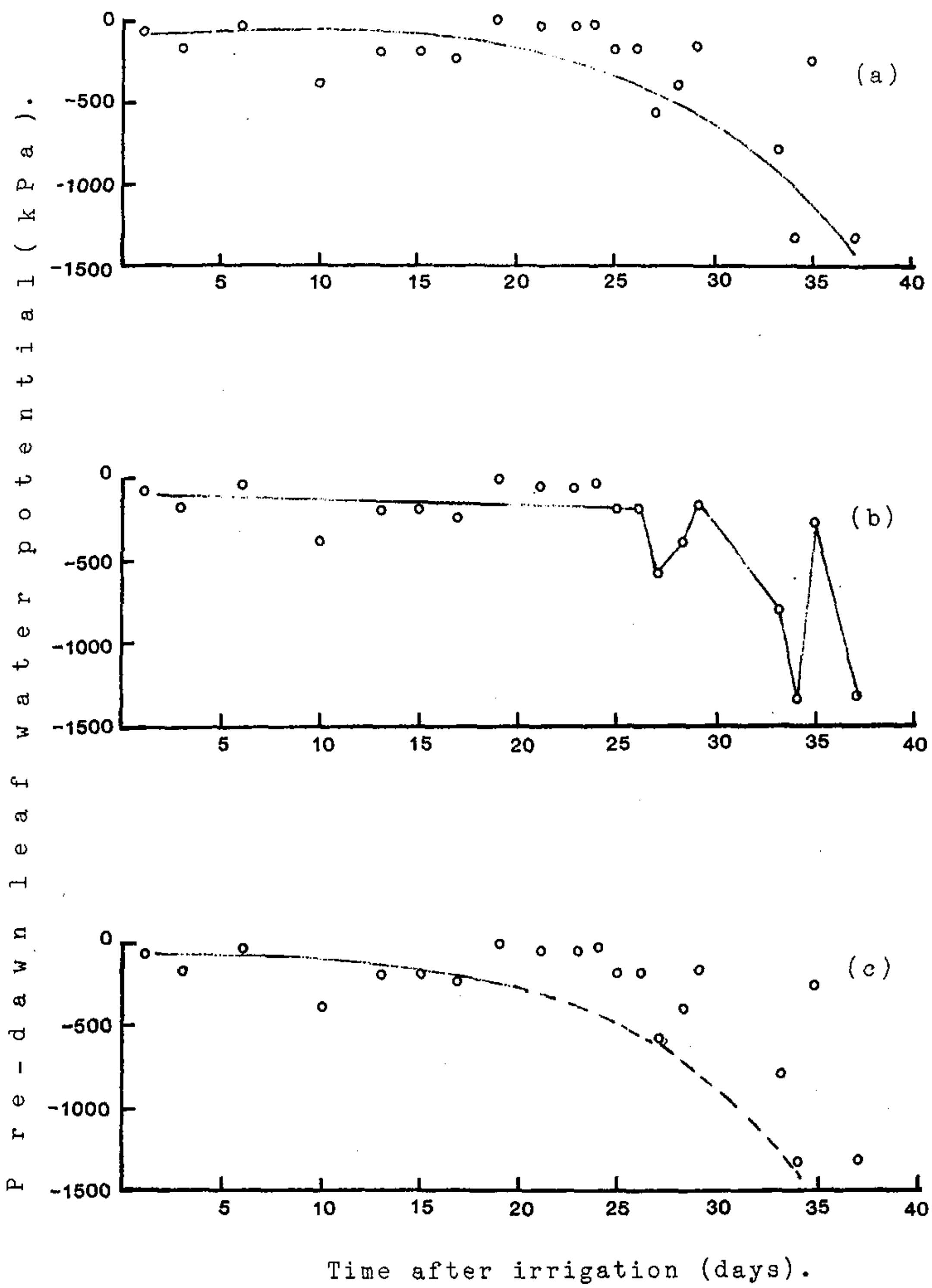


FIG.2.22 Pre-dawn leaf water potential readings for maize at Venter II (different interpretations).

5.9). Figure 2.23 is an adaptation of their Figure 5.7 to illustrate the cyclic nature of the data.

During the period of cyclic decreases and increases in leaf water potential the average soil water content and average soil water potential is steadily decreasing. Cyclic changes in average soil water potential can therefore be ruled out as an explanation for the phenomenon. An explanation must be sought in the basic principles underlying the pre-dawn leaf water potential technique and in the nature of the soil - plant - atmosphere - continuum (SPAC).

According to Pinter (Laker, 1983) pre-dawn leaf water potential is primarily an indicator of the ability of a plant to recover from moisture stress during the previous day. It may be more accurate to describe it as an indicator of the ability of SPAC to enable the plant to recover. The alternating stress and recovery cycles may indicate a specific SPAC situation under which the plant cannot recover overnight but can recover over a longer period. Various mechanisms may be involved, of which four will be outlined here:

Firstly, under high evaporative demand the available

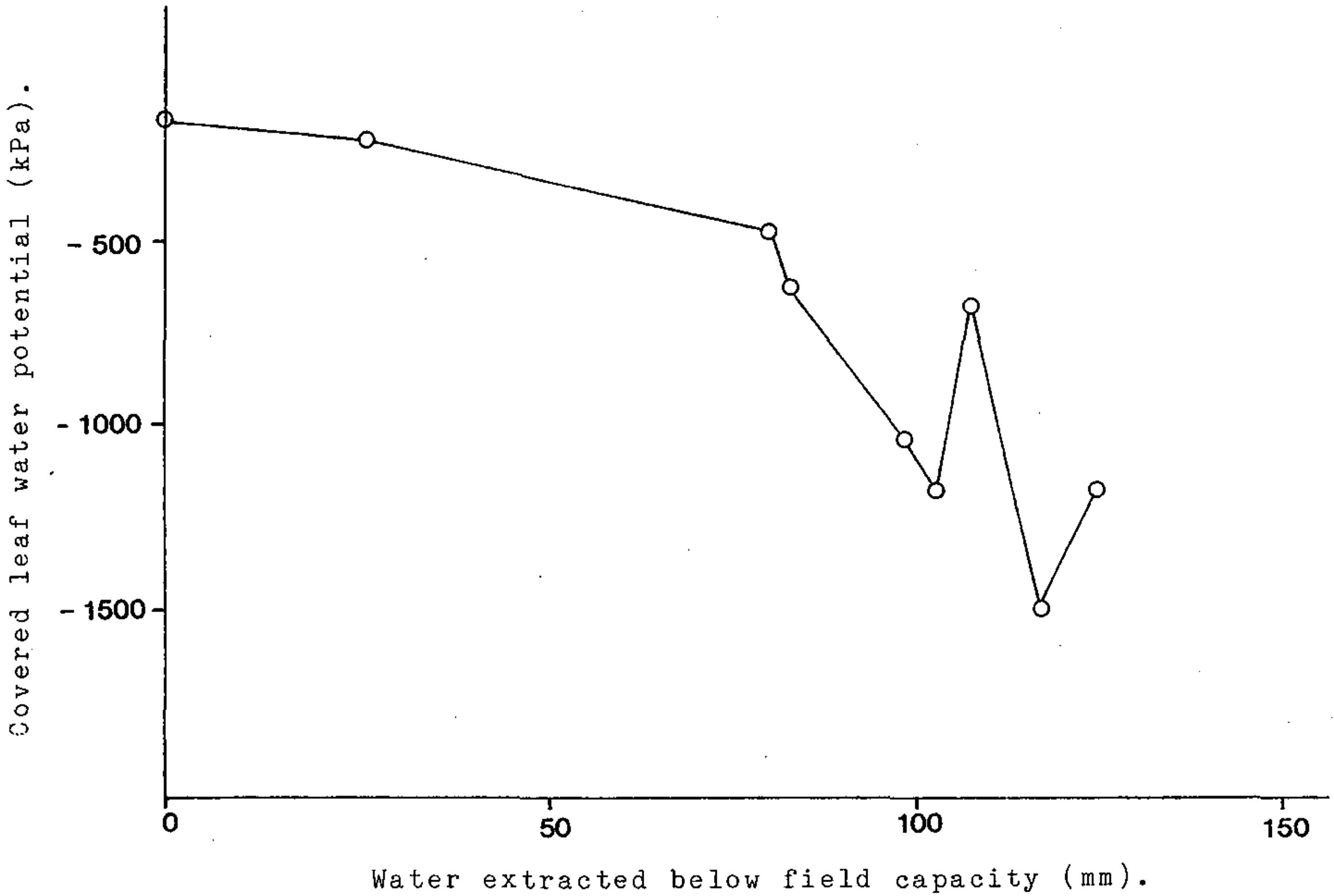


FIG.2.23 Adapted leaf water potential curve for maize in the Ciskei (data from Hensley & De Jager, 1982)

water in the rhizosphere may be depleted quickly, resulting in an extremely dry soil layer around the root. In an average dry soil the hydraulic conductivity from the rest of the soil to the rhizosphere may be so low that it takes more than 24 hours to reach equilibrium with the adjacent soil layers.

Secondly, Larcher (1980) and Klepper (1983) reported shrinkage of the root diameter under very high evaporative demand. This could result in a loss of contact between the root surface and the soil. When a long time interval is required by the root to regain its original diameter, then it is possible that the plant may fail to equilibrate with the soil water overnight but may do so over a longer period.

Thirdly, new, secondary root growth, can invade soil layers with a higher soil water potential causing the pre-dawn leaf water potential to recover temporarily. Klepper, Taylor, Huck & Fiscus (1973) reported an increased rooting density with depth by the end of a drying cycle for mature cotton.

Fourthly it would seem that a prerequisite may be that evaporative demand should be so high on the day on which pre-dawn stress occcurred that the stomata do not open, permitting equilibration between the plant and the soil to proceed throughout that day (without significant water loss to the atmosphere) and the next night. This aspect will have to be investigated during future research.

2.3.1.4. Cotton

As for maize no decrease in pre-dawn leaf water potential was found during the very hot and dry 1982/83 summer at Vaalharts by the time that plants showed severe visual early morning stress. Wilting at 09h00 was therefore taken as indication of the stress. At Loskop prolonged leaf water potential monitoring was again done upon Prof. Impen's recommendation.

The fluctuating pattern found for maize was not clearly observed during the cotton experiments. Only at two sites (Du Preez III and Contour 5) some fluctuations were observed at the end of the drying cycle before pre-dawn leaf water potential values finally fell below -1000kPa (see Appendices 2.27 and 2.28). At Du Preez I and II the readings dropped fairly quickly to values around -600kPa and then stayed more-or-less constant at this level. Then in a matter of a few days leaf water potential dropped to values lower than -1000kPa (see Appendix 2.27). At Contour 10 and Venter I pre-dawn leaf water potentials decreased gradually, almost linearly, from the first day of the drying cycle till the day when values below -1000kPa were reached (see Appendices 2.27 and 2.28).

Again the impression was gained that the crop was already too severely stressed before this was indicated by the pre-dawn leaf water potential readings.

2.3.2 Profile available water capacities

2.3.2.1 Wheat

PAWC - determinations were made for wheat in the Ciskei during the 1982 winter season and at the Vaalharts irrigation scheme during the 1983 winter season. The obtained PAWC - values and the amounts of water extracted from each soil layer at each different site are listed in Tables 2,2 and 2.3.

2.3.2.1.1 Ciskei

The general extraction pattern found for wheat by Hensley

TABLE 2.2 - Quantities of water extracted (determined gravimetrically) by wheat at first stress (indicated by pre-dawn leaf water potential readings) for sites in the Ciskei.

Soil Depth (mm)	Water extracted (mm/100mm)				
	Jozini	Sterk-spruit	Arniston	Marikana	Kinross
0 - 100	19,1	16,6	25,0	29,4	23,7
100 - 200	16,8	13,6	23,6	17,2	21,2
200 - 300	15,6	12,1	22,2**	13,5	19,0
300 - 400	14,5	10,6**	17,4	11,4	15,8**
400 - 500	14,0	5,6	14,4	9,9	14,0
500 - 600	10,3	6,3	13,1	7,8	12,9
600 - 700	9,3*	6,3	11,2	6,7	13,0
700 - 800	8,1	7,8	9,7	7,2	11,7
800 - 900	7,1	6,6	7,5	3,6	9,1
900 - 1000	5,2	3,0	7,0	3,7	7,3
1000 - 1100	3,3		6,2	6,2	5,8
1100 - 1200	3,2		5,2	7,1	5,0
1200 - 1300	2,8*		4,7	3,0*	3,0
1300 - 1400	2,6		3,8	***	***
1400 - 1500	4,0		2,1		
1500 - 1600			2,3		
PAWC	135,9	88,6	175,4	126,7	161,5

* interpolated values.
** start of structured B-horizon.
*** underlain by dolerite saprolite.

TABLE 2.3 - Quantities of water extracted (determined gravimetrically) at first stress (indicated by pré-dawn leaf water potential readings) by wheat at Vaalharts.

Soil Depth (mm)	Water extracted (mm/100mm)				
	Kamp I	Kamp II	V.Linde I	V.LindeII	Dem.Plot
0 - 100	13,3*	14,6*	7,3	8,9	9,2
100 - 200	12,7	12,5	8,0	8,5	10,7
200 - 300	13,3	11,1	8,2	8,6	7,5
300 - 400	12,5	13,1	8,3	8,0	9,2
400 - 500	12,8	17,5	7,6	8,4	8,3
500 - 600	12,6	16,4	8,2	8,3	8,1
600 - 700	13,5	14,2	9,4	8,9	8,8
700 - 800	13,5		7,1	9,7	10,5
800 - 900	12,8		7,7	9,1	10,2
900 - 1000			8,0	7,6	9,2
1000 - 1100			12,1**	7,0	7,8
1100 - 1200			2,1	6,2	8,5
1200 - 1300			5,8	5,6	8,5
1300 - 1400			6,6	6,5	8,2
1400 - 1500			7,4	8,8	9,7
1500 - 1600			7,4	9,0	9,2
1600 - 1700			6,9	8,9	10,1
1700 - 1800			5,9	7,7	9,7
1800 - 1900			5,5	8,1	10,1
1900 - 2000			5,5	8,6	9,8
PAWC	117,0	99,4	144,9	162,4	183,3

* value found by interpretation of neutron hydroprobe data.
** occurrence of thin clay layer.

& *De Jager (1982) for the soil in this region* was confirmed during the experiments: the amount of water extracted per unit depth decreased with increasing depth (Figures 2.24 and 2.25). On the Jozini soil, a site included in the experiments as a control on the reproducibility of the PAWC - values, a PAWC of 135,9mm was found (Table 2.2). This value is almost identical to the PAWC - value of 131mm which Hensley & De Jager (1982) obtained for wheat in sealed plots at the same site. This is an indication that the method for PAWC - determination gives reproducible results.

The structured clayey subsoils at the Arniston, Kinross and Sterkspruit sites (starting at 330mm, 330mm and 400mm depth respectively) contributed unexpectedly much to the profile available water capacities of these soils. At the Sterkspruit site the prismacutanic B horizon contributed almost half of the PAWC of this soil (see Figure 2.26 and Table 2.2). At the Kinross and Arniston sites the extraction pattern seemed not to be influenced at all by the pedocutanic and red structed B horizons (see Figures 2.24 and 2.25 and Table 2.2). Similar tendencies were already observed by Hensley & De Jager (1982) but were confirmed by this study. The current opinion that strongly structured subsoils contribute little or nothing to the effective rooting depth, and consequently to the available water capacities of soils, may have to be reconsidered. The Arniston and Kinross soils actually gave higher PAWC - values than the Marikana and Jozini soils which are usually considered to be more favourable for crop production (see Table 2.2). Laker (1982) concluded already from earlier experiments and observations at Vaalharts and in the Orange Free State and Transkei that wheat seems to be doing particularly well, under irrigation, on soils with moderate to strongly structured subsoils.

The Marikana and Kinross soils are underlain by dolerite saprolite which had a significant effect on available water. This was clearly reflected in the extraction patterns. Sharp increases in water content at field capacity, first stress and quantity of water extracted were found immediately above the saprolite (see Figure 2.24 and Table 2.2). Neutron hydroprobe data obtained during the extraction period between field capacity and first stress revealed that these high values were not caused by slow drainage but represented the "real" field capacity for this zone of the soil profile. This observation stresses the need for <u>in situ</u> determination of field capacity and illustrates that field capacity is influenced by the water transmission characteristics of the whole soil profile. Influences, like the occurrence of saprolite at the bottom of the soil profile is having on the field capacity values of the above lying layers, cannot be detected on a soil sample in the laboratory. In Figure 2.26 two sets of field capacity values are shown for the prismacutanic B horizon of the Sterkspruit soil. Observation of the extraction pattern at this site revealed that the "traditional" field capacity value (after 48 to 72 hours drainage of the pre-saturated soil) over-estimated the upper limit of available water. The low hydraulic conductivity of the prismacutanic horizon resulted in a slow moving wetting front. By the time the wheat started to extract water from the subsoil the soil had slowly drained to the second set of field capacity values (see Figure 2.26) which represent the "real" or "factual" field capacity.

2.3.2.1.2 Vaalharts

a. Observations

The extraction patterns found for wheat at Vaalharts show two striking differences from those for wheat in the Ciskei:

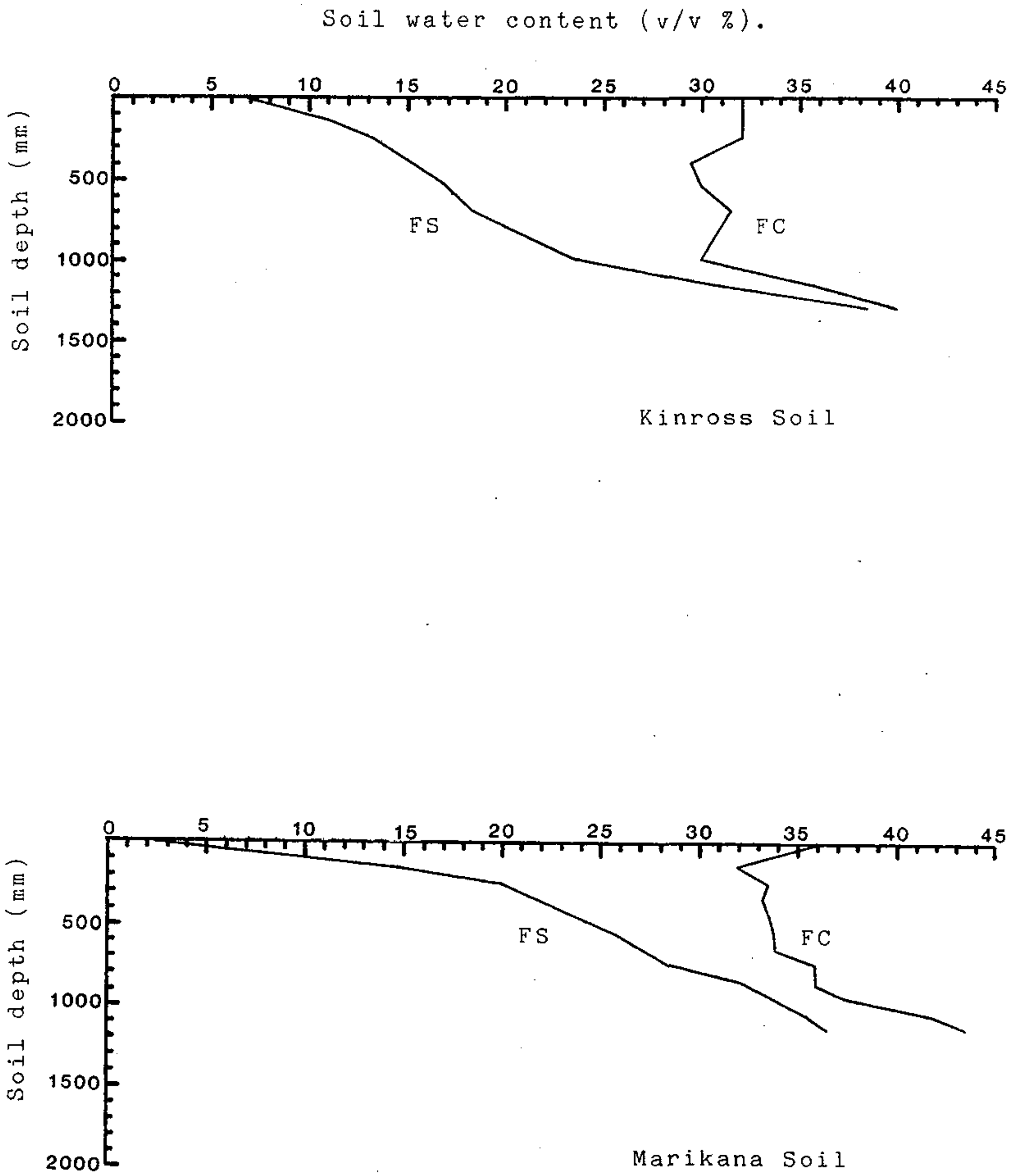


FIG.2.24 Soil water contents at field capacity (FC) and first stress (FS) for wheat at flowering in the Ciskei.

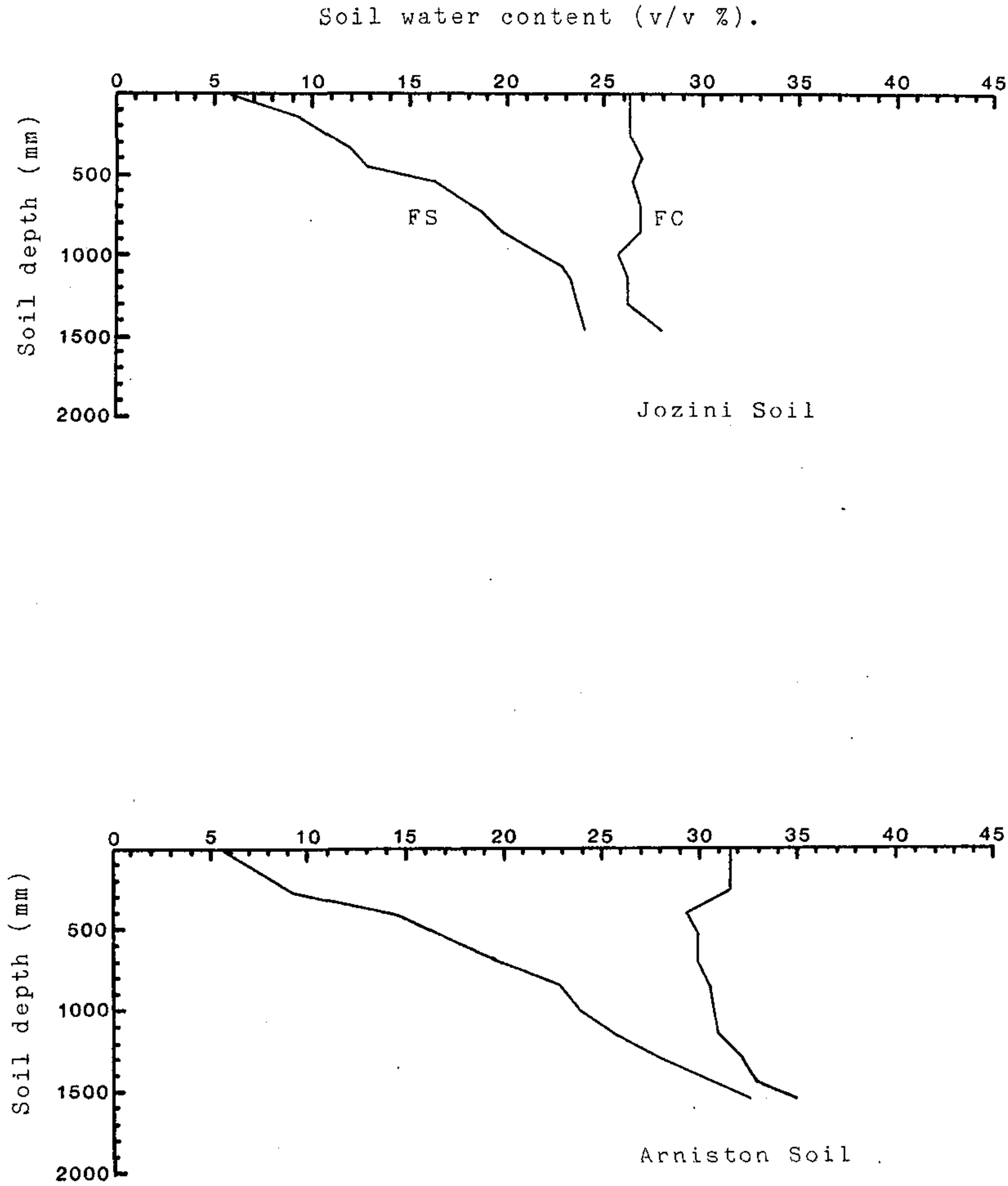


FIG.2.25 Soil water content at field capacity (FC) and first stress for wheat at flowering in the Ciskei.

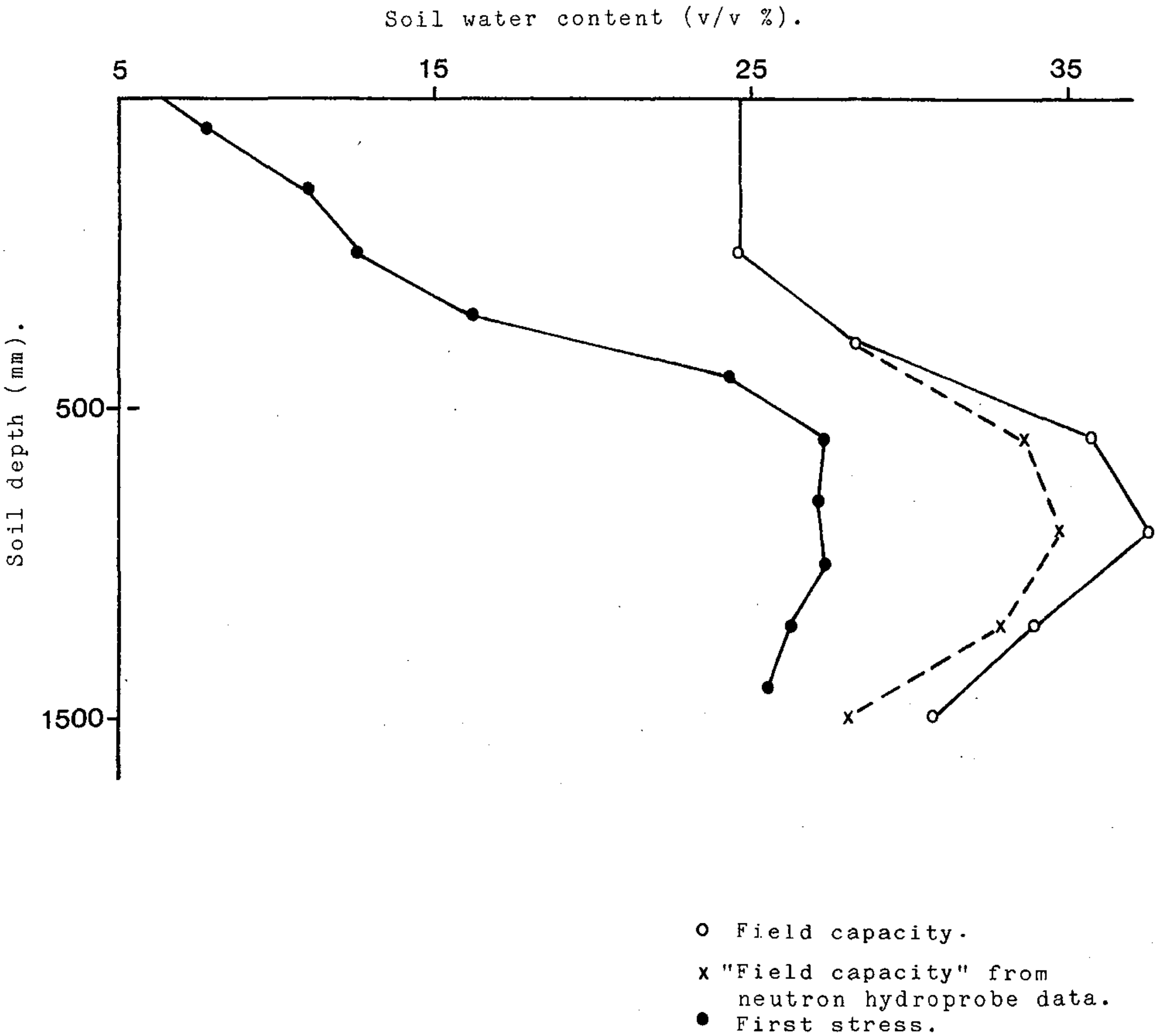


FIG.2.26 Soil water contents at field capacity and first stress for wheat on the Sterkspruit soil (Ciskei).

(a) More-or-less constant quantities of water were extracted per unit depth with increasing depth.

(b) Water was extracted from much deeper soil layers than was the case for the Ciskeian soils.

The constant extraction per unit depth resulted in parallel field capacity and first stress lines at all sites (see Figures 2.27 and 2.28). This pattern is in contrast with the pattern found for wheat in the Ciskei whereby the first stress and field capacity lines are intersecting at the bottom of the rooting zone. For wheat on a deep, sandy Mangano soil at Taung, near the Vaalharts irrigation scheme, Hensley & De Jager (1982) derived an extraction pattern similar to those found for wheat at Vaalharts during the present study (see Figure 2.29).

Only at Van der Linde I there was a reduction in water extraction from the deeper than 1000mm layers. This was caused by the presence of a thin clay layer just below 1000mm depth. Above this thin layer some fine gleying was found and it is, therefore, clear that the clay layer obstructed water movement. It probably also affected soil aeration below it. Rooting densities were apparently also abnormally low below this layer, as could

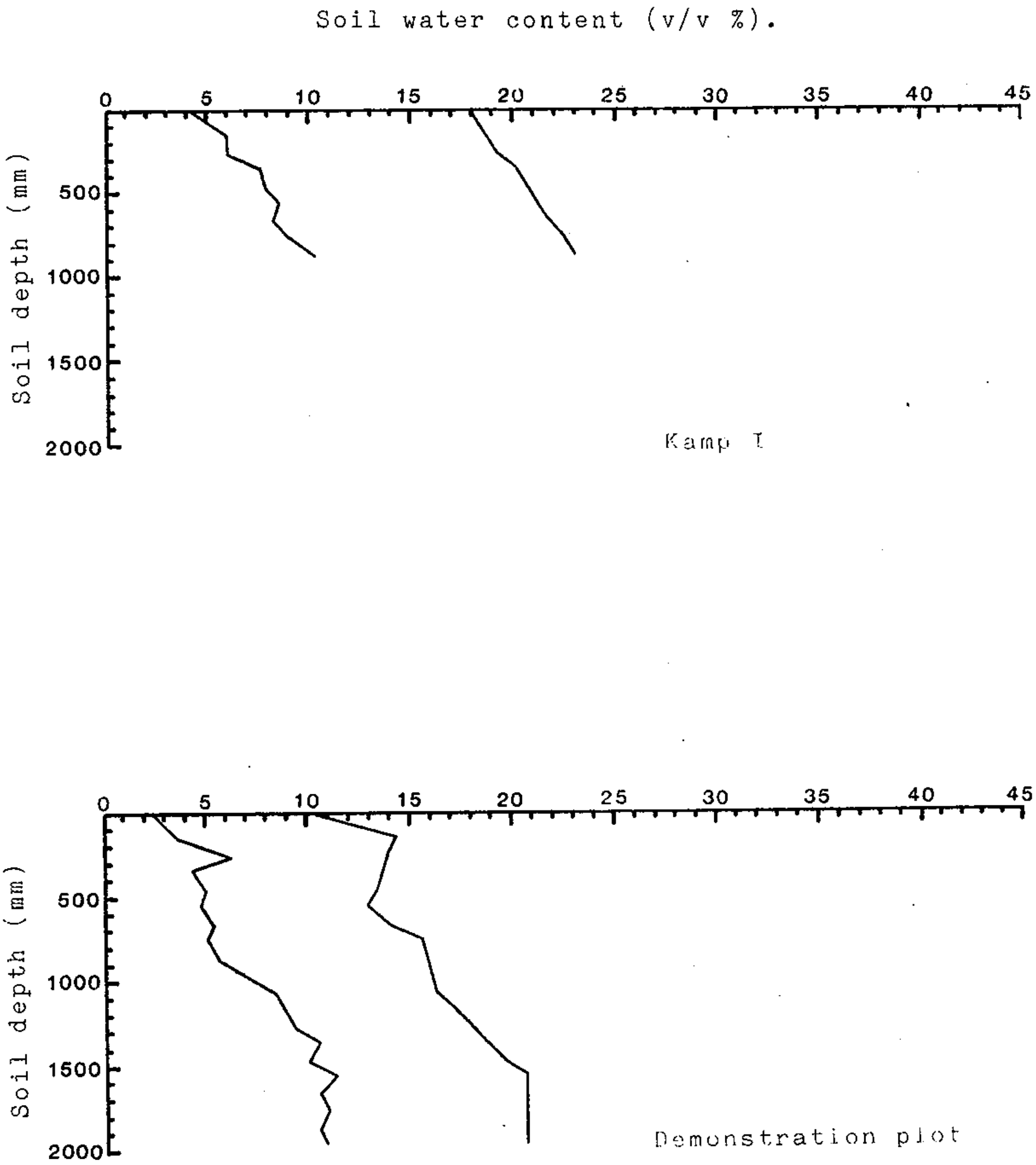


FIG.2.27 Soil water contents at field capacity (FC) and first stress (FS) for wheat at flowering at Vaalharts.

be expected (see also Chapter 3).

It may be considered a surprise that the extraction pattern for wheat on Kamp II (Stanford series, Sterkspruit form) was similar to the ones found on the sandy Huttons. Wheat extracted an unexpectedly large quantity of water from the prismacutanic B horizon (see Figure 2.28). This was probably related to the relatively high rooting densities in this layer (see also Chapter 3). It confirms the observations that wheat roots are capable of exploiting structured subsoils well. It should be kept in mind that the clay content of the prismacutanic B horizon of this soil is only 21,8% and that its structure is not very strong, however.

At Kamp II an access tube was, accidentally, inserted into the underlying soft $CaCO_3$-layer (calcic horizon). Neutron hydroprobe readings revealed that large quantities of water "disappeared" from this layer. It is normally supposed that a calcic horizon does not contribute to the profile available water. To what extend this water "extraction" was due to drainage, actual root penetration or capillary movement of water to the overlying soil is not clear. According to Bennie (1984, personal communication) and Burger (1984, personal

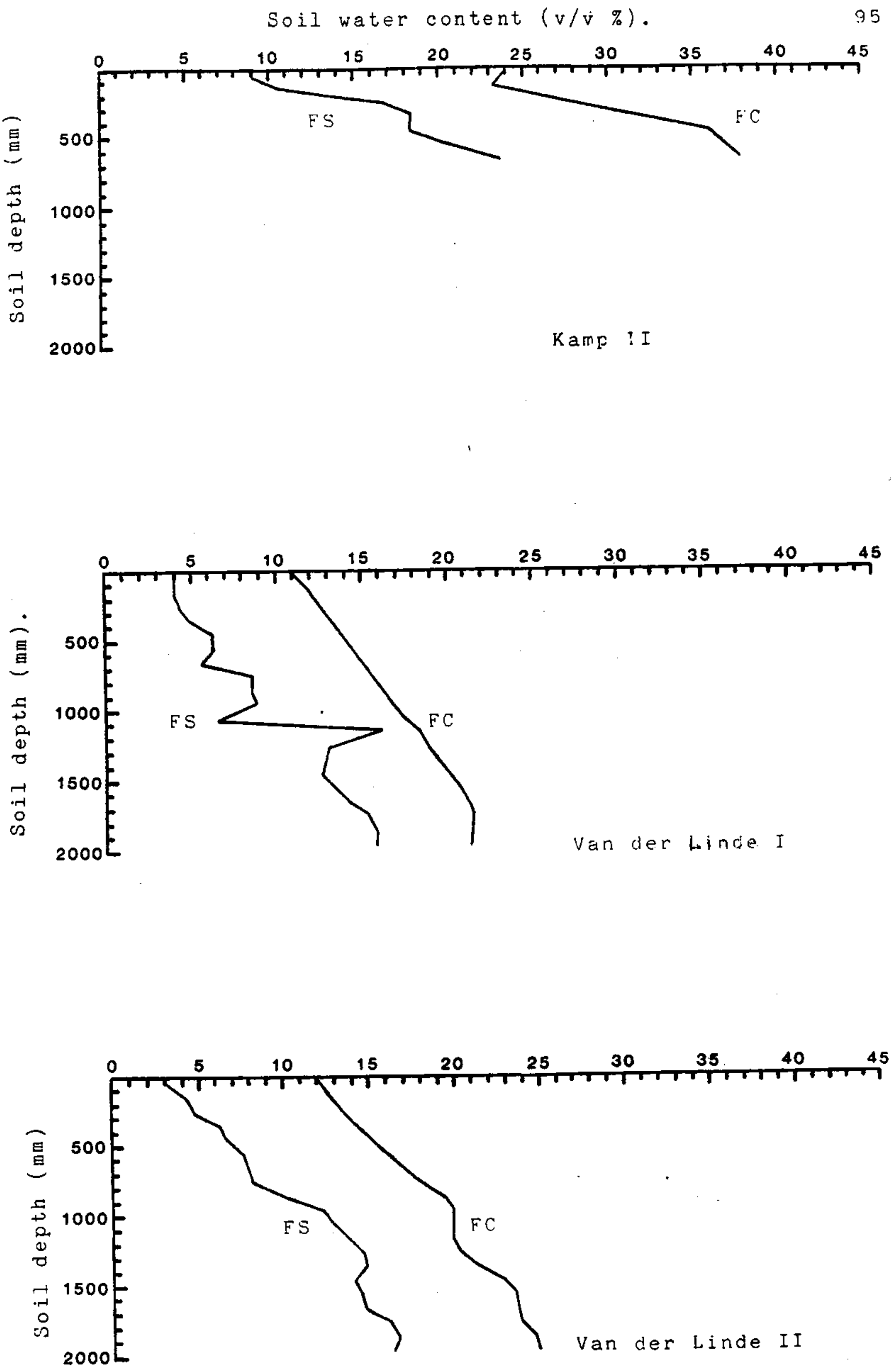


FIG.2.28 Soil water contents at field capacity (FC) and (FS) for wheat at flowering at Vaalharts.

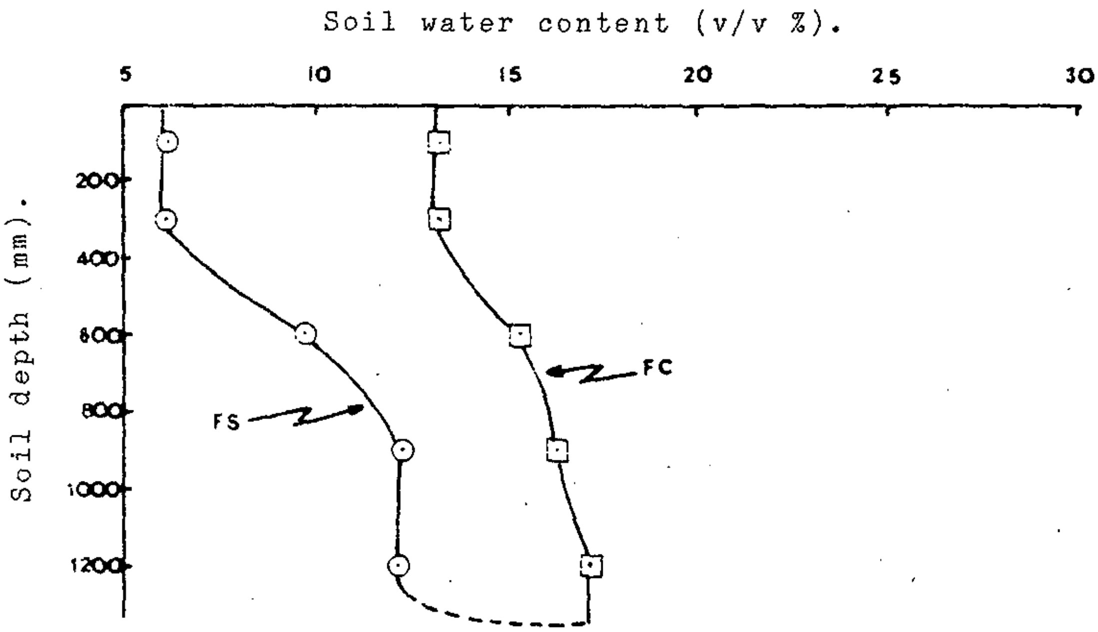


FIG.2.29 Soil water extraction pattern for mature wheat on Mangano series at Vaalharts during a growing season with a mean evaporative demand of about 8mm/day. FS = first material stress, FC = field capacity. From Hensley & De Jager, 1982.

communication) roots actively grow in these $CaCO_3$-layers and these layers form an important water reservoir under dryland conditions.

The water extraction by crops from below 2000mm depth in the deep, fine sandy soils is probably made possible by the ease with which roots can ramify in them. The result is that, although these soils have relatively low water holding capacities per unit of depth, high PAWC - values were found at all the deep, fine sandy soil sites (see Table 2.3). The use of 3000mm access tubes will have to be considered for these soils if one wants to monitor water extraction over the entire rooting zone.

b. Discussion

Originally it was thought that the apparent differences between the extraction patterns found for the Ciskeian soils and the deep apedal, fine sandy Hutton soils of the Vaalharts irrigation scheme were caused by the drainage characteristics of the Vaalharts soils and that a lot of water was lost from the soil profile through deep percolation. Close examination of the soil profile properties revealed that the fine fraction of soil texture range (clay + silt) was increasing almost linearly with depth at the Hutton sites of Vaalharts (see Appendices 2.6, 2.8, 2.9, 2.10 and 2.11). For such sandy soils it could be expected that such increase in fine fraction would affect water holding characteristics. The relationship between soil texture and soil moisture content at field capacity for the Vaalharts sites is shown in Figure 2.30. Similar relationships were found by Van der Merwe (1973). Obviously, not only field capacity is changing with texture but also the available water range. In Table 2.4 volumetric soil water contents at 10kPa and 1500kPa soil water tension are listed for two soil horizons with different clay contents. The information was extracted from matric suction curves for the different pedogenetic horizons of a similar Mangano soil in the Vaalharts region.

TABLE 2.4 - Volumetric soil water content at soil water potentials of -10kPa and -1500kPa for two pedogenetic horizons of a Mangano soil at Taung (from Hensley & De Jager, 1982).

horizon	clay%	% H_2O -10kPa	%H_2O -1500 kPa	Difference %
Ap	8,4	15	7	8
B23	10,6	21	9	12

From Table 2.4 it is clear that the available water

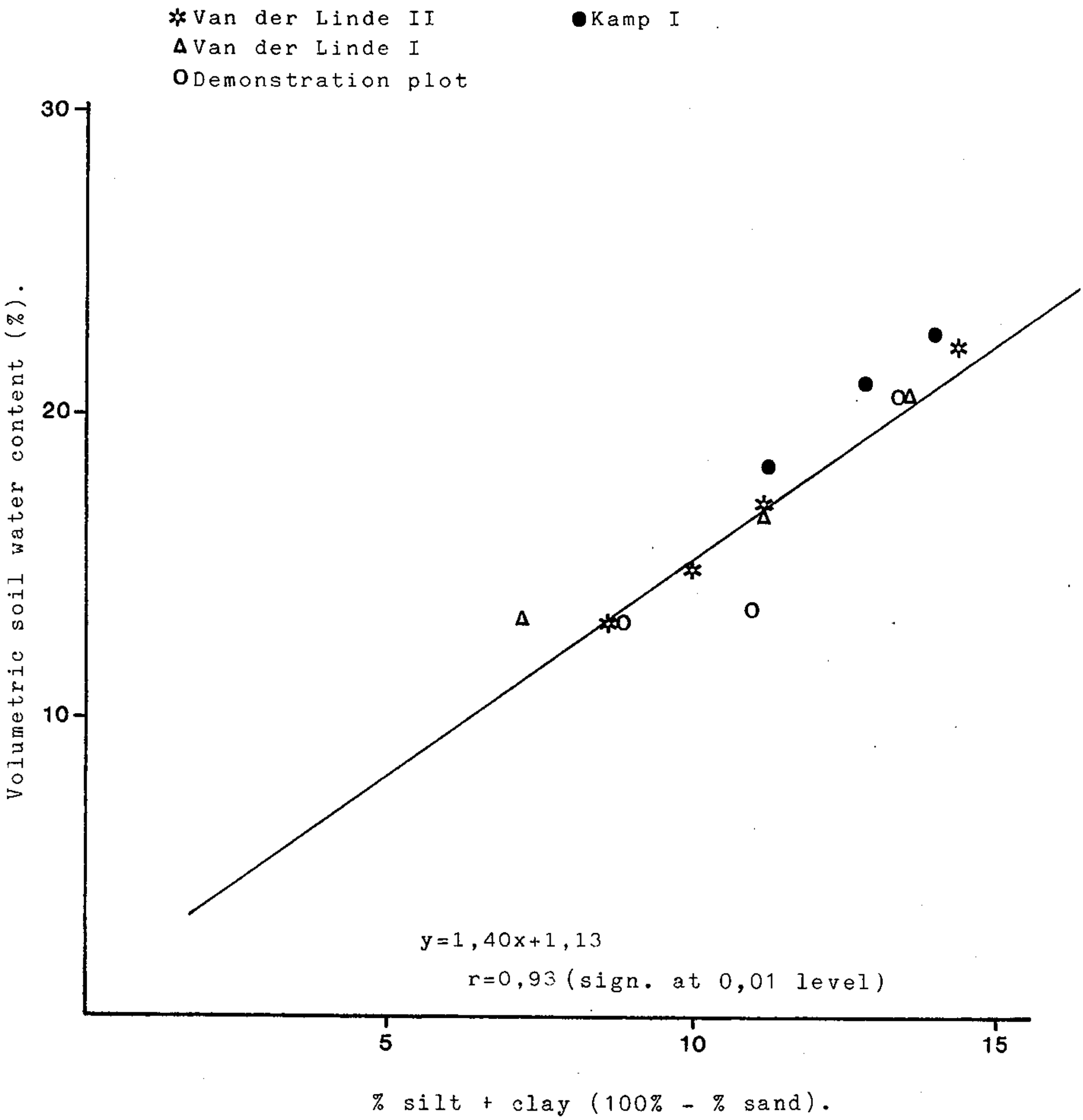


FIG.2.30 Relationship between soil texture and soil water content at field capacity.

content changes drastically with increasing clay content. The lower B horizon holds twice as much available water between -10kPa and -1500kPa as the A horizon. Consider a hypothetical constant extraction of 6mm per unit of soil depth throughout the soil profile: For the soil mentioned in Table 2.4 this would mean that from the Ap horizon 100% of the available water between -10kPa and -1500kPa would have been consumed while only 50% of the water available in that range would have been used in the B horizon. This hypothetical situation can be projected on the Hutton soils at Vaalharts. The observed constant amounts of water extracted throughout the profile are absolute values which do not reflect the decrease in <u>percentage</u> of water extracted from the available water range per unit depth with increasing depth. This phenomenon is masked because both the increase in clay content with depth and the decrease in percentage of water extracted with depth are linear. This is illustrated in Figure 2.31: the quantities of water extracted per unit of depth for the different pedogenetic horizons at Van der Linde II are compared with the percentage of the available water (expressed as the difference between the soil water contents at soil water potentials of -10kPa and -1500kPa) extracted per unit of depth of each pedogenetic horizon. It can be seen that a

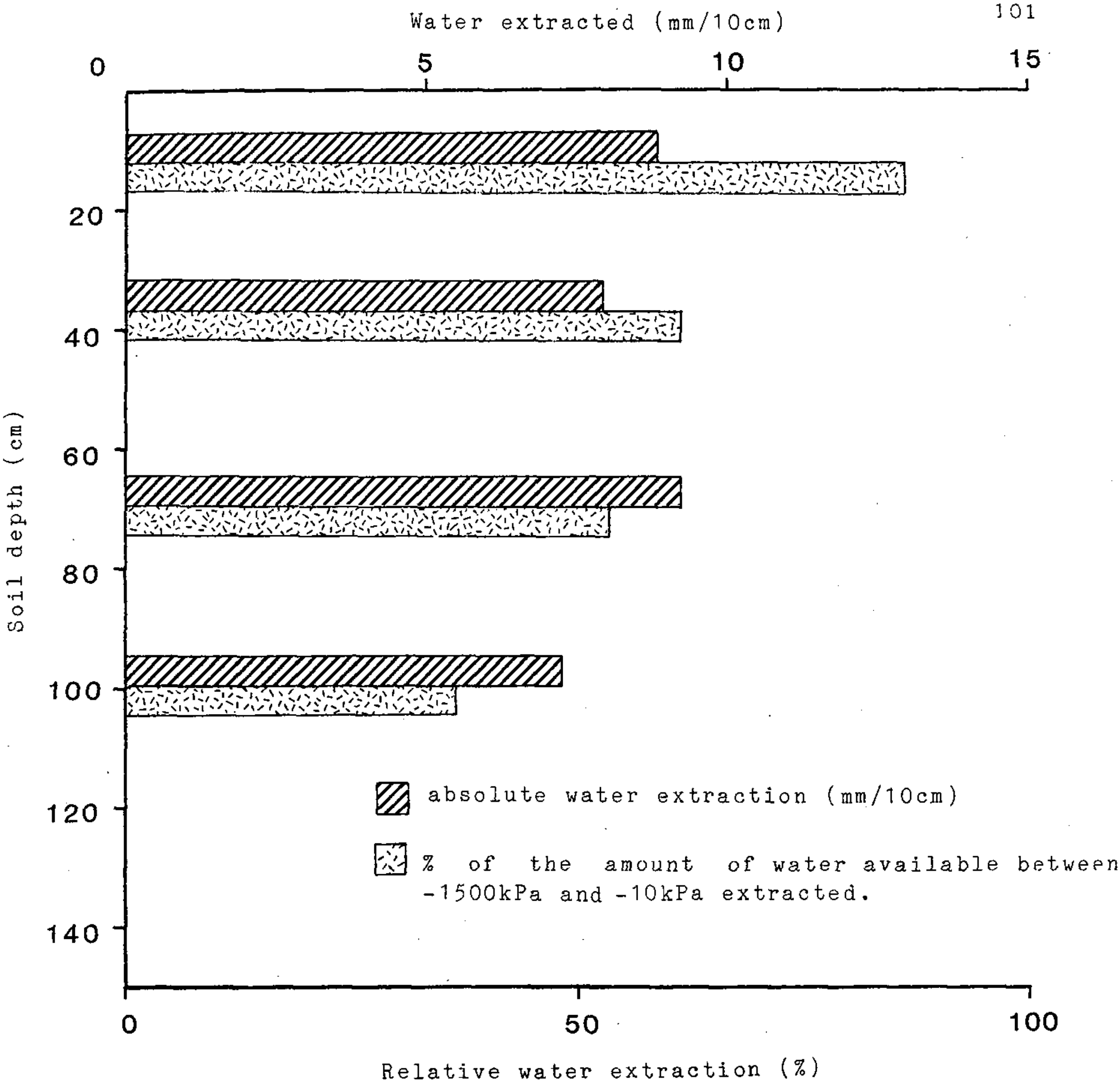


FIG.2.31 Absolute and relative water extraction at different depths of the soil profile at Van der Linde II (Vaalharts).

decreasing percentage of the available water is extracted per unit of depth with increasing depth. This is an indication that if the soil texture would be more uniform throughout the Hutton soil profiles an extraction pattern similar to those for the more clayey soils would appear.

The fact that this "disturbance" of the water extraction pattern by soil texture characteristics does not appear on the Ciskei soils is due to the fact that in the present study and that of Hensley & De Jager (1982) it was found that texture is only influencing soil water holding capacities in the range 0% to 20% Clay + Silt (see Figure 2.32) and soils of the Ciskei experiments contained more than 20% Clay + Silt. This aspect will be discussed in more detail in Chapter 7.

2.3.2.2 Peas

2.3.2.2.1 Ciskei

Peas were planted only on the Jozini, Marikana and Kinross soils because it was expected that peas would do badly on the Arniston and Sterkspruit soils with their strongly structured B horizons. On the Kinross soil,

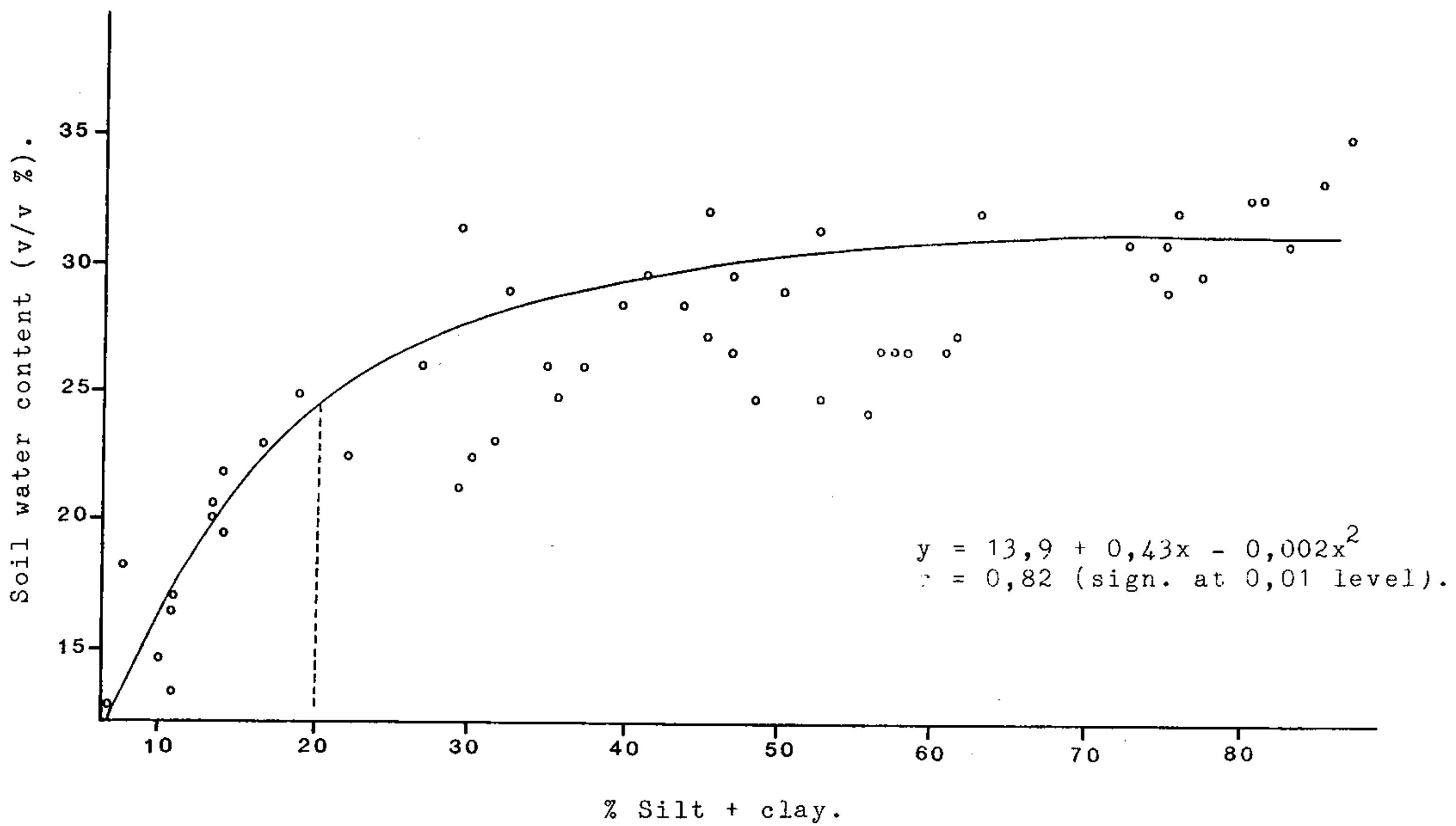


FIG.2.32 Relationship between soil water content at Field Capacity and percentage silt + clay in a soil.

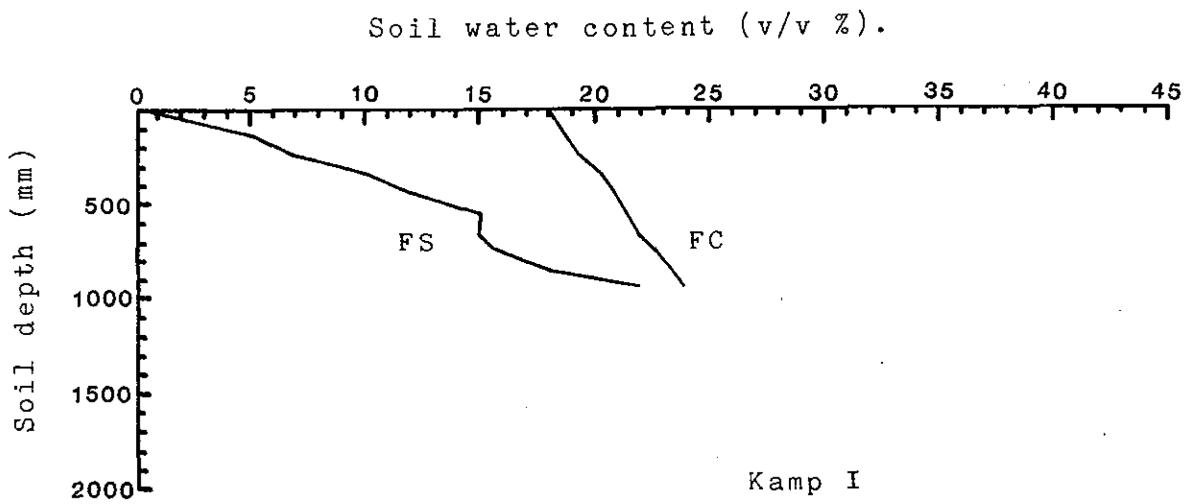
with a strong to moderately strong structured B horizon peas performed badly and a low PAWC value was obtained (see Table 2.5 and Figure 2.33). This was mainly due to the fact that roots could not penetrate deeper than 700mm. A low PAWC - value was also found for peas on the Marikana soil, the limiting factor to root development being the occurrence of a compacted layer at 400mm to 600mm depth. The best result was obtained at the Jozini-site. The effective rooting depth was 1500mm and a high PAWC - value was found (see Table 2.5 and Figure 2.33).

2.3.2.2.2 Vaalharts

The general trend in the water extraction pattern for peas is that relatively large quantities of water are extracted from the toplayers (of the same order as that for wheat). Below this there is a decrease in the quantity of water extracted per unit depth with increasing soil depth until a more-or-less constant figure is reached for the deeper layers (see Figures 2.34 and 2.35). These values for the deeper layers are considerably less than those found for wheat at corresponding depths. The result is that peas have a

TABLE 2.5 - Quantities of water extracted (determined gravimetrically) at first stress (indicated by pre-dawn leaf water potential) by peas in the Ciskei.

Soil Depth (mm)	Water extracted (mm/100mm)		
	Jozini	Marikana	Kinross
0 - 100	16,6	29,4	17,5
100 - 200	16,6	17,2	16,5
200 - 300	16,6	12,8	15,2
300 - 400	12,5	7,8	9,4
400 - 500	8,5	3,4	4,4
500 - 600	5,7	2,1	0,7
600 - 700	5,5	2,2	0,5
700 - 800	5,3	3,4	
800 - 900	4,8	2,5	
900 - 1000	2,4	1,3	
1000 - 1100	3,0		
1100 - 1200	3,2		
1200 - 1300	3,0		
1300 - 1400	2,8		
1400 - 1500	2,4		
PAWC	108,9	82,1	64,2



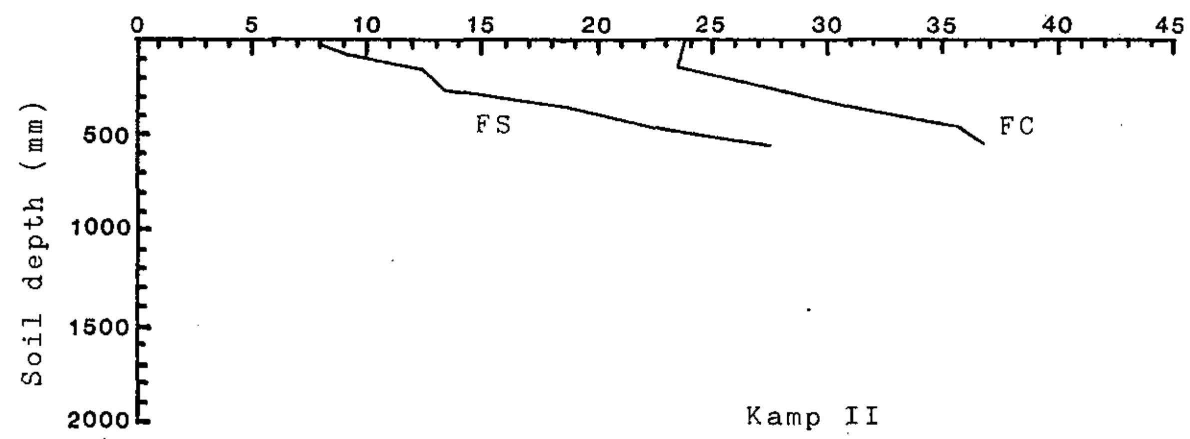


FIG.2.33 Soil water contents at field capacity (FC) and first stress (FS) for peas at flowering at Vaalharts.

much lower PAWC than wheat on any specific soil (see Table 2.3 and Table 2.6).

The moderately structured B horizons at Kamp II and Kamp I only slightly hampered root development. They were not as high in clay and silt content as the Ciskeian soils (see Appendices 2.6 and 2.7). Only a slight decrease of water extracted per unit of depth with increasing depth was found at the Stanford site (see Figure 2.34). At Kamp I the field capacity line and the first stress line are bending towards each other in the bottom of the soil profile (see Figure 2.34). This is probably due to the high concentration of $CaCO_3$-nodules in this part of the soil profile.

2.3.2.3 Maize

2.3.2.3.1 Vaalharts (summer 1982/83)

Visual symptoms were used to indicate stress. For the deep sandy Mangano soils (Kamp III, Van der Linde I and II, Demonstration Plot) similar extraction patterns were found as for wheat. See Table 2.7 and Figures 2.36 and 2.37. More-or-less constant quantities of water were extracted per unit depth throughout the profile. At some

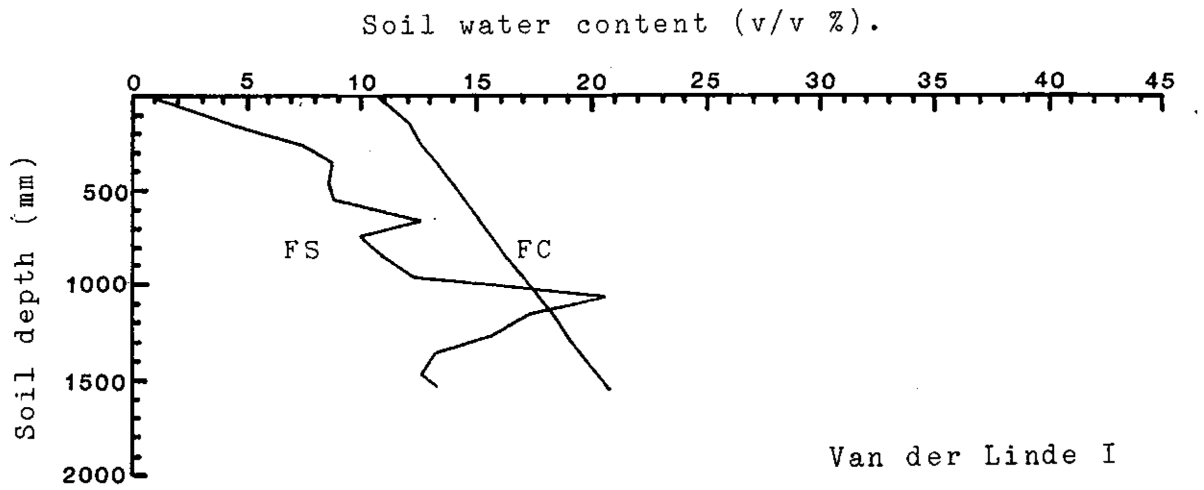
TABLE 2.6 - Quantities of water (determined gravimetrically) extracted by peas at first stress (indicated by pre-dawn leaf water potential readings) at Vaalharts.

Soil Depth (mm)	Water extracted (mm/100mm)			
	Kamp I	Kamp II	V.Linde I	V.Linde II
0 - 100	16,2	14,6	9,7	9,5
100 - 200	13,6	11,1	7,6	9,1
200 - 300	12,2	14,5	5,1	8,5
300 - 400	10,0	12,9	4,4	6,7
400 - 500	8,9	13,0	5,3	6,9
500 - 600	6,2	9,3	5,7	7,3
600 - 700	6,9		2,4	6,6
700 - 800	7,0		5,8	5,8
800 - 900	5,1		5,3	5,4
900 - 1000	1,9		4,7*	4,3
1000 - 1100			(0)	4,1
1100 - 1200			1,0	3,7
1200 - 1300			3,2	3,2
1300 - 1400			6,3	2.8
1400 - 1500			7,5	5,3
1500 - 1600			7,5	6,9
PAWC	88,0	75,4	81,5	96,1

*occurrence of thin clay layer.

TABLE 2.7 - Water extracted (determined gravimetrically) at first stress (indicated by visual symptoms) by maize at Vaalharts.

Soil Depth (mm)	Water extracted (mm/100mm)						
	KI	KII	KIII	VdlI	VdlII	D.E.	Joubert
0 - 100	13,4	13,1	11,9	10,5	6,2	6,8	16,7
100 - 200	12,8	9,9	10,1	8,7	5,5	8,3	11,1
200 - 300	12,5	13,0	8,1	8,1	4,6	5,9	9,7
300 - 400	12,9	15,3	6,4	7,0	4,2	7,1	9,2
400 - 500	10,4	14,4	6,4	6,4	4,8	7,9	10,1
500 - 600	6,3	11,6	7,5	7,0	6,3	7,4	9,6
600 - 700	7,1	11,3	8,5	7,5	6,2	8,5	9,3
700 - 800	6,7	8,6	9,4	7,7	6,1	9,6	8,1
800 - 900	5,9	7,9	10,2	7,8	6,5	9,2	6,9
900 - 1000		6,3	10,2	7,3	6,0	8,6	4,3
1000 - 1100		4,9	10,0	7,5	5,2	8,1	6,6
1100 - 1200		1,3	9,5	7,7	4,8	8,3	
1200 - 1300				7,7	4,7	8,7	
1300 - 1400				7,8	5,1	9,2	
1400 - 1500				7,9	6,0	9,6	
1500 - 1600				6,7	5,1	9,1	
PAWC	88,0	117,6	108,2	123,3	87,3	132,2	101,6



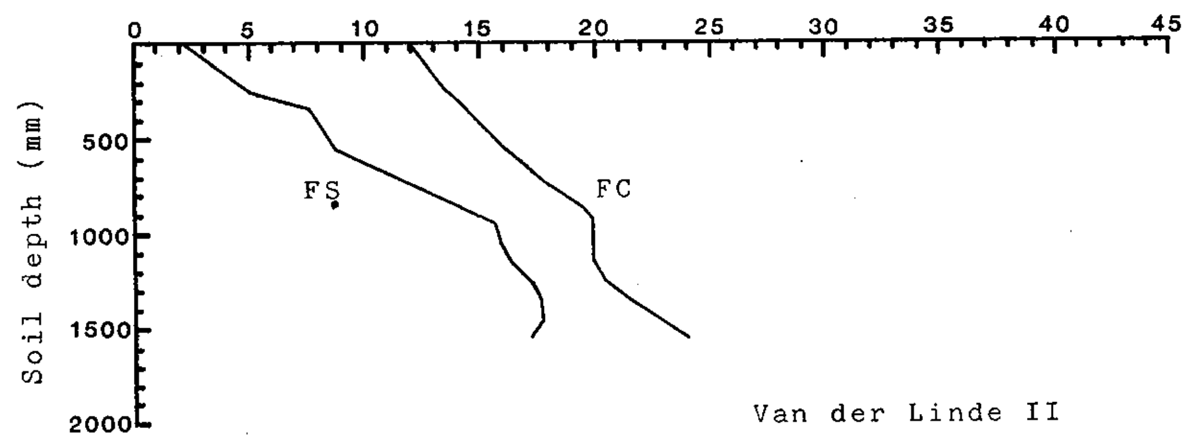


FIG.2.34 Soil water contents at field capacity (FC) and first stress (FS) for peas at flowering at Vaalharts.

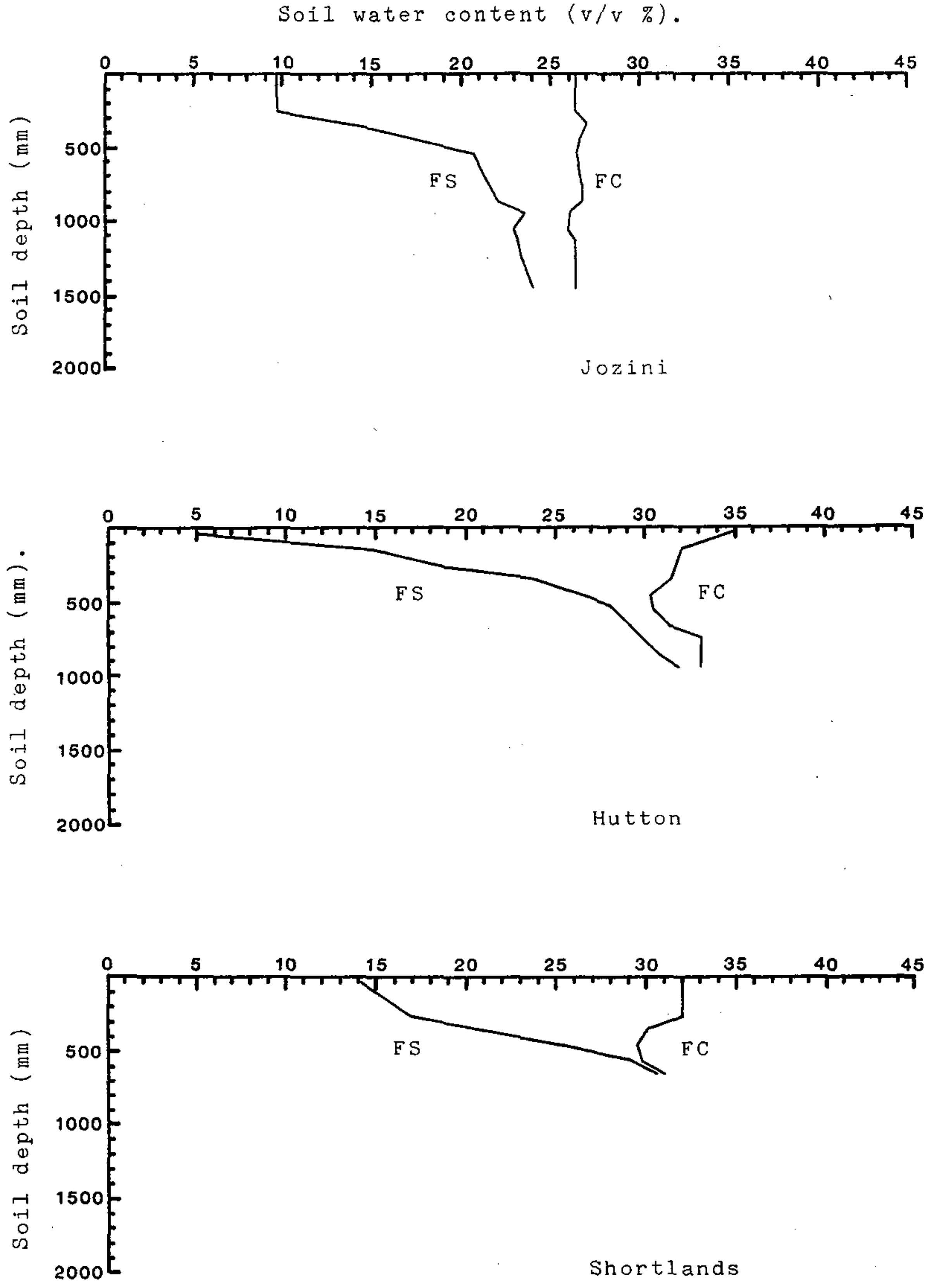


FIG.2.35 Soil water content at field capacity (FC) and first stress (FS) for peas at flowering in the Ciskei.

of the sites (Van der Linde I, Kamp III, Demonstration plot - see Figures 2.36 and 2.37) slight deviations from linearity were observed at a depth varying from 250mm to 400mm, depending on the site. The reduction in soil water extraction at these depths is attributed to severe soil compaction, which is a characteristic of these fine sandy soils.

The thin clay layer that occurred at about 1000mm depth in the soil profile where the experiments for wheat were conducted at Van der Linde I was not found at the adjacent site where the maize experiment was done. A normal extraction pattern was found (see Figure 2.38).

At the Van der Linde II site a very low PAWC - value was found, compared with results on the other similar soils (see Table 2.8). No explanation could be found for this low value.

The extraction pattern found for maize on the medium textured Stanford site (Sterkspruit form, Kamp II) was strikingly different from the extraction pattern found at the other (deep, sandy) Vaalharts sites (see Figures 2.36 and 2.37). A pattern identical to those for the medium to fine textured Ciskeian soils, with decreasing amounts

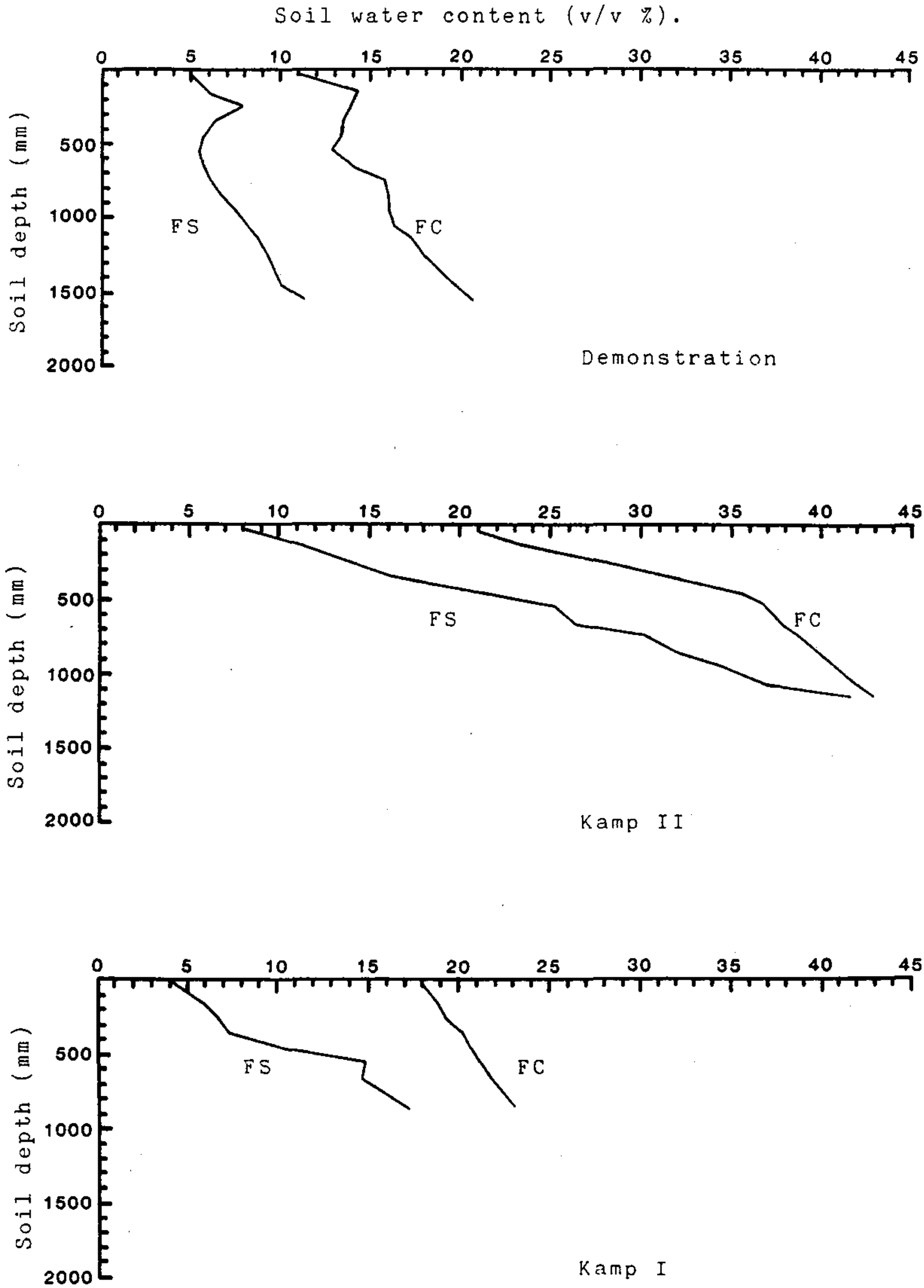


FIG.2.36 Soil water contents at field capacity (FC) and first stress (FS) for maize at flowering at Vaalharts.

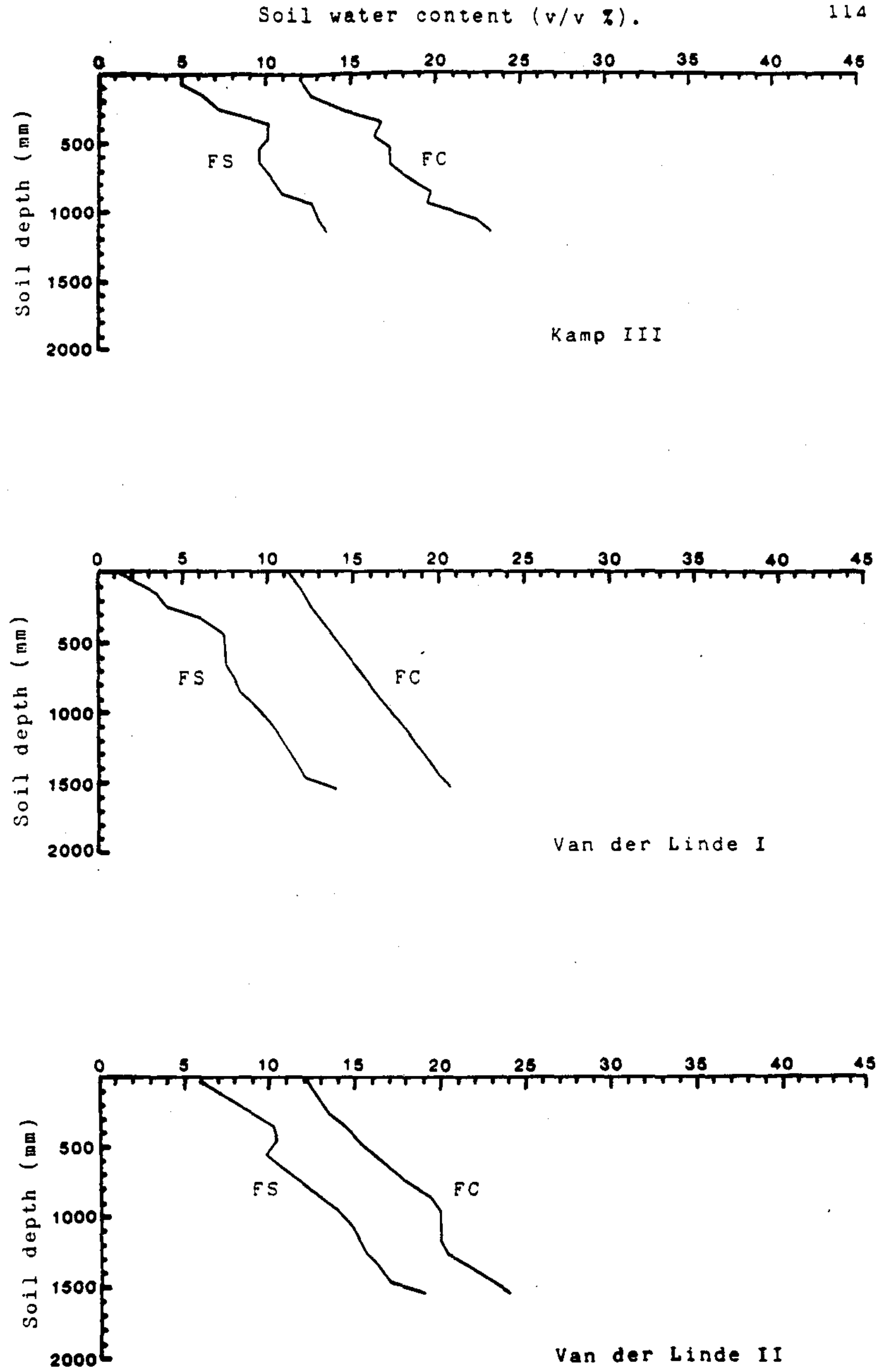


FIG.2.37 Soil water contents at field capacity (FC) and first stress (FS) for maize at flowering at Vaalharts.

of water extracted with increasing depth, was found. The pattern was remarkably similar to those found for maize in the Ciskei by Hensley & De Jager (1982). In Figure 2.38 the data for maize at Kamp II are compared with the common relationship found by Laker (1982) for maize on Ciskeian soils. The only real discrepancies between the calculated regression line and the data for the Stanford soil are for the 0 to 300mm soil layers (a sandy layer covering the prismacutanic B horizon).

2.3.2.3.2 Loskop

As previously indicated prolonged leaf water potential monitoring, which was eventually suspected of allowing water extraction beyond first stress, was used in a attempt to detect first stress. Because of this extremely high PAWC values were obtained (see Table 2.8).

There was at all sites a clear tendency towards an extraction pattern of decreasing amounts of water extracted per unit depth with increasing depth (Figures 2.39, 2,40 and 2,41). This trend was somewhat masked by the high quantities of water extracted from the lower parts of the soil profile at the end of the drying cycle when the crops were visually already past first stress. This will be discussed in detail in Chapter 3.

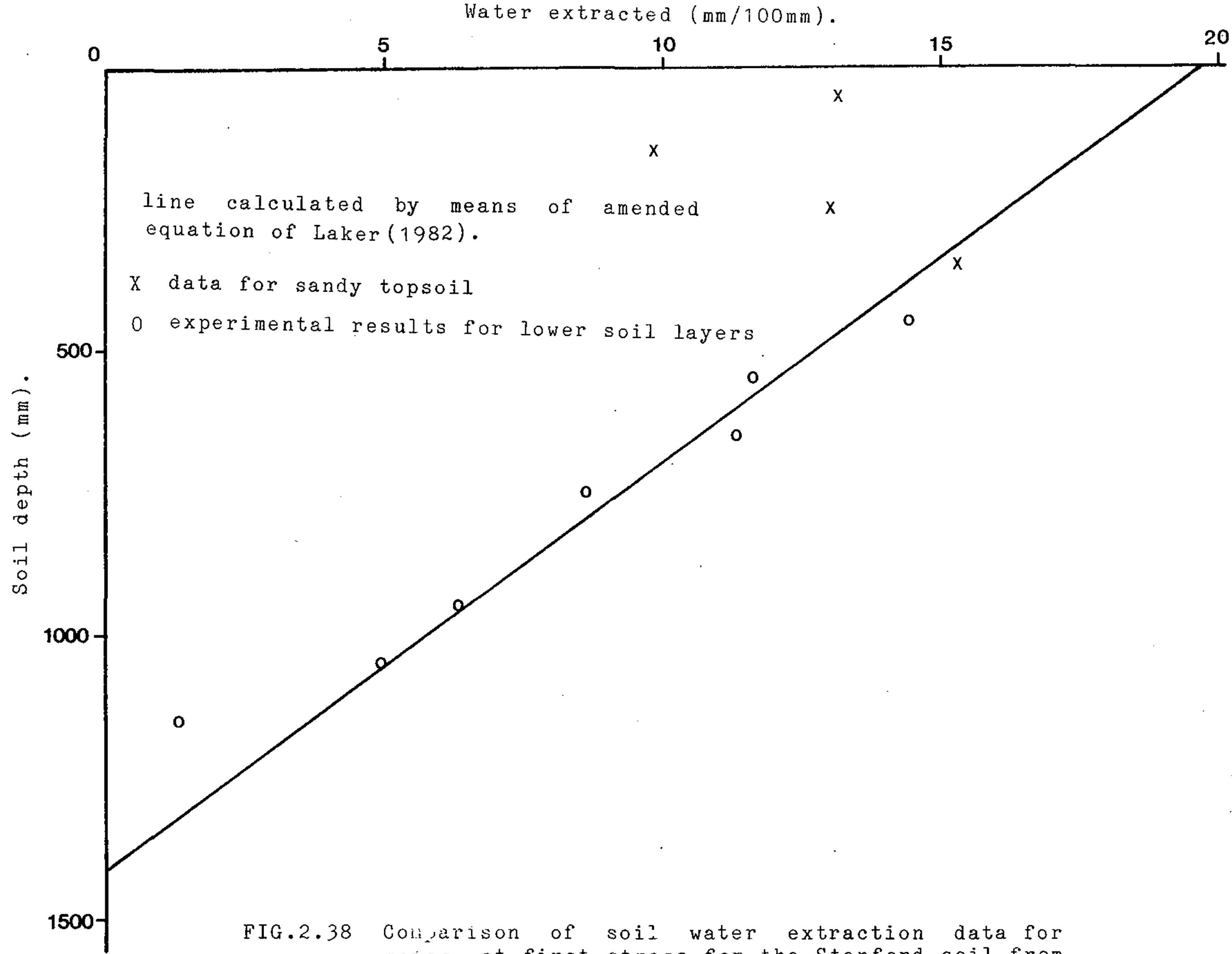


FIG.2.38 Comparison of soil water extraction data for maize at first stress for the Stanford soil from Vaalharts with the regression line of Laker (1982) for maize at first stress on Ciskeian soils.

TABLE 2.8 - Water extracted (determined gravimetrically) by maize at first stress (indicated by pre-dawn leaf water potential) at Loskop.

Soil Depth (mm)	Water extracted (mm/100mm)						
	C5	C10	DI	DII	DIII	VI	VII
0 - 100	21,0	15,6	19,2	17,3	13,9	20,3	21,7
100 - 200	11,4	12,4	16,0	13,3	12,1	14,7	18,0
200 - 300	9,2	10,6	15,4	12,8	6,1	13,8	15,8
300 - 400	9,6	6,4	11,7	9,0	8,6	13,1	12,0
400 - 500	9,8	12,2	12,1	8,9	9,1	14,1	13,5
500 - 600	9,1	13,7	11,9	10,4	11,9	15,0	12,6
600 - 700	9,0	15,1	12,5	12,4	10,9	13,5	12,5
700 - 800	8,5	16,6	10,9	10,2	10,9	12,5	13,1
800 - 900	6,9	14,7	9,8	8,2	10,5	11,1	14,7
900 - 1000			6,3	5,7	9,8	8,4	15,1
1000 - 1100			5,0		8,9		12,9
1100 - 1200			5,1		7,7		10,1
1200 - 1300			6,4		7,5		6,2
1300 - 1400			4,6		9,2		3,9
1400 - 1500			4,1		9,2		1,7
1500 - 1600			3,2		9,2		
PAWC	101,2	117,3	154,2	108,2	155,5	136,5	183,8

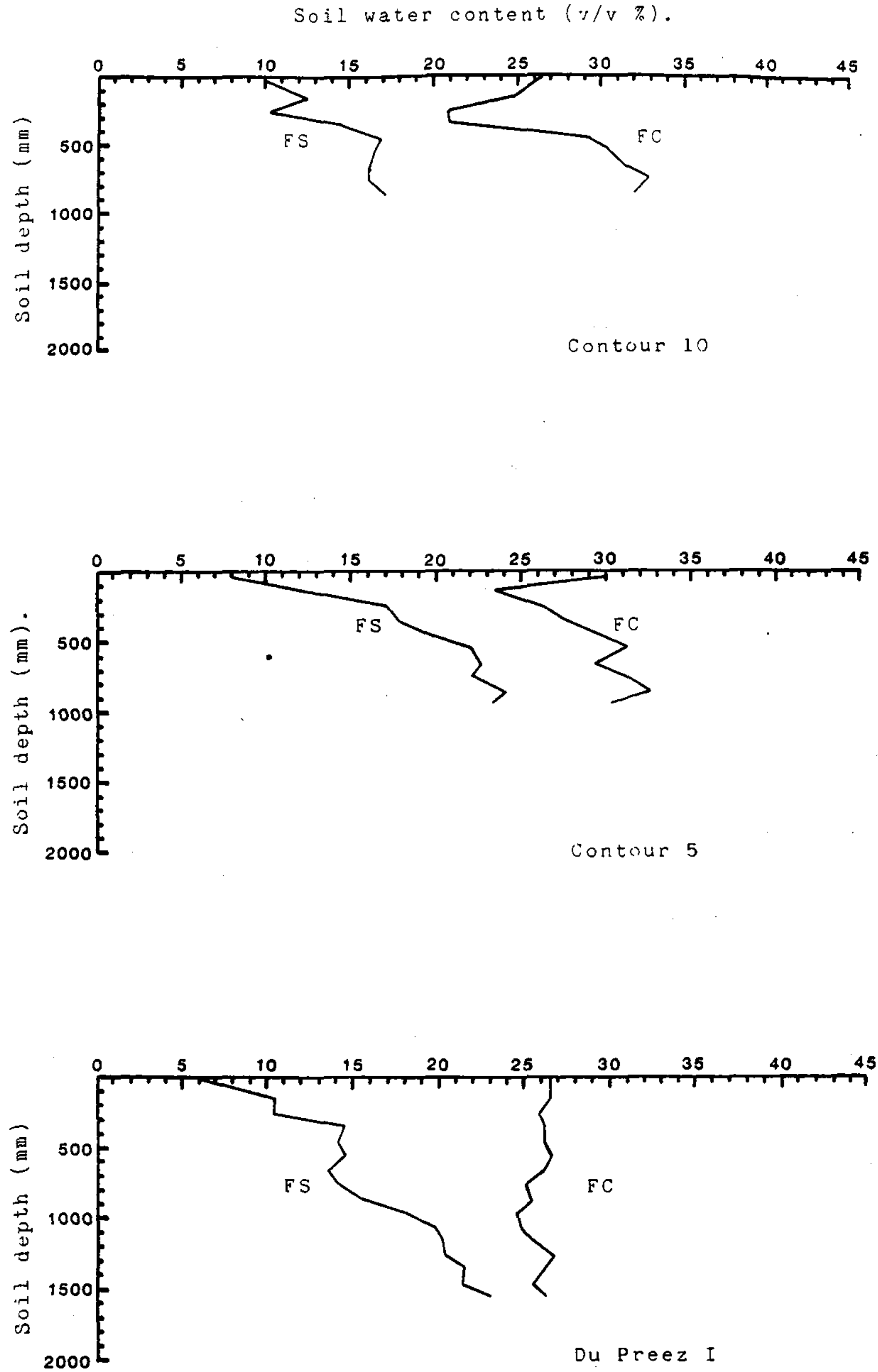
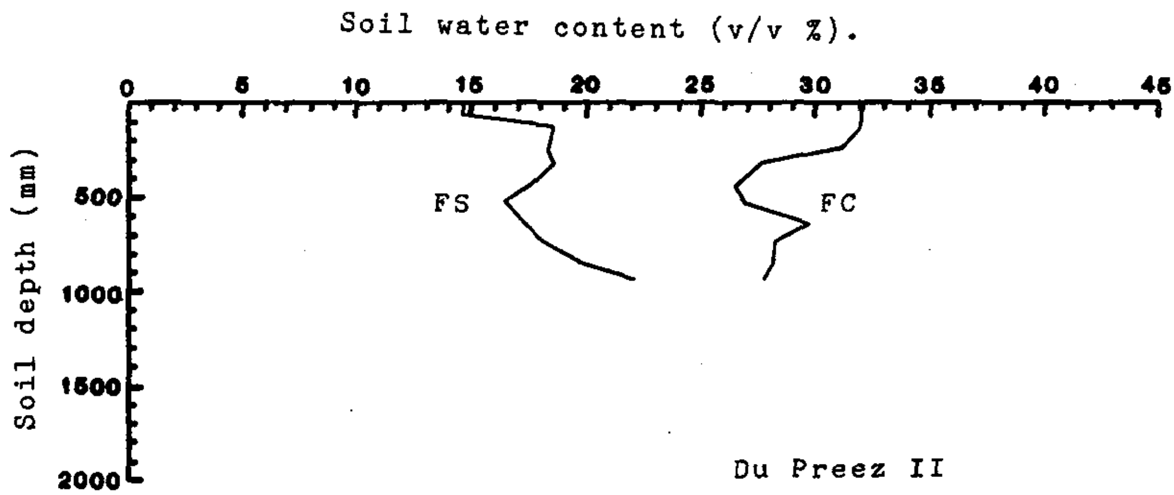


FIG.2.39 Soil water contents at field capacity (FC) and first stress (FS) for maize at flowering at Loskop.



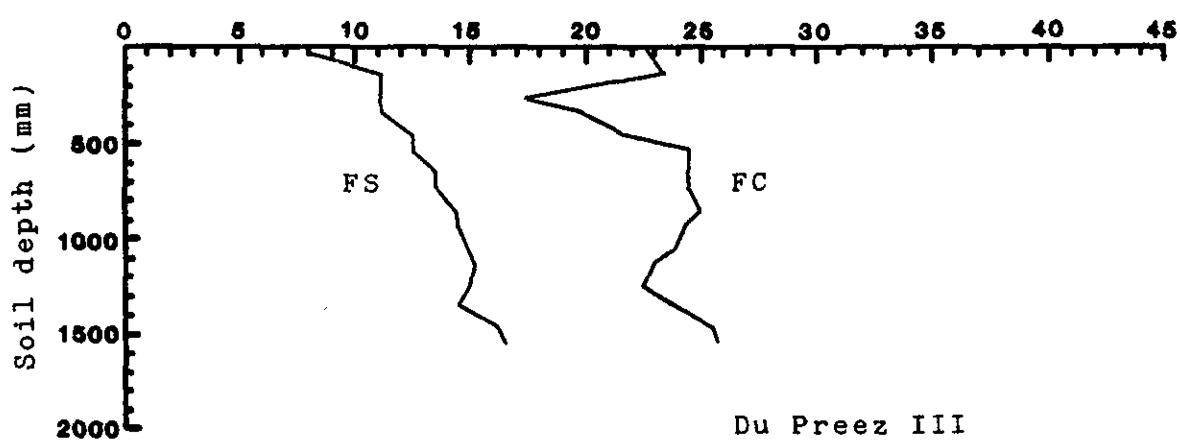
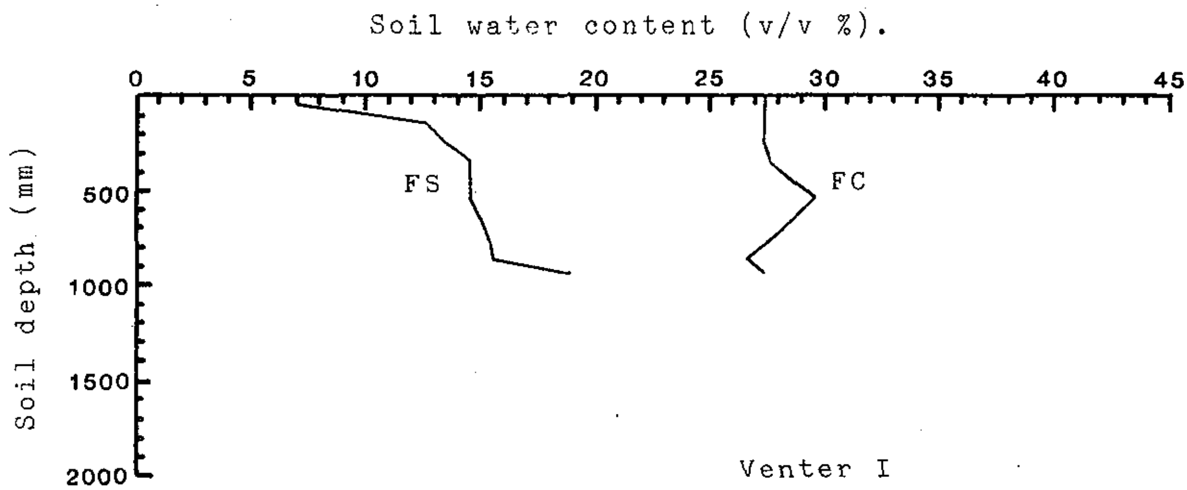


FIG.2.40 Soil water contents at field capacity (FC) and first stress (FS) for maize at flowering at Loskop.



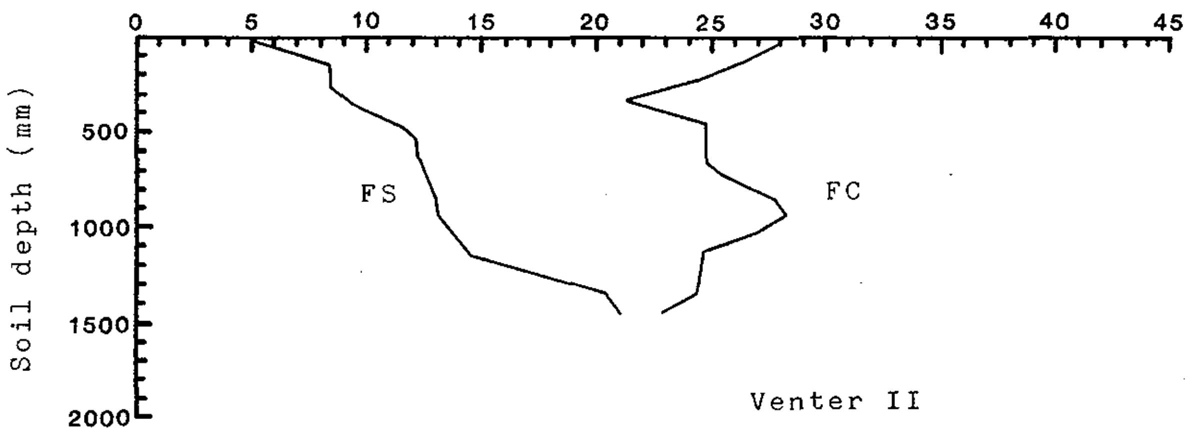


FIG.2.41 Soil water content at field capacity (FC) and first stress (FS) for maize at flowering at Loskop.

At Du Preez I, II and III and Contour 10 the extraction pattern shows deviations at the transition between the A and B horizons. Relatively less water is extracted from this zone. This is probably due to temporary poor aeration conditions when water is stagnating on the more structured B horizon (Contour 10, Du Preez I and II) or to the occurrence of a compacted layer (Du Preez I) (see Figures 2.39 and 2.40).

2.3.2.4 Cotton

2.3.2.4.1 Vaalharts

The final water extraction patterns for cotton on the well drained, deep Mangano soils were very similar to the ones observed for maize and wheat (see Figures 2.42 and 2.43). On average cotton extracted 30% more water from the soils than maize (compare Tables 2.7 and 2.9). The cotton root system is very sensitive to compacted soil layers and at Demonstration Plot and Kamp III the experiments had to be abandonned because root development was severely limited by a compacted layer occurring close to the soil surface.

TABLE 2.9 - Quantities of water extracted (determined gravimetrically) at first stress (indicated by visual stress symptoms) by cotton at Vaalharts.

Soil Depth (mm)	Water extracted (mm/100mm)			
	Kamp I	Kamp II	V.d.L.I	V.d.L.II
0 - 100	11,5	12,6	10,4	7,5
100 - 200	10,8	10,4	9,3	6,8
200 - 300	10,2	11,8	8,1	6,4
300 - 400	9,9	15,1	7,1	5,9
400 - 500	10,3	17,8	7,6	6,6
500 - 600	11,4	15,8	8,5	8,4
600 - 700	10,8	17,0	9,3	8,5
700 - 800	10,2	17,6	9,8	8,6
800 - 900	9,5	17,5	10,0	9,0
900 - 1000	8,0	16,1	10,0	8,5
1000 - 1100	6,8	10,9	10,0	7,7
1100 - 1200	6,0	4,9	10,0	7,3
1200 - 1300			9,9	7,2
1300 - 1400			9,8	7,5
1400 - 1500			9,6	8,3
1500 - 1600			9,0	8,2
PAWC	115,4	167,5	148,4	122,4

Cotton is known to do very well on structured clayey soils and exploited the prismacutanic B horizon of the Stanford soil (Kamp II) very well and a high PAWC value was found for this site (see Table 2.9 and Figure 2.42).

2.3.2.4.2 Loskop

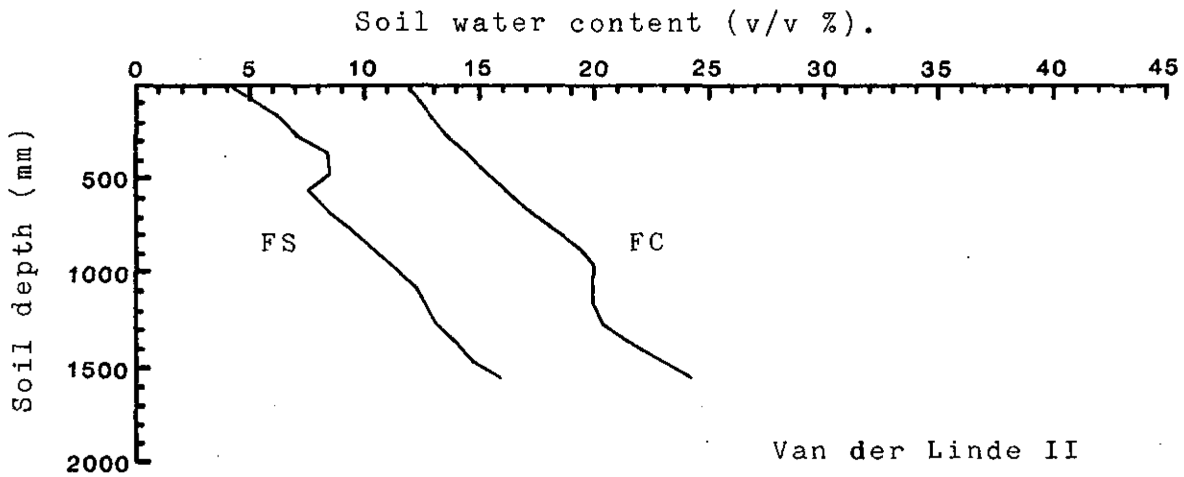
The extraction patterns for cotton were very similar to the ones found for maize in this region. Again the drying cycle was probably stretched too far. For this reason very high PAWC values were found (see Table 2.10 and Figures 2.44, 2.45 and 2.46). Slight deviations also occurred in the transition zone between the A and the B horizons, as for maize.

2.4 CONCLUSIONS

a. Medium to strongly structured subsoil horizons make considerable contributions towards the available water capacity of a soil. Especially wheat seems to be able to draw large quantities of water from soils with red structured, pedocutanic or prismacutanic horizons. Certain limitations are put on the ramification of roots in these horizons. This probably results in a slow, but steady water flow to the roots in them. Pre-dawn leaf

TABLE 2.10 - Quantities of water extracted (determined gravimetrically) by cotton at first stress (indicated by pre-dawn leaf water potential) at Loskop.

Soil Depth (mm)	Water extracted (mm/100mm)						
	C5	C10	DI	DII	DIII	VI	VII
0 - 100	21,1	14,7	20,0	19,5	16,1	21,9	22,9
100 - 200	11,9	12,4	15,4	14,8	13,3	16,4	18,2
200 - 300	10,8	10,3	11,0	11,6	6,3	15,9	13,5
300 - 400	11,4	10,3	14,0	9,3	8,4	14,9	9,7
400 - 500	12,5	15,6	15,7	9,4	10,4	14,6	11,0
500 - 600	12,8	15,3	16,1	11,5	12,5	15,1	9,4
600 - 700	10,5	16,6	16,0	14,2	11,4	13,8	8,3
700 - 800	9,1	17,8	13,4	10,6	9,7	14,3	10,1
800 - 900	5,8	15,9	12,1	10,7	9,4	12,6	10,2
900 - 1000	3,5	10,1	12,7	6,9	6,5		7,9
1000 - 1100			11,4		4,3		5,3
1100 - 1200			10,6		1,9		0,7
1200 - 1300			10,7		0,6		
1300 - 1400			9,5		1,7		
1400 - 1500			8,1		3,3		
1500 - 1600			9,4		3,2		
PAWC	109,4	139,0	206,1	118,5	119,0	139,5	127,2



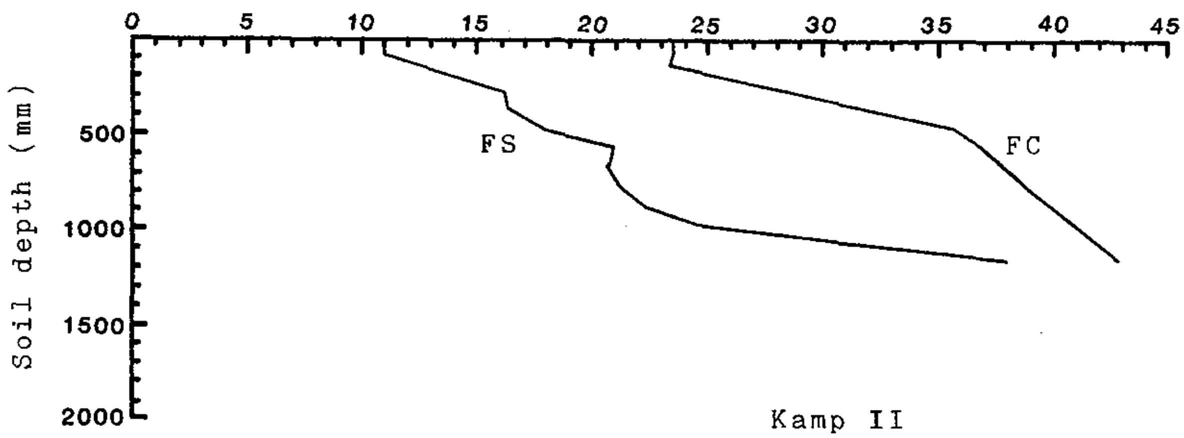


FIG.2.42 Soil water content at field capacity (FC) and first stress (FS) for cotton at flowering at Vaalharts.

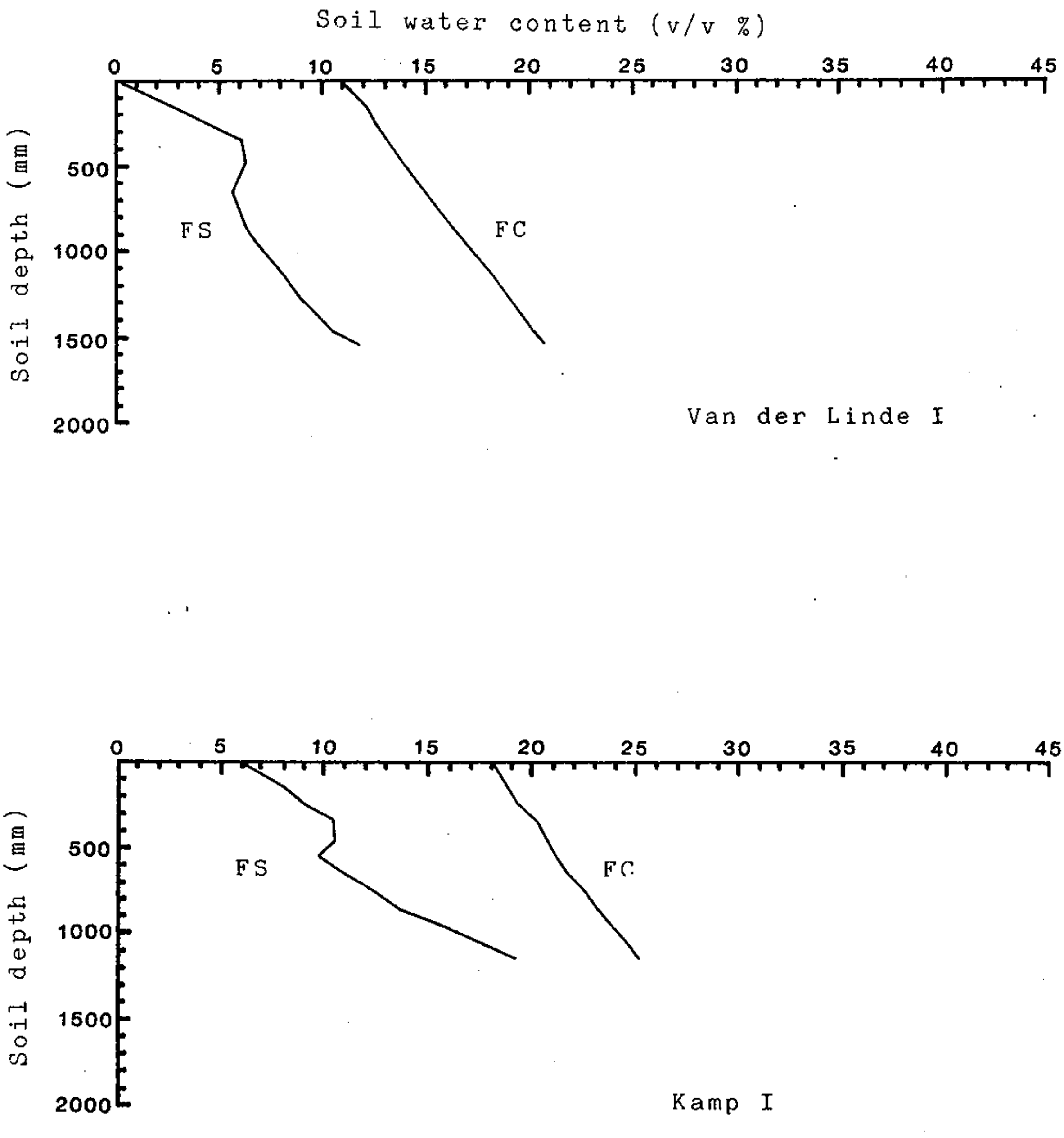
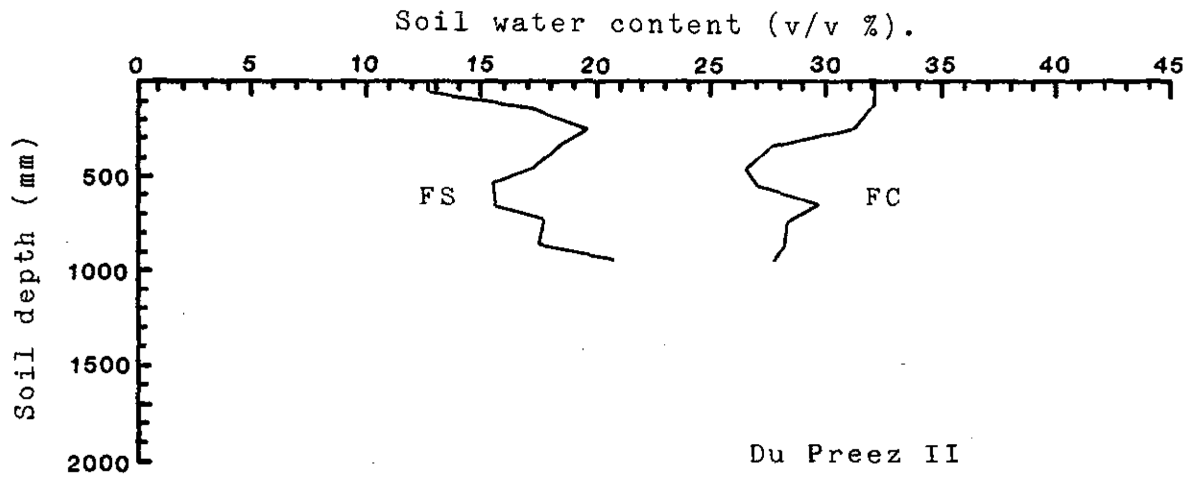


FIG.2.43 Soil water content at field capacity (FC) and first stress (FS) for cotton at flowering at Vaalharts.



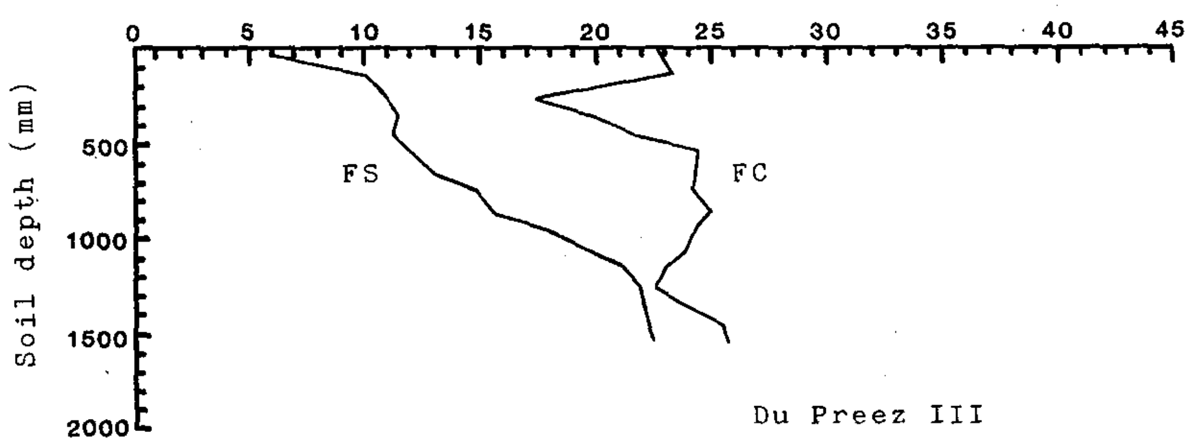


FIG.2.44 Soil water content at field capacity (FC) and first stress (FS) for cotton at flowering at Loskop.

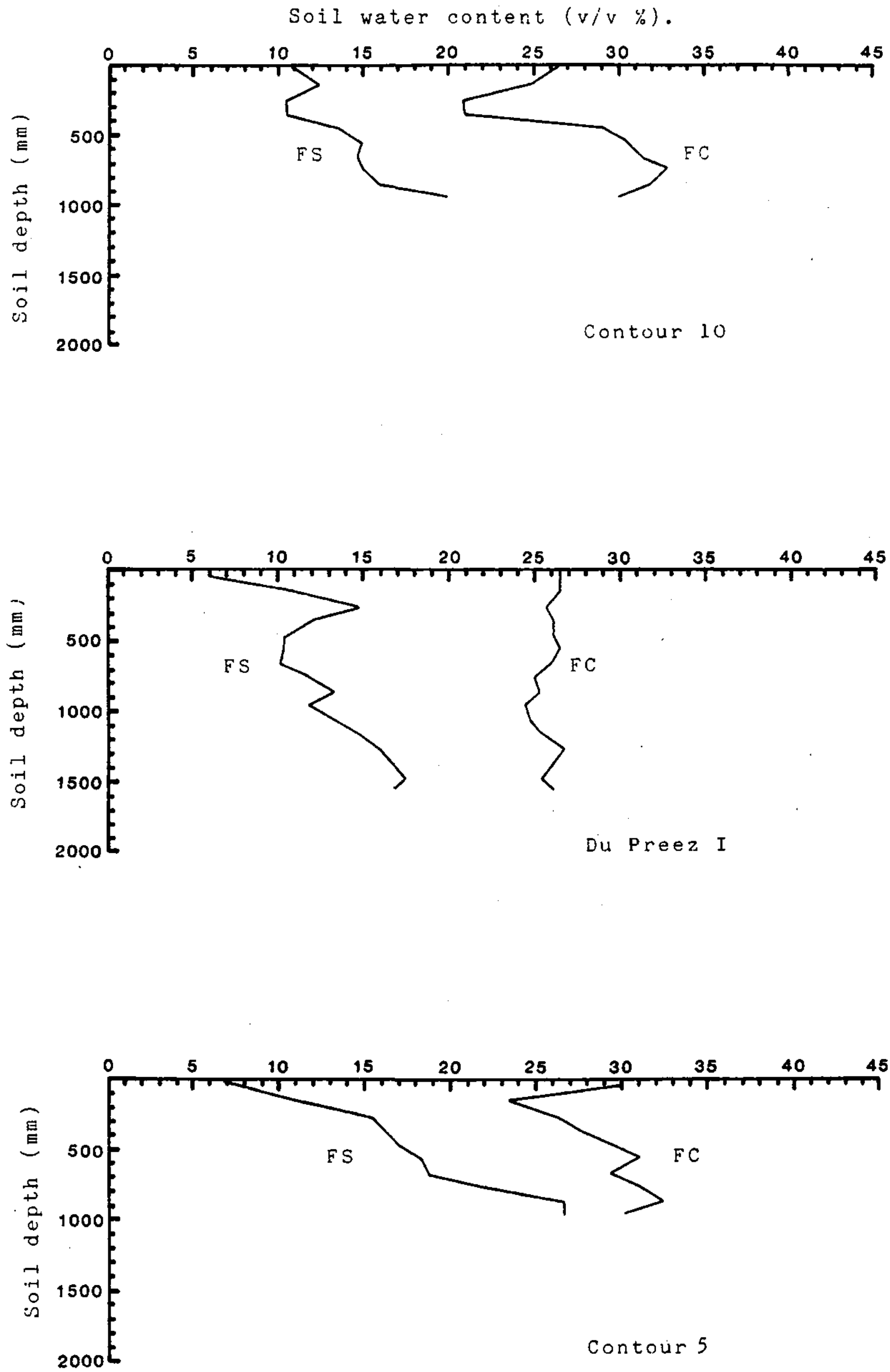
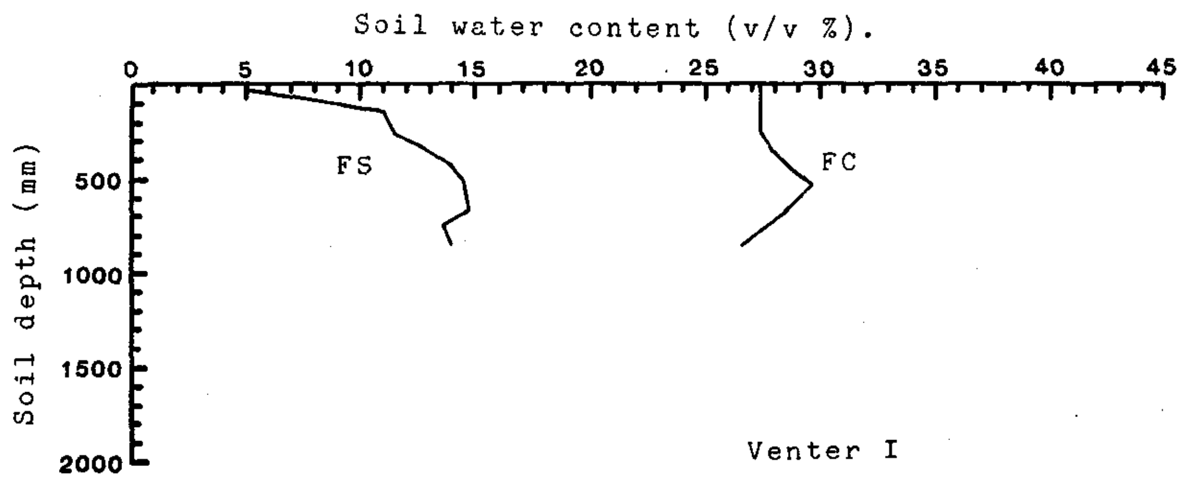


FIG.2.45 Soil water content at field capacity (FC) and first stress (FS) for cotton at flowering at Loskop.



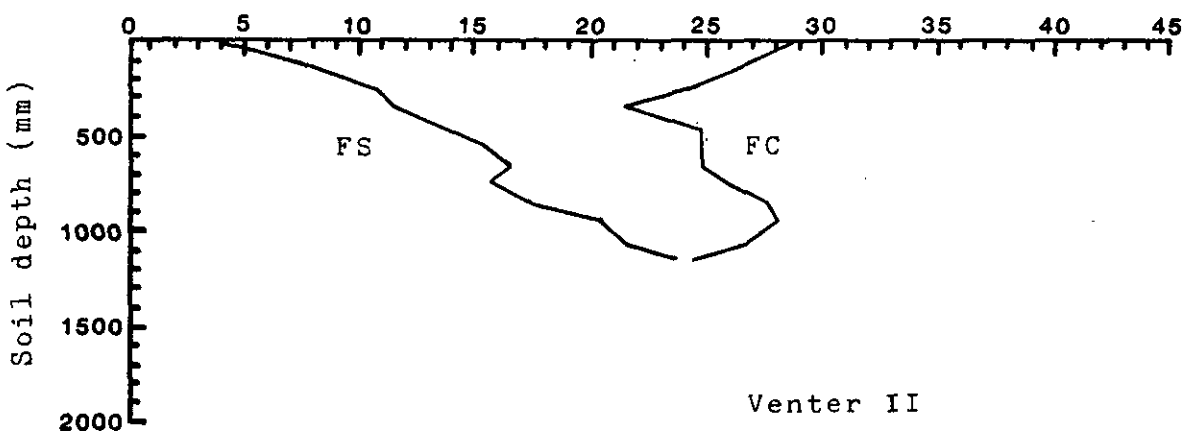


FIG.2.46 Soil water content at field capacity (FC) and first stress (FS) for cotton at flowering at Loskop.

water potentials can be maintained at a relatively high level for long periods.

b. The importance of _in situ_ determinations of profile available water was clearly confirmed. For example moisture contents at field capacity and first stress were dependent on the occurrence of dolerite saprolite at the Kinross and Marikana sites in the Ciskei. The presence of a $CaCO_3$- layer in the bottom part of some Vaalharts soils reduced the profile available water considerably because the actual volume of soil in such layers is reduced.

c. The results confirmed that root development is tremendously influenced by soil compaction. At the sites where soil compaction was found, deviations from the "normal" extraction patterns were found.

d. The results further confirmed that compaction limits the amount of water that can be extracted from a soil layer. When compaction is very severe it prevents roots from developing in lower lying soil horizons. Its impact on PAWC is therefore considerable and when a soil is evaluated for irrigation it must be established if compacted layers are occurring in the soil profile. Some experiments failed at Vaalharts because of a compacted layer occurring close to the soil surface: the crop roots could not penetrate this layer and effective rooting depth was reduced to a few centimeter.

e. Pre-dawn leaf water potentials cannot consistently indicate the onset of stress under high evaporative demand. During both summer seasons, at Vaalharts and at Loskop, pre-dawn leaf water potential was still at a high level while visual stress symptoms were already apparent at mid-morning.

f. The percentage of the available water (based on soil water contents at soil water potentials of -10kPa and -1500kPa) that is extracted per unit of depth by the crop decreases with depth. The apparent constant extraction per unit of depth with increasing depth on the sandy soils of the Vaalharts region may be somewhat misleading. The clay content, and consequently the available water range, increase with depth and in reality a lesser percentage of the available water per unit of depth is extracted with increasing depth on these soils.

g. Comparison of the PAWC data for wheat and maize at the different sites at Vaalharts confirms that the PAWC values are very similar for the two crops if the necessary provision is made for the spatial variations found between the test plots and for the fact that measurements for maize were made only to a depth of 1600mm on the deep soils (see Table 2.11). Van der Linde II is an exception, but there is serious doubt about the PAWC results for maize at this site. The observed similarities between the two crops agree with previous observations by Hensley & De Jager (1982) in the Ciskei.

TABLE 2.11 - Comparison of PAWC data for maize and wheat on Vaalharts soils.

Site	Soil depth * mm	PAWC (mm) Maize	Wheat
Kamp I	900	88,0	117,0
Kamp II	700	93,2	99,4
Van der Linde I	1600	125,4	121,2
Demonstration plot	1600	132,3	143,6

*Depth to which data are available for both crops.

CHAPTER 3

S O I L   W A T E R   U P T A K E   P A T T E R N S

3.1 INTRODUCTION

Withdrawal of water from the soil profile at or below field capacity is mainly caused by evaporation from the soil surface and by transpiration by plants. Drainage, lateral and vertical unsaturated water flow out of the soil profile are considered to be negligible under these conditions.

Parallel to evaporation of soil water there is a continuous removal of water from the soil to the atmosphere through plants. This soil - plant - atmosphere continuum (SPAC) forms a physically integrated system in which various flow processes occur interdependently (Philip, 1966). As most plants can only store limited amounts of water, soil will have to provide the necessary water for transpiration and photosynthesis.

In the SPAC water moves from where its potential is high to where its potential is low. The steeper the water potential gradient, the faster the water moves, other things being equal. An important factor affecting the rate of water movement and the final amount of water extracted is the ability of the pathway to conduct the water flow.

The pathway the water must follow includes liquid water movement from the soil to the roots, absorption at the soil-root interface into the roots, radial movement in the roots towards the xylem vessels, transport in the xylem vessels to stems and leaves, evaporation in the intercellular air spaces of the leaves and vapour diffusion through the substomatal cavities and stomatal openings to the quiescent boundary air layer in contact with the leaf surface and through it to the turbulent air layer surrounding the plant whence the vapour is finally transported to the external atmosphere (Hillel, 1980). The total potential difference between the air moisture and the soil water can be several thousands of kPa and is ultimately the driving force causing water flow in the SPAC system. Philip (1966) estimates the differences in water potential between soil and root surface, root surface and root xylem, root xylem and leaves not to exceed 1000 to 3000 kPa. This means that the biggest difference occurs at the leaf-atmosphere interface. It is, however, dominantly the plant-soil system that will determine how much of the available water will be depleted.

Mathematically this water flow (Q) from the soil to the leaves can be expressed as follows (Hsiao et al , 1980):

$$Q = C_{s,l} (\Psi_s - \Psi_l) \qquad (3.1)$$

with: Q = rate of water movement (length/time)

$C_{s,l}$ = conductance of the pathway between soil and leaf

Ψ_s = soil water potential (kPa)

Ψ_l = leaf water potential (kPa)

It is important to realize that conductance is not similar to conductivity in this equation. Conductance incorporates the effects of path length and cross-sectional area, as well as the intrinsic conductivity of the pathway. It allows for the intricacies of the vascular system in the roots and shoots.

The resistance against water flow along the pathway can be subdivided in three components. Conductance is often expressed as the inverse of resistance (R). Equation 3.1 can be written as:

$$Q = \frac{1}{Rs + Rr + Rsc} (\Psi s - \Psi l) \qquad (3.2)$$

With: Rs = resistance encountered in the soil

Rr = resistance encountered in the roots

Rsc = resistance encountered in the shoot

Furthermore:

$$Q = T + P \qquad (3.3)$$

with T = transpiration of soil water by the plant

P = loss of water by the plant itself

When leaf water potential is not changing rapidly in time (when no sudden high evaporative demands occur) we can consider P to be negligible and with Q equal to T equation 3.2 becomes:

$$\Psi l = \Psi s - T\,(Rs + Rr + Rsc) \qquad (3.4)$$

Equation 3.4 shows that Ψs must be greater than T (Rs +

Rr + Rsc) to maintain a certain leaf water potential. When Ψs is lower than T (Rs + Rr + Rsc) the result will be that Ψl will have to drop to prevent water loss from the plant itself. This illustrates that whenever stress is observed (low leaf water potentials) this can be caused by low soil water potential, a high evaporative demand (climate induced stress), or high resistance in the flow path of the soil water.

Soil resistance to water flow is determined by a number of interdependent parameters. The relationship between soil texture, soil structure, hydraulic conductivity, matric suction, soil solutes and soil porosity will determine the encountered soil resistance. Root geometry (genetically and environmentally determined) will determine the length of the pathway the soil water has to flow before it reaches the root surface, thereby indirectly influencing soil resistance to water flow.

Root resistance can be subdivided into radial and axial resistances. Over the years radial resistance, encountered when the water is moving through the cortex, endodermis and pericycle towards the xylem vessels, has been considered as the dominant parameter in root resistance. Recently the importance of axial root resistance has been recognized (Klepper, 1983). Conductance can be severely limited by the length of the pathway in the xylem vessels, at places where younger vessels connect up with older vessels and where the roots pass through dry soil layers. Klepper (1983) observed changes in root diameter under high evaporative demand. The smaller root diameter under such conditions will increase axial root resistance. This axial resistance probably continues in the xylem vessels of the shoot.

The relative magnitude of the resistance in the soil and in the root system has been a matter of controversy. Gardner (1964) stressed the importance of soil resistance. Recent studies indicate, however, that root resistance plays an important role (Reicosky & Ritchie, 1976). Botha, Bennie & Burger (1983) and others showed experimentally that soil resistance only becomes limiting near a soil water potential of -1500kPa, thereby proving that the relative importance of these two resistances is actually changing with soil water potential.

3.2 MODELLING OF SOIL WATER UPTAKE

Many researchers developed models to describe the uptake of soil water by plants. Gupta, Tanji, Nielsen, Biggar, Simmons & MacIntyre (1978) discuss the major factors affecting soil water uptake. The complexity of the problem is graphically presented in Figure 3.1.

Basically two approaches were followed to solve the problem. In a "microscopic" approach flow processes to a single root are described. The obtained relations are then applied to a fixed root geometry, supposed to represent root distribution in the soil, to explain water uptake by crops from a soil profile. Gardner (1960), Cowan (1965), Lambert & Penning de Vries (1973) and Hillel, van Beeck & Talpaz (1975) developed microscopic scale water extraction models.

In macroscopic models the water flow to individual roots is ignored and the overall root system is assumed to extract soil moisture from each differential volume of the root zone at some rate (Molz & Remson, 1970). Ogata, Richards & Gardner (1960), Gardner (1964), Whisler & Millington (1968), Nimah & Hanks (1973) and Hillel &

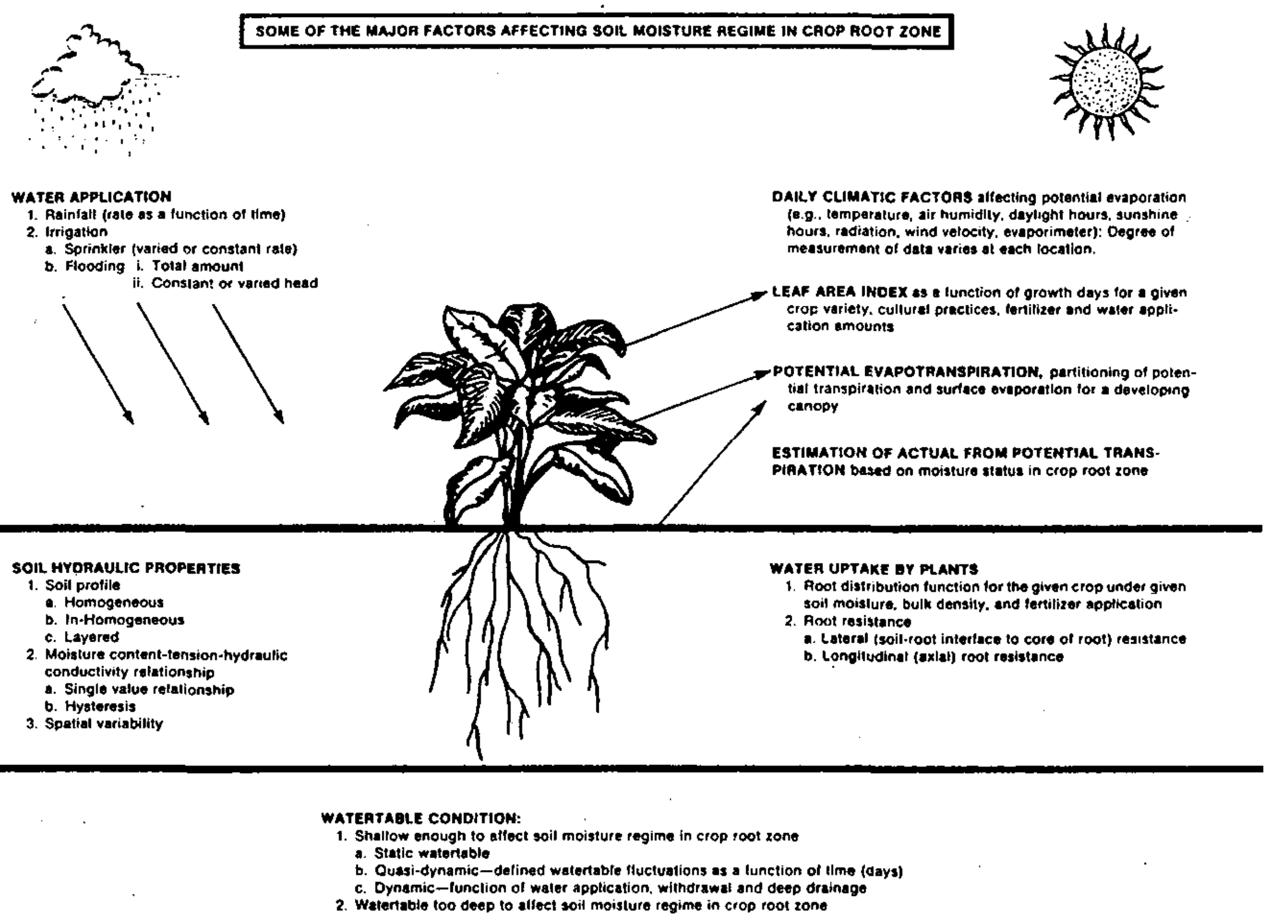


FIG.3.1 Major factors affecting soil moisture regime in the crop root zone (from Gupta et al , 1978).

Talpaz (1976) followed this approach in solving the problem of soil moisture uptake.

Mathematical models can be used provided that they are used as a combination of empirical data and a sound theoretical basis. Botha et al (1983) used both the microscopic and the macroscopic approaches to investigate the relationships between the hydraulic parameters in plant and soil. The research was conducted with pot experiments in glasshouses and in the field. They confirmed that both approaches can be succesfully applied in glasshouse experiments. After adaptation the models could be used to predict water uptake by crops under field conditions.

Difficulties in bridging the gap between theory and practice stay, however. One major limitation to the application of any of the uptake models is the lack of an adequate model for describing root distribution and root uptake of water (Gardner, 1983).

Gardner (1983) therefore suggest that, until more information is available on several vital points such as, for example, water potential values at the different interfaces in the water flow pathway or effective rooting densitiy, the examination of empirical data on water uptake and use of these data as a guideline to the relative availability of water in the soil profile could be very useful.

3.3 EVOLUTION OF SOIL WATER EXTRACTION PATTERNS AS MOISTURE EXTRACTION PROCEEDS FROM FIELD CAPACITY TO FIRST STRESS

Neutron hydroprobe determinations of soil water were done at regular intervals during the PAWC-determination experiments. Besides the possibility to calculate water consumption of crops over short periods (see Chapter 4), these neutron hydroprobe readings facilitated a study of extraction patterns as the drying cycle advanced from field capacity towards first stress. This is of extreme interest because the results will give an indication of the soil moisture extraction patterns that will be operative during irrigation scheduling.

3.3.1 Ciskei

3.3.1.1 Wheat

Two basic extraction patterns were observed. In the first type of extraction the water is initially extracted only from relatively shallow soil layers. No water is extracted from the rest of the profile during this period. Within the shallow extraction zone water consumption is faster the nearer a soil layer is to the surface. This results in a "fan" effect with the "pivot" of the fan at the point marking the maximum depth to which water extraction occurs during this period (Figure 3.2). This initial extraction pattern ends when the line, representing the soil water content in the profile at a certain time during the drying cycle, becomes parallel to what will eventually be the final first stress line. With further extraction the line undergoes parallel displacement until first stress is reached. This results in a progressively increasing depth from which soil water is extracted. This evolution of the extraction pattern is illustrated in the patterns of the Arniston, Kinross and Sterkspruit sites (see Figure 3.2 and Appendices 3.1 and 3.2). An idealized version of

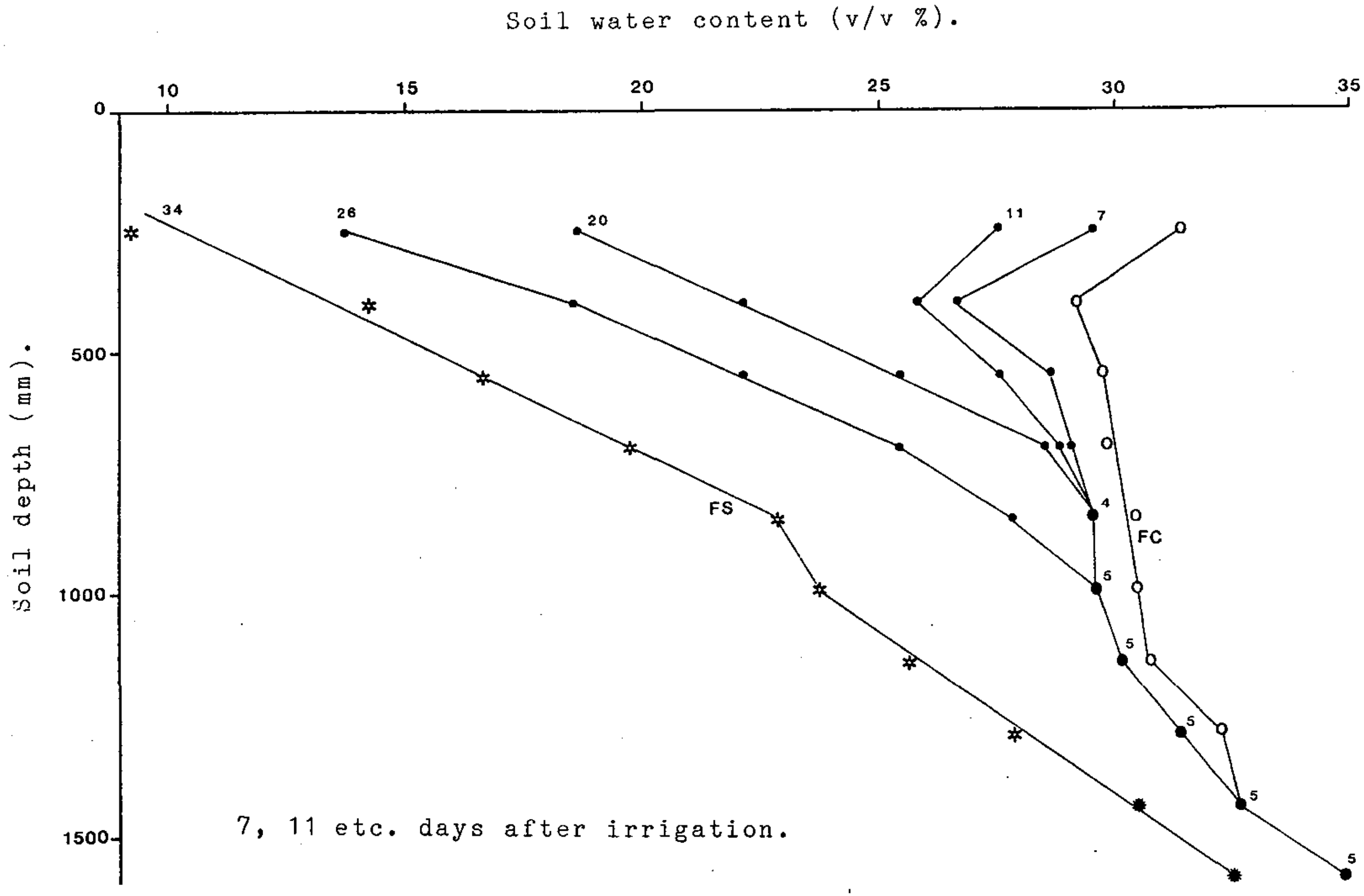


FIG.3.2 Soil water extraction pattern for wheat on the Arniston soil (Ciskei).

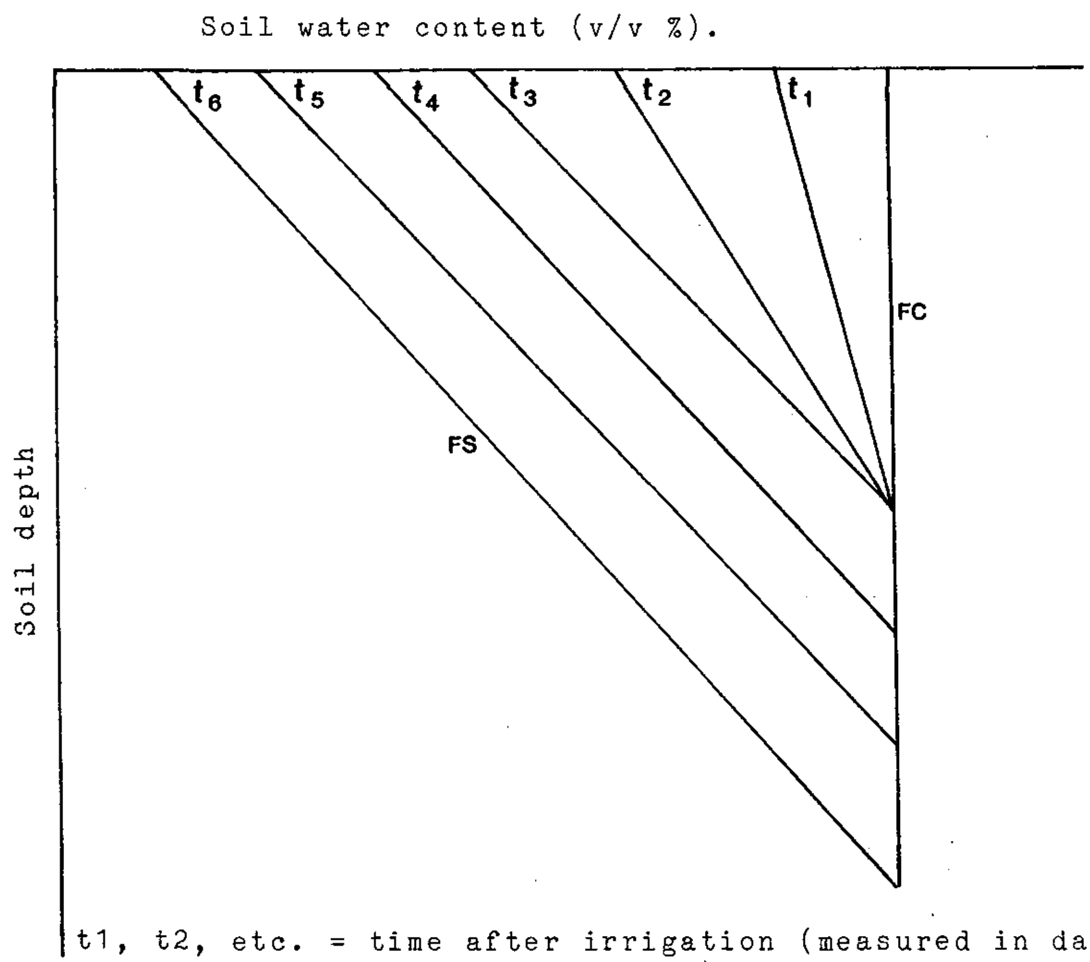
FC = field capacity.

FS = first stress.

this evolution of the soil moisture extraction pattern is shown in Figure 3.3.

The second basic pattern is found at the Jozini site (Figure 3.4) and the idealised representation is illustrated in Figure 3.5. This model represents a "fan" effect throughout the total rooting zone from the start of the drying cycle onwards. The pivot of the fan is situated at the bottom of the rooting zone. It consists of proportional extraction at all depths. In ideal circumstances this means that if 10% of the final extraction figure at 200mm depth is extracted after 5 days, then 10% of the final extraction figure at 800mm depth will also be extracted after 5 days. Again the actual extraction is higher in the top layers of the soil profile. In a shallow soil the pivot of the fan is situated at an imaginary point below the lower boundary of the rooting zone.

Both types of extraction pattern resulted in a final extraction model at first stress that roughly resembled the form of an inverted triangle. The field capacity and first stress line tend to converge at the bottom of the rooting zone. Examples of this type of extraction are abundant in literature. Gardner (1983) grouped a number



t1, t2, etc. = time after irrigation (measured in days).

FIG.3.3 Idealised representation of experimentally observed evolution pattern for soil water extraction from a deep soil by a deep-rooted crop.

FC = field capacity.

FS = first stress.

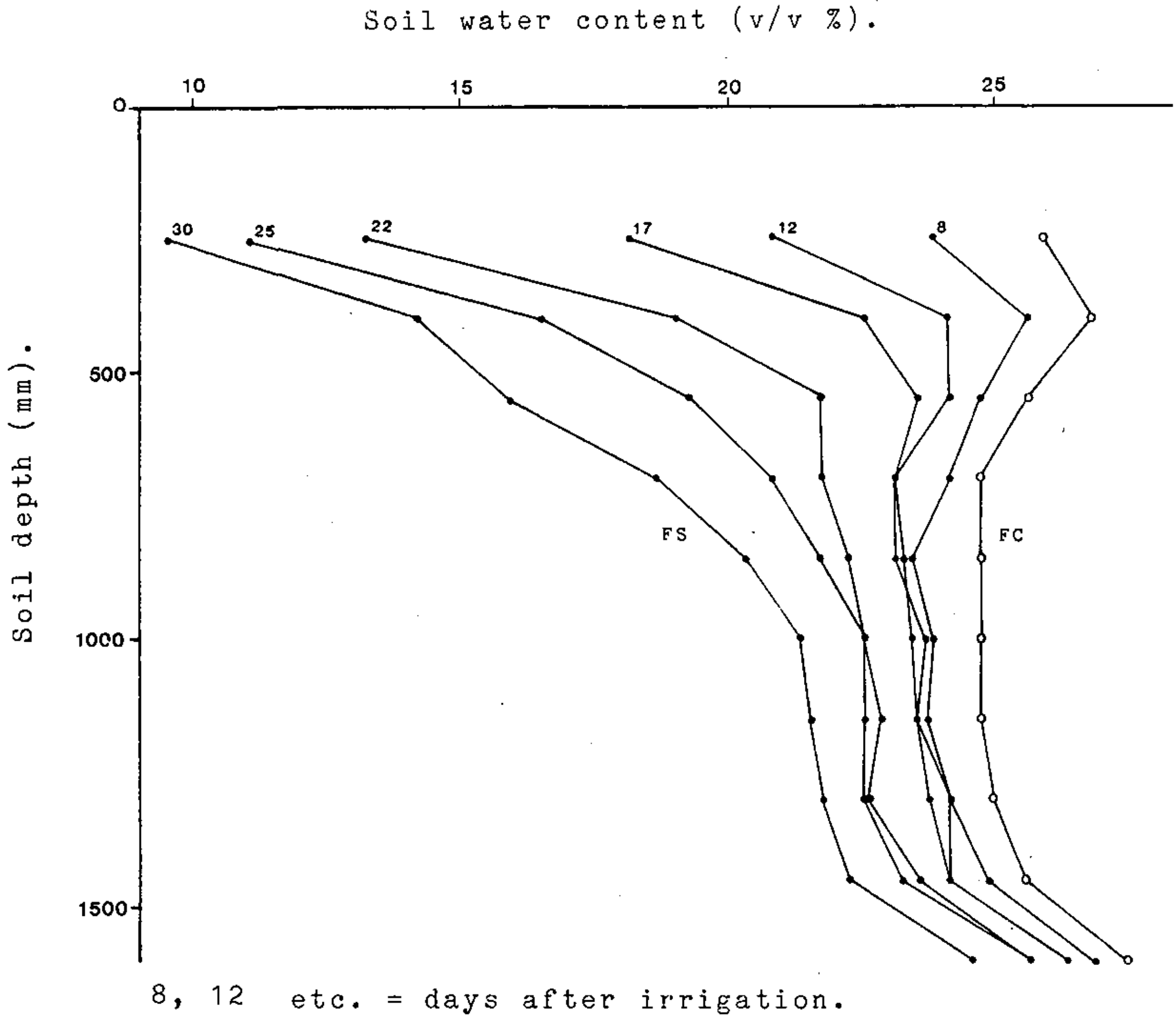


FIG.3.4 Soil water extraction pattern for wheat on the Jozini soil (Ciskei).

FC = field capacity.

FS = first stress.

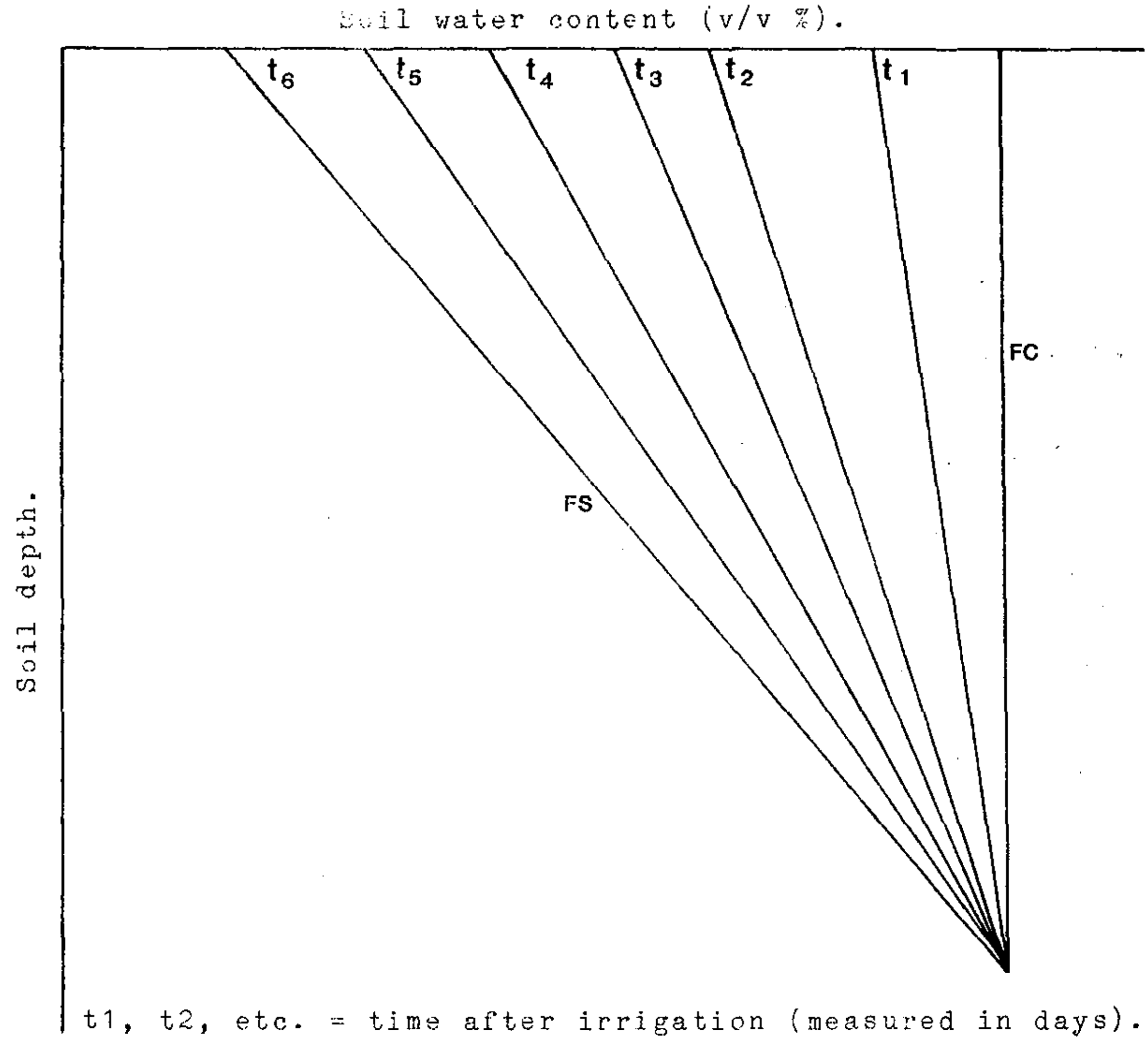


FIG.3.5 Idealised representation of evolution pattern for soil water extraction from a deep soil by a deep-rooted crop.

FC = field capacity.

FS = first stress.

of curves showing total soil water uptake at different depths at "initial wilting" (comparable with initial, but not well defined stress) by different crops (see Figure 3.6). All curves show a distinct decrease in water uptake with increasing depth. Gardner (1983) indicates that although a wide variety of soil textures is represented in Figure 3.6 the basic extraction pattern is remarkably uniform for all soils. A similar common relationship was found for maize on a wide range of soils in the Ciskei (Laker, 1982).

3.3.1.2 Peas

Peas did not show the first type of extraction pattern in which water is in the initial stage only extracted from the top soil layers. This was probably related to the fact, that apart from the Jozini site where the second type of extraction pattern was observed for wheat also, shallow rooting depths were found for peas. The extraction pattern for peas at the Jozini site is illustrated in Figure 3.7.

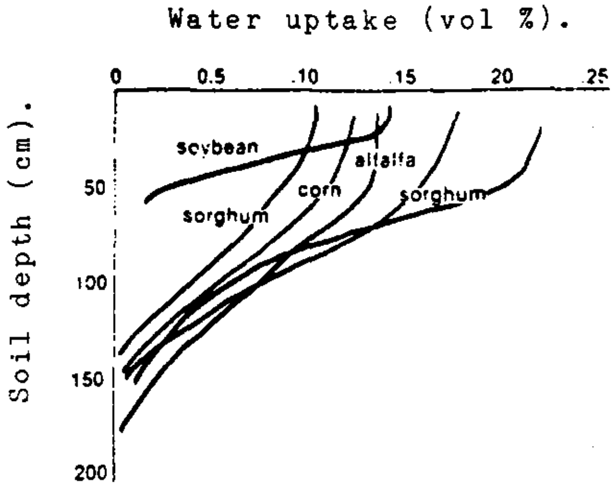


FIG.3.6 Water extraction pattern for several crops at time of initial wilting. Gardner (1983).

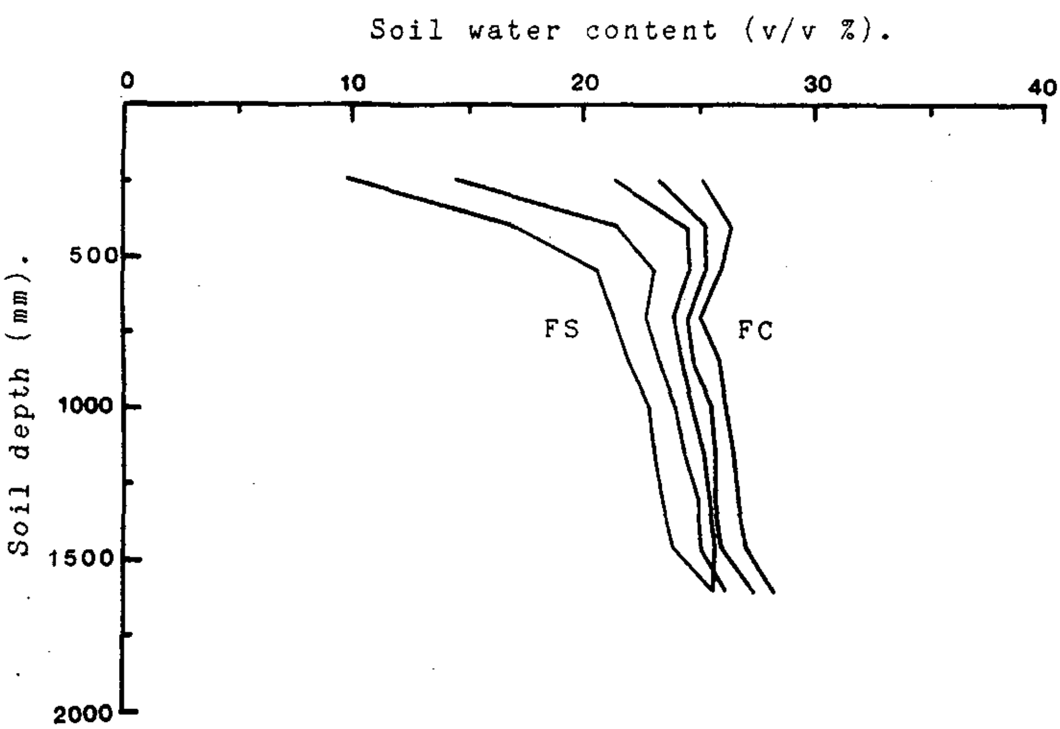


FIG.3.7 Soil water extraction pattern for peas on the Jozini soil (Ciskei). 4 to 6 day intervals.

FC = field capacity.

FS = first stress.

3.3.2 Vaalharts

3.3.2.1. Maize

The evolution of the soil water extraction pattern for maize on the Stanford (Sterkspruit) soil at Kamp II is shown in Figure 3.8. The similarities with the extraction patterns observed on the heavy textured and structured Ciskeian soils (Arniston, Kinross, Sterkspruit) is evident: a "shallow-fan" extraction during the first part of the drying cycle, followed by extraction lines parallel to the first stress line. Remarkable is the amount of water extracted from the lower part of the soil profile during the last days of the drying cycle.

This observed pattern at the Stanford site contrasts sharply with what was found for maize at the more sandy Hutton sites. At Demonstration Plot, Van der Linde I and II, and Kamp I (see Figure 3.9 and Appendices 3.3 to 3.6) the extraction lines move parallel with the field capacity line towards first stress. This is related to the increase in silt + clay content, and consequently in available water, with increasing depth in these sandy soils (see Chapter 2). Percentages of the available

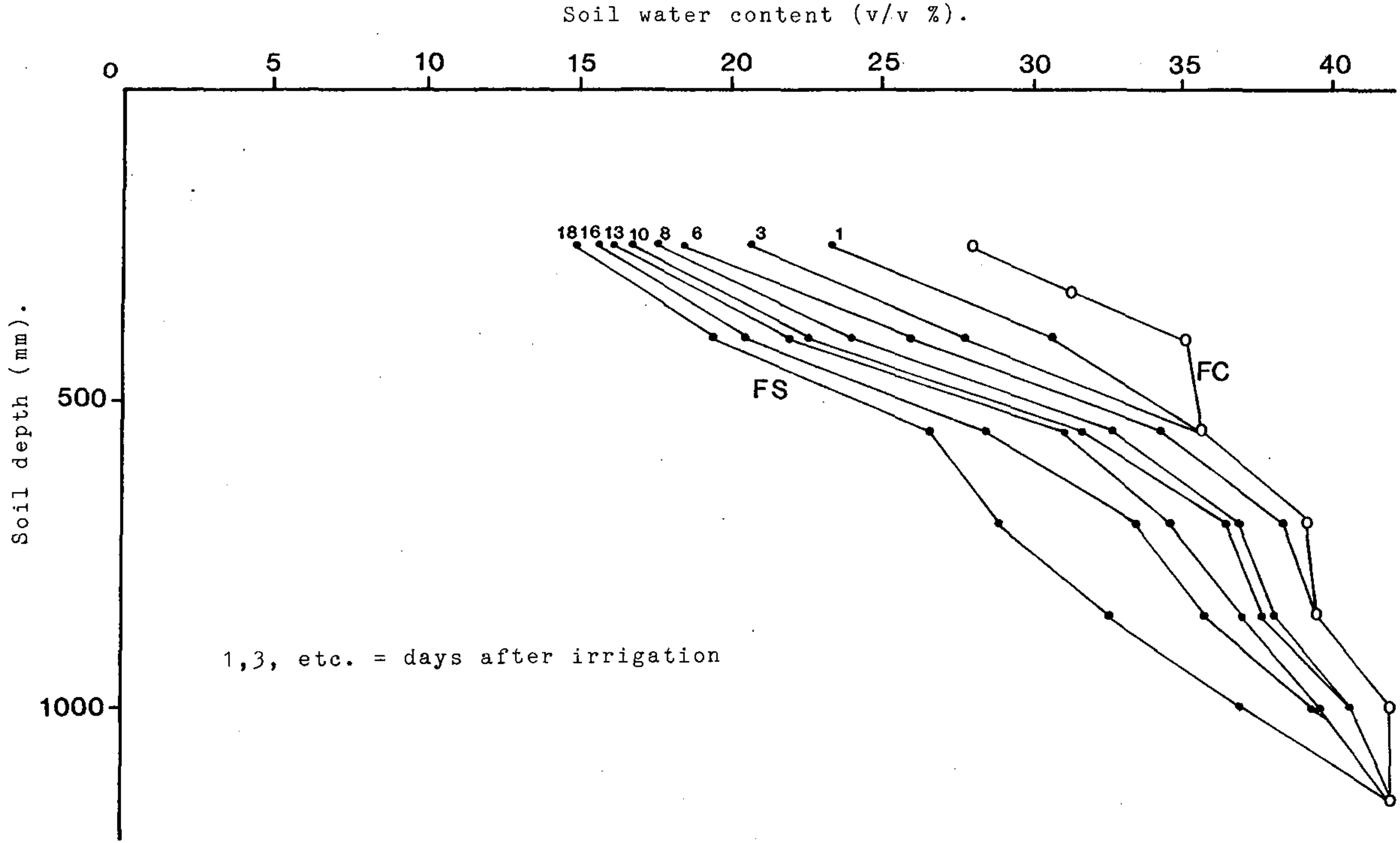
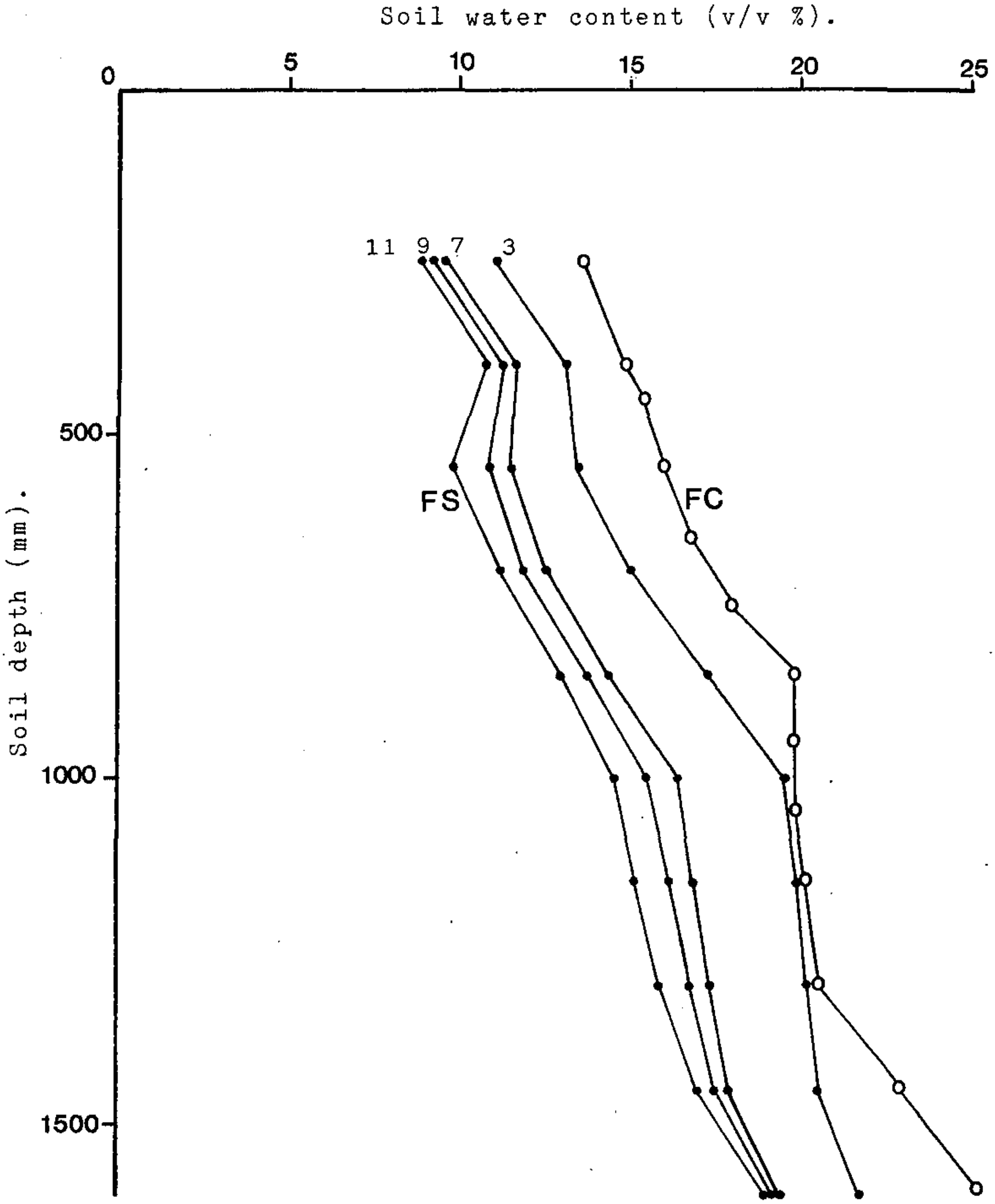


FIG.3.8 Soil water extraction pattern for maize at Kamp II (Vaalharts).

FC = field capacity.

FS = first stress.



3, 7, etc. = days after irrigation.

FIG.3.9 Soil water extraction pattern for maize at Van der Linde II (Vaalharts).

FC = field capacity.

FS = first stress.

water extracted at different depths are shown in Appendices 3.7 to 3.10 for the different sites. The available water is expressed here as the difference between the soil water content at soil water potentials of -10kPa and -1500kPa. The moisture contents at -10 and -1500kPa were calculated with regression equations relating texture to water retention (Van der Merwe, 1973).

3.3.2.2 Cotton

The moisture extraction patterns and their evolution was very similar to the ones found for maize (see Appendices 3.11 to 3.14). At the Stanford site cotton extracted a surprisingly big amount of water. In general cotton extracted slightly more water than maize. This came as no surprise as cotton is known to be a drought tolerant crop.

3.3.2.3 Wheat

The observed extraction patterns for wheat on the sandy soils are very similar to the ones found for maize at the same sites. Again the extraction lines are parallel to the field capacity line. At the Demonstration plot site the uvidek plastic raincover was ripped off during a heavy storm on 21/9/1983. The top zone of the soil profile was wetted again and, although the effect on pre-dawn leaf water potentials was short-lived (see Chapter 2), the partial rewetting of the soil is reflected in the final extraction pattern (Figure 3.10). The occurrence of a slightly compacted soil layer at about 400 to 500 mm depth shows up as a deviation from the linear pattern at the Van der Linde I and II sites (Figures 3.11 and 3.12). At Van der Linde I the presence of a thin clay layer at about 1100mm depth can be seen clearly on the extraction pattern. Water is accumulating on top of this layer, which results in a sudden deviation of the linearity of the extraction lines at this depth (Figure 3.11). Roots obviously struggled to penetrate this layer and this resulted in root densities lower than normal in the lower layers of the soil profile and consequently a smaller amount of water was extracted. (Compare root length per unit of volume at Van der Linde I and Van der Linde II and Demonstration plot, see Table 3.1).

The occurrence of $CaCO_3$ nodules in the lower part of the B horizon at Kamp I caused a decreasing amount of water per unit of depth to be extracted with increasing depth

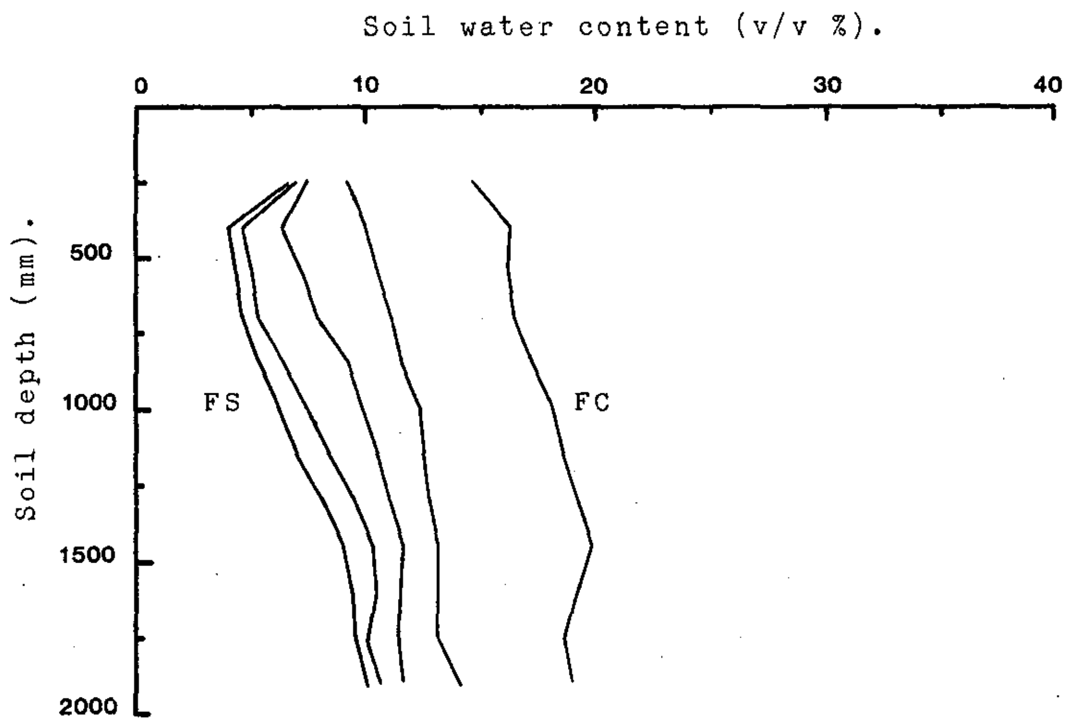


FIG.3.10 Soil water extraction pattern for wheat at Demonstration plot (Vaalharts). 4 day intervals

FC = field capacity.

FS = first stress.

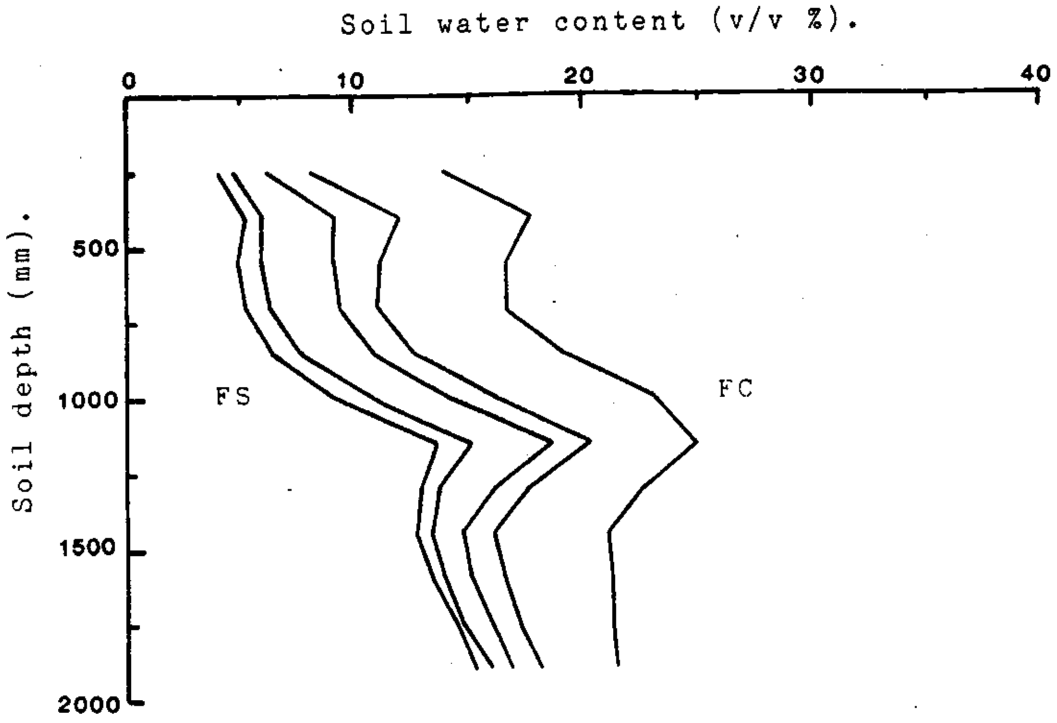


FIG.3.11 Soil water extraction pattern for wheat at Van der Linde I (Vaalharts). 4 to 6 day intervals

FC = field capacity.

FS = first stress.

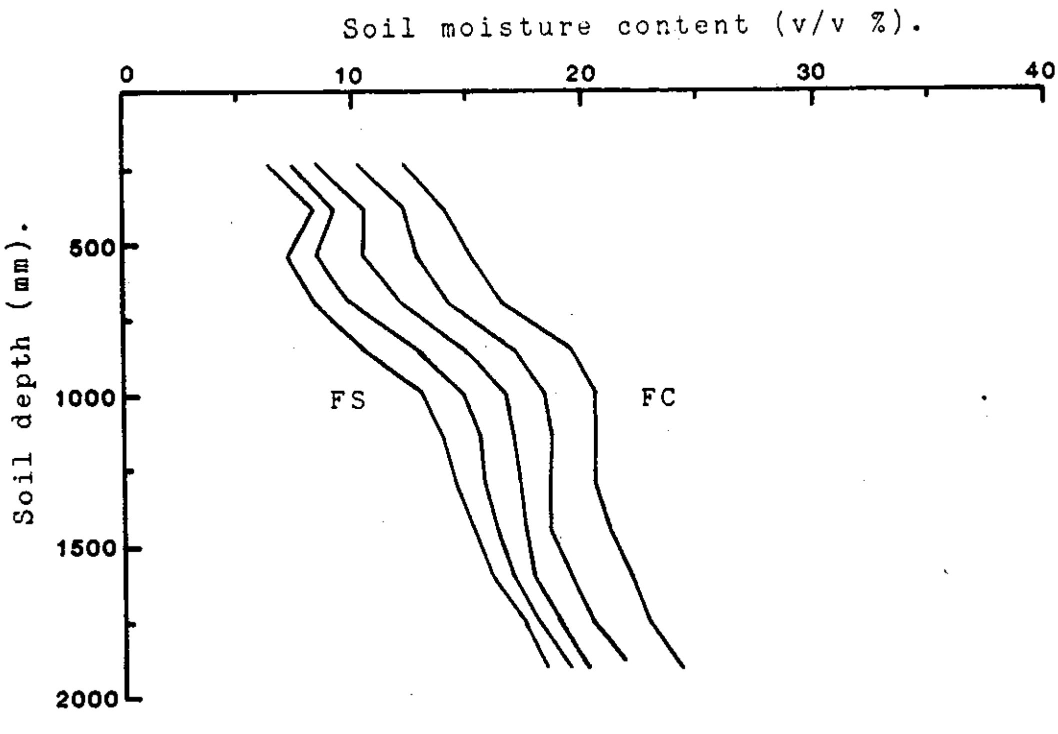


FIG.3.12 Soil water extraction pattern for wheat at Van der Linde II (Vaalharts). 4 to 6 day intervals

FC = field capacity.

FS = first stress.

in this part of the soil profile (Figure 3.13).

The pattern for the Stanford site (Kamp II) was unexpected. The extraction pattern found for maize during the previous summer season at this site, was similar to the pattern found for wheat on the fine textured, strongly structured soils in the Ciskei. The fact that wheat was extracting water throughout the soil profile from the beginning of the drying cycle came therefore as a surprise (Figure 3.14). The reason for this difference in water extraction is not clear. Probably the wheat root system develops much better than maize roots in a prismacutanic horizon. Another possible explanation is the spatial variation of the soil characteristics. The thickness of the the strongly structured B-horizon varied from place to place at this site.

3.3.2.4 Peas

Peas extracted water from the whole soil profile from the start of the drying cycle onwards (also at the Stanford site). The clay layer occurring at 1100mm depth at the Van der Linde I site did not have a detrimental influence on root development below the clay layer and a

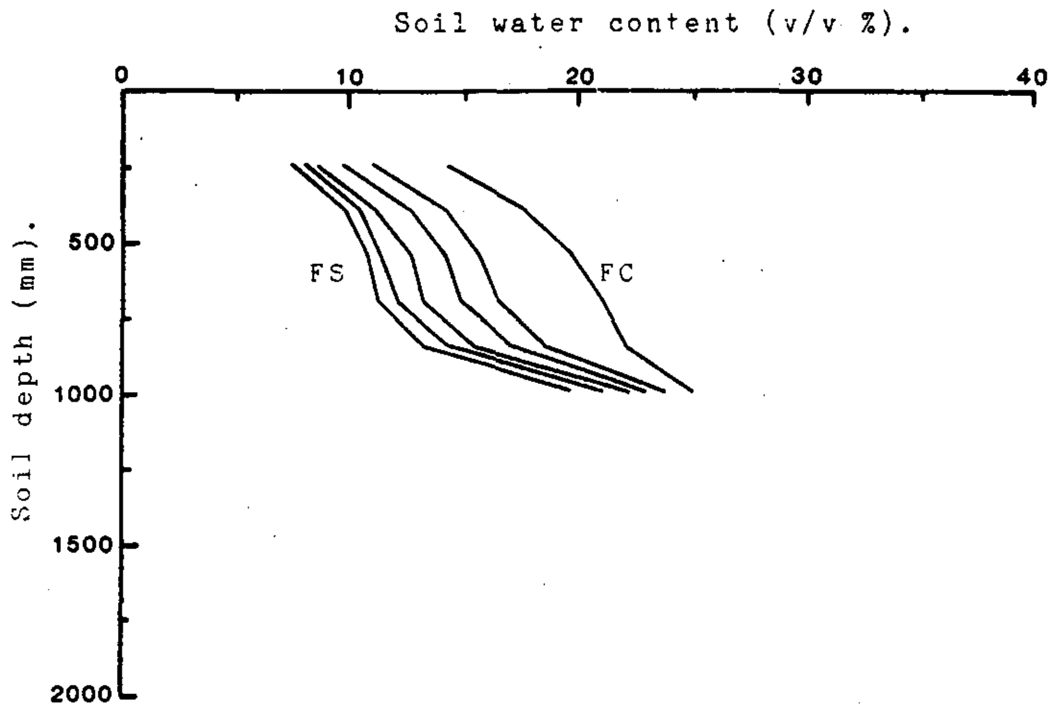


FIG.3.13 Soil water extraction pattern for wheat at Kamp I (Vaalharts). 4 to 6 day intervals

FC = field capacity.

FS = first stress.

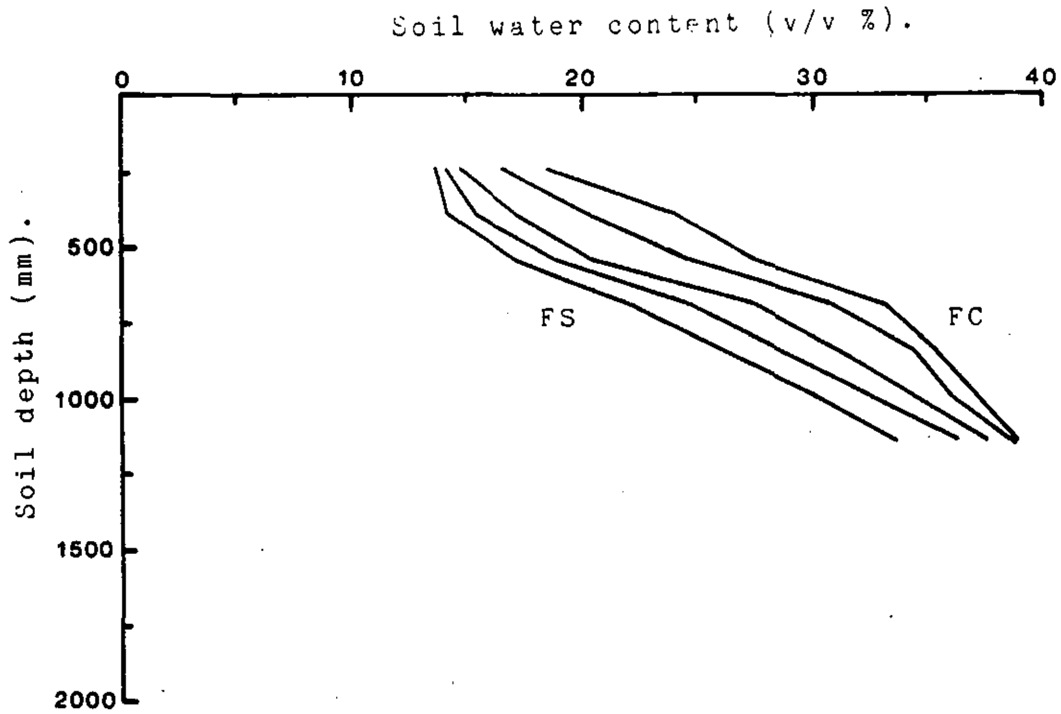


FIG.3.14 Soil water extraction pattern for wheat at Kamp II (Vaalharts). 4 to 6 day intervals

FC = field capacity.

FS = first stress.

surprisingly high amount of water was consumed from the lower parts of the soil profile. At the other sites extraction patterns were "normal" but, compared with wheat, relatively less water was extracted from the lower layers of the soil (see Appendices 3.1 and 3.2).

3.3.2.5 Final extraction patterns at Vaalharts

Extraction lines moved parallel to the field capacity line towards the first stress lines on the deep, well drained, sandy Hutton soils of the Vaalharts region. This resulted in the typical "parallel-block" final extraction pattern for these soils.

In the previous chapter is was shown that the "parallel-block" pattern found on the sandy soils at Vaalharts is caused by a gradual, linear increase in clay content, and consequently in available water, with depth. The relative extraction, i.e. where the amounts of water extracted at different depths are plotted as percentages of the water between -10 and -1500kPa soil water potential at that depth, decreases gradually with increasing depth.

3.3.3 Loskop

The observed extraction patterns for maize and cotton at Loskop are very complex. At Du Preez I, a soil of the Hutton form with a uniform sandy loam texture throughout the profile, an extraction pattern similar to the idealized "deep-fan" extraction pattern was found (Figure 3.15). Throughout the major part of the drying cycle a decreasing amount of water was extracted with increasing depth and a clear fan pattern emerged. At the end of the drying cycle more water was extracted from the zones below 500mm depth than from the top layers. A parallel extraction was observed from 500mm to 1500mm depth in the final phase of the drying cycle.

At the other sites the extraction patterns are not so clear. From the beginning of the drying cycle crops extracted water throughout the soil profile, but there is initially a clear trend towards a "deep-fan" pattern. This can be seen in Figures 3.16 to 3.21: To the right of the dashed lines, decreasing amounts of water were extracted with increasing depth. As will be indicated later, the dashed lines are believed to represent the correct lower limits of PAWC for these soils (see Chapter 6). As the drying cycles advanced beyond true first

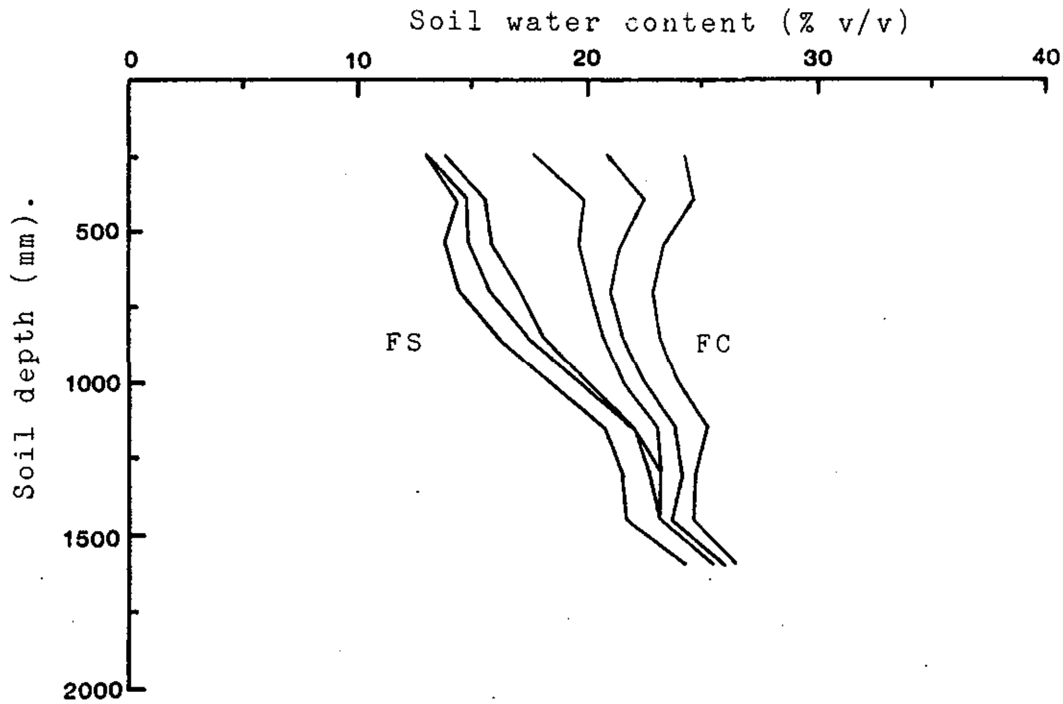


FIG.3.15 Soil water extraction pattern for maize at Du Preez I (Loskop). 4 day intervals.

FC = field capacity.

FS = first stress.

stress the zone of maximum extraction rate (which is close to the soil surface before the true first stress) moved downwards in the soil profiles. These are represented by the areas to the left of the dashed lines in Figures 3.16 to 3.21. Final extraction patterns, which appear as parallel-block patterns similar to the ones found on sandy Huttons at Vaalharts, were caused by this extraction beyond PAWC (see also Section 3.3.4 and Chapter 6).

Both maize and cotton showed basically the same extraction patterns. In the case of cotton the zone of maximum water extraction rate did during the latter part of the drying cycle not move so deep in the soil profile as for maize, causing the final extraction pattern to "bulge out" in the central part of the soil profile (see Appendices 3.19 to 3.25). At Contour 5 only a small amount of water was extracted between field capacity and first stress by cotton, apparently because cotton roots did not develop well at this site.

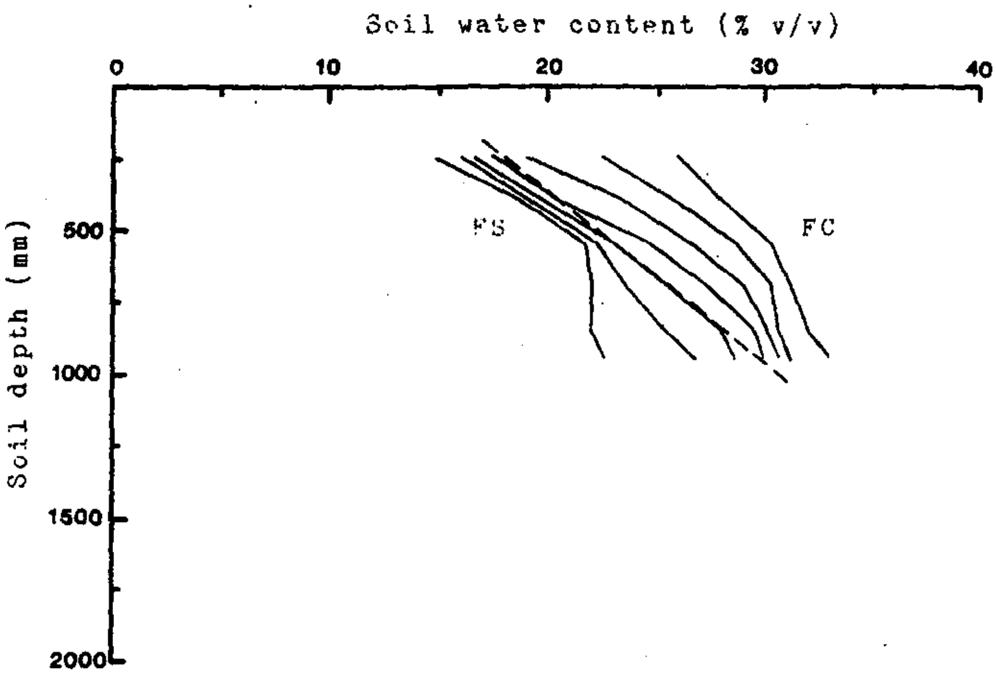


FIG.3.16 Soil water extraction pattern for maize at Contour 5 (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

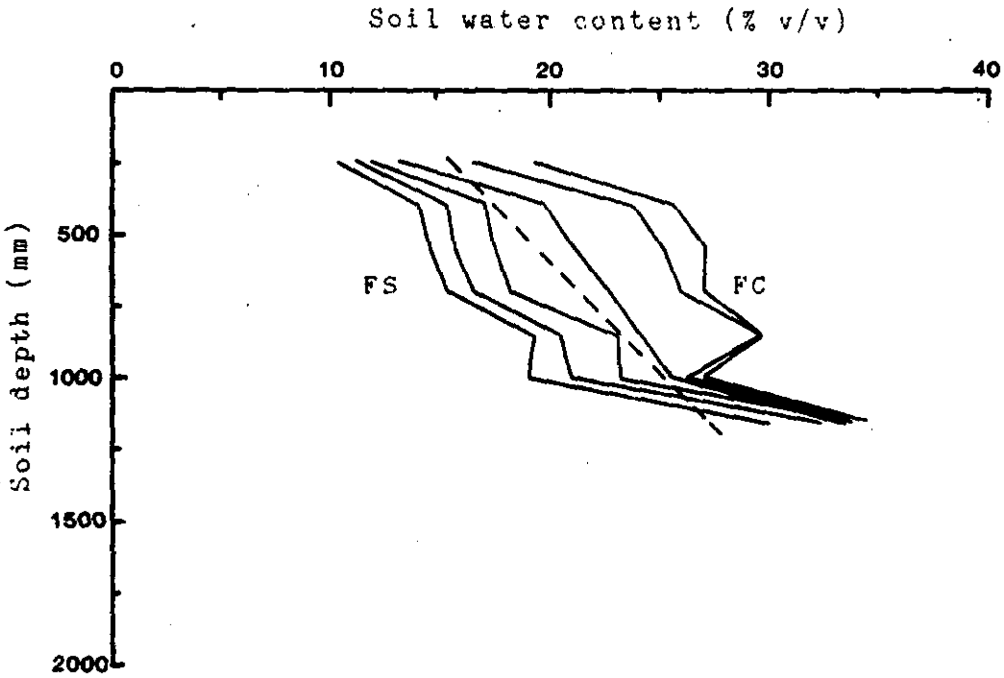


FIG.3.17 Soil water extraction pattern for maize at Contour 10 (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

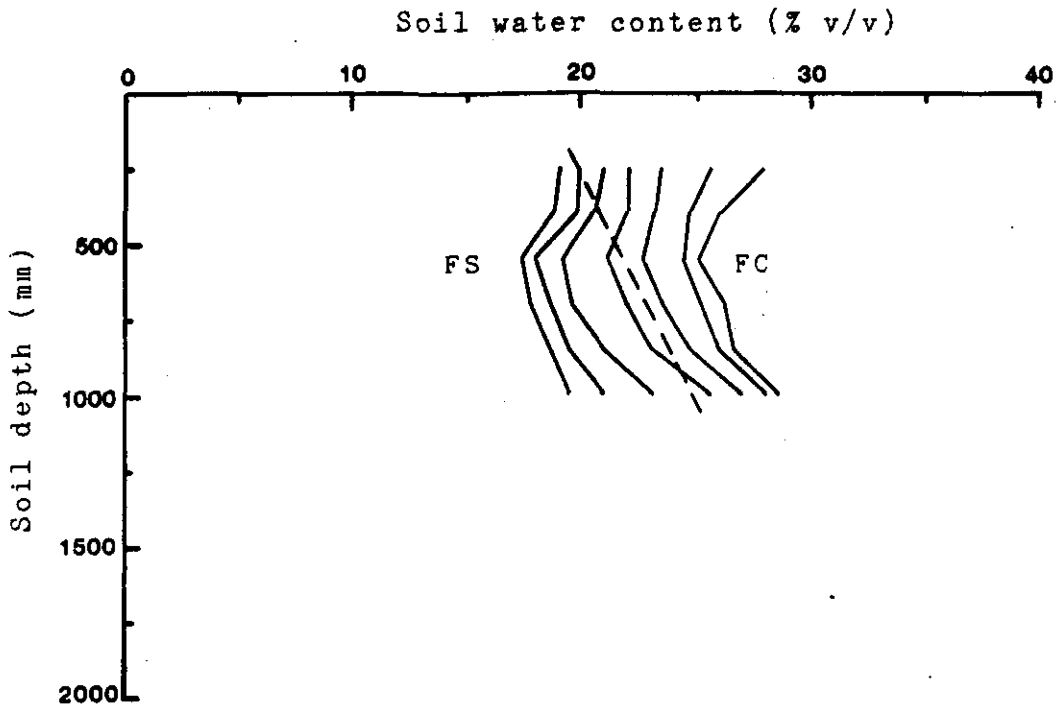


FIG.3.18 Soil water extraction pattern for maize at Du Preez II (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

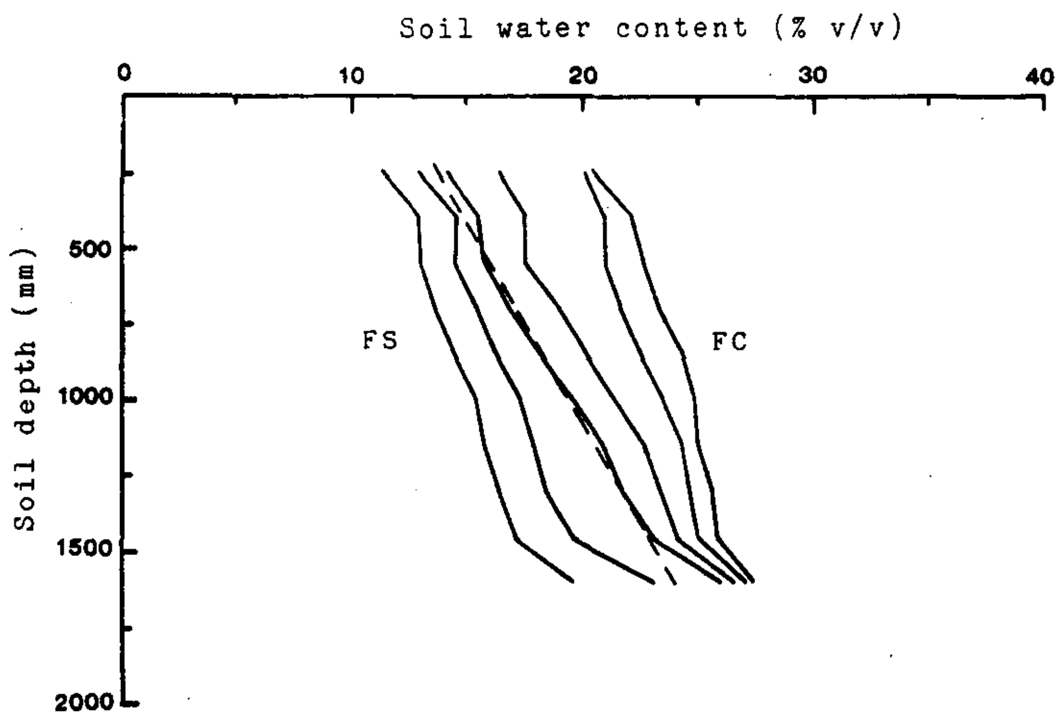


FIG.3.19 Soil water extraction pattern for maize at Du Preez III (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

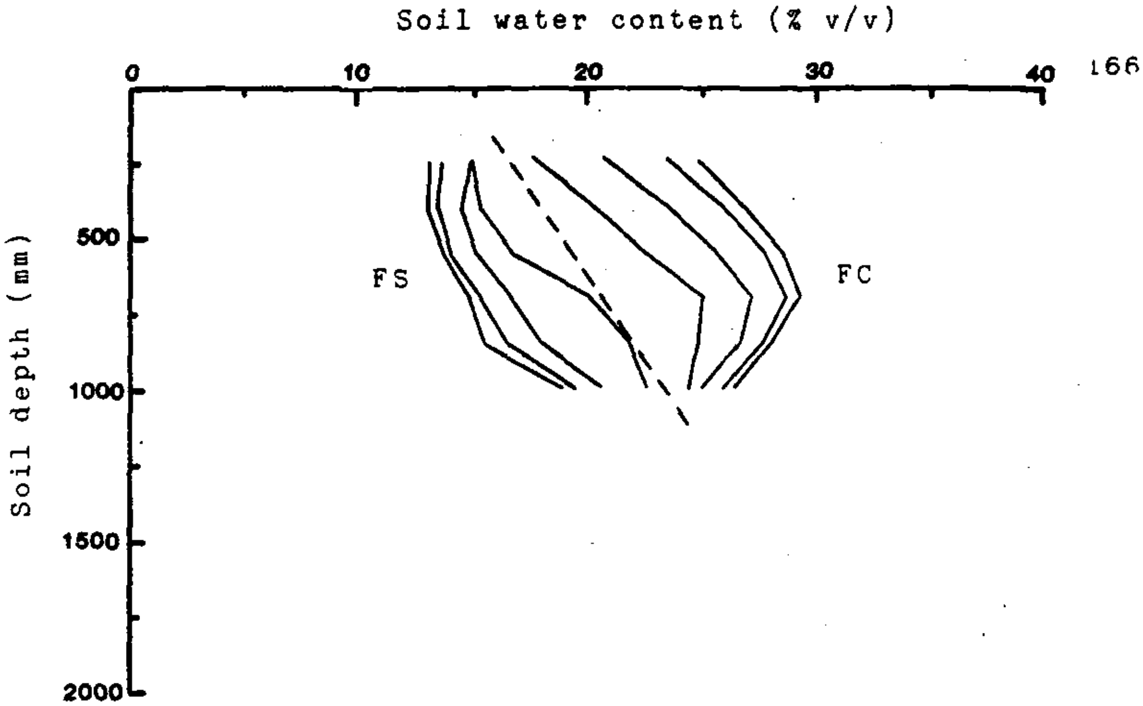


FIG.3.20 Soil water extraction pattern for maize at Venter I (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

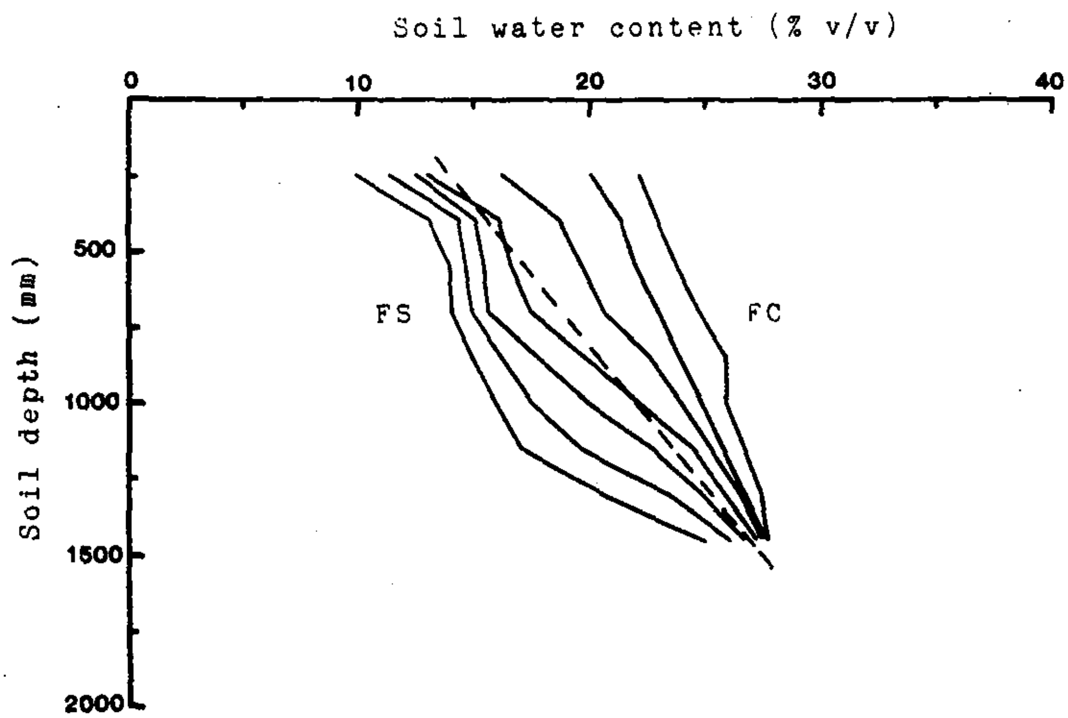


FIG.3.21 Soil water extraction pattern for maize at Venter II (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached (see Chapter 6).

FC = field capacity

FS = first stress

3.3.4 Lysimeter experiments

During the 1982 winter season irrigation scheduling experiments for wheat were done on the Fort Hare lysimeter (see Chapters 2 and 5). The extraction pattern was a shallow fan extraction followed by parallel movement of the extraction lines towards the first stress line (see Figure 3.22). In treatment 3 the crops were allowed to extract soil water beyond the PAWC-value. Beyond PAWC the roots extracted more water from the deeper soil layers than from the shallower layers. This caused the final extraction pattern to be more uniform throughout the rooting zone. This downward movement of the zone of maximum water extraction rate in the profile beyond PAWC is similar to what happened at the Loskop sites.

In the "completely adequate water" treatment (treatment 1, with irrigation intervals of 3 to 4 days) no water was extracted below 250mm from the soil surface, whereas for the other treatments water was extracted to the full lysimeter depth of 1500mm. This observation is of extreme importance in respect to irrigation scheduling methods presently applied by a considerable number of

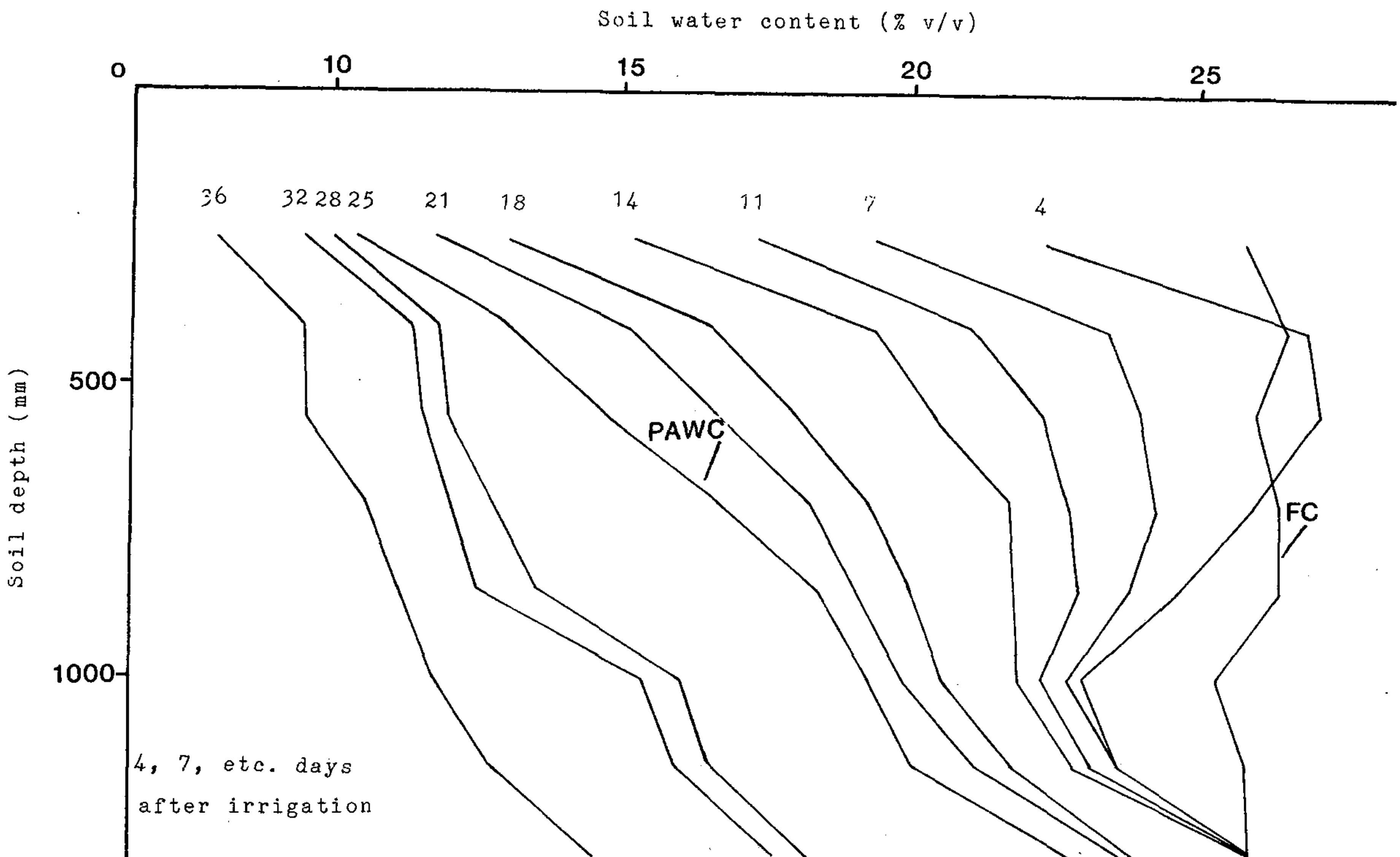


FIG.3.22 Soil water extraction pattern for wheat during the "very dry" treatment in the lysimeter experiment. The soil failed to reached field capacity in the bottom layers of the soil profile four days after irrigation was applied.
FC = field capacity
PAWC indicates when the field determined PAWC value for wheat on a nearby Jozini soil was reached.

farmers at the Loskop and Vaalharts irrigation schemes and whereby frequent light irrigations are given. This practice leads to a limitation of the "effective" rooting depth (as defined by Molz, 1971, on the basis of water extraction) and which makes the crops more sensitive to adverse conditions (e.g. unexpected breakdowns in the irrigation systems or extreme evaporative demands) (Laker, 1983).

The observed extraction pattern for wheat (Figure 3.22) was very similar to the extraction pattern found for maize by Marais & Hensley (1982) on the same lysimeter (Figure 3.23): after the initial fan pattern a constant amount of water was extracted per unit of depth with increasing depth which caused the extraction lines on 12/1 and 21/1 to be parallel to each other. After 21/1, the day the field determined PAWC value for maize was reached, the rate of water extraction per unit of depth increased with increasing depth and when first stress (obtained with visual stress symptoms) was reached a final extraction pattern resembling the "parallel-block" pattern was found. (The first stress line is connected with the field capacity line in the lower zone of the lysimeter in Figure 3.23 because the authors suspected the existence of a perched watertable in the bottom of the lysimeter).

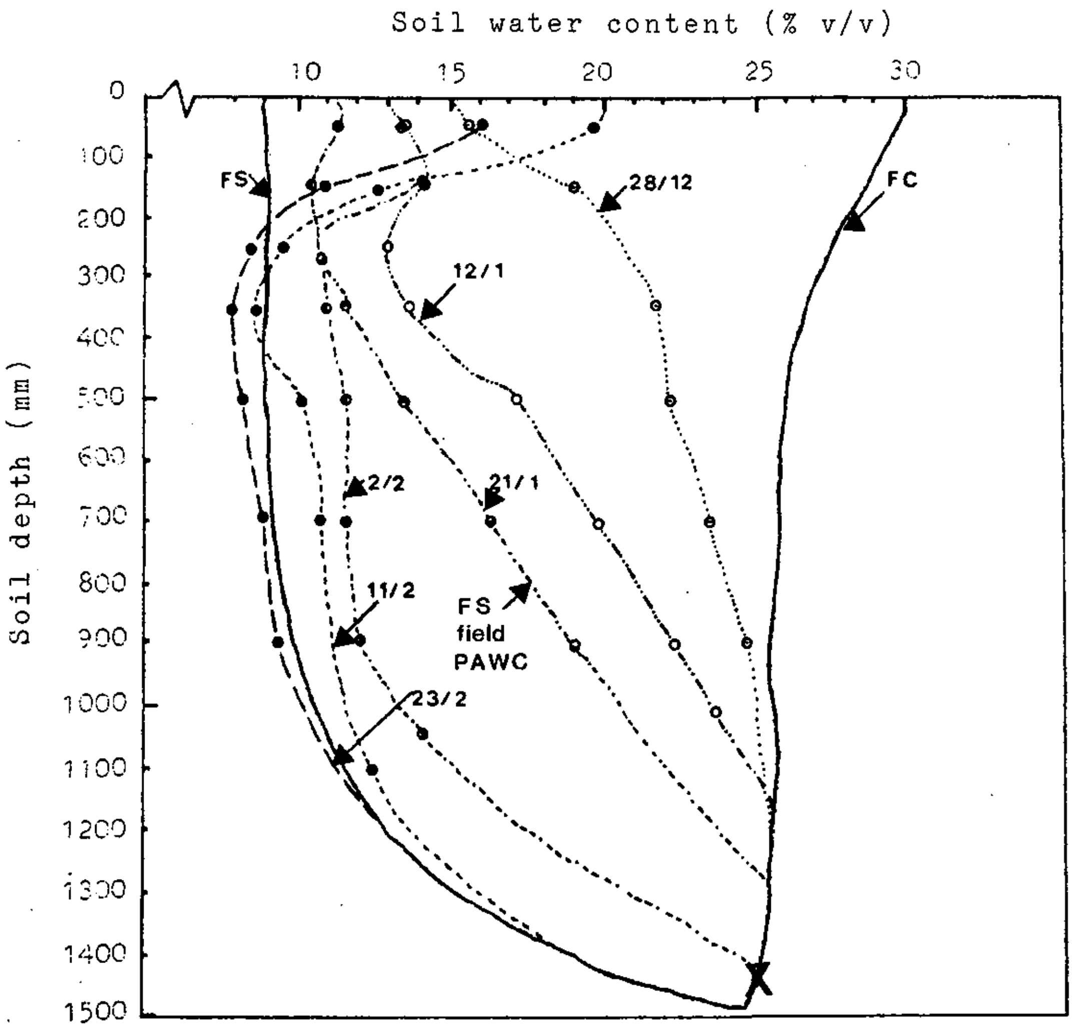


FIG.3.23 Soil water extraction pattern for maize on the Fort Hare lysimeter between field capacity and first stress (indicated by visual stress symptoms). FS field PAWC indicates when the lower limit of the field determined PAWC for maize was reached. (After Marais & Hensley, 1982).

The changes in the rates of water extraction by wheat at different depths in the lysimeter with time are illustrated in Figure 3.24. During the first days after irrigation the rate of water extraction is very high in the surface soil layers. As the drying cycle advances the rate of extraction becomes more uniform throughout the profile. When the drying cycle is extended the crops start extracting water from the lower soil layers at a higher rate than from the top layers.

3.4 DISCUSSION

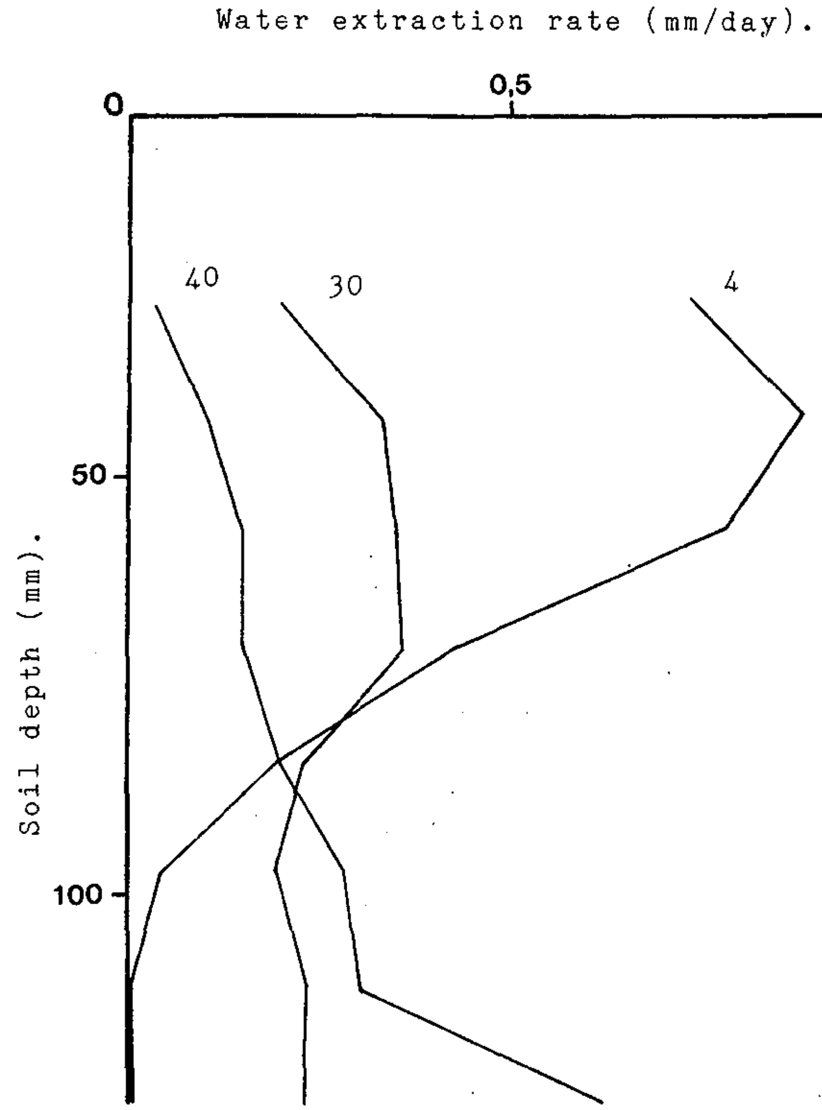
3.4.1 General

Three typical extraction patterns were observed:

(a) An initial shallow "fan" that moves gradually deeper in the soil profile until the extraction lines become parallel with the first stress line.

(b) A "deep-fan" pattern with the pivot of the fan at the bottom of the rooting zone or at an imaginary point below the rooting zone.

(c) A "parallel-block" pattern with extraction lines moving parallel with the field capacity line towards first stress. This pattern was related to <u>sandy</u>



4, 30, 40 days after irrigation.

FIG.3.24 Rate of water extraction (mm/day) at different soil depths at different times after irrigation for wheat in the lysimeter experiment.

soils in which a gradual increase in clay content with increasing depth was found.

The first two extraction models lead to final extraction patterns that have roughly the form of an inverted triangle. Examples of this type of extraction are found abundantly in literature. Gardner (1983) grouped a number of curves showing total soil water uptake at different depths, by different crops, at "initial wilting" (comparable with initial stress but not well defined by the author). All curves show a distinct decrease in water uptake with increasing depth.

This type of extraction is exemplified by Figure 3.25 from Willatt & Olsson (1982). They monitored rates of water extraction by soybeans at different depths during different periods after irrigation. As can be deduced from Figure 3.25 the crop extracted water at the highest rate close to the soil surface just after an irrigation. This leads obviously to a "fan" pattern. As the drying cycle advanced, and the available soil water in the upper layers was depleting, the rate of extraction became fairly uniform throughout the soil profile (see Figure 3.25). This uniformity of extraction at all depths of the soil profile causes the extraction lines to move

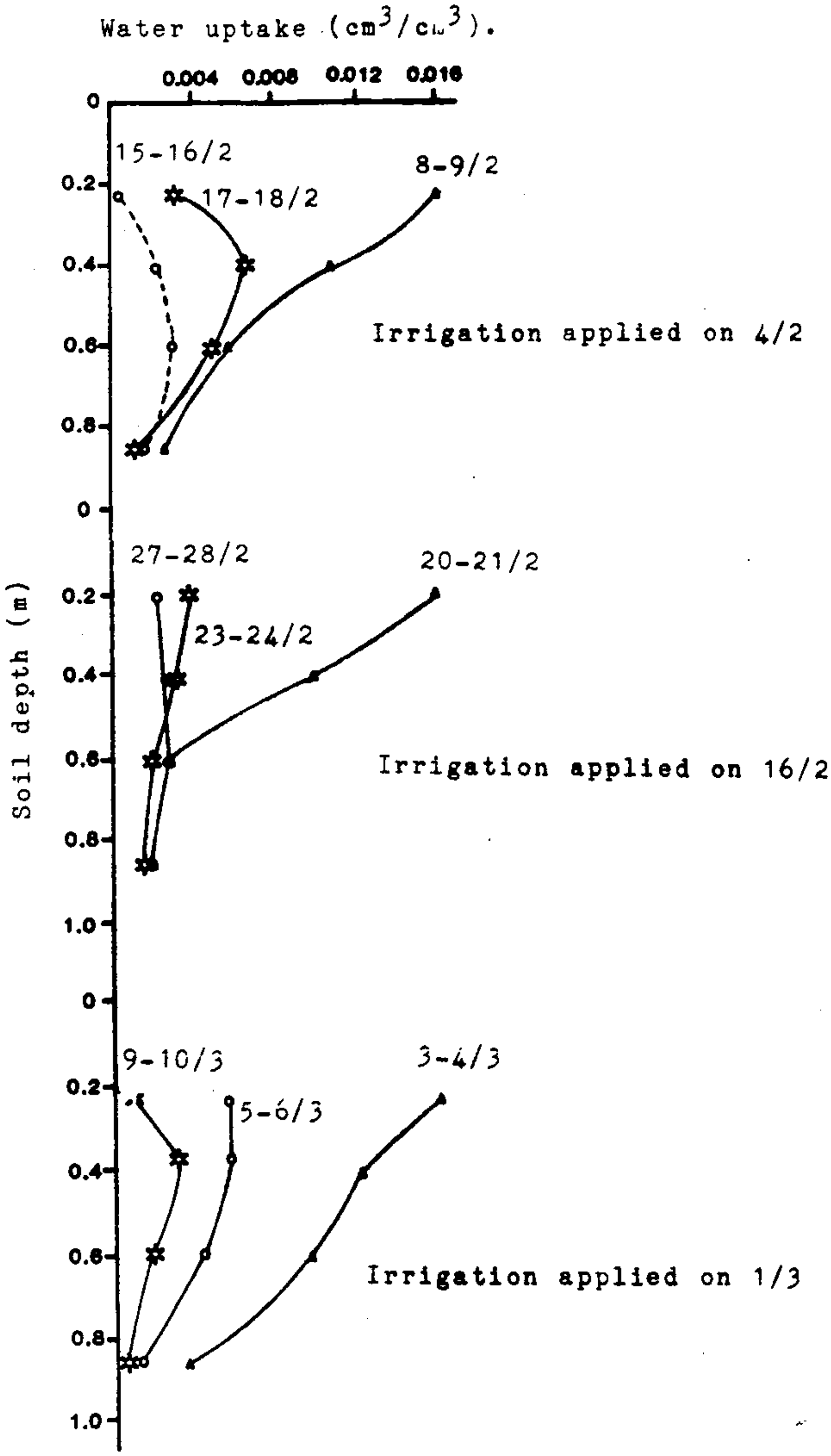


FIG.3.25 Rates of water withdrawal by soybean roots at different soil depths and different times after irrigation (From Willatt & Olsson, 1982).

parallel towards first stress.

Where crops were allowed to extract water beyond PAWC extraction rates in the subsoils became greater than the extraction rates in the topsoils (see Figures 3.15 to 3.24). This phenomenon was not observed by Willatt & Olsson (1982) because their drying cycles were much shorter than the cycles applied during the PAWC research. Increased water extraction from lower soil layers as the soil became drier was also observed by Ogata, Richards & Gardner (1960): after "first wilt" less water was extracted from the top layers while water was consumed at an increasing rate in the lower soil layers (Figure 3.26).

3.4.2 Possible explanation for the observed water extraction patterns

Although equation (3.4) does not give specific solutions for soil water uptake patterns, it describes the processes during soil water extraction very well and partly explains the observed final extraction patterns.

Under a certain evaporative demand there is a threshold value of leaf water potential (specific for crop, growth

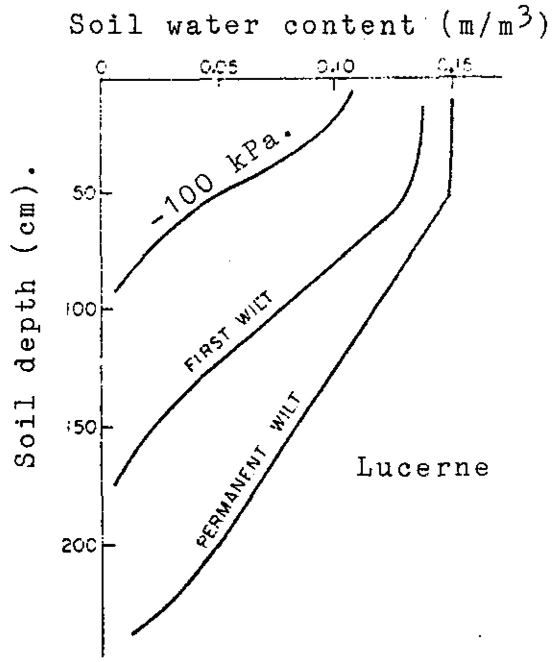


FIG.3.26 Water extraction by one year old lucerne 10, 22, and 58 days after deep irrigation (From Gardner, 1983).

stage, cultivar...) at which stomates begin to close and transpiration, and photosynthesis, are drastically reduced. According to Slayter (1967) there is a narrow critical range of leaf water potential at which this phenomenon happens. Gardner & Ehlig (1963) proved a clear drop in transpiration rate near -1200kPa for cotton. For beans -1100kPa was found by Kanemasu & Tanner (1969). Hsiao (1980) mentions -1200 to -1600kPa for rice. In a rather general approach Cowan (1965) proposes -1500kPa as a guideline for all crops.

At this specific value equation (3.4) becomes:

$$T = (\Psi s - \Psi stress) \frac{1}{Rs + Rr + Rsc}$$

with Ψ stress = critical leaf water potential value for stomata closure.

This equation will determine the final extraction pattern. The data from the present and other studies shows that at this critical leaf water potential value (and its corresponding stress-associated pre-dawn leaf water potential), there is an increase in soil water content, and in soil water potential with depth. The situation is illustrated in Figure 3.27. Consider the soil water potential at point A to be -700kPa while the pre-dawn leaf water potential at that stage is -1500kPa. The stomatal apertures are considerably reduced and as

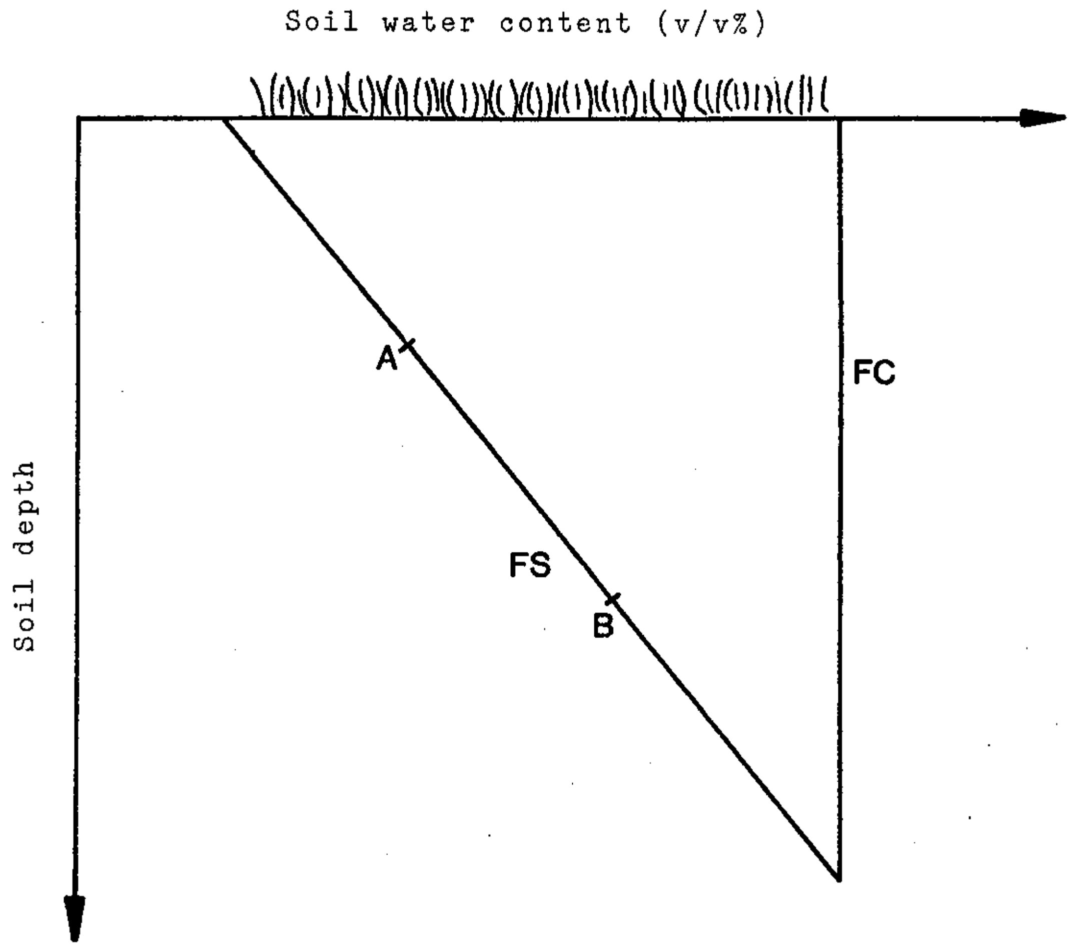


FIG.3.27 Hypothetical water extraction pattern.

FC = field capacity

FS = first stress

long as the leaf water potential remains at -1500kPa the potential gradient between A and the leaf is -800kPa. At this stage the water potential gradients between these points provides the energy needed to overcome the resistance offered by the pathway between A and the leaf. At the same moment, in point B, the soil water potential might be as high as -300kPa. But the plant is nevertheless wilting and one must conclude that the pathway resistance between A and B is such that a gradient of at least -400kPa is necessary to overcome this resistance. The cause of the increasing pathway resistance per unit of depth with depth is complex and the nature of all factors involved not fully understood as yet.

In a soil with a uniform texture the intrinsic soil conductivity will certainly not decrease with depth as the soil is becoming wetter with increasing depth. It can also be assumed that radial root resistance is constant, or is even decreasing with increasing depth in the soil profile. This is a fair assumption as the diameter of the roots will be smaller in the lower zones of the soil profile and suberization will increase resistance in the upper layers of the profile. This leaves the axial resistance in the xylem vessels, root distribution and resistances occurring at the soil/root interface to explain the increasing resistance with depth.

3.4.2.1 Root distribution

Root distribution influences the average distance between the roots and consequently the length of pathway along which the soil water must move towards the roots. During the 1983 winter season root density samples for wheat and peas were taken at the different experimental sites at Vaalharts (Tables 3.1 and 3.2). The samples were collected when first stress had been reached during the PAWC studies. The sampling and counting techniques were as described by Botha et al (1983). The relationship between root length per unit volume and fraction of water extracted from the available water range at a certain depth was tested. For wheat a rather low, but still significant, correlation coëfficient was found when the relationship between relative amount of water extracted per unit of depth was compared with root density at the same depths for all sites (see Table 3.3). When the data for the similar, very deep, apedal, sandy Hutton sites (Van der Linde I and II and Demonstration Plot) were considered separately a highly significant

TABLE 3.1 Rooting density data: wheat

Site	Soil depth (mm)	Root length (mm/cm 3)*
Kamp I	0- 200	9,78
	200- 400	24,01
	400- 600	3,30
	600- 800	3,06
Kamp II	0- 200	6,55
	200- 400	18,33
	400- 600	8,98
Van der Linde I	0- 200	10,57
	200- 400	6,29
	400- 600	4,76
	600- 800	5,79
	800-1200	4,92
	1200-1600	0,76
	1600-2000	0,75
Van der Linde II	0- 200	18,74
	200- 400	13,30
	400- 600	11,37
	600- 800	11,22
	800-1200	8,38
	1200-1600	3,93
	1600-200	1,04
Demonstration Plot	0- 200	27,66
	200- 400	5,74
	400- 600	3,79
	600- 800	5,44
	800-1200	4,21
	1200-1600	2,61
	1600-2000	1,53

* The root length data are extremely low, compared to the data reported by Botha et al (1983) for their pot experiments (see Table 3.4). The values of the data are however of the same order as the data reported by the same authors for their field experiments (Botha et al , 1983; see their appendices 2.1 and 2.2).

TABLE 3.2 Rooting density data: peas

Site	Soil depth (mm)	Root length (mm/cm^3)
Kamp I	0- 200	6,39
	200- 400	1,45
	400- 600	1,91
	600- 800	0,85
	800-1200	0,82
Kamp II	0- 200	2,30
	200- 400	4,12
	400- 600	2,05
Van der Linde I	0- 200	----
	200- 400	1,55
	400- 600	1,07
	600- 800	3,68
	800-1200	2,55
	1200-1600	0,29
Van der Linde II	0- 200	7,65
	200- 400	0,28
	400- 600	0,25
	600- 800	1,59
	800-1200	0,76
	1200-1600	0,12

correlationcoefficient was found (see Table 3.3). For peas no significant correlations could be found.

It is evident that root distribution patterns could partially explain the observed soil water extraction patterns. It did not provide a complete explanation, however. It is a pity that it was not possible to conduct root distribution studies for the Ciskei and Loskop and for the Vaalharts summer experiments also.

Even in well-controlled pot experiements with wheat Botha et al (1983) failed to establish clear-cut relationships between root densities and water extraction (Table 3.4). At relatively low rooting densities there was always a direct positive relationship between rooting density and water extraction (compare treatments 2 and 3 at all growth stages), At relatively high rooting densities water extraction was independent of rooting density, except for the final extraction period, i.e. for days 94 to 98 (compare Treatments 1 and 2 at all growth stages). They found similar trends in a pot experiment with maize (See Table 3.5 in Botha et al , 1983). Again, rooting densities only partially explained differences in water extraction. It should be kept in mind however that Botha et al (1983) (a) worked in pots, where rooting densities

TABLE 3.3 Observed relative water extraction and root densities at different depths for wheat on some Vaalharts soils.

SITE	DEPTH (cm)	RELATIVE WATER* EXTRACTION (%)	ROOT DENSITY (mm/cm^3)
Kamp I	10	123,8	9,8
	31	112,6	24,1
	50	68,9	3,3
	80	75,3	3,1
Kamp II	14	69,8	6.6
	39	54,8	18,3
	59	57,1	9,0
V.d.Linde I	25	109,3	18,7
	90	54,1	8,4
V.d.Linde II	12	87,2	18,7
	37	62,0	13,3
	70	54,1	11,2
	100	37,1	8,4
Dem. Plot	8	93,9	27,7
	22	54,3	5,7
	61	53,7	5,4

Relationship relative water extraction/ root density for all sites:

$Y = 1,0 + 0,15X$ (with $r = 0,51$ sign. at 0,01 level).

Relationship relative water extraction/ root density for Van der Linde I and II, Demonstration Plot:

$Y = -4,4 + 0,26X$ (with $r = 0,83$ sign. at 0,01 level).

* relative water extraction = % of water between -10 and -1500 kPa soil moisture potential extracted.

TABLE 3.4 Average daily transpiration rate of wheat as affected by rooting density at different growth stages (adapted from Botha et al , 1983).

Water extraction (Days after planting)	Treat= ment	Mean rooting density (mm/mm^3)	Average trans= piration rates during the wa= ter extraction periods (mm per day)
36 to 43	1	1,78	5,34
36 to 46	2	1,39	4,45
36 to 48	3	0,92	3,27
63 to 67	1	5,22	8,05
63 to 67	2	3,70	8,89
63 to 69	3	2,37	6,26
69 to 74	1	6,19	11,90
69 to 75	2	4,66	11,95
69 to 76	3	3,25	7,44
80 to 83	1	7,76	13,48
80 to 84	2	6,18	13,23
80 to 85	3	4,76	9,33
94 to 96	1	9,70	13,53
94 to 98	2	8,82	10,71
94 to 98	3	6,04	8,26

|| = no statiscal significant difference.
↑ = statiscal significant difference.

are very high and extraction is (compared with the field) from a shallow soil layer only and (b) used short extraction periods, i.e. the soil was relatively wet. As a result rooting density would be less important than where rooting densities are low and where extraction is permitted to proceed to a relatively dry state, e.g. first stress.

In Figure 3.28 from Willatt & Olsson (1982) the rate of water withdrawal by roots at different depths in the profile and at different times after irrigation are plotted on the the right-hand side of the Figure. On the left-hand side root density variations with depth and time after irrigation are plotted. Although there is at some instances a good correlation between water withdrawal and root distribution, there are some striking differences at certain dates. For example on 7/2 an almost uniform root distribution was observed throughout the soil profile, however, on 8/2 and 9/2 considerable more water was extracted from the top layers than from the bottom layers (Figure 3.28). This again illustrates that root distribution only partly explains the observed water extraction patterns.

The possibility exists that root length is not a

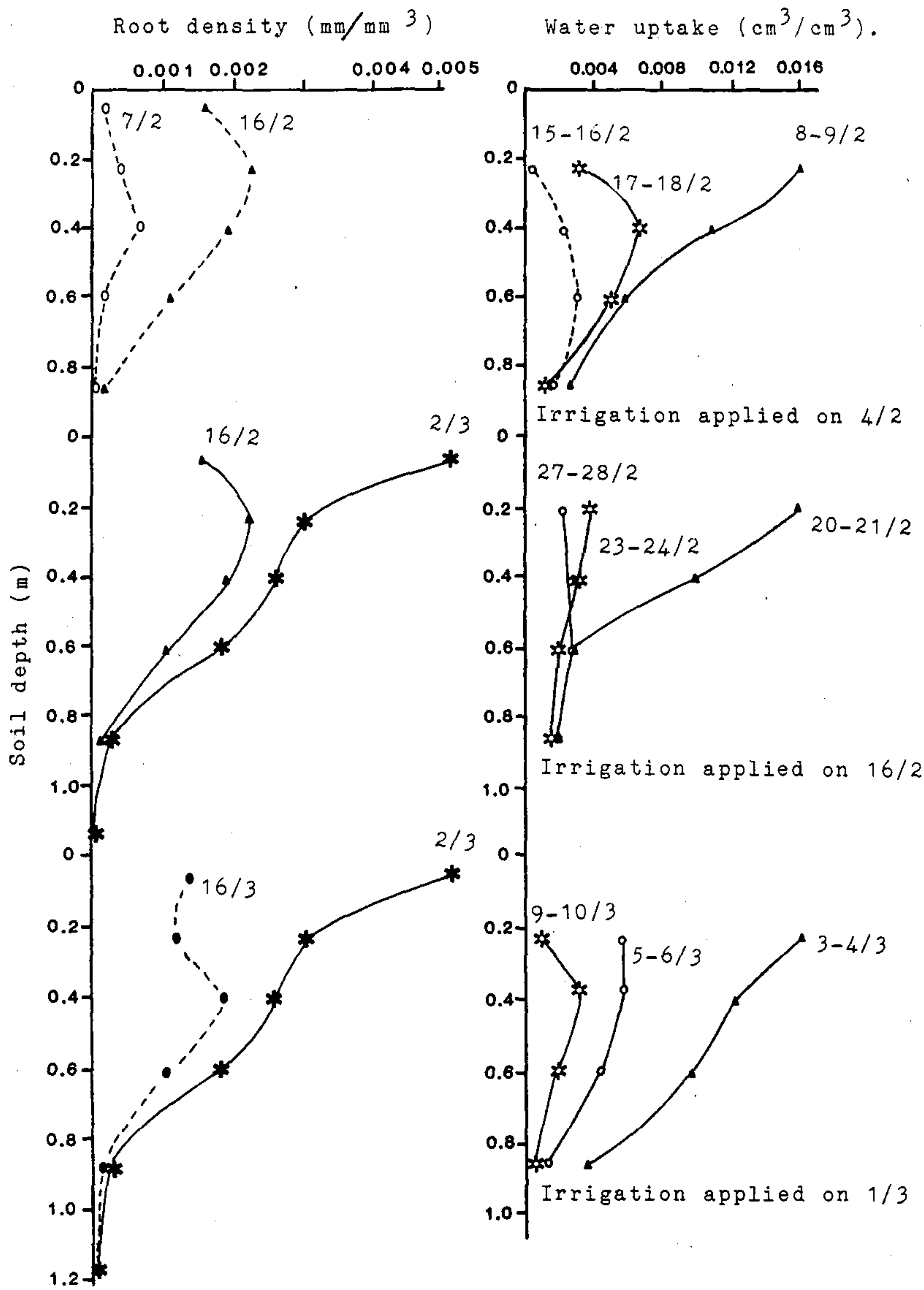


FIG.3.28 Root density variation with depth and time (a) and rates of water withdrawal by soybean roots at different soil depths and different times (b) after irrigation (From Willatt & Olsson, 1982).

sufficient description of the effective water absorption system and that it is necessary to know the fraction of effective roots, their absorption characteristics and their distribution in the soil profile.

3.4.2.2 Resistances occuring at the soil/root interface

Botha & Bennie (1983) postulated that a significant resistance in the soil-root contact area seems to be a controlling factor in water uptake by roots. As the soil is drying out, increased resistance in the soil-root contact zone may result from a decrease in contact area between the root and soil water films, from the formation of a drier soil layer (with, consequently, a lower soil hydraulic conductivity) near the root surface or from the formation of vapour gaps across the soil-root contact due to root shrinkage during transpiration (Botha & Bennie, 1983). Botha & Bennie (1983) concluded from their research that a lower rooting density will result in a higher dependency of water uptake on conditions existing in the soil-root contact zone.

The above mentioned conditions are applicable to the situation occuring at the end of a drying cycle. The soil water reserve in the upper layers is depleted and the relatively wetter soil layers, occuring lower in the soil profile, with their lower rooting densities, must provide the water to meet a certain evaporative demand. The result is that a higher water uptake per unit of area of root surface must occur (higher flux) if wilting is to be avoided. This causes the shrinking of the root diameter and gives origin to high resistances in the soil-root interface.

Indirectly the resistances occurring at the soil/root interface are thus dependent on rooting density and flux.

3.4.2.3 Axial root resistance

The morphological development of a root system is genetically determined, but is modified according to the soil environment in which the crop is growing. Mechanical resistance, pore size distribution and moisture holding characteristics are especially important. The large differences between the maximum depths to which water was extracted from deep soils in the present study is related to this. (E.g. the deep Jozini soils in the Ciskei and the deep Mangano soils at Vaalharts were all more than three metres deep, but on the Jozini crops like wheat and maize extracted practically no water below 1500mm depth whereas on the Mangano water was extracted to more than 2000mm below the surface). The relatively high silt contents of the Jozini leads to highly compacted subsoils with unfavourable poer size distribution which severely restricts root development. This is a characteristic of most Ciskeian soils. On the other hand pore size distribution, and the nature of the soil moisture tension curves, of the subsoils of the Mangano soils at Vaalharts encourages root proliferation in the deeper layers of the profile. The plant-available water in these soils is held at very low tensions and can, therefore, be extracted easily. (See data of Bennie & Burger, 1979 and Hensley & De Jager, 1982).

The role of axial root resistance in regard to differential water absorption from different soil depths is not clear. Axial root resistance to water flow has always been considered as being insignificant (e.g. Rowse & Goodman, 1981). Recently researchers (e.g. Klepper, 1983) have concluded that axial root resistance to water flow can be considerable. Klepper (1983) indentified a number of causes of this resistance. Since the magnitude of axial resistance will be related to the total length of the pathway in the root, axial resistance should increase with increasing depth. This would limit water extraction from deeper soil layers.

Molz (1971) concluded that: "Quite possibly there is sufficient impedence in the plant roots so that a sufficient potential gradient is required to move moisture through the root system. For deeper roots most of the available energy would already have been spent in moving the moisture longitudinally through the rootvascular system and little would be left over to induce radial moisture flow from the root to the vascular system". This outline of Molz (1971) implies that water absorption is an active process in which work (energy) is involved. It is generally accepted that water absorption and transport in the plant is a passive process, however. Even in such passive system axial resistance could be very important. In swelling clay soils roots are often subjected to severe pressure, which would close xylem vessels. In compacted soils roots are often bent sharply (See, for example, plates in Bennie, 1971). At each sharp bend in a tube a high resistance is introduced. (It is not uncommon to stop water flow through a hose pipe by simply bending the pipe!) The longer, and the deeper, a root is, the more of these resistant areas can be in the axial pathway. In the light of the recent data of Klepper (1983) and others this aspect needs very definite attention.

CHAPTER 4

DAILY WATER CONSUMPTION BY CROPS DURING DRYING CYCLES

4.1 INTRODUCTION

There exists a wide variety of opinion on the problem of availability of water between the upper and lower limit of soil available water. The problem was briefly discussed in paragraph 1.2.5 of Chapter 1.

At present it is generally accepted that for a relatively long period after a soil has been brought to field capacity the plants can obtain water with equal facility. For maize this period is predicted to be 10 days for a potential evapotranspiration of 10mm/day (Doorenbos & Kassam, 1979). This principle is illustrated for cotton in Figure 4.1.

Non-destructive methods for soil water content

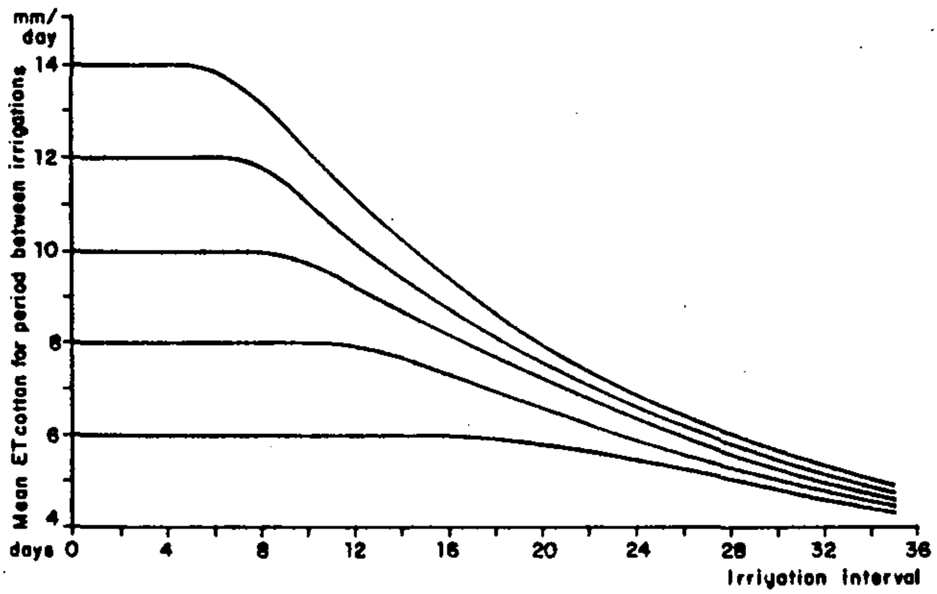


FIG.4.1 Mean actual evapotranspiration of cotton over the irrigation interval for different ET cotton levels. The lines illustrate the change in actual ET cotton with time (from Doorenbos & Pruitt, 1977).

determination (neutron hydroprobes) can help to test this "equal" availability of soil water just after irrigation. Crop coefficients (crop evapotranspiration / potential evapotranspiration) are expressions of the availability of soil water: A significantly decreasing crop coefficient (= crop factor = kc) means decreasing availability.

4.2 RESEARCH PROCEDURES

During the PAWC determinations for wheat and peas at Vaalharts during the 1983 winter season and those for maize and cotton during the 1983/84 summer season at Loskop, neutron hydroprobe determinations of soil water were made at daily intervals. It was ensured that the readings at each site were done at approximately the same time every day. This permitted calculation of daily water consumption by the crops. In combination with daily potential evapotranspiration data (class A pan reading x pan factor) these data were used to calculate "crop factors" for different stages of the extraction period between field capacity and first stress (see also Doorenbos & Pruitt, 1977).

During the 1983/84 irrigation scheduling experiments with maize at Vaalharts and Loskop frequent neutron hydroprobe measurements were also made during the drying cycles. These could also be used to calculate "crop factors" at different stages of water extraction.

4.3 RESULTS AND DISCUSSION

Useful crop factor data were obtained during the PAWC studies with wheat and peas at Vaalharts during the 1983 winter. A number of heavy rainstorms during the PAWC studies for maize and cotton at Loskop during the 1983/84 summer led to very erratic "crop factor" patterns and these will not be discussed. The irrigation scheduling studies with maize at Vaalharts at Loskop during the 1983/84 summer yielded useful crop factor data.

4.3.1 **Wheat and peas at Vaalharts**

The crop factor data obtained during drying cycles for wheat and peas at Vaalharts are listed in Appendices 4.1 to 4.9. The results for Van der Linde II will be used as an example in the following discussions (Figures 4.2 and

4.3).

There is a distinct difference between the trends for the first three days after irrigation (the period of drainage towards field capacity) and those for the rest of the drying cycles (see Figures 4.2 and 4.3). During the first three days there is a sharp decline in crop factor with time. It is in fact not correct to use the term "crop factor" for this part of the drying cycle as drainage is the dominant process during this period. The term water loss ratio would be more appropriate at this stage. It should be kept in mind that for the PAWC-determination experiment the soil was over-saturated with water to ensure that the soil would be brought to field capacity throughout the profile.

During the second part, the true crop extraction phase, there is an almost perfect gradual linear decline in crop coefficient (crop factor) with time. The three to four day averages show this clearly for both crops (see linear regression equations on Figures 4.2 and 4.3). It is striking that this decline seems to be independent of actual evapotranspiration (see Appendices 4.7 and 4.8). For wheat the highest potential evapotranspiration rates occurred at the beginning of the drying cycle, whereas

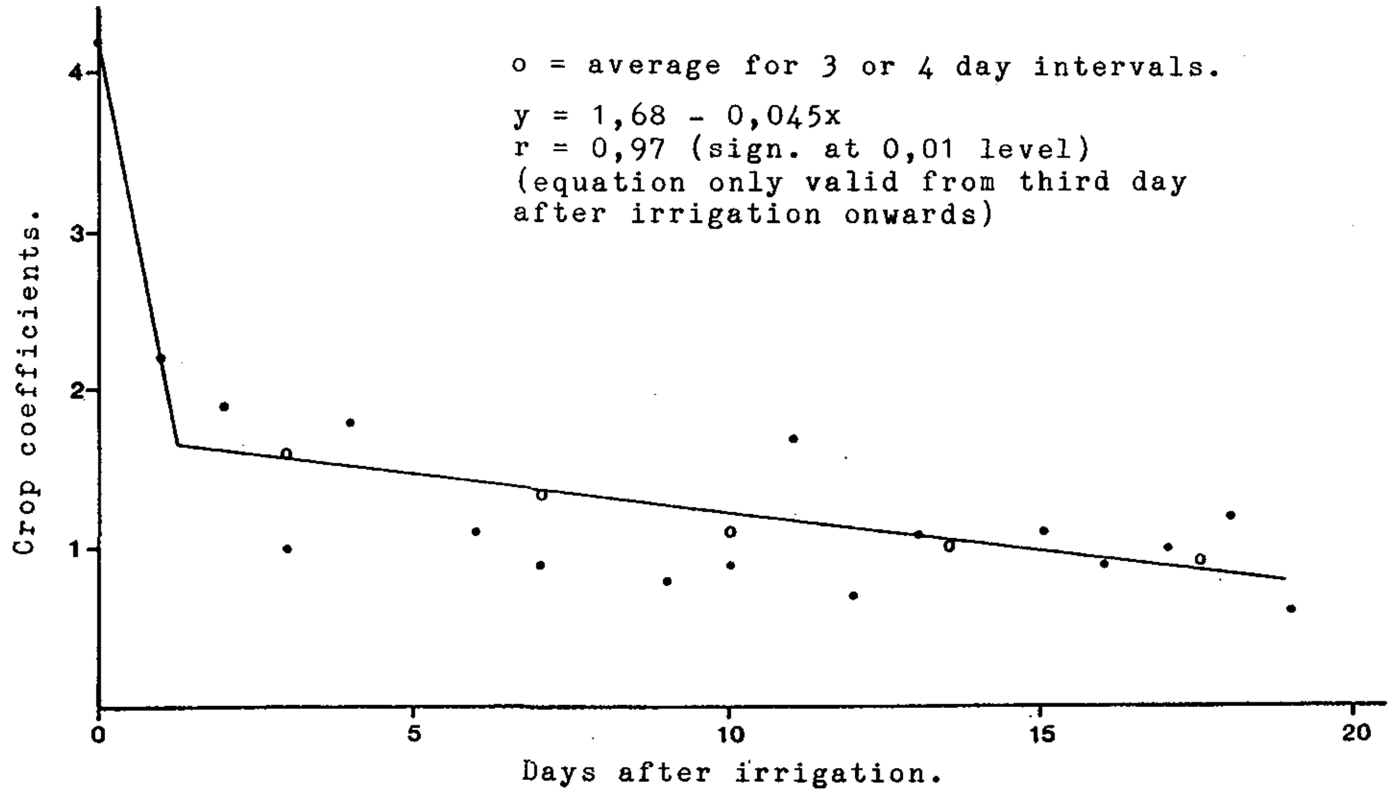


FIG.4.2 Change in crop coefficients for wheat with time after irrigations. The high values at the beginning of the drying cycle are due to drainage.

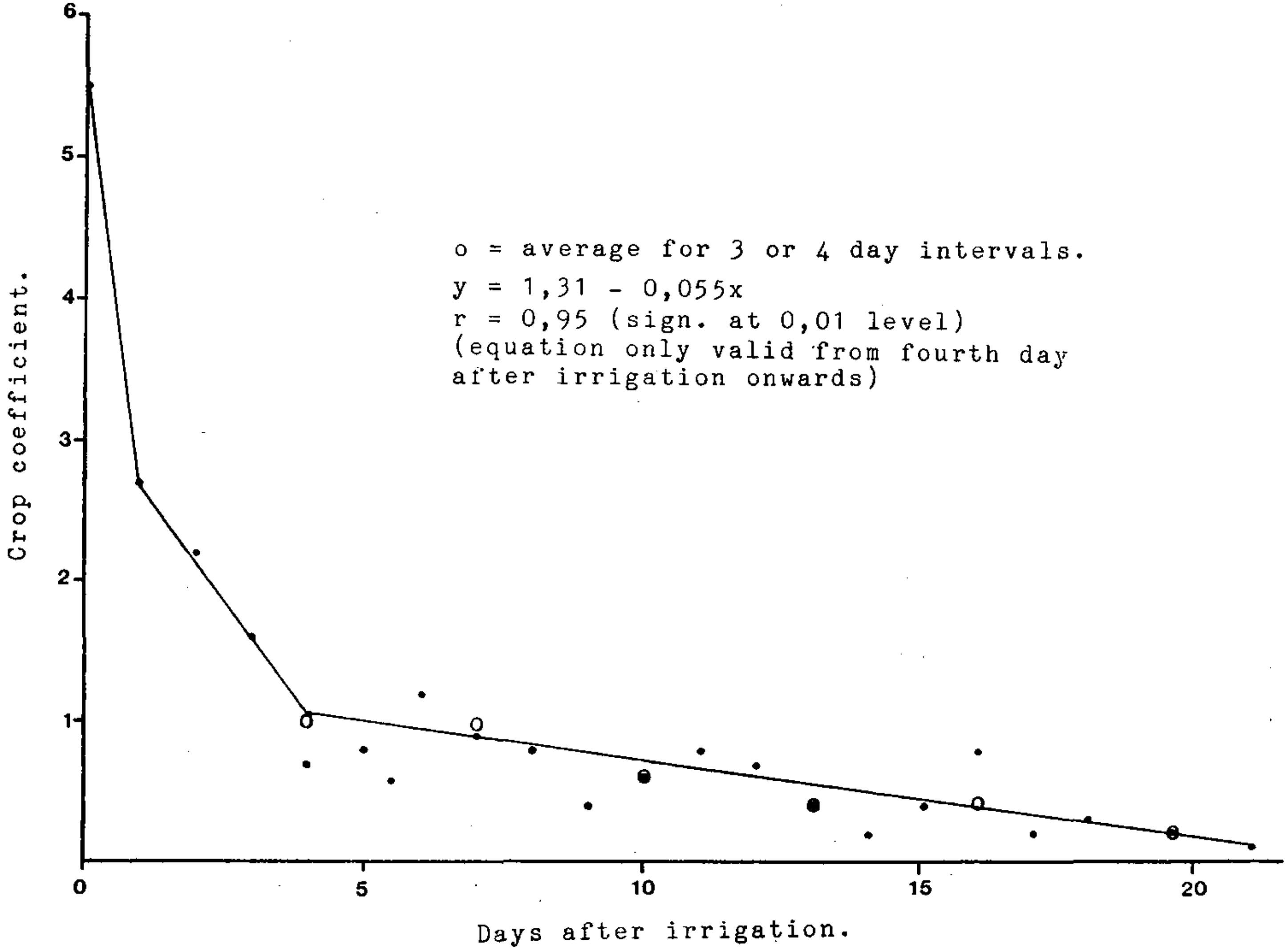


FIG.4.3. Change in crop coefficient for peas with time after irrigation. The high values at the beginning of the drying cycle are due to drainage.

for peas they occurred at the end of the cycle. This independence of potential evapotranspiration rate may be of great practical significance in using crop factors in irrigation scheduling.

It can be seen from Figures 4.2 and 4.3 that the daily patterns are somewhat erratic. This is due to the fact that readings were taken for relatively thin individual soil layers and that very small differences therefore had to be measured accurately, which was not always possible to achieve. Hensley & De Jager (1982) and Green (1984) also obtained erratic data in similar experiments when water consumption was calculated on a daily basis. Present methods for measuring soil water content are apparently not sufficiently sensitive for daily water loss studies.

Peas had lower crop factors, and thus extracted less water per day than wheat, at corresponding stages of the drying cycle. The result is that, although peas extracted much less water than wheat between field capacity and first stress (i.e. peas have a much lower PAWC) the duration of the drying cycle was practically the same for the two crops. The slower extraction rate of peas may be related to the smaller percentage canopy cover and the much lower rooting density found for this crop at the Van der Linde II site (see Chapter 3). The observed difference in extraction rate and crop factor between peas and wheat is in contrast with crop factors for wheat and peas given by Doorenbos & Kassam (1979). They advocate the use of crop factors (at flowering) between 1,05 and 1,20 for both peas and wheat.

These observations for wheat and peas must be treated with caution. It was already mentioned that, at the beginning of the drying cycle, the crop coefficients (water loss ratios) were unnaturally high because of the drainage process. After the initial period it can be assumed that the dominant soil water removing process was evapotranspiration, but unsaturated flow out of the soil profile may still be significant (Hillel, 1980). The extremely high "extraction" at the beginning of the cycle could also be caused by the "oasis-effect" (Oosterhuis, 1984). All Vaalharts experiments were conducted at sites isolated from other irrigated areas so that this effect could have influenced the results considerably.

4.3.2 Maize at Vaalharts

The validity of the results found for wheat and peas could be tested during the following summer season when irrigation scheduling experiments for maize were conducted at the same sites used for the PAWC-determinations.

At flowering the maize was subjected to irrigation cycles of different duration: when 25, 50, 75, or 100% of PAWC was consumed the soil profile was refilled to field capacity (see Chapter 5). Between irrigations soil moisture content was determined with a neutron hydroprobe. At the start of each drying cycle the soil profiles were filled exactly to field capacity. No surplus water was applied, as was done for the PAWC-determination experiments. The possibility of water loss through deep percolation was, therefore, reduced to insignificant levels.

The obtained crop factors for the different extraction periods (25, 50, 75, 100% PAWC) are listed in Table 4.1. Unfortunately water content determinations were not made at regular intervals during a specific extraction period and therefore only the average crop factor for the whole extraction period, and not the changes in crop factor in time during an extraction period, are given.

TABLE 4.1 Observed and relative crop factors for maize at flowering for different lenghts of irrigation intervals (determined by % of PAWC extracted). The values between brackets represent the relative crop factors (highest observed crop factor at a site taken as 1,00).

	% of PAWX extracted			
Sites	25	50	75	100
Van der Linde II	1,5 (1,00)	1,5 (1,00)	1,2 (0,78)	0,7 (0,46)
Kamp II	1,5 (1,00)	1,2 (0,80)	1,3 (0,86)	1,3 (0,84)
Kamp I	1,4 (1,00)	1,3 (0,92)	1,1 (0,81)	0,7 (0,51)

* the data for the Van der Linde I are not mentioned in this Table because of the unnatural nature of the crop factors found at this site (see also Chapter 5).

As can be deduced from Table 4.1 and from Figure 4.4 average crop factors for the different extraction periods decrease curvilinear with percentage of PAWC extracted and thus with time after irrigation. The regression coefficient (see Figure 4.4) would be higher if Kamp II is not taken into account. The deviating pattern at Kamp II is probably caused by the fact that PAWC was apparently underestimated at this site (see Chapter 2 and

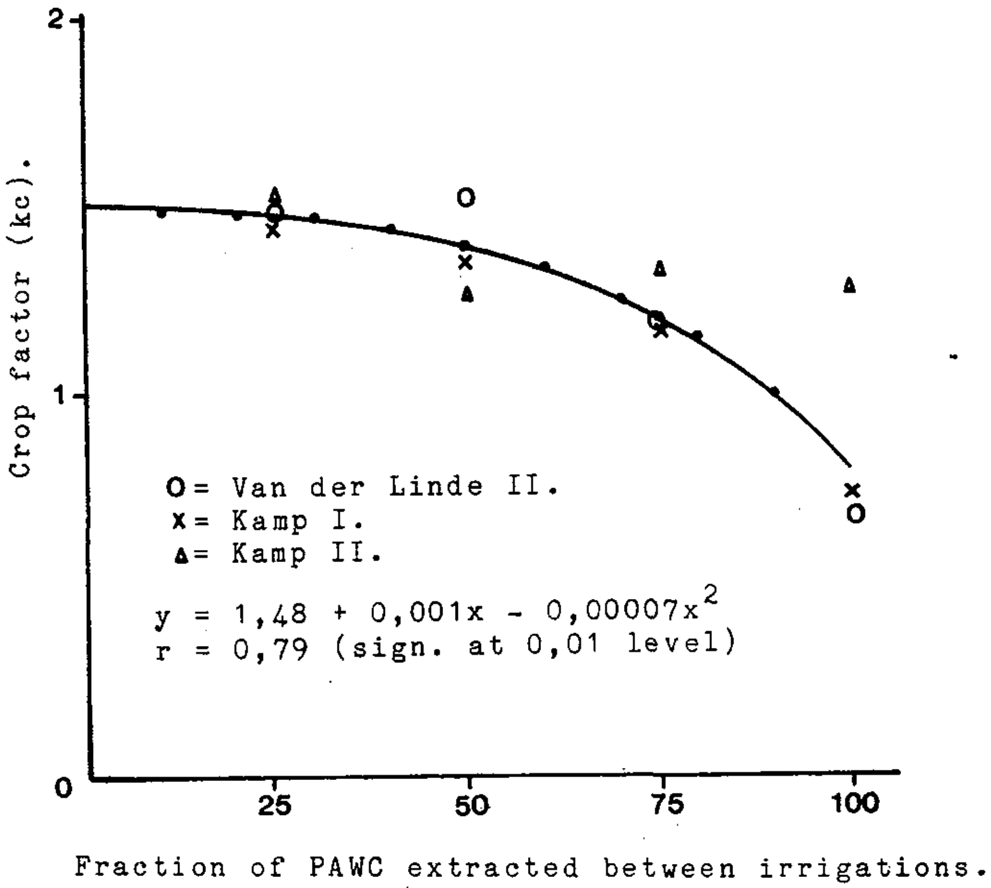


FIG.4.4 Change in crop factor for maize with fraction of PAWC extracted between irrigations.

6).

The crop factors did not drop dramatically before 75% of PAWC was consumed. The relatively high crop coefficients found up to 75% extraction of PAWC are slightly higher or equal to crop coefficients proposed for maize at flowering by Doorenbos & Kassam (1979) and by the Bureau of Reclamation (1983). They predict the crop factor for maize at flowering to be 1,2 under a high evaporative demand.

The relative crop factor values (given between brackets in Table 4.1) for maize on the different Vaalharts sites were correlated with the relative water use and relative yield figures obtained during the same experiments (Figures 4.5 and 4.6). The highest correlation coefficient was found between relative crop factor and seasonal water use (see Figure 4.5).

Also between relative crop factor and relative yield a statistically significant linear relationship was found (see Figure 4.6). A significant reduction in average crop factor, therefore, invariably implies a corresponding reduction in yield. As the crop factors are decreasing curvilinearly with fraction of PAWC extracted

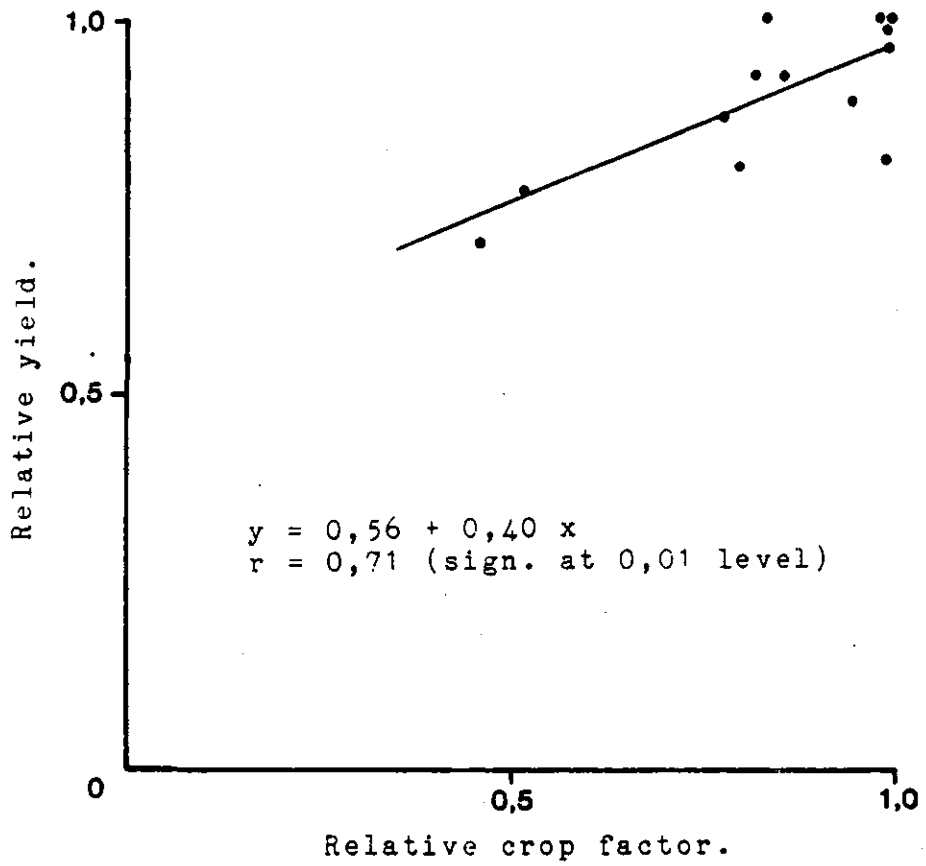


FIG.4.5 Relationship between relative yield and relative crop factor.

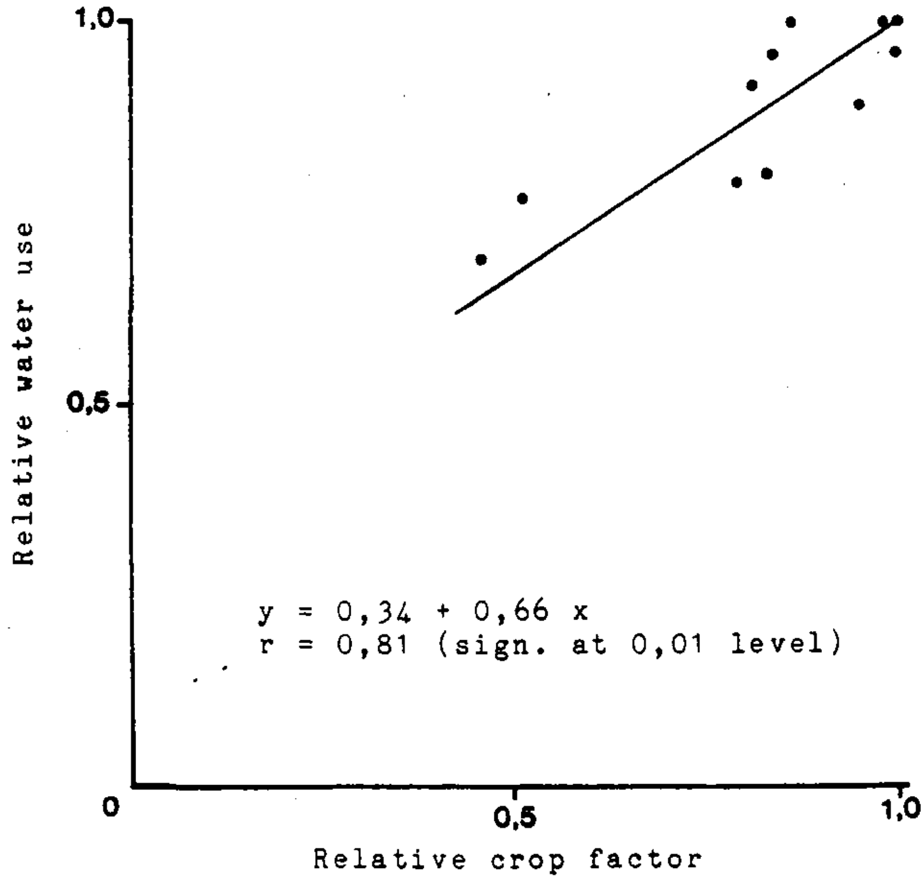
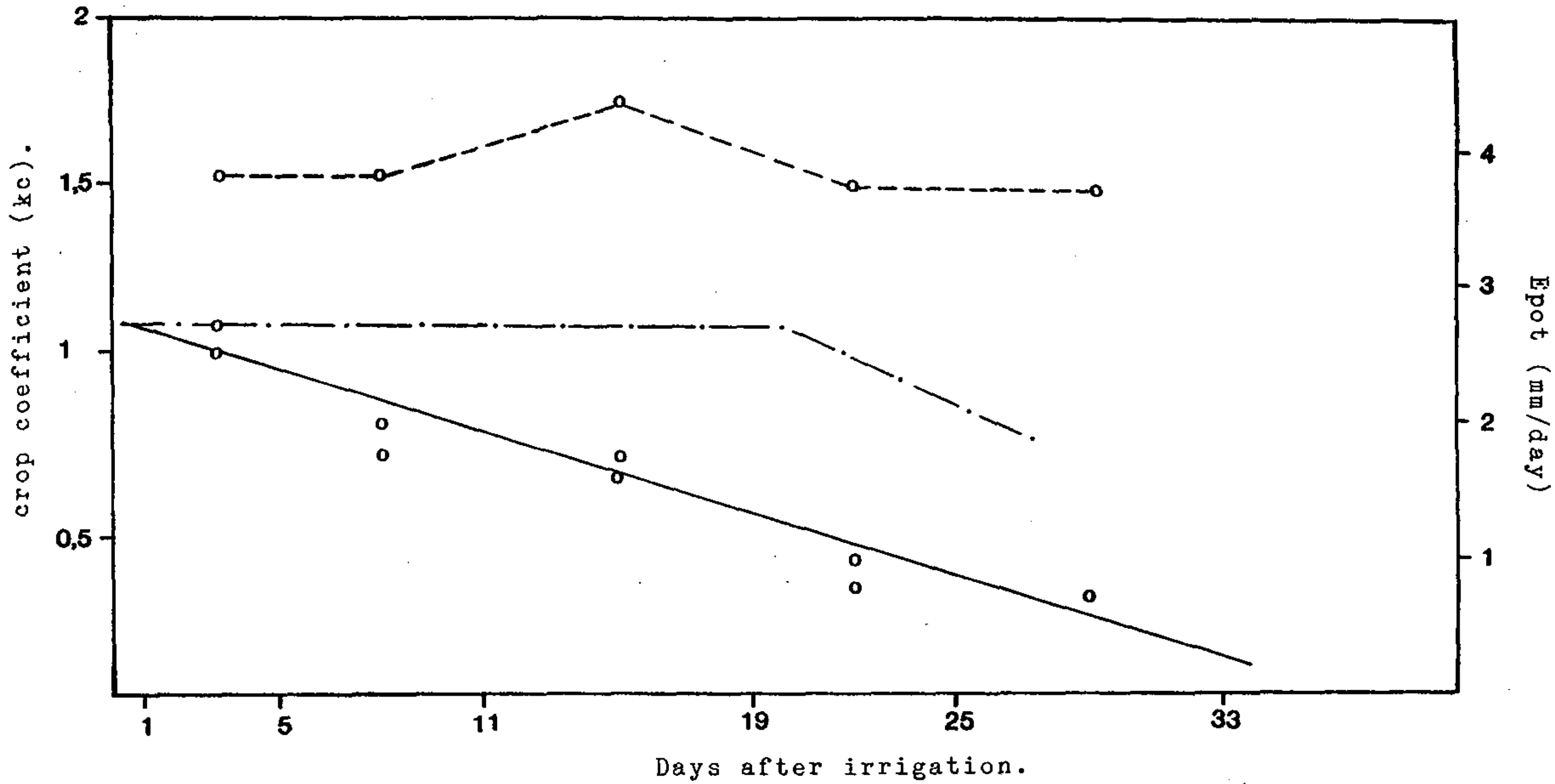


FIG.4.6 Relationship between relative water use and relative crop factor.

between irrigations it can be concluded that yield will also decrease curvilinearly with increasing fraction of PAWC extracted between irrigations. These relationships will be discussed in more detail in Chapter 5 and 6.

4.3.3 Maize at Loskop

The irrigation scheduling experiment, conducted on the Contour 10 site at Groblersdal, was used for data collection. Frequent light rains during the experiment made it impossible to give representative, average crop factors for the different extraction periods. Only some crop factors, found at specified days after irrigation was applied, are illustrated in Figure 4.7. Again a distinct linear decrease in crop factor with time after irrigation was found. On the same figure the average lengths of the extraction periods of the different treatments are also shown. As could be expected, the relative length of the extraction period increases with decreasing crop factor. Again the relationship between average crop factor and fraction of PAWC extracted between irrigations was curvilinear (Figure 4.8).



o---o Epot = A pan reading x pan factor.

o—o actual kc

—.— kc as predicted by Doorenbos & Kassam (1979).

FIG.4.7 Crop coefficient for maize and potential evapotranspiration during a drying cycle (Groblersdal, 1984).

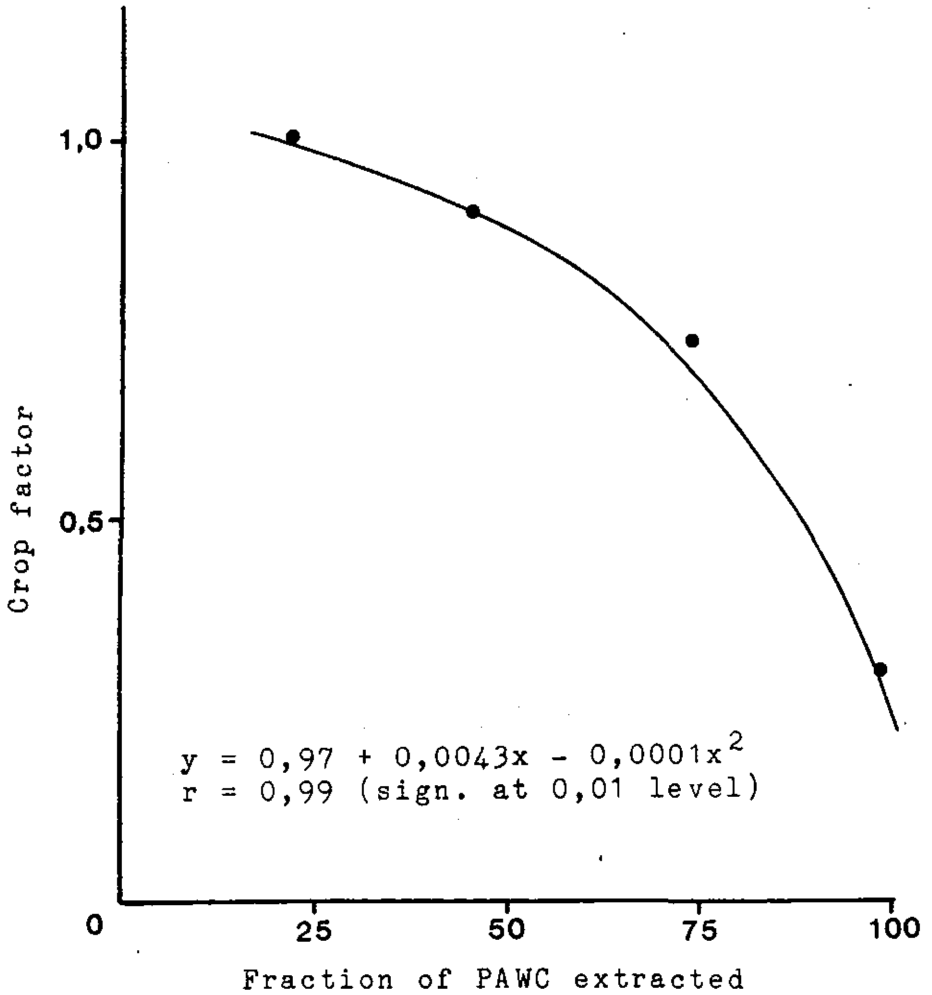


FIG.4.8 Change in crop factor for maize at Loskop with fraction of PAWC extracted between irrigations.

4.4 CONCLUSIONS

a. Within any defined extraction period a linear decrease in crop factor with time was found. This was found for all sites during the PAWC determination experiments for wheat and peas at Vaalharts and in all irrigation scheduling experiments with maize at Vaalharts and Loskop, except at the Kamp II site for maize. The average crop coefficient for an extraction period, therefore, also decreases with increasing length of the extraction period. This implies that seasonal water use of crops can be reduced by increasing the irrigation intervals. Unfortunately the reduction in average crop factor is accompanied by a parallel reduction in yield.

b. When the average crop factor is related to fraction of PAWC extracted between irrigations a curvilinear relationship, described by a quadratic function, is found (see Figures 4.4 and 4.8).

c. The observed decline in crop coefficient with time after irrigation contrasts with other models (e.g. Doorenbos & Kassam, 1979). The Doorenbos & Kassam model assumes that crops extract water at the maximum possible rate until a certain percentage of the profile available water has been consumed. This model would have estimated a water extraction of 60mm by maize at the Contour 10 site at Loskop during a two-week drying cycle with an average potential evapotranspiration of approximately 3,9mm/day (see Figure 4.8). Neutron hydroprobe data revealed an actual extraction of only 47,2 mm during this period. Doorenbos & Pruitt (1977) recommend adaptation of kc according to different irrigation intervals and evaporative demands during _initial_ growth stages, while the degree of ground cover is still low (see Figure 4.9). The differences in kc with different irrigation intervals at these early growth stages are related to "wet soil surface evaporation" after each irrigation (Bureau of Reclamation, 1983). At full ground cover this is assumed to be negligible.

d. The traditional way of using climatic data combined with crop coefficients (kc), should be used with caution in irrigation scheduling. If there is indeed a decline in kc with time after irrigation, the use of a constant kc for the calculation of amounts of water to be applied at the next irrigation, irrespective of the length of the irrigation cycle will lead to over irrigation and finally to water loss through deep percolation.

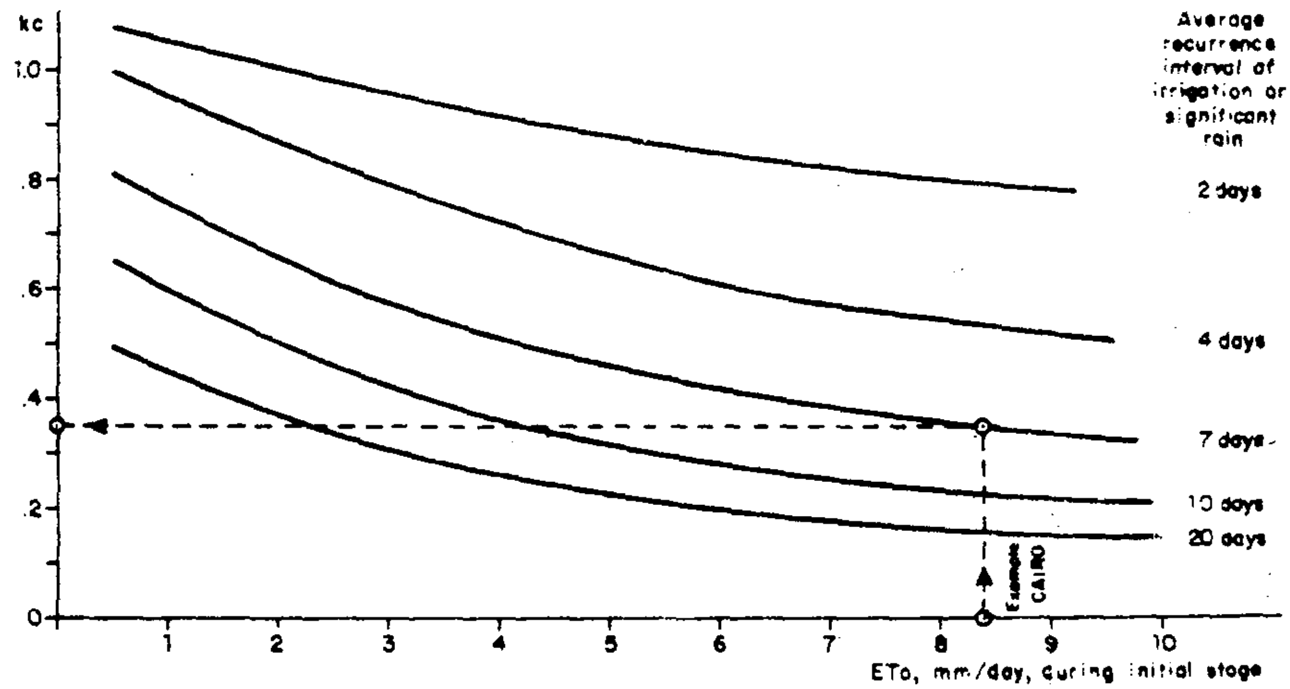


FIG.4.9 Average crop coefficient (kc) for initial crop development stage as related to level of ETo and frequency of irrigation and/or significant rain (from Doorenbos & Pruitt, 1977).

When irrigation intervals exceed 4 days other techniques should be used to calculate the amount of water to be applied. Modern equipment (for example hydroprobes) allows for correct soil water determinations. Using *in situ* soil water measurements for irrigation scheduling may achieve the highest water use efficiency.

Recommended kc values should only be used in circumstances identical to the ones in which they were determined: on a soil close to field capacity and irrigated at short intervals.

CHAPTER 5

IRRIGATION SCHEDULING EXPERIMENTS

5.1 INTRODUCTION

The classical questions involved in irrigation management are "when" to irrigate and "how much" water to apply at each irrigation (Hillel, 1980). The answers to these questions are very complex and involve the interrelationships between soil, water, crop and climate.

For a long time the main objective of irrigation scheduling studies was to maximize yield per unit area. Researchers concentrated dominantly on yield/ evapotranspiration relationships and found that any irrigation scheduling which reduces ET (seasonal consumptive use) will also cause reductions in yield (e.g. Wenda & Hanks, 1981; Hanks, 1982 and English & Nakamura, 1982). Some authors concluded from this observation that one should irrigate as frequently as is practicable (Hillel, 1980).

The decreasing availability of water resources for irrigation (due to climatic hazards and competition of other users) shifted the aim of irrigation scheduling research towards maximizing water use efficiency without significantly reducing yield per unit area.

It is believed that stretching the intervals between irrigations as long as possible will increase water use efficiency (Montgomery, according to Laker, 1983). In this regard the objective is to define the "optimum soil moisture deficit" or the "allowable depletion" (Buchheim & Ploss, 1977). This quantity of water is defined as: "The soil water that may be utilized from the root zone without causing plant stress or yield reduction" (Buchheim & Ploss, 1977).

The assessment of this critical proportion of the available water in the soil profile, which will help to answer both the critical questions involved in irrigation scheduling, is difficult. The traditional approach considers this proportion to be the water held between soil water tensions of 10 or 33 kPa (field capacity) and 1500 kPa (permanent wilting point). It is obvious that this approach is an oversimplification of the problem. Nevertheless many researchers still use it as a basis from which "allowable depletion" is calculated: extraction of a certain fraction (%) of the available water between field capacity and permanent wilting point is used as a criterion for irrigation scheduling. Usually this percentage is chosen by trial-and-error and sometimes even arbitrarily (Hsiao et al., 1980). Doorenbos & Kassam (1979) discussed this method in detail and gave a list of allowable soil water depletions for different crops.

More recently the PLEXW - concept of Ratliff et al (1983) (see Chapter 2) has been used as a basis for determining allowable depletion. Again arbitrary portions of PLEXW are taken as the "allowable depletion". Sixty percent of PLEXW (potential extractable soil water) is proposed by the Bureau of Reclamation as the allowable depletion for grain crops and 40% for potatoes (Buchheim, according to Laker, 1983). During non-sensitive stages of crops 65% of PLEXW is taken as allowable depletion and 35% during sensitive stages, according to Rasmussen (see Laker, 1983).

Buchheim & Ploss (1977) developed a method for the in *situ* determination of allowable depletion. In this method three values are needed to determine "allowable depletion":

(a) "full value" = soil water content after drainage of excess water (similar to *in situ* determined field capacity).

(b) "refill level" = minimum allowable moisture content in the top 300mm of the soil profile.

(c) "root decimal" = ratio of the extraction rate in the top zone to the extraction rate in the total soil profile (rooting depth). This ratio, determined empirically during previous research, reflects the changes in soil water extraction pattern during a drying cycle. The change in soil water content of the top 30cm with respect to the change in the profile is used to obtain the "root decimal".

"Refill level" and "root decimal" are established using three criteria: (a) at what depletion would irrigation result in optimum yields, (b) at what depletion would the crop show water stress and (c) at what depletion should the farmer irrigate? The "refill level" is determined with neutron hydroprobe and/or tensiometer monitoring and may vary slightly due to growth stage and climatic conditions. Plant water stress is assessed with visual stress symptoms or, more recently, infra-red thermometer readings.

It is clear that some judgement and technical know-how is required from the irrigator to decide on the point of refill. Once this point is established the rate of extraction, determined dominantly by climatic conditions, will determine when irrigation will be applied. This system is clearly demonstrated in Figures 5.1 (a, b, c) : Knowing the allowable depletion, and estimating the extraction rate from climatic data, the next irrigation is planned to take place 20 days after the profile was filled up to field capacity. The date of the next irrigation was corrected after neutron hydroprobe data showed a faster depletion of the soil profile than expected.

In a later modification of this method Carter & Conway (undated) measured soil moisture content at all depths of the profile to establish the "allowable depletion".

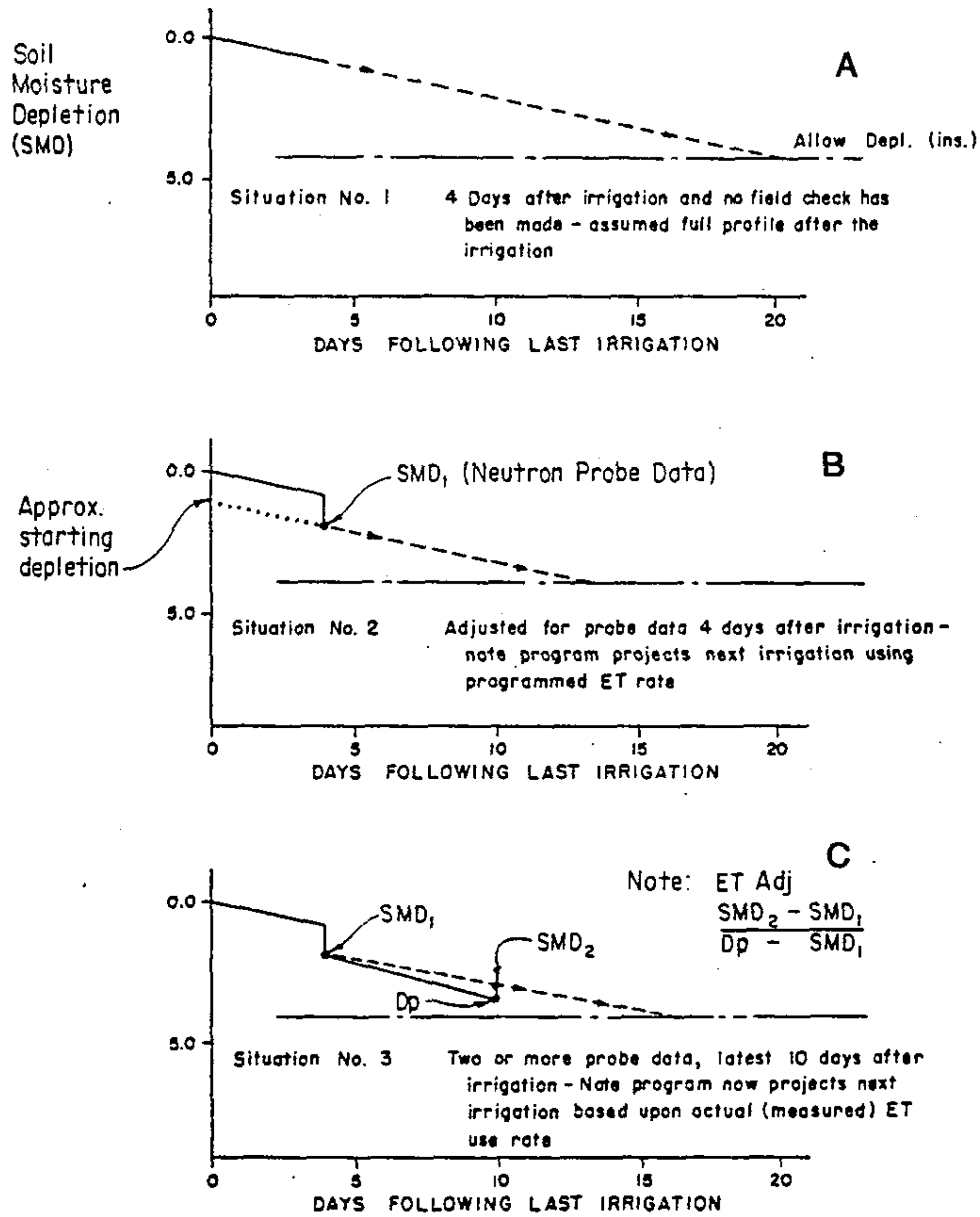


FIG.5.1 Example of the prediction of the day of the following irrigation. The calculation is based on neutron hydroprobe data. Adjustments to the prediction are made during the irrigation interval (from Buchheim & Ploss, 1977).

This method developed by Buchheim & Ploss (1977) and Carter & Conway (undated) is used extensively in most areas the American Bureau of Reclamation is serving. The neutron hydroprobe data, collected on individual farms, are used by irrigation districts to schedule water deliveries throughout the district. This resulted in higher water use efficiencies in the districts and some remarkable successes were obtained (Carter & Conway, undated).

Green (1982) found that 70 to 75% of "plant available water" (PAW) could be depleted without discernably affecting crop yield. PAW was defined as "the difference in profile water content at field capacity and at maximum depletion i.e. when well-established crops have been allowed to deplete soil water to the point of severe, irreversible wilting and death" (Green, 1982). In this context PAW is quite similar to the PLEXW - concept of Ratliff et al (1983).

Hensley (1984) used the observations of Green (1982) as a guideline to develop the PAWC - concept. He recommends that irrigation scheduling should be based on the amount of water that has been consumed when the crops have reached "well defined stress". PAWC is intended to serve as a definite measurement of "allowable depletion", instead of using an arbitrary fraction of "available water" or "PLEXW" as is done in other irrigation scheduling models.

Hensley (1984) tested the PAWC - principle for wheat and maize at maturity in sealed plots (to avoid lateral water movement) on a Jozini soil at Fort Hare Farm. Yields on plots which were irrigated when the crops had extracted an amount of water equal to PAWC for the site, were compared with yields obtained on control plots that were irrigated at frequent intervals. Maize yields for both treatments were almost identical (around 10500kg/ha). Statistical proof of the significance of this finding was lacking, however. For wheat similar observations were made. Hensley (1984) concluded from these experiments that: "PAWC is a valid parameter for irrigation scheduling".

An additional aspect of the question of "when" to irrigate is the sensitivity of crops to water stress at certain growth stages. Salter & Goode (1967) give an extensive review of the different studies concerning this aspect. Doorenbos & Kassam (1979) found that yield response to water deficit varied greatly depending on the growth stage at which the water stress occurred. In a more recent approach Hsiao (1982) concentrated on the effect of water stress on source size. This is illustrated in Figure 5.2. With regard to Figure 5.2 he states (according to Laker, 1983):

> "In the past attention has often been directed at effects of stress on source intensity. However, as Figure 5.2 makes clear, the effects on source size are equally or even more critical. Source size is considerably more sensitive to water stress during the canopy development phase than is source intensity. Also, reductions in source size can be reversed only slowly, if at all, whereas source intensity usually recovers fully in a matter of one to a few days after water becomes available."

Special attention should be given to water deficits during the initial growth stages of the crops. Although there is sometimes still abundant water in the soil profile, it is possible that soil water in the top layer, where the crop must develop its first roots, is completely depleted because of evaporation. This was clearly illustrated for wheat at crown root initiation (see Chapter 2).

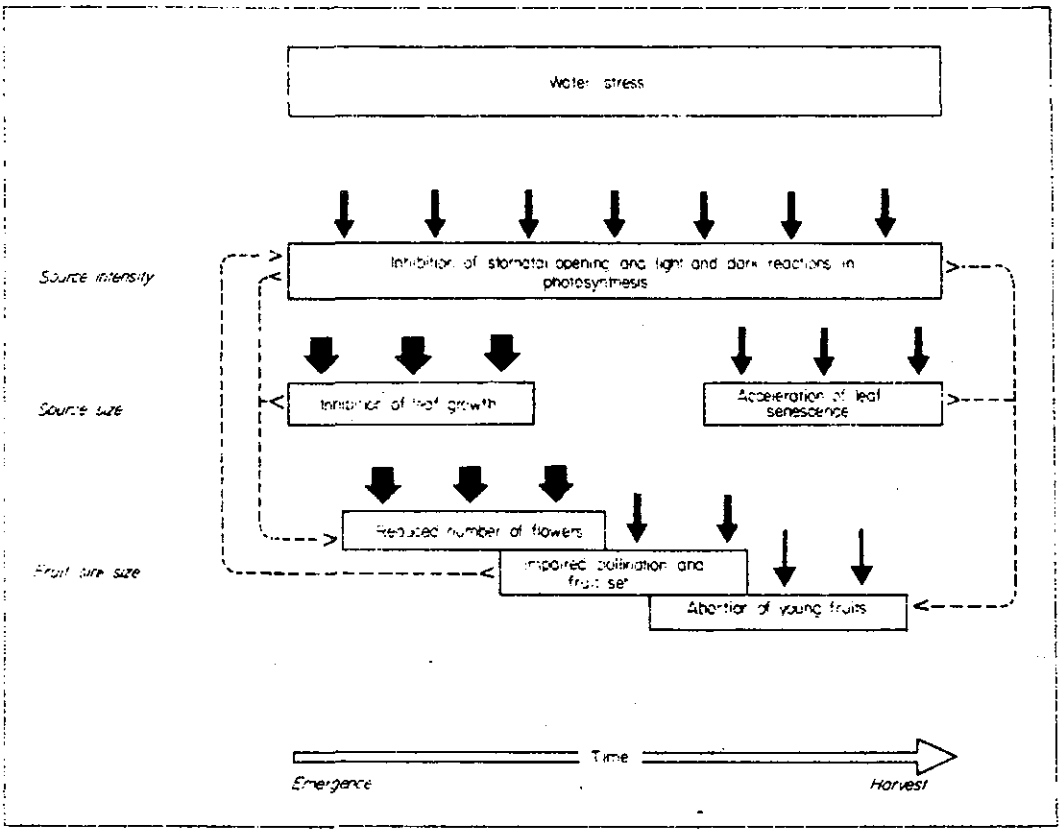


FIG.5.2 Effects of water stress on the physiological and morphological parameters underlying source intensity, source size and sink for assimilation at various times of ontogeny, generalized for annual crops grown for grain or fruit. The time intervals within the crop ontogeny when water stress can cause physiological and morphological changes are indicated by the locations of the rectangles outlining the changes. Arrow shafts widths indicate the sensitivity of the parameters to water stress. For example, leaf growth is the most sensitive to stress and flower number is the next most sensitive. Dashed arrows and lines indicate casual relations among the parameters. For example, inhibition of leaf growth, of stomatal opening, and of photosynthesis results in fewer flowers being differentiated, probably because the number of reproductive axes is determined by plant size and the amount of assimilates available. Another example of casual relations is that impaired fruit setting reduces the number of sinks for assimilates and usually leads to a reduction in stomatal opening and photosynthesis via feedback inhibition. (Adapted from Hsiao, 1982).

A contrary view is offered by Stewart et al (1977). They stated that the effects of irrigation at a particular growth stage could be explained largely by changes in evapotranspiration. Although Stewart et al . (1977) recognize that the sensitivity to water stress in the pollination period of growth is critical, they found that the sensitivity of this period was easily reduced by management, which causes an earlier water deficit during the vegetative growth period, thereby conditioning or hardening the crops.

Two approaches have been followed to determine how much water should be given at each irrigation. In a first approach climatic data are used to calculate at what rate soil water is extracted by the crops. Potential evapotranspiration (estimated from class A pan readings, or calculated from climate parameters) is multiplied by a crop factor to obtain daily water extraction. The length of the extraction interval then determines the amount of water to be applied. The use of this method can easily lead to under or over irrigation (see Chapter 4).

An alternative way to determine the amount to be given, is by assessing the soil water content just before the irrigation is applied. Three techniques are mainly used: (a) gravimetric sampling, (b) tensiometer, (c) neutron hydroprobe. Gravimetric determination of soil water content is too laborious to be successfully applied in irrigation scheduling. Tensiometers combined with matric suction curves give an indication of soil water content. This technique is widely used, although the calibration of the device is very cumbersome and the accuracy of the technique is doubtful (Marais, 1984, personal communication). Additionally the moisture range in which tensiometers can measure is limited. Soil water determinations with neutron hydroprobes is increasingly applied and gives accurate results for practical irrigation scheduling.

5.2 IRRIGATION SCHEDULING EXPERIMENTS AT VAALHARTS AND LOSKOP IRRIGATION SCHEMES

5.2.1 General

Numerous studies, with the main objective of optimizing irrigation scheduling, have been conducted in different parts of the world. Three main types can be distinguished (Laker, Boedt, Van Assche & Le Maire, 1984): (a) those in which various fractions of the estimated crop water requirements are applied at constant intervals, (b) those in which the estimated crop water requirement is replenished at different intervals and (c) those which consist of combinations of these two.

The disadvantage of most studies is that the variable time intervals were usually chosen on a purely arbitrary basis. This severely limits the possibility to transfer the models obtained from such data to other sites (Laker et al , 1984).

The PAWC concept of Hensley & De Jager (1982), although it is still in an initial stage of development, offers a sound basis for irrigation scheduling studies.

During the 1983 winter and 1983/84 summer seasons irrigation scheduling experiments, based on the PAWC - concept, were conducted at the Vaalharts and Loskop irrigation schemes. The main objective of this research was to determine the effect of irrigation, at extraction of different, arbitrarily chosen, fractions of PAWC, on seasonal water use, yield and water use efficiency.

5.2.2 Wheat experiments

5.2.2.1 Research procedures

During the 1983 winter season five experiments with wheat (cultivar SST44) were conducted at the Vaalharts irrigation scheme, at sites previously used for PAWC-determinations (Kamp I, II, III, Van der Linde I and II). The experiment at Kamp III had to be abandoned because of the occurrence of toxic substances in the soil. Soil profile descriptions for the different sites can be found in Appendices 2.6 to 2.12. The profile available water capacities for the soils are given in Chapter 2. Agronomic practices used were those recommended by the local researchers and extension officers as optimal for the Vaalharts area. The wheat was planted between 13 and 17 July in blocks arranged in a "latin square" design. This was to avoid possible influences of soil variability. The layout and the experimental design of the experiments are explained in detail in Appendix 5.1.

Until the wheat reached full canopy development all plots received similar irrigation treatments: the plots were filled to field capacity before planting, at the crown root stage 50mm was given, then water was supplied at regular intervals until full canopy development was reached. It was ensured that ample water was available at the drought sensitive stages of crop development so that possible yield variations could not be attributed to a limited water supply at these important stages of crop development.

When full canopy development was reached all plots were filled to field capacity and the different treatments were applied until maturity was reached. The treatments started only at this late stage in the development of the crop because for the present the PAWC concept of Hensley & De Jager (1982) is only applicable to crops with a fully developed root system.

The treatments consisted of refilling the soil to field capacity upon extraction of the following fractions of PAWC from different plots: 50%, 75%, 100% or 125%. Four replicates were used.

Soil water content was determined by means of neutron hydroprobes. Daily water content monitoring during PAWC-determinations for wheat showed that little or no drainage occurred when the soil profile was not refilled above field capacity. At harvesting the residual water in the soil was determined. Consumptive use (ET) was calculated by means of the following equation:

$$ET = FC + IR + RN - RW \qquad (5.1)$$

where: FC = field capacity. (The experiment started on full profiles).

IR = irrigation applied during the season. (Excluding pre-plant irrigation to fill the soil profile to field capacity).

RN = rain during the growing season.

RW = residual water in profile at harvesting.

The sites were isolated areas, which could have led to large oasis effects.

5.2.2.2 Results

Seasonal water use, grain yields, water use efficiencies and applied water use efficiencies for the different treatments are listed in Table 5.1.

From Figures 5.3 to 5.6 it is clear that there is a strong relationship between seasonal water use (ET) and yield. At Kamp I, Van der Linde I and Van der Linde II

TABLE 5.1 - Seasonal water use, grain yields, water use efficiencies and number of irrigations applied for wheat at four sites at Vaalharts.

SITE	TREATMENT (% OF PAWC) 50	75	100	125	L.S.D.
	Seasonal water use (mm)				
Kamp I	448 (1,00)*	440 (0,98)	353 (0,79)	185 (0,41)	
Kamp II	524 (0,97)	539 (1,00)	421 (0,78)	375 (0,70)	
V.d.Linde I	585 (1,00)	576 (0,98)	439 (0,75)	359 (0,61)	
V.d.Linde II	567 (0,92)	614 (1,00)	490 (0,80)	372 (0,61)	
	Grain yield (kg/ha)				L.S.D.
Kamp I	5728 (1,00)	5123 (0,89)	4335 (0,76)	2938 (0,51)	1100
Kamp II	4478 (1,00)	3755 (0,91)	3908 (0,82)	2330 (0,52)	1825
V.d.Linde I	3020 (1,00)	2998 (0,99)	2790 (0,92)	1428 (0,47)	624
V.d.Linde II	4118 (0,91)	4540 (1,00)	3670 (0,81)	2993 (0,66)	1259
	Water use efficiency (kg/ha/mm)				
Kamp I	12,8 (15,6)**	11,6 (15,1)	12,3 (16,9)	15,9 (31,9)	
Kamp II	8,5 (11,8)	7,0 (9,4)	9,2 (14,2)	6,2 (10,9)	
V.d.Linde I	5,2 (6,0)	5,2 (5,9)	6,4 (7,6)	4,0 (5,6)	
V.d.Linde II	7,3 (7,6)	7,4 (8,8)	7,4 (9,7)	8,0 (11,9)	
Average	8,5 (10,7)	8,0 (10,6)	8,7 (12,9)	8,5 (15,9)	
	Number of irrigations applied				
Kamp I	7	5	3	1	
Kamp II	6	5	3	2	
V.d.Linde I	7	5	3	2	
V.d.Linde II	7	5	3	2	

* Figures in brackets give the relative value for that site.
** Figures in bracket give applied water use efficiency.
L.S.D. = Least significant difference

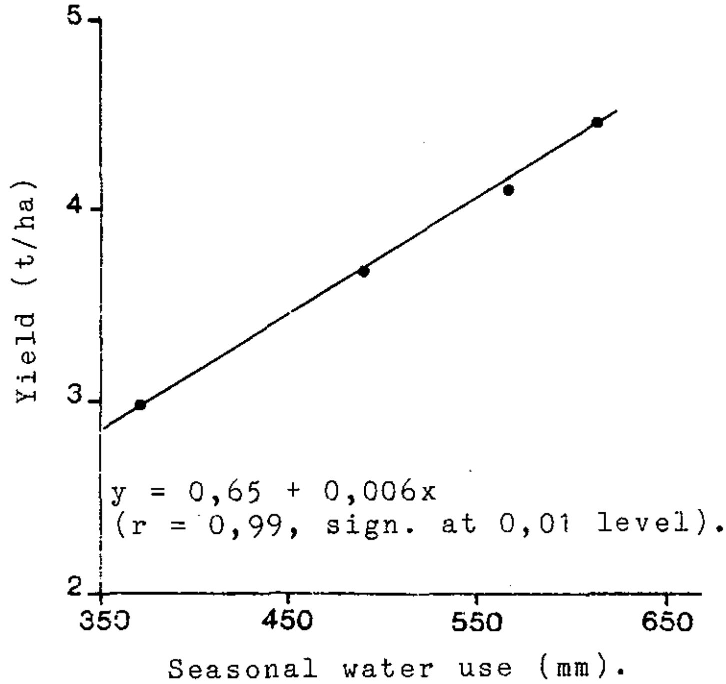


FIG.5.3 Relationship between total water use and wheat grain yield at Van der Linde II.

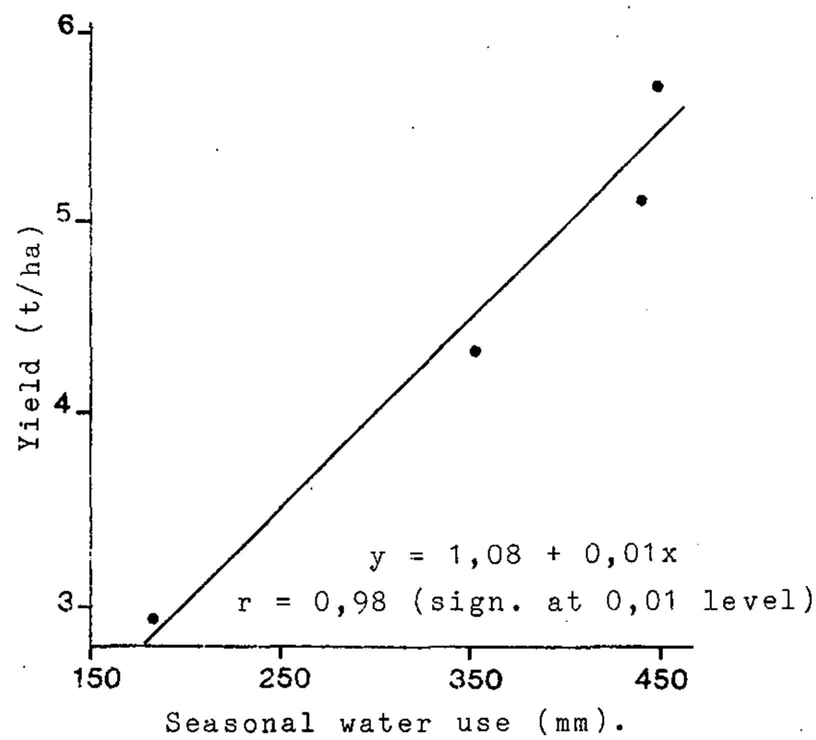


FIG.5.4 Relationship between total water use and wheat grain yield at Kamp I.

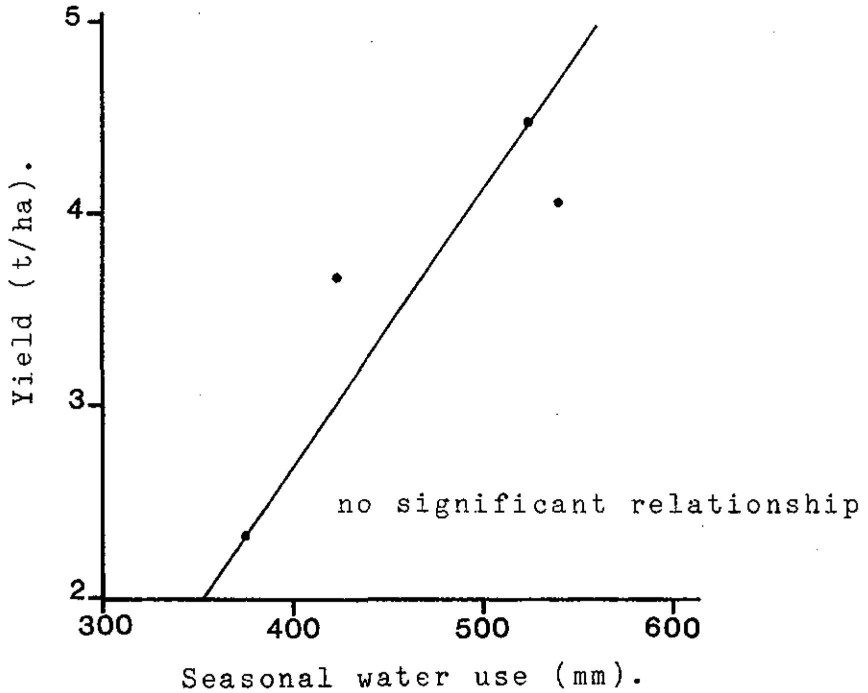


FIG.5.5 Relationship between total water use and wheat grain yield at Kamp II.

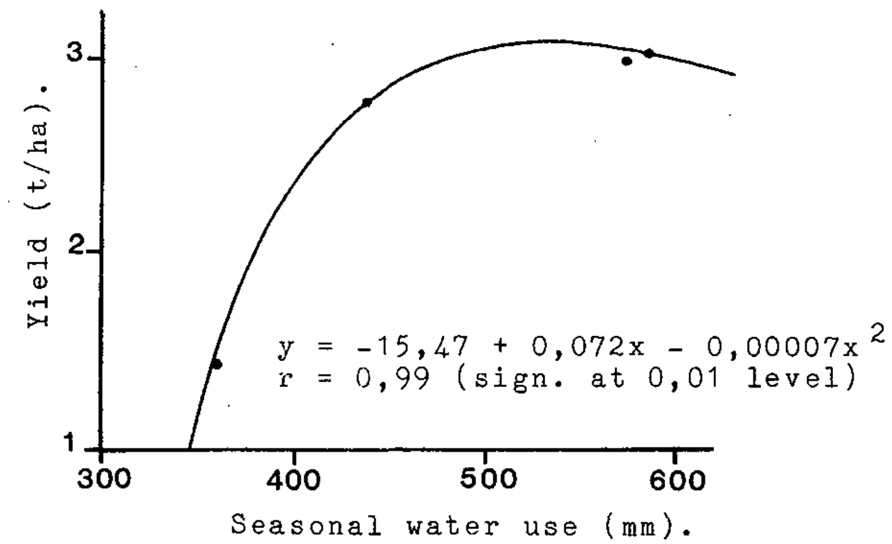


FIG.5.6 Relationship between total water use and wheat grain yield at Van der Linde I.

significant linear or curvilinear relationships were found. At Kamp II the points were too scattered to give statistical significance but a linear trend is observable. At Van der Linde I some unknown factor severely restricted yield. This did not affect consumptive use of water, however, leading to a strong convex relationship between yield and consumptive use and very low water use efficiencies.

A significant linear relationship was found between relative yields and relative water consumption of the different sites (even with the strongly deviating Van der Linde I site included) (see Figure 5.7). The slope of the regression line is identical to the slope of the regression line found for irrigated winter wheat during experiments conducted by Hanks (1982).

The 50% and 75% PAWC treatments gave almost identical seasonal water use figures at Kamp I, II and Van der Linde I. Also at Van der Linde II the difference between the two treatments is small. At all sites consumptive use for the 100% PAWC treatment was reduced by a relatively constant margin, ranging from 20% to 25% below the maximum (see Figure 5.8). At Kamp I, II and Van der Linde II this was accompanied by a relative constant

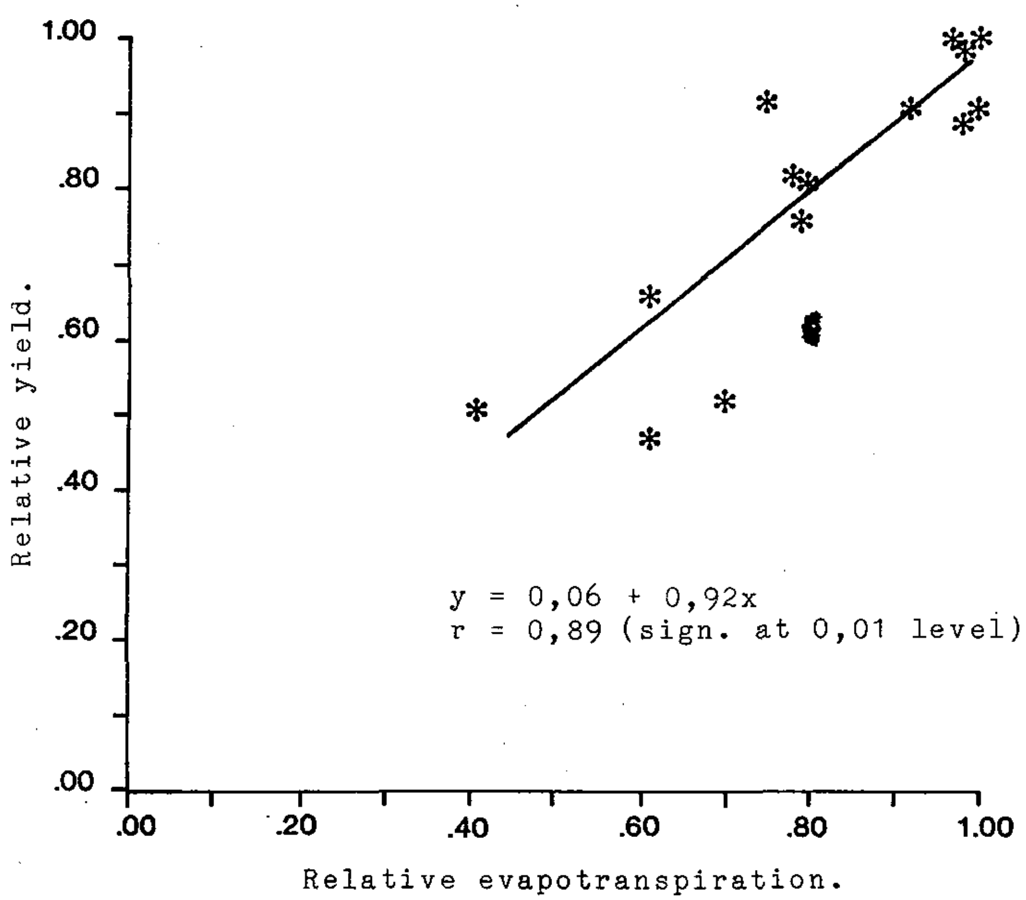


FIG.5.7 Relative yield / relative evapotranspiration relationship for wheat experiments.

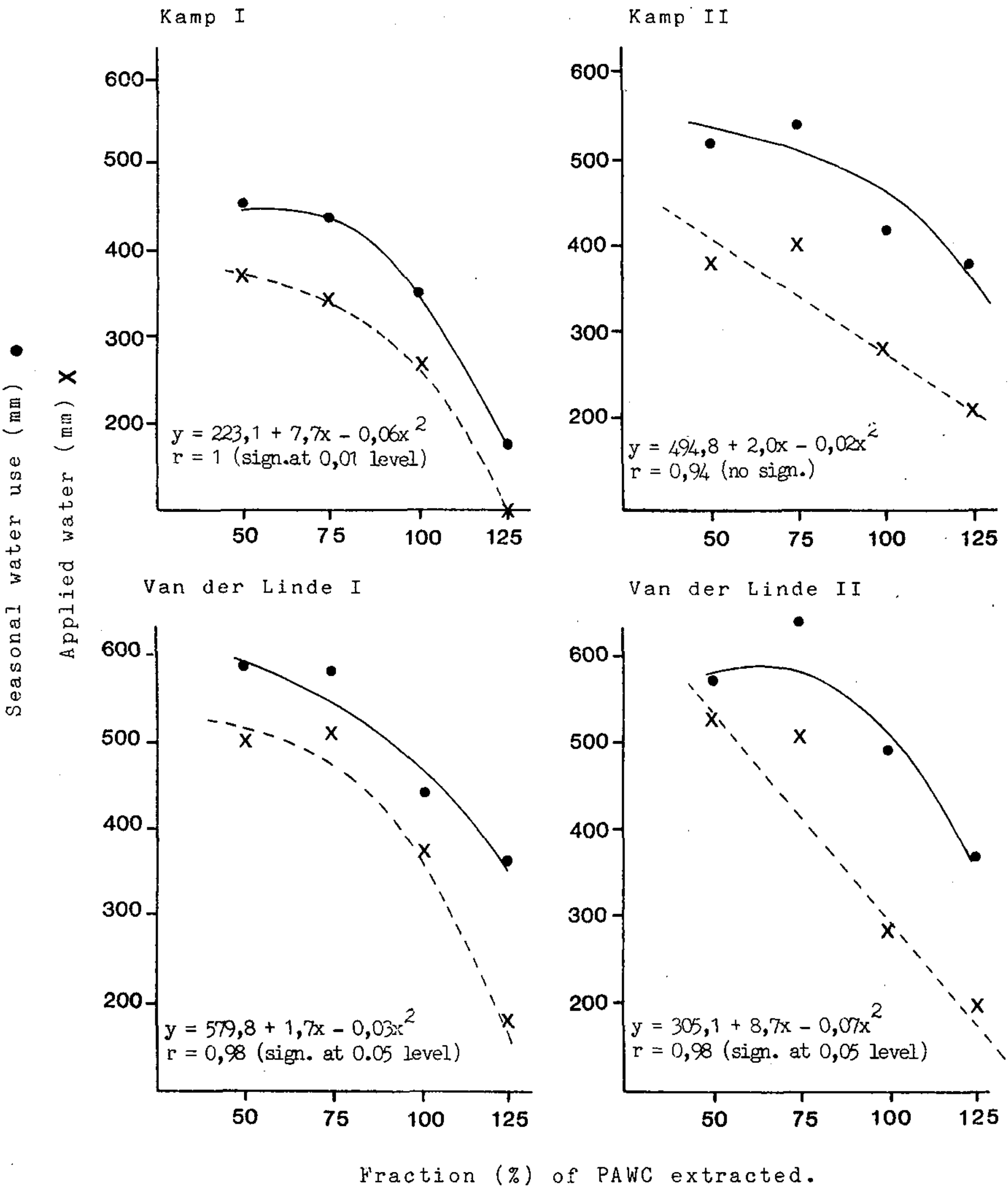


FIG.5.8 Seasonal water use and amount of applied water per percentage of PAWC extracted for wheat. The equations are only valid for the seasonal water use relationships.

yield reduction of more-or-less the same order. It is therefore evident that water use efficiencies were not affected.

The reduced consumptive use (ET) in the 125% PAWC treatments had dramatic influences on yield. Statistically significant differences with the other treatments were found at Kamp I and the Van der Linde I and II sites. This is reflected in Figure 5.9 in which the relationship between yield and percentage of PAWC extracted, are illustrated. Yields and water consumption in general stayed fairly constant for the 50, 75 and (in a less degree) 100% PAWC treatments, but it dropped to significantly lower levels for the 125% treatment. At Kamp I the decrease is not so clear but is significantly different from the 50 and 75% treatments.

5.2.3 Maize experiments

5.2.3.1 Research procedures

At Vaalharts the same four sites (Kamp I, II, Van der Linde I and II) as for wheat were used to conduct the experiments for maize. At Loskop a moderately deep, medium textured soil from the Kinross series (Shortlands

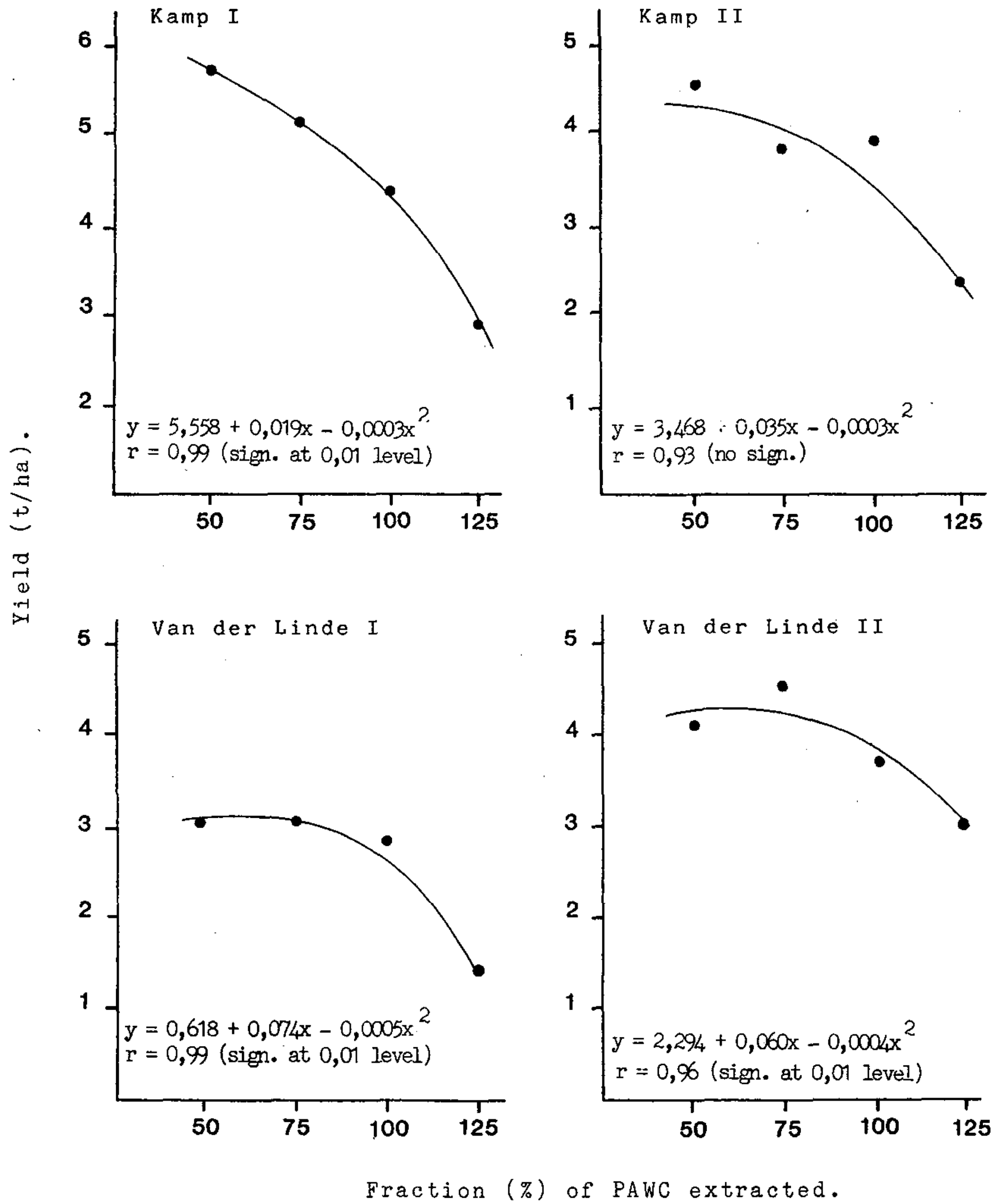


FIG.5.9 Wheat grain yield per percentage of PAWC extracted.

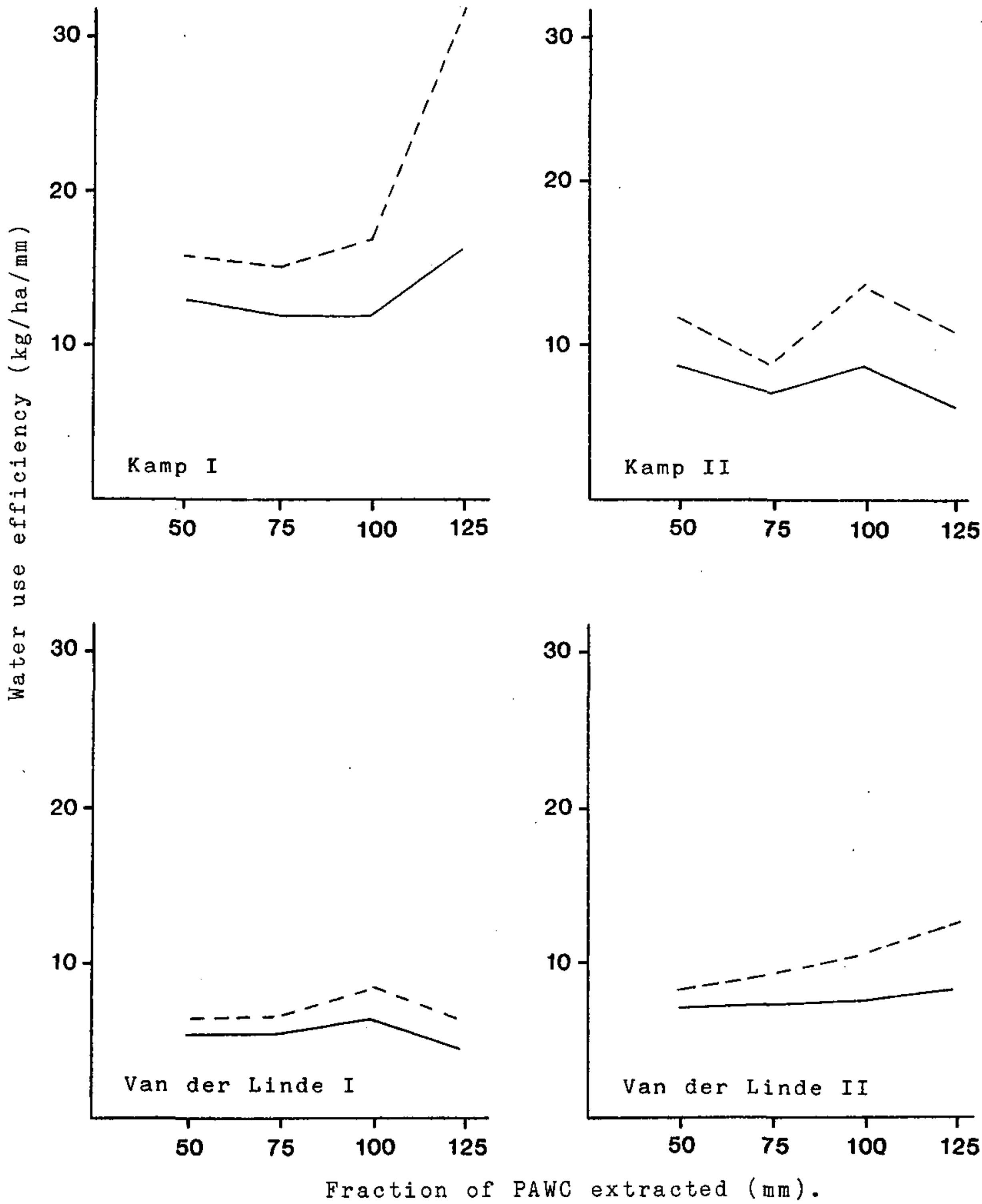


FIG.5.10 Water use efficiency (——) and applied water use efficiency (-----) per percentage of PAWC extracted (wheat).

form) was selected. The site (Contour 10, for soil description see Appendix 2.19, for PAWC value see Chapter 2) was situated on the research farm of the Department of Agriculture at Groblersdal. This site formed part of a relatively large maize field so that oasis effects were avoided.

At Van der Linde I, II and Kamp I maize (cv. PNR 542) was planted between 18 and 21 November 1983. At Kamp II maize was planted much later, on 6 December 1983. This was due to late ripening of wheat at this site. At Contour 10, in Groblersdal, the maize (cv. SSM 2039) was planted only on 28 December 1983. This was due, on the one hand, because of late realization that information was required for a moderately deep, medium textured , strongly structured soil and on the other hand because only at this late stage an additional researcher became available.

The experiments were arranged in a latin square design at Vaalharts using plot sizes of 3 x 3 m of which the central 2 x 2 m sections were harvested. A randomized block design was used at Loskop. The experimental procedures for Loskop are detailed in Appendix 5.2.

Quantities of water required to refill the soil to field capacity were determined with neutron hydroprobes. The same equation as for wheat (Equation 5.1) was used to calculate consumptive use (ET).

All the plots were filled to field capacity before planting. At each site the crops received a number of identical irrigations until the flowering stage when all plots were filled again to field capacity. From then until harvesting the different irrigation treatments were given. (The reasons for the late start in the growing season of the different treatments being the same as for wheat). In the different treatments the soil profile was refilled to field capacity when 25%, 50%, 75% or 100% of the PAWC-value was extracted by the maize. During the wheat experiments during the previous growing season it was found that the 125% treatment resulted in unacceptably low yields. Therefore this treatment was excluded and to gain more information on high frequency irrigation the 25% PAWC-treatment was included.

5.2.3.2 Results

Seasonal water use, grain yields, water use efficiencies and applied water use efficiencies for each treatment are presented in Table 5.2.

TABLE 5.2 - Seasonal water use, grain yields, water use efficiencies and number of irrigation applications given for maize at four sites at Vaalharts and Contour 10 (Groblersdal).

SITE	TREATMENT (% OF PAWC)				
	25	50	75	100	
	Seasonal water use (mm)				
Kamp I	1215 (1,00)*	1112 (0,92)	968 (0,80)	747 (0,61)	
Kamp II	892 (1,00)	856 (0,96)	895 (1,00)	843 (0,94)	
V.d.Linde I	1155 (1,00)	1057 (0,92)	972 (0,84)	824 (0,71)	
V.d.Linde II	1074 (1,00)	1035 (0,96)	850 (0,79)	741 (0,69)	
Contour 10	572 (1,00)	531 (0,93)	501 (0,88)	418 (0,73)	
	Grain yield (kg/ha)				L.S.D.
Kamp I	7751 (1,00)	6880 (0,89)	7146 (0,92)	5970 (0,77)	2326
Kamp II	10349 (0,99)	10433 (1,00)	9566 (0,92)	8347 (0,80)	1973
V.d.Linde I	4940 (0,98)	5035 (1,00)	4649 (0,92)	2984 (0,59)	1442
V.d.Linde II	7044 (1,00)	5740 (0,81)	6115 (0,87)	4955 (0,70)	1352
Contour 10	8022 (1,00)	7440 (0,93)	7201 (0,90)	4685 (0,58)	1247
	Water use efficiency (kg/ha/mm)				
Kamp I	6,4 (8,5)**	6,2 (8,5)	7,4 (10,8)	8,0 (11,5)	
Kamp II	11,6 (15,9)	12,2 (16,1)	10,7 (14,3)	9,9 (13,6)	
V.d.Linde I	4,3 (6,4)	4,8 (7,4)	4,8 (7,2)	3,6 (6,1)	
V.d.Linde II	6,6 (9,9)	5,5 (10,2)	7,2 (13,8)	6,7 (14,0)	
Contour 10	14,0 (21,4)	14,0 (22,3)	14,4 (23,7)	11,2 (21,2)	
Average	8,8 (12,4)	8,5 (12,9)	8,8 (13,8)	7,9 (13,3)	
	Number of applied irrigations				
Kamp I	21	13	7	3	
Kamp II	16	9	7	5	
V.d.Linde I	15	8	5	3	
V.d.Linde II	16	9	5	3	
Contour 10	8	4	2	0	

* Figures in brackets give the relative use for that site.
** Figures in brackets give the applied water use efficiency for that site.
L.S.D. = Least signifant difference.

Yield/ET relationships are illustrated in Figures 5.11 to 5.15. The relationships between yield and seasonal water use were not so clear as for wheat. Only at Van der Linde I, Kamp I and Contour 10 statistically significant relationships were found (see Figures 5.11 to 5.15). At Kamp II the seasonal water consumption was so similar for all treatments that no relationship with yield could be derived (see Figure 5.11). Van der Linde I again gave, as with wheat, poor yields. The yields levelled off at high consumptive use, illustrating that whatever the factor was that limited yield, it did not limit water uptake. No statistically significant relationship, as was found for wheat, was observed between relative yield and relative water use. This may be partly due to the effect of the extreme summer conditions and partly due to the replacement of the 125% PAWC treatment with the 25% treatment.

The 25% PAWC treatments gave the highest (or practically) the highest consumptive use values in all five experiments and this was accompanied with the highest, or extremely close to the highest yields in all cases (see Table 5.2 and Figures 5.16 to 5.19). It was expected that the high irrigation frequency (intervals of 1 to 3 days) in this treatment would result in a considerable

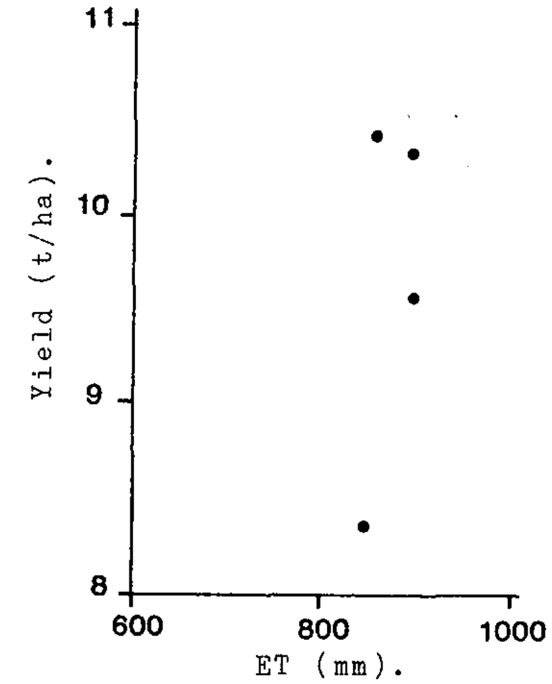


FIG.5.11 Yield/ evapotranspiration (ET) relationships for maize at Kamp II.

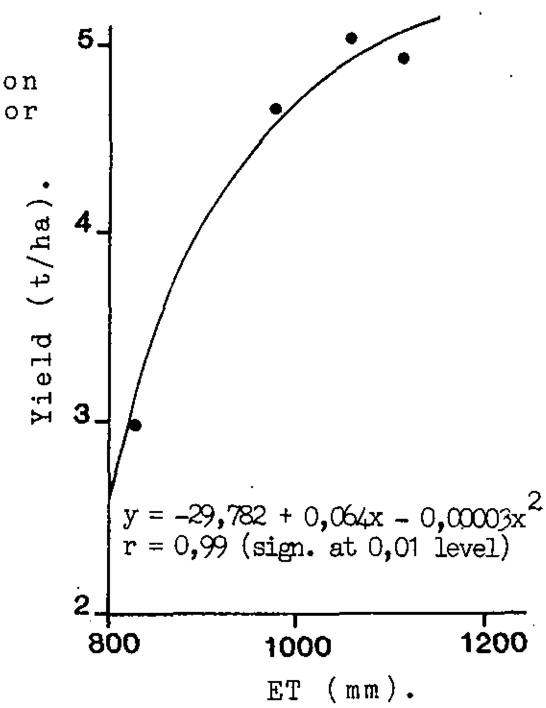


FIG.5.12 Yield/ evapotranspiration (ET) relationships for maize at Van der Linde I.

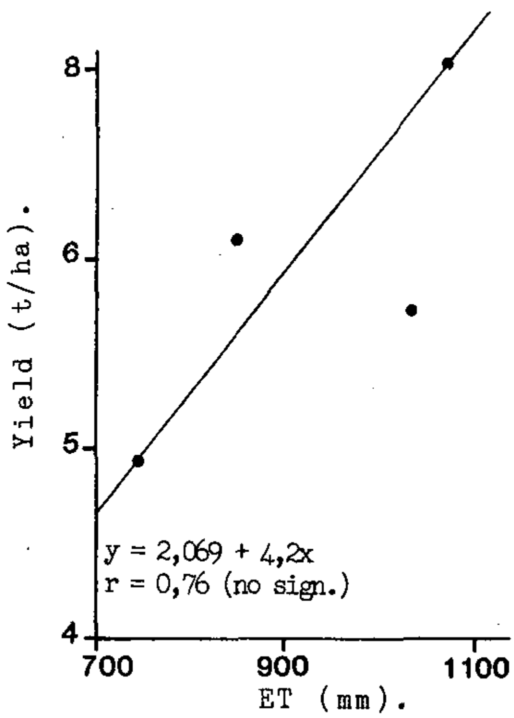


FIG.5.13 Yield/evapotranspiration (ET) relationships for maize at Van der Linde II.

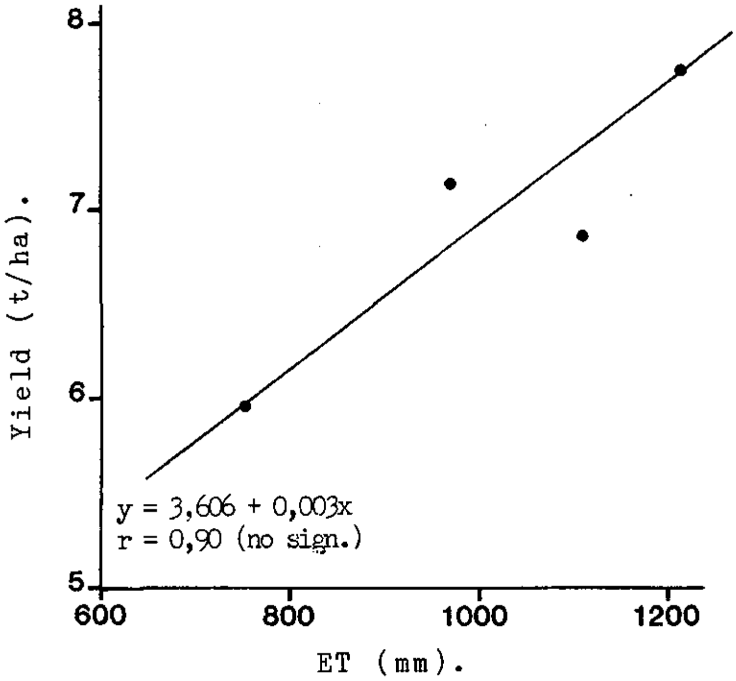


FIG.5.14 Yield/evapotranspiration (ET) relationships for maize at Kamp I.

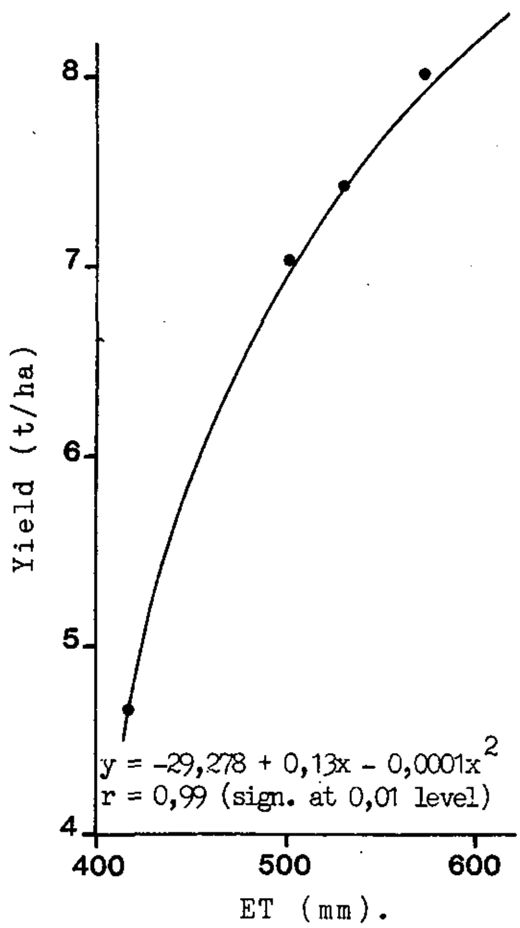


FIG.5.15 Yield/evapotranspiration (ET) relationships for maize at Contour 10 (Groblersdal).

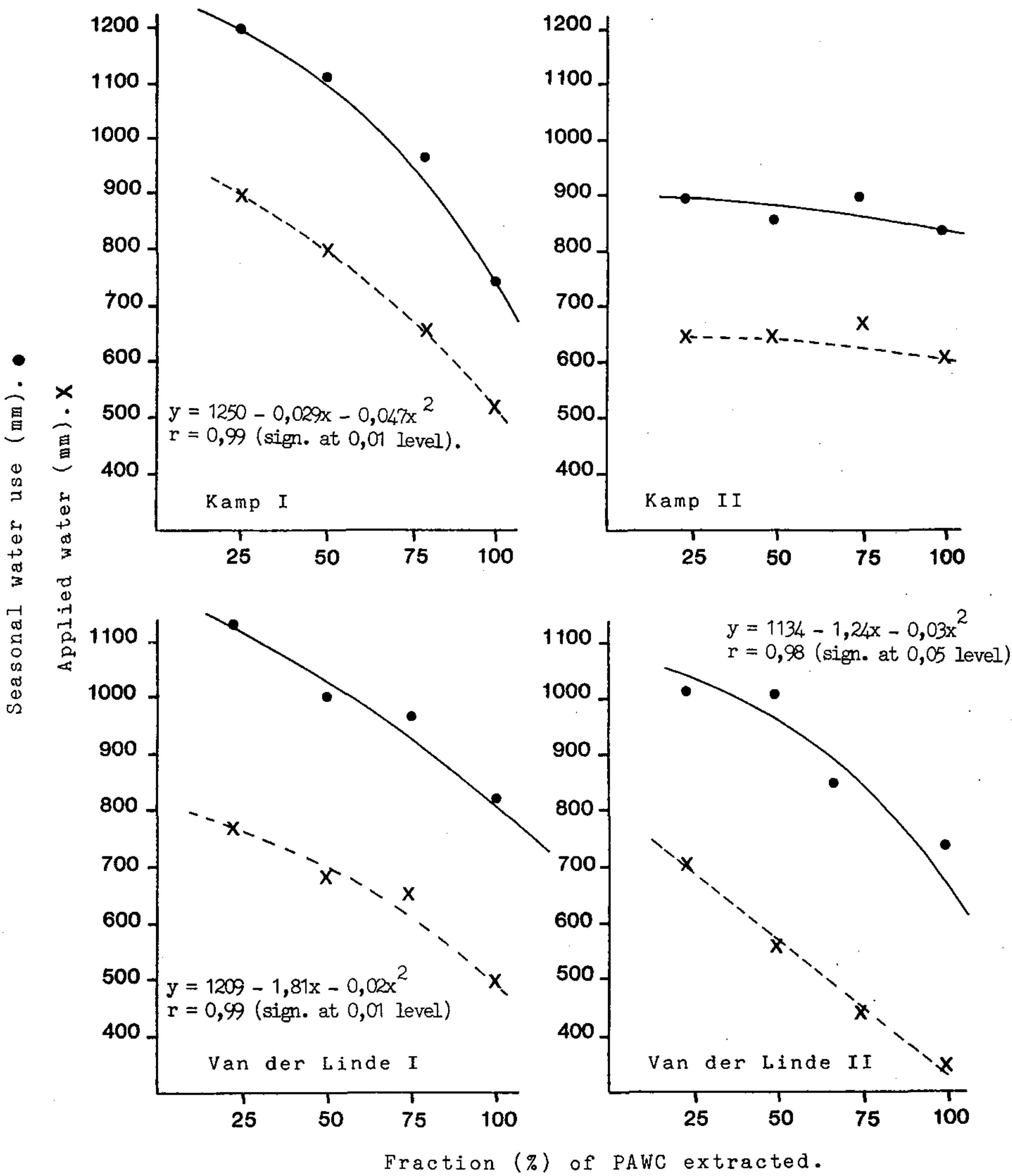


FIG.5.16 Seasonal water use and applied water use per percentage of PAWC extracted (maize). Equations applicable on seasonal water use relationship.

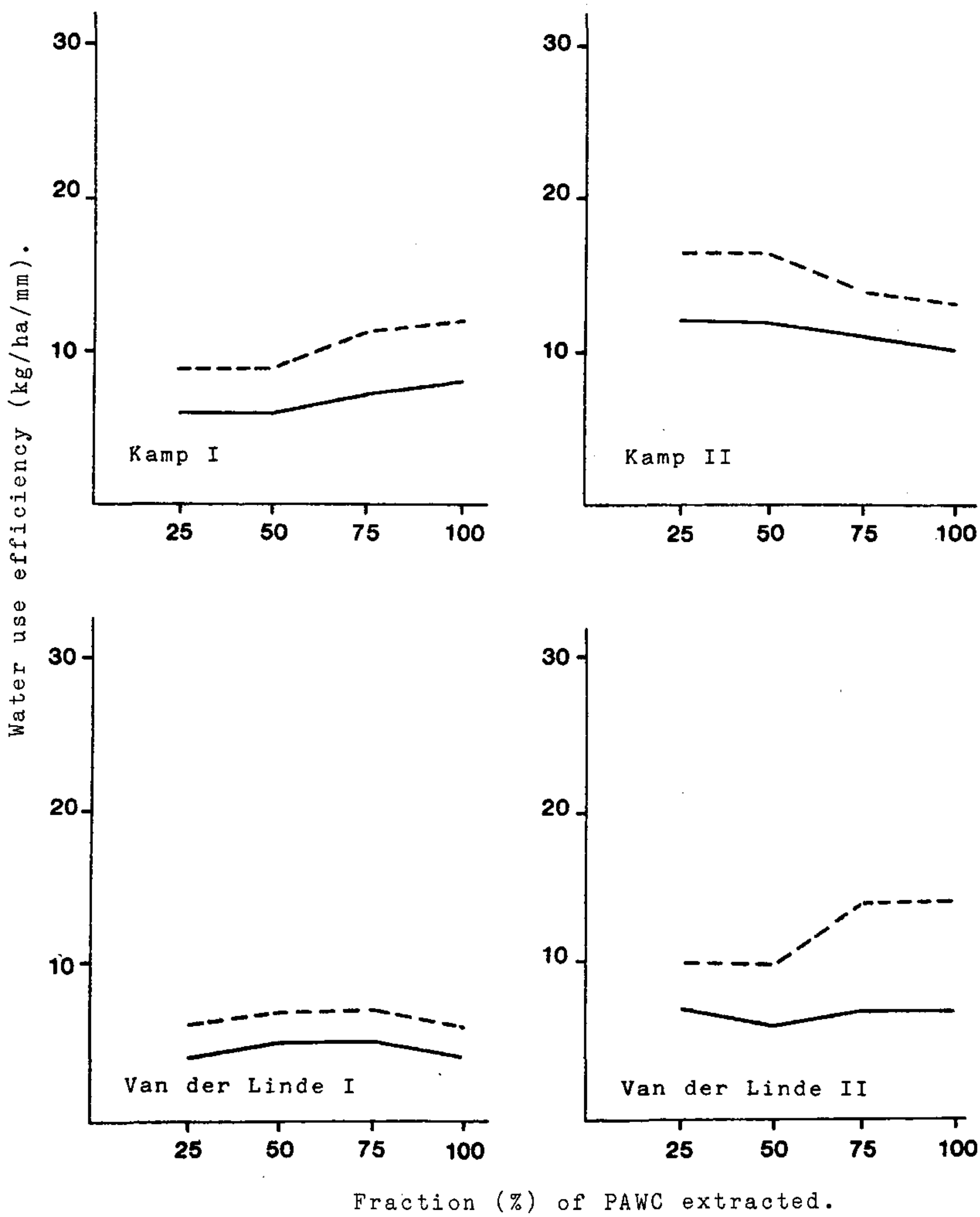


FIG.5.17 Water use efficiency (——) and applied water use efficiency (– – – –) per percentage of PAWC extracted (maize).

decrease in water use efficiency. Although the water use efficiency and especially the _applied_ water use efficiency is in general lower than for the other treatments (see Table 5.2) differences between the treatments were not statistically significant.

The relationship between yield and fraction of PAWC extracted is illustrated in Figures 5.18 and 5.19. At Kamp II, Van der Linde I and Contour 10 yields seem to stay more-or-less constant up to 75% extraction of the PAWC value. The same trend is to a lesser degree observable at Kamp I. Beyond 75% PAWC yields drop to lower values. The difference from the other treatments is, however, only statistically significant for the Contour 10 and Van der Linde I sites.

At Contour 10 and Kamp II much higher yields and water use efficiencies were obtained than on the other sites. No obvious reason could be found for this but the high yields were probably related with the fact that the maize was planted late in the season on these plots. The high yield late in the season at Kamp II was not an isolated case: apparently all late planted maize did very well in the Vaalharts region during this season. Originally it was thought that the better results were caused by a

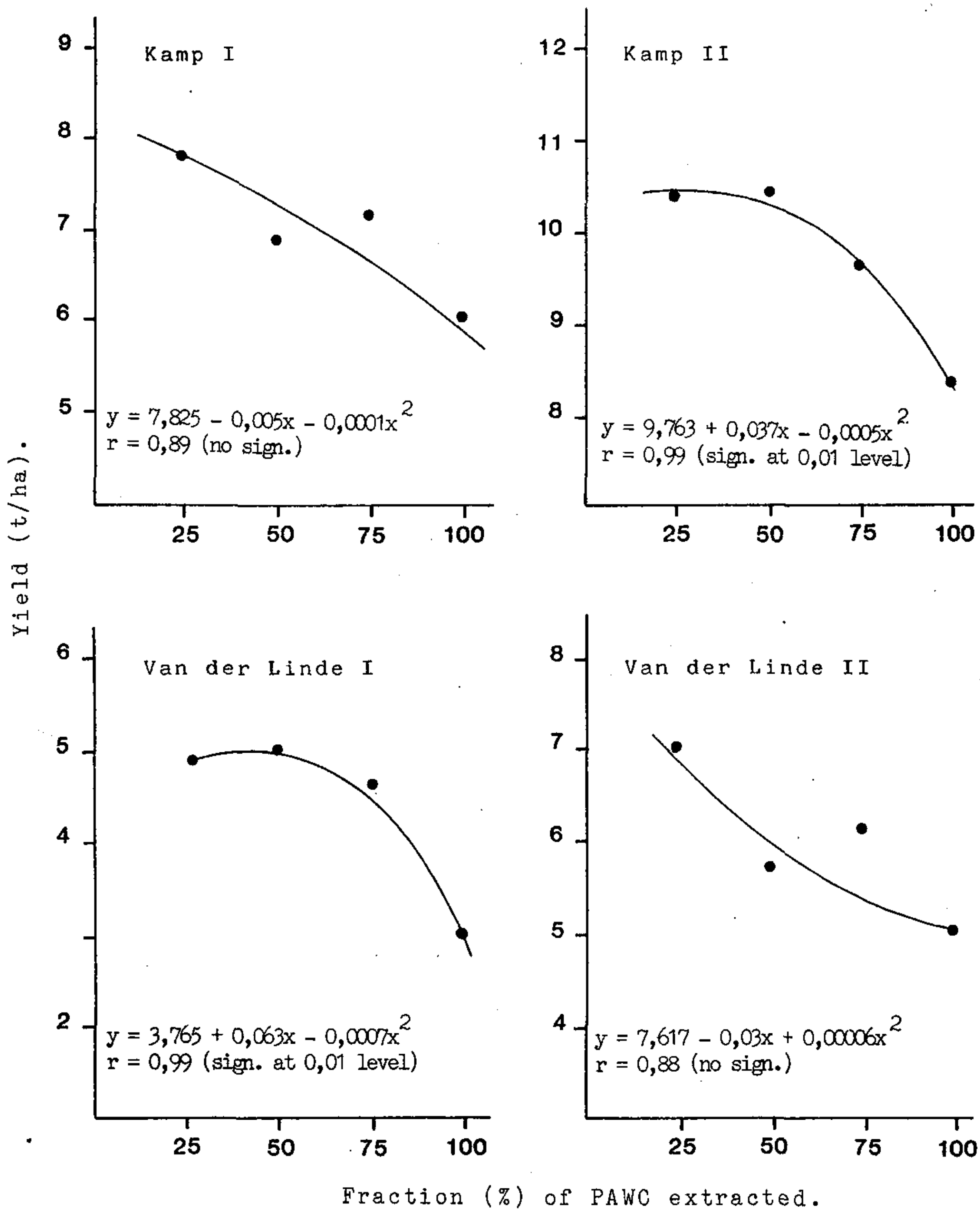


FIG.5.18 Maize grain yield per percentage of PAWC extracted.

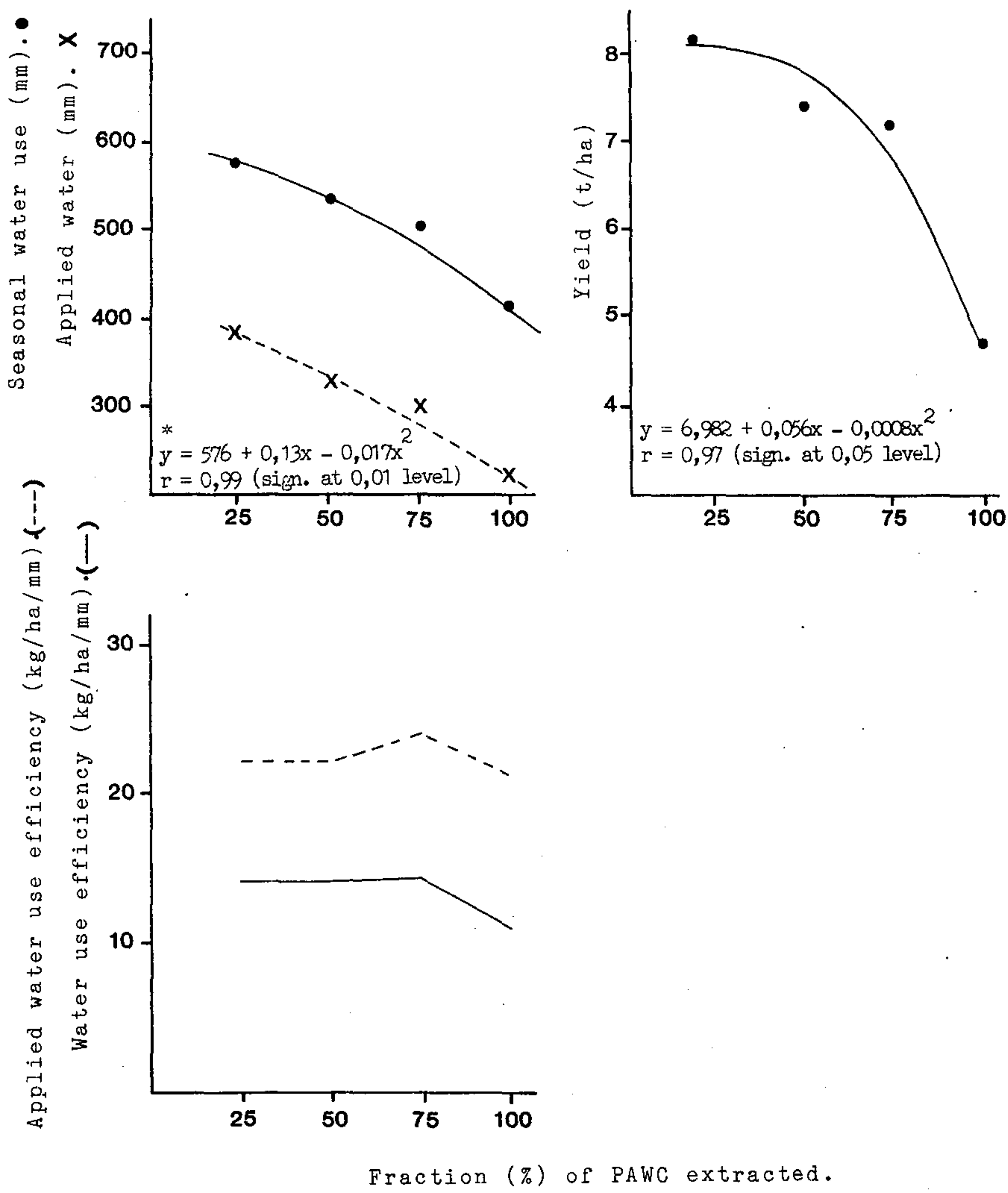


FIG.5.19 Seasonal water use, applied water use, yield, water use efficiency and applied water use efficiency per percentage of PAWC extracted (maize at Contour 10).

* Equation only valid for seasonal water use relationship.

lower evaporative demand later in the growing season. Observation of class A pan data revealed, however, that during the time the experiments were running an average daily evaporative demand of 8,2mm was found for the early planted and an average of 8,3mm was registered for the late planted crops. Contour 10 received about 140mm of rain during the latter part of the growing season. This might have caused favourable humidities which would enhance water use efficiency (Streutker, 1984).

5.3 IRRIGATION SCHEDULING EXPERIMENT WITH WHEAT ON FORT HARE LYSIMETER

Irrigation scheduling based on the PAWC concept was studied during a lysimeter experiment at Fort Hare. The main objectives of this experiment were: (a) To determine how irrigation scheduling based on the PAWC-concept affects wheat yields (expressed as kg/ha) relative to the yields obtained with other methods of irrigation scheduling; (b) To compare water use efficiency, by determining yield per unit water for different methods of irrigation scheduling.

The layout of the experiment, the agronomic practices and experimental methods used are extensively explained in Appendix 5.3.

The experiment was conducted in absence of the researcher and due to inexperience of the technicians involuntary changes were brought about in the experimental layout. The rainshed was built too low so that air movement under it was limited. Condensation occurred under it during the night, which caused a lot of water to drip back onto the plants. This led to totally abnormal pre-dawn leaf water potential readings. The irrigation treatments were changed and finally only three types of application were given:

(a) "Completely adequate moisture" treatment. During this treatment the crops were irrigated twice a week at three or four day intervals.

(b) "Field PAWC" treatment. The wheat extracted water from the soil profile up to about 140mm (PAWC value for wheat on a Jozini soil at Fort Hare; the lysimeter is filled with soil material from the Jozini site) before the next irrigation was applied. The actual PAWC value of the lysimeter could not be determined because of the occurrence of condensation water on the wheat leaves in the morning.

(c) "Very dry" treatment. The wheat extracted far beyond the field PAWC value before the profile was refilled to field capacity.

The treatments started when the wheat had reached the "first node" stage (around 6/9/1982). Before this date all plots received similar amounts of water at the same time.

Where the "adequate moisture" treatment was applied the soils stayed close to field capacity throughout the growing season. During the short intervals (3 to 4 days) between irrigations water was only extracted from the top 250mm of the soil profiles. The stored water below 250 mm in the profile was never used and this part of the soil profile stayed at about field capacity throughout the growing season. As expected this treatment resulted in the highest yield (Table 5.3).

By 6/9/1982 the wheat had already extracted 136,3mm water from the soil profile in treatment (b). Then the profiles were refilled to field capacity and allowed to dry out until 14/10/1982 by which time 137,6mm was consumed. From then onwards the profile was only partly refilled on 21/10, 2/11 and 16/11 respectively. The result was that after 14/10/82 the profile was never entirely replenished with water and the lower parts of the profile did not reach field capacity anymore. Involuntarily a sort of "deficit"-irrigation was, therefore, applied. Despite the lower moisture level in the layers below 700mm depth, wheat continued to extract water from these layers and this resulted in a dry soil profile at harvest (see Figures 5.20 to 5.23). In spite of the long irrigation intervals at the beginning of the growing season and the rather arbitrary water applications afterwards a good yield was obtained for this treatment (see Table 5.3).

More than 188mm water was consumed from the soil profiles in treatment (c) before the profile was brought to field capacity again. This treatment was obviously too drastic and resulted in extremely low yields (Table 5.3). This was unfortunately not reflected in the leaf water potentials: constantly high readings were found and only by 14/10/1982 pre-dawn leaf water potentials had dropped to about -900 kPa (the influence of the low cover was already mentioned). The same observation was made for

TABLE 5.3 Lysimeter results for wheat

	Yield (kg/ha)	Seasonal water use use (mm)	Water use efficiency (kg/ha/mm)
"Adequate moisture"	5718	655	8,7
"Field-PAWC"	5548	423	13,1
"Very dry"	2803	343	8,2

TABLE 5.4 Total water applied, depleted from soil, and total used by plants as affected by irrigation treatment, june 17 to sept. 1, 1976. Dry beans. Harvested sept. 7 (from Miller, 1976).

Irrigation Treatment	Total Applied[a/]	Depleted from Soil	Total Used	Yield per Unit of Water
	cm			kg/ha/cm
1. 100% Et daily	34.0	0.5	34.5	126
2. 75% Et daily	26.4**	3.8	30.2*	146
3. 50% Et daily	21.1**	8.1**	29.2**	146
4. 100% to Aug. 6, then 50%	28.7**	6.6**	35.3	123
5. 50% to Aug. 6, then 75%	23.1**	4.6	27.7**	180**
6. 50% to Aug. 6, then 100%	25.1**	6.4**	31.5	139

[a/] Includes rainfall of 2.9 cm.

*,**Significantly different from treatment 1 at 5% and 1% probability, respectively.

maize in a similar experiment on the same lysimeter (Marais & Hensley, 1982, unpublished data). Crops failed to show visual stress symptoms at "field PAWC" and extracted up to 200mm water before stress was observed, resulting in drastic yield reductions.

Nett quantities of water consumed were calculated (pre-plant water application + water application during the growing season - percolation water; see Table 5.3). This facilitated calculation of water use efficiencies for the different treatments (see Table 5.3). The "field-PAWC" treatment shows the best water use efficiency. During the incomplete refilling of the soil profile not even the top layers were brought back to field capacity (Figures 5.20 to 5.23). It appears as if the relatively low soil water potentials in the subsoils caused a tension gradient of such magnitude that during deficit irrigation the top part of the profile did not fully reach normal field capacity. "Luxury" water loss, such as could occur from a topsoil near field capacity, was apparently avoided. This is clearly illustrated by the average daily evapotranspiration rates for the "adequate moisture" treatment and the "field PAWC": the adequate moisture treatment, with soil moisture values around field capacity gave an average daily

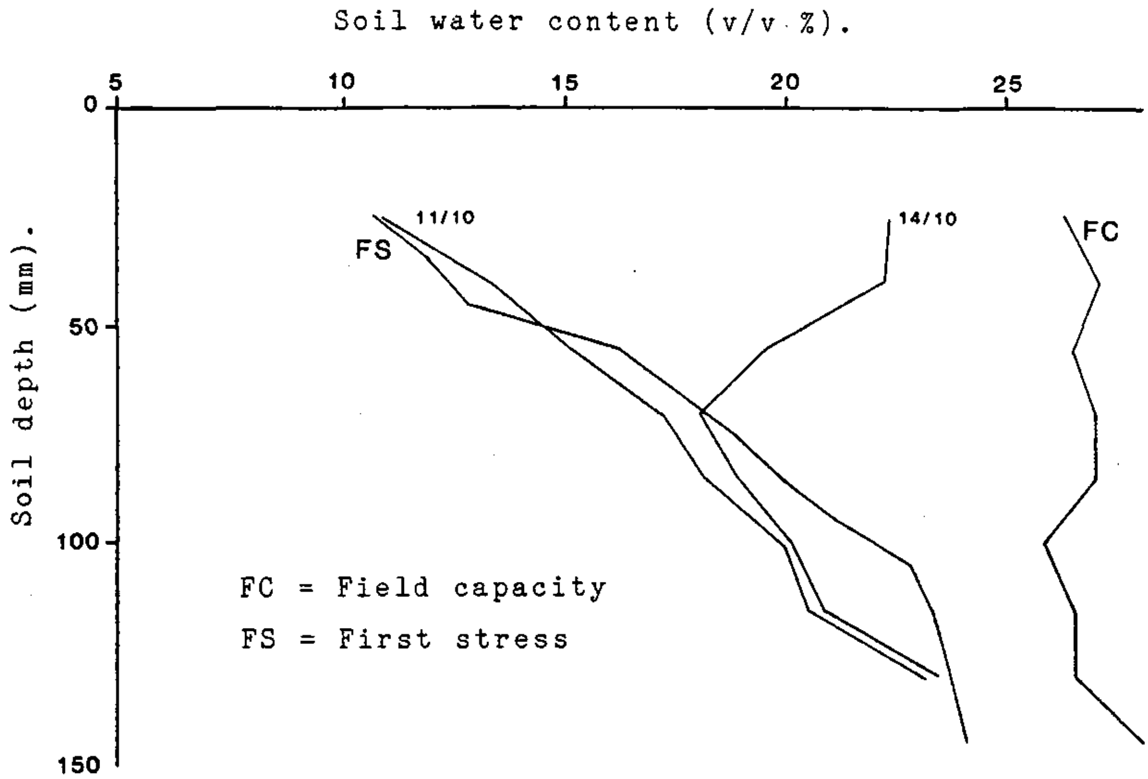


FIG.5.20 Soil water extraction patterns for the deficit irrigation applied in treatment (b) of the lysimeter experiment (before and after water was applied on 13/10).

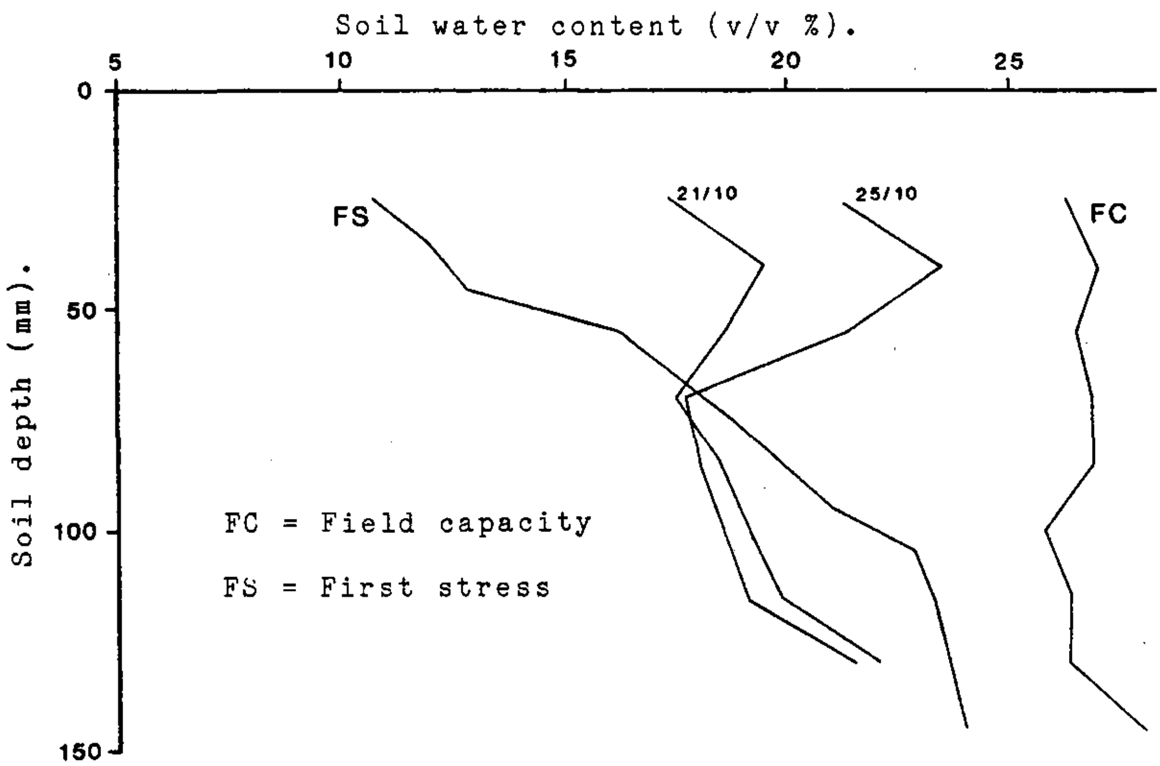


FIG.5.21 Soil water extraction patterns for the deficit irrigation applied in treatment (b) of the lysimeter experiment (before and after water was applied on 24/10).

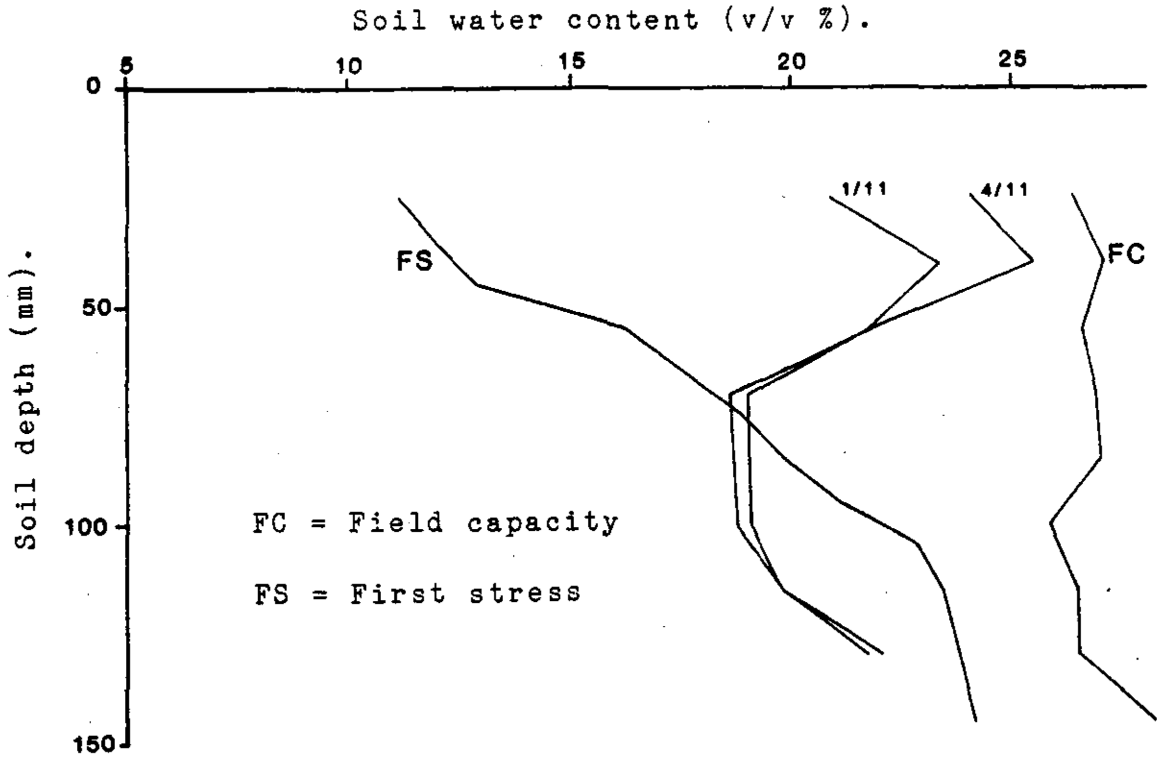


FIG.5.22 Soil water extraction patterns for the deficit irrigation applied in treatment (b) of the lysimeter experiment (before and after water was applied on 3/11).

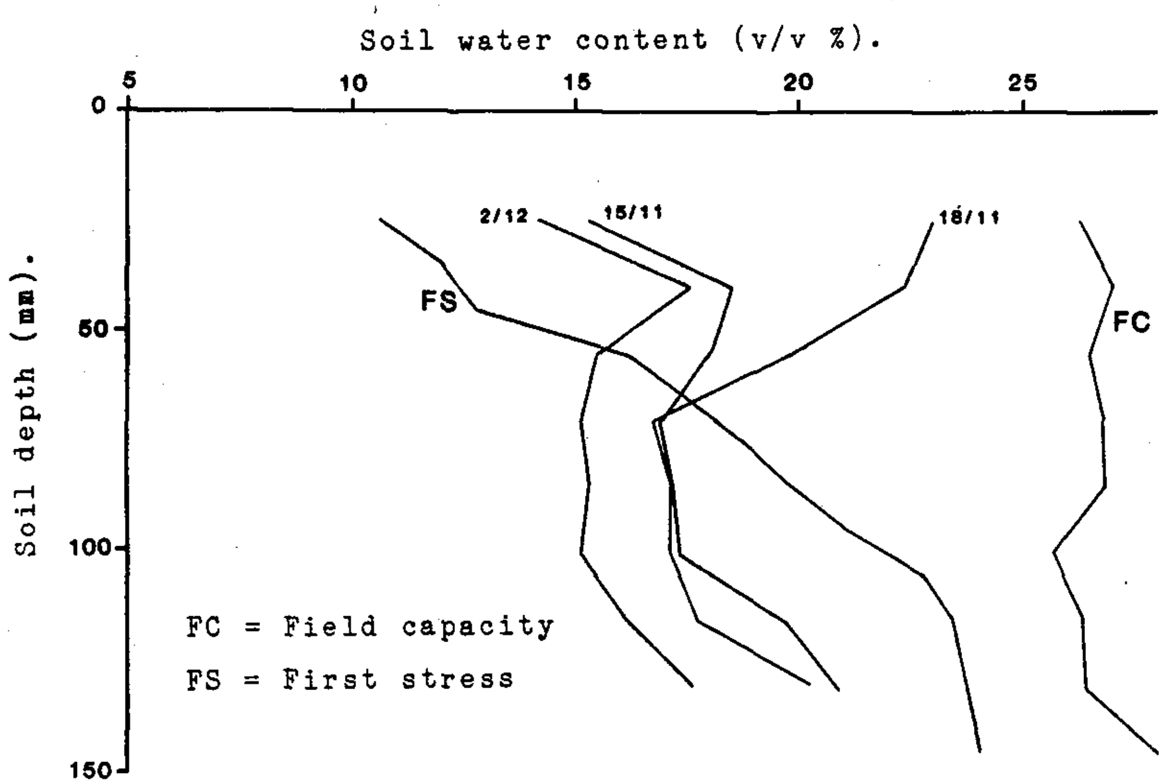


FIG.5.23 Soil water extraction patterns for the deficit irrigation applied in treatment (b) of the lysimeter experiment (before and after water was applied on 17/11).

evapotranspiration of 6,2mm for the period 18/11 to 21/12 while for the field PAWC treatment this value was only 4mm per day for the same period.

Miller (1977) observed similar trends in some deficit irrigation experiments (fractions of daily Et given in high frequency irrigation). High water use efficiencies were obtained with deficit irrigation. Stored soil water, as with the "field PAWC" treatment in the present study, was depleted. Miller (1977) indicates that "stored soil water must be sufficient so that water can be supplied to the crop" (see Table 5.4).

The fact that at harvest the soil profile of the "field PAWC" treatments was very dry in this treatment contributed to the high water use efficiency. The yield of this treatment was not significantly less than the yield obtained on the "adequate moisture treatment".

The "very dry" treatment stretched the intervals too far and consequently transpiration was greatly reduced. This caused a significant decrease in yield, but water use efficiency was similar to that for Treatment (a) ("adequate water"). Although water use efficiency was still equal to that for the adequate water treatment, the large yield reduction is unacceptable.

5.4 CONCLUSIONS

It is obvious from the obtained results that seasonal water use can be reduced by increasing the intervals between irrigations. This was accompanied by a parallel reduction in yield, however, and consequently water use efficiencies were not improved.

Prolonged irrigation intervals have no distinctive negative effect on yield as long as a certain threshold fraction of PAWC is not exceeded. During the experiments it was clearly demonstrated that past this threshold value yields decreased rapidly to economically unacceptable levels (see 125% PAWC treatment during winter experiments, 100% PAWC treatment during summer experiments; Tables 5.1 and 5.2). This is of extreme importance for two aspects of irrigation scheduling because:

(a) Longer irrigation intervals could save on the fixed costs that accompany each irrigation application. English & Nakamura (1982) found that irrigation costs could be reduced significantly by reducing irrigation frequency which meant savings in annualized capital, labour and maintenance costs. Water loss during transport of the water from its source to the field will also be reduced (Marais, 1984).

(b) The threshold value beyond which yields drop significantly will indicate to what level soil water can be depleted if one is aiming for an optimum irrigation scheduling method.

The models of Hanks (1982) and others for predicting crop production focus strongly on Relative yield/ Relative ET relationships. These relationships must be viewed with caution (Laker *et al* , 1984). During the present research a regression line, almost identical to the one found for winter wheat by Hanks (1982), was found for irrigated wheat at Vaalharts (compare Figures 5.7 and 5.24). Actual relationships and water use efficiencies differed widely however, (compare Tables 5.1 and 5.5).

During the PAWC determination for maize and cotton on soils of the Vaalharts and Loskop irrigation schemes

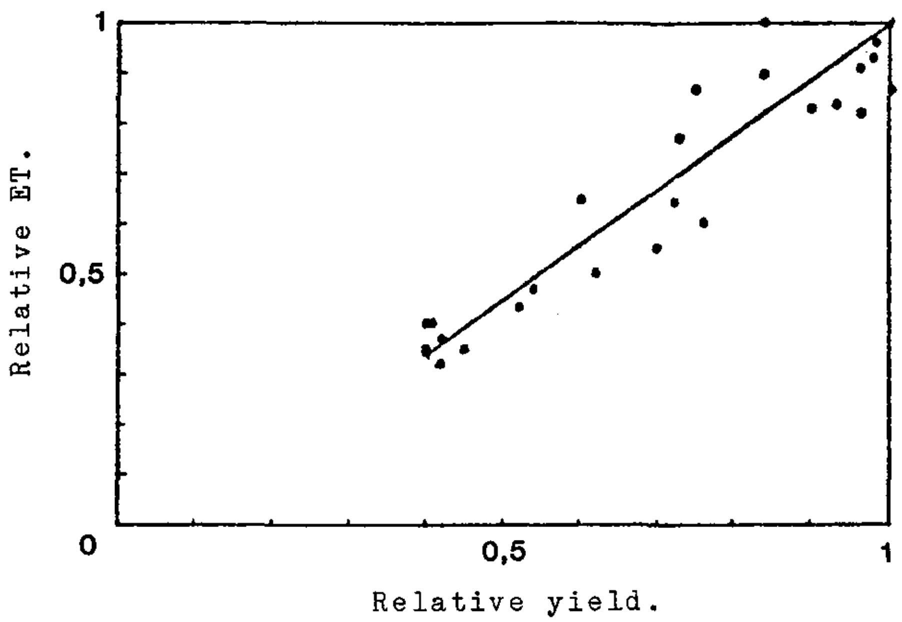


FIG.5.24 Relation of relative yield of winter wheat to relative evapotranspiration (from Hanks, 1982).

TABLE 5.5 Yield and water use efficiencies for winter wheat (from Hanks, 1982).

Yields (tons/ha)	Evapotranspiration (mm)	Water use efficiency
2,5	134	18,6
2,8	141	19,8
3,1	201	15,4
3,5	258	13,6
4,6	314	14,6
6,4	381	16,7
2,9	134	21,6
3,3	199	16,6
3,9	298	13,1
5,5	318	17,2
6,2	328	18,9
7,1	378	18,7

doubts developed concerning the accuracy with which pre-dawn leaf water potential and visual stress symptoms indicated the onset of stress. The yield and water use efficiency data obtained during this study permitted empirical verification of the validity of this parameter as an indicator of first stress. The severe yield reduction found for the 100% treatments for maize in summer at Kamp I, Van der Linde I and II and Contour 10 indicated that the pre-dawn leaf water potential method indeed overestimated PAWC values under high evaporative demand.

At some sites (e.g. Kamp I and Contour 10) crops were extracting water at an extremely slow rate close to PAWC. At Kamp I the crops needed 7 days to bring the extraction from 81 to 84mm. At Contour 10 the crops never reached 100% PAWC, although the plot where the actual PAWC was determined was close to the site where the experiments were done. It is obvious that much better results (yield and water use efficiency) would have been obtained if irrigation was given just before the extraction rate started to show a severe decline.

The higher yields found for maize on the Kamp II and Contour 10 sites was probably due to the later planting dates for these two sites. It was not clear whether the higher yield was caused by a climatic factor. Class A pan data did not provide an explanation. It is however possible that other climatic factors influenced the condition of the crop. Bennett (according to Dreyer, 1984) obtained higher water use efficiencies by adjusting planting dates to let crops grow during a period of the year when the relative humidity in the air is relatively high.

The involuntary deficit irrigation given in the field-PAWC treatment gave exciting results. As the extraction pattern showed (see paragraph 5.3) crops continued to extract water from the bottom soil layers while only the top layers were refilled to field capacity. This resulted in a dry soil profile by the end of the season and a high water use efficiency was found. The fact that frequent partial refilling and exploitation of the fertile topsoil was combined with this drying process may be a key factor. This experiment was quite unique. The current procedure in deficit irrigation research is to irrigate fractions of potential evapotranspiration at a high frequency (e.g. Miller, 1977). Research on the combined effects of the amount and frequency of irrigations has been very limited and

English & Nakamura (1982) stated: "as far as we have been able to determine, there has been no research done on the combined effects of low frequency irrigation and deficit irrigation". English & Nakamura (1982) found crop yields under low frequency irrigation that were even higher than what was found for non-deficit irrigation, but remarked that this could have been as an effect of good rains during the growing season.

CHAPTER 6

E V A L U A T I O N O F T H E P A W C C O N C E P T

6.1 INTRODUCTION

6.1.1 PAWC determinations

During this research PAWC values were determined on a variety of soils in three different regions of Southern Africa. The determinations were made according to the definition of PAWC as proposed by Hensley & De Jager (1982):

> "For a specified crop (specified cultivar and growth stage), soil, and evaporative demand, PAWC is the amount of water which is held in the effective root zone between field capacity and first material stress."

In the original concept the lower limit, first material stress, was defined as: "The quantity of water in the soil profile at the degree of crop water stress at which the next irrigation should be applied if optimum yield is to be attained." This allowed for some flexibility and, depending upon the situation, one could consider either "initial stress" or "well defined stress" as being "first material stress", to demarcate the lower limit (Hensley & De Jager, 1982). Hensley (1984) subsequently indicated that: "Maximum yield per unit of land is expected to be attained if irrigation water is to be applied at "initial stress". On the other hand a significant increase in water use efficiency was expected if irrigation is delayed until "well defined stress" has been reached. Hensley (1984), therefore, recommended that irrigation scheduling be based on this well defined stress condition. He defined well defined stress as the soil water content at which plant physiological processes have been reduced by 25 per cent of their normal rate. Hensley (1984) considered this to be the stage at which the next irrigation should be applied if optimum yield is to be obtained.

Equating "first material stress" with "well defined stress" only (Hensley, 1984) instead of with either "initial stress" or "well defined stress" (Hensley & De Jager, 1982) caused PAWC to become the quantity of water held in the effective root zone between field capacity and well defined stress. Since well defined stress was in practice invariably used as indicator of the lower limit of PAWC by Hensley (1984) it was also used in the present study.

The pre-dawn leaf water potential method was used to determine first material stress in the present research, as was discussed extensively in Chapter 2. No difficulties were encountered with this method to indicate crop water stress during winter but it was found that during summer, under high evaporative demand, the method was less reliable. At Vaalharts it was decided to abandon this method and to use visual stress symptoms to indicate stress. During the Loskop experiments, the following summer, it was decided to continue the pre-dawn leaf water potential readings until they indicated stress, to test the usefulness of the method under summer conditions. As it turned out, pre-dawn leaf water potential, after a period of inconsistent decrease, eventually clearly indicated crop water stress (see Chapter 2). It was believed that at this stage plants were beyond the "well defined stress" limit defined by Hensley (1984). In other words these determinations were believed not to represent PAWC, but a value in excess of

PAWC. This hypothesis will be tested in this chapter.

6.1.2 Irrigation scheduling experiments

The validity of the obtained PAWC values could be tested empirically by using the results of the irrigation scheduling experiments conducted at the Vaalharts and Loskop irrigation schemes. Indications were that a threshold fraction of PAWC exists, beyond which yields will significantly decrease (See Chapter 5). Such threshold value would be of extreme importance in the evaluation of PAWC because it will:

(a) Demarcate the allowable lower limit of available water for irrigated conditions, i.e. the threshold value below wich significant yield reduction will occur. Such reductions cannot be permitted in irrigated agriculture, where a certain productivity must be obtained because of the costly inputs (water, energy ...).

(b) Indicate the length of the optimum interval between irrigations. Optimum here refers to minimizing the amount of irrigations given during the growing season without exceeding the allowable lower limit of available water.

The main objectives in the present chapter will be to identify principles for establishing the critical threshold soil water extraction values and to adapt the PAWC concept accordingly, if necessary.

6.2 DETERMINATION OF THE THRESHOLD VALUE

In Chapter 5 yields were plotted against percentage of PAWC extracted for each site. At six of the nine sites significant correlations were found and the relation between the two parameters can be described by a function of the second degree.

Because the number of observations at each site are rather limited it was decided to combine the results of all sites. In order to do this meaningfully, relative yields were correlated with fractions of PAWC extracted between irrigations. For both wheat and maize highly significant curvilinear relationships were found (Figure 6.1), the correlation coefficient for wheat being slightly higher than the one for maize. Again these figures suggest the existence of a point below which yields drop significantly.

Cate & Nelson (1971) developed a simple statistical procedure for partitioning soil test correlation data, which show similar distribution as the data found in the current irrigation scheduling research, into two classes. The method consist of "splitting the data into two groups, using successive tentative critical levels to ascertain that particular level which will maximize overall predictive ability (R^2), with the means of the two groups (classes) as the predictor values." (Cate & Nelson, 1971).

The two groups of data distinguished by the Cate & Nelson (1971) method are:

(a) a group in which the reaction of plant performance to changes in the plant production factor is insignificant, and

(b) a group in which plant performance reacts strongly to changes in the plant production factor.

A threshold value for the production factor, separating the two groups, is identified by the method.

This Cate - Nelson method was applied on to the curves obtained for wheat and maize (Figure 6.1). For wheat the critical PAWC fraction that divides the "yield versus percentage of PAWC extracted" curve, was found at 100,5%

PAWC! (Figure 6.1.a and Table 6.1). For maize the critical PAWC fraction was only 71,5% (see Figure 6.1.b and Table 6.1).

TABLE 6.1 Predictive ability (R^2) values found for different fractions of PAWC extracted between irrigations.

WHEAT

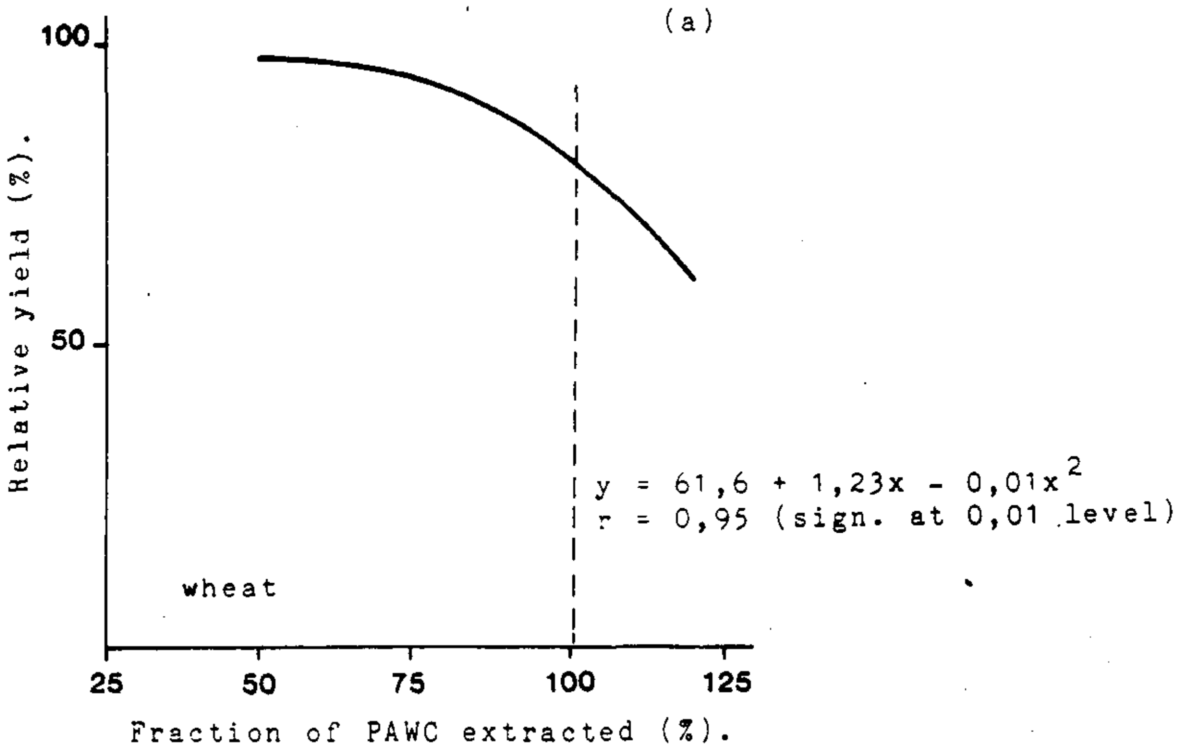
General*		Detailed**	
Fraction of PAWC extracted	Predictive ability	Fraction of PAWC extracted	Predictive ability
75	0,41	98	0,58
85	0,62	99	0,69
90	0,71	100	0,76
95	0,75	101	0,74
100	0,79	102	0,71
105	0,76	103	0,62

MAIZE

General*		Detailed**	
Fraction of PAWC extracted	Predictive ability	Fraction of PAWC extracted	Predictive ability
60	0,71	68	0,56
65	0,76	69	0,57
70	0,80	70	0,58
75	0,79	71	0,76
80	0,77	72	0,69
85	0,66	73	0,59

* 5% steps.
** 1% steps around value identified during general evaluation.

The correctness with which pre-dawn leaf water potential monitoring predicted PAWC for wheat is remarkable.



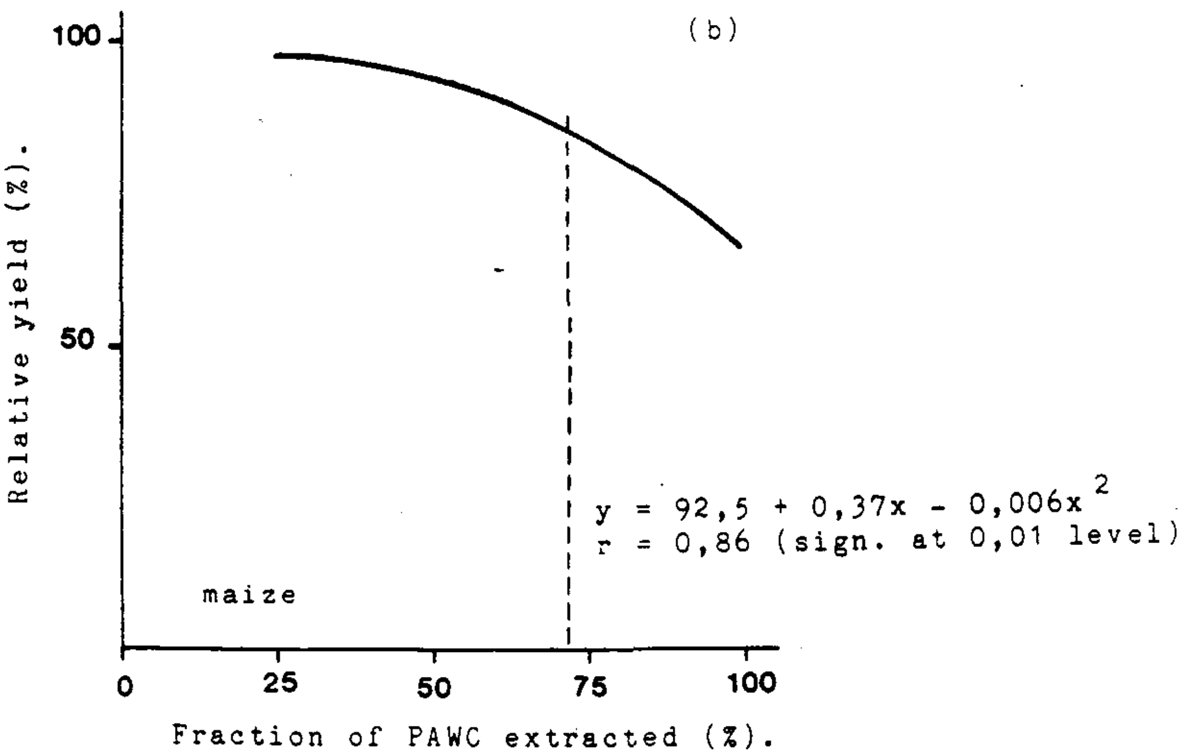


FIG.6.1 Relationship between relative yield and percentage of PAWC extracted for wheat (a) and maize (b). The dashed lines indicate at what percentage of extraction yields start to drop significantly. The curves were calculated with data obtained from Tables 5.1 and 5.2.

The results for maize clearly illustrate the lack of accuracy of pre-dawn leaf water potential readings and visual symptom observations to indicate first stress (the lower limit of PAWC) under conditions of very high evaporative demand. On average PAWC was over-estimated by nearly 30% at all sites for maize. As the impression that PAWC was over-estimated during summer already existed before this statistical evidence was encountered, this value could be extrapolated to the sites were no irrigation scheduling experiments were done during summer.

The differences in accuracy found between winter and summer experiments is undoubtedly due to the high evaporative demands during summer. Under such conditions crops suffer considerable water stress before it is indicated by pre-dawn leaf water potentials.

The Cate - Nelson method for partitioning data into two classes was also applied to the "yield versus percentage of PAWC extracted" curve for each site separately (Table 6.2).

TABLE 6.2 Critical percentage of PAWC at which yield decreased significantly. (Determined with the Cate-Nelson method).

	Wheat	Maize
Van der Linde I	95	82
Van der Linde II	98	55
Kamp I	95	77
Kamp II	103	91
Contour 10		74

As could be expected from the general relative yield function for wheat, the individual sites did not deviate significantly from the 100% PAWC value.

For maize the determined PAWC at Kamp II was the closest to the critical value at which yield significantly drops. This is reflected in the relatively high yields found for the 100% PAWC treatment during the irrigation scheduling experiments with maize at this site (See Chapter 5). The low threshold value for Van der Linde II is due to the fact that an "artificial" PAWC was used in the scheduling studies with maize at this site. This artificial value of 175mm was used because the very low PAWC of only 87,5mm found for maize during the previous summer was thought to be caused by experimental error since this value was completely out of line with the PAWC values for maize at other similar sites (Van der Linde I and Demonstration Plot) and for wheat at this site.

6.3 ADAPTED PAWC VALUES

With the information obtained from Table 6.2 "adapted" values for PAWC for the different sites can be calculated. It is perhaps wrong to use the term PAWC in this discussion because in the latest definition of PAWC (current opinion) the concept refers to a "well established stress" condition as the lower limit while the adapted values proposed in this paragraph refer to a lower limit defined by the onset of stress (see paragraph 6.5).

The adapted values are listed in Table 6.3 and were obtained with the following formula:

$$\frac{PAWC \times T}{100} = \text{"adapted-PAWC" value}$$

with PAWC = profile available water capacities used during the irrigation scheduling experiments.

T = threshold percentage of PAWC extraction at which yield significantly dropped.

TABLE 6.3 Field determined and adapted PAWC values.

	PAWC (mm)			
	wheat		maize	
SITES	Field determined	Adapted **	Field determined	Adapted **
Kamp I	117,0	90,3	88,0	77,9
Kamp II	99,4	95,5	122,2	84,8
Van der Linde I	144,9	133,0	125,4	114,8
Van der Linde II	162,4	137,2	87,3	96,3
Contour 10			117,3	92,5
Contour 5			101,2	80,5*
Du Preez I			154,2	94,5*
Du Preez II			108,2	67,7*
Du Preez III			155,5	115,3*
Venter I			136,5	93,9*
Venter II			183,8	108,6*

* Threshold value of Contour 10 and field determined PAWC values were used to calculate "adapted PAWC" values.
** Field determined PAWC vary slightly with PAWC values used in the irrigation scheduling experiments at certain sites because allowance for changing soil depth had to be made. This obviously influenced the adapted values.

6.4 IMPACT OF THE "ADAPTED" PAWC VALUES ON SOIL WATER EXTRACTION PATTERNS, LEAF WATER POTENTIAL AND RELATIVE YIELD.

6.4.1 Impact on extraction patterns

On the sandy Hutton soils of the Vaalharts region the modified PAWC values did not influence the final extraction patterns. At these sites constant amounts of water were extracted from all depths of the soil profile from the start of the drying cycle onwards. With the adapted PAWC the final extraction line just moves closer to the field capacity line (see the example given in Figure 6.2).

At Loskop it was found that extraction patterns were influenced by the length of the drying cycle. At the beginning of the extraction period, just after the soil was brought to field capacity, the extraction pattern was a "deep fan" pattern (see Chapter 3). As the drying cycle progressed towards determined PAWC more water was extracted from the lower soil layers of the soil profile during the later stages. At all sites but Du Preez I this resulted in a final extraction pattern with more-or-less parallel field capacity and first stress lines and consequently the pattern resembled the final extraction pattern of the Vaalharts sites. The daily monitoring of soil water content with neutron hydroprobes permitted indentification of the day on which the adapted PAWC value was extracted from the soil profile. This day could then be retraced on the plotted extraction patterns of the Loskop sites. The result is illustrated in Figures 6.3 to 6.9. It can clearly be seen from the

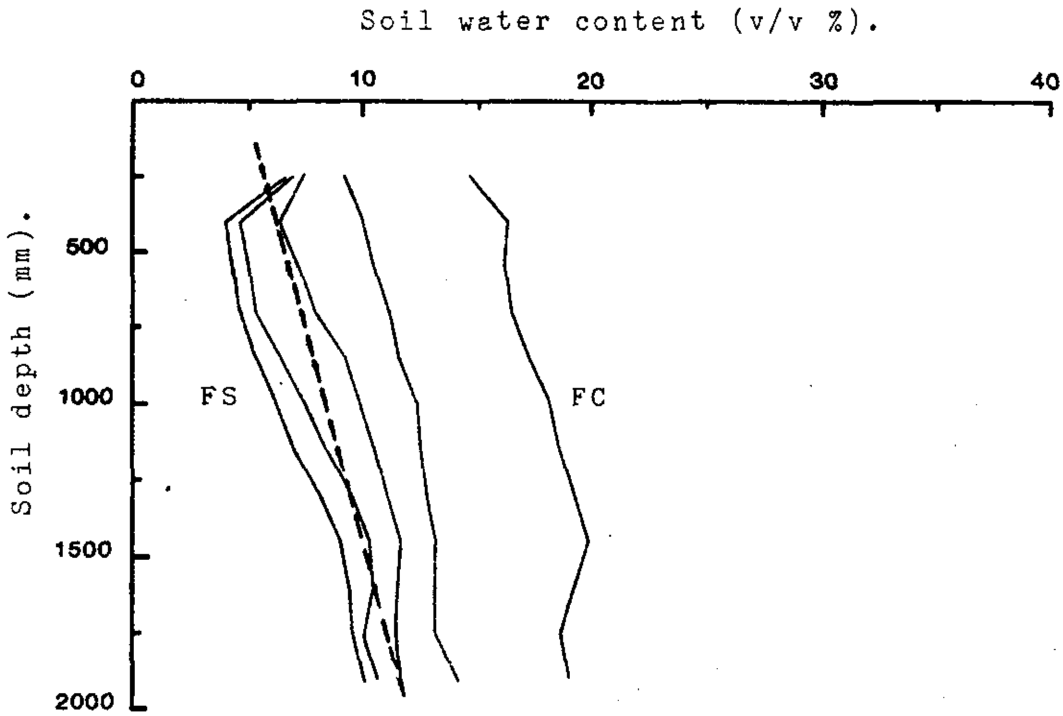


FIG.6.2. Soil moisture extraction pattern for maize at Demonstration plot (Vaalharts). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress.

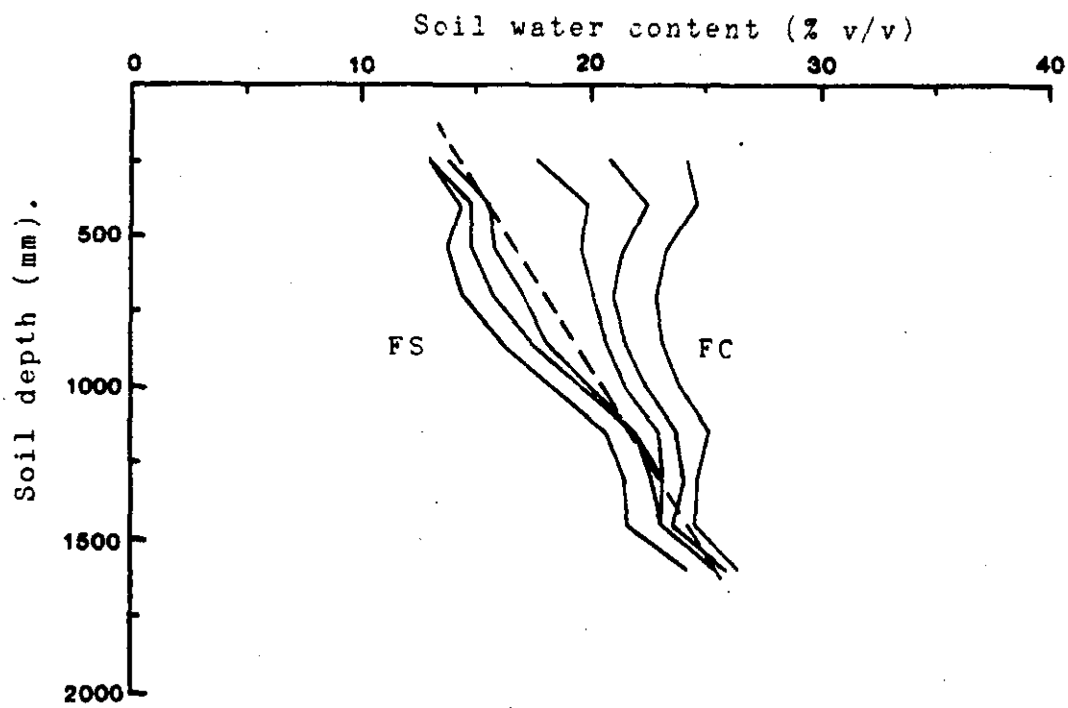


FIG.6.3 Soil water extraction pattern for maize at Du Preez I (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity.

FS = first stress.

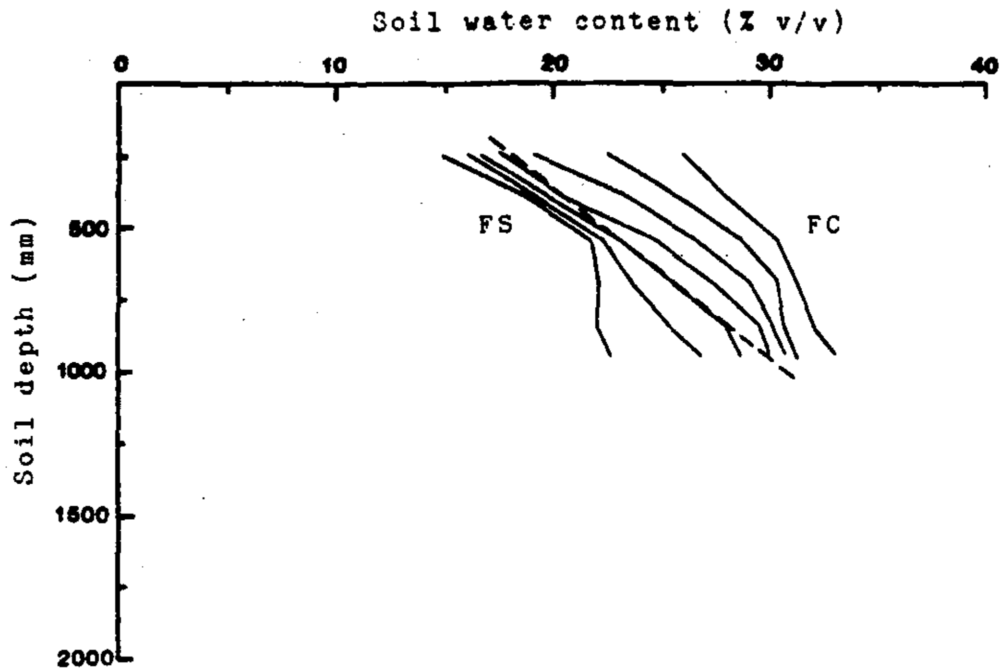


FIG.6.4 Soil water extraction pattern for maize at Contour 5 (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress

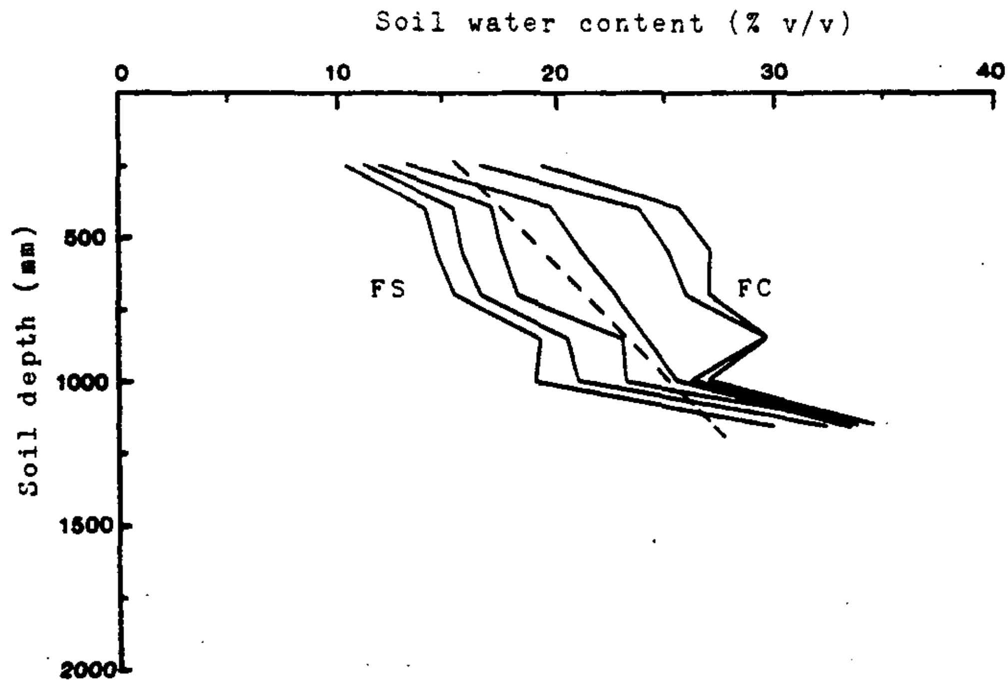


FIG.6.5 Soil water extraction pattern for maize at Contour 10 (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity
FS = first stress

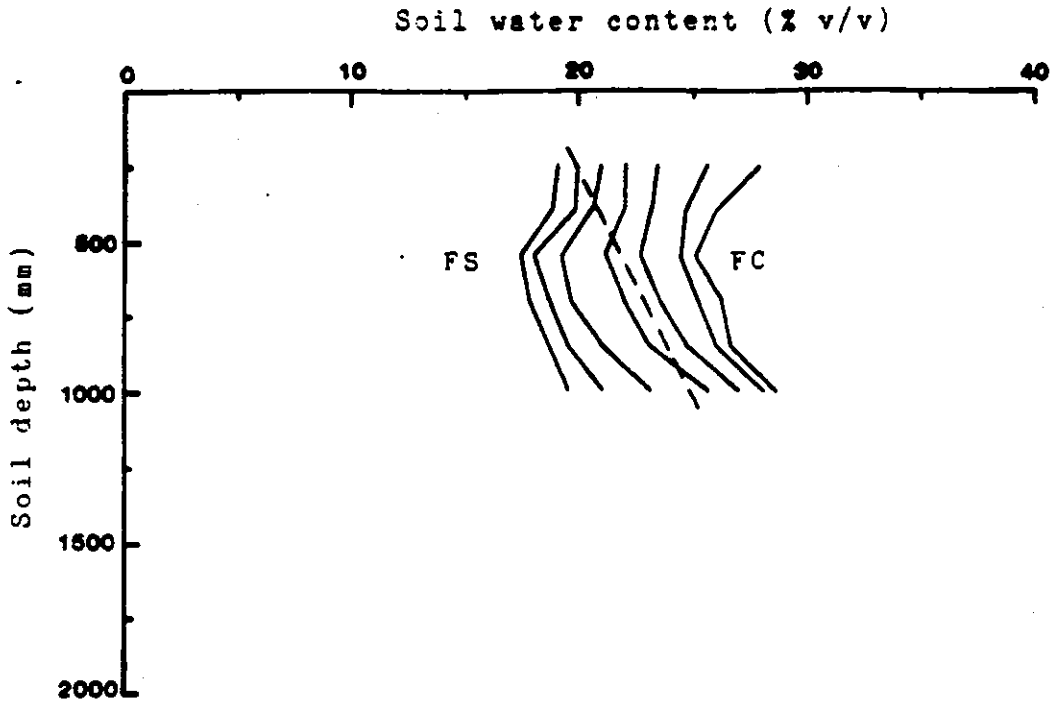


FIG.6.6 Soil water extraction pattern for maize at Du Preez II (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress

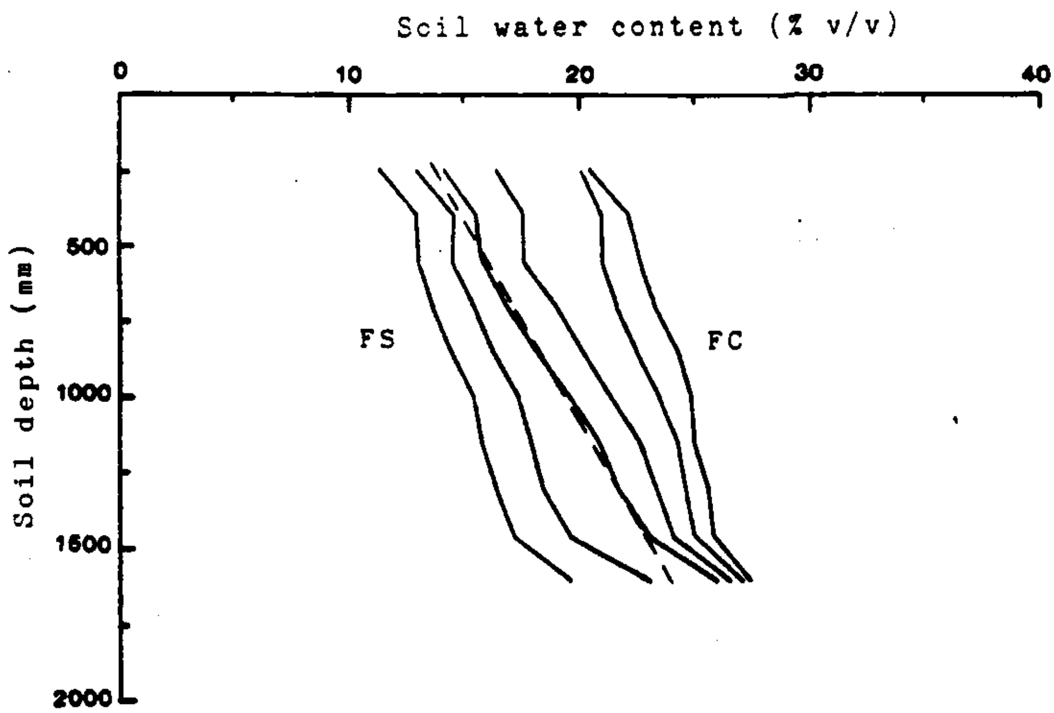


FIG.6.7 Soil water extraction pattern for maize at Du Preez III (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress

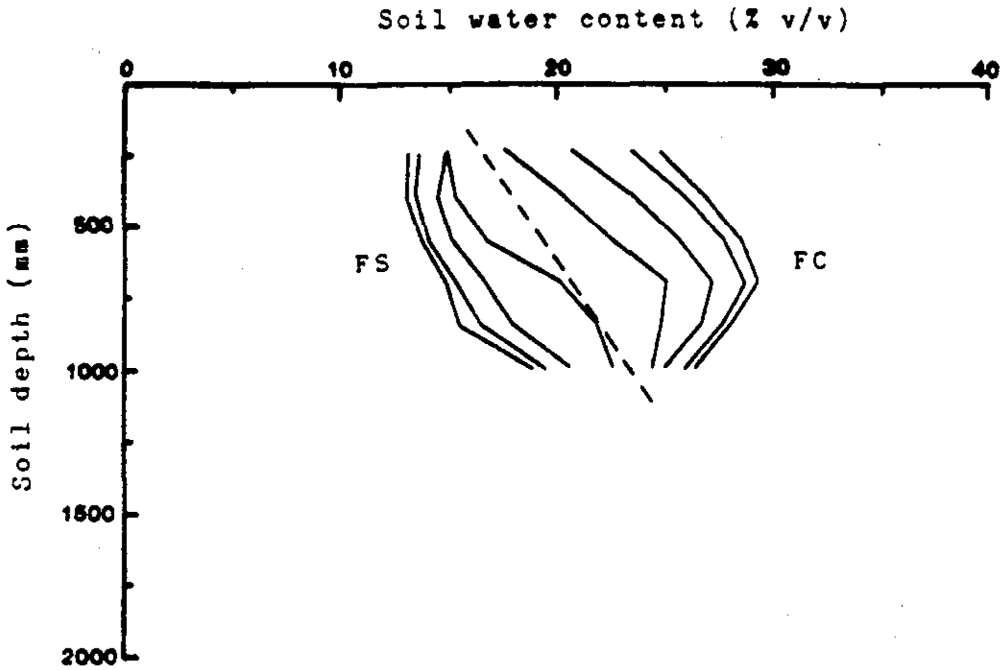


FIG.6.8 Soil water extraction pattern for maize at Venter I (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress

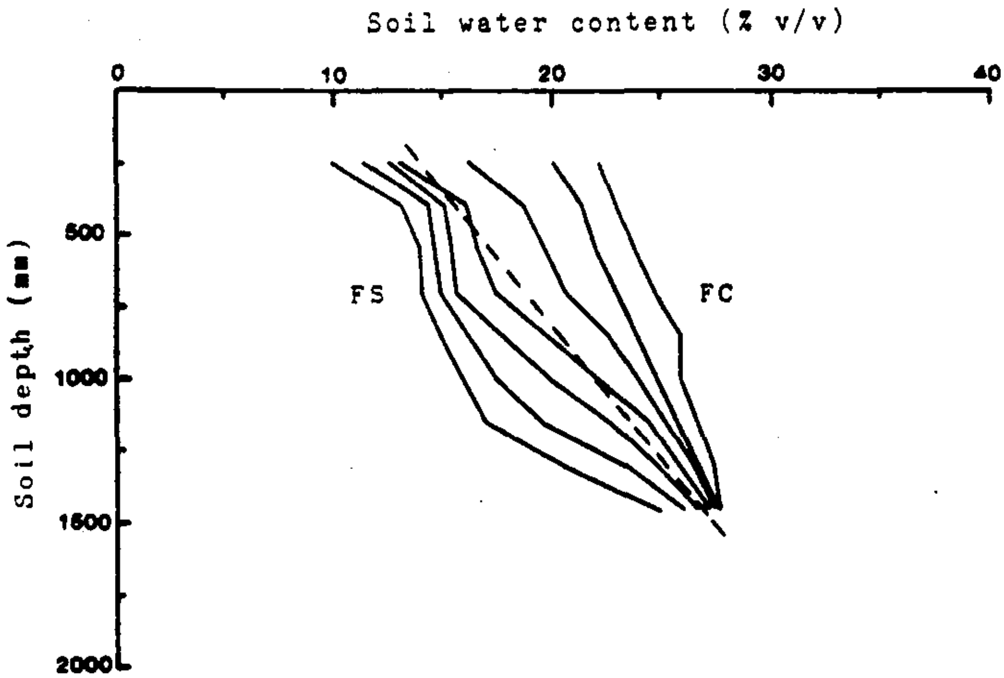


FIG.6.9 Soil water extraction pattern for maize at Venter II (Loskop). 4 day intervals. The dashed line coincides more-or-less with the day PEW was reached.

FC = field capacity

FS = first stress

figures that the "adapted" PAWC values bring the extraction lines back to just before the period where the maize started to extract water from the subsoil layers at an increasing rate. The final extraction pattern at the "adapted" PAWC point resembles an inverted triangle. This pattern is very similar to the extraction patterns found for maize and wheat on medium textured soils in the Ciskei.

The increased extraction from the lower layers of the soil profile is happening at the cost of yield. Past the "adapted" PAWC values yields dropped significantly at Contour 10, the only site actually tested.

6.4.2 Impact on pre-dawn leaf water potentials

The day on which adapted PAWC was reached was plotted on the pre-dawn leaf water potential curves found for maize at the different Loskop sites (Figures 6.10 to 6.13). No consistent relationship between the reaching of adapted PAWC and specific changes in pre-dawn leaf water potential was found. Certain trends were observed, however. At two sites (Du Preez III and Contour 5), the day on which adapted PAWC was reached coincided with the day on which the researcher noted visual stress (see

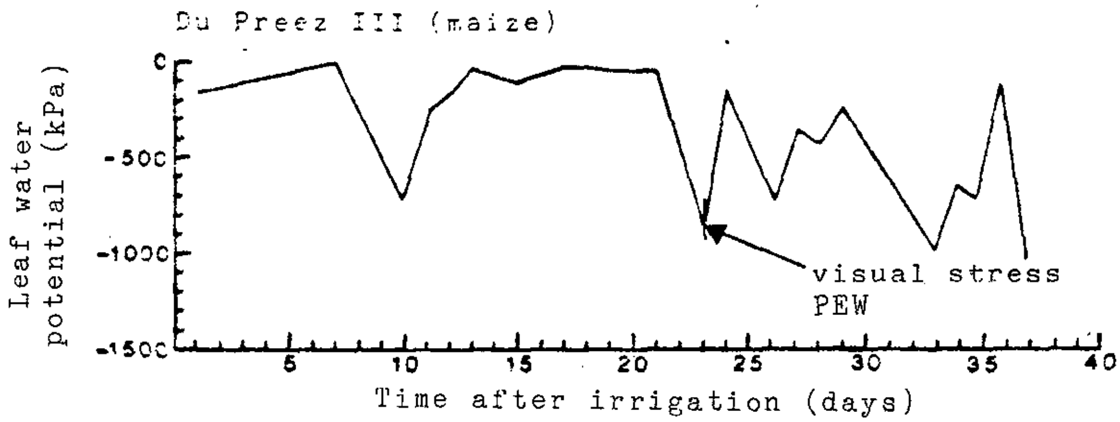


FIG.6.10 Pre-dawn leaf water potential readings at different times after irrigation.

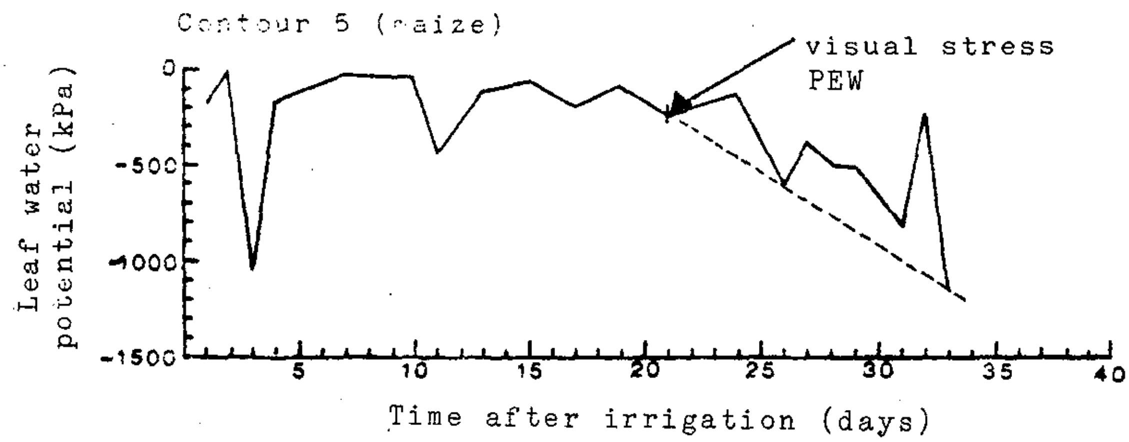


FIG.6.11 Pre-dawn leaf water potential readings at different times after irrigation.

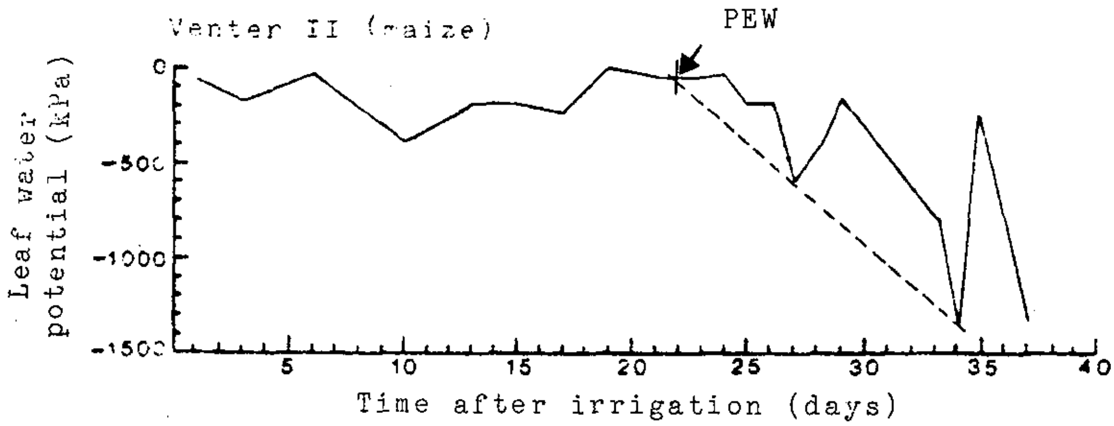


FIG.6.12 Pre-dawn leaf water potential readings at different times after irrigation.

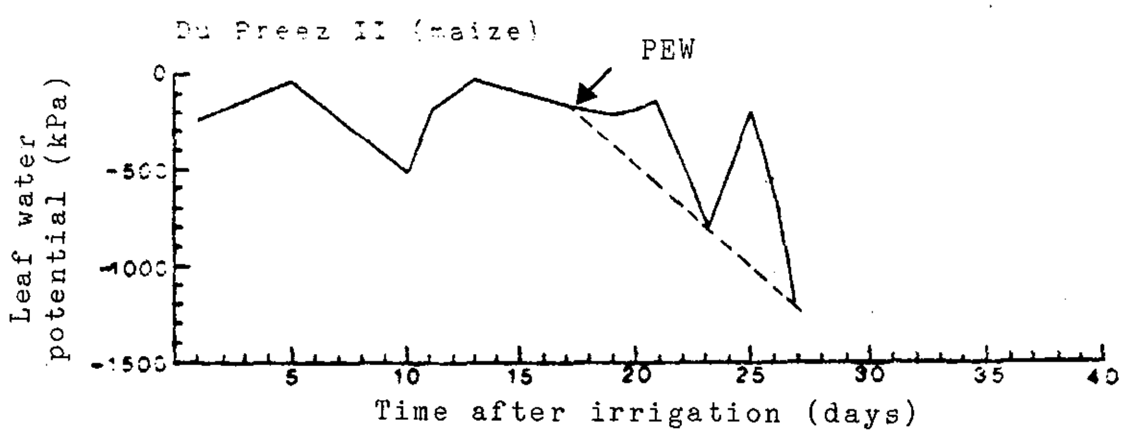


FIG.6.13 Pre-dawn leaf water potential readings at different times after irrigation.

Figures 6.10 and 6.11). At some sites (Du Preez II, Venter II, Contour 5) the adapted PAWC could be traced back by drawing a line through the low range pre-dawn leaf water potential readings observed during the period of fluctuating pre-dawn leaf water potential values (see also Chapter 2). This line meets the pre-dawn leaf water potential graph close to the day on which adapted PAWC was reached (see Figures 6.11, 6.12 and 6.13). Only at Du Preez III this critical day was accompanied by a clear drop in leaf water potential (see Figure 6.10). It would appear that for maize the lower limit of PAWC would be much more closely related to "initial stress", as defined by Hensley & De Jager (1982), than to "well defined stress" (the criterion recommended by Hensley, 1984).

6.4.3 Impact on relative yield functions

In order to establish whether a common relative yield function existed for maize and wheat at any specific site, relative yields, obtained during the irrigation scheduling experiments, were compared with fractions of observed PAWC extracted between irrigations. To make evaluation possible the yield obtained at 50% PAWC extraction was considered to be 100%.

At all sites statistically highly significant relationships were obtained. At Kamp II the relative yields of wheat and maize fitted each other perfectly. At Van der Linde I and II the correlation coefficients were somewhat lower but still significant (see Figures 6.14 to 6.17).

Very similar relationships were obtained for some sites. This is, for example, illustrated for the curves obtained at Kamp I and Contour 10. If the curve for maize at Contour 10 is shifted somewhat to the right, it fits the data obtained at Kamp I perfectly (see Figure 6.18). This shifting of the yield production curve is in fact an <u>adaptation</u> of the obtained results at Contour 10 to the results found at Kamp I. This observation urged a study of whether a common relationship between relative yield and the fraction of <u>adapted PAWC</u> extracted between irrigations existed for all sites.

The fraction of adapted PAWC extracted between irrigations was calculated by means of Equation 6.1:

$$FAPAWC = FPAWC \times (1 + AF) \qquad (6.1)$$

where: FAPAWC = Fraction of adjusted PAWC extracted

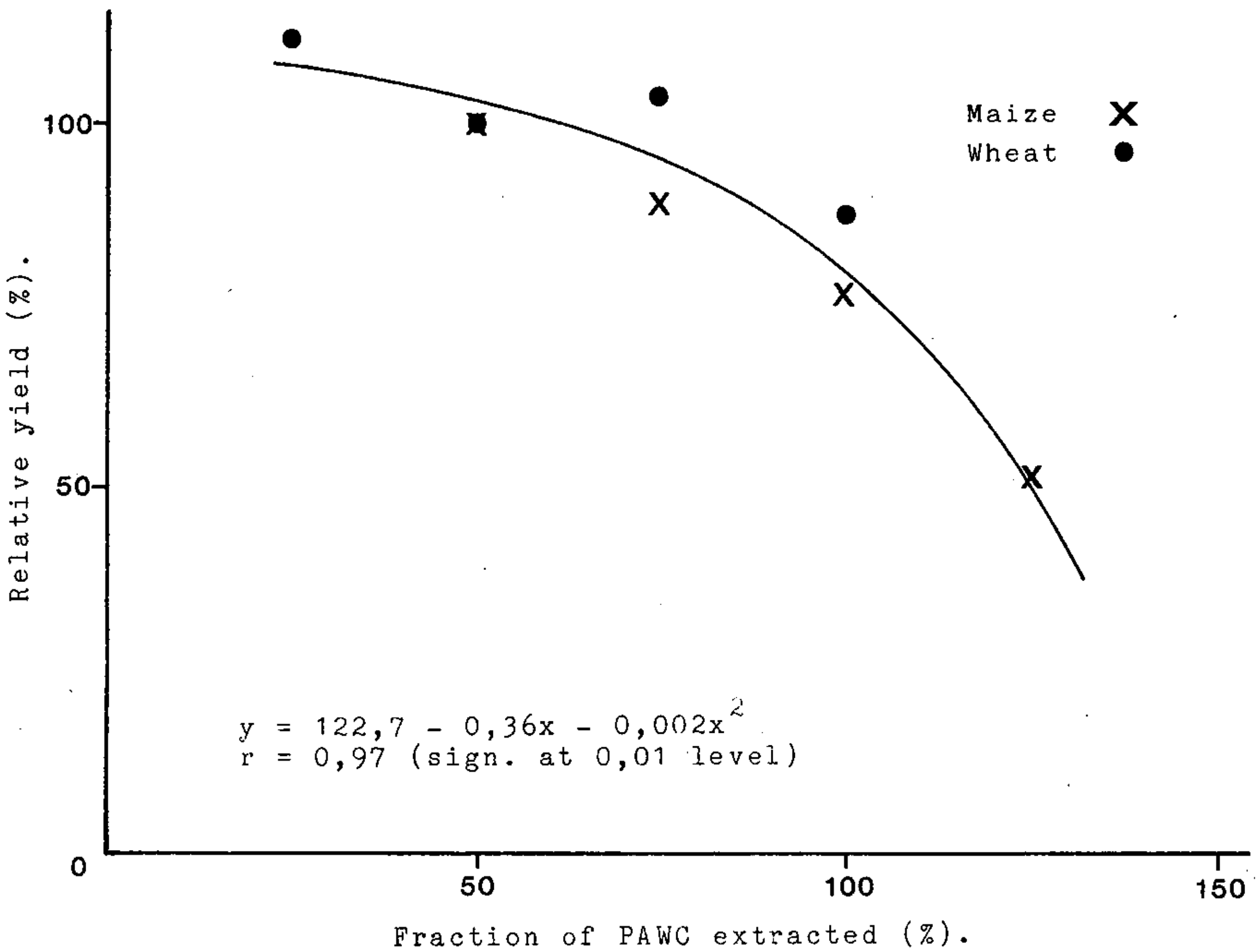


FIG.6.14 Relationship between percentage of PAWC extracted and relative yield for Kamp I. (yield at 50% extraction taken as 100%).

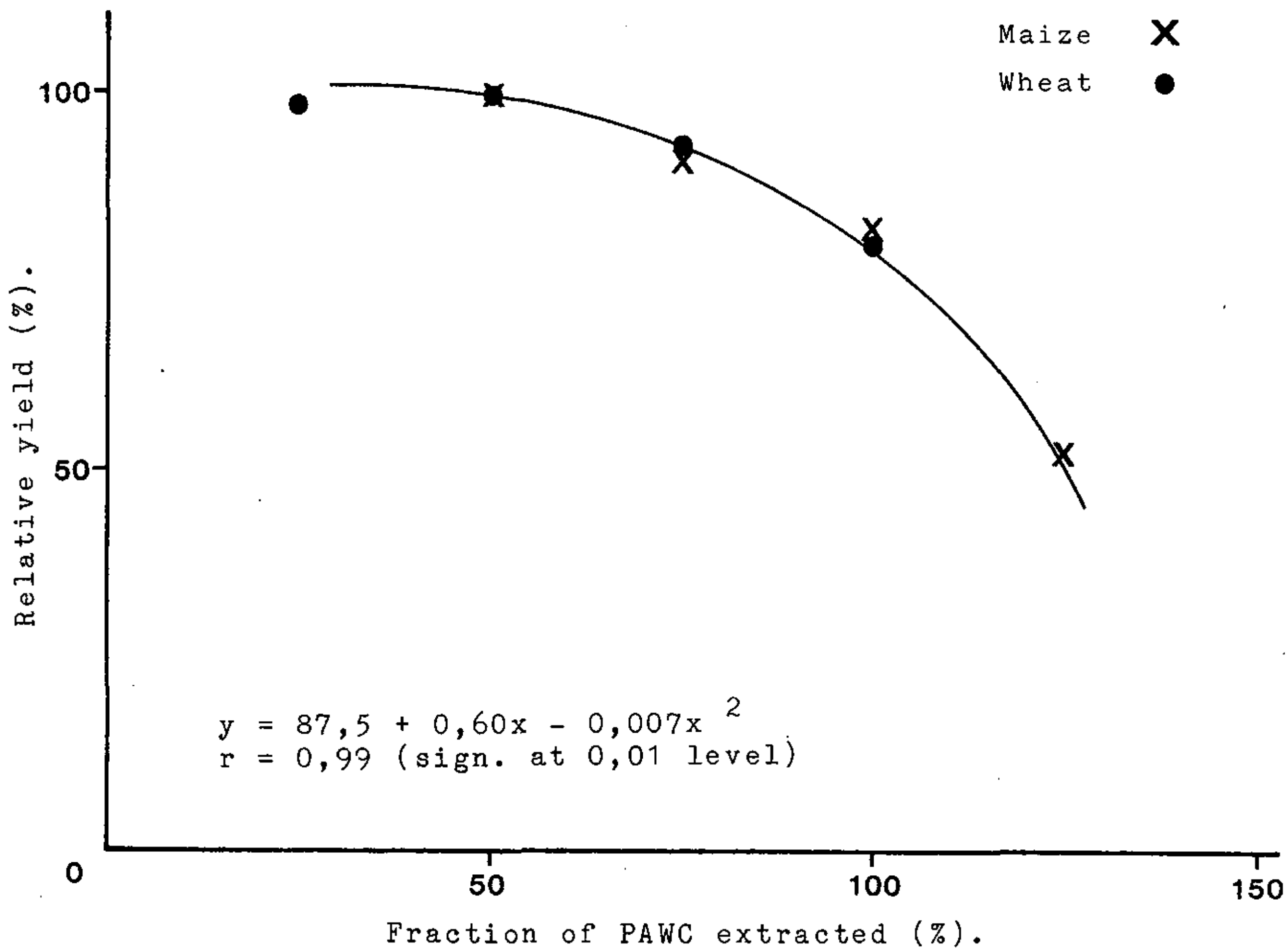


FIG.6.15 Relationship between percentage of PAWC extracted and relative yield for Kamp II. (yield at 50% extraction taken as 100%).

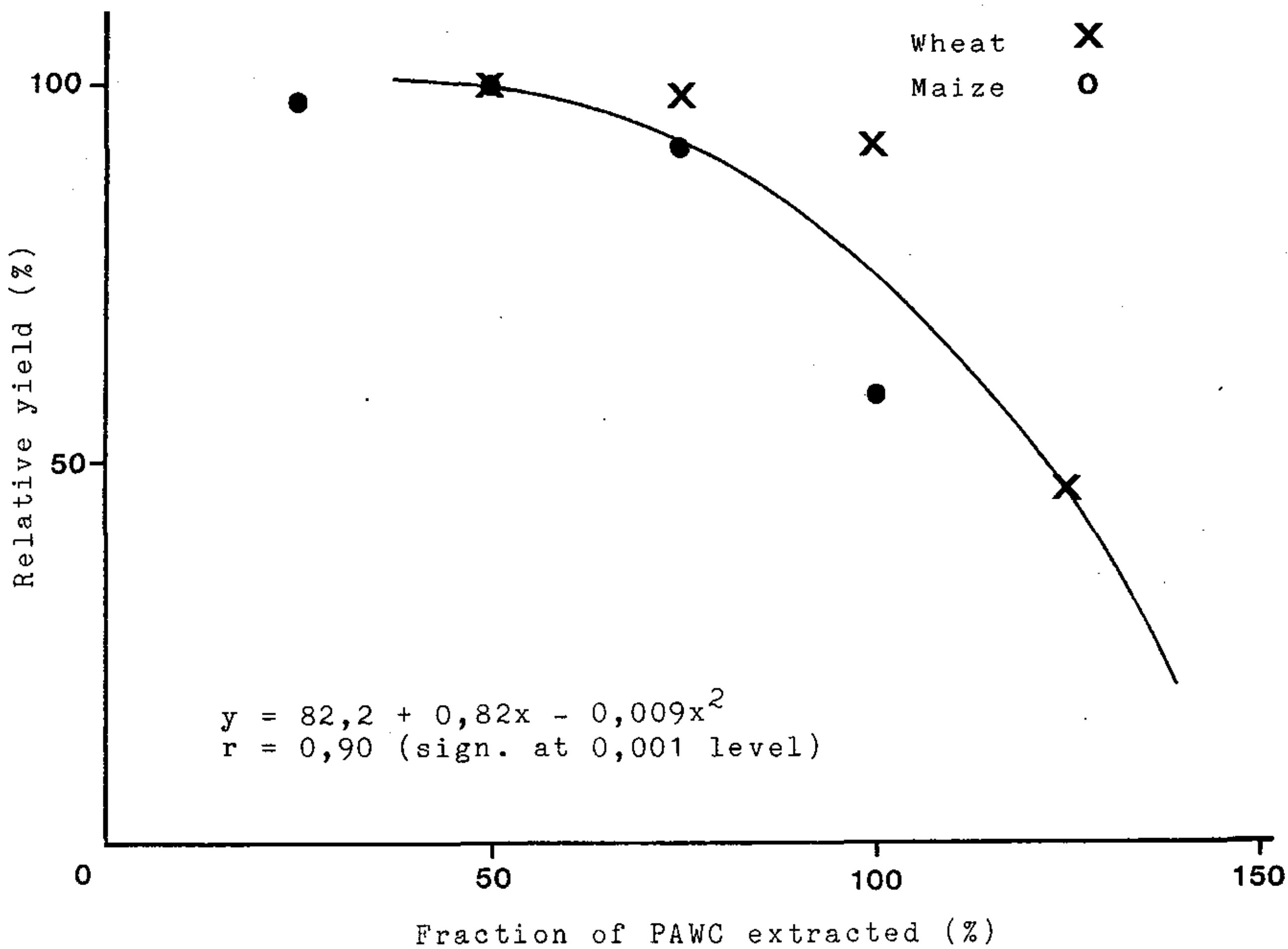


FIG.6.16 Relationship between percentage of PAWC extracted and relative yield at Van der Linde I. (yield at 50% PAWC extracted taken as 100%).

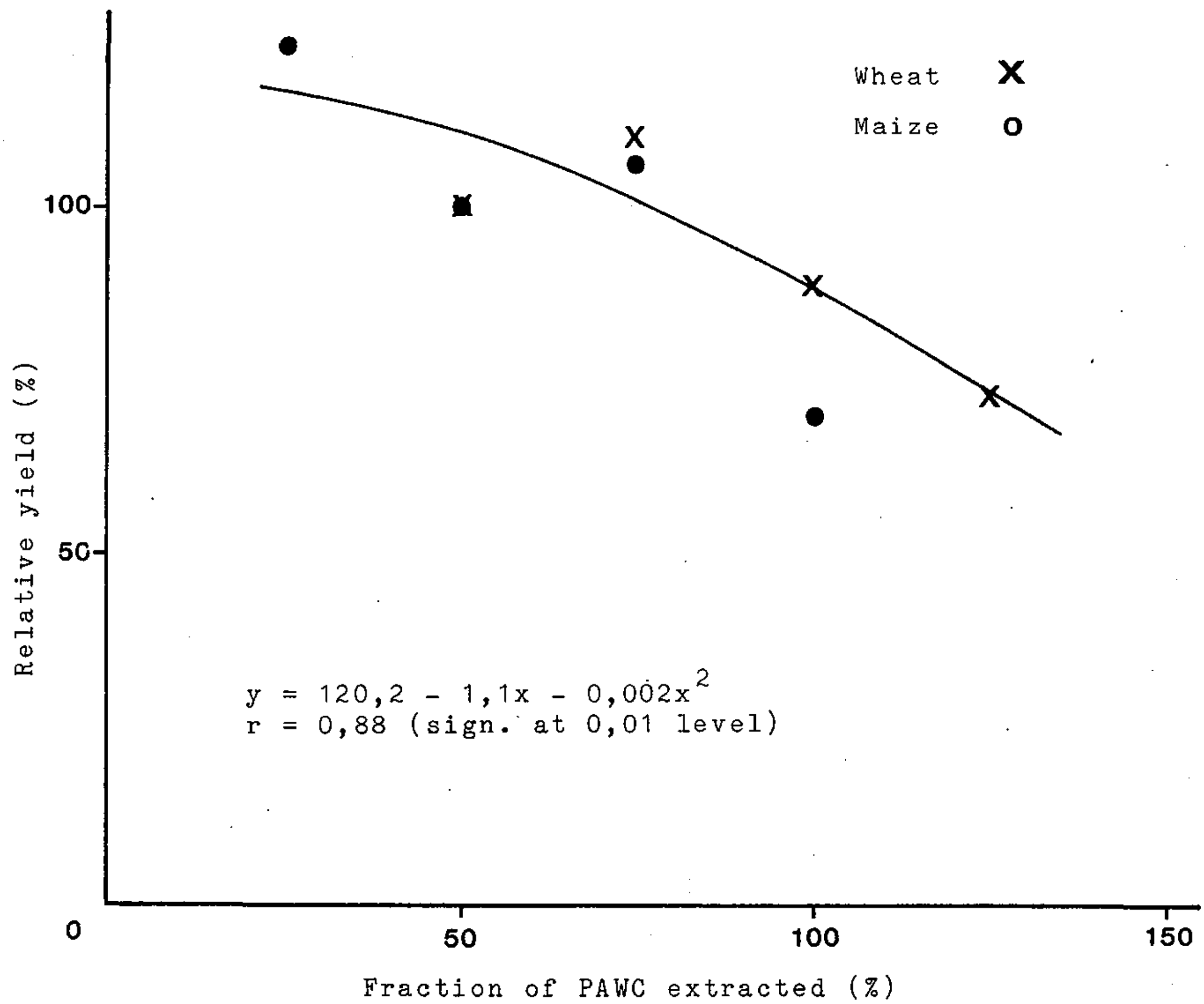


FIG.6.17 Relationship between percentage of PAWC extracted and relative yield at Van der Linde II. (yield at 50% PAWC extracted taken as 100%).

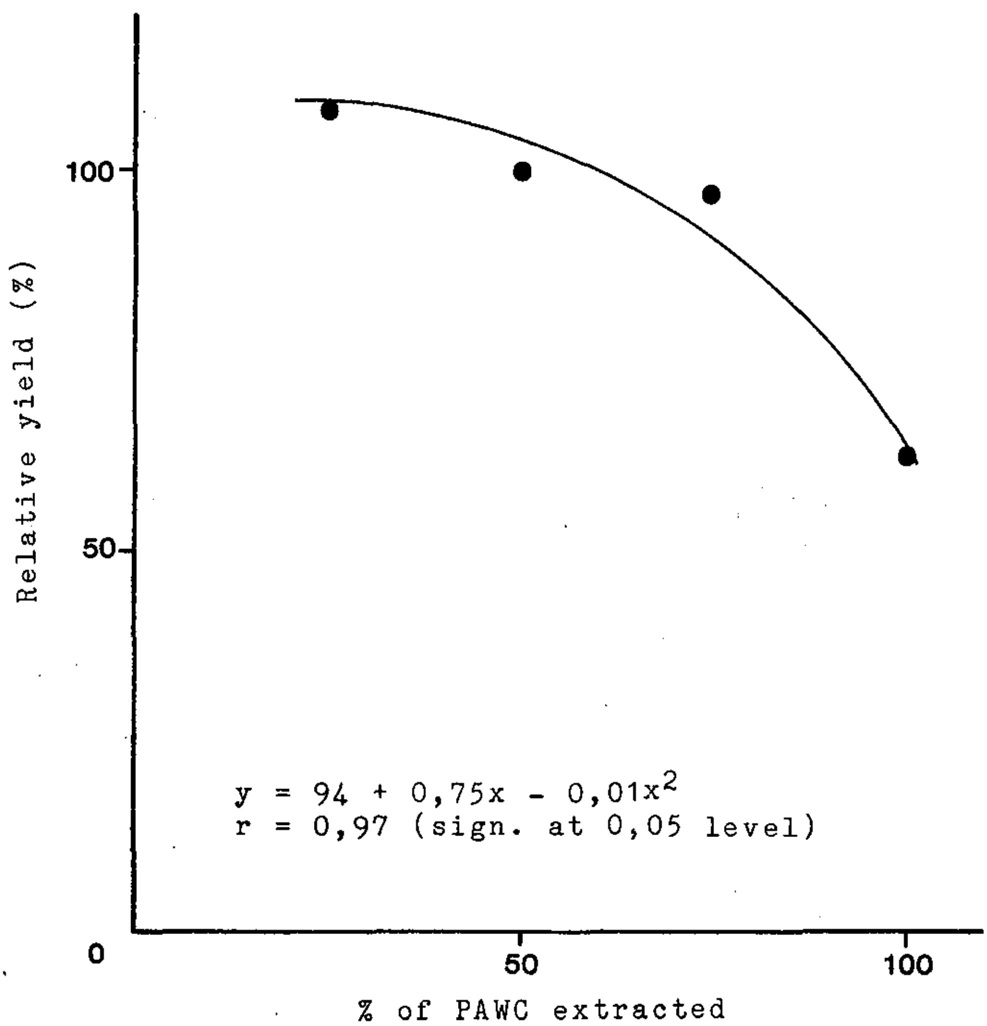


FIG.6.18 Relative yield curve for maize at Contour 10 (yield at 50% PAWC extracted taken as 100%).

TABLE 6.4 Relative yield and "adapted" fraction of PAWC extracted during the irrigation scheduling experiments.

SITE	CROP	Fraction of PAWC	Adapted fraction	Relative Yield*
Kamp I	wheat	50	53	100
		75	79	89
		100	105	76
		125	131	51
	maize	25	31	112
		50	62	100
		75	92	85
		100	123	57
Kamp II	wheat	50	49	100
		75	73	91
		100	98	82
		125	122	52
	maize	25	27	99
		50	55	100
		75	82	92
		100	109	80
Van der LindeI	wheat	50	53	100
		75	79	99
		100	105	92
		125	131	47
	maize	25	30	98
		50	59	100
		75	89	92
		100	118	47
Van der LindeII	wheat	50	51	100
		75	77	110
		100	102	89
		125	128	73
	maize	25	36	123
		50	73	100
		75	109	107
		100	145	86
Contour 10	maize	25	32	100
		50	63	100
		75	95	97
		100	126	63

* Yield obtained at 50% PAWC is taken as 100%.

between irrigations (%).

FPAWC = Fraction of determined PAWC extracted between irrigations (%).

AF = Adjustment fraction, i.e. fraction of over or under estimation of PAWC (Table 6.2).

The obtained fractions of PAWC extracted between irrigations are listed in Table 6.4.

A statistically highly significant relationship was found between relative yield and fraction of adapted PAWC extracted (see Figure 6.19). The obtained curve predicts that relative yield losses will be the same at a certain percentage of adapted PAWC extracted, irrespective of crop (maize or wheat) or site.

Although adapted PAWC indicates the limit of water extraction at which no _statistically_ significant reduction in yield is found, it does already represent an average yield reduction of between 20 and 25 per cent. This magnitude of reduction is probably _economically_ unacceptable, especially since it is not accompanied by increased water use efficiency (Hensley, 1984, predicted that it would give increased water use efficiency).

From Figure 6.19 it is evident that up to a certain degree of water extraction yield reduction is really negligible. It can be considered that up to this point maximum yield is maintained. It can be seen that this maximum extraction for maintaining maximum yield is at 65% of adapted PAWC. For practical irrigation scheduling this will be a very important figure. This maximum extractable fraction for maintaining maximum yield is similar to what is normally termed "allowable depletion".

6.5 DISCUSSION

The obtained results indicate that there indeed exists a threshold fraction of PAWC beyond which yields are significantly reduced. This observation does not fit in with the current PAWC concept in which the lower limit of available water (first material stress) is defined by the water content in the soil at which plant physiological functions are reduced by 25% of their normal rate without yields being seriously affected (Hensley, 1984). The results obtained in this research show that under conditions of high evaporative demand there is a significant decrease in yield when the crops are allowed to extract water until well defined stress is reached.

In irrigated agriculture the input costs are very high and a reasonable return on the invested capital is expected. Therefore one cannot allow the soil to dry out to a point that yields are reduced too much (whatever the improved water use efficiency may be). This illustrates the importance of the threshold value beyond which yields are significantly reduced. The knowledge of this threshold value is vital for irrigation planning in general and for irrigation scheduling in particular.

In this chapter the term adapted PAWC was used to accommodate this new threshold value concept. Because of its substantial difference from PAWC in concept (it does not allow for significant reduction in plant physiological activity) and to avoid confusion it would perhaps be useful to introduce a new term for this threshold value concept. At this stage "Profile Extractable Water" (PEW) is proposed to describe this adjusted PAWC concept. PEW is simply defined as: "the amount of water that can be extracted from the soil profile by a specific crop without causing significant yield reductions". It is clear from the above mentioned results that this term does not give a vague definition of available water nor does it give arbitrarily chosen limits. From the production functions and with the "Cate-Nelson" method for partioning soil correlation data into two classes PEW could be exactly determined. In the following chapter a model for predicting PEW at untested sites is presented.

Obtained data suggest that below 65% extraction of PEW yields are at or close to maximum obtainable yield and if maximizing yield is the objective then no extraction of more than 65% PEW should be allowed (see Figure 6.19). This quantity will be referred to as "Profile Allowable Depletion" (PAD).

PEW and PAD are seen as fairly fixed constants for a specific soil-crop-atmosphere combination. The optimum degree of water extraction at which to irrigate may be a flexible quantity, which will depend upon the available resources (land and water) and production costs. For any specific case an "optimum extraction value" could be calculated by using PEW and the characteristic "Yield/PEW Fraction" function. Usually PAD will be expected to represent the optimum extraction value.

The crop water stress indicators used in this research

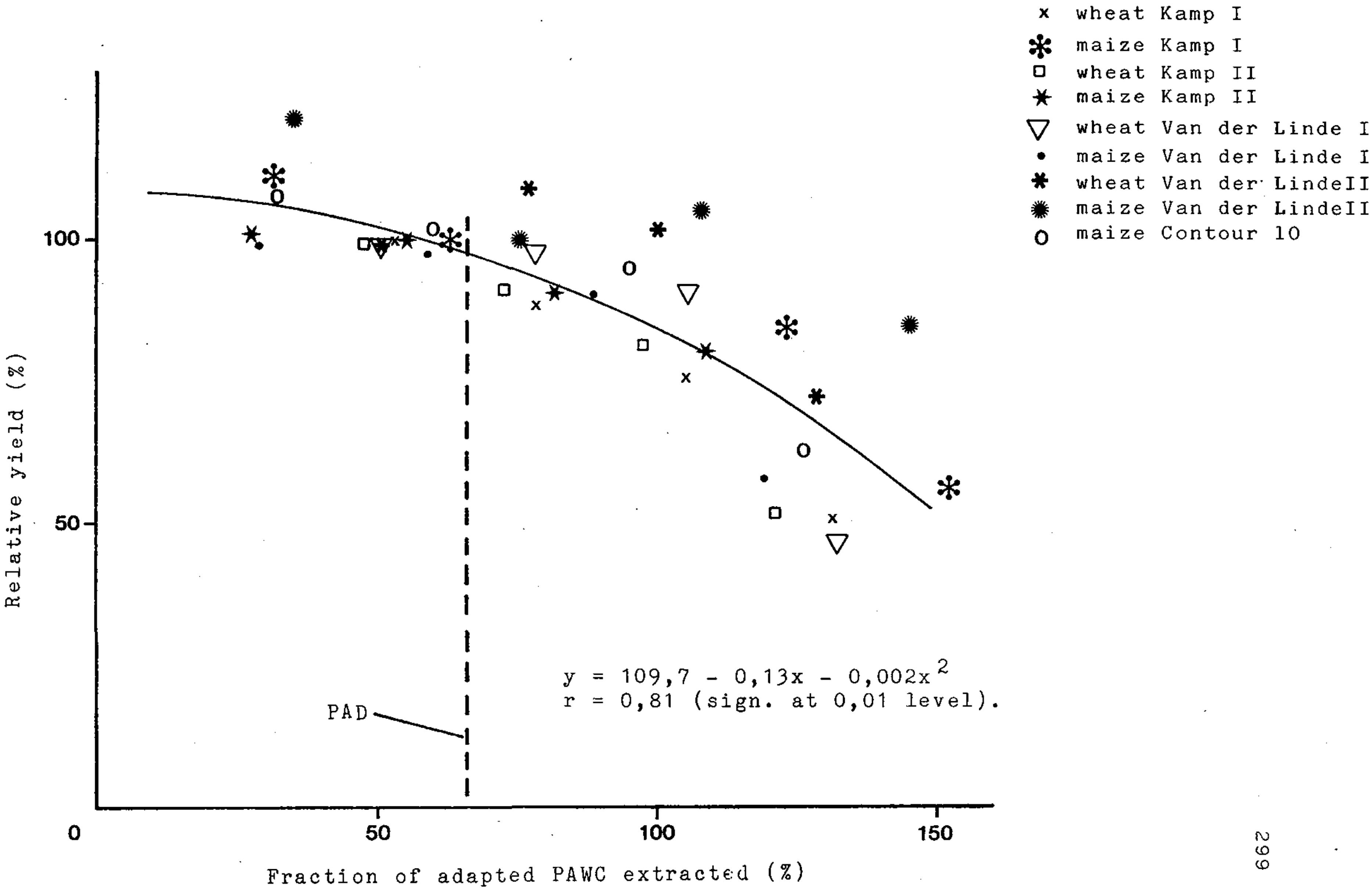


FIG.6.19 Relative yield curve for different fractions of adapted PAWC (PEW) extracted. The dashed line suggest up to what fraction of PEW (PAD) can be extracted before yield decrease below maximum yield.

(visual stress symptoms; pre-dawn leaf water potential readings) failed to indicate the onset of stress in the crops during summer. Pre-dawn leaf water potential therefore consistently overestimated PEW during summer time.

CHAPTER 7

MODELS FOR ESTIMATING PAWC AND PEW FOR SOILS UNDER IRRIGATION, USING SIMPLE PHYSICAL AND CHEMICAL SOIL PROPERTIES

7.1 INTRODUCTION

The capacity of soils to retain water and make it available to plants is an extremely important determinant in the evaluation of the suitability of a soil for irrigation. Direct experimentation to assess available water is obviously the best method, but this is often not possible and too tedious for researchers involved in land evaluation and planning. A close approximation of this capacity of soils would in many situations be very helpful.

The determination of this soil parameter in the classical concept of soil available water (being the difference between soil moisture content at -10 or -33 kPa and -1500 kPa) is quite laborious and often fails to give reliable results when compared with field observation of available water (Hillel, 1980; Skaggs et al, 1980; Ritchie, 1981; Hensley & De Jager, 1982; Ratliff et al, 1983).

A model to estimate available water will have to be based on scientifically sound principles and should be "molded by the reality of direct experimentation" (Hsiao et al, 1980).

Cassel et al (1983) developed models for estimating in situ potential extractable water (PLEXW). Their models are based on numerous field observations and give results that are easily applicable in real life conditions. Their models originated from observations under dryland farming conditions. Their use for irrigated agriculture is limited because a very harsh lower limit, at which plants virtually die, is used. An arbitrary fraction of the extractable water predicted by these models is usually taken as allowable depletion for irrigated crops (see Chapter 5). Alternatively allowable depletion is determined by trial and error methods. These approaches are considered to have limitations for application in irrigation scheduling.

Hensley & De Jager (1982) predicted "Profile Available

Water Capacities" (PAWC) for untested sites using rooting characteristics, bulk density and soil water contents at -10 kPa and -1500 kPa. Although the model specified available water for irrigated crops quite accurately, the models require data for soil parameters that are cumbersome to determine (soil water content at -10kPa and -1500 kPa, bulk density).

Laker (1982) proposed a model for predicting PAWC for irrigated maize on medium-textured to clayey Ciskeian soils, using only rooting depth as independent variable. The model allowed for a quick assessment of available water in the soil profile, while maintaining a high degree of accuracy. The model originated because the data of Hensley & De Jager (1982) revealed that rooting depth was the absolutely dominant factor determining PAWC for these soils. Laker (1982) expected that this model would not be valid for sandy and extremely clayey soils.

A major objective of the present study was to extend PAWC models to include a wide range of soils from different areas.

7.2 MODELS FOR PREDICTING PAWC FOR WHEAT

7.2.1 Procedures

PAWC was determined at several sites in different regions. The upper and lower limits used during the study were outlined in Chapter 2. At each site an accurate profile description was made and samples were taken from each pedogenetic horizon (see Appendices 2.1 to 2.19).

From the data collected in the field and determined in the laboratory a number of variables, expected to have an important impact on soil available water were selected: effective rooting depth, organic carbon, cation exchange capacity, soil structure, silt and clay content, field measured field capacity.

It is obvious that effective rooting depth has an important impact on profile available water. This impact has two aspects: (1) The total depth of the profile is important. (The deeper the effective rooting the more water is available) (2) The depth at which a specific soil layer occurs has an influence on the amount of water that can be extracted from it (see model Laker (1982); see also Chapter 2).

Although organic carbon as such does not have a high moisture holding capacity, its impact on soil structure and consequently porosity and storable water are important (Buckman & Brady, 1969).

Cation exchange capacity is a reflection of the amount of clay present in a soil and of its clay mineralogy.

Soil texture, especially the fine fraction (silt and clay), influences the soil moisture retention characteristics. This is illustrated in Figure 7.1 where field capacity and permanent wilting point (upper and lower limit of available water in the classical concept) are shown as functions of the soil texture.

Soil structure influences root development and porosity and thereby availability of water. This is shown by the relatively smaller amounts of water extracted from strongly structured soils during the present experiments (e.g. wheat on Sterkspruit soil). In an attempt to quantify this qualitative soil characteristic the ratio of (Na + Mg) to total exchangeable cations, expressed as

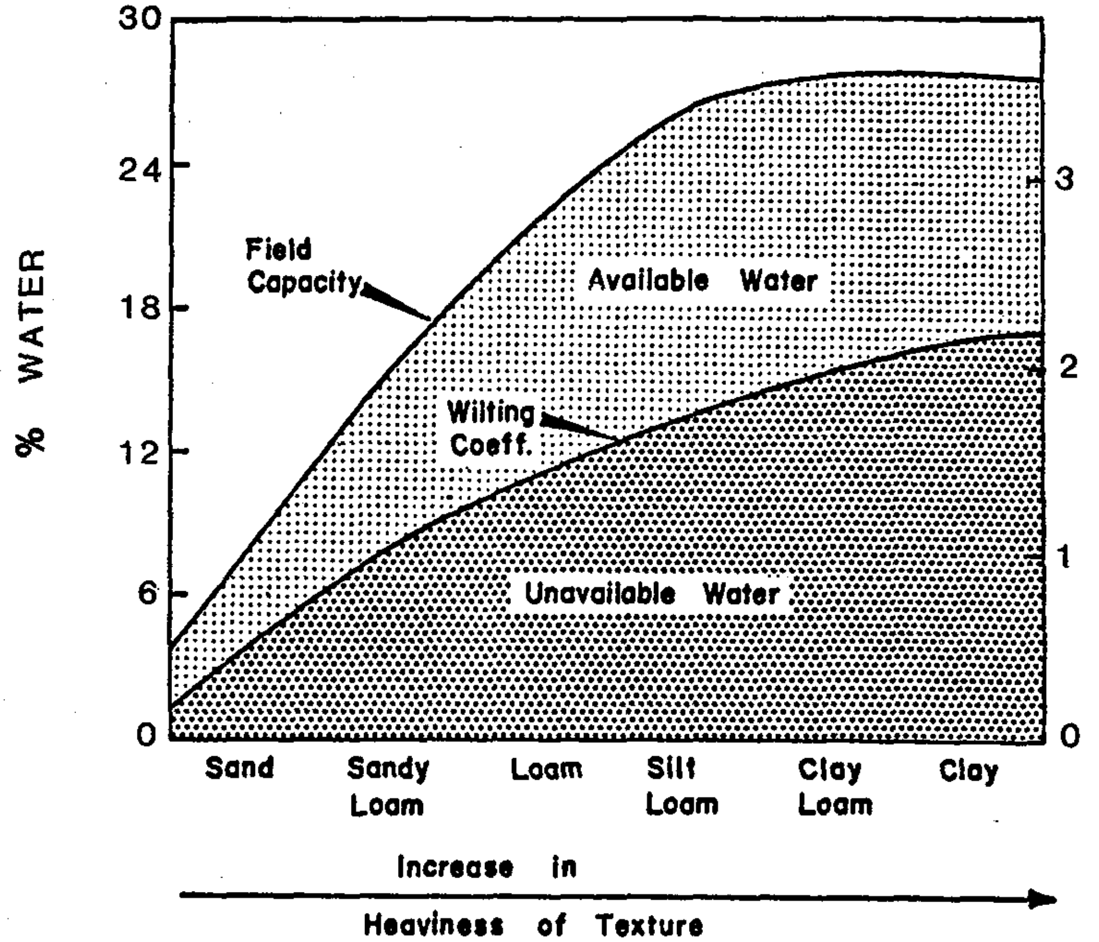


FIG.7.1 The general relationship between soil water characteristics and soil texture (from Buckman & Brady, 1969).

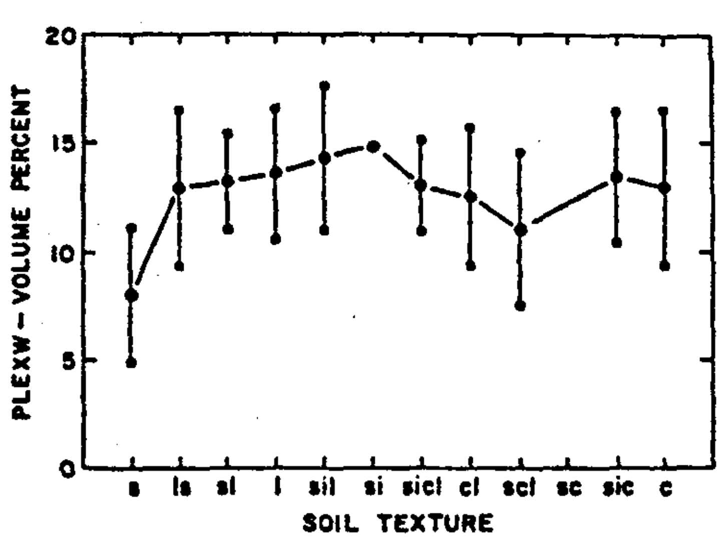


FIG.7.2 Change in PLEXW value with soil texture (from Ratliff <u>et</u> <u>al</u> , 1983).

a percentage, was calculated (Verheye, 1984, personal communication). This so-called structure index (S.I.) gave a fairly good reflection of the degree of structure encountered. Field capacity was selected because it reflects the totality of factors affecting water holding capacities of soils.

7.2.2 Results and discussion

Available water data, expressed as available water index (AWI = amount of available water in a 10cm thick layer of a specific horizon),are given in Table 7.1. Data are grouped per pedogenetic horizon. Depth index is the (lower limit + higher limit) of the pedogenetic horizon divided by two and reflects the depth at which the horizon is occurring.

7.2.2.1 General

Laker (1982) indicated that his model would have to be adapted or would not be applicable on sandy or clayey soils. The continuous soil water content monitoring during the PAWC determination experiments at Vaalharts

TABLE 7.1. List of soil data used to develop PAWC models for wheat.

D.I. (cm)	A.W.I. (mm/10cm)	O.C. (%)	C.E.C. (meq/100g)	S.I. (%)	F.C. (%)	SICL (%)
10	13,0	0,26	6,4	40	18,3	8,1
31	12,9	0,16	8,8	24	19,7	14,1
54	12,9	0,13	11,0	38	21,0	13,8
14	12,9	0,24	12,6	41	23,2	16,8
39	14,8	0,17	19,2	52	31,5	29,2
59	15,5	0,10	16,4	69	36,8	29,9
12	8,7	0,23	7,0	28	13,0	8,6
37	8,3	0,18	4,8	45	14,8	10,0
67	8,2	0,11	7,0	41	17,3	11,2
142	7,7	0,10	12,0	41	22,2	14,4
38	8,1	0,23	6,0	38	13,2	7,2
88	7,7	0,11	5,6	52	16,6	11,2
150	6,4	0,11	8,0	42	20,5	13,6
8	9,8	0,21	5,2	36	13,0	8,9
61	9,1	0,12	7,2	35	13,4	11,0
148	9,2	0,07	6,0	38	20,5	13,4
10	23,3	1,03	22,8	27	33,0	80,3
35	11,6	0,71	12,2	30	33,4	84,3
70	9,2	0,31	22,4	41	35,0	86,0
110	7,3	0,26	29,0	48	43,0	85,9
5	19,1	0,56	16,0	29	26,8	56,7
18	16,3	0,51	15,6	30	26,8	52,9
46	12,7	0,43	18,0	30	26,8	57,9
79	7,7	0,23	15,0	34	26,8	55,8
106	3,8	0,13	17,0	40	26,8	52,9
11	22,0	0,94	14,8	36	32,0	74,8
28	18,0	0,80	17,0	28	31,2	74,0
45	13,4	0,47	18,0	54	29,6	76,2
74	11,4	0,23	21,0	43	31,0	81,8
10	24,3	0,72	20,4	27	31,2	71,8
45	15,7	0,64	22,0	37	29,4	74,1
85	8,1	0,40	24,0	33	29,6	73,0
11	14,8	0,54	12,4	34	24,8	51,8
28	11,7	0,51	14,4	35	25,0	48,4
48	7,3	0,33	32,8	65	33,0	79,7
73	7,3	0,11	24,4	66	37,0	70,8
91	3,3	0,10	28,4	68	32,5	62,2

A.W.I. = Available water index: available water (mm) per 10cm of a pedogenetic horizon
D.I. = Depth index (cm)
O.C. = Organic carbon content (%)
C.E.C. = Cation exchange capacity (meq./100 g. soil)
S.I. = Structure Index (%)
F.C. = Soil water content at depth index at field capacity
SICL = Silt + clay (%)

(dominantly sandy Hutton soils) confirmed that the available soil water characteristics differed considerably from what was observed for the more clayey soils of the Ciskei. In sandy textural ranges available water increases with increasing clay content. This increase continues until a certain textural composition is reached above which the available water remains more-or-less constant. This is clearly illustrated in Figure 7.1: in soils with textures heavier than loam the available water between field capacity and permanent wilting point stays more-or-less constant. Ratliff *et al* (1983) observed this also for their PLEXW (see Chapter 2) values. PLEXW stays almost constant in the texture range loam to clay (see Figure 7.2). Field measured field capacities obtained during the present study were plotted against (silt + clay) content (Figure 7.3). The Cate-Nelson method identified 20% (silt + clay) as the value above which texture had no effect on field capacity. As field capacity is partly reflecting the moisture characteristics of a soil it was decided to use 20% (silt + clay) as a first approximation to divide soils into sandy and clayey subgroups.

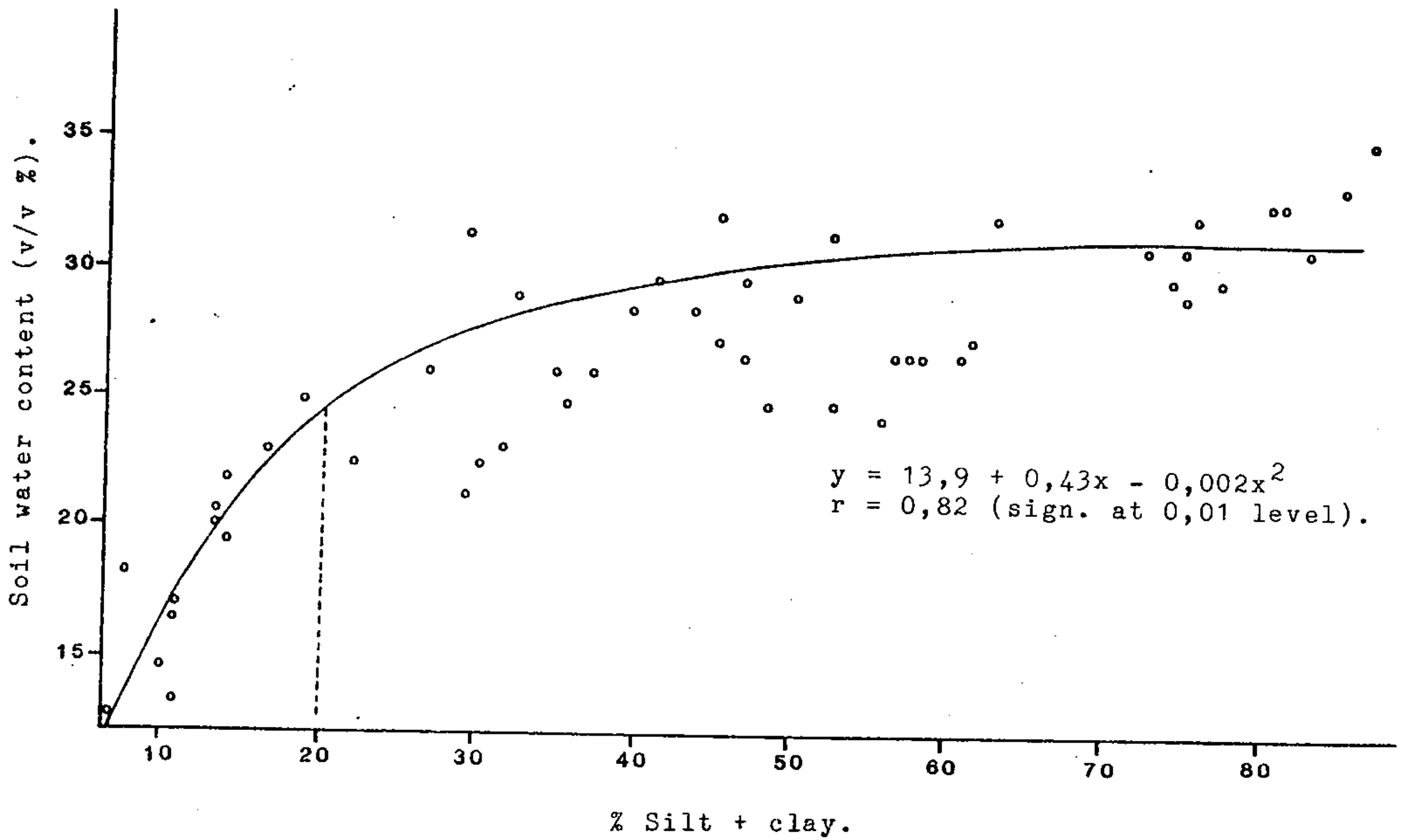


FIG.7.3 Relationship between soil water content at Field Capacity and percentage (silt + clay) in a soil.

7.2.2.2 Models for predicting PAWC for wheat for soils containing less than 20% silt + clay

Table 7.2 indicates the correlations between the selected variables and available water. It is clear that field capacity, C.E.C. and (silt + clay) percentages are having an almost similar correlation with available water. This was expected because the parameters are partly dependent upon each other: C.E.C. is a reflection of the clay content of a soil. Field capacity is closely related to clay content in sandy soils (see Figure 7.3). The "truly" independent variable of the three, viz. silt + clay was, therefore, selected to be used together with depth index in a simple multiple regression.

Preference was, furthermore, given to silt + clay content and depth index , above the other variables (C.E.C., F.C., SI-index and O.C. content) because of the ease with which both parameters can be determined. Organic carbon and Structure Index were omitted because of too low correlations with available water.

The equation was:

$$y = 0{,}31x_1 - 0.03x_2 + 7{,}93 \qquad (7.1)$$

with y = available water per 10 cm of a certain pedogenetic horizon.

TABLE 7.2 Correlation coefficients between the different soil variables and AWI for wheat.

Soils containing		DI	OC	SI	FC	SiCl	CEC
less than 20% (silt + clay)	AWI	-0,48	0,21	0,31	0,70	0,68	0,70
more than 20% (silt + clay)	AWI	-0,87	0,36	-0,64	-0,18	0,07	-0,37

A.W.I. = Available water index: available water (mm) per 10cm of a pedogenetic horizon
D.I. = Depth Index (lower + higher limit of horizon / 2)
O.C. = Organic carbon content (%)
C.E.C. = Cation exchange capacity (meq./100 g. soil)
S.I. = Structure Index (%)
F.C. = Soil water content at depth index at field capacity
SICL = Silt + clay (%)

x_1 = (silt + clay) percentage

x_2 = depth index (cm)

r = correlation coefficient = 0,87

F (2,13) = 20,222 (significant at the 0,01 level)

Table 7.3 compares the observed and calculated values for PAWC for wheat.

PAWC for the whole soil profile is given by

$$PAWC = \sum_{i=1}^{i=n} \frac{di}{10} (0,31x_1 - 0,03x_2 + 7,93) \qquad (7.2)$$

with n = number of the ith pedogenetic horizon

di = thickness of the ith pedogenetic horizon in cm

x_1 and x_2 as for Equation (7.1).

The obtained regression could be tested for wheat on a Mangano soil from Taung, near Vaalharts. (See Table 7.4 for the necessary soil parameters). Human _et al_ (according to Hensley & De Jager, 1982) found a PAWC of 132 mm for mature wheat at this site. The model predicted 134,9 mm.

TABLE 7.3 Observed and predicted values for soils containing less than 20% silt + clay.

AWI = mm of water available per 10cm of a pedogenetic horizon.
EWI = mm of extractable water per 10cm of a pedogenetic horizon.

WHEAT		MAIZE	
Observed AWI (mm/10cm)	Predicted AWI (mm/10cm)	Observed EWI (mm/10cm)	Predicted EWI (mm/10cm)
13,0	10,1	10,1	7,2
12,9	11,3	8,1	8,2
12,9	10,5	6,6	7,7
12,9	12,7	12,2	9,2
14,8	15,8	11,8	11,6
15,5	15,4	10,5	11,4
8,7	10,2	5,6	7,3
8,3	9,2	4,5	6,3
8,2	9,3	6,3	6,8
7,7	7,9	5,3	6,5
8,1	9,0	6,5	6,4
7,7	8,6	6,2	6,4
6,4	7;4	6,2	6,2
9,8	10,5	7,4	7,4
9,1	9,4	6,6	6,9
9,2	7,4	8,8	6,0

TABLE 7.4 . Characteristics of Mangano soil at Taung (near Vaalharts).

Horizon	Depth (mm)	DI(cm)	SiCl(%)
Ap	0 - 22	11	11,1
B21	22 - 57	40	12,1
B22	57 - 120	89	12,5
B23	120 - 140	130	14,0

7.2.2.3 Models for wheat for soils containing more than 20% silt + clay

Table 7.2 shows the correlation coefficients between the different soil variables. Soils from the Ciskei and Vaalharts were used together.

The correlations between field capacity, (silt + clay) content and available water (or extractable water, since PAWC and PEW for wheat are equal) are insignificant (see Table 7.2). Depth index and structure index are the dominant parameters. Organic carbon was not selected because of its close relationship with soil depth and because data for organic carbon are often not available for subsoil horizons.

A multiple regression analysis with depth index and structure index as independent variables was done. The regression equation obtained for wheat is:

$$y = 24{,}00 - 0{,}13x_1 - 0{,}12x_2 \qquad (7.3)$$

with y = available or extractable water per 10 cm of a specific pedogenetic horizon

x_1 = depth index (cm)

x_2 = structure index (%)

$r = 0{,}89$

$F\ (2{,}18) = 35{,}83$ (significant at the 0,01 level).

The observed values of available (extractable) water and the values obtained with the regression equation are compared in Table 7.5.

The PAWC value for a whole soil profile is given by

$$PAWC = \sum_{i=1}^{i=n} \frac{di}{10} \quad (24{,}00 - 0{,}13x_1 - 0{,}12x_2) \qquad (7.4)$$

with n = number of pedogenetic horizons

di = thickness of the ith horizon in cm.

x_1 = depth index

x_2 = structure index

This equation was tested for a Shorrocks soil in the Ciskei. Table 7.6 given the parameters required for the calculation of PAWC with the proposed equation. For mature wheat Hensley (1982) found a PAWC value of 131 mm (the average of two determinations: 125 and 137 mm) for this soil. The equation predicted it to be 122,9mm.

TABLE 7.5 Observed and predicted values for soils containing more than 20% silt + clay

AWI = mm of available water per 10 cm of a pedogenetic horizon
EWI = mm of extractable water per 10cm of a pedogenetic horizon

WHEAT		MAIZE	
Observed AWI (mm/10cm)	Predicted AWI (mm/10cm)	Observed AWI (mm/10cm)	Predicted AWI (mm/10cm)
23,3	19,5	12,5	12,7
11,6	15,8	12,5	10,8
9,2	9,8	10,5	8,5
7,3	3,6	5,8	5,9
19,1	19,9	15,1	12,7
16,3	18,1	9,4	8,8
12,7	14,3	1,5	3,0
7,7	9,4	11,4	13,0
3,8	5,1	6,7	9,9
22,0	18,3	4,4	3,5
18,0	17,0	13,0	13,0
13,4	11,6	9,6	10,5
11,4	9,0	3,8	4,2
24,3	19,5	11,3	12,9
15,7	13,6	7,6	8,9
8,1	8,7	5,4	5,2
14,8	18,5	15,7	13,2
11,7	16,1	10,4	11,9
7,3	9,9	12,7	9,3
7,3	6,5	9,2	6,6
3,3	3,8	13,9	13,1
		9,6	11,6
		8,5	9,8
		5,4	7,0

TABLE 7.6 Horizons, depth indexes and structure index for a Shorrocks soil (Ciskei)

Horizon	Depth (mm)	DI(cm)	SI(%)
Ap	0 - 25	13	22
B21	25 - 40	33	23
B22	40 - 60	50	33
B31	60 - 80	70	36
C1	80 - 100	90	30*

*Estimate

7.3 MODELS FOR PREDICTING PEW FOR WHEAT AND MAIZE

PEW was calculated for the different experimental sites as outlined in Chapter 6. For wheat PEW values are almost identical to the determined PAWC values. For maize differences between PAWC and PEW can be considerable (see Chapter 6). PEW will be dependent upon the same factors as PAWC, since both represent plant-available water. PEW models were therefore developed along the same lines as the PAWC models.

For wheat no new models are proposed. As PAWC is almost identical to PEW for wheat the equations obtained in paragraph 7.2 can be used to determine PEW for wheat. For maize new equations had to be derived. As with wheat the soils were grouped into two textural classes. The data used, are listed in Table 7.7.

7.3.1 Model for predicting PEW for maize on soils containing less than 20% silt + clay

Table 7.8 indicates the selected variables which have an important impact on PEW for maize. As expected, the same soil parameters as with wheat are dominantly influencing

TABLE 7.7 List of soil data used to develop the PEW models for maize.

D.I. (cm)	E.W.I. (mm/10cm)	O.C. (%)	C.E.C. (meq/100g.)	S.I. (%)	F.C. (%)	SICL (%)
10	10,0	0,26	6,4	40	18,3	8,1
31	8,1	0,16	8,8	24	19,7	14,1
54	6,6	0,13	11,0	38	21,0	13,8
14	12,2	0,24	12,6	41	23,2	16,8
39	11,8	0,17	19,2	52	31,5	29,2
59	10,5	0,10	16,4	69	36,8	29,9
12	5,6	0,23	7,0	28	13,0	8,6
37	4,5	0,18	4,8	45	14,8	10,0
67	6,3	0,11	7,0	41	17,0	11,2
142	5,3	0,10	12,0	41	22,2	14,4
38	6,5	0,23	6,0	38	13,2	7,2
88	6,2	0,11	5,6	52	16,6	11,2
150	6,2	0,11	8,0	42	20,5	13,6
8	7,4	0,21	5,2	36	13,0	8,9
61	6,6	0,12	7,2	35	13,4	11,0
148	8,8	0,07	6,0	38	20,5	13,4
13	12,5	0,43	12,4	29	27,3	31,0
34	12,5	0,32	12,4	29	27,6	42,2
62	10,5	0,20	16,0	47	29,1	46,7
90	5,8	0,17	16,0	44	27,0	45,0
13	15,1	0,41	11,6	29	26,3	34,3
58	9,4	0,15	15,0	41	24,8	46,7
120	1,5	0,07	15,2	26	24,5	54,9
10	11,4	0,33	12,0	38	23,2	25,5
45	6,7	0,20	12,0	47	21,6	29,1
115	4,4	0,18	12,6	51	22,9	30,5
10	13,0	0,35	9,6	31	26,5	26,6
38	9,6	0,16	14,0	44	26,0	28,8
108	3,8	0,16	15,2	48	25,1	34,5
11	11,3	0,67	18,0	31	32,0	37,8
57	7,6	0,27	31,2	37	26,9	59,0
96	5,4	0,12	25,0	26	27,7	55,6
7	15,7	0,41	10,8	30	26,0	28,6
22	10,4	0,32	10,8	36	22,9	26,3
52	12,7	0,27	18,0	48	29,7	37,2
83	9,2	0,19	20,8	54	32,3	42,0
9	13,9	0,36	11,6	32	29,6	31,3
26	9,6	0,33	13,2	37	26,3	33,6
47	8,5	0,23	19,2	41	29,6	43,7
79	5,4	0,17	20,0	53	31,8	52,2

E.W.I = Extractable water index: extractable water per 10cm of a pedogenetic horizon (mm/10cm).
D.I. = Depth Index (cm)
O.C. = Organic carbon content (%)
C.E.C. = Cation exchange capacity (meq./100g. soil)
S.I. = Structure Index (%)
F.C. = Soil water content (v/v %) at depth index at field capacity
SICL = Silt + clay content (%).

PEW. It is notable that the correlation coefficients in general are lower than in the case of wheat. (Silt + clay) content together with depth index and structure index were selected to be used in a multiple regression equation.

The obtained multiple regression equation was:

$$y = 6,1 + 0,26x_1 - 0,02x_2 - 0,02x_3 \qquad (7.5)$$

with y = extractable water index (mm/dm)

x_1 = silt + clay content (%)

x_2 = structure index (%)

x_3 = depth index (cm)

$r = 0,73$

$F(2,13) = 7,4$ (significant at the 0,01 level)

Table 7.3 compares the observed and calculated values for PEW for maize for soils containing less than 20 % (silt + clay).

The PEW for a soil profile is calculated with:

$$PEW = \sum_{i=1}^{i=n} \frac{di}{10} (6,1 + 0,26x_1 - 0,02x_2 - 0,02x_3) \qquad (7.6)$$

TABLE 7.8 Corelation coefficients between the different soil variables and EWI for maize.

Soils containing		DI	OC	SI	FC	SICL	CEC
less than 20% (silt + clay)	EWI	-0,28	-0,23	0,34	0,67	0,64	0,63
more than 20% (silt + clay)	EWI	-0,88	0,72	0,36	0,20	-0,51	-0,41

E.W.I = Extractable water index: extractable water per 10cm of a pedogenetic horizon (mm/10cm).
D.I. = Depth Index (cm)
O.C. = Organic carbon content (%)
C.E.C. = Cation exchange capacity (meq./100g. soil)
S.I. = Structure Index (%)
F.C. = Soil water content (v/v %)at depth index at field capacity
SICL = Silt + clay content (%).

with n = number of the ith pedogenetic horizon

d_i = thickness of the ith pedogenetic horizon (cm)

x_1 = silt + clay content

x_2 = structure index

x_3 = depth index

7.3.2 Model for PEW for maize on soils containing more than 20 % silt + clay

For maize it was found that in fact only depth index and organic carbon content were having a significant correlation with EWI (see Table 7.2). Therefore only linear regression analysis with depth index was done for maize (note: Laker's model (1982) used also only depth to predict PAWC for maize).

The equation obtained was:

$$y = 13{,}91 - 0{,}09x \qquad (7.7)$$

with y = EWI (mm/10cm)

x = depth index (cm)

$r = 0{,}88$

$F\ (1{,}22) = 78{,}544$ (significant at the 0,01 level).

The observed values were compared with calculated values (Table 7.5).

The PEW value for the whole soil profile is calculated with the equation:

$$PEW = \sum_{i=1}^{i=n} \frac{di}{10} \; (13{,}91 - 0{,}09x) \qquad (7.8)$$

with n = number of pedogenetic horizons.

di = thickness of the ith horizon (cm).

x = depth index

7.4 CONCLUSIONS

Highly significant regression equations could be developed for predicting PAWC for wheat and PEW for maize and wheat. The models give the possibility to assess PAWC and PEW quickly and with a high degree of accuracy for soils from different textural classes.

By improving the technique for determining the lower limit of PEW, especially under conditions of high evaporative demand, it will be possible to perfect the models for maize. Soils containing less than 20% (silt + clay) especially require additional studies.

Soil depth is an important parameter for all models and illustrates hereby that in evaluating soils for irrigation primary attention should be given to the effective rooting depth.

Similarity was found for models developed on different soils from different regions. This illustrates that general models could be used over a wide area until more accurate regional models are developed.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The "plant available water capacity" (PAWC) concept of Hensley & De Jager (1982) was developed in an attempt to provide a scientifically sound criterion for plant available water which would be useful in an irrigation situation. The aim was to improve upon the rather arbitrary and/or artificial methods which are normally employed to determine this parameter. The emphasis was on obtaining field determined values.

Hensley & De Jager (1982) obtained very promising results with their approach. Very interesting simple models for estimating PAWC at untested sites were developed. During this pioneering phase of the PAWC research Hensley & De Jager (1982) could not get to the point of critically evaluating the PAWC concept by means of extensive comparative irrigation scheduling studies. Due to the pioneering nature of the work their data were for a limited geographical area with a relatively uniform climatic regime. Studies on certain other types of soils, especially sandy soils, were also still required. These research needs were recognised and the research reported here was undertaken to supplement the work of Hensley & De Jager (1982) in order to fill these gaps.

Studies in the Ciskei on sites similar to those used by Hensley & De Jager (1982) yielded results which were almost identical to theirs. This indicated that the PAWC concept gives reproducible results, even if determined by completely different researchers.

During summer at Vaalharts and Loskop, when very high evaporative demands prevailed, serious problems in regard to identification of the lower limit of PAWC were encountered. Both visual symptom criteria (wilting by 10h00) and pre-dawn leaf water potential monitoring were unsuitable for identification of the lower limit. It was found that "well defined stress" over-estimated the critical point beyond which significant yield reduction starts to by 25 to 30%.

By means of the simple Cate-Nelson statistical method the threshold soil water content at which significant yield losses start to occur could be identified from the irrigation scheduling results. This water content more-or-less coincides with "initial stress" (as defined by Hensley & De Jager, 1982). In order to avoid confusion, this adjusted PAWC value is called "Profile Extractable Water" (PEW). Profile extractable water is defined as:

> "The amount of water that can be extracted from a specific soil profile by a specific crop (cultivar, growth stage) without causing significant yield reduction."

PEW differs fundamentally from PAWC because it does not allow for significant reduction in plant physiological functioning. Futhermore, the lower limit is strictly defined by the "significant yield loss" condition which is statistically defined.

For each of maize and wheat a characteristic common yield function, relating relative yield to relative fraction of PEW extracted between irrigations, was derived. Models relating PEW to simple soil parameters were also derived. Different models were derived for soils with less than

20% (silt + clay) and those with more than 20% (silt + clay). By combining the Yield/PEW and PEW/Soil Parameter functions, _relative_ yield at extraction of a specific _quantity_ of water by a specific crop on a specific soil can be predicted. If an estimate can be made of the maximum potential yield on the specific soil, then this can be used to estimate yields at extraction of different quantities of water, for a specific crop on a specific soil. These could be combined with cost (fertilizer, etc.)/benefit analyses to take scheduling decisions.

Although PEW represents a limit of no _statistically_ significant yield reduction, yields are already reduced by 20 to 25% at this point of water extraction. From the Yield/PEW Fraction function it is seen that practically no yield reduction occurs at extraction up to 65% PEW. This will normally be the maximum permissible extraction, in order to combine the benefits of maximum yield at least frequent irrigation applications, and is called "Profile Allowable Depletion" (PAD).

Studies of the relationships between yield and consumptive use of water revealed a direct relationship between these two parameters. This means that water use efficiency could not be improved by reducing consumptive use. This agrees with the results of Hanks (1982) and his co-workers and others. The relationships found in this study were in fact almost identical to those of Hanks (1982) and his co-workers.

The Bureau of Reclamation (1983) has indicated that wet surface soil evaporation during early growth stages, i.e. before full canopy development is reached, may be an important cause of unproductive loss of water. Measures aimed at reduction of this type of loss may improve water use efficiency, according to the Bureau of Reclamation (1983). In the present study differential treatments were unfortunately not applied during these early growth stages.

A deficit irrigation treatment applied during a lysimeter study in 1982 yielded increased water use efficiency. Planned deficit irrigation apparently has possibilities as a measure to increase water use efficiency (Miller, 1977; English & Nakamura,1982).

Daily studies of the evolution of water extraction patterns in the soil profiles revealed that PEW represents a threshold between a phase during which extraction from the upper parts of a profile exceeds extraction from the lower parts and a phase during which the reverse is true. When water extraction from the bottom parts of the part of a profile starts to dominate, production is reduced sharply.

Daily soil water monitoring, combined with Class A pan data, revealed that "crop factors" were strongly dependent upon the degree of water extraction over time. Generalized crop factors cannot be considered to be valid. They tend to over-estimate consumptive use. In the U.S.A. major increases in irrigation water use efficiencies were effected by doing irrigation scheduling according to actual soil water monitoring with neutron probes instead of relying upon crop factors.

The present research underlined the importance of conducting studies of this nature on a variety of soils. One or two experiments on selected soils may give totally misleading results if these are generalized.

8.2 RECOMMENDATIONS

8.2.1 Research

Further research with regard to improved definition and determination of the lower limit of available water, especially under conditions of very high evaporative demand, is required. This will have to include basic plant physiological studies. Combination of plant parameters with evaporative demand, similar to the "Crop Water Stress Index" concept of Reginato and his co-workers should receive attention.

Crop root parameters should receive attention, with special emphasis on the relative importance of radial and axial resistance.

Further irrigation scheduling studies, based upon the PEW concept, on larger plots than those used during the present study are required. Field-scale on-farm testing should be the ultimate phase. Differential scheduling studies during early growth stages are essential, as well as field-testing of deficit irrigation.

8.2.2 Practical on-farm scheduling

In the U.S.A. large increases in irrigation water use efficiencies have been achieved by the use of the new, highly efficient neutron probes for in-field soil water monitoring. The main exponents of these are Hill in Utah

(Laker, 1983) and the Bureau of Reclamation (Buchheim & Ploss, 1977; Conway & Carter, undated). The monitoring system is not only used to assist the farmer in regard to decision-making on when to irrigate and how much water to apply, but is very effectively used by the water controllers on irrigation schemes to project how much water will be required in a specific section of a scheme on a specific date. Much more meaningful distribution of water in main supply canals is achieved in this way, to ensure that water will be available to farmers where they need it when they need it. There is no reason why these very simple systems cannot be implemented in South Africa immediately.

The biggest weakness in the systems of Hill and the Bureau of Reclamation is the fact that the lower limit (i.e. the soil water content at which to irrigate), also called the "refill line" or "allowable depletion" is either decided upon arbitrarily or determined on a trial-and-error basis for each case (Buchheim & Ploss, 1977; Conway & Carter, undated).

The pioneering work of Hensley & De Jager (1982) in regard to PAWC and the results of the present study provides a much sounder foundation for estimating a meaningful "profile allowable depletion". Although it is still a very long way to go, the present models could already be used advantageously for at least two important crops (wheat and maize). Most important is that a principle has been developed which could, especially upon completion of the proposed additional research, be extended quite easily to other crops and situations.

In regard to the breeding of high yielding wheat and maize cultivars, Winkleman of CIMMYT once stated: "We do not have a technology (i.e. an adapted cultivar) for all situations, but we have developed a technology to develop suitable technologies" (Laker, 1978 b). The same could hopefully be said about the work of Hensley & De Jager (1982) and the present study.

REFERENCES

BARRS, H.D. 1968. Determination of water deficits in plant tissues. In: Water Deficits and Plant Growth (Kozlowski, T.T.,ed.), 235-368. New York: Academic Press.

BENNIE, A.T.P. 1972. 'n Ondersoek na sekere aspekte van grondsterkte in gronde van die Manganoserie. M.Sc. Thesis. Bloemfontein: U.O.F.S.

BENNIE, A.T.P. & BURGER, R. du T. 1979. Grondverdigting onder besproeiing op die Vaalhartsbesproeiing= skema. Volume II: Die invloed van grondverdigting op die grond-plant sisteem. Dept. Grondkunde. Verslag Nr 79/2. Bloemfontein: U.O.F.S.

BERLINER, P., OOSTERHUIS, D.M. & GREEN, G.C. 1984. Evaluation of the infrared thermometer as a crop stress detector. Agr. and Forest Met. 31, 219-230.

BOTHA, F.J.P., & BENNIE, A.T.P. Water uptake by maize and wheat: II. Critical evaluation of soil-root contact resistance. Paper presented at the 11th national congress of the Soil Science Society of South Africa, Stellenbosch.

BOTHA, F.J.P., BENNIE, A.T.P. & BURGER R. du T. 1983. Water use efficiency of irrigated crops as influenced by varying cultivation practices and root configurations. Bloemfontein: U.O.F.S.

BRIGGS, L.J. & SHANTZ, H.L. 1921. The relative wilting coefficient for different plants. Bot. Gaz. 53, 229-235.

BUCHHEIM, J.F. & PLOSS, L.F. 1977. Computerized irrigation scheduling using neutron probes. St. Joseph, Michigan: ASAE.

BUCKMAN, H.O. & BRADY, N.C. 1969. The nature and properties of soils. London: Collier-Macmillan.

BUREAU OF RECLAMATION 1983. Estimating agricultural crop water requirements. Denver: Bureau of Reclamation.

BURGER, R.du T., BENNIE, A.T.P., BOTHA, F.J.P. & DU

PREEZ, C.C. 1979. Grondverdigting onder besproeiing op die Vaalhartsbesproeiingskema. Bloemfontein: U.O.F.S.

CASSEL, D.K., RATLIFF, L.F. & RITCHIE, J.T. 1983. Models for estimating in-situ potential extractable water using soil physical and chemical properties. Soil Sci. Soc. Am. J. 47, 764-769.

CATE, R.B. & NELSON, L.A. 1971. A simple statistical procedure for partitioning soil test correlation data into two classes. Soil Sci. Soc. Amer. Proc. 35, 658-660.

COWAN, I.R. 1965. Transport of water in the soil-plant atmosphere system. J. Appl. Ecol. 2, 221-229.

CARTER, V.H. & CONWAY, S. Undated. Predicting irrigation dates and amounts with a neutron moisture gage. Denver: USBR.

DOORENBOS, J. & KASSAM, A.H. 1979. Yield response to water. F.A.O. Irrigation and drainage paper No.33. Rome: F.A.O.

DOORENBOS, J & PRUITT, W.O. 1977. Crop water requirements. F.A.O. Irrigation and drainage paper No.24. Rome: F.A.O.

DREYER, J. 1983. Verslag van 'n studietoer na die Verenigde State van Amerika vir 'n ondersoek na fisiologiese en verwante navorsing op grondbone en sojabone. Potchefstroom: NIGG.

ELOFF, J.F. 1984. Die grondhulpbronne van die Vrystaatstreet. Ph.D. Thesis. Stellenbosch: Univ. Stell.

ENGLISH, M.J. & NAKAMURA, B.C. 1982. Deficit irrigation: Effects of irrigation frequency on crop yield, 162-172. In: The Irrigation Association. 1982 Technical Conference Proceedings. "Water, Energy and Economic Alternatives".

F.A.O. 1979. Soil survey investigations for irrigation. F.A.O. Soil Bulletin No. 42. Rome: F.A.O.

GARDNER, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89, 63-73.

GARDNER, W.R. 1964. Relation of root distribution to water uptake and availability. Agron. J.56,35-41.

GARDNER, W.R. 1983. Soil properties and Efficient Water use: an overview, 45-63. In: Limitations to efficient water use in crop production. Taylor, H.M., Wayne, R.J. & Sinclair, T.R., (Ed.). Madison: ASA.

GARDNER, W.R. & EHLIG, C.F. 1963. J. Geophys. Res.68, 5719-5824.

GREACEN, E.L. 1976. Mechanisms and models of water transfer. In: Water and Plant life: Problems and modern approaches. Eds. Lange, O.L., Knappen L. & Schulse E.D. New York: Springer.

GREEN, G.C. 1982. Progress report for 1981/1982 on the research project titled: "Evaporation and water use studies by means of weighing lysimeters: determination of water requirements of certain annual crops at Roodeplaat as a function of soil, plant and atmospheric factors." Dept. of Agric. Pretoria: SIRI.

GUPTA, S.K., TANJI, K.K., NIELSEN, D.R., BIGGAR, J.W., SIMMONS, C.S. & MACINTYRE, J.L. 1978. Field simulation of soil water movement with crop water extraction. Water science & engineering papers No.4013. Davis: Univ. of California.

HANKS, R.J. (Editor) 1982. Predicting crop production as related to drought stress under irrigation. Logan: Utah State Univ.

HANKS, R.J. & RASMUSSEN, V.P. 1982. Predicting crop production as related to plant water stress. Adv. Agron. 35, 193-215..

HENSLEY, M. 1984. The determination of profile available water capacities of soils. Ph.D. Dissertation. Bloemfontein: Univ. of the O.F.S.

HENSLEY, M & DE JAGER, J.M. 1982. The determination of the profile available water capacities of soils. Alice: University of Fort Hare.

HILLEL, D. 1980. Applications of Soil Physics. New York: Academic Press.

HILLEL, D & TALPAZ, H. 1977. Simulation of soil water dynamics in layered soils. Soil Sci. 123, 54-62.

HILLEL, D., VAN BEEK,C. & TALPAZ, H. 1975. A microscopic-scale model of soil water uptake by a nonuniform root system and of water and salt movement in the soil profile. Soil Sci. 121, 242-255.

HSIAO, T.C. 1982. The Soil-Plant Atmosphere Continuum in Relation to Drought and Crop Production. pp. 39-52.In: Drought resistance in crops, with emphasis on rice. Los Banos: IRRI.

HSIAO, T.C., O'TOOLE, J.C. & TOMAR, V.S. 1980. Water stress as a constraint to crop production in the tropics. pp. 339-369. In: Priorities for aleviating Soil-Related Constraints Food Production in the Tropics. Los Banos; IRRI.

HUMAN, J.J., DE BRUYN, L.P. & SPAMER, J.M. 1980. Die invloed van plantvogstremmings op die groei en produksie van sekere akkergewasse. Bloemfontein: U.O.F.S.

IDSO, S.B., JACKSON, R.D., PINTER, P.J., REGINATO, R.J. & HATFIELD, J.L. 1981. Normalising the stress-degree-day parameter for environmental variability. Agrics.Met. 24, 45-55.

KANEMASU, E.T. & TANNER, C.B. 1969. Stomatal diffusion resistance of snap beans. I. Influence of leaf water potential. Plant Phys. 44, 1547-1552.

KLEPPER, B. 1983. Managing root systems for efficient water uses: Axial resistances to flow in root systems - Anastomical considerations, 115-124. In: Limitations to efficient water use in crop production. Taylor, H.M., Wayne, R.J. & Sinclair, T.R. (Ed). Madison, U.S.A.: Am. Soc. of Agron., Inc., Crop Sci. Soc. of Am., Inc., Soil Science Soc. of Am., Inc.

KLEPPER, B., TAYLOR, H.M., HUCK, M.G. & FISCUS, E.L. 1973. Water relations and growth of cotton in drying soil. Agron. J. 65, 307 - 310.

LAKER, M.C. 1978 a. The agriculture potential of the Ciskei: Amended Report. Alice: Univ. of Fort Hare.

LAKER, M.C. 1978 b. Agricultural research and development strategies in less developed countries. Alice: Univ. Fort Hare.

LAKER, M.C. 1982. A provisional simple model for predicting PAWC for maize on certain Ciskeian soils. In: The determination of the profile available water capacities of soils, by Hensley & De Jager. Alice: Univ. of Fort Hare.

LAKER, M.C. 1983. Report on a study tour to Belgium, the Netherlands and the United States of America. Alice: Univ. Fort Hare.

LAKER, M.C., BOEDT, L.J.J., VAN ASSCHE, F. & LEMAIRE, C. 1984. The effect of irrigation scheduling on yields and water use efficiencies of maize and wheat. Paper presented at the 12th national congress of the Soil Science Society of South Africa, Bloemfontein.

LAMBERT, J.R., & PENNING DE VRIES, F.W.T. 1973. Dynamics of water in the soil plant atmosphere system: A model named "Troika". In: Physical Aspects of

Soil, Water and Salts in Ecosystems. Berlin: Springer.

LARCHER, W. 1980. Physiological plant ecology. New York: Springer.

MACVICAR, C.N., DE VILLIERS, J.M., LOXTON, R.F., VERSTER, E., LAMBRECHTS, J.J.N., MERRYWEATHER, F.R., LE ROUX, J., VAN ROOYEN, T.H. & HARMSE, H.J. von M. 1977. Soil Classification. A Binomial System for South Africa. Pretoria: Dept. of Agric.

MALLETT, J.B. & DE JAGER, J.M. 1971. Effect of a moisture stress day upon maize performance. Agroplantae 3, 15-20.

MARAIS, J.N. & HENSLEY, M. 1982. Unpublished data. Alice: Univ. Fort Hare.

MICHAEL, A.M. 1978. Irrigation, theory and practice. New Delhi: Vikas.

MILLER, D.E. 1963. Lateral moisture flow as a source of error in moisture retention studies. Soil Sci. Soc. Am. Proc. 27, 716-717.

MILLER, D.E. 1973. Water retention and flow in layered soils. USDA Cons. Res. Rep. No.13.

MILLER, D.E. 1977. Deficit high-frequency irrigation of sugarbeats, wheat and beans. Proc. Speciality Conf. on Water, Irrigation and Management for Drainage. New York: ASCE.

MILLER, D.E. & AARSTAD, J.S. 1971. Available water as related to evapotranspiration rates and deep drainage. Soil Sci. Soc. Am. Proc. 35: 131-134.

MILLER, D.E. & AARSTAD, J.S. 1973. Effective available water and its relation to evapotranspiration rate, depth of wetting, and soil texture. Soil Sci. Soc. Am. Proc. 37, 763-766.

MILLER, D.E. & AARSTAD, J.S. 1974. Calculation of the drainage component of soil water depletion. Soil Sci. 118, 11-15.

MOLZ, F.J. 1971. Interaction of water uptake and root distribution. Agron. J. 63, 608-610.

MOLZ, F.J. & REMSON, I. 1970. Extraction term models of soil moisture use by transpiring plants. Water Resources Res.6, 1346-1356.

NIMAH, M.N. & HANKS, R.J. 1973. Model for estimating soil water, plant and atmosphere interactions: 1. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37,522-527.

OGATA, G. & RICHARDS, L.A. 1957. Water content changes following irrigation of bare-field soil that is protected from evaporation. Soil Sci. Soc. Am. Proc. 21, 355-356.

OGATHA, G., RICHARDS, L.A. & GARDNER, W.R. 1960. Transpiration of alfalfa determined from soil water content changes. Soil Sci. 89, 179 - 182.

OOSTERHUIS, D. 1984. Crop water use efficiency. S.A. Water-bulletin. May 1984, 23- 28.

PHILIP, J.R. 1966. Plant water relations: some physical aspects. Ann. Rev. Plant Phys. 17, 245-268.

RATLIFF, L.F., RITCHIE, J.T. & CASSEL, D.K. 1983. Field measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47, 770-775.

REGINATO, R.J. 1983. Field quantification of crop water stress. Transactions of the ASAE 26, 772-775 & 781.

REICOSKY, D.C. & RITCHIE, J.T. 1976. Relative importance of soil resistance and plant resistance in root water absorption. Soil Sci. Soc. Am. J. 40, 293-297.

RICHARDS, L.A. & WADLEIGH, C.H. 1952. Soil water and plant growth, pp. 73-251. In: Soil physical conditions and plant growth. Shaw, B.T. (Ed.) Am. Soc. Agron. Monog. 2.

RICHARDS, L.A. & WEAVER, L.R. 1944. Fifteen atmosphere percentage as related to the permanent wilting percentage. Soil Sci. 56, 331-339.

RITCHIE, G.A. & HINCKLEY, T.M. 1975. The pressure chamber as an instrument for ecological research. Ad. in Ecol. Res. 9, 165-254.

RITCHIE, J.T. 1981. Soil Water Availability. Plant and Soil 58, 327-338.

ROBINS, L.J.S. 1959. Moisture movement and profile characteristics in relation to field capacity. Internl. Comm. Irrig. Drain. 8, 509-521.

ROBINS, J.S., PRUITT, W.O. & GARDNER, W.H. 1954. Unsaturated flow of water in field soils and its effect on soil moisture investigations. Soil Sci. Soc. Am. Proc. 18, 344-347.

ROWSE, H.R. & GOODMAN, D. 1981. Axial resistance to water movement in broad bean (Vicia faba) roots. J. Exp. Bot. 32, 591-598.

SALTER, P.J. & GOODE, J.E. 1967. Crop responses to water at different stages of growth. Research review No. 2 of the Commonwealth Bureau of Horticulture and Plantation Crops. East Malling: CAB

SCHOLANDER, P.F., HAMMEL, H.T., HEMMINGSEN, E.A. & BRADSTREET, E.D. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. Proc. Nat. Acad. Sci. U.S.A. 52, 119-125.

SKAGGS, R.W., MILLER, D.E. & BROOKS R.H. 1982. Soil water. Part I - Properties, 77-123. In: Design and operation of farm irrigation systems. Jensen, M.E. (Ed). St.Joseph, Michigan: ASAE.

SLATYER, R.O. 1967. Plant water relationships. New York: Academic Press.

STEWART, J.I., HANKS, R.J., DANIELSON, R.E., JACKSON, E.B., HAGAN, R.M., RILEY, J.P., FRANKLIN, W.T. & PRUITT, W.O. 1977. Optimising crop production through control of water and salinity levels in the soil. Logan: Utah Water Res. Lab.

STONE, L.R., HORTON, M.L. & OLSON, T.C. 1973. Water loss from an irrigated sorghum field: II. Evapotranspiration and root extraction. Agronomy Journal 65, 495-497.

STORIE, R.E. 1964. Soil and land classification for irrigation development. Proc. 8th International Congress of Soil Science, Bucharest, Romania.

STREUTKER, A. 1984. Verlaging van droogterisiko van gewasverbouing deur aanvullende besproeiing. Paper presented at the 12th national congress of the Soil Science Society of South Africa, Bloemfontein.

VAN DER MERWE, A.J. 1973. Physico-chemical relationships of selected O.F.S. soils. A statistical approach based on taxonomic criteria. D.Sc. Dissertation. Bloemfontein. Univ. of the O.F.S.

VIEHMEYER, F.J. & HENDRICKSON, A.H. 1927. Soil moisture conditions in relation to plant growth. Plant Physiol 2, 71-78.

VIEHMEYER, F.J. & HENDRICKSON, A.H. 1931. The moisture equivalent as a measure of the field capacity of soils. Soil Sci. 32, 181-194.

VIEHMEYER, F.J. & HENDRICKSON, A.H. 1949. Methods of measuring field capacity and wilting percentages of soils. Soil Sci. 32, 181-193.

VIEHMEYER, F.J. & HENDRICKSON, A.H. 1950. Soil moisture in relation to plant growth. Ann. Rev. Plant

Physiol. 1, 285 - 304.

WARING, R.H. & CLEARY, B.D. 1967. Plant moisture stress: Evaluation by pressure bomb. Sci. 155, 1248-1254.

WENDA, W.I. & HANKS, R.J. 1981. Corn yield and evapotranspiration under simulated drought conditions. Irr. Sci. 2, 193-204.

WHISLER, F.D & MILLINGTON, R.J. 1968. Analysis of steady-state evapotranspiration from a soil column. Soil Sci. Soc. Am. Proc. 32, 167-174.

WILCOX, J.C. 1962. Rate of soil drainage following an irrigation. III A new concept of the upper limit of available water. Can. J. Soil Sci: 42, 122 - 128.

WILLATT, S.T. & OLSSON, K.A. 1982. Root distribution and water uptake by irrigated soybeans on a duplex soil. Aust. J. Soil Res. 20, 139-46

APPENDIX 2.1

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR JOZINI (CISKEI)

FORM: Oakleaf SERIES:Jozini
Locality: Fort Hare Farm , Alice
Factors of soil formation:
-Climate: Semi-arid
-Parent Material: No of kinds: single
Lithology: mixed dolerite, sandstone and mudstone
Underlying material: old alluvium
Mode of accumulation: subrecent alluvium
Weathering: partly
-Topography: unit 5 slope 1% aspect N
-Vegetation: irrigated land

HORIZON	DEPTH	DESCRIPTION
Ap	0-100	moist; 5.5 YR 3/3, dark brown; loam; apedal; friable; gradual, smooth transition.
A1	100-260	moist; 10 YR 3/2, very dark brown; loam; apedal; friable; gradual, smooth transition.
B21	260-650	moist; 10 YR 2/3, very dark grey; loam; weak, fine, subangular blocky; friable; evidence of abundant faunal activity; gradual, smooth transition.
B22	650-930	moist; 7.5 YR 3/4, dark brown; loam; apedal; friable; evidence of frequent faunal activity; gradual, smooth boudary.
B23	930-1190	moist; 7.5 YR 3/4, dark brown; fine sandy clay loam; apedal; friable; evidence of frequent faunal activity; gradual, smooth boundary.

B31 1190-1540

moist; 5 YR 3/4, dark red brown; fine sandy clay loam; apedal; friable; evidence of frequent faunal activity.

APPENDIX 2.1 (continued)

ANALYTICAL DATA FOR JOZINI (CISKEI)

Lab. No.	38/83	39/83	40/83	41/83	42/83
Horizon	Ap	A1	B21	B22	B23
Particle size distribution (%)					
co Sa	1,0	1,0	1,0	0,6	1,0
me Sa	0,8	1,1	1,1	1,4	2,0
fi Sa	13,5	15,1	16,2	17,9	24,1
vf Sa	28,0	29,9	24,2	26,5	21,7
Total Sand	43,3	47,1	42,1	44,2	47,1
co Si	29,6	24,4	21,9	19,2	16,4
fi Si	14,0	13,6	13,1	12,4	10,5
Total Silt	43,6	38,0	35,0	31,6	26,9
Clay	15,2	17,2	22,0	23,5	23,2
Exchangeable cations (me/100 g soil)					
Ca	6,1	7,0	8,8	6,8	4,2
Mg	2,7	2,8	3,5	3,3	2,7
K	0,1	0,1	0,1	0,1	0,1
Na	0,2	0,3	0,3	0,3	0,2
S. value (me/100 g soil)	9,1	10,2	12,7	10,5	7,2
C.E.C. (me/100 g soil)	16,0	15,6	18,0	15,0	17,0
Organic C (%)	0,56	0,51	0,43	0,23	0,13
pH					
water 1:2,5	7,4	7,5	7,3	7,4	7,4
KCl 1:2,5	6,6	6,5	6,2	6,2	6,2

APPENDIX 2.3
PROFILE DESCRIPTION AND ANALYTICAL DATA FOR HUTTON (CISKEI)

FORM: Hutton SERIES:Marikana
Locality: Amatola Basin
Factors of soil formation:
-Climate: sub-humid
-Parent Material: No of kinds: binary
Lithology: sandstone + dolerite
Underlying material: dolerite
Mode of accumulation: drift
Weathering: well weathered
-Topography: unit 3 slope 8% aspect NE
-Vegetation: cultivated land.

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-200	dry; 5 YR 3/5, dark reddush brown (moist); 5 YR 3/4, dark reddish brown (dry); clay; massive to weak, medium angular blocky; hard; many fine and medium roots; clear transition.
B21	200-500	dry; 5 YR 3/3, dark reddish brown (moist); 5 YR 3/3, dark reddish brown (dry); heavy clay to silty clay; moderate to strong, fine angular blocky; extremely hard; few small IM concretions; signs of much faunal activity; clear, smooth boundary.
B22	500-900	dry; 2.5 YR 3/3, dark reddish brown (moist); 5 YR 3/4, dark reddish brown (dry); heavy clay; moderate to strong, coarse, angular blocky; very hard; few small IM concretions; few fine roots; abundant well defined clay skins; clear, smooth boundary.
B3	900-1300	moist; 2.5 YR 3/5, dark reddish brown (dry); 2.5 YR 3/4, dark reddish brown (moist); heavy clay; weak, coarse, subangular blocky; firm; few, medium to fine grained sandstone fragments; few small IM conctretions; gradual,

smooth boundary.

C 1300-1500

moist; matrix colour 5 YR 3/4, dark reddish brown (moist); abundant yellowish brown and black spots; loam; massive; friable; frequent fine roots; many concretions.

Note: a well defined plough pan occurs at the top of the B21 horizon (very hard when dry, due to compaction).

APPENDIX 2.3 (continued)

ANALYTICAL DATA FOR HUTTON (CISKEI)

Lab. No.	33/83	34/83	35/83	36/83	37/83
Horizon	Ap	B21	B22	B3	C
Particle size distribution (%)					
co Sa	0,8	0,6	0,7	1,5	9,6
me Sa	0,9	1,1	1,2	1,6	8,3
fi Sa	9,7	3,5	2,6	4,0	12,6
vf Sa	8,3	10,5	9,5	6,4	10,7
Total Sand	19,7	15,7	14,0	14,1	41,0
co Si	20,9	18,7	14,9	11,3	21,6
fi Si	22,8	21,3	18,3	17,3	16,8
Total Silt	43,7	40,0	33,2	30,6	38,4
Clay	37,3	45,7	51,5	57,4	16,8
Exchangeable cations (me/100 g soil)					
Ca	5,3	6,0	5,3	7,2	8,7
Mg	2,2	2,7	3,8	6,7	14,3
K	1,0	0,6	0,4	0,2	0,1
Na	0,1	0,1	0,1	0,3	0,7
S. value (me/100 g soil)	8,6	9,5	9,6	14,5	23,8
C.E.C. (me/100 g soil)	22,8	12,2	22,4	29,0	32,4
Organic C (%)	1,03	0,71	0,31	0,26	0,20
pH					
water 1:2,5	6,4	6,8	6,8	7,2	7,3
KCl 1:2,5	5,5	5,6	5,7	5,9	5,8

APPENDIX 2.2

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR STERKSPRUIT (CISKEI)

FORM: Sterkspruit SERIES:Sterkspruit
Locality: Fort Hare Farm, Alice
Factors of soil formation:
-Climate: Semi-arid
-Parent Material: No of kinds: binary
Lithology: mixed dolerite, sandstone, mudstone.
Underlying material: old alluvium
Mode of accumulation: colluvium over alluvium
Weathering: partly
-Topography: unit 4 slope 4% aspect S-W
-Vegetation: fallow land

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-220	moist; 7.5 YR 2/2, dark brown; sandy clay loam; moderate, fine granular; friable; slightly plastic, non sticky; some dolerite and mudstone fragments; abundant occurence of IM concretions; clear smooth tansition.
A12	220-330	moist; 7.5 YR 3/4, dark brown; sandy clay loam; weak, fine, subangular blocky; friable; slightly sticky, plastic; dolerite and mudstone fragments; many IM concretions; on transition with B-horizon occurs a layer of fine concretions 50mm thick; abrupt transition.
B21	330-620	moist; 7.5 YR 2/3, very dark brown, also pale red-brown colours; sandy clay/clay; strong, medium to coarse prismatic; plastic, sticky, firm; prominent cutans on ped surfaces; fine roots between structural units; IM and mudstone occur frequently; gradual, smooth boundary.
B22	620-860	moist; dominant matrix colour 10 YR 4/4, dark yellowish brown, occurence

of black, pale yellow, red brown mottles; sandy clay to clay; strong, medium to coarse prismatic; prominent cutans on ped surfaces; development of roots between the structural units; fine IM concretions; diffuse transition.

B3/C	860+	moist; strong mottling: black, white, red brown, yellow and dark brown spots; clay; massive; friable; slightly sticky, slightly plastic; some $CaCO_3$ nodules; irregular clay illuviation.

APPENDIX 2.2 (continued)

ANALYTICAL DATA FOR STERKSPRUIT(CISKEI)

Lab. No.	50/83	51/83	52/83	53/83	54/83
Horizon	Ap	A12	B21	B22	B3/C
Particle size distribution (%)					
co Sa	2,7	5,4	2,5	1,0	1,5
me Sa	1,1	1,1	1,0	0,8	0,8
fi Sa	16,9	17,4	6,7	10,0	13,2
vf Sa	27,5	27,8	10,1	17,8	22,4
Total Sand	48,2	51,6	20,3	29,2	37,8
co Si	23,2	17,7	11,5	14,9	17,2
fi Si	10,3	10,0	7,0	11,3	13,4
Total Silt	33,5	27,7	18,5	26,2	30,6
Clay	17,2	17,8	58,7	40,7	29,9
Exchangeable cations (me/100 g soil)					
Ca	4,2	4,5	11,5	8,1	6,5
Mg	1,9	2,1	18,9	9,2	7,6
K	0,5	0,5	0,5	0,4	0,4
Na	0,6	0,6	3,5	7,2	6,8
S. value (me/100 g soil)	7,2	7,7	34,4	24,9	21,3
C.E.C. (me/100 g soil)	12,4	14,4	32,8	24,4	28,4
Organic C (%)	0,54	0,51	0,33	0,11	0,10
pH					
water 1:2,5	7,2	7,1	7,8	8,3	8,9
KCl 1:2,5	6,4	6,2	6,8	7,5	7,2

APPENDIX 2.4

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR SHORTLANDS (CISKEI)

FORM: Shortlands SERIES: Kinross

Locality: Alice plot (on gravel road to the Amatola Basin).

Factors of soil formation:

-Climate: Semi-arid

-Parent Material: No of kinds: binary
Lithology: mixed dolerite, sandstone and mudstone
Underlying material: dolerite
Mode of accumulation: local colluvium
Weathering: partly

-Topography: unit 1-3, aspect E

-Vegetation: fallow land, cultivated last year.

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-225	moist; 2.5 YR 2/3, very dark reddish brown; loam/silt loam; weak, fine to medium granular; abundant fine roots; friable; few faunal activity; abrupt regular transition.
A3	225-330	moist; 2.5 YR 2/3, very dark reddish brown; loam/silty clay loam; moderate to strong, medium angular blocky; ped surfaces darkened by organic material; few roots; friable; some termite holes; gradual, smooth transition.
B21t	330-570	moist; 10 R 3/3, dusky red; clay loam; strong, medium to coarse angular blocky; firm; few IM concretions; dark red cutans on ped surfaces; some faunal activity; clear to gradual, smooth transition.
B22t	570-1290	moist; 10 R 3/6, dark red; clay; strong, medium angular blocky; well developed cutans on all ped surfaces; firm; some roots; some pedotubules; gradual transition.

all

C(with auger)	1290+	moist; dominant matrix colour 2.5 YR, dark red; clay/loam; occurrence of yellow and black (IM) spots; firm.

APPENDIX 2.4 (continued)
ANALYTICAL DATA FOR SHORTLANDS (CISKEI)

Lab. No.	43/83	44/83	45/83	46/83
Horizon	Ap	A3	B21t	B22t
Particle size distribution (%)				
co Sa	0,4	0,8	2,5	1,2
me Sa	0,4	0,8	0,6	0,6
fi Sa	6,0	5,8	4,4	3,3
vf Sa	18,4	18,9	16,2	13,1
Total Sand	25,2	26,0	23,8	18,2
co Si	31,5	29,9	24,4	18,7
fi Si	19,3	15,5	16,3	12,8
Total Silt	50,8	45,4	40,7	31,5
Clay	22,1	26,6	35,1	48,0
Exchangeable cations (me/100 g soil)				
Ca	3,7	4,7	2,5	2,6
Mg	1,6	1,8	2,9	3,9
K	0,4	0,4	0,2	0,3
Na	0,7	0,2	0,2	0,3
S. value (me/100 g soil)	6,4	7,1	5,8	7,1
C.E.C. (me/100 g soil)	14,8	17,0	18,0	21,0
Organic C (%)	0,94	0,80	0,47	0,23
pH				
water 1:2,5	6,8	6,3	6,3	6,6
KCl 1:2,5	5,3	5,1	5,0	5,4

APPENDIX 2.5

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR VALSRIVIER (CISKEI)

FORM: Valsrivier SERIES: Arniston
Locality: Amatola Basin
Factors of soil formation:
-Climate: Sub-humid
-Parent Material: No of kinds: 3
Lithology: mixed dolerite, sandstone and mudstone
Underlying material: old alluvium
Mode of accumulation: sub-recent alluvium
Weathering: partly
-Topography: unit 5 slope 0%
-Vegetation: fallow land (cultivated last season)

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-200	moist; 7.5 YR 2/3, very dark brown; loam to silt loam; massive; very friable; abundant fine roots and faunal activity; clear smooth boundary.
B21t	200-700	moist; 7.5 YR 2/2, very dark brown; clay loam; strong, medium angular blocky; friable; few fine roots; abundant well developed cutans on ped surfaces; signes of faunal activity; diffuse, smooth boundary.
B3	700-1000	moist; 7.5 YR 3/3, dark brown; silt loam; moderate, medium subangular blocky; friable to firm; some clay cutans; gradual, smooth transition.
C(with auger)	1000+	moist; dominant matrix colour 7.5 YR 4/4, dark brown; silt loam; firm; some mottling and occurrence of IM concretions.

APPENDIX 2.5 (continued)

ANALYTICAL DATA FOR VALSRIVIER (CISKEI)

Lab. No.	47/83	48/83	49/83
Horizon	Ap	B2t	B3
Particle size distribution (%)			
co Sa	0,2	0,5	0,3
me Sa	0,3	0,2	0,6
fi Sa	9,6	9,3	10,0
vf Sa	18,1	15,9	16,1
Total Sand	28,2	25,9	27,0
co Si	21,5	22,5	19,0
fi Si	25,7	18,2	39,6
Total Silt	47,2	40,7	58,6
Clay	22,9	32,4	10,4
Exchangeable cations (me/100 g soil)			
Ca	7,1	5,6	13,6
Mg	2,5	3,2	6,6
K	0,2	0,1	0,1
Na	0,2	0,2	0,2
S. value (me/100 g soil)	10,0	9,1	20,5
C.E.C. (me/100 g soil)	20,4	22,0	24,0
Organic C (%)	0,72	0,64	0,40
pH			
water 1:2,5	6,6	7,0	6,8
KCl 1:2,5	5,2	5,5	5,4

APPENDIX 2.6

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR KAMP I (VAALHARTS)

FORM: Hutton SERIES:Maitengive

Locality: Agriculture research station, Jan Kempdorp

Factors of soil formation:

-Climate: Semi-arid

-Parent Material: No of kinds: single

Lithology: kalahari sands

Underlying material: $CaCO_3$-layer

Mode of accumulation: aeolian

Weathering:partly

-Topography: unit 5 slope: 0%

-Vegetation: deserted plot, before used for other exteriments

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-200	dry; 5 YR 3/4, dark reddish brown; sand; weak, fine granular; very friable; many fine roots; clear, smooth boundary.
A/B	200-420	dry; 5 YR 3/4, dark reddish brown; loamy sand; massive, very compacted in some places; hard; few fine roots; clear, smooth boundary.
B21t	420-650	dry; 5 YR 5/8, bright reddish brown; loamy sand; moderate to strong, angular blocky; firm; 50 % cutans on surface of peds; moderately to well developed $CaCO_3$ mycelia; few fine roots; gradual, smooth boundary.
B22t	650-920	dry; 5 YR 4.5/8, reddish brown; loamy sand; weak, coarse subangular blocky; occurence of cutans on surface of peds; firm; clear $CaCO_3$-enrichment in root channels; occurrence of IM concretions; indications that water sometimes stagnates on the underlying $CaCO_3$-layer; abrupt, smooth boundary.
	920+	$CaCO_3$ - layer

APPENDIX 2.6 (continued)

ANALYTICAL DATA FOR KAMP I

Lab. No.	1/83	5/83	2/83	3/83
Horizon	Ap	A/B	B21t	B22t
Particle size distribution (%)				
co Sa	1,0	0,6	1,1	1,4
me Sa	4,2	4,4	6,8	6,1
fi Sa	55,0	57,0	55,0	53,9
vf Sa	31,7	26,9	23,0	25,3
Total Sand	91,9	90,9	85,9	86,2
co Si	1,9	2,4	1,6	2,3
fi Si	1,0	0,2	0,3	1,3
Total Silt	2,9	2,6	1,9	3,6
Clay	3,8	9,7	11,8	9,2
Exchangeable cations (me/100 g soil)				
Ca	1,8	1,8	5,7	3,2
Mg	1,3	1,1	1,7	2,1
K	0,3	0,2	0,5	0,4
Na	0,1	0,1	0,2	0,1
S. value (me/100 g soil)	3,5	3,2	8,1	5,8
C.E.C. (me/100 g soil)	6,4	6,0	8,8	11,0
Organic C (%)	0,26	0,16	0,16	0,13
pH				
water 1:2,5	5,6	5,6	7,7	8,4
KCl 1:2,5	4,4	4,3	6,9	7,6

APPENDIX 2.7

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR KAMP II (VAALHARTS)

FORM: Sterkspruit SERIES: Stanford

Locality: Agriculture Research Station, Jan Kempdorp

Factors of soil formation:

-Climate: Semi-arid

-Parent Material: No of kinds: binary
Lithology: Kalahari sands
Underlying material: $CaCO_3$-layer
Mode of accumulation: aeolian + colluvium
Weathering: partly

-Topography: 5

-Vegetation: veld

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-270	dry; 7.5 YR 4/4, brown; 7.5 YR 3.5/4 (moist), brown; loamy sand; weak, very fine to fine granular; very friable; non sticky, non plastic; some fine roots; abrupt, smooth boundary.
B2t	270-510	moist; 10 YR 4/4, dark yellowish brown, dominant colour; sandy clay loam; strong, medium, prismatic; very dark clay cutans on ped surfaces, abundant occurrence of these cutans; sticky, plastic; fine roots between the structural units; some mottling in top part of horizon; gradual, smooth, boundary.
B3	510-660	moist; dominant colour 10 YR 4/4, dark yellowish brown; sandy loam; weak, coarse angular blocky; sticky, plastic; gleying in the bottom part; no roots; abrupt, smooth boundary with underlying $CaCO_3$-layer.

APPENDIX 2.7 (continued)

ANALYTICAL DATA FOR KAMP II

Lab. No.	8/83	9/83	10/83
Horizon	Ap	B2t	B3
Particle size distribution (%)			
co Sa	2,2	1,6	1,9
me Sa	5,9	6,0	5,1
fi Sa	52,0	40,7	40,3
vf Sa	23,1	22,1	22,8
Total Sand	83,2	70,8	70,1
co Si	3,3	3,0	2,7
fi Si	1,4	1,9	3,2
Total Silt	4,7	4,9	5,9
Clay	10,3	21,8	18,9
Exchangeable cations (me/100 g soil)			
Ca	5,1	8,7	5,2
Mg	3,6	8,0	6,7
K	0,4	0,4	0,4
Na	0,3	1,9	6,0
S. value (me/100 g soil)	9,4	19,0	18,3
C.E.C. (me/100 g soil)	12,6	19,2	16,4
Organic C (%)	0,24	0,17	0,10
pH			
water 1:2,5	7,6	8,3	8,8
KCl 1:2,5	7,3	7,8	7,9

APPENDIX 2.8

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR KAMP III (VAALHARTS)

FORM: Hutton SERIES:Mangano
Locality: Agriculture research station, Jan Kempdorp.
Factors of soil formation:
-Climate: Semi-arid.
-Parent Material: No of kinds: single
Lithology: kalahari sands
Underlying material: thick gravel layer, gravel dominantly Ventersdorp lava.
Mode of accumulation: aeolian
Weathering: weathering
-Topography: unit 5 slope 0%
-Vegetation: fallow land, had been used for experiments before.

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-230	moist; 5 YR 4/8, reddish brown (dry); 5 YR 3/5, dark reddish brown (moist); sand; single grain; non sticky, non plastic; abundant fine roots; clear, smooth boundary.
A/B	230-430	dry; 5 YR 4/8, reddish brown (dry); 5 YR 3/6, dark reddish brown (moist); loamy sand; very weak, fine, subangular blocky; hard; very compacted in places; gradual, smooth boundary.
B2	430-1150	dry; 5 YR 6/8, reddish yellow (dry); 5 YR 4/8, reddish brown (moist); sandy loam; weak, medium subangular blocky; very friable; few fine roots; lot of faunal activity (ants); abrupt, smooth boundary.
	1150+	gravel/boulder layer.

APPENDIX 2.8 (continued)

ANALYTICAL DATA FOR KAMP III

Lab. No.	12/83	13/83	14/83
Horizon	Ap	A/B	B2
Particle size distribution (%)			
co Sa	2,2	2,0	2,0
me Sa	10,9	9,7	9,7
fi Sa	49,9	46,5	45,3
vf Sa	25,0	26,0	26,1
Total Sand	88,0	85,0	83,1
co Si	2,2	3,8	2,8
fi Si	2,1	1,6	0,9
Total Silt	4,3	5,4	3,7
Clay	5,7	7,1	14,7
Exchangeable cations (me/100 g soil)			
Ca	0,5	0,4	2,6
Mg	0,6	0,5	1,4
K	0,3	0,2	0,4
Na	---	---	---
S. value (me/100 g soil)	1,4	1,1	4,4
C.E.C. (me/100 g soil)	6,8	6,1	8,8
Organic C (%)	0,22	0,15	0,14
pH			
water 1:2,5	4,6	4,2	6,0
KCl 1:2,5	3,7	3,6	4,7

APPENDIX 2.9

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR DEMONSTRATION PLOT (VAALHARTS)

FORM: Hutton SERIES: Mangano

Locality: Agriculture research Station, Jan Kempdorp.

Factors of soil formation:

-Climate: Semi-arid.

-Parent Material: No of kinds: single
Lithology: kalahari sands
Underlying material: kalahari sands
Mode of accumulation: aeolian
Weathering: partly

-Topography: unit 5
slope 0%

-Vegetation: Irrigated land.

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-160	wet; 5 YR 3/5, dark reddish brown; sand; weakly developed, medium granular;non sticky, non plastic; abundant fine roots; gradual, smooth boudary.
A/B	160-280	wet; 5 YR 3/6, dark reddish brown; sand; massive, compacted layer; non sticky, non plastic; few fine roots; gradual, smooth boundary.
B2	280-940	wet; 5 YR 4/8, reddish brown; loamy sand; very weak, medium subangular blocky; non sticky, non plastic;abundant fine roots; diffuse smooth boundary.
B3/C	940-1400+	wet; 5 YR 5/8, bright reddish brown; loamy sand; apedal; non sticky, non plastic; occurrence of some yellow spots (7,5 YR 5/8); occurrence of IM concretions lower in the soil profile; gradually becomes a C-horizon.

APPENDIX 2.9 (continued)

ANALYTICAL DATA FOR DEMONSTRATION PLOT

Lab. No.	28/83	29/83	32/83
Horizon	A1	B2	B3
Particle size distribution (%)			
co Sa	2,2	2,2	2,9
me Sa	6,3	5,9	6,0
fi Sa	52,4	54,3	48,5
vf Sa	30,2	26,6	28,4
Total Sand	91,1	89,0	86,6
co Si	2,9	2,7	2,9
fi Si	1,0	1,2	1,4
Total Silt	3,0	3,9	4,3
Clay	3,6	5,8	10,0
Exchangeable cations (me/100 g soil)			
Ca	1,3	1,5	1,9
Mg	0,9	1,1	1,6
K	0,3	0,8	0,8
Na	0,1	0,1	0,1
S. value (me/100 g soil)	2,5	3,5	4,4
C.E.C. (me/100 g soil)	5,2	7,2	6,0
Organic C (%)	0,21	0,12	0,07
pH			
water 1:2,5	6,5	6,9	7,0
KCl 1:2,5	5,2	5,6	5,9

APPENDIX 2.10

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR VAN DER LINDE I

FORM: Hutton SERIES: Mangano
Locality: Farm A2Y, Vaalharts irrigation scheme.
Factors of soil formation:
-Climate: Semi-arid.
-Parent Material: No of kinds:single
Lithology: kalahari sands
Underlying material: kalahari sands
Mode of accumulation: aeolian
Weathering: partly
-Topography: unit 5 slope:0%
-Vegetation: irrigated land.

HORIZON	DEPTH	DESCRIPTION

General: The profile is strongly disturbed because the farmer tried to break a compacted subsurface layer by means of deep ploughing. Locally a fine clay layer occurs at 100cm depth.

Ap	0-750	dry; dominant colour 5 YR 3/6, dark reddish brown; also 5 YR 4/8, reddish brown; sand; single grain; very friable; abundant fine roots; broken, irregular boundary.
B2	750-1000	dry; 5 YR 5/8, bright reddish brown; loamy sand; weak, medium,subangular blocky; very friable; gradual, diffuse boundary.
B3/C	1000-1400+	dry; 5 YR 5/8, bright dark brown; loamy sand; weak, medium, subangular blocky; very friable; occurrence of IM concretions lower in the profile; the horizon gradually transfers in a C-horizon.

APPENDIX 2.10 (continued)

ANALYTICAL DATA FOR VAN DER LINDE I

Lab. No.	24/83	26/83	27/83
Horizon	Ap	B2	B3/C
Particle size distribution (%)			
co Sa	3,3	3,0	3,0
me Sa	11,4	9,7	8,9
fi Sa	55,9	51,5	48,3
vf Sa	22,1	24,6	26,2
Total Sand	92,7	88,8	86,4
co Si	2,3	2,2	1,4
fi Si	0,9	0,9	0,6
Total Silt	3,2	3,1	2,0
Clay	4,1	8,9	8,0
Exchangeable cations (me/100 g soil)			
Ca	1,7	1,7	2,5
Mg	1,2	1,7	1,9
K	0,3	0,2	0,3
Na	---	0,4	0,1
S. value (me/100 g soil)	3,2	4,0	4,8
C.E.C. (me/100 g soil)	6,0	5,6	8,0
Organic C (%)	0,23	0,11	0,11
pH			
water 1:2,5	6,5	6,8	7,1
KCl 1:2,5	5,5	6,2	5,4

APPENDIX 2.11

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR VAN DER LINDEII (VAALHARTS)

FORM: Hutton SERIES:Mangano
Locality: Farm A2Y, Vaalharts irrigation scheme.
Factors of soil formation:
-Climate: Semi-arid.
-Parent Material: No of kinds: single
Lithology: Kalahari sands
Underlying material: Kalahari sands
Mode of accumulation: aeolian
Weathering: partly
-Topography: unit 5 slope: 0%
-Vegetation: irrigated land

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-240	dry; 7.5 YR 4/6, brown; sand; weak,coarse,granular; hard; abundant fine and coarse roots; gradual, smooth boudary.
A/B	240-500	dry; 5 YR 4/8, reddish brown; sand; weak,fine subangular blocky; very friable; abundant fine roots; gradual, smooth boundary.
B2	500-840	dry; 5 YR 5/8, bright reddish brown; sand; very weak, coarse subangular blocky; very friable; gradual smooth boundary.
B/C	840-1400+	moist; 5 YR 5/8, bright reddish brown; sand; very, coarse, angular blocky; non sticky, non plastic; occurence of some yellowish spots (7.5 YR 6/8); occurrence of IM concretions lower in the profile; slowly this horizon goes over in a C-horizon.

APPENDIX 2.11 (continued)

ANALYTICAL DATA FOR VAN DER LINDE II

Lab. No.	20/83	21/83	22/83	23/83
Horizon	Ap	A/B	B2	B3/C
Particle size distribution (%)				
co Sa	2,4	2,4	2,2	3,2
me Sa	7,4	9,5	8,6	10,5
fi Sa	55,1	55,5	53,5	51,0
vf Sa	26,5	22,6	24,5	20,9
Total Sand	91,4	90,0	88,8	85,6
co Si	2,1	1,6	0,1	1,4
fi Si	1,1	0,4	1,6	1,4
Total Silt	3,2	2,0	1,7	2,8
Clay	4,3	8,0	9,5	9,1
Exchangeable cations (me/100 g soil)				
Ca	2,5	1,6	2,4	3,5
Mg	1,1	1,4	1,8	2,6
K	0,4	0,3	0,3	0,3
Na	---	---	0,1	0,1
S. value (me/100 g soil)	4,0	3,4	4,6	6,5
C.E.C. (me/100 g soil)	7,0	4,8	7,0	12,0
Organic C (%)	0,23	0,18	0,11	0,10
pH				
water 1:2,5	7,1	6,7	6,7	6,7
KCl 1:2,5	6,5	5,5	5,2	5,1

APPENDIX 2.12
PROFILE DESCRIPTION AND ANALYTICAL DATA FOR JOUBERT (VAALHARTS)

FORM: Sterkspruit SERIES:Swaerskloof
Locality: Farm owned by Mr. Joubert on the E2 block of the Vaalharts irrigation scheme.

Factors of soil formation:
-Climate: Semi-arid.

-Parent Material: No of kinds: binary
Lithology: Ventersdorp lava + Kalahari sands
Underlying material:Ventersdorp lava.
Mode of accumulation:aeolian + colluvium
Weathering: partly.
-Topography: unit 4 slope: 1%
-Vegetation: fallow land.

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-170	dry; 5 YR 2/4, dark reddish brown; sandy loam; strong,fine to medium granular; friable; abundant fine roots; faunal activity; gradual, smooth, boundary.
A/B	170-300	dry; 5 YR 3/6, dark reddish brown; sandy loam; weak, coarse, subangular blocky;friable; abundant fine roots; clear, smooth, boundary.
B2t	300-600	dry; 5 YR 4/8, reddish brown; sandy clay; strong, medium,prismatic; abundant clay cutans; firm; occurrence of fine pieces of Ventersdorp lava; some fine roots; clear, smooth, boundary.
B3	600-790	moist; 7.5 YR 4/6, brown; sandy clay loam; moderate, coarse, subangular blocky; sticky, plastic; few cutans; occurrence of fine Ventersdorp lava

APPENDIX 2.12 (continued)

ANALYTICAL DATA FOR JOUBERT

Lab. No.	15/83	16/83	17/83	18/83
Horizon	Ap	A/B	B2t	B3
Particle size distribution (%)				
co Sa	7,0	10,4	8,7	7,8
me Sa	10,9	12,0	10,1	10,4
fi Sa	28,8	28,6	23,4	24,7
vf Sa	20,5	19,0	14,5	17,2
Total Sand	67,2	70,0	56,7	60,1
co Si	5,4	4,3	2,8	3,2
fi Si	6,4	6,3	3,6	7,2
Total Silt	11,0	10,6	6,4	10,4
Clay	19,4	19,4	34,9	27,6
Exchangeable cations (me/100 g soil)				
Ca	5,3	10,1	5,5	4,8
Mg	4,5	10,4	14,9	15,9
K	1,6	2,0	1,5	1,4
Na	0,1	2,8	13,0	16,4
S. value (me/100 g soil)	11,5	25,3	34,9	38,9
C.E.C. (me/100 g soil)	21,0	24,0	26,0	27,0
Organic C (%)	0,69	0,51	0,23	0,17
pH				
water 1:2,5	7,2	7,3	8,2	7,3
KCl 1:2,5	6,9	6,9	7,1	6,2

APPENDIX 2.13
PROFILE DESCRIPTION AND ANALYTICAL DATA FOR DU PREEZ I (LOSKOP)

FORM: Hutton SERIES: Shorrocks
Locality: farm of Mr. Dupreez, close to Olifants River
Factors of soil formation:
-Climate: sub-humid
-Parent Material: No of kinds: 2
Lithology: alluvial deposit of sandstone and granites
Underlying material: old alluvium
Mode of accumulation: sub recent alluvium
Weathering: partly
-Topography: unit 5 slope 0%
-Vegetation: irrigated land

HORIZON	DEPTH (mm)	DESCRIPTION
A1	0-200	moist; 2.5 YR 2/4, dark reddish brown; sandy loam; fine sand; moderate, fine granular; friable; abundant fine roots; clear smooth boundary.
B2	200-550	moist; 2.5 YR 3/6, dark reddish brown; sandy loam; fine sand; weak, medium subangular blocky; friable; abundant fine roots; diffuse, smooth boundary.
C	550-1800+	moist; 2.5 YR 3/6, dark reddish brown; sandy clay loam; very weak to single grain; friable; occurrence of roots at depths of more than 1500 mm.

APPENDIX 2.13 (continued)

ANALYTICAL DATA FOR DU PREEZ I

Lab. No.	34/84	35/84	36/84
Horizon	Ap	B2	C
Particle size distribution (%)			
co Sa	6,9	5,1	6,4
me Sa	20,0	18,8	19,3
fi Sa	32,3	32,3	27,4
vf Sa	14,1	13,0	11,7
Total Sand	73,3	69,2	64,8
co Si	4,7	4,3	4,8
fi Si	4,3	4,8	4,8
Total Silt	9,0	9,1	9,6
Clay	17,6	19,7	24,9
Exchangeable cations (me/100 g soil)			
Ca	3,0	2,9	4,0
Mg	1,7	2,4	3,7
K	0,7	0,3	0,3
Na	---	0,1	0,2
S. value (me/100 g soil)	5,4	5,7	8,2
C.E.C. (me/100 g soil)	9,6	14,0	15,2
Organic C (%)	0,35	0,16	0,16
pH			
water 1:2,5	7,1	6,3	6,5
KCl 1:2,5	6,6	4,9	5,1

APPENDIX 2.14

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR DUPREEZ II (LOSKOP)

FORM: Shortlands SERIES: Sunvalley

Locality: farm Mr. Dupreez, former Welzijnsplot, Groblersdal

Factors of soil formation:

-Climate: Sub-humid

-Parent Material: No of kinds: micellaneous
Lithology: dominantly granite
Underlying material: granite saprolite
Mode of accumulation: subrecent alluvium
Weathering: partly

-Topography:unit 4 slope 3%

-Vegetation: maize field

HORIZON	DEPTH (mm)	DESCRIPTION
A1	0-220	moist; 5 YR 2/4, very dark reddish brown; sandy clay loam; moderate, medium granular; sticky, plastic; abundant fine roots; clear regular boundary.
B21t	220-700	wet; 5 YR 3/6, dark reddish brown; clay loam; strong, medium angular blocky; sticky, plastic; occurrence of cutans on structural units; well developed roots; some fine $CaCO_3$-concretions in lower parts of this horizon; gradual, smooth boundary.
B22t	700-1100	wet; 5 YR 3/6, dark reddish brown; clay loam; moderate, medium subangular blocky; some cutans; sticky, plastic; occurrence of $CaCO_3$-concretions and granite fragments; abrupt boundary.
	1100+	saprolite

APPENDIX 2.14 (continued)

ANALYTICAL DATA FOR DU PREEZ II

Lab. No.	37/84	38/84	39/84
Horizon	A1	B21t	B22t
Particle size distribution (%)			
co Sa	13,0	6,8	4,6
me Sa	14,9	8,7	8,1
fi Sa	19,5	14,3	14,6
vf Sa	13,0	10,2	11,9
Total Sand	60,4	40,1	39,3
co Si	7,5	3,4	8,0
fi Si	8,8	13,9	20,8
Total Silt	16,3	17,3	28,8
Clay	21,5	41,7	26,8
Exchangeable cations (me/100 g soil)			
Ca	6,1	9,9	20,4
Mg	2,9	5,7	6,8
K	0,6	0,3	0,3
Na	0,1	0,3	0,3
S. value (me/100 g soil)	9,7	16,1	27,7
C.E.C. (me/100 g soil)	18,0	31,2	25,0
Organic C (%)	0,67	0,27	0,12
pH			
water 1:2,5	7,0	7,0	8,2
KCl 1:2,	5,9	6,0	7,4

APPENDIX 2.15

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR DU PREEZ III (LOSKOP)

FORM: Hutton SERIES:Shigalo
Locality: farm of Mr. Du Preez, 1000m from Olifants River.
Factors of soil formation:
-Climate: Sub-humid
-Parent Material: No of kinds: 1
Lithology: granite
Underlying material:granite
Mode of accumulation: old alluvium + colluvium
Weathering: partly
-Topography: unit 4 slope 2%
-Vegetation: maize field

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-200	moist; 5 YR 2/4, very dark reddish brown; sandy loam; moderate, fine granular; friable; abundant fine roots; clear, smooth boundary.
B2	200-700	moist; 2.5 YR 3/6, dark reddish brown; sandy loam; weak, coarse subangular blocky; 30% cutans on peds; friable; abundant fine roots; diffuse, smooth boundary.
B3	700-1200+	moist; 2.5 YR 3/6, dark reddish brown; sandy loam; weak, medium subangular blocky; no cutans; friable; occurrence of small $CaCO_3$ spots; few roots.

APPENDIX 2.15 (continued)

ANALYTICAL DATA FOR DU PREEZ III

Lab. No.	40/84	41/84	42/84
Horizon	Ap	B2	B3
Particle size distribution (%)			
co Sa	8,6	12,8	12,7
me Sa	20,2	23,7	23,9
fi Sa	24,1	21,2	19,9
vf Sa	15,5	13,0	11,4
Total Sand	68,4	70,7	67,9
co Si	5,9	4,7	4,5
fi Si	9,5	5,9	8,2
Total Silt	15,4	10,6	12,7
Clay	10,1	18,5	17,8
Exchangeable cations (me/100 g soil)			
Ca	2,0	1,5	2,2
Mg	1,5	1,6	2,4
K	0,6	0,4	0,2
Na	0,1	0,1	0,2
S. value (me/100 g soil)	4,2	3,6	5,0
C.E.C. (me/100 g soil)	12,0	12,0	12,6
Organic C (%)	0,33	0,20	0,18
pH			
water 1:2,5	6,9	6,4	6,6
KCl 1:2,5	5,6	5,2	5,2

APPENDIX 2.16
PROFILE DESCRIPTION AND ANALYTICAL DATA FOR VENTER I (LOSKOP)

FORM: Shortlands SERIES: Kinross
Locality: farm Mr. Venter (former Welsynsplot, Groblersdal)
Factors of soil formation:
-Climate: sub-humid
-Parent Material: No of kinds:miscellaneous
Lithology: dominantly granite
Underlying material: old alluvium
Mode of accumulation: alluvial
Weathering: partly
-Topography: unit 4 slope 2%
-Vegetation: fallow land

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-250	moist; 2.5 YR 2/4, very dark reddish brown; sandy loam; moderate, fine , angular blocky; friable; abundant fine roots; clear smooth boundary.
B1	250-430	moist; 2.5 YR 3/6, dark red; sandy, clay loam; moderatem medium subangular blocky; sticky and plastic; few cutans; abundant fine roots; gradual, smooth boundary.
B22t	430-800	moist; 2.5 YR 4/6, red; sandy clay loam; moderate, medium angular blocky; sticky and plastic; 80% cutans on ped surfaces; abundant coarse granite elements; diffuse, smooth boundary.
B3t	800-1000	moist; 2.5 YR 3/4, dark reddish brown; sandy clay loam; weak, medium angular blocky; some cutans; sticky and plastic; coarse granite fragments; abrupt boundary.
	1000+	saprolite

APPENDIX 2.16 (continued)

ANALYTICAL DATA FOR VENTER I

Lab. No.	15/84	16/84	17/84	18/84
Horizon	Ap	B1	B2t	B3
Particle size distribution (%)				
co Sa	10,3	9,5	9,8	9,9
me Sa	13,2	10,9	8,8	8,7
fi Sa	27,1	20,8	18,1	19,2
vf Sa	20,0	14,0	14,1	15,8
Total Sand	69,6	55,2	50,6	53,7
co Si	6,8	5,8	7,9	9,0
fi Si	5,0	4,4	5,4	6,8
Total Silt	11,8	10,2	13,3	15,8
Clay	19,2	32,2	33,4	29,2
Exchangeable cations (me/100 g soil)				
Ca	4,4	10,0	3,5	4,2
Mg	1,6	2,3	2,8	3,4
K	0,5	0,6	0,3	0,4
Na	0,4	0,3	0,5	0,2
S. value (me/100 g soil)	7,0	13,2	7,1	8,1
C.E.C. (me/100 g soil)	12,4	10,2	16,0	16,0
Organic C (%)	0,43	0,32	0,20	0,17
pH				
water 1:2,5	7,1	6,9	5,9	6,2
KCl 1:2,5	6,1	5,8	5,0	4,8

APPENDIX 2.17

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR VENTER II (LOSKOP)

FORM: Hutton SERIES: Shorrocks
Locality: Mr. Venters farm on Welsynsplot (Groblersdal)
Factors of soil formation:
-Climate: sub-humid
-Parent Material: No of kinds: miscellaneous
Lithology: dominantly granite
Underlying material: old alluvium
Mode of accumulation: sub recent alluvium
Weathering: partly
-Topography: unit 4 slope 2%
-Vegetation: planted peanuts

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-250	moist; 5 YR 2/4, dark reddish brown; sandy clay loam; moderate, medium granular; non sticky, non plastic; gradual, irregular boundary.
B2t	250-900	wet; 2.5 YR 2/4, dark reddish brown; sandy clay loam; weak, medium, angular to subangular blocky; sticky, plastic; occurrence of cutans; gradual smooth boundary.
B3t	900-1400+	wet; 2.5 YR 2/4, dark reddish brown; loam; moderate, coarse blocky; prominent cutans; plastic and sticky; occurrence of coarse granite fragments.

APPENDIX 2.17 (continued)

ANALYTICAL DATA FOR VENTER II

Lab. No.	19/84	20/84	21/84
Horizon	Ap	B2t	B3t
Particle size distribution (%)			
co Sa	13,5	9,2	6,4
me Sa	12,8	9,1	6,3
fi Sa	21,7	17,3	15,5
vf Sa	15,1	15,3	16,9
Total Sand	63,1	50,9	45,1
co Si	6,1	8,7	14,1
fi Si	7,1	9,6	20,7
Total Silt	13,2	18,3	34,8
Clay	21,1	28,4	20,1
Exchangeable cations (me/100 g soil)			
Ca	4,0	3,4	6,5
Mg	1,7	2,1	1,9
K	0,6	0,2	0,2
Na	0,2	0,4	0,4
S. value (me/100 g soil)	6,5	6,1	9,0
C.E.C. (me/100 g soil)	11,6	15,0	15,2
Organic C (%)	0,41	0,15	0,07
pH			
water 1:2,5	7,3	6,7	6,8
KCl 1:2,5	6,4	5,4	5,5

APPENDIX 2.18

PROFILE DESCRIPTION AND ANALYTICAL DATA FOR CONTOUR 5 (LOSKOP)

FORM: Shortlands SERIES: Glendale

Locality: Agriculture research farm, Groblersdal

Factors of soil formation:

-Climate: sub-humid

-Parent Material: No of kinds: single
Lithology: granite
Underlying material: granite saprolite
Mode of accumulation: weathering *in situ*
Weathering: partly

-Topography: unit 3 slope 5%

-Vegetation: fallow land

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-180	moist; 5 YR 2/4, very dark reddish brown; sandy loam; coarse sand; moderate, fine to medium granular; friable; occurrence of particles > 2mm (granite); abrupt boundary.
A/B	180-330	moist; 5 YR 2/4, very dark reddish brown; sandy loam; moderate, fine to medium subangular blocky; friable; occurrence of coarse granite particles; some clay coatings; abrupt to clear, smooth boundary.
B2t	330-580	moist; 5 YR 2/4, very dark reddish brown; sandy clay loam; moderate, coarse angular blocky; well developed clay cutans; abundant coarse particles; some fine roots; sticky, plastic; gradual boundary.
B3t	580-1000	wet; no uniform colours; 7.5 YR3/4 and 7.5 YR 4/6, dark brown; sandy clay loam; moderate, coarse angular blocky; well developed cutans; sticky, plastic; abrupt boundary; fine gravel 5%.
	1000+	saprolite

APPENDIX 2.18 (continued)

ANALYTICAL DATA FOR CONTOUR 5

Lab. No.	26/84	27/84	28/84	29/84
Horizon	Ap	A1	B2t	B3t
Particle size distribution (%)				
co Sa	18,5	17,3	15,1	12,8
me Sa	14,7	12,6	10,1	8,8
fi Sa	20,7	19,7	15,8	14,8
vf Sa	13,3	16,0	12,2	11,6
Total Sand	67,2	65,6	53,3	48,0
co Si	7,6	6,2	6,4	----
fi Si	4,3	7,6	6,1	22,1
Total Silt	11,9	13,8	12,5	22,1
Clay	19,4	19,8	31,2	30,1
Exchangeable cations (me/100 g soil)				
Ca	4,4	3,8	5,4	4,4
Mg	2,2	2,4	4,0	5,4
K	0,8	0,7	0,5	0,5
Na	0,2	0,2	0,1	0,2
S. value (me/100 g soil)	7,6	7,1	10,0	10,5
C.E.C. (me/100 g soil)	11,6	13,2	19,2	20,0
Organic C (%)	0,36	0,33	0,23	0,17
pH				
water 1:2,5	6,4	5,9	6,3	7,0
KCl 1:2,5	4,9	4,5	4,8	5,6

APPENDIX 2.19
PROFILE DESCRIPTION AND ANALYTICAL DATA FOR CONTOUR 10 (LOSKOP)

FORM: Shortlands SERIES:Kinross
Locality: Agriculture research farm
Factors of soil formation:
-Climate: sub-humid
-Parent Material: No of kinds: sinlge
Lithology: granite
Underlying material:granite
Mode of accumulation: weathering *in situ*
Weathering: partly
-Topography: unit 3 slope 5%
-Vegetation: fallow land

HORIZON	DEPTH (mm)	DESCRIPTION
Ap	0-140	dry; 5 YR 3/6, dark reddish brown (dry), 5 YR 2/4 (wet), very dark reddish brown; sandy loam; moderate, fine granular; non sticky, non plastic; occurrence of a clear plough pan at the bottom of this horizon; abrupt, smooth boundary;
A1	140-290	dry; 5 YR 3/6, dark reddish brown (dry), 5 YR 2/4, very dark reddish brown (wet); sandy loam; moderate, fine granular; non sticky, non plastic; clear, smooth boundary.
B21t	290-750	dry; 5 YR 4/8,reddish brown (dry); 5 YR 3/6, dark reddish brown (wet); sandy clay loam; 80 % cutans on structural units; moderate, medium angular blocky; moderate sticky and plastic; occurence of coarse granite fragments; gradual, smooth boundary.
B22t	750-950	dry; 5 YR 4/8, reddish brown (dry), 5 YR 3/6, dark reddish brown (wet); sandy clay loam; moderate, medium, angular blocky; 50% cutans;

moderately sticky, plastic; at the bottom of this horizon occurs a gravel layer with IM concretions and granite fragments.

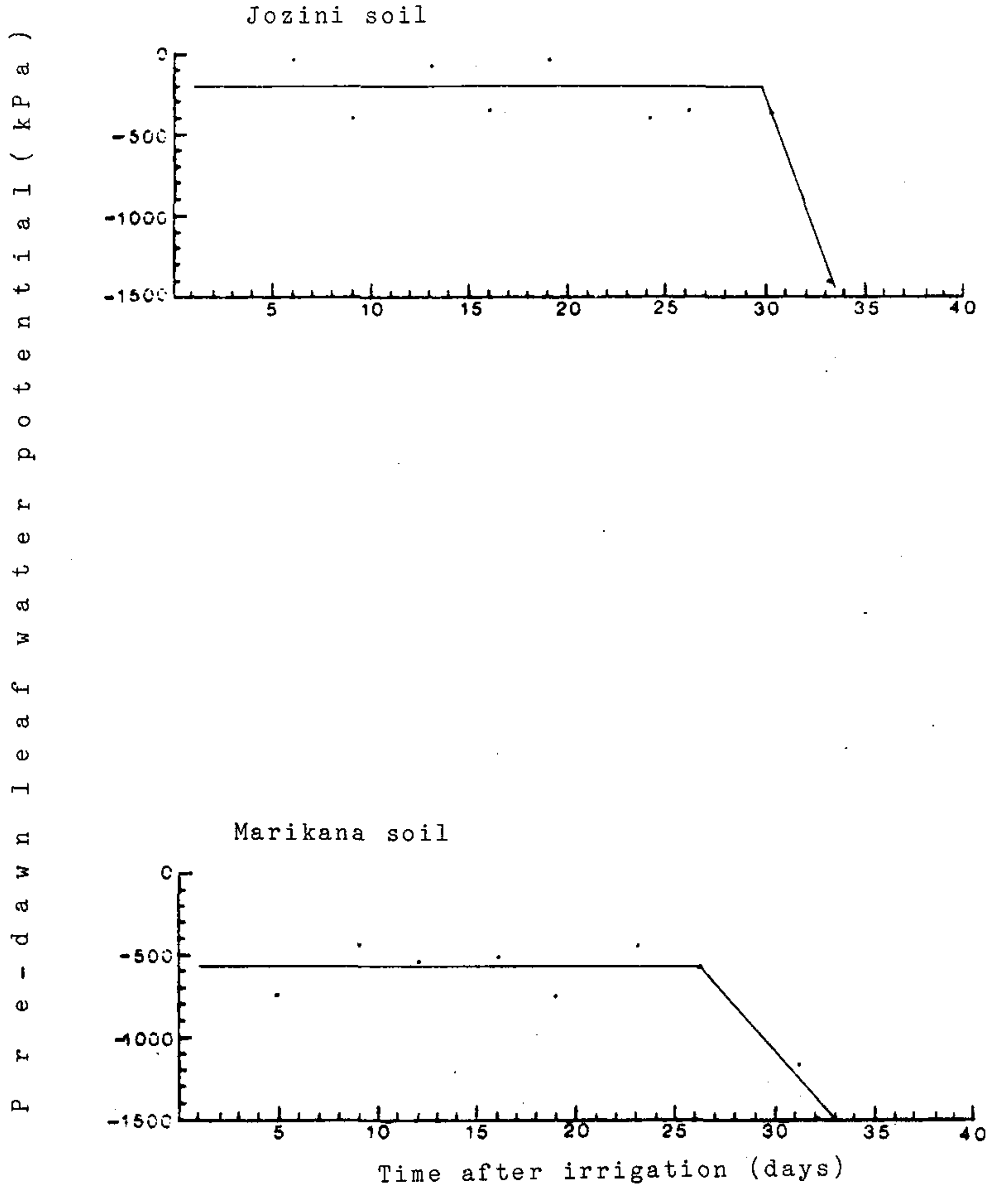
950+

saprolite

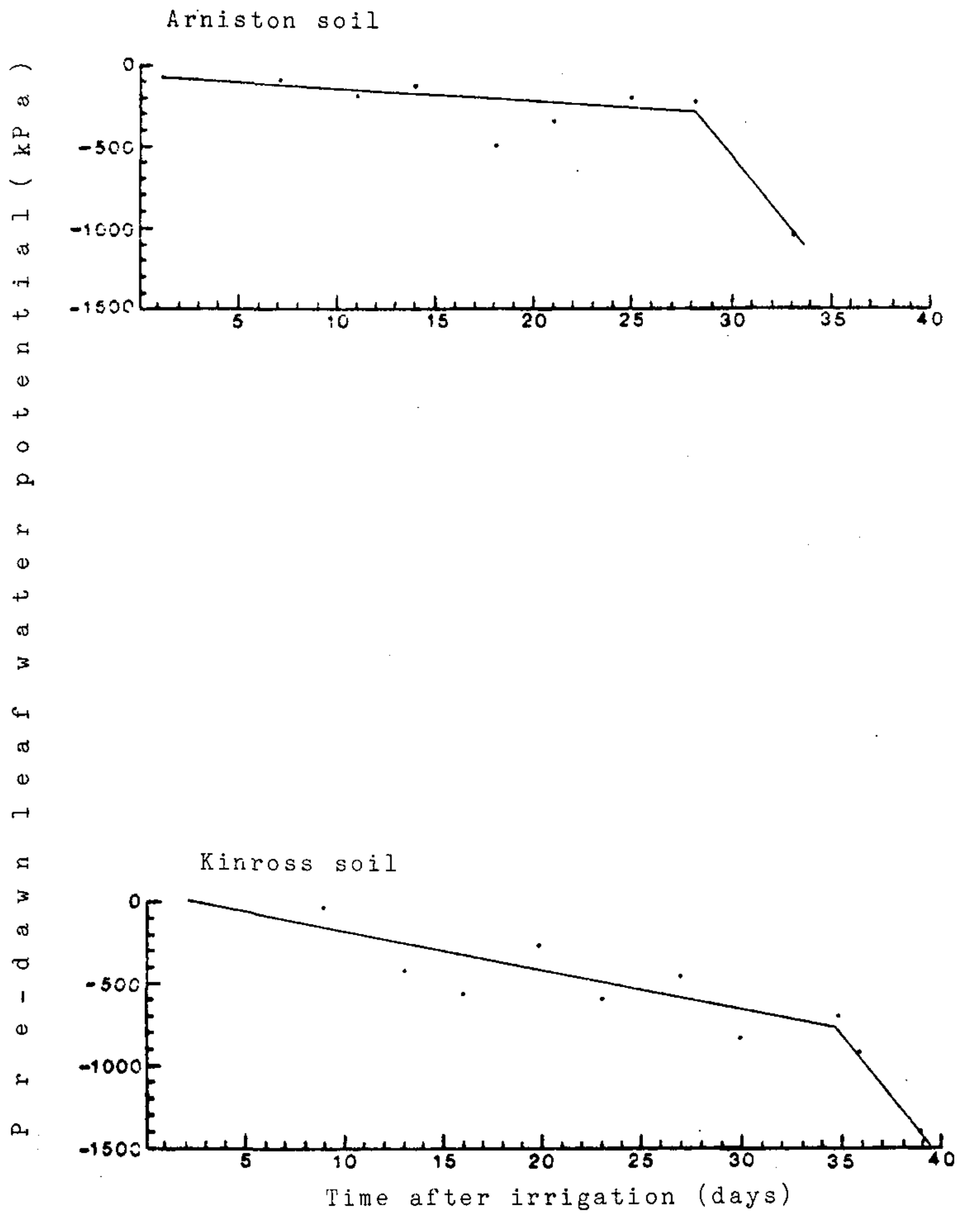
APPENDIX 2.19 (continued)

ANALYTICAL DATA FOR CONTOUR 10

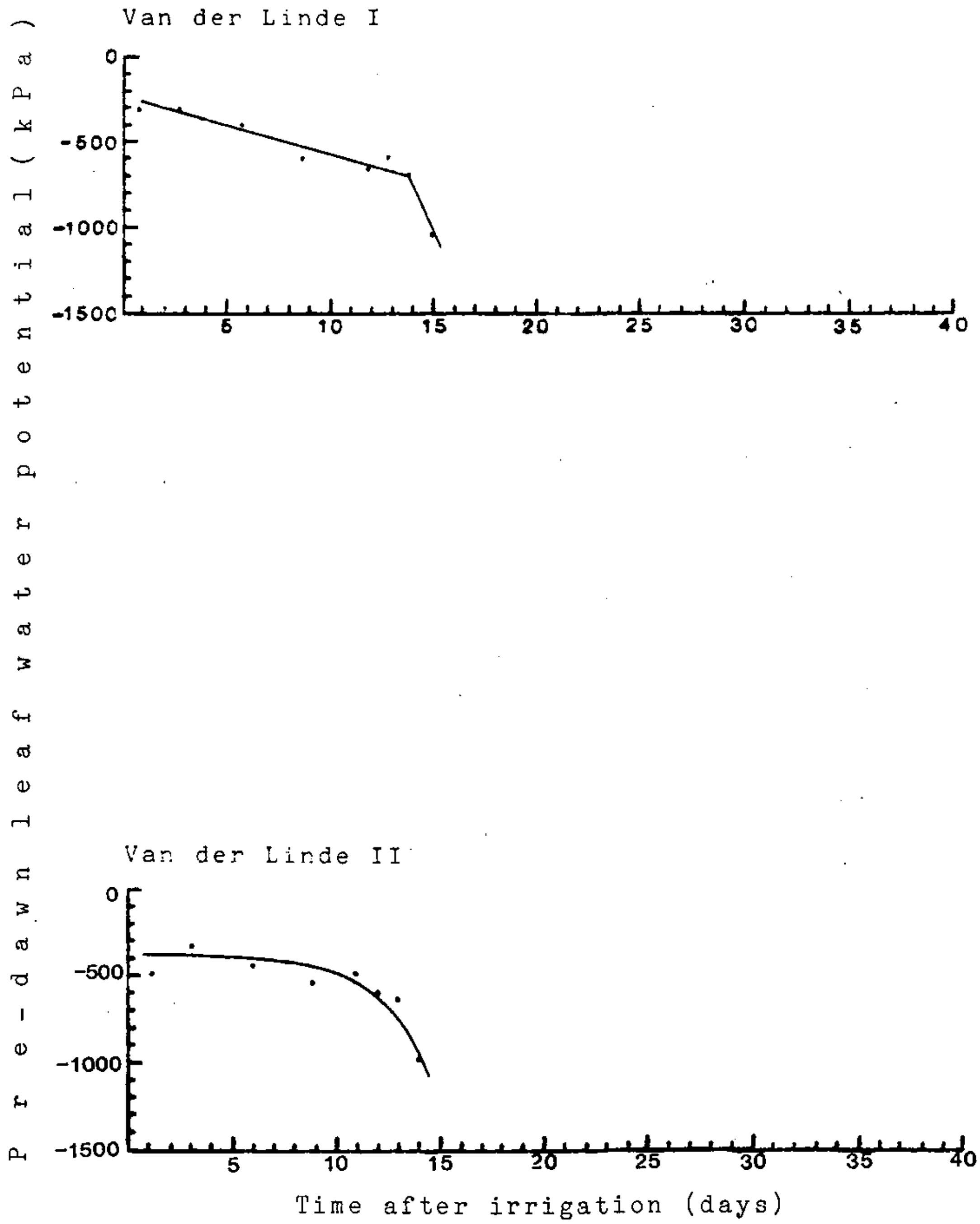
Lab. No.	30/84	31/84	32/84	33/84
Horizon	Ap	A1	B21t	B22t
Particle size distribution (%)				
co Sa	21,8	18,2	22,2	22,0
me Sa	15,6	15,5	11,9	9,6
fi Sa	18,7	21,8	14,3	12,0
vf Sa	13,3	14,6	10,5	11,2
Total Sand	69,4	70,1	58,9	54,8
co Si	5,5	5,4	5,6	4,4
fi Si	6,1	4,9	3,8	6,5
Total Silt	11,6	10,3	9,4	10,9
Clay	17,0	16,0	27,8	31,1
Exchangeable cations (me/100 g soil)				
Ca	3,8	3,1	4,0	5,0
Mg	1,9	1,9	3,8	5,9
K	0,8	0,5	0,3	0,3
Na	0,1	0,1	0,3	0,3
S. value (me/100 g soil)	6,6	5,6	8,3	11,4
C.E.C. (me/100 g soil)	10,8	10,8	18,0	20,8
Organic C (%)	0,41	0,32	0,27	0,19
pH				
water 1:2,5	6,3	6,0	7,9	7,1
KCl 1:2,5	5,2	5,0	5,6	6,0



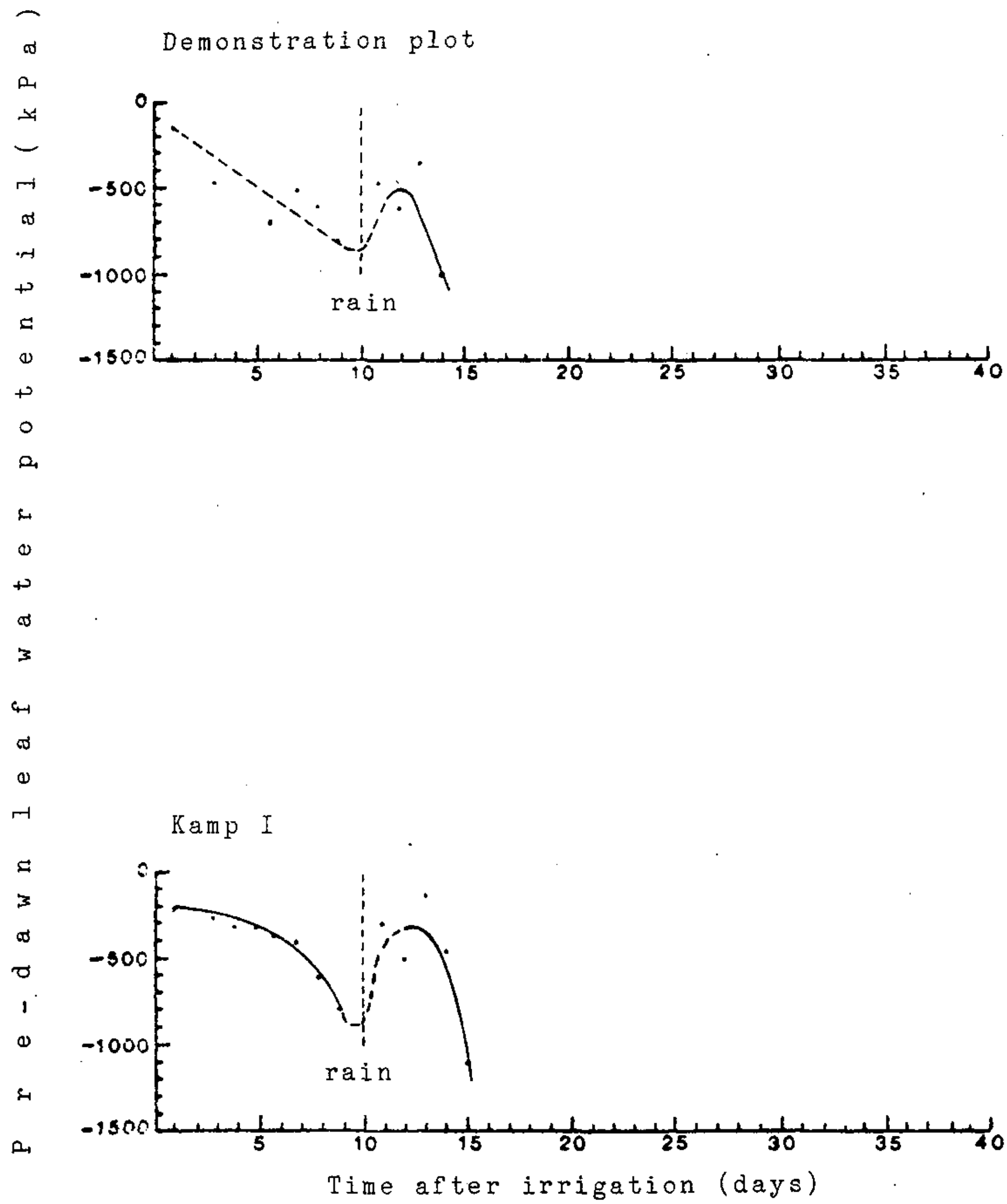
APP.2.20 Pre-dawn leaf water potential readings for wheat at flowering in the Ciskei for different times after irrigation.



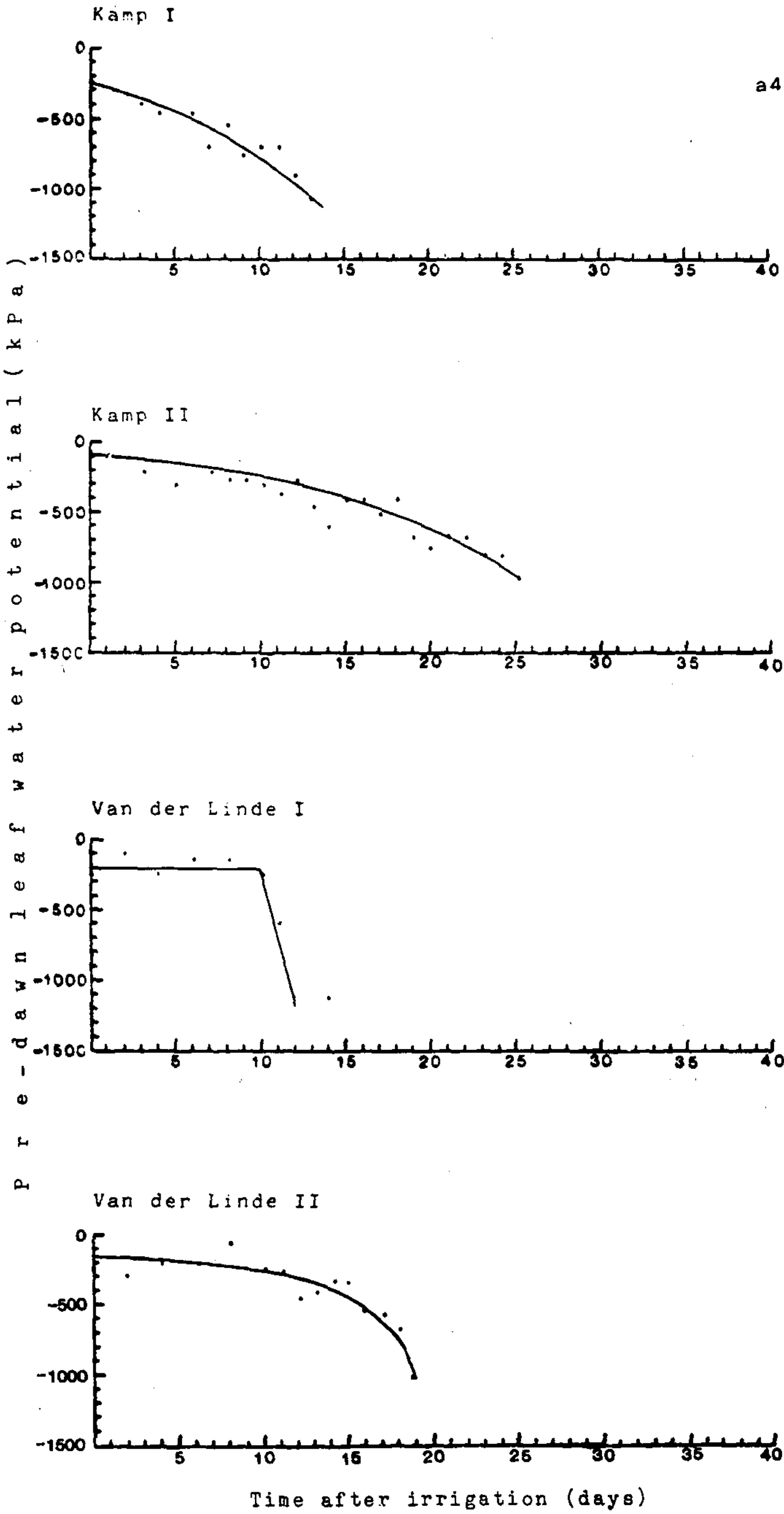
APP.2.21 Pre-dawn leaf water potential readings for wheat at flowering in the Ciskei for different times after irrigation.



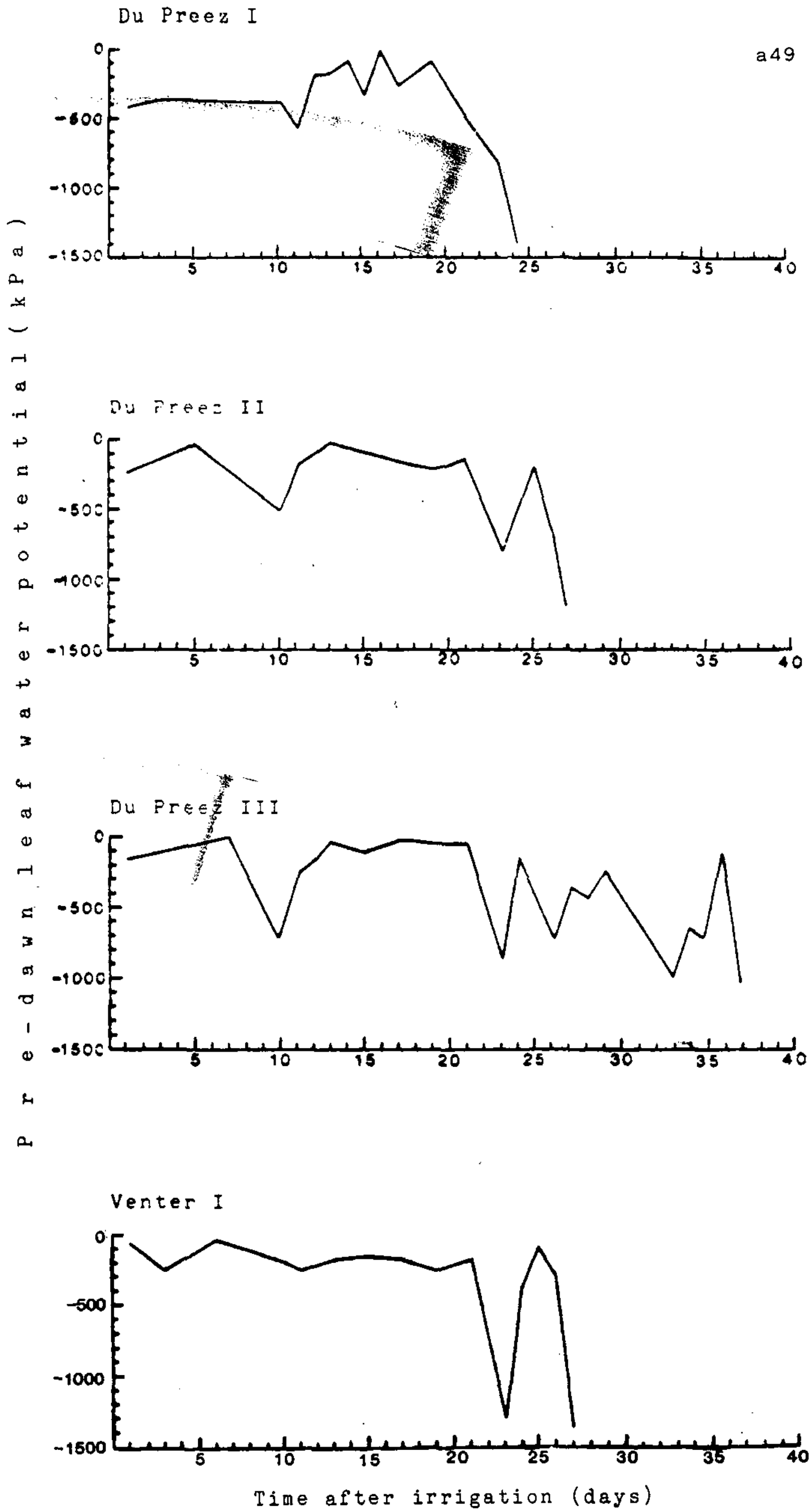
APP.2.22 Pre-dawn leaf water potential readings for wheat at flowering at Vaalharts for different times after irrigation.



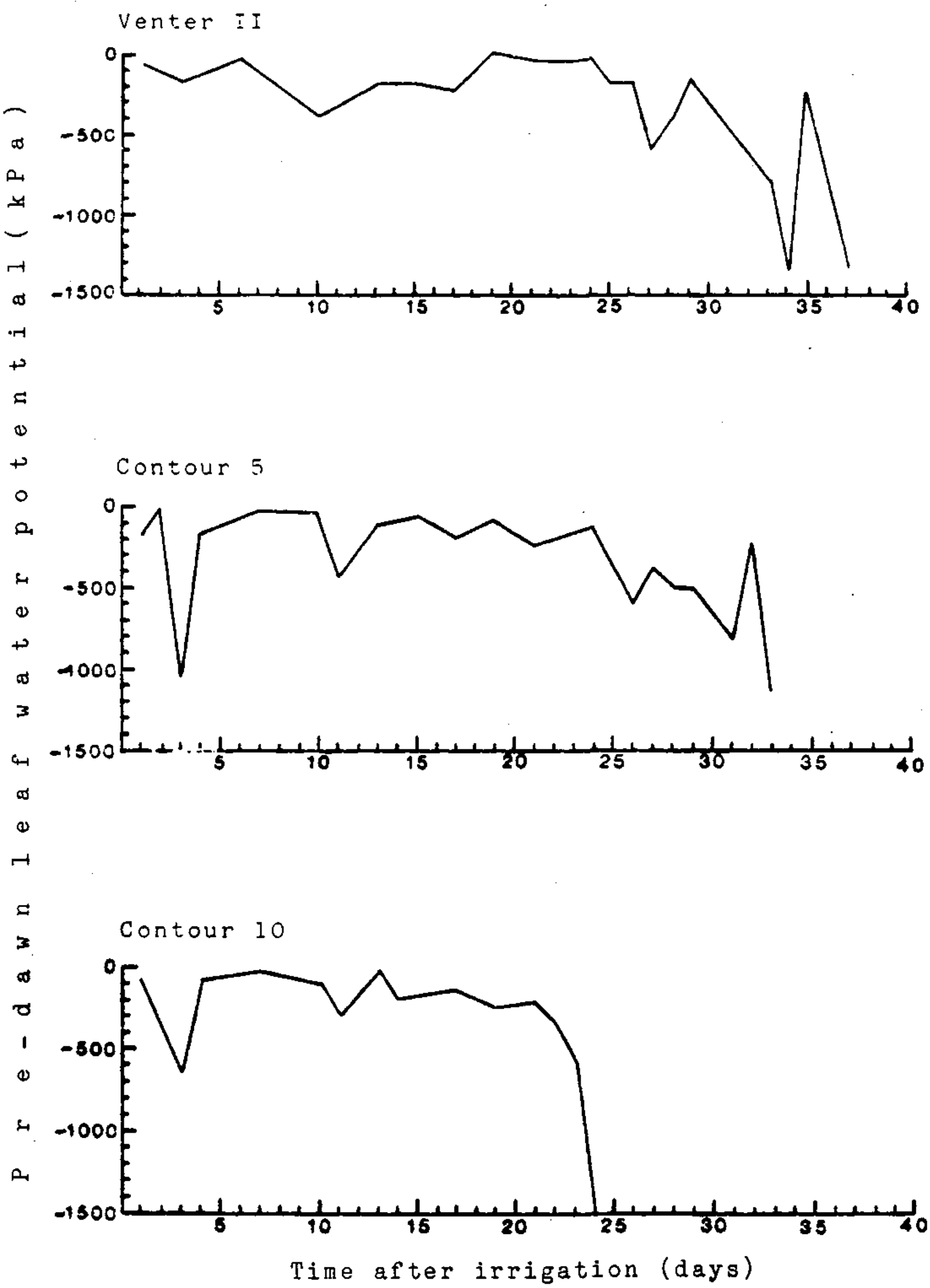
APP.2.23 Pre-dawn leaf water potential readings for wheat at flowering at Vaalharts for different times after irrigation.



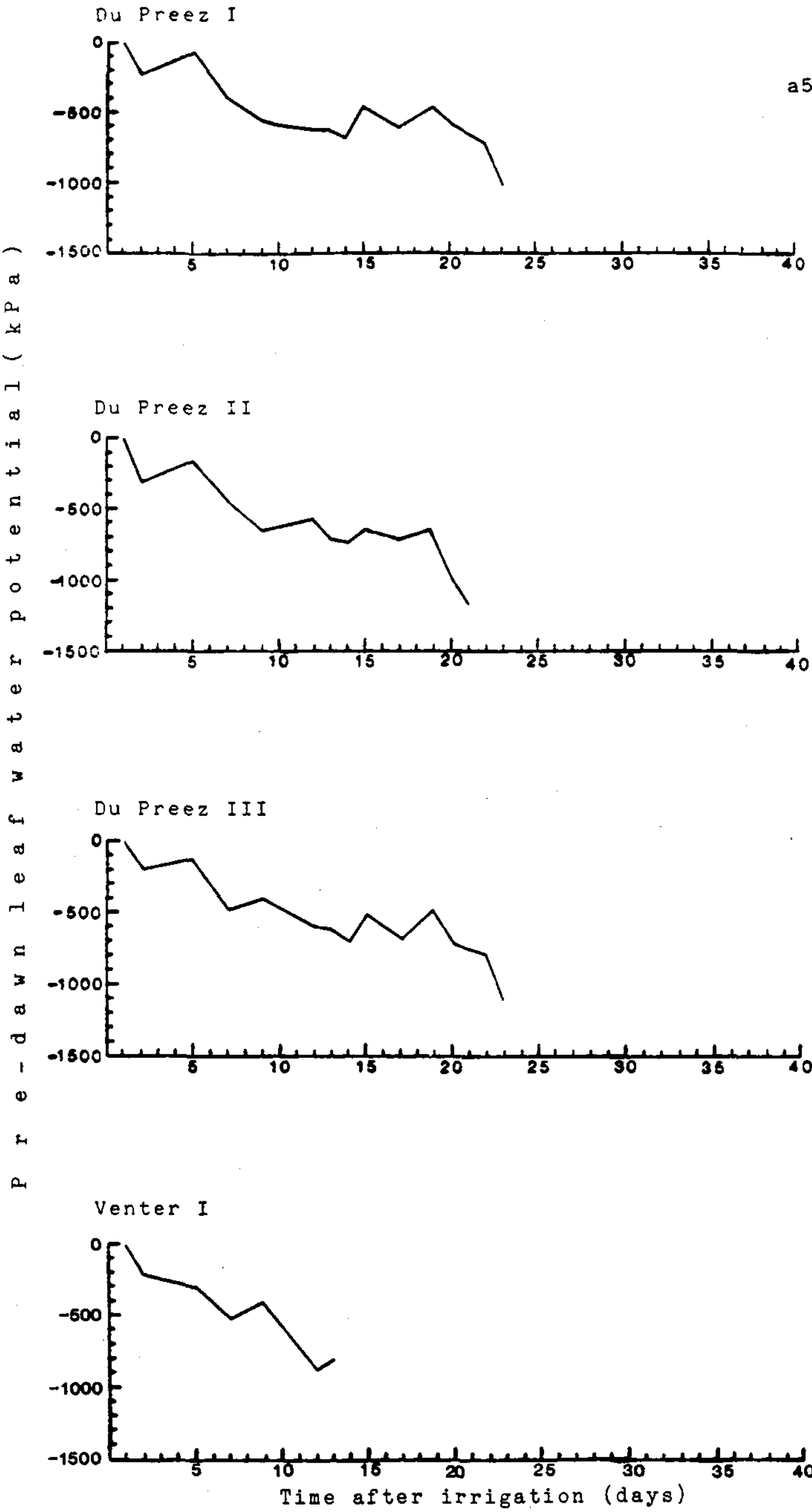
APP.2.24 Pre-dawn leaf water potential readings for peas at flowering at Vaalharts for different times after irrigation.



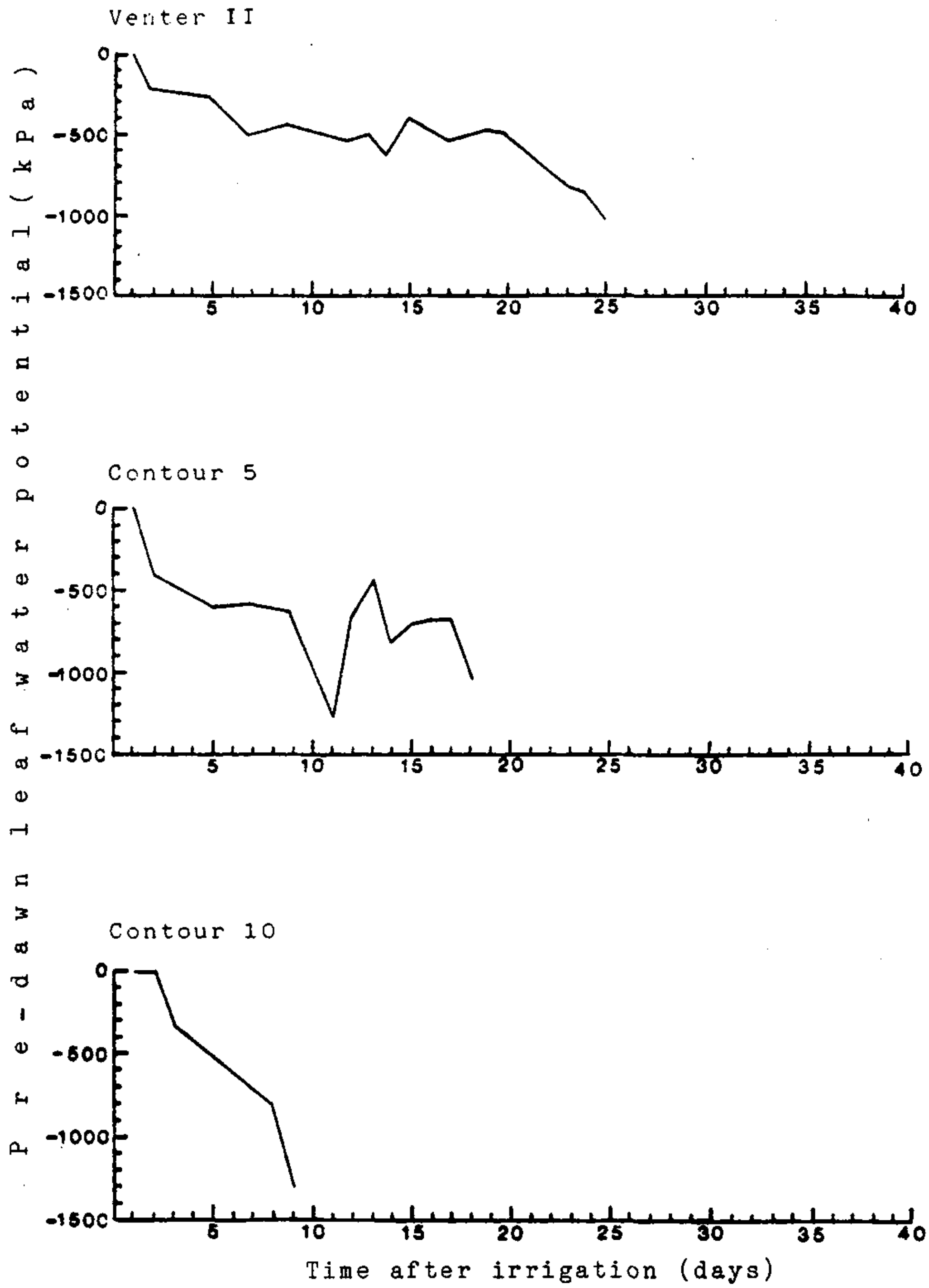
APP.2.25 Pre-dawn leaf water potential readings for maize at flowering at Loskop for different times after irrigation.



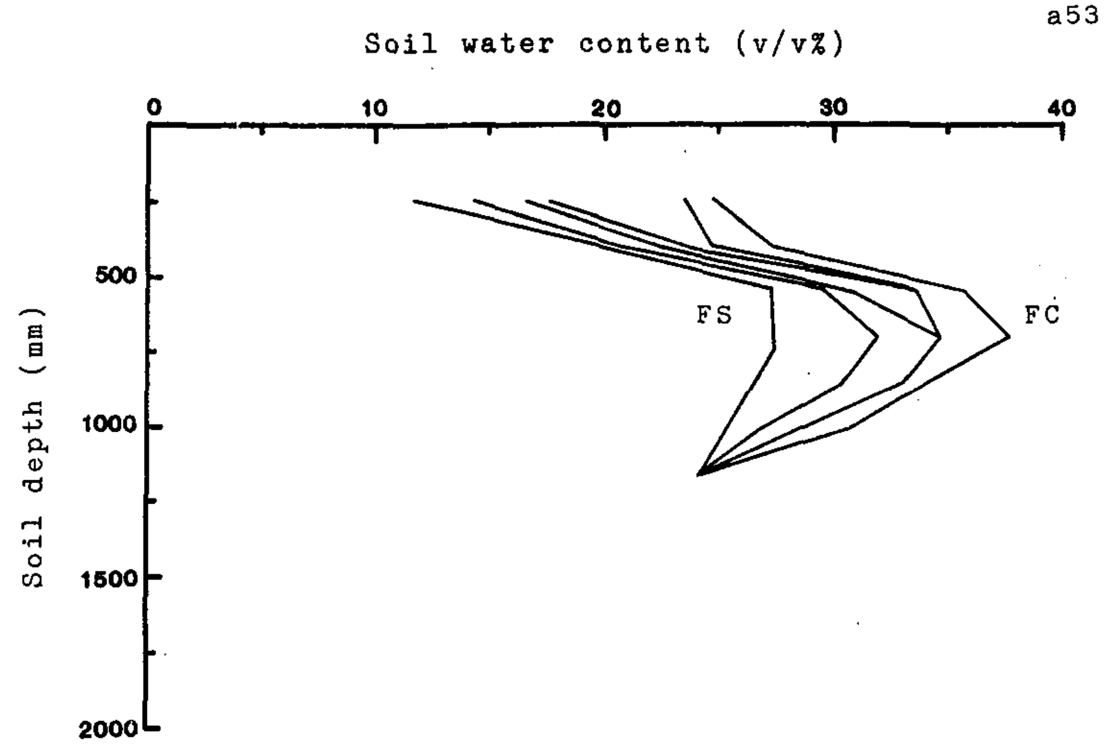
APP.2.26 Pre-dawn leaf water potential readings for maize at flowering at Loskop for different times after irrigation.



APP.2.27 Pre-dawn leaf water potential readings for cotton at flowering at Loskop for different times after irrigation.

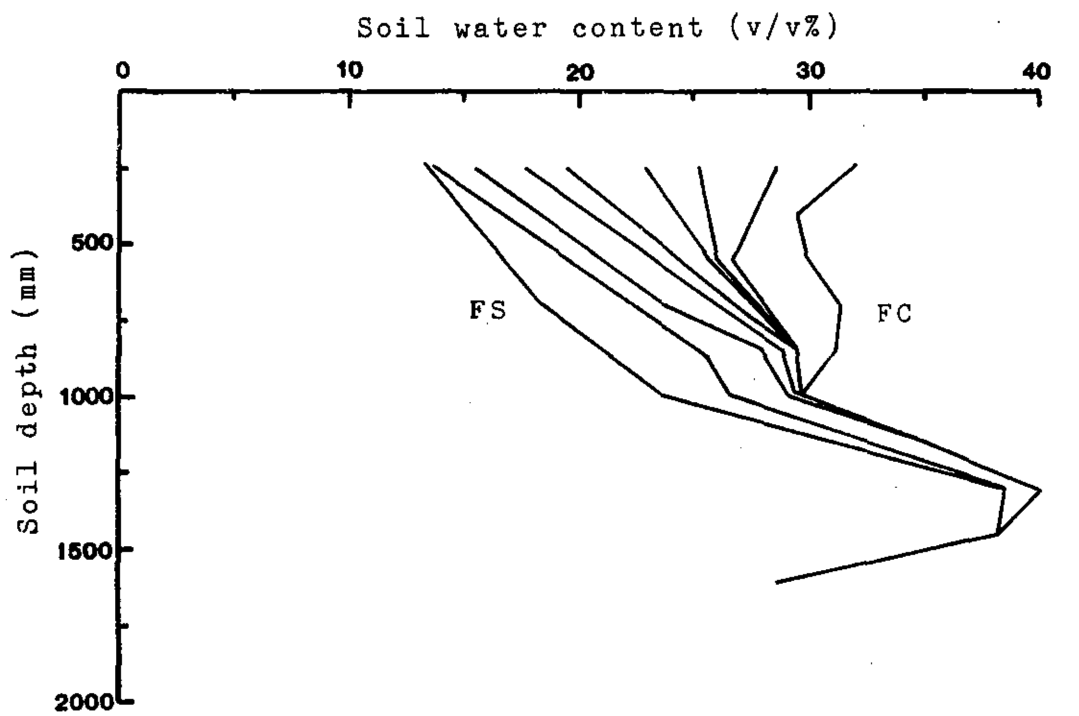


APP.2.28 Pre-dawn leaf water potential readings for cotton at flowering at Loskop for different times after irrigation.



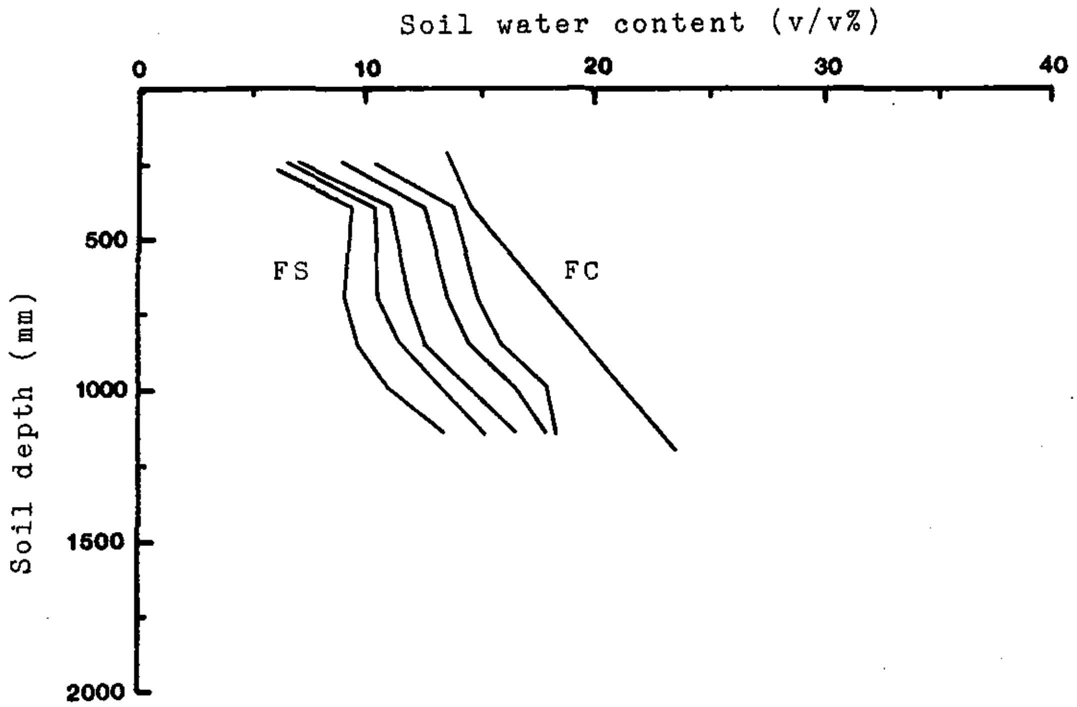
APP.3.1 Soil water extraction pattern for wheat on the Sterkspruit soil (Ciskei). 4 to 6 day intervals.

FC = field capacity
FS = first stress



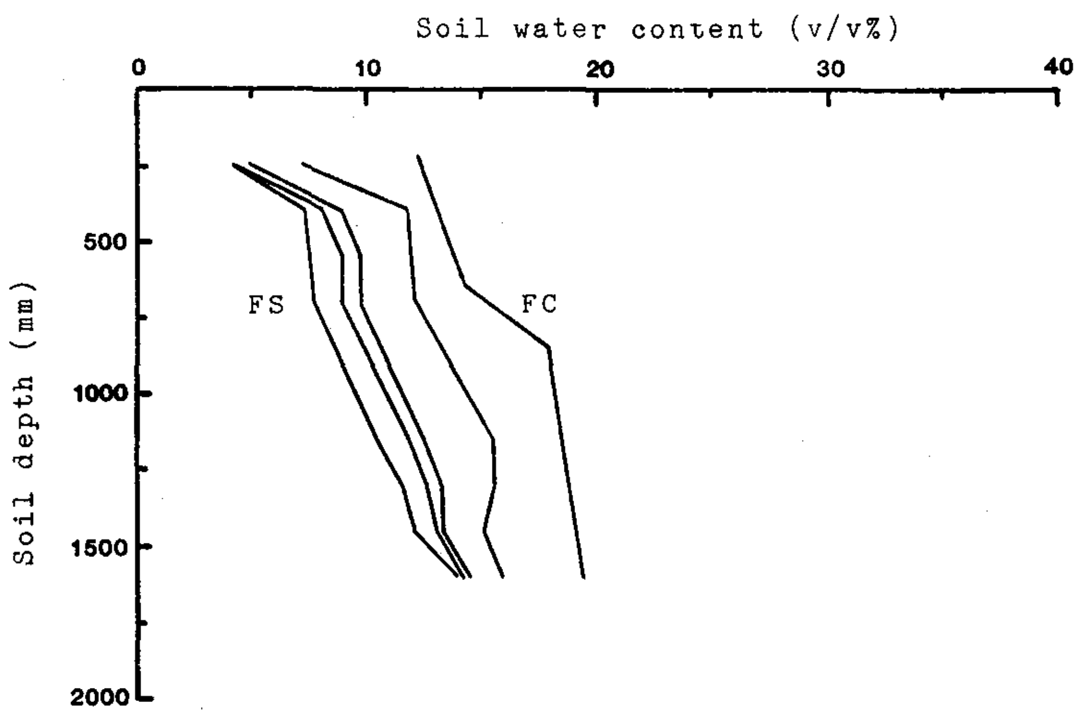
APP.3.2 Scil water extraction pattern for wheat on the Kinross soil (Ciskei). 4 to 6 day intervals.

FC = field capacity
FS = first stress



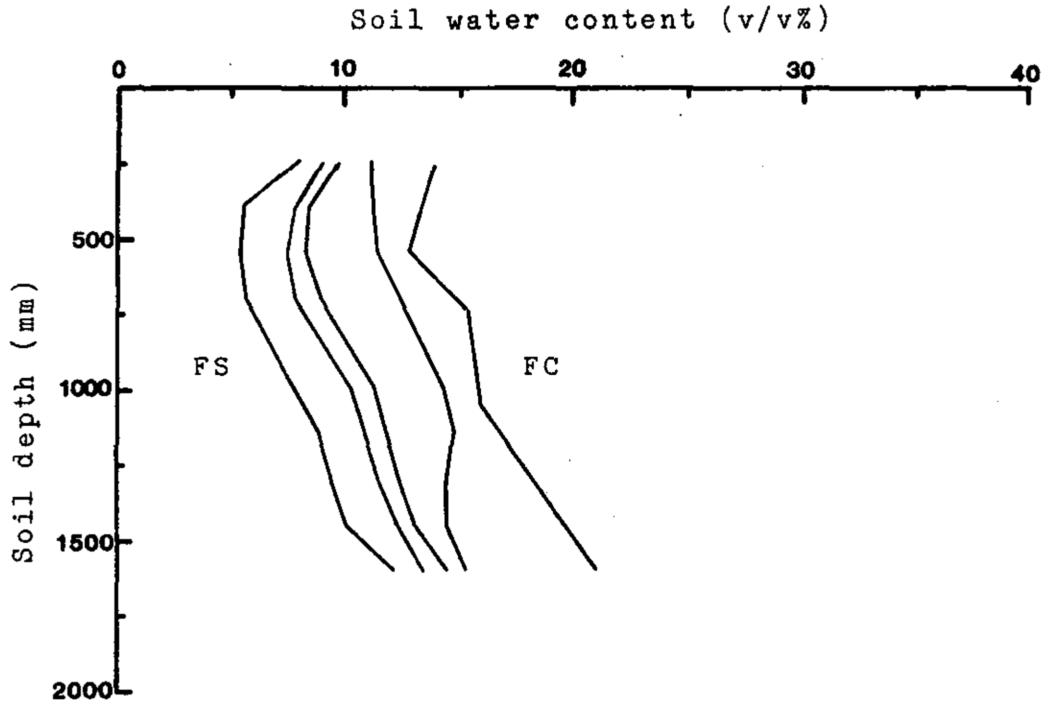
APP.3.3 Soil water extracticn pattern for at maize at Kamp I (Vaalharts). 4 day intervals.

FC = field capacity
FS = first stress



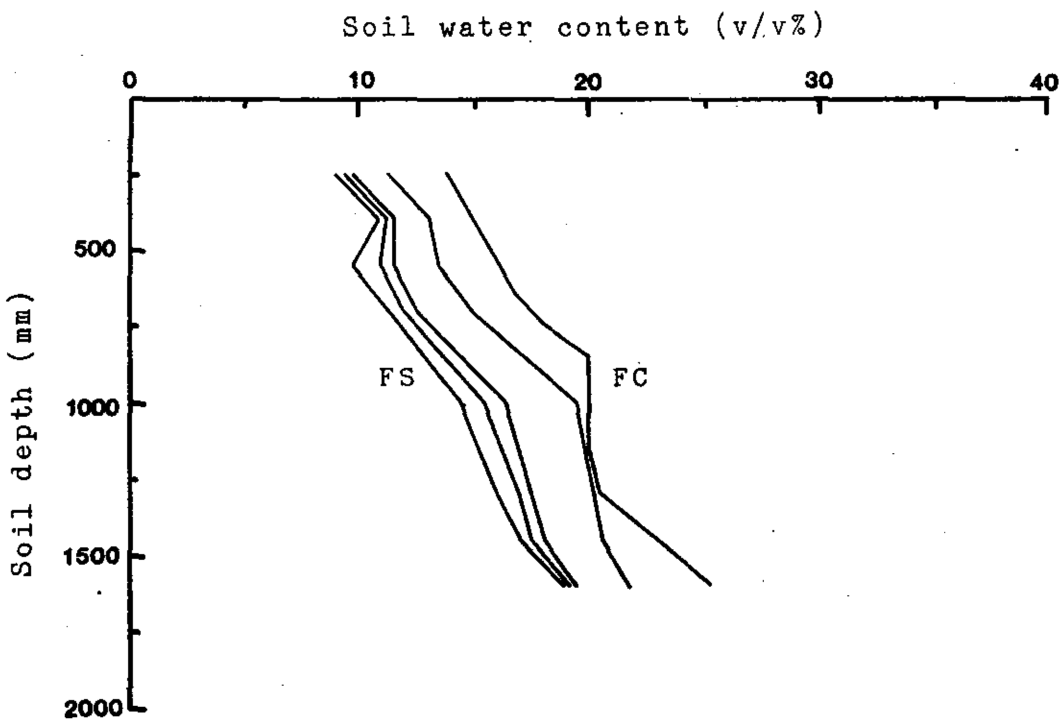
APP.3.4 Soil water extraction pattern for maize at Van der Linde I (Vaalharts). 4 to 6 day intervals.

FC = field capacity
FS = first stress



APP.3.5 Soil water extraction pattern for maize at Van der Linde II (Vaalharts). 4 to 6 day intervals.

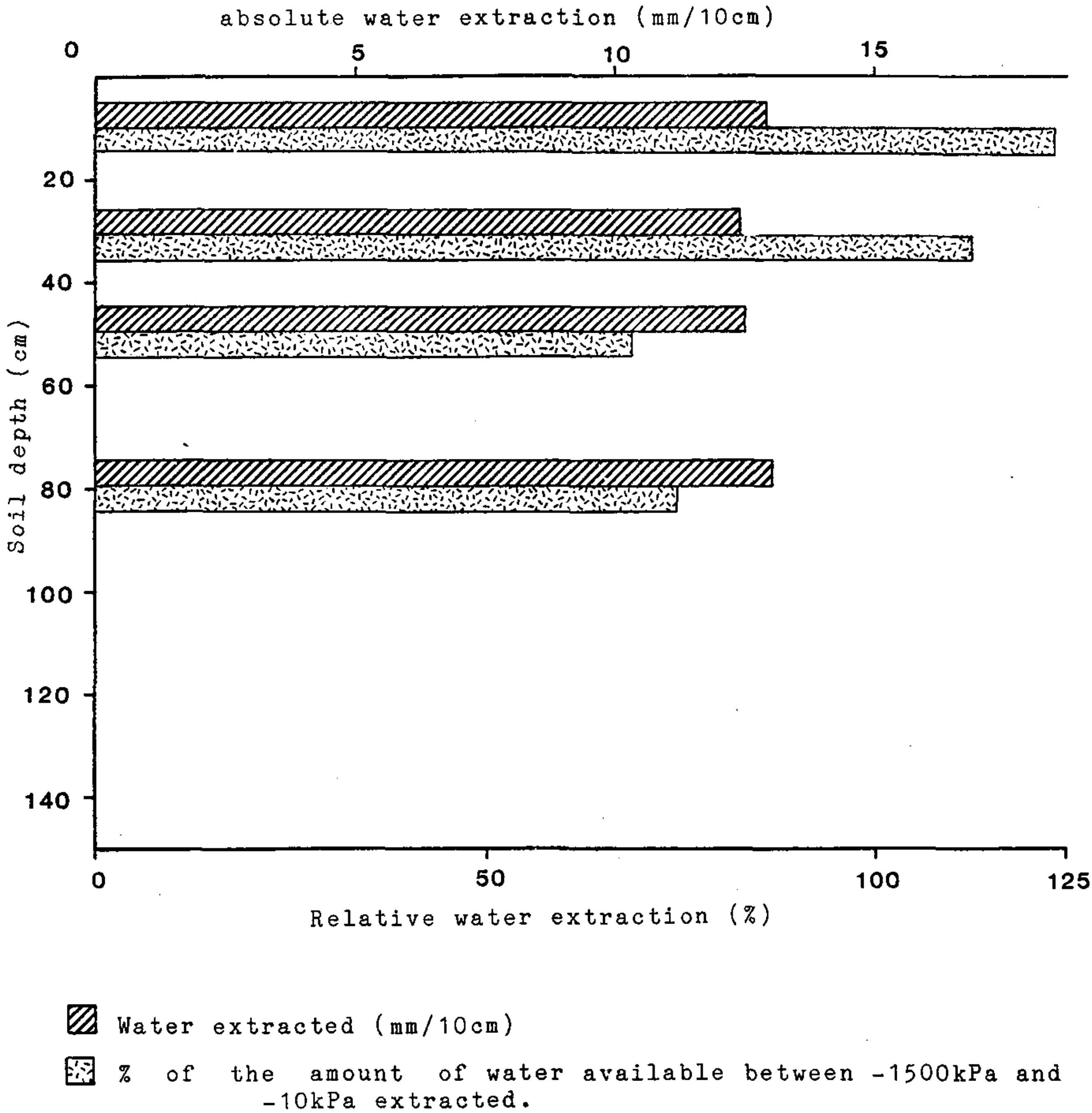
FC = field capacity
FS = first stress



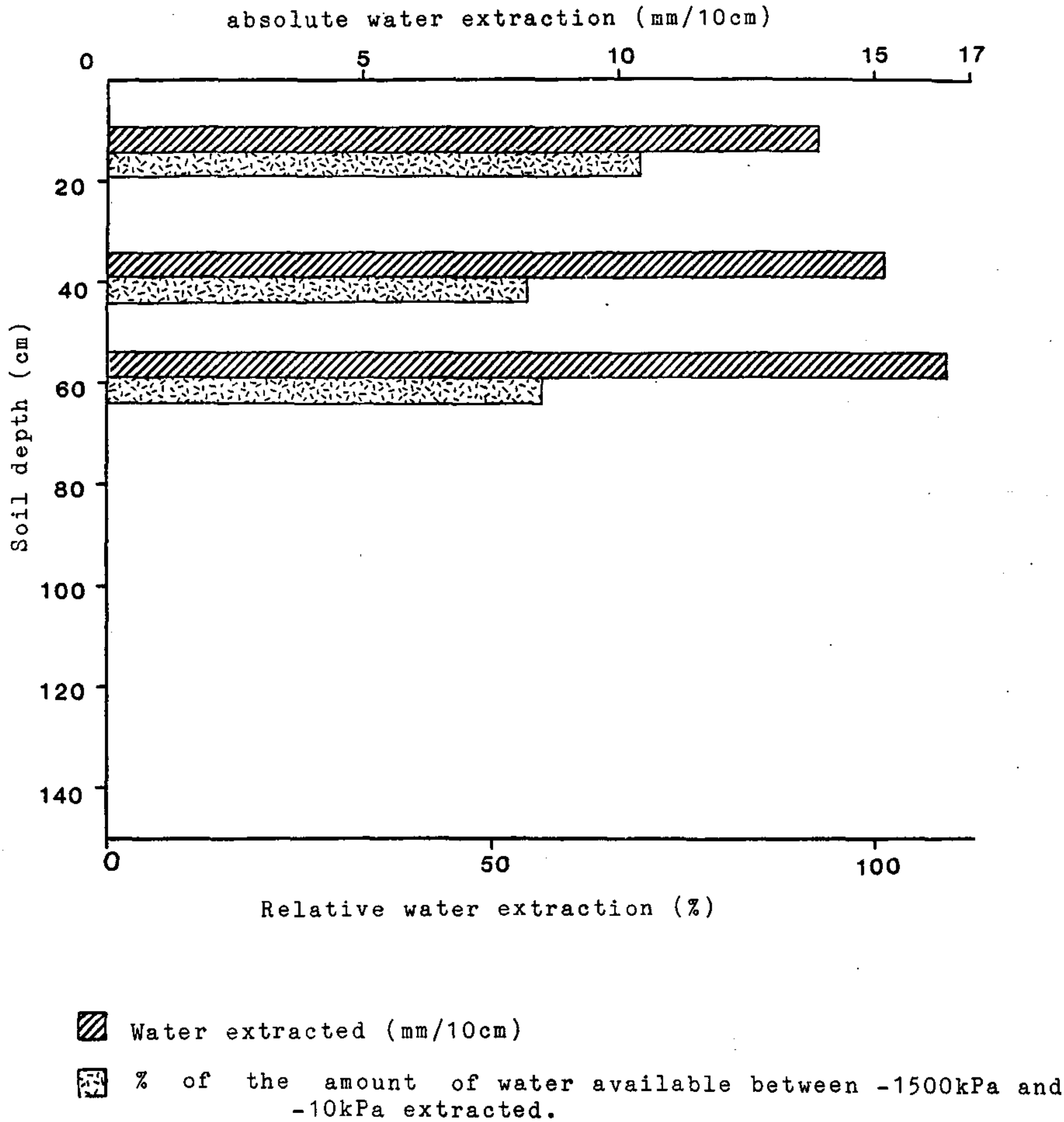
APP.3.6 Soil water extraction pattern for maize at Demonstration plot (Vaalharts). 4 to 5 day intervals.

FC = field capacity

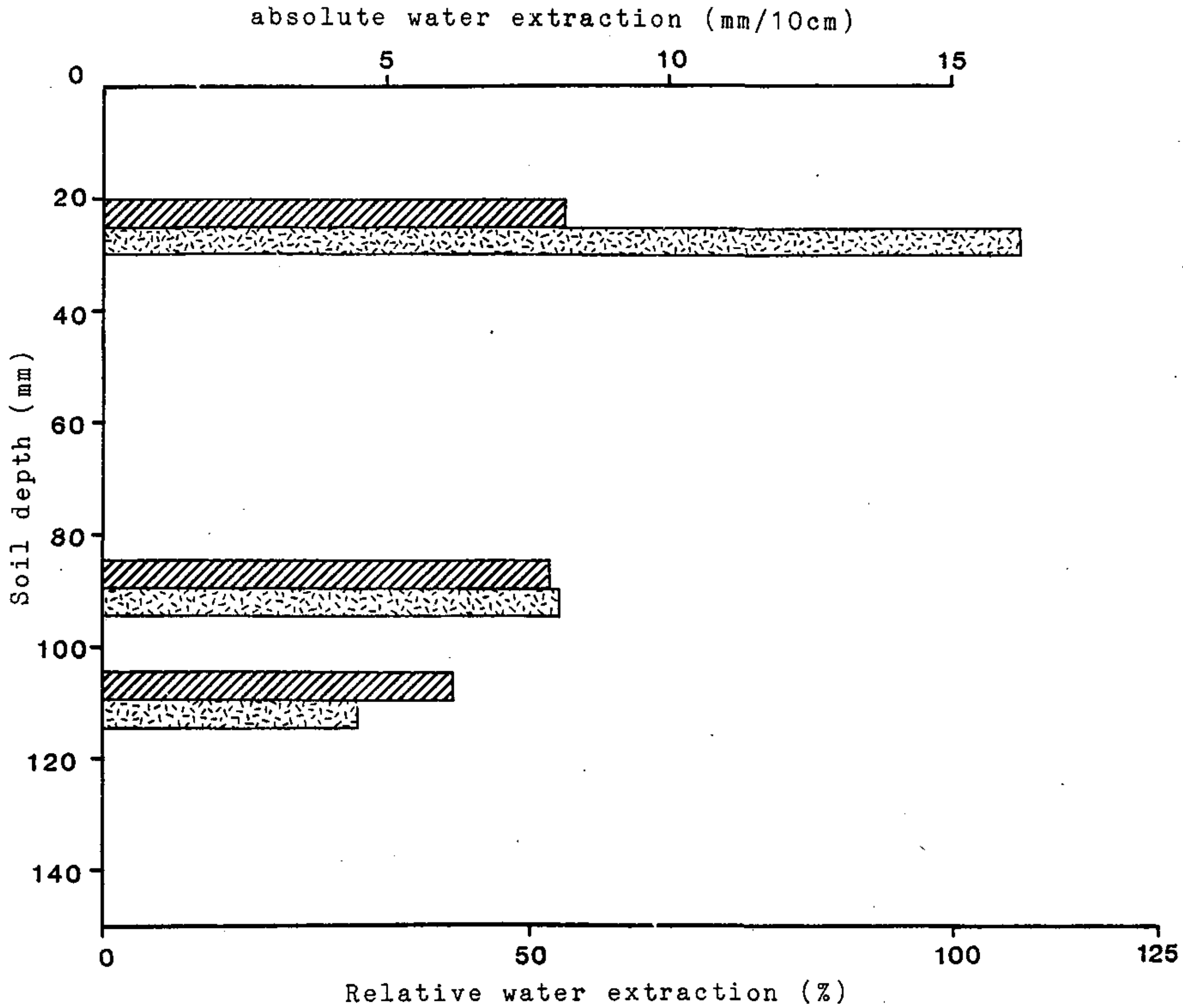
FS = first stress



APP.3.7 Absolute and relative water extraction at different depths of the soil profile at Kamp I (Vaalharts).



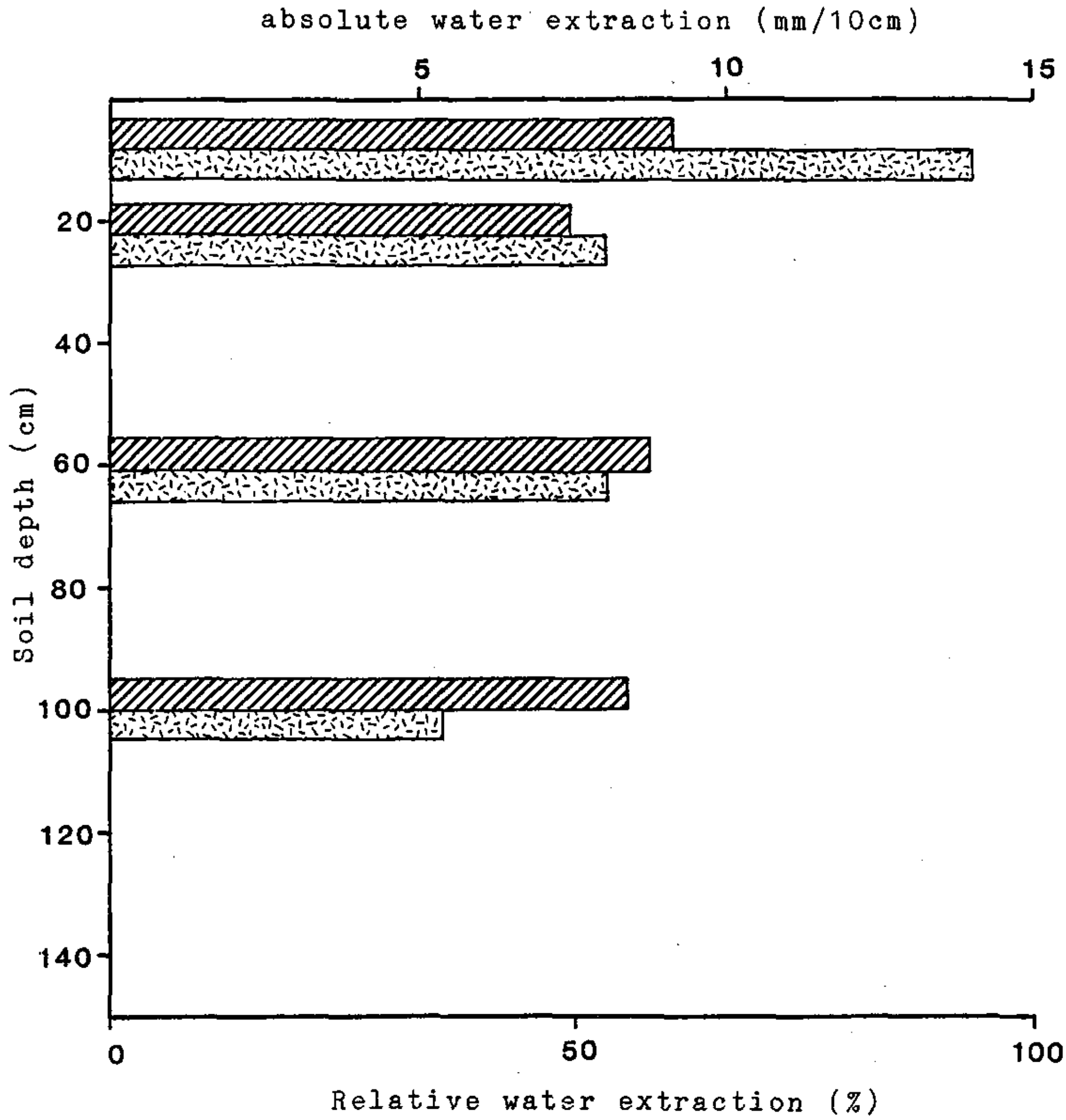
APP.3.8 Absolute and relative water extraction at different depths of the soil profile at Kamp II(Vaalharts).



Water extracted (mm/10cm)

% of the amount of water available between -1500kPa and -10kPa extracted.

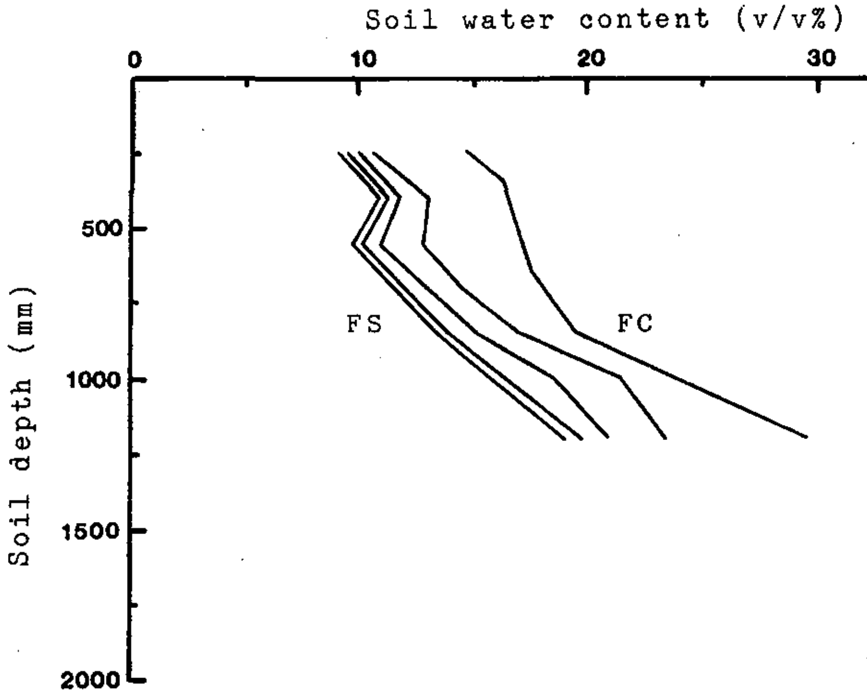
APP.3.9 Absolute and relative water extraction at different depths of the soil profile at Van der Linde I (Vaalharts).



Water extracted (mm/10cm)

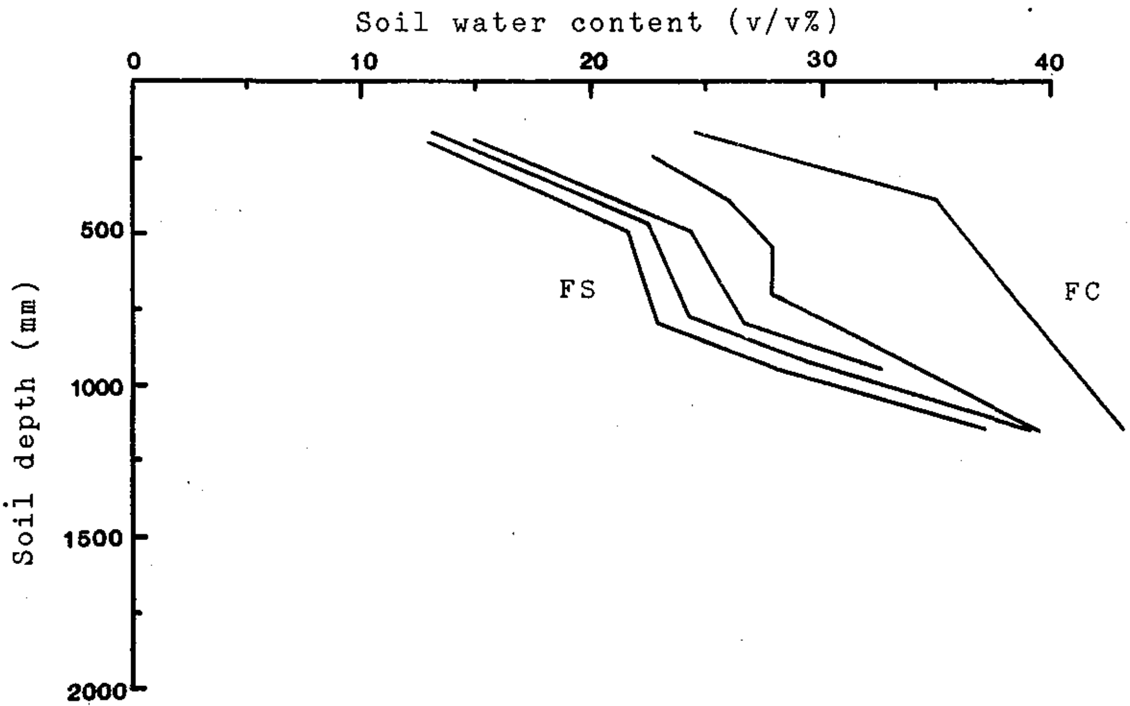
% of the amount of water available between -1500kPa and -10kPa extracted.

APP.3.10 Absolute and relative water extraction at different depths of the soil profile at Demonstration plot (Vaalharts).



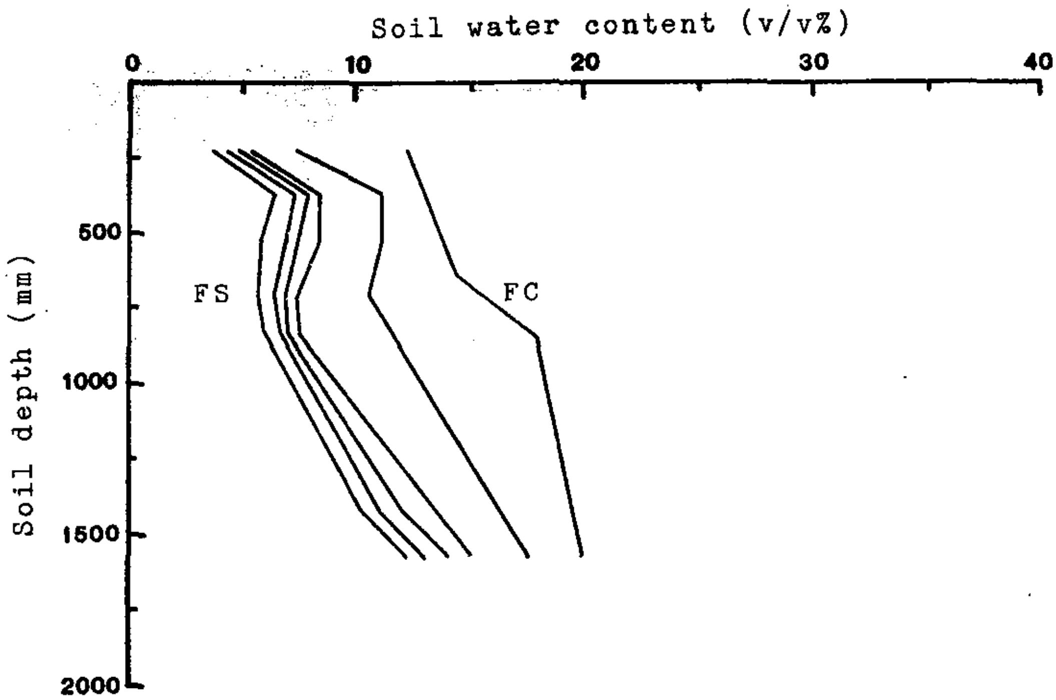
APP.3.11 Soil water extraction pattern for cotton at Kamp I (Vaalharts). 4 to 6 day intervals.

FC = field capacity
FS = first stress



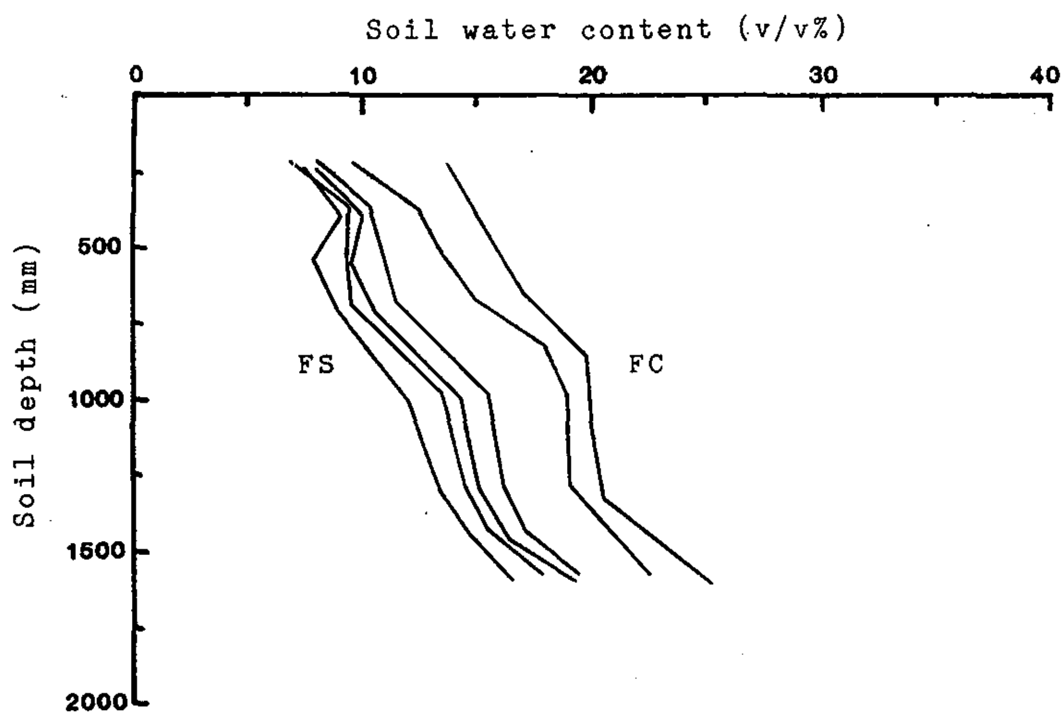
APP.3.12 Soil water extraction pattern for cotton at Kamp II (Vaalharts). 4 to 6 day intervals.

FC = field capacity
FS = first stress



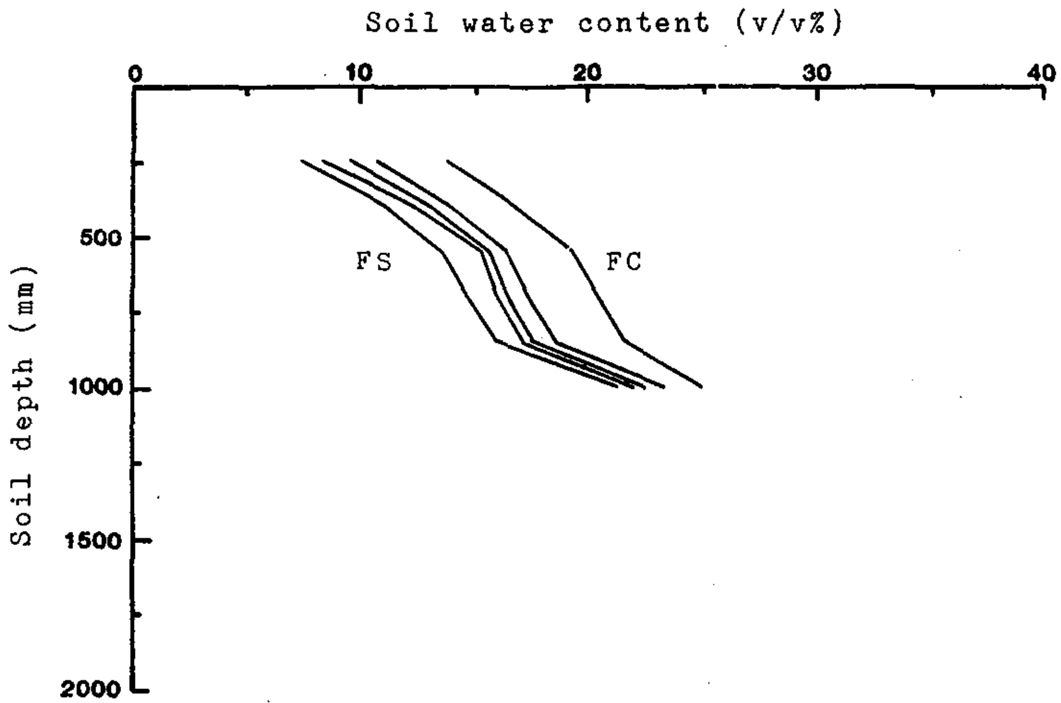
APP.3.13 Soil water extraction pattern for cotton at Van der Linde I (Vaalharts). 4 to 6 day intervals.

FC = field capacity
FS = first stress



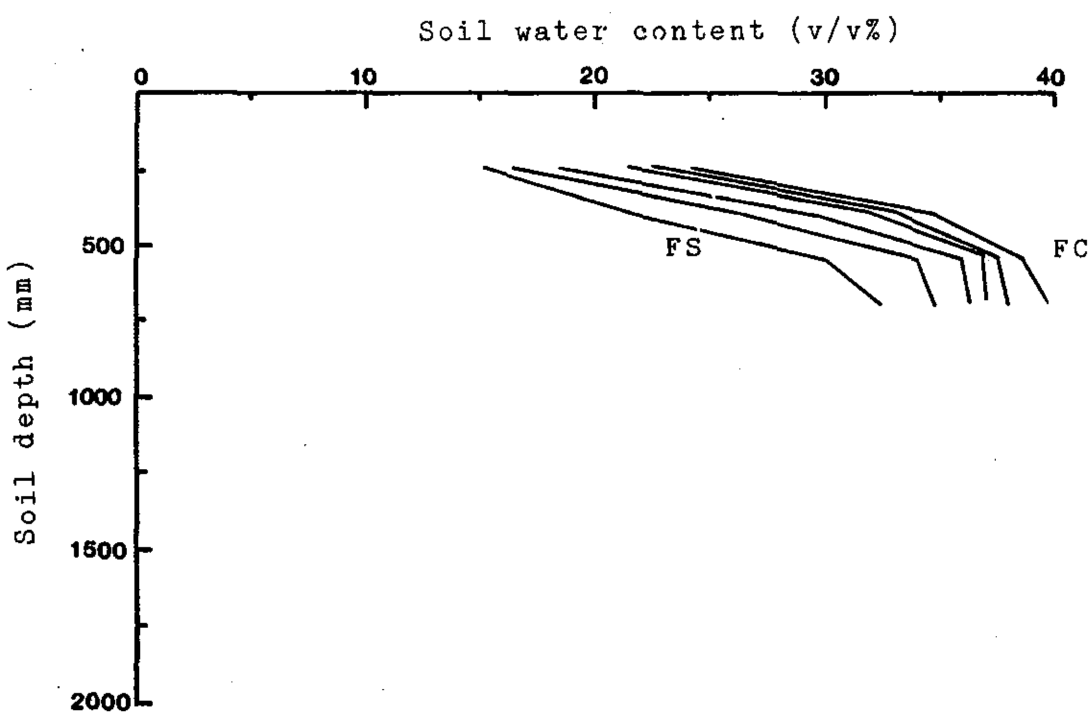
APP.3.14 Soil water extraction pattern for cotton at Van der Linde II (Vaalharts). 4 to 6 day intervals.

FC = field capacity
FS = first stress



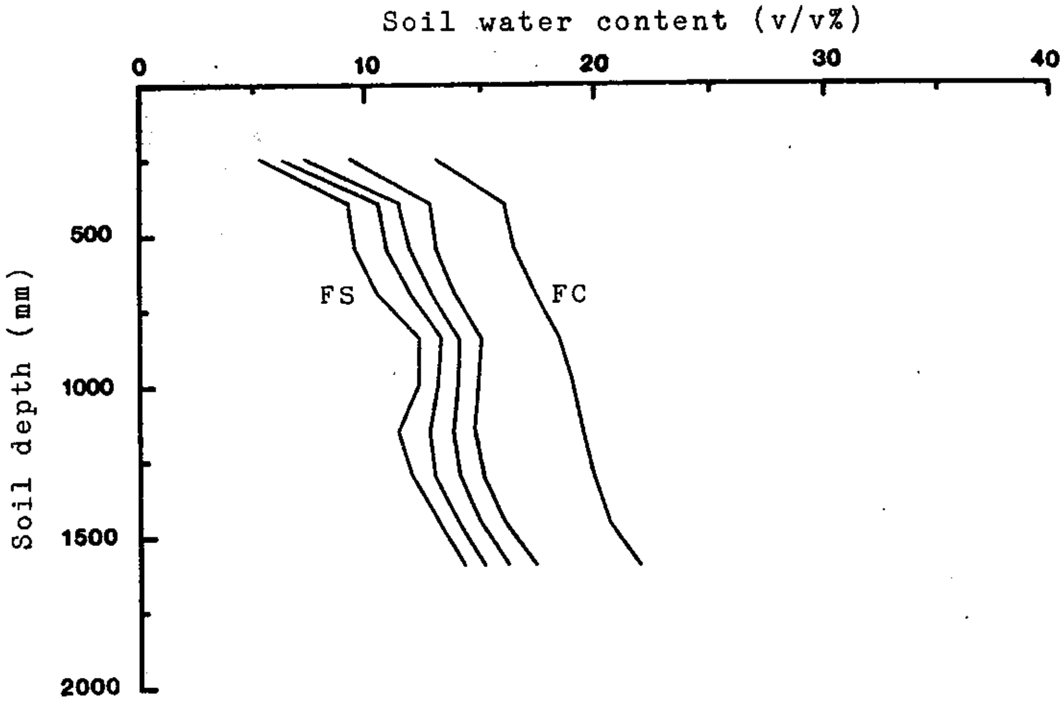
APP.3.15 Soil water extraction pattern for peas at Kamp I (Vaalharts). 4 day intervals.

FC = field capacity
FS = first stress



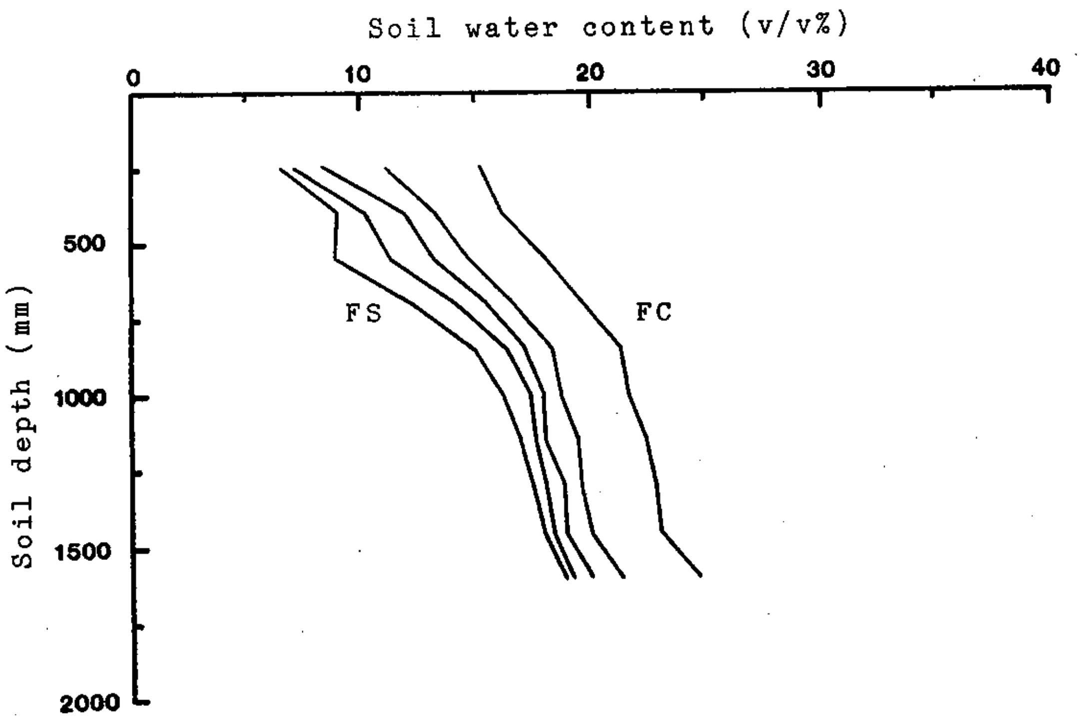
APP.3.16 Soil water extraction pattern for peas at Kamp II (Vaalharts). 5 day intervals.

FC = field capacity
FS = first stress



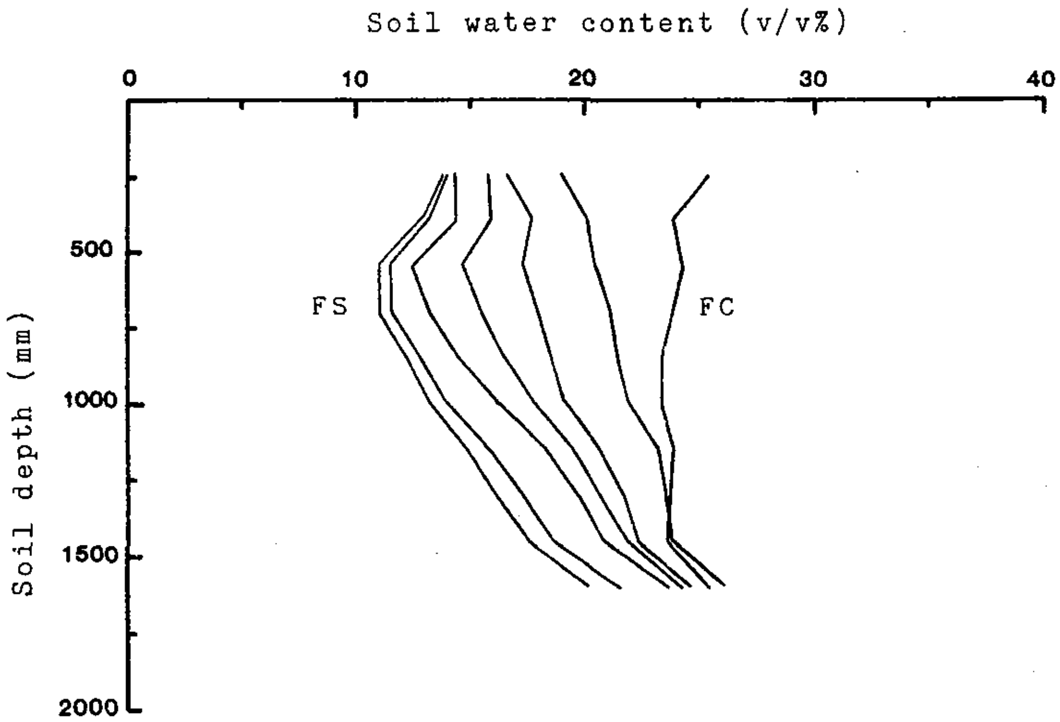
APP.3.17 Soil water extraction pattern for peas at Van der Linde I (Vaalharts). 4 day intervals.

FC = field capacity
FS = first stress



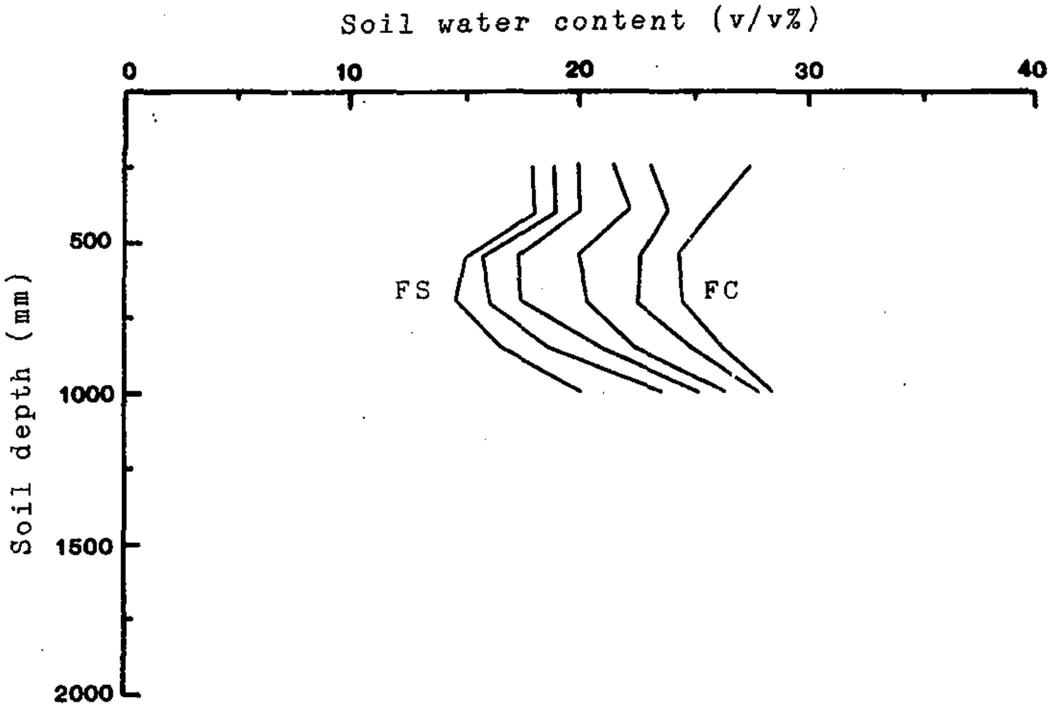
APP.3.18 Soil water extraction pattern for peas at Van der Linde II. 4 day intervals.

FC = field capacity
FS = first stress



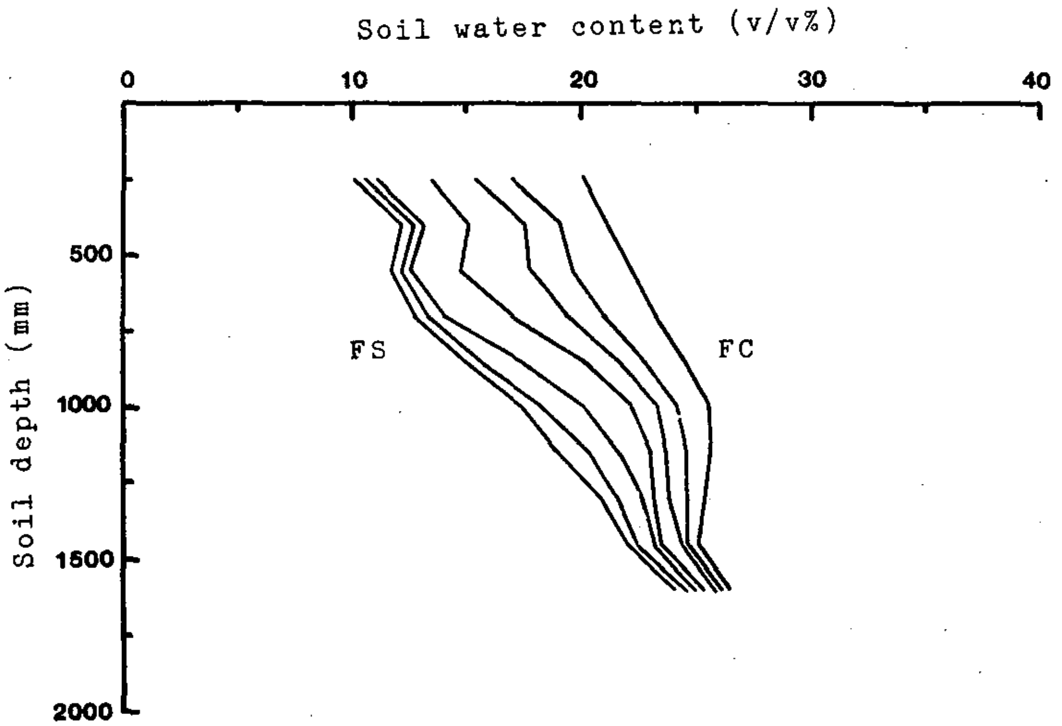
APP.3.19 Soil water extraction pattern for cotton at Du Preez I (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



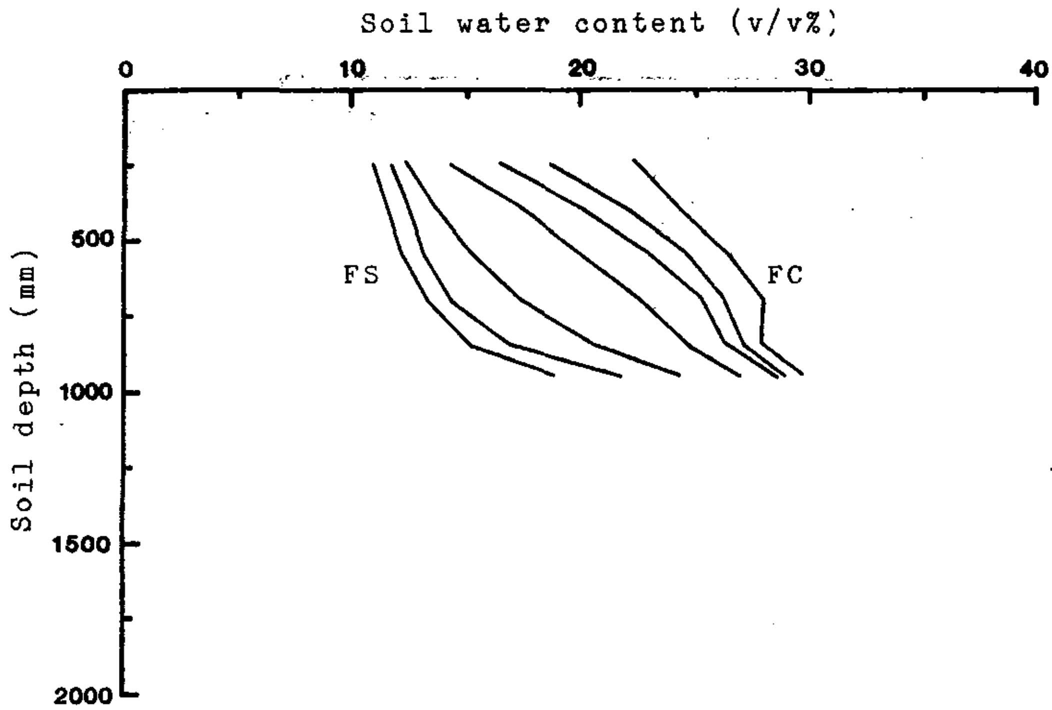
APP.3.20 Soil water extraction pattern for cotton at Du Preez II (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



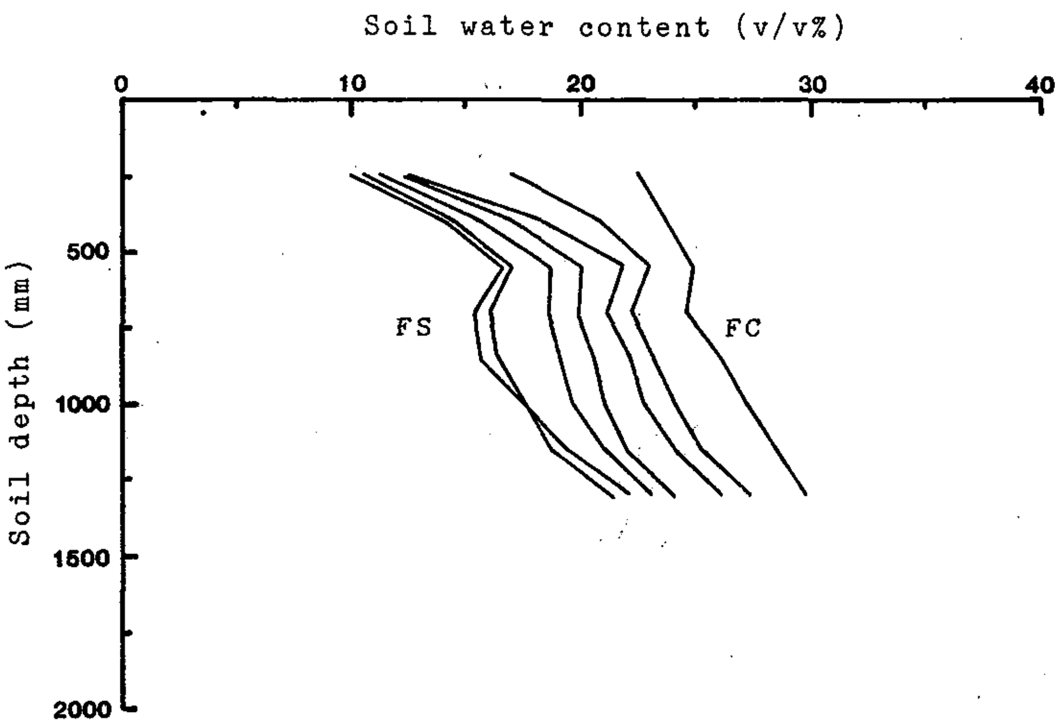
APP.3.21 Soil water extraction pattern for cotton at Du Preez III (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



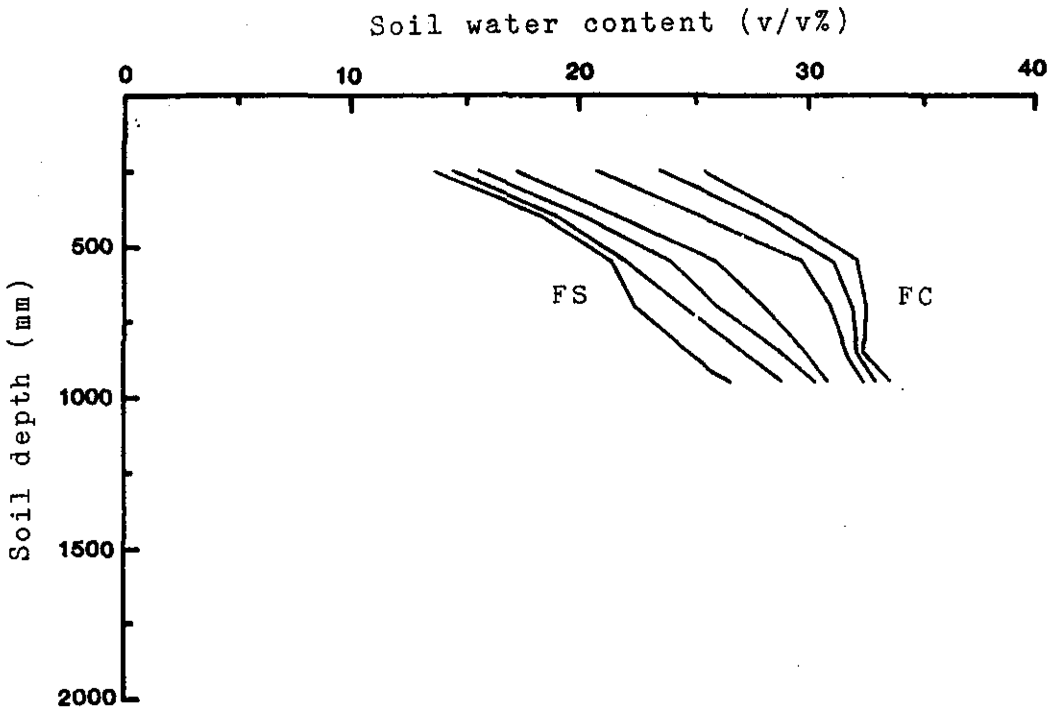
APP.3.22 Soil water extraction pattern for cotton at Venter I (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



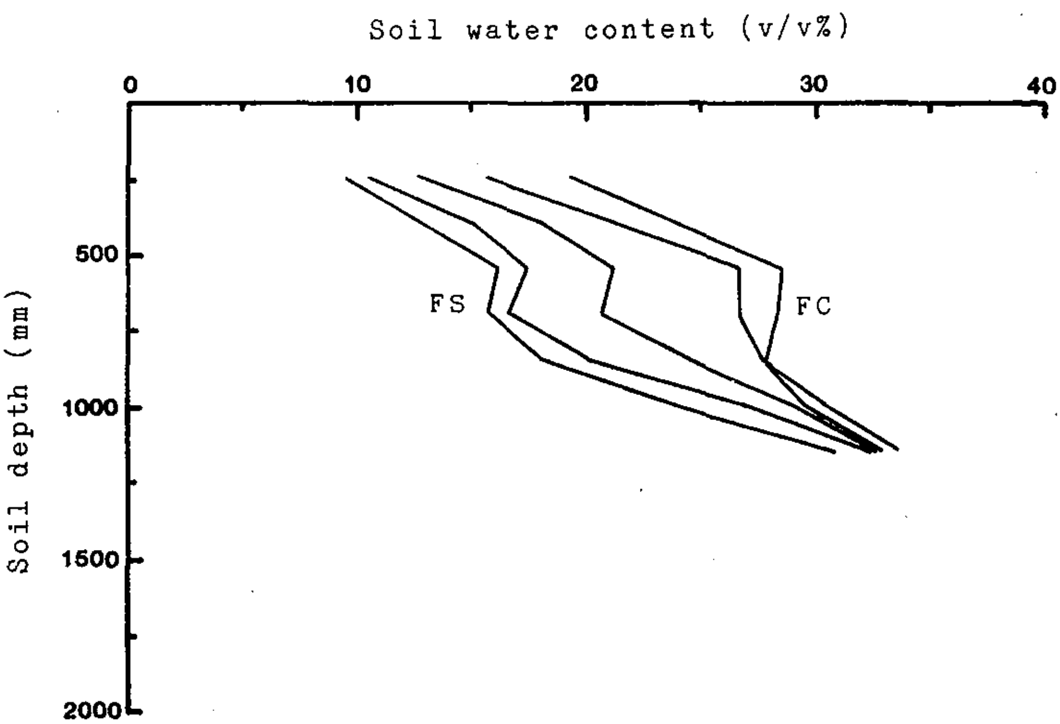
APP.3.23 Soil water extraction pattern for cotton at Venter II (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



APP.3.24 Soil water extraction pattern for cotton at Contour 5 (Loskop). 4 day intervals.

FC = field capacity
FS = first stress



APP.3.25 Soil water extraction pattern for cotton at Contour 10 (Loskop). 4 day intervals.

FC = field capacity
FS = first stress

APPENDIX 4.1 CONSUMPTIVE WATER USE BY WHEAT AT KAMPI

DATE (SEPTEMBER)	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
7	12,4	8,3	1,5****
8	8,2	7,8	1,1****
9	5,0	8,0	0,6
10	5,7	8,5	0,7
11	2,8	5,8	0,5
12	3,0	4,5	0,7
13	2,4	5,3	0,5
14	4,1	5,0	0,8
15	3,0	5,3	0,6
16	3,0	6,3	0,5
17	3,9	6,0	0,7
18	2,4	5,8	0,4
19	4,2	6,8	0,2
20	0,7	3,5	0,2
21	2,3	2,8	0,8
22	1,7	5,0	0,3
23	1,5	4,3	0,4
24	2,1	4,3	0,5
25	2,5	4,8	0,5

** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** *Term crop factor not right for this part of the drying cycle* (see Chapter 4).

APPENDIX 4.2 CONSUMPTIVE WATER USE BY PEAS AT KAMPI
(crops partly destroyed by rabbits)

DATE	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
AUG. 19	10,1	4,3	2,3****
20	5,4	4,5	1,2****
21	4,4	4,5	1,0****
22	1,4	4,5	0,3
23	1,5	5,0	0,3
24	3,2	4,8	0,7
25	1,7	4,5	0,4
26	2,7	4,8	0,6
27	2,7	5,5	0,5
28	0,4	5,5	0,1
29	1,5	5,0	0,3
30	0,7	5,3	0,1
31	1,7	5,8	0,3
SEPT. 1	0,5	6,5	0,1
2	0,9	7,5	0,1
3	2,0	8,3	0,4
4	0,6	6,8	0,1
5	0,6	7,0	0,1
6	0,8	8,5	0,1
7	0,5	8,3	0,1
8	0,8	7,8	*
9	*	8,0	*
10	1,7	8,5	0,2
11	0,4	5,8	0,1
12	0,7	4,3	0,2
13	0,8	5,3	0,2
14	1,1	5,0	0,2
15	1,2	5,3	0,2
16	1,0	6,3	0,2
17	1,2	6,0	0,2
18	0,3	5,8	*

*Ratio irrelevant because of rain.
** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.3 CONSUMPTIVE WATER USE BY WHEAT AT KAMP II

DATE (SEPTEMBER)	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
7	12,4	8,3	1,5****
8	8,2	7,8	1,1****
9	5,0	8,0	0,6
10	5,7	8,5	0,7
11	2,8	5,8	0,7
12	3,0	4,5	0,7
13	4,1	5,0	0,8
14	3,0	5,3	0,6
15	3,0	6,3	0,5
16	3,9	6,0	0,7
17	2,4	5,8	0,7
18	4,2	6,8	0,6
19	0,7	3,5	0,2
20	2,3	2,8	0,8
21	1,7	5,0	0,3
22	1,5	4,3	0,4
23	2,1	4,3	0,4
24	2,5	4,8	0,5

** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.4 CONSUMPTIVE WATER USE BY PEAS AT KAMP II

DATE		WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
AUG.	20	1,6	4,3	0,4
	21	1,5	4,5	0,3
	22	1,1	4,5	0,2
	23	2,2	4,5	0,5
	24	*	5,0	*
	25	3,4	4,3	0,8
	26	1,1	4,5	0,2
	27	2,5	4,3	0,6
	28	3,2	5,5	0,6
	29	*	5,5	*
	30	3,5	5,0	0,7
	31	0,7	5,3	0,1
SEPT.	1	5,4	5,3	0,8
	2	2,6	6,5	0,5
	3	0,6	7,5	0,1
	4	4,6	8,3	0,6
	5	2,7	6,8	0,4
	6	1,7	7,0	0,2
	7	3,3	8,5	0,4
	8	3,2	8,3	0,4
	9	0,4	7,8	0,1
	10	4,4	8,0	0,6
	11	2,6	8,5	0,3
	12	1,0	5,8	0,2
	13	3,3	4,5	4,7
	14	3,4	5,3	0,6
	15	4,2	5,0	0,8
	16	0,5	5,3	0,1
	17	3,6	6,3	0,6
	18	4,4	6,0	0,7
	19	2,2	5,8	0,4
	20	2,5	6,8	0,4
	21	1,1	7,0	0,2

*Ratio irrelevant because of rain.
** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.

APPENDIX 4.5 CONSUMPTIVE WATER USE BY WHEAT AT VAN DER LINDE I

DATE (SEPTEMBER)	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
6	36,5	9,0	4,1****
7	18,0	8,0	2,3****
8	15,9	8,5	1,9****
9	10,8	7,0	1,5
10	15,1	9,0	1,7
11	7,0	8,0	0,9
12	7,9	3,5	2,3
13	5,8	5,5	1,1
14	10,4	5,0	2,1
15	6,6	5,0	1,3
16	6,8	5,5	1,2
17	7,7	7,0	1,1
18	4,8	5,0	1,0
19	7,8	6,5	1,2
20	4,9	7,0	0,7
21	2,8	*	*
22	4,0	5,5	0,7
23	3,6	4,5	0,8
24	5,7	4,0	1,4
25	2,3	4,5	1,5

*Ratio irrelevant because of rain.
** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.6 CONSUMPTIVE USE BY PEAS AT VAN DER LINDE I

DATE	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
AUG. 19	26,3	4,3	6,1****
20	15,7	4,5	3,5****
21	9,3	4,5	2,1****
22	7,5	4,5	1,7
23	1,5	5,0	0,3
24	7,9	4,8	1,6
25	4,1	4,5	0,9
26	4,8	4,8	1,0
27	3,9	5,5	0,7
28	2,7	5,5	0,5
29	5,2	5,0	1,0
30	2,6	5,3	0,5
31	3,6	5,8	0,6
SEPT. 1	1,7	6,5	0,3
2	3,1	7,5	0,4
3	3,3	8,3	0,4
4	4,8	6,8	0,7

** PE = potential evaporation = A - pan reading x pan factor (Doorenbos & Pruitt,1977)
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.7 CONSUMPTIVE USE BY WHEAT AT VAN DER LINDE II

DATE (SEPTEMBER)	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
7	33,5	8,0	4,2****
8	18,9	8,5	2,2****
9	13,5	7,0	1,9****
10	8,8	9,0	1,0
11	14,6	8,0	1,8
12	6,5	3,5	*
13	6,0	5,5	1,1
14	4,5	5,0	0,9
15	10,1	5,0	2,0
16	4,6	5,5	0,8
17	6,0	7,0	0,9
18	8,6	5,0	1,7
19	5,1	6,6	0,7
20	8,0	7,0	1,1
21	3,7	0,0	*
22	6,0	5,5	1,1
23	4,2	4,5	0,9
24	4,0	4,0	1,0
25	5,6	4,5	1,2
26	2,9	5,0	0,6

*Ratio irrelevant because of rain.
** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.8 CONSUMPTIVE WATER USE BY PEAS AT VAN DER LINDE II

DATE		WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
AUG.	20	21,8	4,0	5,5****
	21	13,7	5,0	2,7****
	22	8,8	4,0	2,2****
	23	7,8	5,0	1,6****
	24	3,6	5,0	0,7
	25	3,8	4,5	0,8
	26	5,4	4,5	1,2
	27	4,5	5,0	0,9
	28	4,9	6,0	0,8
	29	2,0	5,0	0,4
	30	4,2	5,0	0,6
	31	4,2	5,5	0,8
SEPT.	1	4,3	6,0	0,7
	2	2,9	7,0	0,4
	3	1,2	8,0	0,2
	4	3,1	8,5	0,4
	5	3,9	5,0	0,8
	6	2,2	9,0	0,2
	7	2,5	8,0	0,3
	8	0,1	8,5	0,2
	9	3,4	7,0	*
	10	1,0	9,0	0,1

* value for 8 september probably wrong. Pooled data for 8 & 9 september.

** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).

*** Crop factor = Water extracted/PE.

**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 4.9 CONSUMPTIVE WATER USE BY WHEAT AT DEMONSTRATION PLOT

DATE (SEPTEMBER)	WATER EXTRACTED (mm)	PE ** (mm)	CROP FACTOR ***
7	40,4	8,0	5,1
8	23,8	8,5	2,8
9	14,8	7,0	2,1
10	16,9	9,0	1,9
11	10,0	8,0	1,3
12	9,1	3,5	2,6
13	5,2	5,5	1,0
14	11,2	5,0	2,2
15	6,3	5,0	1,3
16	8,1	5,5	1,5
17	7,7	7,0	1,1
18	5,1	5,0	1,1
19	7,9	6,5	1,2
20	3,1	7,0	0,4
21	5,6	*	*
22	3,5	5,5	0,6
23	4,0	4,5	0,9
24	5,8	4,0	1,5
25	2,5	4,5	0,6

*Ratio irrelevant because of rain.
** PE = potential evapotranspiration = A - pan reading x pan factor (Doorenbos & Pruitt, 1977).
*** Crop factor = Water extracted/PE.
**** Term crop factor not right for this part of the drying cycle (see Chapter 4).

APPENDIX 5.1 EXPERIMENTAL METHODOLOGY FOR THE IRRIGATION EFFICIENCY EXPERIMENTS WITH WHEAT AT VAALHARTS.

A.5.1.1 Introduction

Four different irrigation treatments, based upon the PAWC concept, were applied to wheat planted at five sites (Kamp I, II and III, and Van der Linde I and II). The following treatments, proposed by the project evaluation committee of the project, were applied:

a. 50% PAWC, i.e. the profile was filled to field capacity every time when a quantity of water amounting to 50% of PAWC was extracted.

b. 75% of PAWC

c. 100% of PAWC

d. 125% of PAWC

The PAWC values obtained for maize during 1982/83 were used since the values for wheat were not known yet. Experiments in the Ciskei have shown that PAWC values for maize and wheat are very similar.

A.5.1.2 Experimental design and general determinations

a. At each site 16 plots (3 x 3 m each) were laid out, to allow four replicates for each of the four treatments (see Figure A.5.1).

b. Around each experiment a 1,5 m wide band of wheat was planted to minimize border effects.

c. Soil water determinations were done by neutron probe. At each site one access tube was installed in each of two replicates of each treatment. It was not practically feasible to have an access tube in each plot.

d. All necessary climatic data (from the weather station at the research farm) and soil data (description, bulk density, penetrometer readings, etc.) were collected.

e. Crop development was rigorously monitored.

A.5.1.3 Agronomic practices

The same practices as used for the PAWC determinations for wheat at Vaalharts (see Chapter two) were applied. Planting dates were:

13/6: Kamp I and II

16/6: Kamp III

Van der Linde II

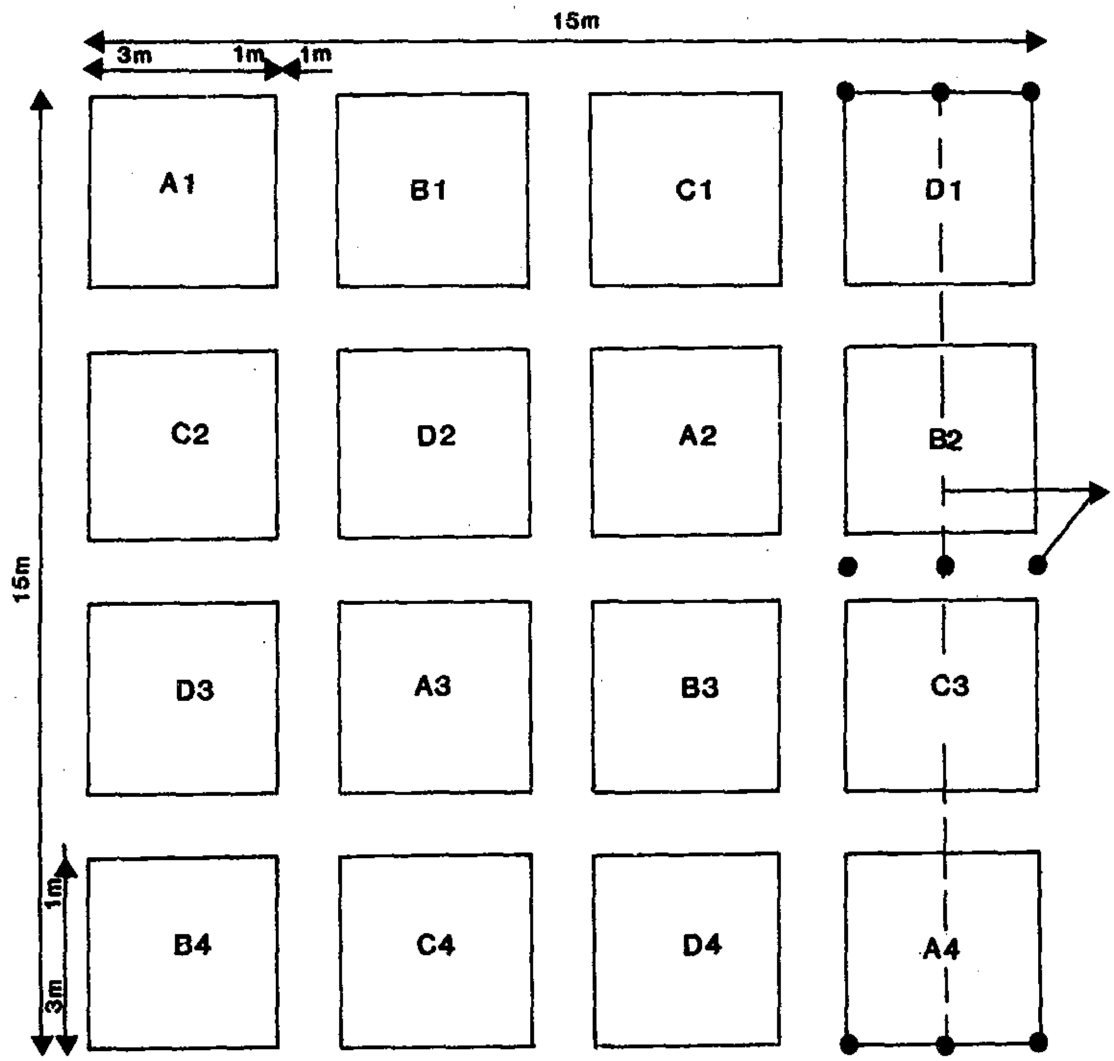


FIG.A.5.1 Layout of the experimental plots at Vaalharts. This design was used for the winter and summer experiments. During the summer experiments treatment D was changed to 25% PAWC.

17/6: Van der Linde II

A.5.1.4 Notes

a. Bird nets had to be installed immediately after planting to avoid loss of seed.

b. At a later stage the experiments had to be protected against rabbits.

c. Later in the season hail netting was installed to prevent hail and bird damage to the grain crop.

A.5.1.5 Water applications

a. All plots were brought to field capacity immediately before planting.

b. All plots received 50 mm water at crown root initiation. Irrigation was applied at regular intervals during the vegetative stage.

c. All plots were filled to field capacity at the start of flowering. Hereafter the different treatments were applied.

A.5.1.6 Yield determinations

The central 2 x 2 m section of each plot was harvested and grain yields determined. Yield per ha, per unit water and per ha per unit water were calculated. At this stage the PAWC values for wheat were known and the actual percentages of PAWC represented by the different treatments were calculated.

APPENDIX 5.2 EXPERIMENTAL PROCEDURES FOR THE IRRIGATION EFFICIENCY EXPERIMENT WITH MAIZE AT THE LOSKOP IRRIGATION SCHEME

A.5.2.1 Site

For logistic reasons a site at the Tobacco and Cotton research farm (Groblersdal) was selected. The soil found at the site (Contour 10) is a Shortlands (Kinross series, 25% to 35% clay content in the B horizon).

A.5.2.2 Experimental design

Four different treatments were applied:

a) 25% PAWC i.c. the profile was refilled to field capacity every time when 25% of PAWC was consumed.

b) 50% PAWC.

c) 75% PAWC.

d) 100% PAWC

Twelve plots were layed out, i.e. three replicates for each of the four treatments (see Figure A.5.2). A randomized block design was used. Each plot was 4x4 m in

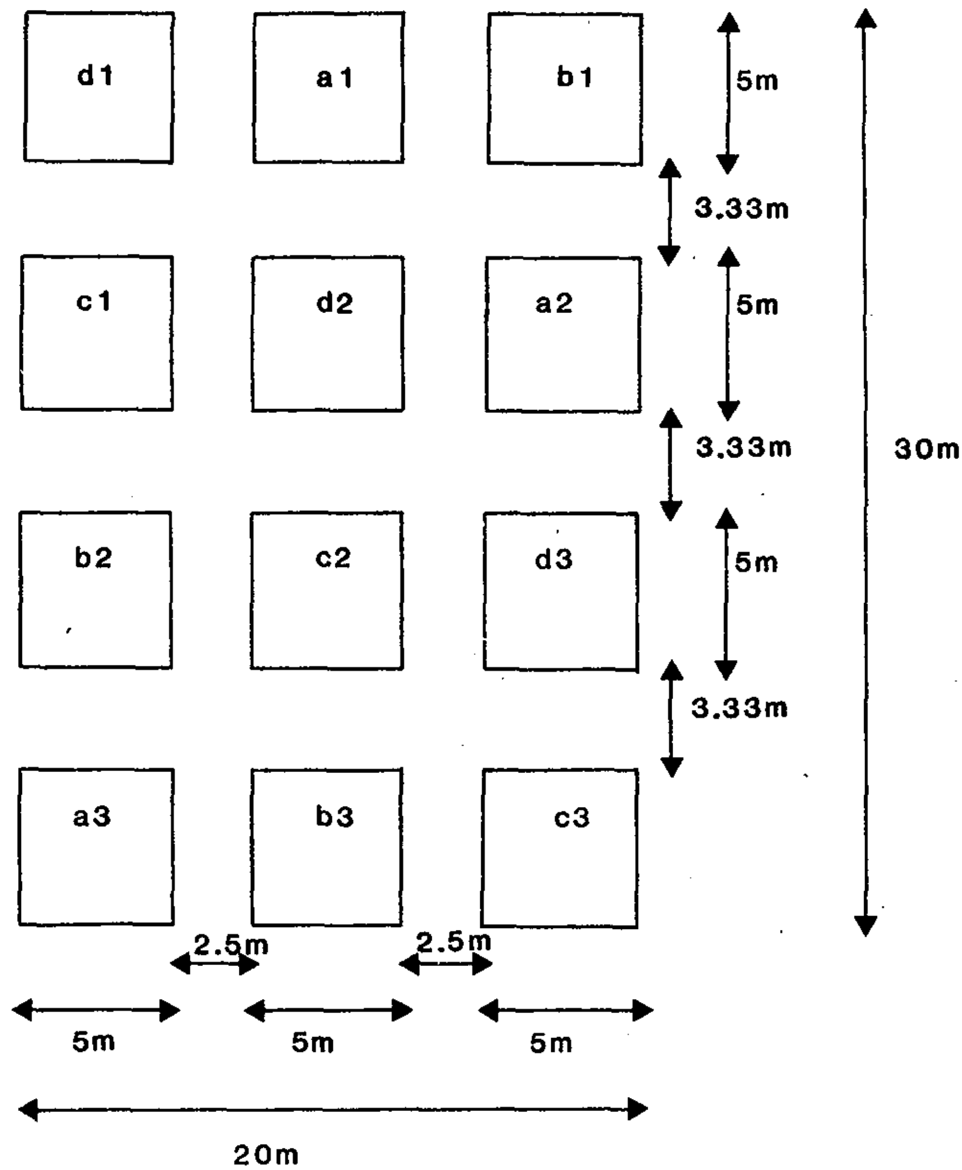


FIG.A.5.2 Layout of the experimental plots at Contour 10 (Loskop).

A = 25% PAWC
B = 50% PAWC
C = 75% PAWC
D = 100% PAWC

size.

Soil water determinations were done by neutron hydroprobe. An access tube was installed in each plot.

All necessary climatic and soil data were collected.

Crop development was rigorously monitored.

A.5.2.3 Agronomic practices

Because the plots were situated on a slightly sloping field (1-2%) it was decided to plant the maize on the ridges. This allowed distribution of water evenly over the plot (see Figure A.5.3). A water meter connected to the water supply permitted correct applications of water in each furrow.

Maize (cultivar SSM2039) was planted on 28-12-83. At planting a fertilizer application (4:1:0(30)) of 200kg/ha was given. This crop was sown in rows 90 cm apart with a spacing of 20 cm between each plant in a row (= 55 500 plants/ha).

Just after planting an irrigation of 50 mm was given to

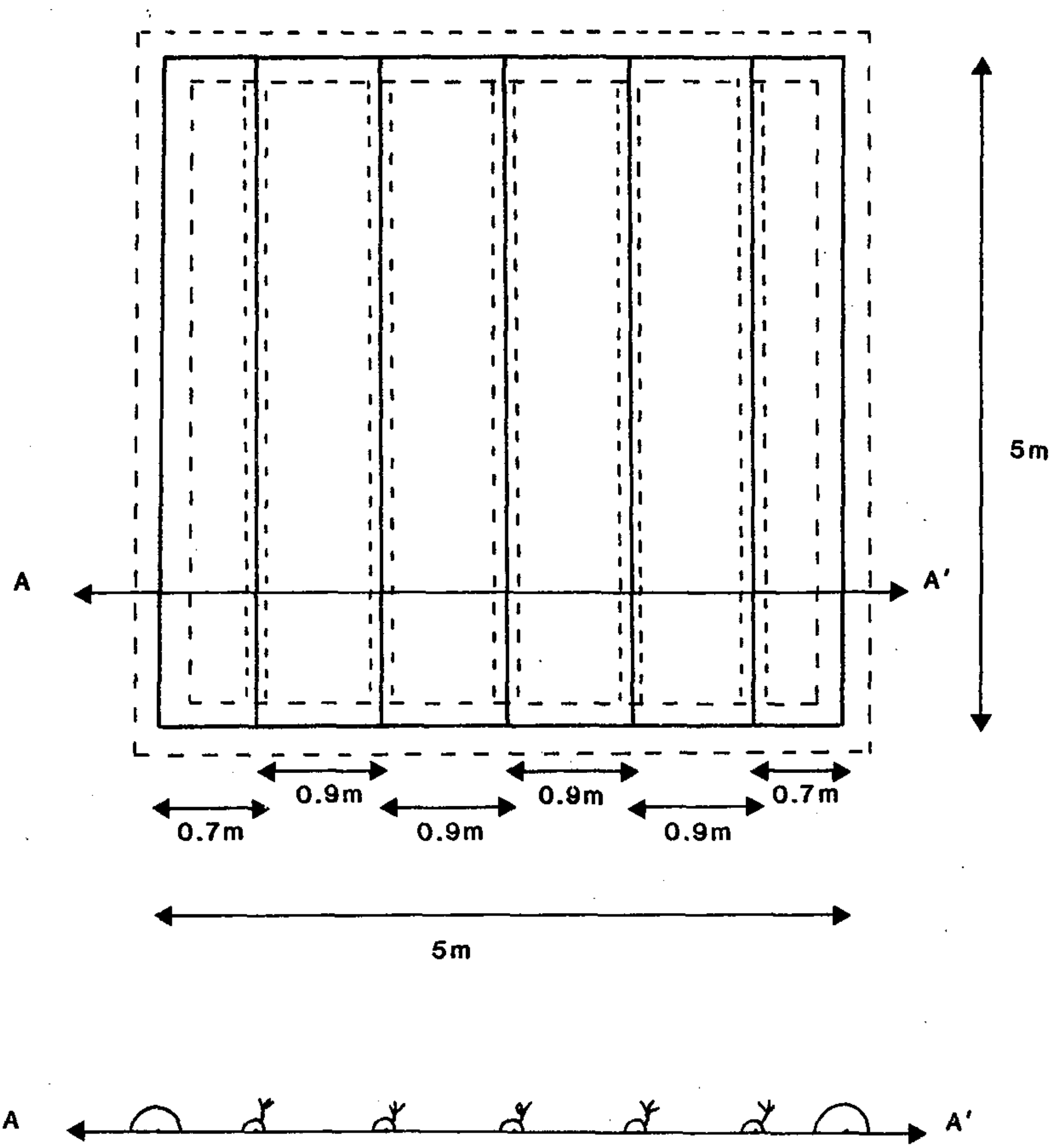


FIG.A.5.3 An experimental plot of the Loskop scheduling experiment in detail.

each plot. This water application, together with the rain that fell during the preceding day, brought the profile to field capacity.

Note: On all plots the plants were well established one week after planting.

A.5.2.4 Water applications

All plots received 50mm just after planting.

Until flowering all plots received adequate water.

At flowering all plots were filled to field capacity. Hereafter the different treatments were applied.

A.5.2.5 Yield determinations

The central 3 x 3 m section (50 plants) of each plot will be harvested and grain yields were determined. Yields per ha. and per ha. per unit water were calculated.

APPENDIX 5.3 EXPERIMENTAL PROCEDURES FOR THE IRRIGATION SCHEDULING EXPERIMENT IN THE FORT HARE LYSIMETER.

A.5.3.1 Description of the lysimeter

The lysimeter consists of 16 plots of 1500mm x 1500mm. The depth of the lysimeter at each plot is 1500mm. The walls of the lysimeter are waterprooF. Suction is applied to the base of the lysimeter by means of a suction pump which evacuates a coiled hose on the base of the lysimeter. Suction from the drainage tube is transmitted to the profile through perforations in the hose which are plugged with glass fibre wicks which in turn are embedded in diatomaceous earth. A cross section of the lysimeter is shown in Figure A.5.4 .

A.5.3.2 Experimental design

Grouped treatments were arranged sequentially in 4 replicates.

A.5.3.3 Agronomical practices.

The fertilizer application, planting densities and pest

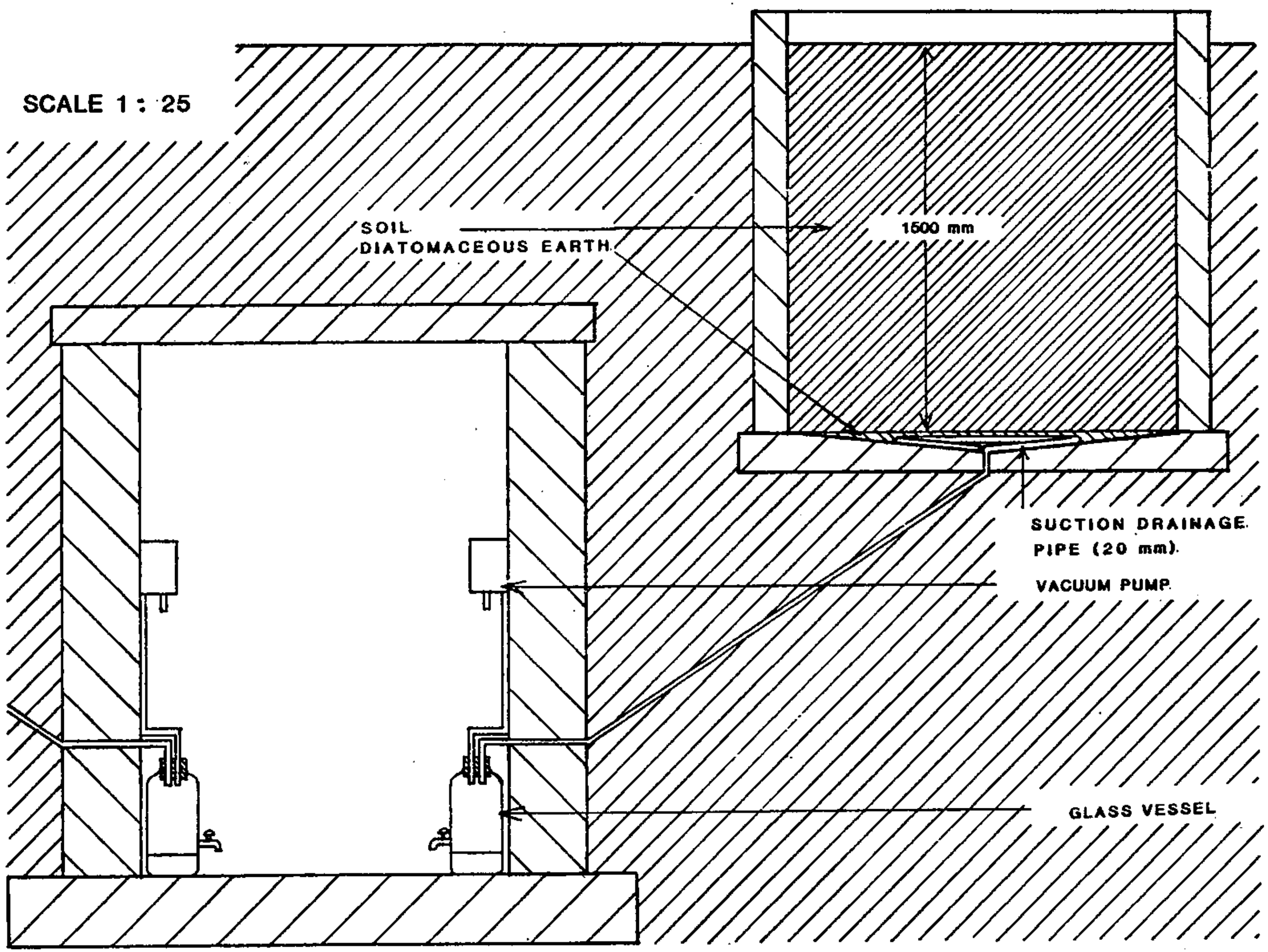


FIG.A.5.4 Cross section of a lysimeter plot.

and weed control were identical to the ones used during the PAWC determinations for wheat in the Ciskei (see paragraph 2.2.4).

A.5.3.4 Planned treatments

a. Completely adequate water:
Soil moisture was raised to Field Capacity (FC) at intervals of 4 days. Soil moisture content were determined by neutron hydroprobe.

b. Irrigation applied at 50% depletion of PAWC i.e. after 75mm water has been consumed.

c. Irrigation at first stress 1 (FS1):
Soil recharged to FC at FS 1 and also at flowering if required. FS 1 taken to occur at leaf water potential of more or less 1000kPa.

d. Irrigation at FS 2 and also at flowering (if necessary). FS 2 (well defined stress) taken to occur at leaf water potential of more or less 1500 kPa.

Note: In effect the actual treatments applied differed from these. See chapter 5.

A.5.3.5 Data collected

A.5.3.5.1 Soil moisture determinations were made by neutron hydroprobe:

a. On all lysimeter plots soil moisture measurements were made at planting and thereafter at intervals of 4 days and immediately before watering.

b. In treatments FS 1 and FS 2 measurements were done daily from the time that leaf water potentials attained values of -500 kPa untill FS1 or FS2 was reached.

A.5.3.5.2 Determination of leaf water potential.

<u>All treatments</u> were measured at:

(i) 4 day intervals and

(ii) immediately before watering

<u>Treatments FS 1 and FS 2</u>

(iii) measurements were done daily from time that leaf water potentials declined to -500 kPa untill FS1 or FS2 was reached.

A.5.3.5.3 Quantity of percolate was determined in all lysimeters

(i) at 4 day intervals and

(ii) immediately before applying water

APPENDIX 5.4 Results: irrigation scheduling experiment

SITE: Kamp I
PLANTINGDATE: 13-06-'83

CROP: Wheat
RAIN: 97 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
50a	5050	471
50b1	5913	448
50b2	5020	448
50b3	6253	448
75a	5135	427
75b1	5248	440
75b2	3552	440
75b3	6570	440
100a	4420	362
100b1	4140	353
100b2	3743	353
100b3	5120	353
125a	2228	172
125b1	3758	185
125b2	2245	185
125b3	2810	185

Note: a indicates a corner plot (see also Appendix 5.1).

APPENDIX 5.5 Results:irrigation scheduling experiment

SITE: Kamp II | CROP: Wheat
PLANTINGDATE: 13-06-'83 | RAIN: 209 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
50a	5640	524
50b1	3648	524
50b2	5305	524
50b3	4478	524
75a	5430	549
75b1	3755	539
75b2	3755	539
75b3	3755	539
100a	3363	421
100b1	3363	421
100b2	3850	421
100b3	4385	421
125a	840	341
125b1	1405	375
125b2	2590	375
125b3	2993	375

Note: a indicates a corner plot (see Appendix 5.1)

APPENDIX 5.6 Results:irrigation scheduling experiment

SITE: V.d.Linde I | CROP: Wheat
PLANTINGDATE: 16-06-'83 | RAIN: 97 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
50a	2703	585
50b1	3393	585
50b2	2880	585
50b3	2785	585
75a	2398	588
75b1	3445	576
75b2	2738	576
75b3	2808	576
100a	1873	439
100b1	2808	439
100b2	2653	439
100b3	2913	439
125a	1525	359
125b1	1395	359
125b2	1510	359
125b3	1378	359

Note: a indicates a corner plot (see Appendix 5.1).

APPENDIX 5.7 Results:irrigation scheduling experiment

SITE: V.d.Linde II CROP: Wheat
PLANTINGDATE: 16-06-'83 RAIN: 97 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
50a	4528	611
50b1	2566	567
50b2	4723	567
50b3	4420	567
75a	4453	591
75b1	4335	614
75b2	4403	614
75b3	4885	614
100a	4175	490
100b1	3478	490
100b2	3778	490
100b3	3755	490
125a	3600	372
125b1	2718	372
125b2	1823	372
125b3	3558	372

Note: a indicates a corner plot (see Appendix 5.1)

APPENDIX 5.8 Results: irrigation scheduling experiment

SITE: Kamp I CROP: Maize
PLANTINGDATE: 21-11-'83 RAIN: 303 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
25a	5508	1607
25b1	8427	1085
25b2	8439	1085
25b3	8631	1085
50a	5498	1174
50b1	8101	1051
50b2	6383	1091
50b3	7540	1091
75a	8167	850
75b1	10336	1007
75b2	4993	1007
75b3	5089	1007
100a	5147	665
100b1	7166	774
100b2	5322	774
100b3	2797	774

Note: a indicates a corner plot (see Appendix 5.1).

APPENDIX 5.9 Results:irrigation scheduling experiment

SITE: Kamp II CROP: Maize
PLANTINGDATE: 6-12-'83 RAIN: 197 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
25a	11210	895
25b1	11580	892
25b2	10305	892
25b3	11063	892
50a	8230	945
50b1	12824	827
50b2	10344	827
50b3	10876	827
75a	10601	962
75b1	9307	872
75b2	9660	872
75b3	10328	872
100a	7842	873
100b1	9515	651
100b2	8881	651
100b3	8986	651

Note: a indicates a corner plot (see Appendix 5.1)

APPENDIX 5.10 Results; irrigation scheduling experiment

SITE: V.d.Linde I CROP: Maize
PLANTINGDATE: 21-11-'83 RAIN: 303 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
25a	5112	1155
25b1	5187	1155
25b2	5402	1155
25b3	6117	1155
50a	5849	1057
50b1	6746	1057
50b2	3660	1057
50b3	5897	1057
75a	4631	972
75b1	5079	972
75b2	5017	972
75b3	4465	972
100a	2965	824
100b1	4738	824
100b2	2154	824
100b3	2814	824

Note: a indicates a corner plot (see Appendix 5.1)

APPENDIX 5.11 Results:irrigation scheduling experiment

SITE: V.d.Linde II
PLANTINGDATE: 18-11-'83

CROP: Maize
RAIN: 303 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
25a	7434	1065
25b1	7182	1077
25b2	7709	1077
25b3	8329	1077
50a	6989	1022
50b1	6608	1039
50b2	7296	1039
50b3	8953	1039
75a	7473	842
75b1	7570	852
75b2	7096	852
75b3	7991	852
100a	5796	732
100b1	6712	744
100b2	7469	744
100b3	4521	744

Note: a indicates a corner plot (see Appendix 5.1)

APPENDIX 5.12 Results: irrigation scheduling experiment

SITE: Contour 10 CROP: Maize
PLANTING DATE: 28-12-'83 RAIN: 197 mm

Plot No.	Yield (kg/ha)	Seasonal water use (mm)
25a1	7987	572
25a2	7310	572
25a3	8767	572
50b1	6432	531
50b2	7553	531
50b3	8332	531
75c1	7205	501
75c2	7541	501
75c3	6858	501
100d1	4757	418
100d2	4878	418
100d3	4426	418

APPENDIX 5.13 Results:irrigation scheduling experiment on the Fort Hare lysimeter

	Yield (kg/ha)		
	Treatment a	Treatment b	Treatment c
Lysimeter No.	1. 5728,0	5. 5838,5	9. 2207,4
	2. 5728,0	6. 4625,6	10. 4242,7
	3. 5874,5	7. 5766,5	11. 2415,6
	4. 5543,0	8. 5959,3	12. 2595,5
			13. 2803,6
			14. 2467,0
			15. 3160,8
			16. 2564,6
	Least significant difference = 1311kg/ha		
Water Application (litres)	1473,4	950,9	770,8